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## Optical Parametric Generation, Amplification, and Oscillation

Several areas of research, such as spectroscopy, semiconductor analysis, photochemistry, and remote sensing, have need of a tunable coherent source of high-power or high-energy radiation. Rugged solid state devices are desired to replace tunable dye lasers to avoid, among other things, the handling of toxic materials and requisite changing of dyes due to their continual photodegradation. In addition, a wider tuning range, especially into the near- and far-infrared, is needed.

For three decades, the development of nonlinear optical parametric devices has held the promise of providing these qualities. In 1965, Giordmaine and Miller [1] built and demonstrated the first tunable optical parametric oscillator. After this pioneering effort, the 1960s witnessed rapid progress in the field. Chromatix introduced a commercial product early in the research and development cycle [2], but it did not remain on the market. The pace of the research slowed as new and better nonlinear materials came under development. Recently, with improvements in materials and laser pump sources, new commercial products have emerged, such as a high-energy nanosecond pulse source tunable from 400 to 2000 nm (Spectra-Physics MOPO-700 series) [3], a femtosecond pulse source tunable across the 1.3 to 1.5  $\mu\text{m}$  telecommunications window (Spectra-Physics Opal) [4], and a device tunable further into the mid-IR, from 1.4–4.6  $\mu\text{m}$  (Continuum Mirage 3000) [5].

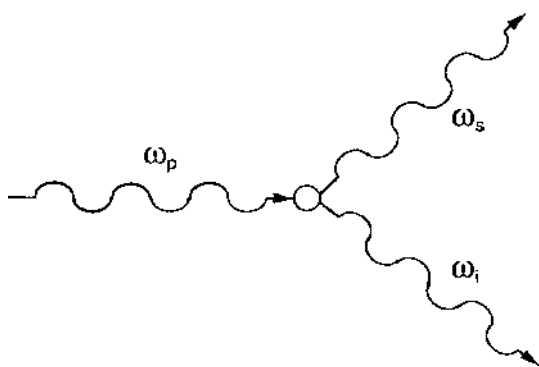
As these devices find their way into new research and applications markets, new devices are continually under development. In addition, optical parametric generation is continuing to be exploited in fundamental research areas.

Parametric devices have been used to generate a nonclassical form of radiation called squeezed light. Optical parametric generation has also been a key element in studying some fundamental properties of quantum mechanics, such as the observation of correlated quantum states.

In this chapter, the major formulas relating to the performance of optical parametric devices are summarized. Spontaneous parametric fluorescence, a quantum mechanical phenomenon key to the operation of optical parametric amplifiers and oscillators, is described first. Parametric gain is introduced and is used in the description of the optical parametric amplifier (OPA). Finally, the bulk of the chapter will be devoted to a discussion of the optical parametric oscillator (OPO). This includes formulas relating to threshold pump power or energy, optical power conversion efficiency, stability, and tuning.

## I. PARAMETRIC FLUORESCENCE

Optical parametric generation (OPG) is illustrated schematically in Fig. 1. A photon of frequency  $\omega_p$  is incident on a nonlinear medium and spontaneously splits into two lower-frequency (and hence lower-energy) photons. These are called the signal photon of frequency  $\omega_s$  and the idler photon of frequency  $\omega_i$ . To conserve energy,  $\omega_p = \omega_s + \omega_i$ . This phenomenon is somewhat analogous to spontaneous Raman or Brillouin scattering with the exceptions that both particles created in the scattering are photons and not, for example, phonons, and that no real material excitation is involved. The material rather acts as a catalyst, generating the new photons through the nonlinear polarization. Optical parametric generation is



**Figure 1** Spontaneous parametric fluorescence in which a pump photon of energy  $\hbar\omega_p$  splits into two photons of energy  $\hbar\omega_s$  (signal) and  $\hbar\omega_i$  (idler).

a strictly quantum mechanical effect that was first predicted and studied by Louisell et al. [6].

Theoretically, parametric fluorescence is treated semiclassically [7,8]. The pump photons are associated with a strong laser field, which has a high photon number and can thus be treated as an approximately constant classical field. A quantized field approach is used for the signal and idler fields, which interact via a perturbation Hamiltonian, based on the second order susceptibility  $\chi^{(2)}$ , and includes the pump field. The average photon numbers for the signal and idler fields are then computed using first order perturbation theory.

The time dependent perturbation results for the average photon numbers are given in Table 1. It can be seen from these equations that the pump field drives the generation of signal and idler photons through the nonlinear polarization, and the number of signal and idler photons grows in time. An equivalent result exhibiting a spatial rather temporal dependence can be obtained by making the substitution  $t \rightarrow (n_s n_i)^{1/2} z/c$ .

Note that when there are no input signal or idler photons (i.e.,  $\langle n_s(0) \rangle = \langle n_i(0) \rangle = 0$ ), these photons are still generated due to the unity factors in the equations of Table 1. These are the spontaneous emission terms. These new packets of energy can be interpreted as being generated by the negative work performed by zero-point vacuum fluctuations of the signal and idler fields interacting with the nonlinear polarization. Effectively, these quantum fluctuations are equivalent to the presence of  $\frac{1}{2}$  photon in both the signal and the idler modes at  $t = 0$ , or one photon in either mode.

The zero-point fluctuations, interacting with the pump field, produce a nonlinear polarization that attempts to radiate at all frequencies in all directions. The only restriction is that energy be conserved. However, the growth of optical radiation is favored by those frequencies and directions that approximately satisfy the phase matching condition introduced in Chapter 2 (i.e.,  $\Delta k \simeq 0$ ).

**Table 1** Formulas for Calculating Numbers of Signal and Idler Photons Produced in Parametric Fluorescence

Average signal photon number

$$\langle n_s(t) \rangle = \langle n_s(0) \rangle \cosh^2(\tfrac{1}{2} G_0 t) + (1 + \langle n_i(0) \rangle) \sinh^2(\tfrac{1}{2} G_0 t)$$

Average idler photon number

$$\langle n_i(t) \rangle = \langle n_i(0) \rangle \cosh^2(\tfrac{1}{2} G_0 t) + (1 + \langle n_s(0) \rangle) \sinh^2(\tfrac{1}{2} G_0 t)$$

Gain coefficient

$$G_0 = 8\pi d_{\text{eff}} \sqrt{\frac{cI_p(0)}{2\varepsilon_0 n_p n_s^2 n_i^2 \lambda_s \lambda_i}} \frac{\sin(\Delta k L/2)}{(\Delta k L/2)} \quad (\text{SI})$$

$$G_0 = 32\pi^2 d_{\text{eff}} \sqrt{\frac{2\pi c I_p(0)}{n_p n_s^2 n_i^2 \lambda_s \lambda_i}} \frac{\sin(\Delta k L/2)}{(\Delta k L/2)} \quad (\text{cgs})$$

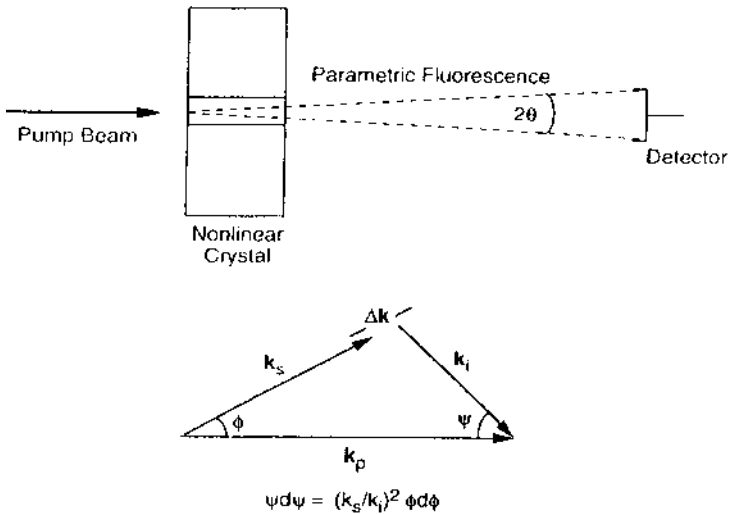
Modes that nearly satisfy this condition are amplified (stimulated emission) as shown by the equations in Table 1. The form of these equations is identical to those given in Chapter 2 for difference-frequency generation under the condition of equal photon fluxes for the pump 2 and difference-frequency waves. Thus, optical parametric generation is formally equivalent to DFG.

Two important experimental parameters in parametric fluorescence are the radiated signal power and bandwidth. Although conservation of energy permits any signal frequency from 0 to  $\omega_p$  that could be radiated in any direction, the signal will peak at that frequency and direction that yields the best phase matching. The phase matching diagram is given in Fig. 2.

There are a finite number of blackbody modes in the vicinity of a particular frequency  $\omega_{i0}$  that act as effective inputs for generating the signal power. One idler photon in each of these modes collectively comprises the incremental input idler intensity. The pump wave then mixes with all possible idler modes to generate the signal modes. A sum over all signal modes yields the net signal power generated [7–9].

A finite phase mismatch in the parametric fluorescence process is due to two sources: (1) a finite input bandwidth of frequencies  $\Delta\omega = -(\omega_i - \omega_{i0}) = \omega_s - \omega_{s0}$ , where the subscript 0 refers to that frequency for which there is perfect phase matching; (2) an angular spread in signal and idler wave vectors as shown in Fig. 2. The phase mismatch is given by

$$\Delta k = a\phi^2 - b\Delta\omega \quad (1)$$



**Figure 2** Optical parametric generation and signal power collection geometry.

where

$$a = \frac{k_s k_p}{2k_i} \quad (2)$$

and

$$b = \left( \frac{dk_s}{d\omega_s} \right)_{\omega_s=\omega_{s0}} - \left( \frac{dk_i}{d\omega_i} \right)_{\omega_i=\omega_{i0}} \quad (3)$$

The physical quantity of interest is the net signal power collected by the detector, which subtends an angle  $2\theta$  at the nonlinear crystal as shown in Fig. 2. (Instead of a detector, the geometry also applies to the aperture of a second nonlinear crystal serving as an OPA. See Sections II and VI.A below.) The results are given in Table 2. The net signal power is dependent on the pump power and the nonlinear coefficient  $d_{\text{eff}}$ , which was described in Chapter 2. The integrand contains the effects of the parametric gain coefficient  $g$  (see Section II below) and the phase mismatch.

For small gain,  $(gL)^2 \ll (aL\phi^2 - bL\Delta\omega)^2/4$ , and therefore  $\sinh \rightarrow \sin$ . The spectral power distribution ( $d\mathcal{P}_s/d\omega_s$ ) under this condition is also given in Table 2. Plots of this distribution are given in Fig. 3 (see [10] for experimental data). The fixed parameter in these plots is  $\Phi = aL\theta^2$ . To understand the meaning of this number, consider the case near degeneracy (i.e.,  $\omega_s = \omega_i = \omega_p/2$ ). Then from Eq. (2),  $a \sim k_s$ . Taking typical values of  $k_s \sim 10,000 \text{ cm}^{-1}$  and  $L \sim 1 \text{ cm}$ , the values of  $\Phi$  in Fig. 3 would correspond to  $\theta \sim 10\text{--}50 \text{ mr}$  (i.e.,  $<0.1^\circ$  to  $\sim 0.3^\circ$ ). For the parameter  $\Delta$ , taking  $b \sim 0.1/c$  and  $L \sim 1 \text{ cm}$ ,  $\Delta \sim \Delta\sigma$ , where  $\sigma$  is the frequency in wave numbers ( $\text{cm}^{-1}$ ). Therefore the abscissas of these plots can be read as approximately the frequency spread in  $\text{cm}^{-1}$ .

It can be seen that for small angles (e.g.,  $\Phi = 1$ ) the spectral distribution is peaked around the frequency corresponding to perfect phase matching along the pump beam axis and has the typical  $\text{sinc}^2$  dependence with a bandwidth independent of angle, as shown in Table 2. For larger angles, this distribution grows and spreads, since more power is collected by the detector. As shown in Table 2, the bandwidth grows as  $\theta^2$ . For  $\omega_s > \omega_i$ , normal dispersion requires that  $b > 0$ . Therefore as  $\theta$  increases,  $\omega_s$  must increase for optimum phase matching, as illustrated in Fig. 2. If  $\omega_s < \omega_i$ , the opposite would be true.

For small gain, the integral over frequency can be performed [7–9]. The result, given in Table 2, shows that the signal power grows linearly with pump power and crystal length, and quadratically with collection angle.

The bandwidth, discussed above, is typically defined by the condition where the phase matching  $\text{sinc}^2$  curve first crosses zero at  $\Delta kL = 2\pi$  (see Fig. 3 in Chapter 2. Note that the bandwidth in Chapter 2 for frequency conversion processes was defined in terms of the full width at half maximum (FWHM) of

**Table 2** Formulas Relating to the Total Signal Power Generated by Parametric Fluorescence and Collected by a Detector Subtending an Angle  $2\theta$  at the Nonlinear Crystal

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Signal power collected in angle  $2\theta$

$$\mathcal{P}_s = \beta \mathcal{P}_p L^2 \int_{-\infty}^{\infty} d\omega_s \int_0^{\theta} \frac{\sinh^2(\sqrt{g^2 - (a\phi^2 - b\Delta\omega)^2/4L})}{[g^2 - (a\phi^2 - b\Delta\omega)^2/4]L^2} \phi d\phi$$

$$\beta = \frac{\hbar\omega_i\omega_s^4 n_s d_{\text{eff}}^2}{2\pi^2 \epsilon_0 n_i n_p c^5} \quad (\text{SI}) \quad \beta = \frac{8\pi\hbar\omega_i\omega_s^4 n_s d_{\text{eff}}^2}{n_i n_p c^5} \quad (\text{cgs})$$

$$g^2 = \frac{2\omega_s\omega_i d_{\text{eff}}^2 I_p}{\epsilon_0 n_p n_s n_i c^3} \quad (\text{SI}) \quad g^2 = \frac{128\pi^3 \omega_s\omega_i d_{\text{eff}}^2 I_p}{n_p n_s n_i c^3} \quad (\text{cgs})$$


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Signal power spectral distribution for small gain ( $g^2 \ll (a\phi^2 - b\Delta\omega)^2/4$ )

$$\frac{d\mathcal{P}_s}{d\omega_s} \approx \beta \mathcal{P}_p L^2 \int_0^{\theta} \frac{\sin^2[(aL\phi^2 - bL\Delta\omega)/2]}{[(aL\phi^2 - bL\Delta\omega)/2]^2} \phi d\phi$$


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Small gain ( $g^2 \ll (a\phi^2 - b\Delta\omega)^2/4$ )

Signal power

$$\mathcal{P}_s \approx \frac{\pi\beta L \mathcal{P}_p}{|b|} \theta^2$$

Bandwidth

$$\Delta\omega_s \approx \frac{\pi}{|b|L} \quad \text{small } \theta$$

$$\Delta\omega_s \approx \frac{a\theta^2}{|b|} \quad \theta > \sqrt{2\pi/aL}$$


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High gain ( $g^2 \gg a\phi^2$ )

Signal power

$\mathcal{P}_s = \text{numerical integration of formula above}$

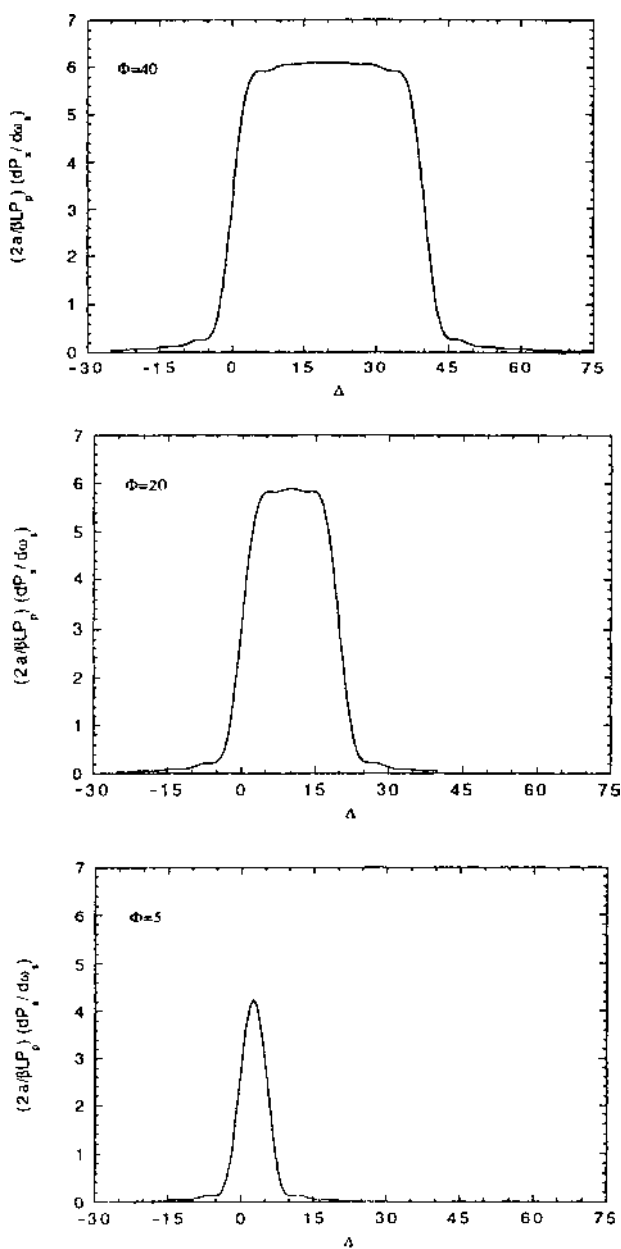
Bandwidth

$$\Delta\omega_s = \frac{2}{|b|} \sqrt{\frac{2g}{L} \ln 2}$$

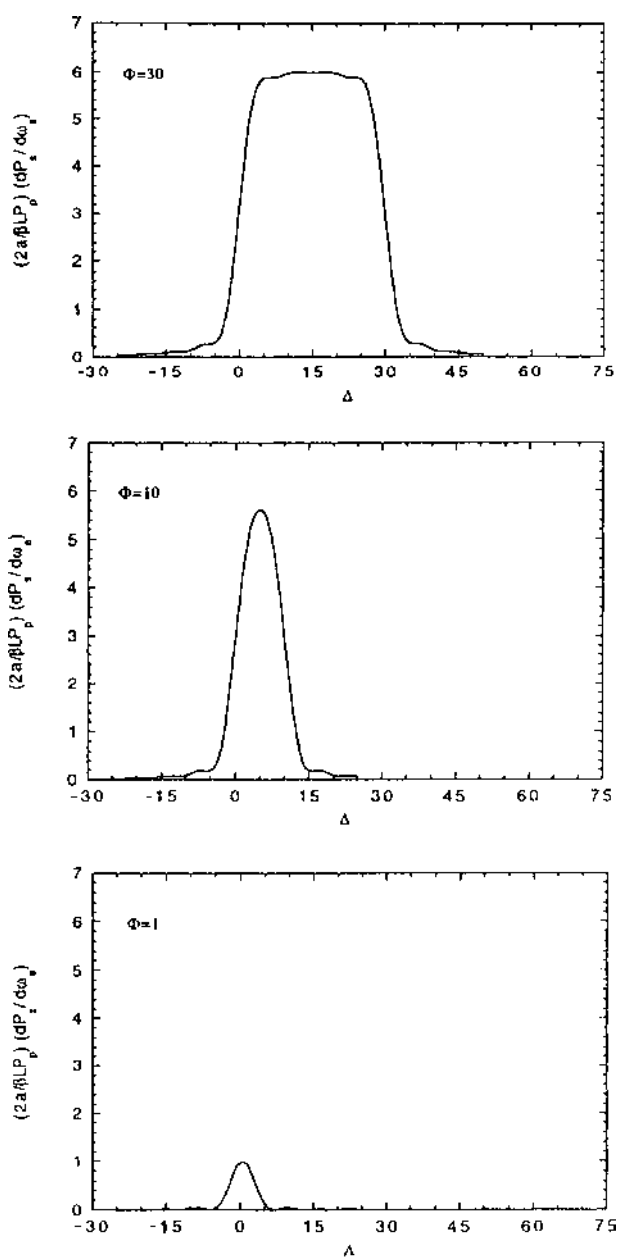

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the  $\text{sinc}^2$  curve. The reader should be aware that bandwidths are defined either way in other texts). For small gain and small angles, the bandwidth is angle independent, but it grows quadratically with collection angle for  $\theta > (2\pi/aL)^{1/2}$ .

For large gain ( $g^2 \gg a\phi^2$ ), the integral must be solved numerically to determine the signal power. The bandwidth in this case is seen to be gain dependent [7]. Note that materials with low dispersion, such that the reciprocal group velocities of the signal and idler waves are nearly equal (i.e.,  $b$  is small), will have large bandwidths. The bandwidth does not actually diverge, even at the degeneracy point, since higher-order group velocity dispersion terms come into play to limit the bandwidth (see Section III.C below).



**Figure 3** Normalized signal spectral power distribution as a function of normalized frequency shift  $\Delta$  from the on-pump-axis perfectly phase matched frequency for several normalized detector collection angles  $\Phi$ .



**Figure 3** Continued.

## II. PARAMETRIC AMPLIFICATION

The physical situation associated with an OPA is that of a pump wave and a signal wave incident on a nonlinear medium. Through the DFG process, the signal wave is amplified, and the idler wave is generated at the difference frequency. This process was described in Chapter 2. Since the one-pass gain through the nonlinear crystal is modest, the process can be described in the nondepleted pump approximation.

The result for the idler wave was given in Table 6 of Chapter 2. Table 3 of the present chapter gives the result for the signal power at the output of the crystal. The parametric gain  $G$  is defined through

$$\frac{\mathcal{P}_s(L)}{\mathcal{P}_s(0)} = 1 + G \quad (4)$$

where the expression for  $G$  is given in Table 3. The important parameter determining the maximum parametric gain is the gain coefficient  $g$ . It can be seen that the gain coefficient is related to the characteristic nonlinear length scale introduced in Chapter 2, i.e.,  $g = (L_{\text{NL}})^{-1}$ .

For small gain, the usual case,  $G$  is given by  $(gL)^2$  multiplied by the  $\text{sinc}^2$  phase matching curve. For perfect phase matching,  $G \approx (gL)^2$ . Formulas for the gain coefficient  $g$  are given in Table 4. Three general conditions are discussed: (1) infinite plane waves; (2) near-field focused Gaussian beams; and (3) optimized tightly focused Gaussian beams, including the effects of double refraction.

**Table 3** Formulas for the Signal Power Gain in an OPA

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$$\begin{aligned} \frac{\mathcal{P}_s(L)}{\mathcal{P}_s(0)} &= 1 + (gL)^2 \frac{\sinh^2(\sqrt{(gL)^2 - (\Delta kL/2)^2})}{(gL)^2 - (\Delta kL/2)^2} \\ &\equiv 1 + G \end{aligned}$$

$$g = 4\pi d_{\text{eff}} \sqrt{\frac{I_p(0)}{2\epsilon_0 n_p n_s n_i c \lambda_s \lambda_i}} \quad (\text{SI}) \qquad g = 16\pi^2 d_{\text{eff}} \sqrt{\frac{2\pi I_p(0)}{n_p n_s n_i c \lambda_s \lambda_i}} \quad (\text{cgs})$$


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Small gain ( $\Delta k/2 \gg g$ )

$$G \approx (gL)^2 \frac{\sin^2(\Delta kL/2)}{(\Delta kL/2)^2}$$


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Small gain ( $\Delta k = 0$ )

$$G \approx (gL)^2$$


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**Table 4** Formulas for Calculating the Small Signal Parametric GainPlane waves ( $A$  = beam area)

$$(gL)^2 = \frac{16\pi^2 d_{\text{eff}}^2 L^2}{\epsilon_0 n_0^2 c \lambda_0^2} \mathcal{P}_p (1 - \delta^2) \frac{1}{2n_p A} \quad (\text{SI})$$

$$(gL)^2 = \frac{1024\pi^5 d_{\text{eff}}^2 L^2}{n_0^2 c \lambda_0^2} \mathcal{P}_p (1 - \delta^2) \frac{1}{2n_p A} \quad (\text{cgs})$$

Near-field Gaussian beams

$$(gL)^2 = \frac{16\pi^2 d_{\text{eff}}^2 L^2}{\epsilon_0 n_0^2 c \lambda_0^2} \mathcal{P}_p (1 - \delta^2) \frac{4M^2}{\pi n_p} \quad (\text{SI})$$

$$(gL)^2 = \frac{1024\pi^5 d_{\text{eff}}^2 L^2}{n_0^2 c \lambda_0^2} \mathcal{P}_p (1 - \delta^2) \frac{4M^2}{\pi n_p} \quad (\text{cgs})$$

$$M = \frac{w_s w_i w_p}{w_s^2 w_i^2 + w_s^2 w_p^2 + w_i^2 w_p^2}$$

$$M_{\text{max}}^2 = \frac{1}{4(w_s^2 + w_i^2)} \quad \text{for} \quad \frac{1}{w_p^2} = \frac{1}{w_s^2} + \frac{1}{w_i^2}$$

Optimized confocal near-field Gaussian beams

$$(gL)^2 = \frac{16\pi^2 d_{\text{eff}}^2 L^2}{\epsilon_0 n_0^2 c \lambda_0^2} \mathcal{P}_p (1 - \delta^2) \frac{1}{\lambda_0 L} \quad (\text{SI})$$

$$(gL)^2 = \frac{1024\pi^5 d_{\text{eff}}^2 L^2}{n_0^2 c \lambda_0^2} \mathcal{P}_p (1 - \delta^2) \frac{1}{\lambda_0 L} \quad (\text{cgs})$$

Optimized confocal tightly focused Gaussian beams (including double refraction)

$$(gL)^2 = \frac{16\pi^2 d_{\text{eff}}^2 L^2}{\epsilon_0 n_0^2 c \lambda_0^2} \mathcal{P}_p (1 - \delta^2) \frac{\bar{h}_m(B, \xi)}{\lambda_0 L} \quad (\text{SI})$$

$$(gL)^2 = \frac{1024\pi^5 d_{\text{eff}}^2 L^2}{n_0^2 c \lambda_0^2} \mathcal{P}_p (1 - \delta^2) \frac{\bar{h}_m(B, \xi)}{\lambda_0 L} \quad (\text{cgs})$$

$\bar{h}_m(B, \xi)$  given in [Fig. 4](#)

$$\lambda_0 = 2\lambda_p \quad \lambda_s = \frac{2\lambda_p}{1 + \delta} \quad \lambda_i = \frac{2\lambda_p}{1 - \delta}$$

$$n_0 \simeq n_s \simeq n_i$$

$$0 \leq \delta \leq 1$$

## A. Infinite Plane Waves

When the sizes of the interacting beams are large compared to the crystal length and aperture length of the crystal (see Chapter 2), the infinite plane wave approximation can be used. Note that the dependence of the parametric gain in the low gain limit is the same as that for frequency conversion efficiency, i.e., the gain is proportional to  $d_{\text{eff}}^2/n^3$ ,  $L^2$ , and  $I_p$ .

The gain coefficient is given in terms of a degeneracy factor  $\delta$  defined through

$$\begin{aligned}\omega_s &= \frac{1}{2}\omega_p(1 + \delta) \\ \omega_i &= \frac{1}{2}\omega_p(1 - \delta)\end{aligned}\tag{5}$$

The limits of  $\delta$  are 0 and 1, with  $\delta = 0$  corresponding to the degenerate point. The gain coefficient is maximum at the degenerate point. The degenerate wavelength is defined as  $\lambda_0 = 2\lambda_p$ , and  $n_0$  is the refractive index at degeneracy, with  $n_0 \simeq n_s \simeq n_i$ . Although the gain is maximized at the degenerate point, the bandwidth increases dramatically there also (See Section III.C). The price for operating off degeneracy is that the small signal gain decreases as  $1 - \delta^2$ .

## B. Focused Gaussian Beams (Near-Field)

To increase the parametric gain, the beams are often focused. Optical parametric amplification in the near field with no double refraction is considered in this section. This approximation is valid when the crystal thickness is less than or on the order of the confocal parameters of the interacting beams, and the aperture length is large, or NCPM conditions are imposed.

When the interacting beams have a Gaussian radial dependence, they are generally not optimally overlapped. This is because the nonlinear driving polarization beam is smaller than the beams that generate it. For example, the polarization source at the signal frequency would be proportional to

$$\exp\left(\frac{-2r^2}{w_p^2}\right)\exp\left(\frac{-2r^2}{w_i^2}\right) = \exp[-2r^2(w_p^{-2} + w_i^{-2})] = \exp\left(\frac{-2r^2}{w_s'^2}\right)\tag{6}$$

where  $w_p$  and  $w_i$  are the  $1/e^2$  radii of the pump and idler beams, respectively. In general  $w_s' \neq w_s$ , the  $1/e^2$  radius of the signal beam. Since the beams are not optimally overlapped, this produces a reduction in the gain coefficient from the plane wave value. The key factor is the near field gain reduction parameter  $M^2$  given in Table 4 [9].

For fixed values of the signal and idler radii,  $M^2$  is maximized for a pump radius given by

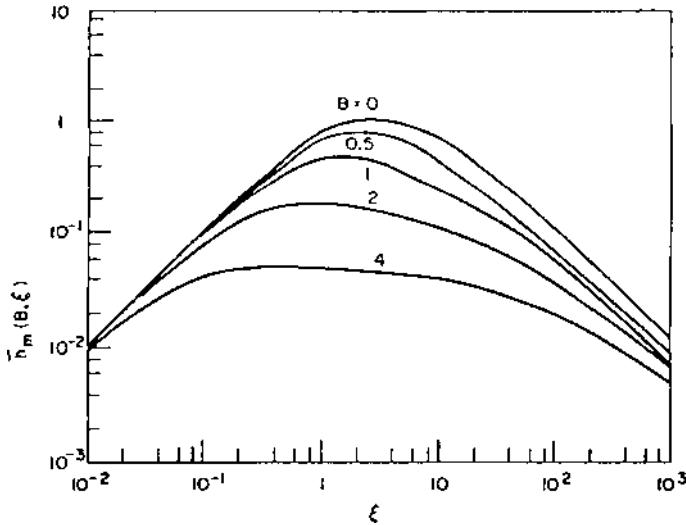
$$\frac{1}{w_p^2} = \frac{1}{w_s^2} + \frac{1}{w_i^2}\tag{7}$$

The maximum value of  $M$  is given in the table.

Although the formula for the gain displays a dependence on  $L^2$ , the intensity will only be large over a distance on the order of the confocal parameter. Setting  $L$  equal to the common confocal parameter of the signal and idler beams, it follows that  $w_s^2 = \lambda_s L / 2\pi n_s$  and  $w_i^2 = \lambda_i L / 2\pi n_i$ . Since  $w^2 \propto \lambda$  and  $\lambda_p^{-1} = \lambda_s^{-1} + \lambda_i^{-1}$ , if the signal and idler beams are confocally focused, then by Eq. (7) the pump beam will be confocally focused as well. Under these conditions, the optimized near field confocal gain is given in Table 4. Note that the gain is proportional to  $L$  in this case and not to  $L^2$ .

### C. Arbitrarily Tightly Focused Gaussian Beams with Double Refraction

The analysis of Boyd and Kleinman [11] concerning frequency mixing with tightly focused beams was discussed in Chapter 2. Here their results for optical parametric gain are given. The formula given in (present) Table 4 is for an optimized confocal geometry in which each beam has a common confocal parameter. Note that the gain is the same as in the near-field analysis of Section II.B multiplied by a gain reduction factor  $\bar{h}_m(B, \xi)$ . The double refraction parameter  $B$  and the focusing parameter  $\xi$  were defined in Chapter 2. Plots of  $\bar{h}_m(B, \xi)$  are shown in (present) Fig. 4.



**Figure 4** Parametric gain reduction factor as a function of focusing parameter  $\xi$  and double refraction parameter  $B$  for optimally tightly focused Gaussian beams. (From Ref. 11.)

As in the case of frequency conversion efficiencies discussed in Chapter 2, the confocal parametric gain is maximized when  $B = 0$  (i.e., no double refraction,  $90^\circ$  phase matching). For  $B \geq 4$ , the maximum value of  $\bar{h}_m(B, \xi)$  is nearly independent of  $\xi$  over a wide range. Within the range  $2/B^2 < \xi < B^2/4$ ,

$$\bar{h}_m(B, \xi) \rightarrow \frac{\pi}{4B^2} \quad (8)$$

to within 10%. Since the optimized confocal gain is proportional to  $L$ , and  $B^2 \propto L$ , the gain is nearly independent of crystal length for large walk-off angles. When  $L$  is of the order of the confocal parameter, the  $B \sim \rho/\theta_d$ , where  $\rho$  is the walk-off angle due to double refraction (see Chapter 2), and  $\theta_d$  is the far-field diffraction angle. Thus under the conditions operative for Eq. (8), the gain reduction factor is approximately  $(\pi/4)(\theta_d/\rho)^2$ . When the beam radii are larger than  $(2)^{1/2}\rho L$ , the gain reduction due to walk-off is  $< 15\%$ . It can be made negligible with wider beams [12].

### III. PARAMETRIC OSCILLATORS

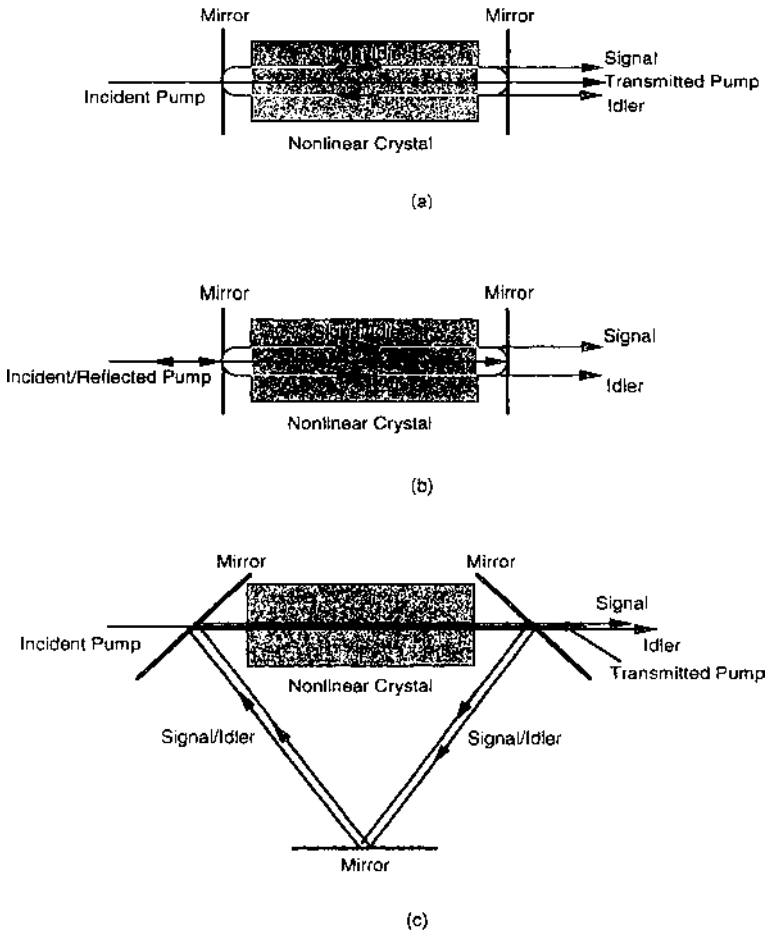
The gain of an OPA is modest even for high pump intensities. The net gain can be increased by providing positive feedback of the signal. A convenient way of achieving this is to place the nonlinear crystal in a two-mirror resonator. When the optical parametric gain of the resonator exceeds its optical loss, oscillation occurs. Such a device is called an optical parametric oscillator (OPO). Above the threshold for oscillation, the signal and idler waves grow dramatically. The output of such a device is coherent radiation like that of a laser.

The signal and idler frequencies will adjust by phase matching to maximize the gain so that these frequencies will achieve the lowest threshold and be selectively amplified. Hence the output of an OPO is wavelength tunable. Tuning can be achieved by angle or temperature control of the phase matching. The Pockels or linear electrooptical effect can sometimes be used to fine-tune the output. The bandwidth of the output will be controlled by the gain bandwidth of the crystal. Line narrowing and control is also possible with the introduction of dispersive elements such as étalons or gratings into the resonator cavity.

There are two main types of OPO: the doubly resonant oscillator (DRO) and the singly resonant oscillator (SRO). Both of these are discussed below. OPOs can also be classified as cw (or quasi-cw), pulsed, or mode-locked. The former is treated first in Section III.A (DROs) and III.B (SROs). Pulsed OPOs are discussed in Section IV, while synchronously pumped (mode-locked) OPOs are discussed in Section V. The important characteristics of OPOs to be described include oscillation thresholds, conversion efficiency and output power, stability, rise time, tuning, and bandwidth.

### A. Doubly Resonant Parametric Oscillators

The simplest DRO consists of a nonlinear crystal inserted in a two-mirror cavity as shown in Fig. 5. The mirrors have low reflectance (near zero) at the pump frequency and high reflectances at the signal and idler frequencies. Both signal and idler frequencies are resonant with the cavity, hence the name of the oscillator. Variations of this simple cavity consist of the double-pass DRO (DPDRO) and the doubly resonant ring oscillator (DRRO), both also illustrated in Fig. 5. In the DPDRO, the back mirror has a high reflectance at the pump frequency



**Figure 5** Doubly resonant oscillator (DRO) geometries. (a) Simple two-mirror DRO. (b) Double-pass DRO (DPDRO). (c) Doubly resonant ring oscillator (DRRO).

frequency as well, so that the pump makes a double pass through the oscillator to increase the gain. In the DRRO, the pump again passes straight through, but the signal and idler waves travel only in one direction through the nonlinear crystal. The purposes of these special oscillator configurations are described below.

*Threshold.* In an OPO, unlike a laser, the signal and idler waves are only amplified when traveling in the same direction as the pump wave. Waves propagating counter to the pump wave are not phase matched for DFG. The steady-state threshold gain is determined under self-consistent conditions where the signal-pass parametric gain equals the round-trip electric field loss. In this way the fields replicate themselves on each round-trip [8].

The minimum threshold gain results when the signal and idler frequencies are both resonant and phase matching is achieved ( $\Delta k = 0$ ). The self-consistent analysis described above leads to the following condition on the small signal gain ( $gL$ ):

$$\cosh(gL)_{\text{th}} = \frac{1 + R_s \exp(-\alpha_s L) R_i \exp(-\alpha_i L)}{R_s \exp(-\alpha_s L) + R_i \exp(-\alpha_i L)} \quad (9)$$

where  $R_s$  and  $R_i$  are the mirror reflectances (assume the same for both cavity mirrors) at the signal and idler frequencies, respectively, while  $\alpha_s$  and  $\alpha_i$  are the intensity absorption coefficients for the signal and idler waves. (They may also include any scattering losses as well as Fresnel reflection losses since the absorption is usually very small.) The subscript th signifies that the gain coefficient is that at threshold. Generally, the reflectances are close to 1 and the other losses are low as well. In the low-loss regime, Eq. (9) can be written as

$$(gL)_{\text{th}}^2 \simeq [1 - R_s \exp(-\alpha_s L)][1 - R_i \exp(-\alpha_i L)] \quad (10)$$

Using the formulas in Table 4 along with Eq. (10), the threshold pump power can be computed. The results are shown in Table 5 under the various approximations considered in Section II.

The threshold gain can be lowered using the DPDRO. In this device, gain is achieved on both the forward pass and the backward pass of the signal and idler fields. The following result for the threshold gain has been derived by Bjorkholm et al. [13]:

$$(gL)_{\text{th}}^2 \text{sinc}^2(\Delta k L / 2) = \frac{[1 - R_s \exp(-\alpha_s L)][1 - R_i \exp(-\alpha_i L)]}{1 + R_p + 2\sqrt{R_p} \cos(\Delta\varphi + \Delta k L)} \quad (11)$$

where

$$\Delta\varphi = \Delta(\varphi_p - \varphi_s - \varphi_i) \quad (12)$$

is the net phase change of the optical fields upon reflection at the back mirror, and  $R_p$  is the reflectance of the back mirror at the pump frequency. Ideally, for  $R_p \sim 1$

**Table 5** Formulas for the Steady-State Threshold Pump Power for Doubly Resonant Optical Parametric Oscillators

---

Plane waves

$$\mathcal{P}_{p,th} = \{\text{beam area}\} \times \frac{\epsilon_0 n_s^2 n_p c \lambda_p^2}{2\pi^2 d_{\text{eff}}^2 L^2 (1 - \delta^2)} (1 - R_s e^{-\alpha_s L}) (1 - R_i e^{-\alpha_i L}) \quad (\text{SI})$$

$$\mathcal{P}_{p,th} = \{\text{beam area}\} \times \frac{n_s^2 n_p c \lambda_p^2}{128\pi^5 d_{\text{eff}}^2 L^2 (1 - \delta^2)} (1 - R_s e^{-\alpha_s L}) (1 - R_i e^{-\alpha_i L}) \quad (\text{cgs})$$


---

Near-field Gaussian beams

$$\mathcal{P}_{p,th} = \frac{\epsilon_0 n_s^2 n_p c \lambda_p^2}{16\pi d_{\text{eff}}^2 L^2 (1 - \delta^2) M^2} (1 - R_s e^{-\alpha_s L}) (1 - R_i e^{-\alpha_i L}) \quad (\text{SI})$$

$$\mathcal{P}_{p,th} = \frac{n_s^2 n_p c \lambda_p^2}{1024\pi^4 d_{\text{eff}}^2 L^2 (1 - \delta^2) M^2} (1 - R_s e^{-\alpha_s L}) (1 - R_i e^{-\alpha_i L}) \quad (\text{cgs})$$


---

Optimized confocal near-field Gaussian beams

$$\mathcal{P}_{p,th} = \frac{\epsilon_0 n_s^2 c \lambda_p^3}{2\pi^2 d_{\text{eff}}^2 L (1 - \delta^2)} (1 - R_s e^{-\alpha_s L}) (1 - R_i e^{-\alpha_i L}) \quad (\text{SI})$$

$$\mathcal{P}_{p,th} = \frac{n_s^2 c \lambda_p^3}{128\pi^5 d_{\text{eff}}^2 L (1 - \delta^2)} (1 - R_s e^{-\alpha_s L}) (1 - R_i e^{-\alpha_i L}) \quad (\text{cgs})$$


---

Optimized confocal tightly focused Gaussian beams (including double refraction)

$$\mathcal{P}_{p,th} = \frac{\epsilon_0 n_s^2 c \lambda_p^3}{2\pi^2 d_{\text{eff}}^2 L (1 - \delta^2) \bar{h}_m(B, \xi)} (1 - R_s e^{-\alpha_s L}) (1 - R_i e^{-\alpha_i L}) \quad (\text{SI})$$

$$\mathcal{P}_{p,th} = \frac{n_s^2 c \lambda_p^3}{128\pi^5 d_{\text{eff}}^2 L (1 - \delta^2) \bar{h}_m(B, \xi)} (1 - R_s e^{-\alpha_s L}) (1 - R_i e^{-\alpha_i L}) \quad (\text{cgs})$$


---

and  $\Delta\phi = \Delta k = 0$ , the threshold gain for the DPDRO is lower than that of the DRO by a factor of approximately 4.

The equations given above hold true when the pump is single mode (one frequency). Often though, the pump beam from a high-power laser will contain many modes. Not all of the power of the beam will then pump specific signal and idler modes. However, Harris [14] has shown that if the idler longitudinal mode spacing is equal to that of the pump laser, then all of the pump modes may act in unison to produce gain at a single signal frequency mode. Although the pump modes are randomly phased, the idler modes develop compensating phases to maximize the gain [15]. The problem of multiple pump modes hampered the early development of pulsed OPOs. The more recent development of single longitudinal mode lasers by seed injection have alleviated this problem.

*Conversion efficiency and output power (plane waves).* When steady-state oscillation has been achieved in the OPO, the gain is clamped at the threshold

value. The signal and idler waves are nearly constant across the cavity, while the pump field is strongly depleted [7]. Under these conditions, the overall conversion efficiency defined by

$$\eta = \frac{\mathcal{P}_s + \mathcal{P}_i}{\mathcal{P}_p(0)} \quad (13)$$

can be computed. The results for the DRO are given in Table 6 in terms of the parameter  $N_{\text{DRO}}$ , which is the number of times the input pump power exceeds the threshold pump power for the DRO. For the DRO, the maximum value of the efficiency is 50% when  $N_{\text{DRO}} = 4$ .

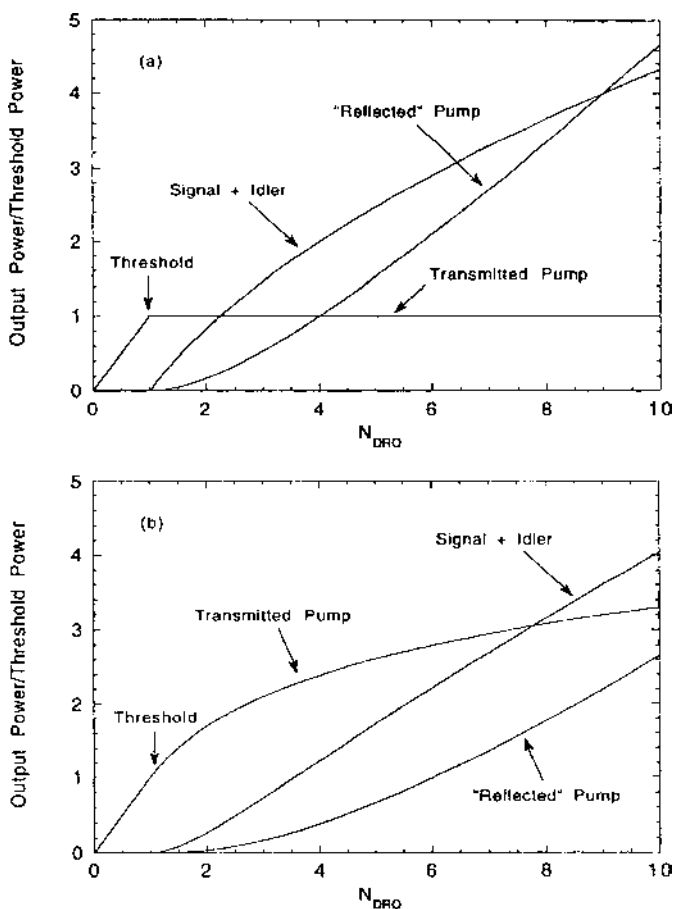
Expressions for the output signal and idler powers are also given in Table 6. Note that the transmitted pump power is clamped at the threshold value. This is a result of the plane wave analysis and was first proposed by Siegman [16] as a means of achieving an optical power limiter. The excess pump power is channeled into the generated signal and idler powers, and into a “reflected” pump wave. The reflected pump power is actually due to a sum-frequency wave generated by the backward traveling signal and idler waves in the resonator cavity. The distribution of the optical power in the various frequencies as a function of input pump power above threshold is shown in Fig. 6a.

The reflected pump wave of the DRO robs energy from the signal and idler waves. In the DRRO, this reflected wave is avoided, since the signal and idler waves travel only in one direction through the nonlinear crystal. The conversion efficiency and output powers for the DRRO are given in Table 7. Note that the maximum efficiency now is 100% when  $N_{\text{DRRO}} = 4$ .

Results for the DPDRO are shown in Table 8. For  $R_p \sim 1$  and proper adjustments of the phase (i.e.,  $\Delta\varphi = \Delta k = 0$ ), the maximum efficiency is again 100% at  $N_{\text{DPDRO}} = 4$ . Thus the DPDRO has the advantage over the DRO of

**Table 6** DRO Efficiency and Output Power Formulas for Plane Waves

|                                                                                                                                                   |
|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Conversion efficiency                                                                                                                             |
| $\eta = \frac{2}{N_{\text{DRO}}}(\sqrt{N_{\text{DRO}}} - 1) \quad N_{\text{DRO}} = \frac{(\mathcal{P}_p)_{\text{in}}}{\mathcal{P}_{p,\text{th}}}$ |
| Output power                                                                                                                                      |
| $\mathcal{P}_s = 2 \frac{\lambda_s}{\lambda_c} \mathcal{P}_{p,\text{th}}(\sqrt{N_{\text{DRO}}} - 1)$                                              |
| $\mathcal{P}_i = 2 \frac{\lambda_i}{\lambda_c} \mathcal{P}_{p,\text{th}}(\sqrt{N_{\text{DRO}}} - 1)$                                              |
| $(\mathcal{P}_p)_{\text{out}} = \mathcal{P}_{p,\text{th}}$                                                                                        |
| “Reflected” pump power                                                                                                                            |
| $(\mathcal{P}_p)_{\text{reflected}} = \mathcal{P}_{p,\text{th}}(\sqrt{N_{\text{DRO}}} - 1)^2$                                                     |



**Figure 6** Output powers for the DRO normalized to the DRO threshold power as functions of the number of times the pump power exceeds threshold. (a) Plane wave approximation. (b) Gaussian beams.

increased efficiency with a reduced threshold. The disadvantage is the dependence of the efficiency and threshold on  $\Delta\phi$  and  $\Delta k$ .

*Conversion efficiency and output power (Gaussian beams).* The results given above are modified for real optical beams with radial intensity dependence. Bjorkholm [17] has treated this case for a “nearly plane wave” pump beam. The meaning of this phrase is that the spatial intensity variation over the beam cross-section is slow enough that the generated signal and idler beams can effectively be divided into independent beamlets of nearly uniform intensity and planar phase over the interaction length of the beams. A uniform plane wave

**Table 7** DRRO Efficiency and Output Power Formulas for Plane Waves

|                                                                                                                                      |                                                                                  |
|--------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Conversion efficiency                                                                                                                |                                                                                  |
| $\eta = \frac{4}{N_{\text{DRO}}} (\sqrt{N_{\text{DRO}}} - 1)$                                                                        | $N_{\text{DRO}} = \frac{(\mathcal{P}_p)_{\text{in}}}{\mathcal{P}_{p,\text{th}}}$ |
| Output power                                                                                                                         |                                                                                  |
| $\mathcal{P}_s = 4 \frac{\lambda_p}{\lambda_s} \mathcal{P}_{p,\text{th}} (\sqrt{N_{\text{DRO}}} - 1)$                                |                                                                                  |
| $\mathcal{P}_i = 4 \frac{\lambda_p}{\lambda_i} \mathcal{P}_{p,\text{th}} (\sqrt{N_{\text{DRO}}} - 1)$                                |                                                                                  |
| $(\mathcal{P}_p)_{\text{out}} = (\mathcal{P}_p)_{\text{in}} \left[ 1 - \frac{4}{N_{\text{DRO}}} (\sqrt{N_{\text{DRO}}} - 1) \right]$ |                                                                                  |
| “Reflected” pump power                                                                                                               |                                                                                  |
| $(\mathcal{P}_p)_{\text{reflected}} = 0$                                                                                             |                                                                                  |

analysis is applied to each beamlet. These solutions are then summed over the nonuniform pump beam to obtain the net signal and idler powers.

The pump beam is taken to have a Gaussian radial distribution

$$I_p(r) + I_p(0) \exp\left(\frac{-2r^2}{w_p^2}\right) \quad (14)$$

where  $w_p$  is the radius of the pump beam waist. This beam is divided into a collection of beamlets of dimension  $\Delta$ . The condition that the beamlets be independent and of uniform intensity and phase places the following restrictions on the dimension  $\Delta$  [17]:

$$\Delta \ll w_p.$$

$\Delta$  is large enough that diffractive mixing of pump, idler, and signal beamlets is negligible.

$\Delta$  is large enough that double refraction effects on the beamlets are negligible.

**Table 8** DPDRO Efficiency and Output Power Formulas for Plane Waves

|                                                                                                                                                                          |                                                                                                     |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|
| Conversion efficiency                                                                                                                                                    |                                                                                                     |
| $\eta = \frac{1 + R_p + 2\sqrt{R_p} \cos(\Delta\phi + \Delta kL)}{1 + \sqrt{R_p} \cos(\Delta\phi + \Delta kL)} \frac{2}{N_{\text{DPDRO}}} (\sqrt{N_{\text{DPDRO}}} - 1)$ | $N_{\text{DPDRO}} = \frac{(\mathcal{P}_p)_{\text{in}}}{(\mathcal{P}_{p,\text{th}})_{\text{DPDRO}}}$ |
| Output power                                                                                                                                                             |                                                                                                     |
| $\mathcal{P}_s = \frac{\lambda_p}{\lambda_s} (\mathcal{P}_p)_{\text{in}} \eta$                                                                                           |                                                                                                     |
| $\mathcal{P}_i = \frac{\lambda_p}{\lambda_i} (\mathcal{P}_p)_{\text{in}} \eta$                                                                                           |                                                                                                     |
| $(\mathcal{P}_p)_{\text{out}} = 0$                                                                                                                                       |                                                                                                     |
| “Reflected” pump power                                                                                                                                                   |                                                                                                     |
| $(\mathcal{P}_p)_{\text{reflected}} \approx (\mathcal{P}_p)_{\text{in}} (1 - \eta)$                                                                                      |                                                                                                     |

**Table 9** DRO Efficiency and Output Power  
Formulas for Gaussian Beams

Conversion efficiency

$$\eta = \frac{4}{N_{\text{DRO}}} (\sqrt{N_{\text{DRO}}} - \ln \sqrt{N_{\text{DRO}}} - 1) \quad N_{\text{DRO}} = \frac{(\mathcal{P}_p)_{\text{in}}}{\mathcal{P}_{p,\text{th}}}$$

Output power

$$\begin{aligned} \mathcal{P}_s &= 4 \frac{\lambda_p}{\lambda_s} \mathcal{P}_{p,\text{th}} (\sqrt{N_{\text{DRO}}} - \ln \sqrt{N_{\text{DRO}}} - 1) \\ \mathcal{P}_i &= 4 \frac{\lambda_p}{\lambda_i} \mathcal{P}_{p,\text{th}} (\sqrt{N_{\text{DRO}}} - \ln \sqrt{N_{\text{DRO}}} - 1) \\ (\mathcal{P}_p)_{\text{out}} &= \mathcal{P}_{p,\text{th}} (1 + \ln N_{\text{DRO}}) \end{aligned}$$

“Reflected” pump power

$$(\mathcal{P}_p)_{\text{reflected}} = \mathcal{P}_{p,\text{th}} (N_{\text{DRO}} - 4\sqrt{N_{\text{DRO}}} + \ln N_{\text{DRO}} + 3)$$

Although these are rather severe restrictions, the results of the analysis show generally good agreement with experiments [17].

The results for conversion efficiency and output power for a DRO with Gaussian beams are given in Table 9. Note that in contrast with the plane wave results, the maximum efficiency now is only 41% for  $N_{\text{DRO}} = 12.5$ . Also note that although there is still a reflected wave, the transmitted pump power is no longer clamped at the threshold value but increases logarithmically with  $N_{\text{DRO}}$ . This is a more gradual power limiting than that of the plane wave case. The distribution of output powers in the various frequencies is shown in Fig. 6b.

Results for the DRRO case with Gaussian beams are given in Table 10. The maximum conversion efficiency is now approximately 78% at  $N_{\text{DRRO}} = 12.5$ . 100% efficiency is not possible, since the pump power in the wings of the Gaussian is too weak to produce any nonlinear frequency conversion. Comparisons of the conversion efficiencies for plane waves and Gaussian beams are given in Fig. 7 for both the DRO and the DRRO.

**Table 10** DRRO Efficiency and Output Power Formulas  
for Gaussian Beams

Conversion efficiency

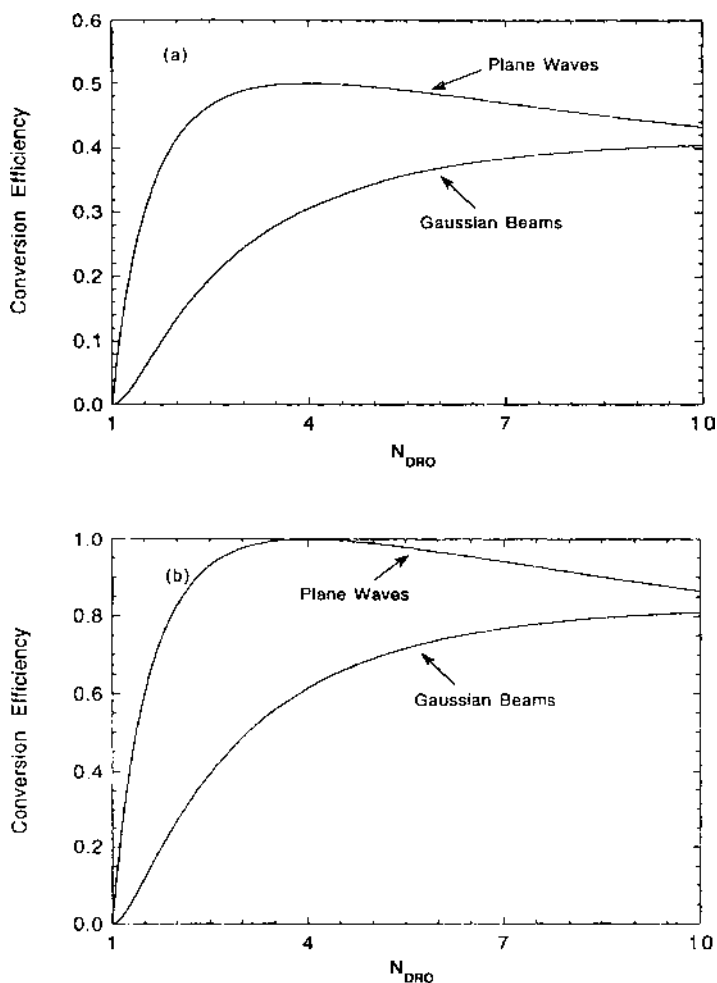
$$\eta = \frac{8}{N_{\text{DRO}}} (\sqrt{N_{\text{DRO}}} - \ln \sqrt{N_{\text{DRO}}} - 1) \quad N_{\text{DRO}} = \frac{(\mathcal{P}_p)_{\text{in}}}{\mathcal{P}_{p,\text{th}}}$$

Output power

$$\begin{aligned} \mathcal{P}_s &= 8 \frac{\lambda_p}{\lambda_s} \mathcal{P}_{p,\text{th}} (\sqrt{N_{\text{DRO}}} - \ln \sqrt{N_{\text{DRO}}} - 1) \\ \mathcal{P}_i &= 8 \frac{\lambda_p}{\lambda_i} \mathcal{P}_{p,\text{th}} (\sqrt{N_{\text{DRO}}} - \ln \sqrt{N_{\text{DRO}}} - 1) \\ (\mathcal{P}_p)_{\text{out}} &= (\mathcal{P}_p)_{\text{in}} \left[ 1 - \frac{8}{N_{\text{DRO}}} (\sqrt{N_{\text{DRO}}} - 1) + \frac{4}{N_{\text{DRO}}} \ln N_{\text{DRO}} \right] \end{aligned}$$

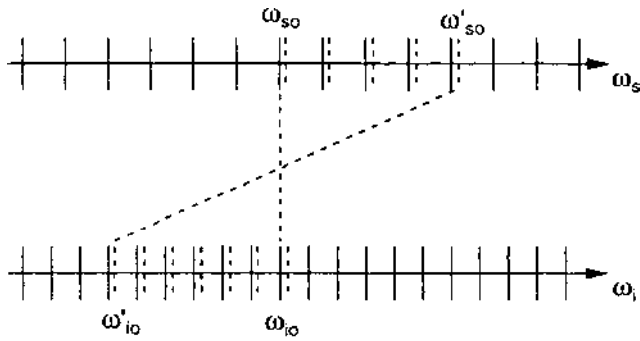
“Reflected” pump power

$$(\mathcal{P}_p)_{\text{reflected}} = 0$$



**Figure 7** DRO conversion efficiencies. (a) Plane wave and Gaussian beam results for a simple DRO. (b) Plane wave and Gaussian beam results for a DRRO.

*Stability.* Small changes in cavity length caused by temperature fluctuations or acoustic vibrations will cause a shift in the resonant frequencies of the cavity. However, oscillating modes of the OPO must sum to  $\omega_p$  to conserve energy. Since modes oscillating at particular values of  $\omega_s$  and  $\omega_i$  will shift in the same direction as the cavity length varies, they cannot sum to  $\omega_p$ . However, there exist other cavity modes that may (see Fig. 8). Thus when the cavity length fluctuates, new modes that are far removed from the original ones may suddenly



$$\omega_{s0} + \omega_{i0} = \omega'_{s0} + \omega'_{i0} = \omega_p$$

$\omega_{s0}, \omega_{i0}$  = original signal/idler cavity modes

$\omega'_{s0}, \omega'_{i0}$  = shifted signal/idler cavity modes

**Figure 8** DRO signal and idler cavity modes, illustrating instability in output frequency as cavity modes fluctuate (i.e., shift).

experience the maximum gain, and the OPO will oscillate on these modes. The output will experience a relatively large change in frequency and possibly output power.

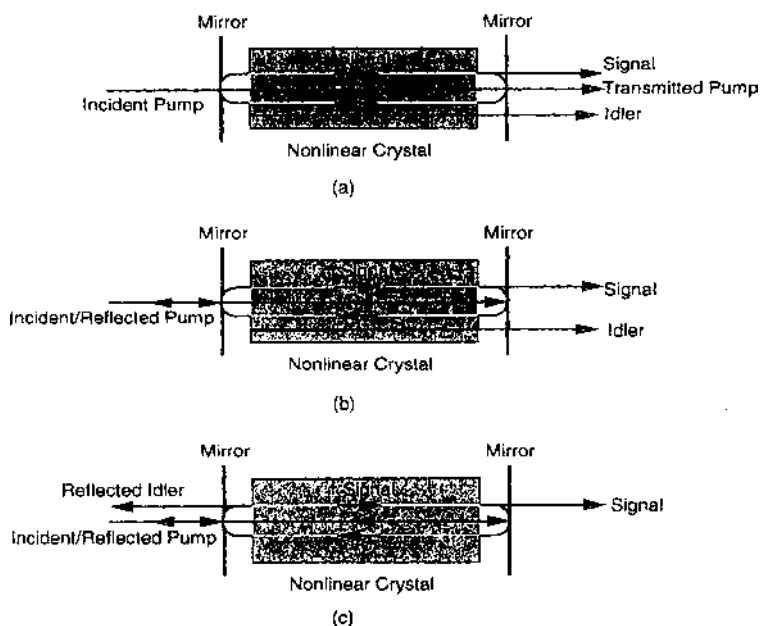
In general, the shift  $\Delta\omega = \omega'_s - \omega_s$  in the output signal frequency (which is the negative of the shift in the idler frequency) is given by

$$\Delta\omega = \frac{n_i}{n_i - n_s} \omega_p \frac{\Delta l}{l} \quad (15)$$

where  $l$  is the cavity length. Typically,  $|n_i - n_s|/n_i \sim 10^{-2} - 10^{-1}$ . Therefore, for  $\Delta l/l \sim 10^{-7}$  the cavity mode shifts only by  $10^{-7} \times \omega_s$ , but the output frequency shifts by  $(10^{-6} - 10^{-5}) \times \omega_p$ . This is a relatively large shift. The result is that the output of the DRO is relatively unstable with respect to small cavity fluctuations. This instability is overcome by going to a singly resonant oscillator.

## B. Singly Resonant Parametric Oscillator

The simplest SRO, as illustrated in Fig. 9, has two cavity mirrors with high reflectance at the single frequency only. Variations of the simple SRO include a double-pass SRO (DPSRO) where the pump experiences a double pass, or where



**Figure 9** Singly resonant oscillator (SRO) geometries. (a) Simple two-mirror SRO. (b) Double-pass SRO (DPSRO)—pump only. (c) DPSRO—pump and idler.

both the pump and the idler are passed twice through the nonlinear crystal. These are also shown in Fig. 9.

In the SRO, only the signal frequency is resonant, so as the cavity resonant modes fluctuate,  $\omega_s$  is free to change continuously to accommodate conservation of energy. Hence there are no large jumps in output frequencies, and the SRO is relatively stable against cavity fluctuations.

*Threshold.* The steady-state threshold gain of the SRO is calculated in the same manner as was done for the DRO. The result in the low-loss regime is

$$(gL)_{th}^2 \approx 2[1 - R_s \exp(-\alpha_s L)] \quad (16)$$

This threshold gain is larger than the threshold gain of the DRO by a factor of  $2/[1 - R_i \exp(-\alpha_i L)]$ . For example, if the net idler round-trip loss for the DRO is 2%, then the SRO threshold gain is larger by a factor of 100. Thus the price of stability bought by the SRO is an increase in threshold pump power by a factor of  $\sim 100$ . This is generally not a problem for pulsed OPOs but is more difficult for cw OPOs. Expressions for the threshold pump power in the various cases are given in Table 11.

**Table 11** Formulas for the Steady-State Threshold Pump Power for Singly Resonant Optical Parametric Oscillators

---

Plane waves

$$\mathcal{P}_{p,th} = \{\text{beam area}\} \times \frac{\epsilon_0 n_s^2 n_p c \lambda_p^2}{\pi^2 d_{\text{eff}}^2 L^2 (1 - \delta^2)} (1 - R_s e^{-\alpha_s L}) \quad (\text{SI})$$

$$\mathcal{P}_{p,th} = \{\text{beam area}\} \times \frac{n_s^2 n_p c \lambda_p^2}{64 \pi^5 d_{\text{eff}}^2 L^2 (1 - \delta^2)} (1 - R_s e^{-\alpha_s L}) \quad (\text{cgs})$$


---

Near-field Gaussian beams

$$\mathcal{P}_{p,th} = \frac{\epsilon_0 n_s^2 n_p c \lambda_p^2}{8 \pi d_{\text{eff}}^2 L^2 (1 - \delta^2) M^2} (1 - R_s e^{-\alpha_s L}) \quad (\text{SI})$$

$$\mathcal{P}_{p,th} = \frac{n_s^2 n_p c \lambda_p^2}{512 \pi^4 d_{\text{eff}}^2 L^2 (1 - \delta^2) M^2} (1 - R_s e^{-\alpha_s L}) \quad (\text{cgs})$$


---

Optimized confocal near-field Gaussian beams

$$\mathcal{P}_{p,th} = \frac{\epsilon_0 n_s^2 c \lambda_p^3}{\pi^2 d_{\text{eff}}^2 L (1 - \delta^2)} (1 - R_s e^{-\alpha_s L}) \quad (\text{SI})$$

$$\mathcal{P}_{p,th} = \frac{n_s^2 c \lambda_p^3}{64 \pi^5 d_{\text{eff}}^2 L (1 - \delta^2)} (1 - R_s e^{-\alpha_s L}) \quad (\text{cgs})$$


---

Optimized confocal tightly focused Gaussian beams (including double refraction)

$$\mathcal{P}_{p,th} = \frac{\epsilon_0 n_s^2 c \lambda_p^3}{\pi^2 d_{\text{eff}}^2 L (1 - \delta^2) \bar{h}_m(B, \xi)} (1 - R_s e^{-\alpha_s L}) \quad (\text{SI})$$

$$\mathcal{P}_{p,th} = \frac{n_s^2 c \lambda_p^3}{64 \pi^5 d_{\text{eff}}^2 L (1 - \delta^2) \bar{h}_m(B, \xi)} (1 - R_s e^{-\alpha_s L}) \quad (\text{cgs})$$


---

For the DPSRO with only the pump beam reflected at the back cavity mirror [13],

$$(gL)_{\text{th}}^2 \simeq \frac{2[1 - R_s \exp(-\alpha_s L)]}{1 + R_p} \quad (17)$$

When  $R_p \sim 1$ , a threshold gain reduction of approximately 2 is achieved.

Harris [18] has treated the case of the DPSRO when both the pump and the idler experience a double pass through the nonlinear crystal. The gain in this case depends on the relative phase shifts of these waves and the signal wave upon reflection at the mirror. When  $\Delta k = 0$  and the net phase shift upon reflection is zero, the round-trip gain is  $4(gL)^2$ . For a phase shift upon reflection of  $\Delta(\varphi_p - \varphi_s - \varphi_i) = \pi/2$ , the gain on the first pass is exactly cancelled on the return pass. Harris has shown, however, that this is not the case when  $\Delta k \neq 0$ . When  $|2\Delta k L| \leq 2\pi$ , the net round-trip gain has a maximum value of  $1.6 (gL)^2$ .

**Table 12** SRO Efficiency and Output Power Formulas for Plane Waves

|                        |                                                                                                                                         |                                                                                    |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| Conversion efficiency  |                                                                                                                                         |                                                                                    |
| $\eta = \sin^2 \Gamma$ | $\frac{\sin^2 \Gamma}{\Gamma^2} = \frac{1}{N_{\text{SRO}}}$                                                                             | $N_{\text{SRO}} = \frac{(\mathcal{P}_p)_{\text{in}}}{(\mathcal{P}_p)_{\text{th}}}$ |
| Output power           |                                                                                                                                         |                                                                                    |
|                        | $\mathcal{P}_s \simeq \frac{\lambda_p}{\lambda_s} \left( \frac{1 - R_s}{1 - R_s + \alpha_s L} \right) \eta (\mathcal{P}_p)_{\text{in}}$ |                                                                                    |
|                        | $\mathcal{P}_i = \frac{\lambda_p}{\lambda_i} \eta (\mathcal{P}_p)_{\text{in}}$                                                          |                                                                                    |
|                        | $(\mathcal{P}_p)_{\text{out}} = (1 - \eta) (\mathcal{P}_p)_{\text{in}}$                                                                 |                                                                                    |
| “Reflected” pump power |                                                                                                                                         |                                                                                    |
|                        | $(\mathcal{P}_p)_{\text{reflected}} = 0$                                                                                                |                                                                                    |

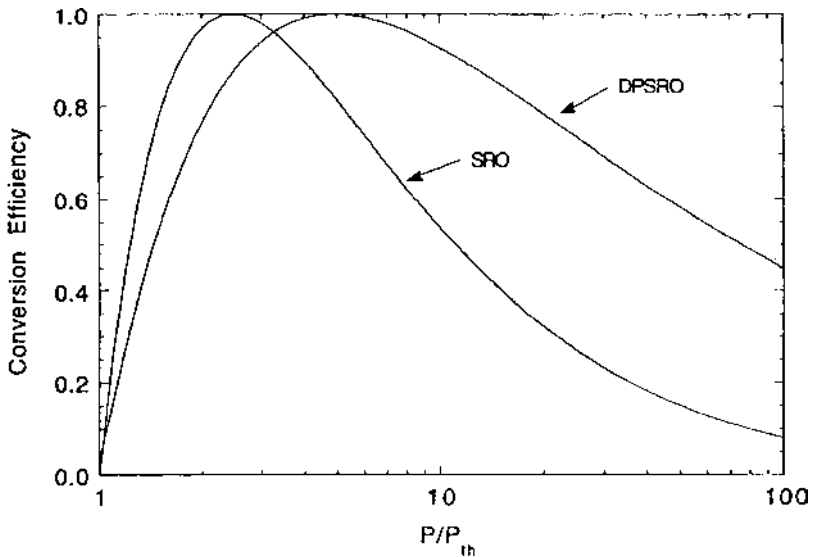
*Conversion efficiency and output power (plane waves).* In the SRO, the signal field is approximately constant over the cavity under steady-state conditions, but both the pump and the idler fields may vary [7]. The computed conversion efficiency and output power under these conditions, assuming the fields are infinite plane waves, are given in Table 12 in terms of the parameter  $N_{\text{SRO}}$ , which is the number of times the input pump power exceeds the SRO threshold pump power.

In this case, when  $N_{\text{SRO}} = 4$  the conversion efficiency is approximately 90%. The conversion efficiency reaches a maximum of 100% for  $N_{\text{SRO}} = (\pi/2)^2$ . There is no power limiting for the transmitted pump in this case, and there is no reflected pump wave.

Table 13 gives the conversion efficiency and output power of the DPSRO under the condition of only the pump wave experiencing a double pass. For this

**Table 13** DPSRO Efficiency and Output Power Formulas for Plane Waves

|                        |                                                                                                                                         |                                                                                                   |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Conversion efficiency  |                                                                                                                                         |                                                                                                   |
| $\eta = \sin^2 \Gamma$ | $\frac{\sin^2 \Gamma}{\Gamma^2} = \frac{2}{1 + R_p \cos \Gamma} \frac{1}{N_{\text{DPSRO}}}$                                             | $N_{\text{DPSRO}} = \frac{(\mathcal{P}_p)_{\text{in}}}{(\mathcal{P}_p)_{\text{th}} \text{DPSRO}}$ |
| Output power           |                                                                                                                                         |                                                                                                   |
|                        | $\mathcal{P}_s \simeq \frac{\lambda_p}{\lambda_s} \left( \frac{1 - R_s}{1 - R_s + \alpha_s L} \right) \eta (\mathcal{P}_p)_{\text{in}}$ |                                                                                                   |
|                        | $\mathcal{P}_i = \frac{\lambda_p}{\lambda_i} \eta (\mathcal{P}_p)_{\text{in}}$                                                          |                                                                                                   |
|                        | $(\mathcal{P}_p)_{\text{out}} = 0$                                                                                                      |                                                                                                   |
| “Reflected” pump power |                                                                                                                                         |                                                                                                   |
|                        | $(\mathcal{P}_p)_{\text{reflected}} = (\mathcal{P}_p)_{\text{in}} - (\mathcal{P}_s + \mathcal{P}_i)$                                    |                                                                                                   |



**Figure 10** Conversion efficiency as a function of the number of times the pump power exceeds threshold for the SRO and DPSRO (pump only).

case a maximum conversion efficiency of  $>90\%$  is obtained over a rather broad range of  $2.5 \leq N_{\text{DPSRO}} \leq 8.5$ . Plots of the SRO and DPSRO efficiencies are given in Fig. 10.

*Conversion efficiency and output power (Gaussian beams).* The analysis proceeds analogously to the DRO case [17]. The results for the SRO are given in Table 14. The integral must be numerically evaluated. Plots of the efficiency for the SRO in the plane wave and Gaussian beam approximations are shown in Fig. 11. Note again that it is impossible to achieve 100% conversion efficiency when Gaussian beams are used.

### C. Tuning and Bandwidth

The output frequencies of the OPO are determined by conservation of energy ( $\omega_s + \omega_i = \omega_p$ ) and momentum ( $\mathbf{k}_s + \mathbf{k}_i = \mathbf{k}_p$ ). For collinear propagation of all three waves, these conditions imply

$$\omega_p[n(\omega_p) - n(\omega_p - \omega_s)] = \omega_s[n(\omega_s) - n(\omega_p - \omega_s)] \quad (18)$$

This relationship dictates the value of  $\omega_s$  given  $\omega_p$  and the dispersion of the refractive index of the nonlinear crystal. Tuning is thus achieved by controlling the refractive index. The two principal methods used are angle tuning (critically phase matched, CPM) and temperature tuning (noncritically phase matched, NCPM).

**Table 14** SRO Efficiency and Output Power Formulas for Gaussian Beams

Conversion efficiency

$$\eta = 1 - \left[ \frac{1}{N_{\text{SRO}}} + \int_0^{\ln N_{\text{SRO}}} e^{-x} \cos^2 \Gamma(x) dx \right] \quad \frac{\sin^2 \Gamma(x)}{\Gamma^2(x)} = \frac{e^x}{N_{\text{SRO}}} \quad N_{\text{SRO}} = \frac{(\mathcal{P}_p)_{\text{in}}}{\mathcal{P}_{p,\text{th}}}$$

Output power

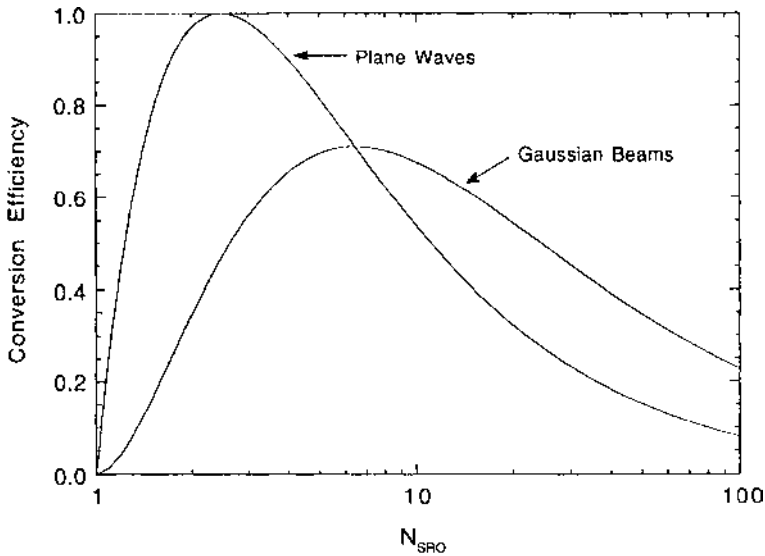
$$\begin{aligned} \mathcal{P}_s &\approx \frac{\lambda_p}{\lambda_s} \left( \frac{1 - R_s}{1 - R_s + \alpha_s L} \right) \eta (\mathcal{P}_p)_{\text{in}} \\ \mathcal{P}_i &= \frac{\lambda_p}{\lambda_i} \eta (\mathcal{P}_p)_{\text{in}} \\ (\mathcal{P}_p)_{\text{out}} &= (\mathcal{P}_p)_{\text{in}} (1 - \eta) \end{aligned}$$

“Reflected” pump power

$$(\mathcal{P}_p)_{\text{reflected}} = 0$$

Another method that is seeing increased use is injection seeding, which controls not only the output frequency of the OPO but also its line width.

*Angle tuning.* Consider a uniaxial crystal with its  $c$ -axis set at an angle  $\theta$  with respect to the direction of the pump wave in a collinear OPO geometry. The wavelength  $\lambda_s$  selected will depend on  $\theta$  and the pump frequency through



**Figure 11** Conversion efficiency as a function of the number of times the pump power exceeds threshold for the SRO, comparing plane wave the Gaussian beam results.

**Table 15** Formulas for Calculating Angle Tuning Curves<sup>a</sup>

|         |                                                                                                                                    |
|---------|------------------------------------------------------------------------------------------------------------------------------------|
| Type I  |                                                                                                                                    |
| oeo     | $\lambda_s^{-1} n^o(\lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^o(\lambda_i) = \lambda_p^{-1} n^e(\theta, \lambda_p)$         |
| eeo     | $\lambda_s^{-1} n^e(\theta, \lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^e(\theta, \lambda_i) = \lambda_p^{-1} n^o(\lambda_p)$ |
| Type II |                                                                                                                                    |
| oee     | $\lambda_s^{-1} n^o(\lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^e(\theta, \lambda_i) = \lambda_p^{-1} n^e(\theta, \lambda_p)$ |
| eo e    | $\lambda_s^{-1} n^e(\theta, \lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^o(\lambda_i) = \lambda_p^{-1} n^e(\theta, \lambda_p)$ |
| oeo     | $\lambda_s^{-1} n^o(\lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^e(\theta, \lambda_i) = \lambda_p^{-1} n^o(\lambda_p)$         |
| eo o    | $\lambda_s^{-1} n^e(\theta, \lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^o(\lambda_i) = \lambda_p^{-1} n^o(\lambda_p)$         |

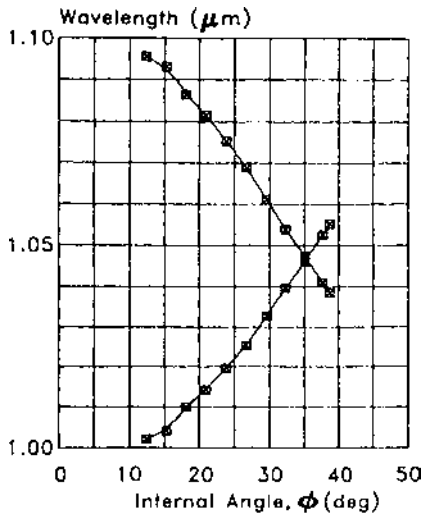
$n(\lambda)$  = index of refraction as a function of wavelength

$$\lambda_i = \frac{\lambda_s \lambda_p}{\lambda_s - \lambda_p}$$
$$\frac{1}{[n^e(\theta, \lambda)]^2} = \frac{\cos^2 \theta}{[n^o(\lambda)]^2} + \frac{\sin^2 \theta}{[n^e(\lambda)]^2}$$

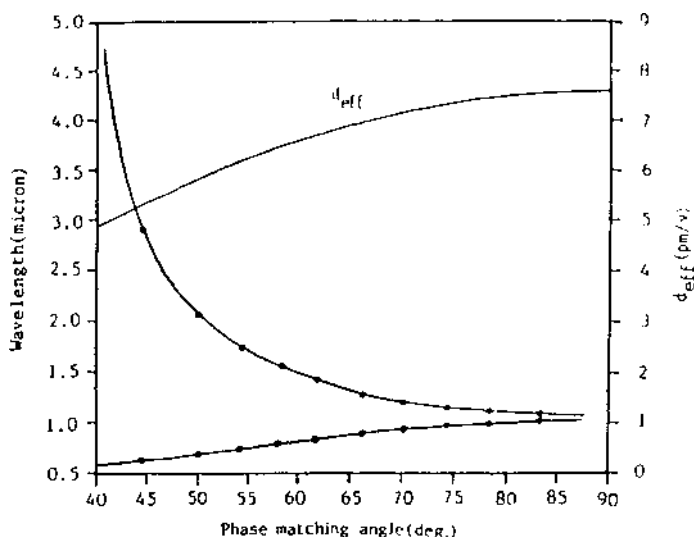
<sup>a</sup> In this case, type I refers to generated signal and idler having parallel polarizations, while type II implies orthogonal polarizations.

the phase matching conditions. These conditions are given in Table 15 for the various type I and type II frequency mixing processes in uniaxial crystals.

To obtain accurate tuning curves from these equations, the refractive index as a function of frequency or wavelength should be known to an accuracy of



**Figure 12** Angle tuning curves for type II cut ( $\theta = 90^\circ$ ,  $\phi = 26^\circ$ ) KTP pumped at 523.5 nm. (From Ref. 19.)

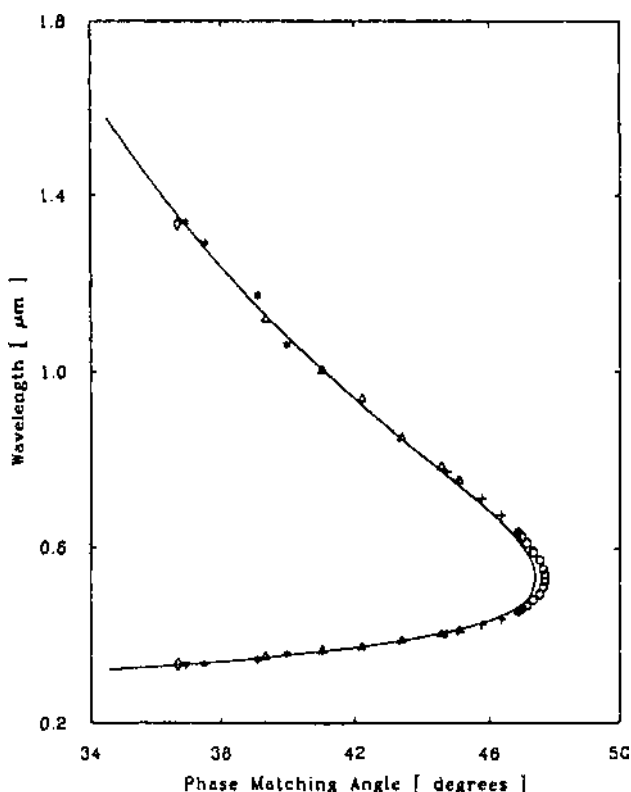


**Figure 13** Angle tuning curves for type II cut ( $\theta = 67^\circ$ ) KTP in the XZ plane pumped at 532 nm. (From Ref. 20.)

0.01–0.1%. Normally, given the pump frequency and angle of propagation with respect to the  $c$ -axis, a Sellmeier equation for the refractive index dispersion is used to make these computations. The expression for the extraordinary index of refraction as a function of  $\theta$  is given by Eq. (48) of Chapter 2. Examples from the literature of angle tuning curves for different materials and pump frequencies are shown in (present) Figs. 12 through 26.

Tuning rates ( $\Delta\omega$  vs.  $\Delta\theta$ ) can be found by expanding the phase matching equations in a Taylor series. For most of the tuning curve, only first order terms are kept, so that  $\Delta\omega$  depends linearly on  $\Delta\theta$ . However, near the degeneracy point in the curve, the rate begins to diverge for type I phase matching. It is then necessary to include second order terms in the Taylor series expansion for type I processes. Angular tuning rates for the various type I and II processes are given in Table 16. Expressions that are valid near the degeneracy point in type I processes are given in Table 17. To obtain the rate of wavelength change, make the substitution  $\Delta\lambda = -(\lambda^2/c)(\Delta\omega/2\pi)$ .

**Temperature tuning.** Consider collinear propagation of the waves in a uniaxial crystal (held at some temperature  $T$ ) at  $\theta = 90^\circ$  with respect to the  $c$ -axis (NCPM). The conditions for phase matching in type I and type II processes are listed in Table 18. To compute the tuning curves, the refractive index as a function of temperature as well as wavelength or frequency must be known. Again, through the use of appropriate Sellmeier equations, these computations can be made. Examples of temperature tuning curves are shown in Figs. 27 through 36.

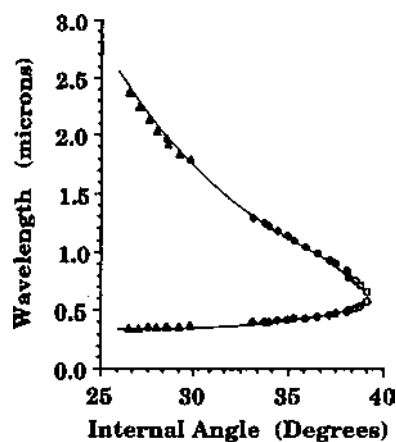


**Figure 14** Angle tuning curves for type I cut ( $\theta = 39.1^\circ$ ) BBO pumped at 266 nm. (From Ref. 21.)

Tuning rates ( $\Delta\omega$  vs.  $\Delta T$ ) are again obtained by a Taylor series expansion of the phase matching conditions. Tuning rate expressions are given in [Table 19](#). [Table 20](#) lists expressions valid near the degeneracy point for type I processes. To obtain the wavelength changes, make the substitution  $\Delta\lambda = -(\lambda^2/c)(\Delta\omega/2\pi)$ .

**Bandwidth.** The gain bandwidth of an OPO is normally defined through the relation  $\Delta kL = 2\pi$ . Expanding the wave vector phase matching condition as a function of frequency in a Taylor series and setting the result equal to  $2\pi/L$  will yield the bandwidth  $|\delta\omega|$ . Near the degeneracy point, it is necessary to retain terms to second order in the Taylor series expansion for type I processes. Expressions for the gain bandwidth are shown in [Table 21](#). Equivalent expressions in terms of wave numbers or wavelength can be found from

$$|\delta\sigma(\text{cm}^{-1})| = \frac{|\delta\omega|}{2\pi c(\text{cm/s})} \quad (4.19)$$

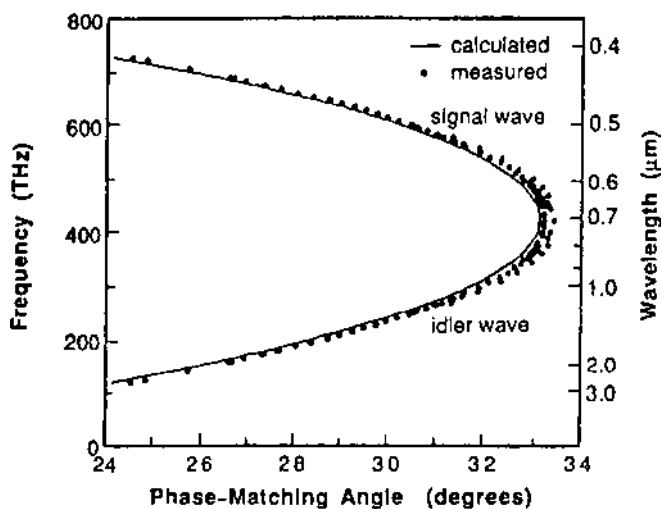


**Figure 15** Angle tuning curves for type I cut ( $\theta = 32^\circ$ ) BBO pumped at 308 nm. (From Ref. 22.)

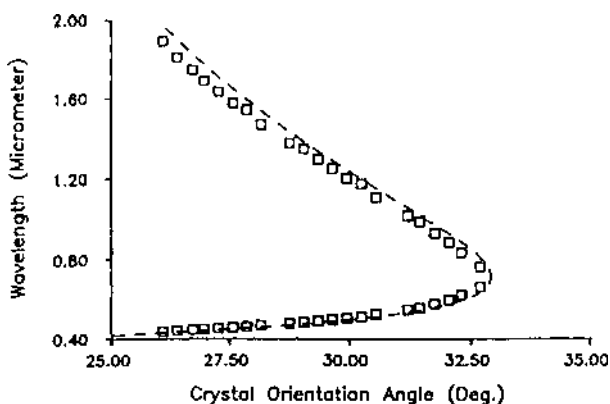
and

$$|\delta\lambda| = \left(\frac{\lambda^2}{c}\right) \frac{|\delta\omega|}{2\pi} \quad (4.20)$$

The detailed spectral characteristics of an OPO will depend on the longitudinal mode structure of the pump laser and the mode spacing ( $c/2l$ ) of

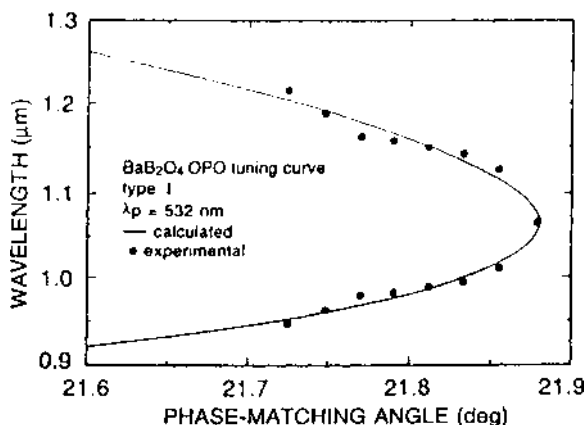


**Figure 16** Angle tuning curves for BBO cut at  $25^\circ$  and pumped at 355 nm. (From Ref. 23.)

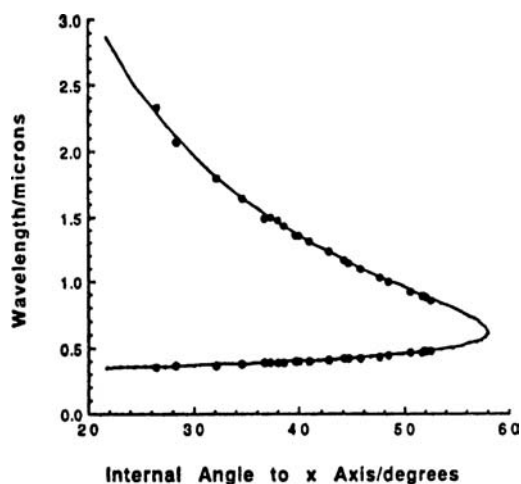


**Figure 17** Angle tuning curves for type I cut ( $31^\circ$ ) BBO pumped at 355 nm. (From Ref. 24.)

the signal and idler cavity modes. A DRO can exhibit clusters of modes spaced a few mode intervals apart within the gain bandwidth profile. In an SRO the idler frequency adjusts freely to optimize the gain and avoid this clustering effect. It is still possible, however, to have several modes oscillating over the gain bandwidth. Étalons, birefringent filters, and gratings have been employed to select a single cavity mode for preferential gain and thus narrow the line width of the output. Current techniques also include injection seeding from a narrow line

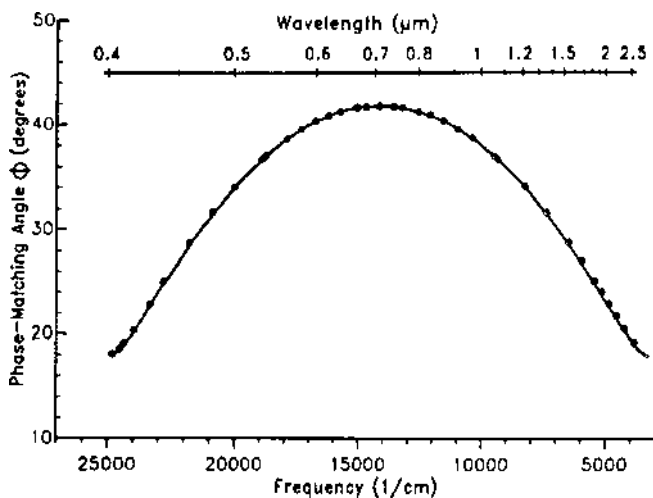


**Figure 18** Angle tuning curves for type I cut BBO pumped at 532 nm. (From Ref. 25.)

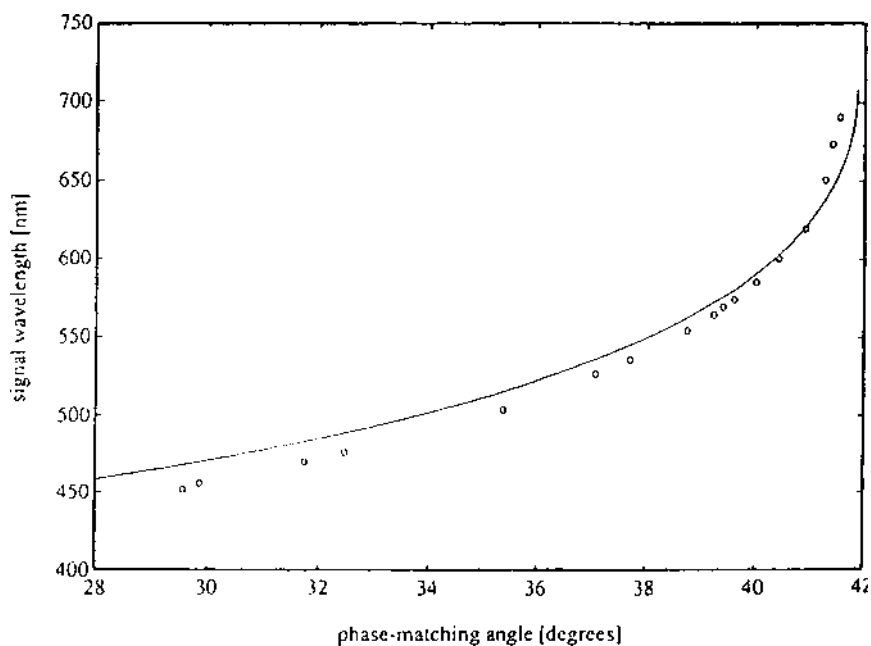


**Figure 19** Angle tuning curves for type I cut ( $\theta = 40^\circ$ ) LBO pumped at 308 nm. (From Ref. 26.)

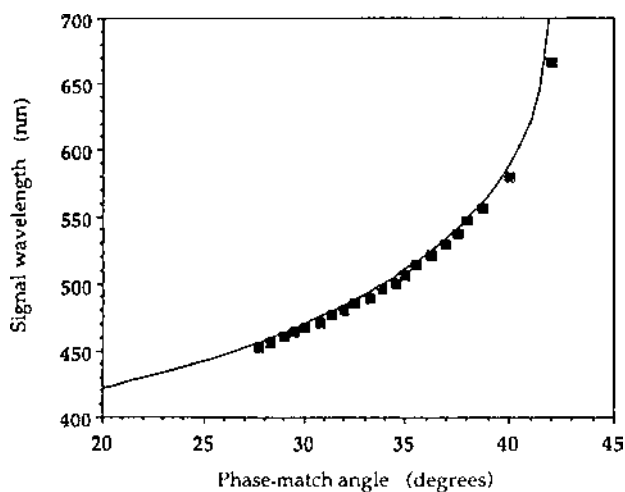
low-energy single-mode oscillator. This could come from another tunable laser or from another OPO operated just above threshold. The injected signal controls the output frequency and line width of the high power OPO. This is sometimes called a master oscillator/power oscillator system.



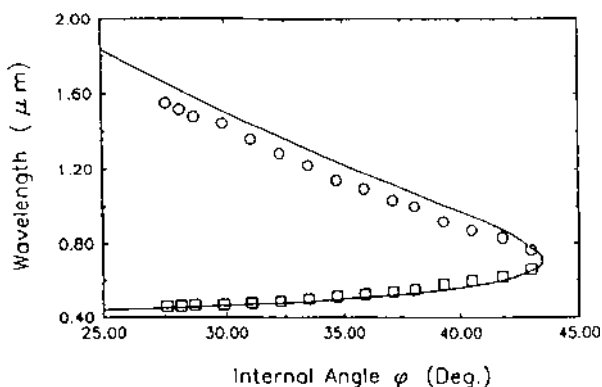
**Figure 20** Angle tuning curves for type I cut ( $\theta = 90^\circ$ ,  $\phi = 24.5^\circ$ ) LBO pumped at 255 nm. (From Ref. 27.)



**Figure 21** Angle tuning curves for type I cut ( $\theta = 90^\circ$ ,  $\phi = 39^\circ$ ) LBO pumped at 355 nm. (From Ref. 28.)



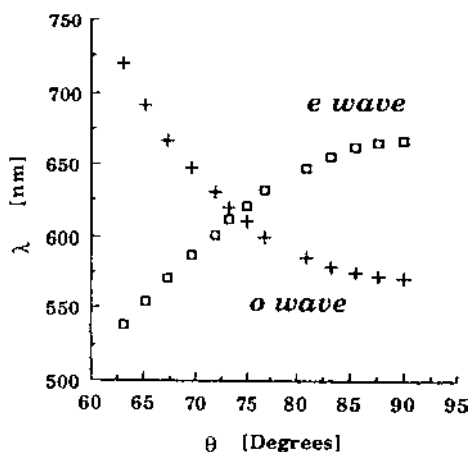
**Figure 22** Angle tuning curves for type I cut ( $\theta = 25^\circ$  and  $\theta = 40^\circ$ ) LBO crystals pumped at 355 nm. (From Ref. 29.)



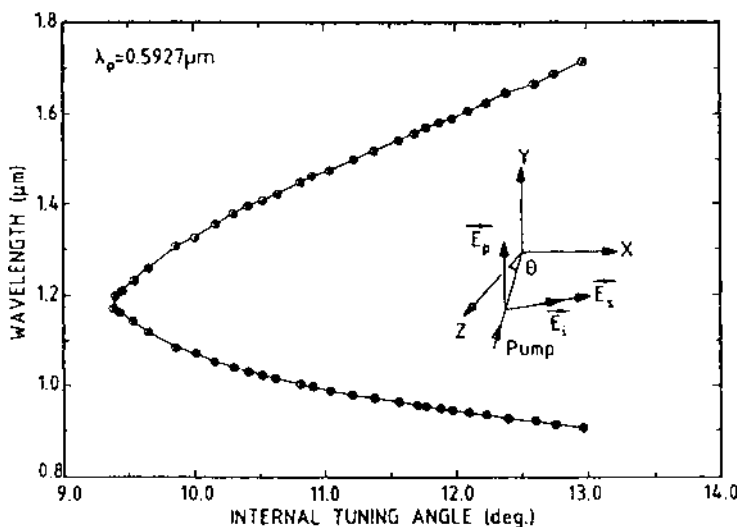
**Figure 23** Angle tuning curves for type I cut LBO pumped at 355 nm. (From Ref. 24.)

#### IV. PULSED OPOS

These systems are typically pumped by Q-switched lasers and produce nanosecond scale pulses at low repetition rates ( $\sim 1\text{--}50$  Hz). The mainly different parameters to consider for pulsed OPOs are rise time and threshold. The two are related, since the pump power incident on the OPO over a finite rise time will require a specific amount of accumulated energy to turn the OPO “on.” These parameters are discussed in the paragraphs below.



**Figure 24** Angle tuning curves for type II cut urea pumped at 308 nm. (From Ref. 30.)



**Figure 25** Angle tuning curves for type I cut *N*-(4-nitrophenyl)-*L*-prolinol (NPP) in the XZ plane pumped at 592.7 nm. (From Ref. 31.)

## A. Rise Time

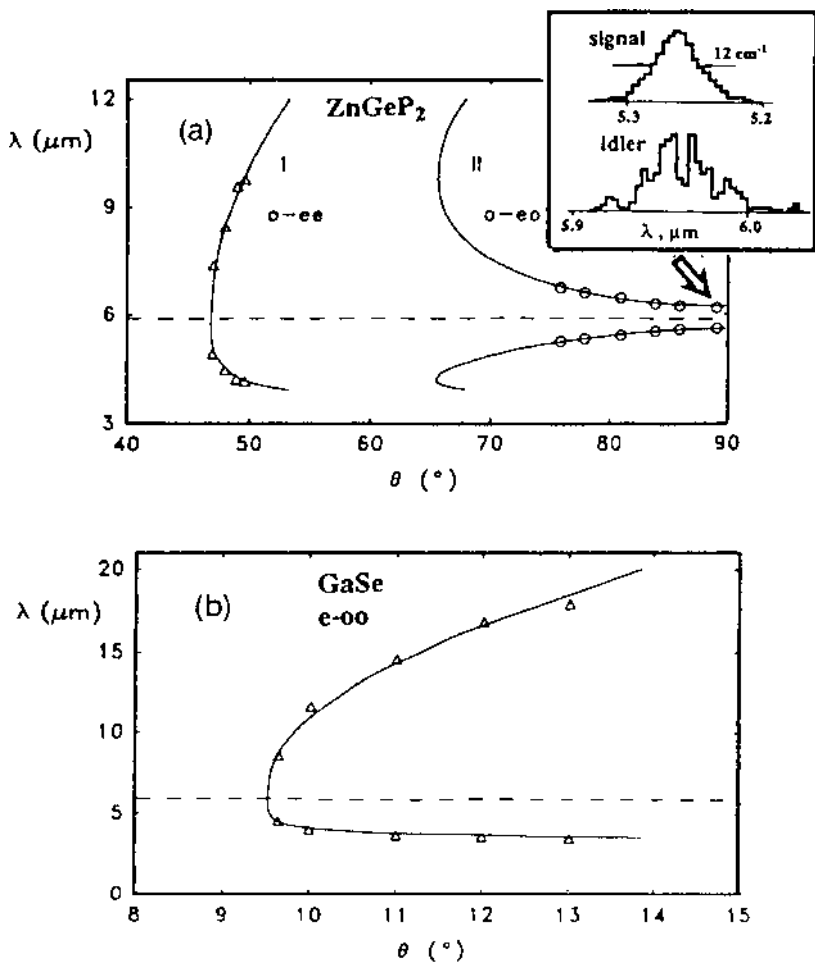
Siegman [16] was the first to consider the rise time of a degenerate OPO. Operationally the rise time is the time required to amplify the quantum noise (i.e., spontaneous parametric fluorescence) to a steady-state signal power of the order of the pump power. As discussed earlier, exponential growth of the signal wave can only occur when the net one-way gain exceeds the round-trip loss. In other words, the instantaneous pump power must exceed the steady-state threshold pump power.

Since the one-way gain is modest, many round-trips are required to reach the steady-state regime. After many passes, the signal power will be of the order of the pump power, and pump depletion will then become evident. Until such a condition is reached, the pump power can be treated as a constant. Table 22 gives expressions for the rise time of a DRO and an SRO for the two cases of a step input pulse and a Gaussian-shaped input pulse.

*Step input DRO with equal signal and idler losses.* Notice that the rise time is given in terms of the usual cavity decay time of a Fabry–Perot resonator, i.e.,

$$\tau_{\text{cav}} = \frac{l/c}{1 - R_s \exp(-\alpha_s L)} \quad (21)$$

where  $l$  is the length of the cavity, and  $L$  is the length of the nonlinear crystal.



**Figure 26** Angle tuning curves for (a) types I and II ZnGeP<sub>2</sub> and (b) type I GaSe pumped at 2900 nm. The inset shows the spectral characteristics of OPG for type II ( $\theta = 84^\circ$ ) ZnGeP<sub>2</sub> pumped at 2790 nm. (From Ref. 32.)

Eq. (21) defines the rate that optical energy “leaks” out of a lossy cavity. Thus the rise time of the OPO must be of the order of this value.

Note that the rise time depends on the amount of gain needed to amplify the signal to the steady state, but only logarithmically through the factor  $\ln[\mathcal{P}_s(\text{ss})/\mathcal{P}(0)]$ , where  $\mathcal{P}_s(\text{ss})$  is the value of the signal power at steady state, and  $\mathcal{P}_s(0)$  is the signal power at  $t = 0$ , equivalent to one photon in the signal channel. This logarithmic dependence indicates that the rise time is not critically

**Table 16** Formulas for Calculating Angular Tuning Rates<sup>a</sup>

Type I

$$\begin{aligned} \text{oeo} \quad \Delta\omega &= \frac{-\frac{1}{2}\omega_p[n_p^e(\theta)]^3[(n_p^e)^{-2} - (n_p^o)^{-2}]\sin 2\theta}{n_s^o - n_i^o + \omega_s(\partial n^o/\partial\omega)_{\omega_s} - \omega_i(\partial n^o/\partial\omega)_{\omega_i}} \Delta\theta \\ \text{e eo} \quad \Delta\omega &= \frac{\frac{1}{2}\{\omega_s[n_s^e(\theta)]^3[(n_s^e)^{-2} - (n_s^o)^{-2}] + \omega_i[n_i^e(\theta)]^3[(n_i^e)^{-2} - (n_i^o)^{-2}]\}\sin 2\theta}{n_s^e(\theta) - n_i^e(\theta) + \omega_s[\partial n^e(\theta)/\partial\omega]_{\omega_s} - \omega_i[\partial n^e(\theta)/\partial\omega]_{\omega_i}} \Delta\theta \end{aligned}$$

Type II

$$\begin{aligned} \text{oe e} \quad \Delta\omega &= \frac{-\frac{1}{2}\{\omega_p[n_p^e(\theta)]^3[(n_p^e)^{-2} - (n_p^o)^{-2}] - \omega_i[n_i^e(\theta)]^3[(n_i^e)^{-2} - (n_i^o)^{-2}]\}\sin 2\theta}{n_s^o - n_i^e(\theta) + \omega_s(\partial n^o/\partial\omega)_{\omega_s} - \omega_i[\partial n^e(\theta)/\partial\omega]_{\omega_i}} \Delta\theta \\ \text{e oe} \quad \Delta\omega &= \frac{-\frac{1}{2}\{\omega_p[n_p^e(\theta)]^3[(n_p^e)^{-2} - (n_p^o)^{-2}] - \omega_s[n_s^e(\theta)]^3[(n_s^e)^{-2} - (n_s^o)^{-2}]\}\sin 2\theta}{n_s^e(\theta) - n_i^o + \omega_s[\partial n^e(\theta)/\partial\omega]_{\omega_s} - \omega_i(\partial n^o/\partial\omega)_{\omega_i}} \Delta\theta \\ \text{oe o} \quad \Delta\omega &= \frac{\frac{1}{2}\omega_i[n_i^e(\theta)]^3[(n_i^e)^{-2} - (n_i^o)^{-2}]\sin 2\theta}{n_s^o - n_i^e(\theta) + \omega_s(\partial n^o/\partial\omega)_{\omega_s} - \omega_i(\partial n^e(\theta)/\partial\omega)_{\omega_i}} \Delta\theta \\ \text{e oo} \quad \Delta\omega &= \frac{\frac{1}{2}\omega_s[n_s^e(\theta)]^3[(n_s^e)^{-2} - (n_s^o)^{-2}]\sin 2\theta}{n_s^e(\theta) - n_i^o + \omega_s[\partial n^e(\theta)/\partial\omega]_{\omega_s} - \omega_i(\partial n^o/\partial\omega)_{\omega_i}} \Delta\theta \\ \frac{\partial n^e(\theta)}{\partial\omega} &= [n^e(\theta)]^3 \left[ \frac{\cos^2\theta \partial n^o}{(n^o)^3 \partial\omega} + \frac{\sin^2\theta \partial n^e}{(n^e)^3 \partial\omega} \right] \\ \Delta\lambda &= -\left(\frac{\lambda^2}{c}\right) \frac{\Delta\omega}{2\pi} \end{aligned}$$

<sup>a</sup> See footnote in Table 15, (p. 148).

dependent on the ratio  $\mathcal{P}_s(\text{ss})/\mathcal{P}(0)$ . This is reflective of the explosive nature of the exponential signal growth. A value of  $10^8$  is typical to assume for this ratio, although a variance of two orders of magnitude will not affect the outcome significantly.

From the expression in Table 22, it appears that  $\tau_R$  will be smaller for larger cavity losses. Note, however, that since  $\mathcal{P}_{p,\text{th}} \propto [1 - R_s \exp(-\alpha_s L)]^2$ , the rise

**Table 17** Formulas for Calculating Angular Tuning Rates for Type I Processes Near Degeneracy<sup>a</sup>

$$\begin{aligned} \text{oeo} \quad \Delta\omega &= \left\{ \frac{|\omega_p[n_p^e(\theta)]^3[(n_p^e)^{-2} - (n_p^o)^{-2}]\sin 2\theta|}{4(\partial n^o/\partial\omega)_{\omega_p/2} + \omega_p(\partial^2 n^o/\partial\omega^2)_{\omega_p/2}} \right\}^{1/2} (\Delta\theta)^{1/2} \\ \text{e eo} \quad \Delta\omega &= \left\{ \frac{|\omega_p[n^e(\theta, \omega_p/2)]^3\{[n^e(\omega_p/2)]^{-2} - [n^o(\omega_p/2)]^{-2}\}\sin 2\theta|}{4[\partial n^e(\theta)/\partial\omega]_{\omega_p/2} + \omega_p[\partial^2 n^e(\theta)/\partial\omega^2]_{\omega_p/2}} \right\}^{1/2} (\Delta\theta)^{1/2} \end{aligned}$$

$$\Delta\lambda = -\left(\frac{\lambda^2}{c}\right) \frac{\Delta\omega}{2\pi}$$

<sup>a</sup> See footnote in Table 15.

**Table 18** Formulas for Calculating Temperature Tuning Curves<sup>a</sup>

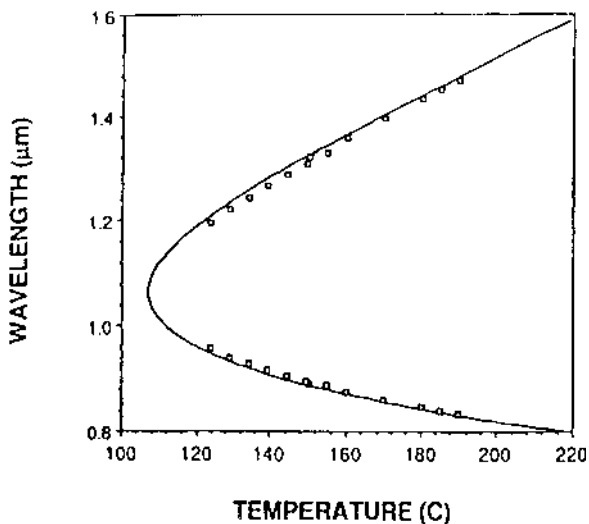
|         |                                                                                                                             |
|---------|-----------------------------------------------------------------------------------------------------------------------------|
| Type I  |                                                                                                                             |
| oeo     | $\lambda_s^{-1} n^o(T, \lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^e(T, \lambda_i) = \lambda_p^{-1} n^e(T, \lambda_p)$ |
| eeo     | $\lambda_s^{-1} n^e(T, \lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^e(T, \lambda_i) = \lambda_p^{-1} n^o(T, \lambda_p)$ |
| Type II |                                                                                                                             |
| oeo     | $\lambda_s^{-1} n^o(T, \lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^e(T, \lambda_i) = \lambda_p^{-1} n^e(T, \lambda_p)$ |
| oeo     | $\lambda_s^{-1} n^e(T, \lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^o(T, \lambda_i) = \lambda_p^{-1} n^e(T, \lambda_p)$ |
| oeo     | $\lambda_s^{-1} n^o(T, \lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^e(T, \lambda_i) = \lambda_p^{-1} n^o(T, \lambda_p)$ |
| eeo     | $\lambda_s^{-1} n^e(T, \lambda_s) + (\lambda_p^{-1} - \lambda_s^{-1}) n^o(T, \lambda_i) = \lambda_p^{-1} n^o(T, \lambda_p)$ |

$n(T, \lambda)$  = index of refraction as a function of temperature and wavelength

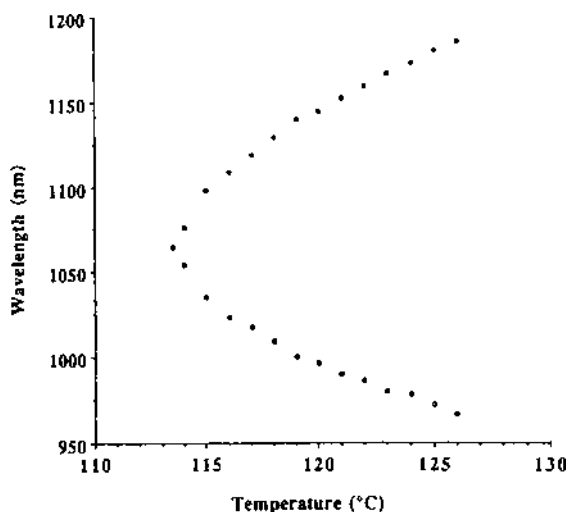
$$\lambda_i = \frac{\lambda_s \lambda_p}{\lambda_s - \lambda_p}$$

<sup>a</sup> See footnote in Table 15.

time will actually be longer for larger cavity losses. In this case larger loss means that longer times are required to build up the signal to steady state because of “leakage” of energy out of the cavity. For  $\mathcal{P}_p \gg \mathcal{P}_{p,th}$ ,  $\tau_R$  will be independent of the cavity losses.

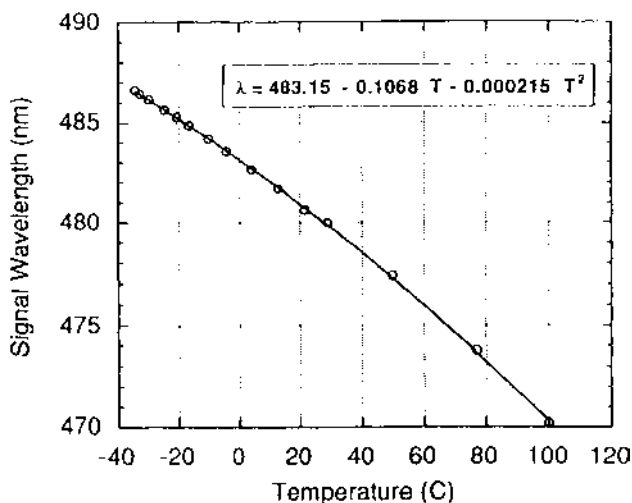


**Figure 27** Temperature tuning curves for MgO:LiNbO<sub>3</sub> pumped at 532 nm. (From Ref. 33.)

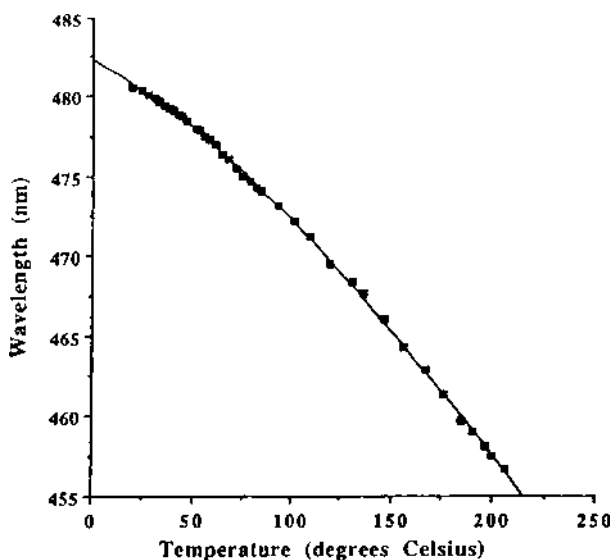


**Figure 28** Temperature tuning curves for LiNbO<sub>3</sub> pumped at 532 nm. (From Ref. 34.)

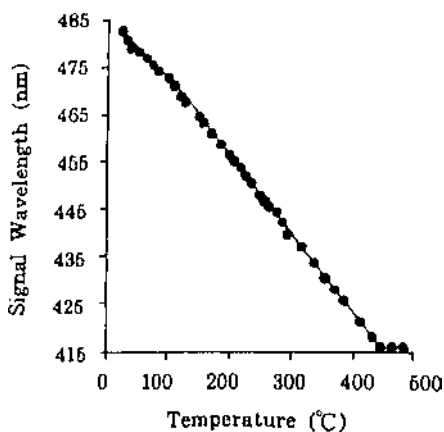
Byer [43] has given an approximate expression of the rise time near degeneracy for a DRO, shown in Table 22, when the input pulse has a Gaussian shape. The primary result is that  $(N_{\text{DRO}})^{1/2}$  is replaced by approximately  $0.88(N_{\text{DRO}})^{1/2}$ , as long as  $\tau_R < \tau_p$ , where  $\tau_p$  is the full width at half maximum



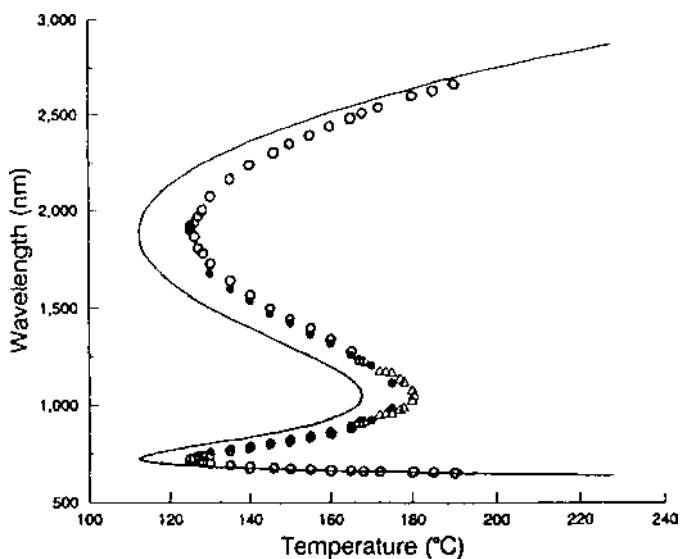
**Figure 29** Temperature tuning curves for LBO pumped at 355 nm. (From Ref. 35.)



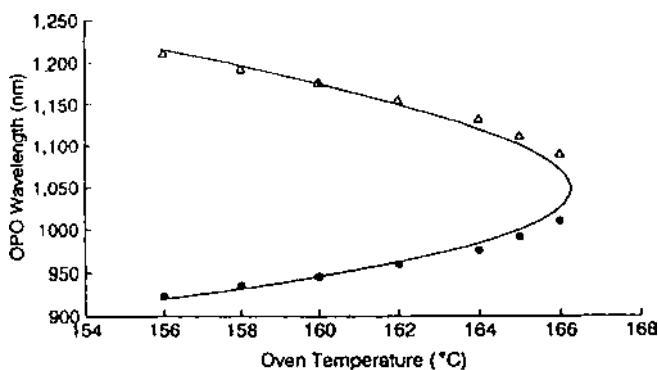
**Figure 30** Temperature tuning curves for type II LBO pumped at 355 nm. (From Ref. 36.)



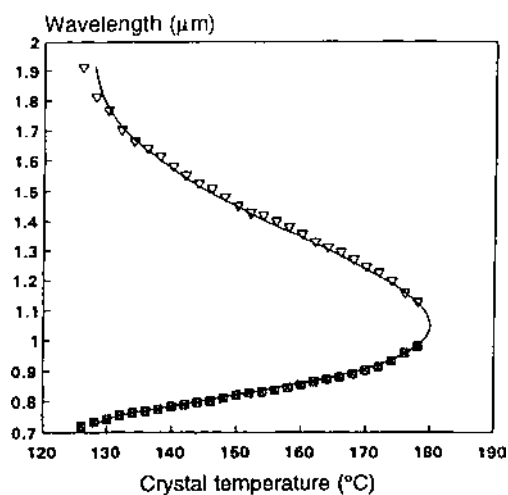
**Figure 31** Temperature tuning curves for type II LBO pumped at 355 nm. (From Ref. 37.)



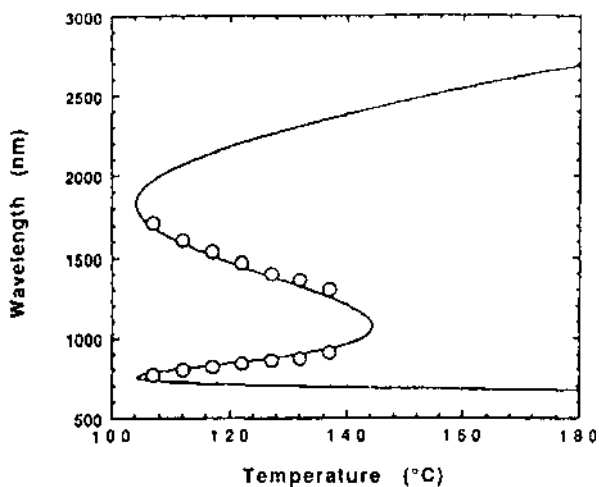
**Figure 32** Temperature tuning curves for type I cut LBO in the XY plane pumped at 523.5 nm. The curves show a retracted behavior for LBO in which four distinct wavelengths (two signal and two idler) can be simultaneously obtained at one temperature. (From Ref. 38.)



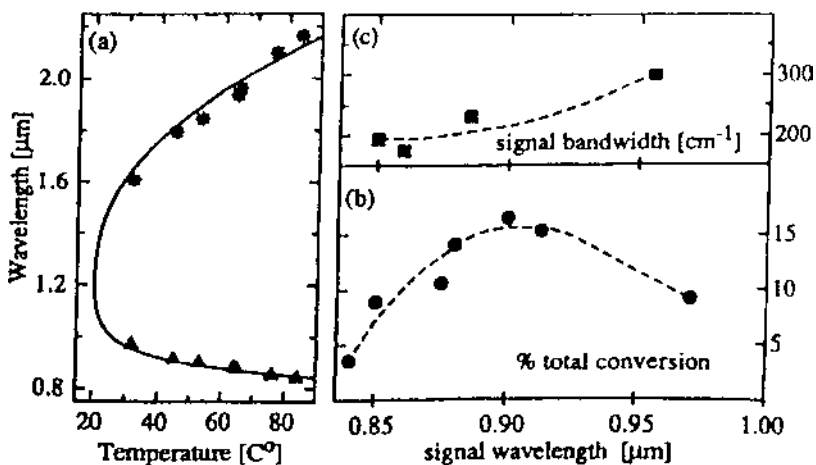
**Figure 33** Temperature tuning curves for type I LBO pumped at 523.5 nm. (From Ref. 39.)



**Figure 34** Temperature tuning curves for LBO pumped at 523.5 nm. (From Ref. 40.)



**Figure 35** Temperature tuning curves for type I LBO pumped at 532 nm. (From Ref. 41.)



**Figure 36** (a) Temperature tuning curves, (b) conversion efficiency, and (c) signal bandwidth for LBO pumped at 605 nm. (From Ref. 42.)

**Table 19** Formulas for Calculating Temperature Tuning Rates<sup>a</sup>

| Type I                                                                        |                                                                                                                                                                                                                                                                                                                  |
|-------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| oeo                                                                           | $\Delta\omega = \left[ \frac{\omega_p(\partial n_p^e/\partial T)_{T_o} - \omega_s(\partial n_s^o/\partial T)_{T_o} - \omega_i(\partial n_i^o/\partial T)_{T_o}}{n_s^o - n_i^o + \omega_s(\partial n^o/\partial\omega)_{\omega_s, T_o} - \omega_i(\partial n^o/\partial\omega)_{\omega_i, T_o}} \right] \Delta T$ |
| eeo                                                                           | $\Delta\omega = \left[ \frac{\omega_p(\partial n_p^o/\partial T)_{T_o} - \omega_s(\partial n_s^e/\partial T)_{T_o} - \omega_i(\partial n_i^e/\partial T)_{T_o}}{n_s^e - n_i^e + \omega_s(\partial n^e/\partial\omega)_{\omega_s, T_o} - \omega_i(\partial n^e/\partial\omega)_{\omega_i, T_o}} \right] \Delta T$ |
| Type II                                                                       |                                                                                                                                                                                                                                                                                                                  |
| oeo                                                                           | $\Delta\omega = \left[ \frac{\omega_p(\partial n_p^e/\partial T)_{T_o} - \omega_s(\partial n_s^o/\partial T)_{T_o} - \omega_i(\partial n_i^e/\partial T)_{T_o}}{n_s^o - n_i^e + \omega_s(\partial n^o/\partial\omega)_{\omega_s, T_o} - \omega_i(\partial n^e/\partial\omega)_{\omega_i, T_o}} \right] \Delta T$ |
| eeo                                                                           | $\Delta\omega = \left[ \frac{\omega_p(\partial n_p^e/\partial T)_{T_o} - \omega_s(\partial n_s^e/\partial T)_{T_o} - \omega_i(\partial n_i^o/\partial T)_{T_o}}{n_s^e - n_i^o + \omega_s(\partial n^e/\partial\omega)_{\omega_s, T_o} - \omega_i(\partial n^o/\partial\omega)_{\omega_i, T_o}} \right] \Delta T$ |
| oeo                                                                           | $\Delta\omega = \left[ \frac{\omega_p(\partial n_p^o/\partial T)_{T_o} - \omega_s(\partial n_s^o/\partial T)_{T_o} - \omega_i(\partial n_i^e/\partial T)_{T_o}}{n_s^o - n_i^e + \omega_s(\partial n^o/\partial\omega)_{\omega_s, T_o} - \omega_i(\partial n^e/\partial\omega)_{\omega_i, T_o}} \right] \Delta T$ |
| eeo                                                                           | $\Delta\omega = \left[ \frac{\omega_p(\partial n_p^o/\partial T)_{T_o} - \omega_s(\partial n_s^e/\partial T)_{T_o} - \omega_i(\partial n_i^o/\partial T)_{T_o}}{n_s^e - n_i^o + \omega_s(\partial n^e/\partial\omega)_{\omega_s, T_o} - \omega_i(\partial n^o/\partial\omega)_{\omega_i, T_o}} \right] \Delta T$ |
| $\Delta\lambda = -\left(\frac{\lambda^2}{c}\right) \frac{\Delta\omega}{2\pi}$ |                                                                                                                                                                                                                                                                                                                  |

<sup>a</sup> See footnote in Table 15.

**Table 20** Formulas for Calculating Temperature Tuning Rates for Type I Processes Near Degeneracy<sup>a</sup>

---

|     |                                                                                                                                                                                                                                                                                                |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| oeo | $\Delta\omega = \left\{ \frac{2\omega_p  (\partial n^e / \partial T)_{\omega_p, T_0} - (\partial n^o / \partial T)_{\omega_p/2, T_0} }{4(\partial n^o / \partial \omega)_{\omega_p/2, T_0} + \omega_p (\partial^2 n^o / \partial \omega^2)_{\omega_p/2, T_0}} \right\}^{1/2} (\Delta T)^{1/2}$ |
| eeo | $\Delta\omega = \left\{ \frac{2\omega_p  (\partial n^o / \partial T)_{\omega_p, T_0} - (\partial n^e / \partial T)_{\omega_p/2, T_0} }{4(\partial n^e / \partial \omega)_{\omega_p/2, T_0} + \omega_p (\partial^2 n^e / \partial \omega^2)_{\omega_p/2, T_0}} \right\}^{1/2} (\Delta T)^{1/2}$ |
|     | $\Delta\lambda = -\left(\frac{\lambda^2}{c}\right) \frac{\Delta\omega}{2\pi}$                                                                                                                                                                                                                  |

---

<sup>a</sup> See footnote in Table 15.

**Table 21** Formulas for Calculating Gain Bandwidths<sup>a</sup>

---

|                      |                                                                                                                                                                                                   |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Type I               |                                                                                                                                                                                                   |
| oeo                  | $ \delta\omega  = \frac{2\pi c/L}{ n_s^o - n_i^o + \omega_s (\partial n^o / \partial \omega)_{\omega_s} - \omega_i (\partial n^o / \partial \omega)_{\omega_i} }$                                 |
| eeo                  | $ \delta\omega  = \frac{2\pi c/L}{ n_s^e(\theta) - n_i^e(\theta) + \omega_s [\partial n^e(\theta) / \partial \omega]_{\omega_s} - \omega_i [\partial n^e(\theta) / \partial \omega]_{\omega_i} }$ |
| Type II              |                                                                                                                                                                                                   |
| oeo                  | $ \delta\omega  = \frac{2\pi c/L}{ n_s^o - n_i^e(\theta) + \omega_s (\partial n^o / \partial \omega)_{\omega_s} - \omega_i [\partial n^e(\theta) / \partial \omega]_{\omega_i} }$                 |
| oeo                  | $ \delta\omega  = \frac{2\pi c/L}{ n_s^e(\theta) - n_i^o + \omega_s [\partial n^e(\theta) / \partial \omega]_{\omega_s} - \omega_i (\partial n^o / \partial \omega)_{\omega_i} }$                 |
| oeo                  |                                                                                                                                                                                                   |
| Type I (near degen.) |                                                                                                                                                                                                   |
| oeo                  | $ \delta\omega  = \left[ \frac{4\pi c/L}{4(\partial n^o / \partial \omega)_{\omega_p/2} + \omega_p (\partial^2 n^o / \partial \omega^2)_{\omega_p/2}} \right]^{1/2}$                              |
| eeo                  | $ \delta\omega  = \left[ \frac{4\pi c/L}{4[\partial n^e(\theta) / \partial \omega]_{\omega_p/2} + \omega_p [\partial^2 n^e(\theta) / \partial \omega^2]_{\omega_p/2}} \right]^{1/2}$              |

---


$$|\delta\sigma(\text{cm}^{-1})| = \frac{|\delta\omega|}{2\pi c(\text{cm/s})}$$

$$\delta\lambda = \left(\frac{\lambda^2}{c}\right) \frac{|\delta\omega|}{2\pi}$$


---

<sup>a</sup> In this case, type I refers to generated signal and idler having parallel polarizations, while type II implies orthogonal polarizations.

**Table 22** Formulas for Calculating the Rise Time of Pulsed OPOs

|                      |                                                                                                                                                     |
|----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| Step input pulse     |                                                                                                                                                     |
| DRO (at degeneracy)  | $\tau_R \approx \frac{l/c}{(1 - R_s e^{-\alpha_s L})(\sqrt{N_{\text{DRO}}} - 1)} \ln \left[ \frac{\mathcal{P}_s(ss)}{\mathcal{P}_s(0)} \right]$     |
| SRO                  | $\tau_R \approx \frac{l/c}{(1 - R_s e^{-\alpha_s L})(N_{\text{SRO}} - 1)} \ln \left[ \frac{\mathcal{P}_s(ss)}{\mathcal{P}_s(0)} \right]$            |
| Gaussian input pulse |                                                                                                                                                     |
| DRO (at degeneracy)  | $\tau_R \approx \frac{l/c}{(1 - R_s e^{-\alpha_s L})(0.88\sqrt{N_{\text{DRO}}} - 1)} \ln \left[ \frac{\mathcal{P}_s(ss)}{\mathcal{P}_s(0)} \right]$ |
|                      | (see also Figs. 39 and 40)                                                                                                                          |
| SRO                  | (see Figs. 37 and 38)                                                                                                                               |

(FWHM) of the pump pulse. It will be remembered that  $N_{\text{DRO}}$  is the number of times that the incident (peak) pump power exceeds the steady-state DRO threshold pump power.

*Step input SRO.* For the SRO, the following simple change is made:  $(N_{\text{DRO}})^{1/2} - 1 \rightarrow N_{\text{SRO}} - 1$ . Now, since  $\mathcal{P}_{p,th} \propto [1 - R_s \exp(-\alpha_s L)]$ , statements made above for the DRO apply equally well to the SRO. Again, for  $\mathcal{P}_p \gg \mathcal{P}_{p,th}$ , the rise time will be independent of cavity losses.

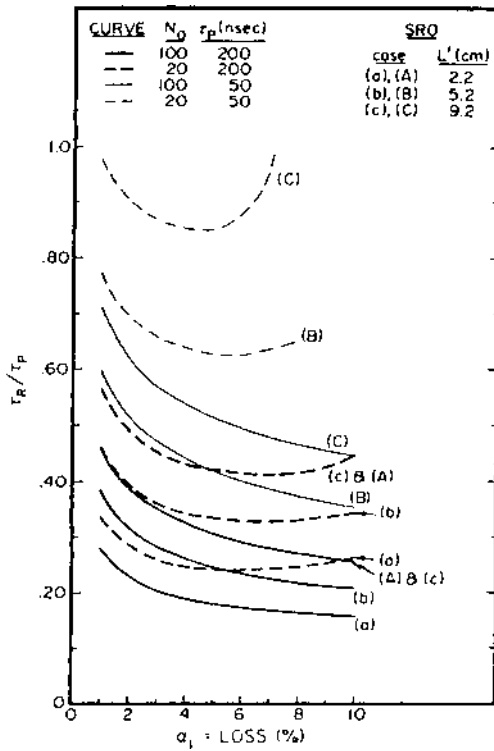
*Gaussian input pulse SRO.* Pearson et al. [44] have analyzed in detail the rise time of OPOs with Gaussian input pulses. For the SRO,  $\tau_R$  is again defined operationally by

$$\mathcal{P}_s(\tau_R) = \mathcal{P}_s(0) \frac{r}{a} \quad (22)$$

where  $a = 1 - R_s \exp(-\alpha_s L)$  is the cavity loss and  $r$  is a number of the order of the amplification factor needed to reach threshold. As before, the explosive nature of the signal growth makes  $\tau_R$  relatively insensitive to the exact value of  $r$  (a change in  $r$  by two orders of magnitude changes  $\tau_R$  by only 10%).

Pearson et al. computed a value for Eq. (22) by solving the time dependent coupled wave equations for the signal and idler waves in the nondepleted pump approximation. The final result must be found numerically. Again, the rise time depends on the amount by which the peak pump power exceeds the steady-state threshold. Pearson et al. performed their calculations in terms of a normalized pump ratio  $N_0 = N_{\text{SRO}}(100a)$ , where  $a$  is the cavity loss in %.

The rise time of an SRO as a function of cavity loss for given pump pulse width, normalized pump power ratio, and cavity length  $L'$  is shown in Fig. 37. Figure 38 shows  $\tau_R$  vs.  $L'$  for given pump pulse width, pump power ratio, and a cavity loss of 1%. In all of these plots, a value of  $r = 10^8$  was assumed.



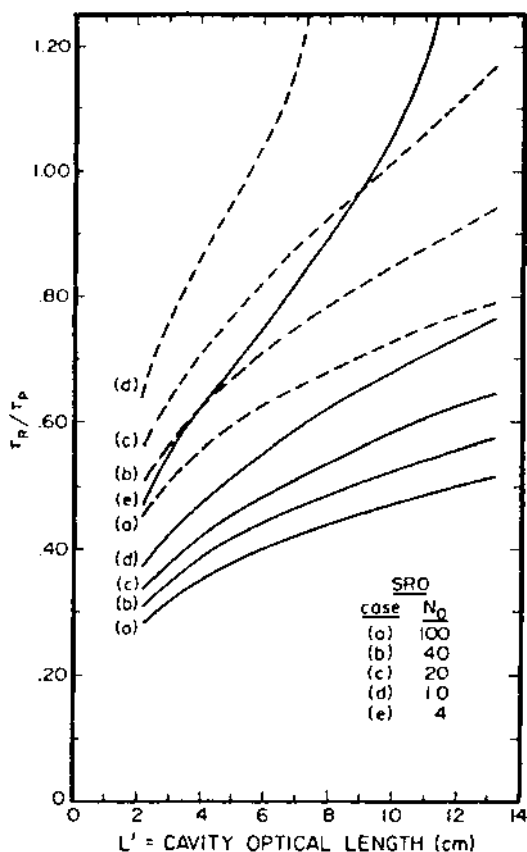
**Figure 37** Rise time of a Gaussian-shaped pulse pumped SRO as a function of cavity loss for various pump ratios and cavity lengths. Heavy curves, 200 ns pump pulse. Light curves, 50 ns pump pulse. (From Ref. 44 © IEEE 1972.)

*Gaussian input pulse DRO.* The DRO treated by Pearson et al. has equal signal and idler losses. The operational definition for  $\tau_R$  in this case is

$$\mathcal{P}_s(\tau_R) = \mathcal{P}_s(0) \frac{r}{a^2} \quad (23)$$

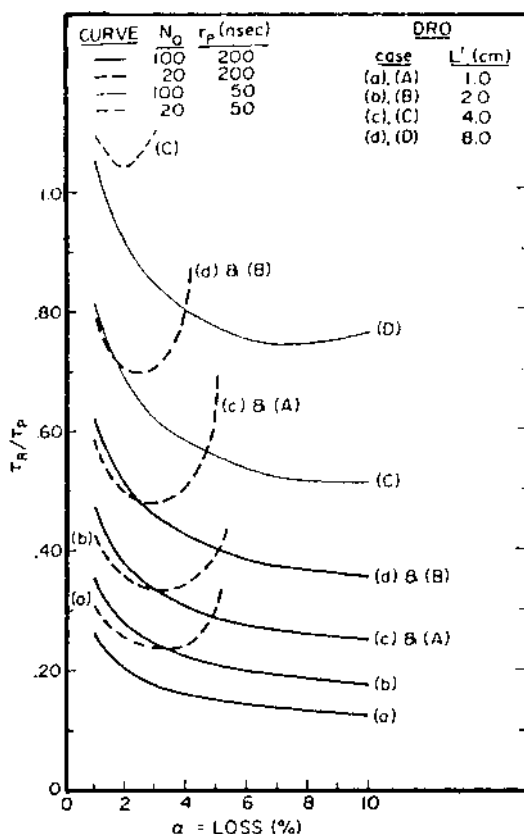
and  $\tau_R$  is a function of the normalized pump power ratio for the DRO,  $N_0 = N_{\text{DRO}}(100a)^2$ . The rise time as a function of cavity loss given  $\tau_p$ ,  $N_0$ , and  $L'$  is shown in Fig. 39. In Figure 40,  $\tau_R$  vs.  $L'$  is plotted for given  $\tau_p$ ,  $N_0$ , and  $a = 1\%$ . Again, a value of  $r = 10^8$  was assumed in the calculations. The dashed curves in these figures are computed from the formula for the step pulse input given in Table 22.

Figures 37 and 39 show that increasing cavity losses may actually decrease the rise time even though larger loss means larger steady-state threshold. As Pearson et al. have pointed out, this is due to the nature of the Gaussian pulse,



**Figure 38** Rise time of a Gaussian-shaped pulse pumped SRO as a function of cavity length for various pump ratios. Cavity loss, 1% Heavy curves, 200 ns pump pulse. Light curves, 50 ns pump pulse. (From Ref. 44 © IEEE 1972.)

which is illustrated in Fig. 41. For  $(t/\tau)^2 > \frac{1}{2}$ , where  $\tau^2 = \tau_p^2/2 \ln(2)$  is the square of the  $1/e^2$  half-width of the pump pulse, the slope of the Gaussian increases in magnitude as  $(t/\tau)^2$  decreases. The rate of growth of the signal power is proportional to the amount by which the instantaneous pump power exceeds threshold, and the signal power will grow rapidly when this ratio grows rapidly. When the cavity loss is low, the threshold pump level occurs further out in the tail of the Gaussian where the pump ratio changes slowly. Thus the rise time can be longer for smaller losses. Pearson et al. have shown, however, that the amount of time by which the rise time precedes the peak of the pulse increases

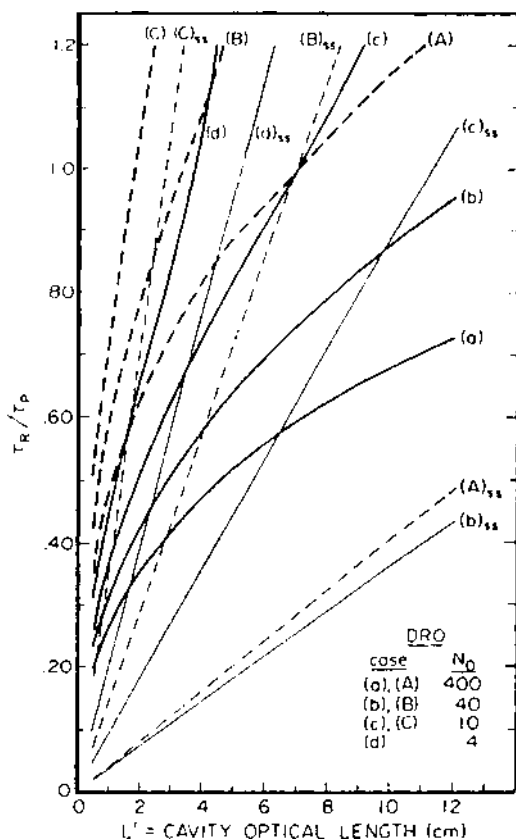


**Figure 39** Rise time of a Gaussian-shaped pulse pumped DRO as a function of cavity loss for various pump ratios and cavity lengths. Heavy curves, 200 ns pump pulse. Light curves, 50 ns pump pulse. (From Ref. 44 © IEEE 1972.)

monotonically with increasing cavity losses. This reflects the fact that for larger cavity losses, the pump power is above threshold for a shorter total time.

A critical result of the finite rise time of the OPO is the minimum peak pump power required to reach oscillation. This value  $N_{\min}$  as a function of cavity length is shown in Fig. 42 for various values of the pulse width and cavity loss. The values for Gaussian-shaped input pulses are compared to the step input results. It can be seen that as small as possible cavity lengths are desired to decrease the oscillation pumping conditions.

The quantity  $N_{\min}$  is the factor by which the pulse threshold is increased due to the finite DRO rise time. Once a steady-state threshold is calculated and a cavity length chosen, the threshold peak pump power is found by multiplying

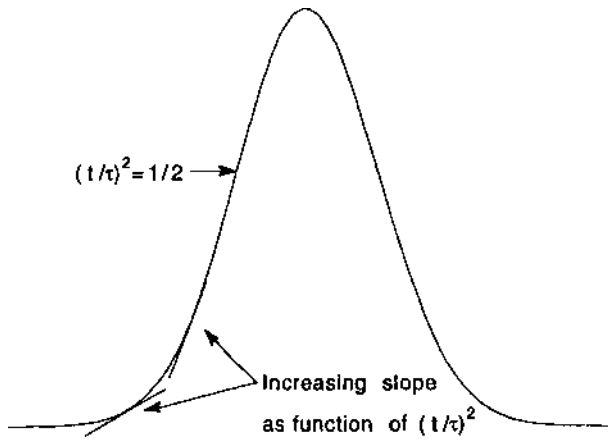


**Figure 40** Rise time of a Gaussian-shaped pulse pumped DRO as a function of cavity length for various pump ratios. Cavity loss, 1% Heavy curves, 200 ns pump pulse. Light curves, 50 ns pump pulse. (From Ref. 44 © IEEE 1972.)

the steady-state threshold by  $N_{\min}$ . The pulsed DRO threshold is thus defined by the minimum peak pump power for which the oscillator will turn on rather than by the pump power for which the net parametric gain for the signal and idler waves exceeds the cavity loss.

## B. Threshold

A finite rise time indicates that a certain minimum energy must accumulate before an OPO turns on. Therefore the threshold can be measured in terms of energy or fluence. Simple expressions for fluence thresholds of the DRO and



**Figure 41** Gaussian-shaped temporal pulse illustrating an increasing slope as a function of decreasing  $(t/\tau)^2$  for  $(t/\tau)^2 > \frac{1}{2}$ .

SRO, assuming step pulse inputs, can be found by multiplying the peak pump intensity by the rise time [43]. These expressions are found in Table 23.

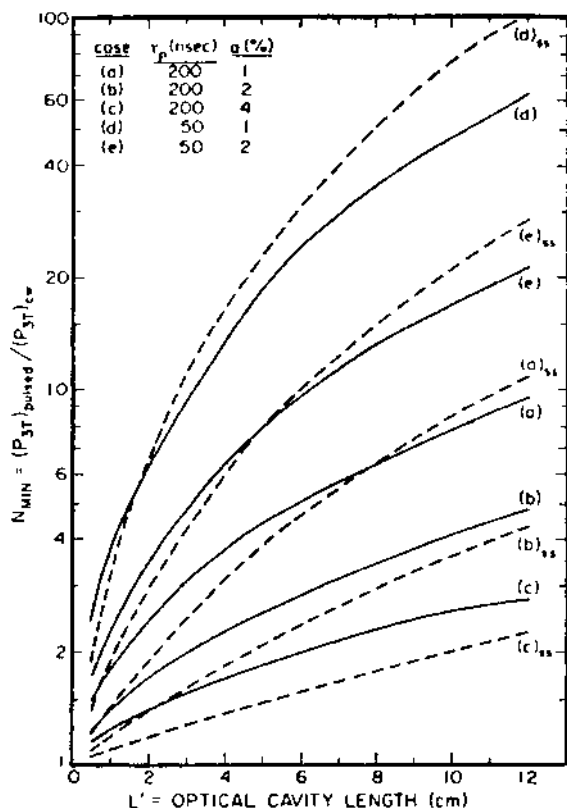
From the results of Pearson et al. [44] (see Fig. 42), the threshold energy  $\mathcal{E}_{th}$  can be found by integrating  $N_{min}$  up to the rise time  $\tau_R$ . Thus

$$\mathcal{E}_{th} = \int_{-\infty}^{\tau_R} N_{min} \mathcal{P}_{p,th} \exp \left[ -\frac{2(t - \tau_T)^2}{\tau^2} \right] dt \quad (24)$$

where  $\tau_T$  is the time corresponding to the peak of the pulse, and  $N_{min} = \mathcal{P}_p(\tau_T)/\mathcal{P}_{p,th}$ .

Brosnan and Byer [45] have analyzed the threshold conditions of an SRO pumped by a Gaussian pulse, including the effects of spatial mode overlap and beam walk-off. They considered the duration of time over which multiple passes amplify the signal power to the steady state from quantum noise. This establishes a condition on the peak of the time dependent parametric gain. They then computed the effective width of the time dependent gain profile for which the net gain exceeds loss (so that a net amplification occurs on each resonator pass) and set this time equal to  $2\tau$ , where again  $\tau$  is the  $1/e^2$  half-width of the Gaussian pulse. Integrating over the pump intensity, the threshold fluence is found. This formula is given in Table 23.

Note that although the threshold fluence of the SRO is larger than that of the DRO, the rise time of the SRO may be smaller at high pump power. This implies that a DRO may reach threshold and oscillate as an SRO before the DRO threshold is achieved under certain conditions. For stability reasons, the SRO is



**Figure 42** Minimum pump ratio required for oscillation for a Gaussian-shaped pump pulse as a function of cavity length for various pulse widths and cavity losses. Dashed curves correspond to a step input pulse. (From Ref. 44 © IEEE 1972.)

more common than the DRO in the pulse regime since adequate pump power for threshold is readily available.

## V. SYNCHRONOUSLY PUMPED OPOs

Many applications require the use of ultrashort pulses. Mode-locked lasers have been heavily employed in such instances, but the wavelength coverage has been limited, especially in the near and mid-IR. A natural extension to fill these needs has been the development of synchronously pumped OPOs. The short pulses have been derived from the mode-locked laser pump, and the properties of the OPO

**Table 23** Formulas for Calculating the Threshold Fluence of Pulsed OPOs

Step input pulse

$$\begin{aligned}
\text{DRO (at degeneracy)} \quad F_{p,th} &\approx \frac{(l/c)I_{p,peak}}{(1 - R_s e^{-\alpha_s L})(\sqrt{N_{DRO}} - 1)} \ln \left[ \frac{\mathcal{P}_s(ss)}{\mathcal{P}_s(0)} \right] \\
\text{SRO} \quad F_{p,th} &\approx \frac{(l/c)I_{p,peak}}{(1 - R_s e^{-\alpha_s L})(N_{SRO} - 1)} \ln \left[ \frac{\mathcal{P}_s(ss)}{\mathcal{P}_s(0)} \right]
\end{aligned}$$

Gaussian input pulse (including effects of spatial mode overlap and beam walk-off)

$$\begin{aligned}
\text{SRO} \quad F_{p,th} &= \frac{2.25\tau}{\kappa g_s \bar{L}^2} \left\{ \frac{l}{2\tau c} \ln \left[ \frac{\mathcal{P}_s(ss)}{\mathcal{P}_s(0)} \right] + \alpha_s L + \ln \frac{2}{\sqrt{R_s}} \right\} \\
\kappa &= \frac{2\pi^2 d_{eff}^2 (1 - \delta^2)}{\epsilon_0 n_s^2 n_p \lambda_p^2 c} \quad (\text{SI}) \\
g_s &= \frac{w_p^2}{w_p^2 + w_s^2} \\
\bar{L} &= L_w \operatorname{erf} \left( \frac{\sqrt{\pi}}{2} \frac{L}{L_w} \right) \\
L_w &= \frac{\sqrt{\pi}}{2} \frac{w_p}{\rho} \sqrt{\frac{w_p^2 + w_s^2}{w_p^2 + \frac{1}{2}w_s^2}} \\
\tau &= 1/e^2 \text{ pulse half-width} \\
\rho &= \text{walk-off angle}
\end{aligned}$$

provide the wide tunability. Synchronous pumping implies that the round-trip time of a pulse in the OPO cavity equals the interpulse time of the pump laser. In this way, the nonlinear crystal is pumped at the appropriate time when the signal pulse to be amplified arrives.

There are two types of mode-locked laser used as a pump source: Q-switched mode-locked, and cw mode-locked. In the first type, the laser is Q-switched to boost the peak power, and the result is a nanosecond scale pulse envelope containing several mode-locked pulses with widths in the picosecond or femtosecond regime. The cw mode-locked laser produces a continuous stream of picosecond or femtosecond pulses which generally have lower peak powers than those of a Q-switched mode-locked laser.

The parameters discussed above for cw and pulsed OPOs are also appropriate for the synchronously pumped OPOs. In particular, thresholds, gain bandwidths, and tuning parameters are calculated in the same way. Rise times and fluence thresholds, discussed in Section III, apply equally well to the Q-switched mode-locked case, since the pulse envelope of the pump has a finite rise time. Rise time is not an issue for cw mode-locked OPOs because the system is in a steady state for periods long compared to the turn-on time of the device.

New parameters of importance for these devices include time synchronization between the pump and the OPO signal pulses, and pulse walk-off and pulse group velocity delay between signal and pump. These arise because of the short time scale of the pulses. Also, the short duration of the pulses results in a finite spectral bandwidth. These spectral properties can be modified by the spectral dispersion and bandwidth of the cavity.

Systems employed for ultrafast spectroscopy are required to have truly repetitive pulses for improved signal-to-noise ratio. The cw mode-locked OPOs with very high pulse repetition rates are well matched to this application. Cheung and Liu [46] have presented a model of these cw systems based on the theory governing actively or passively mode-locked lasers.

The model developed by Chung and Liu treats a cw synchronously pumped, singly resonant OPO. They derived the following differential equation describing the temporal behavior of the signal field amplitude of repetitive pulses in the steady-state regime of the synchronously pumped OPO:

$$\left[ G(t) - \Gamma - S(t) + \frac{\pi^2}{3(\Delta\omega_n)^2} a I_p(t) \frac{d^2}{dt^2} + \frac{1}{(\Delta\omega_c)^2} \frac{d^2}{dt^2} - i \frac{D_s L}{\omega_s c} \frac{d^2}{dt^2} - \delta T_n(t) \frac{d}{dt} - 2\delta T_{sp} \frac{d}{dt} + \delta T \frac{d}{dt} \right] A_{\omega_{so}}(t) = 0 \quad (25)$$

In this expression,  $G(t)$  is the time dependent gain. Since in the steady state the gain per pass is small, this term is given by an expansion of the exact expression, related to the Jacobi elliptic function, keeping terms quadratic in the pump intensity:

$$G(t) = a I_p(t) + \frac{2}{3} a^2 I_p^2(t) \quad (27)$$

The term  $S(t)$  is another term of this expansion and represents gain saturation due to pump depletion:

$$S(t) = \frac{2a^2\omega_p}{3\omega_s} I_p(t) I_s(t) \quad (28)$$

The static distributed linear loss is given by the term  $\Gamma$ :

$$\Gamma = \alpha_s l - \ln \sqrt{R_{s1} R_{s2}} \approx 1 - \sqrt{R_{s1} R_{s2}} \exp(-\alpha_s l) \quad (29)$$

for  $\alpha_s l \ll 1$  and  $R_{s1} \sim R_{s2} \sim 1$ , where  $l$  is the cavity length and  $\alpha_s$  is the effective cavity loss coefficient, which includes all absorption, scattering, and Fresnel reflection losses.  $R_{s1}$  and  $R_{s2}$  are the mirror reflectances at the signal frequency for the front and back mirrors. The nonlinear parametric coefficient  $a$  is

related to the loss term and the steady-state threshold pump intensity by

$$I_{p,th} = \frac{\Gamma}{a} \quad (30)$$

The fourth term of Eq. (25) represents the gain reduction due to the finite phase mismatch of the frequency components comprising the ultrashort pulse, and is related to the gain bandwidth of the crystal  $\Delta\omega_n$ . (The subscript n signifies the nondegenerate bandwidth.) The fifth term describes the effect of the finite cavity bandwidth determined by the cavity finesse and any frequency dispersing elements present. The last second order time derivative term represents the effects on the pulse due to group velocity dispersion, and  $D_s = \omega_s c(d^2k/d\omega^2)|_{\omega_s}$  is the dimensionless dispersion constant.

The three first order derivative terms describe phase shifts. The first is intensity dependent, derived again from an expansion of the exact Jacobi elliptic function, and is present when a finite phase mismatch is present. It is also given in terms of the gain bandwidth:

$$\delta T_n(t) = \frac{2\pi}{3\Delta\omega_n} a I_p(t) \left\{ 1 - \frac{2}{5} \left[ 2a I_p(t) + \frac{\omega_p}{\omega_s} a I_s(t) \right] \right\} + \frac{2}{3} a I_p(t) \delta T_{sp} \quad (31)$$

The second phase shift term is due to the pulse walk-off time  $\delta T_{sp}$ , which is given by the difference of the reciprocal group velocities of the two pulses. Finally, the last term is due to cavity detuning, where the cavity detuning time  $\delta T$  is defined as the difference between the repetition period of the pump pulses and the round-trip time of the signal pulses.

Cheung and Liu solved Eq. (25) by the numerical finite difference method. They took the pump intensity to have a Gaussian temporal profile, and ignored the group velocity dispersion term since this is normally zeroed out experimentally using a set of prisms.

*Detuning time.* Cheung and Liu defined an effective cavity detuning time as  $\delta T_{eff} = \delta T - 2\delta T_{sp}$ . This is a static number determined by the cavity length and linear dispersion properties of the nonlinear crystal. To present the calculations,  $\delta T_{eff}$  was normalized to the full width at half maximum (FWHM) of the Gaussian-shaped pump pulse. (All normalized quantities are designated in the following figures with a caret: ^.) The numerical calculations were performed on 2048 equally spaced time points from  $-5 \times \text{FWHM}$  to  $+5 \times \text{FWHM}$ . In the results presented below, the following parameters were used:  $\Delta\omega_n \times \text{FWHM} = 25$ ,  $\Delta\omega_c \times \text{FWHM} = 5000$ ,  $\omega_s/\omega_p = 0.4$ ,  $R_{s1} = 1$ , and  $1 - R_{s2} = 0.03$ .

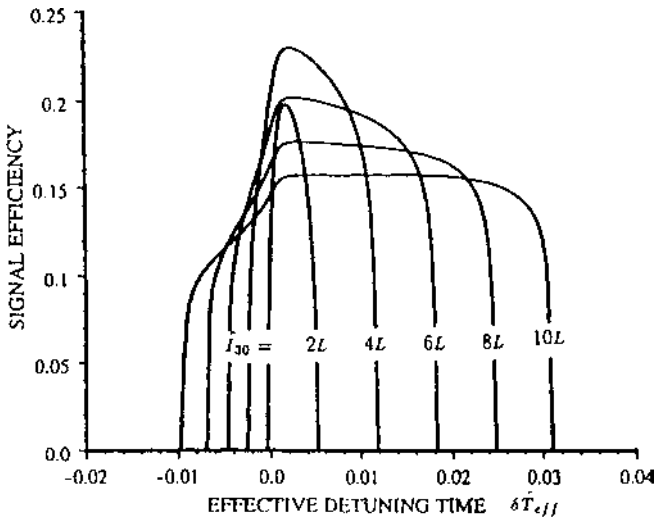
The output signal pulses are asymmetric in time, even for  $\delta T_{eff} = 0$ . This is due to the nonlinear dephasing term  $\delta T_n(t)$ . A finite phase mismatch, present because of the finite frequency spread of an ultrashort pulse, will produce opposite excursions of the net phase difference between the interacting waves

about the optimum value of  $-\pi/2$  during the rising and falling parts of the pump pulse. The net effect is that the leading edge of the signal pulse is favored for amplification.

The effect of the cavity detuning on the signal efficiency is shown in Fig. 43. In these plots, the peak pump intensity is normalized to  $a^{-1}$ . In the notation of Cheung and Liu, “3” corresponds to the pump frequency ( $I_{p0} \rightarrow I_{30}$ ), and “L” is the cavity loss ( $\Gamma \rightarrow L$ ), not to be confused with the notation of  $L$  as the nonlinear crystal length in this book. The notation for the normalized peak pump intensity as some number times loss can be read directly as the pump intensity equalling that number times the steady-state pump threshold (e.g.,  $aI_{30} = 4L \rightarrow I_{p0} = 4I_{p,th}$ ).

The cavity detuning can have some obvious dramatic effects on the signal efficiency. The curves in Fig. 43 do not peak at  $\delta T_{eff} = 0$ . This is due to the nonlinear dephasing term  $\delta T_n(t)$ . However, because  $\delta T_{eff}$  is a constant, its effect can be minimized by active tuning of the cavity length. This fine tuning is normally performed by mounting one of the cavity mirrors on a piezoelectric transducer.

*Gain bandwidth.* The gain bandwidth is normalized to  $(FWHM)^{-1}$ . Other parameters are as specified above, and the effective cavity detuning parameter was chosen to compensate for the intensity dependent phase shift produced by the term proportional to  $\delta T_n(t)$ .



**Figure 43** Signal efficiency as a function of the normalized effective cavity dephasing time for various normalized pump intensities (number of times above steady-state threshold) in a cw synchronously pumped singly resonant OPO. (From Ref. 46.)

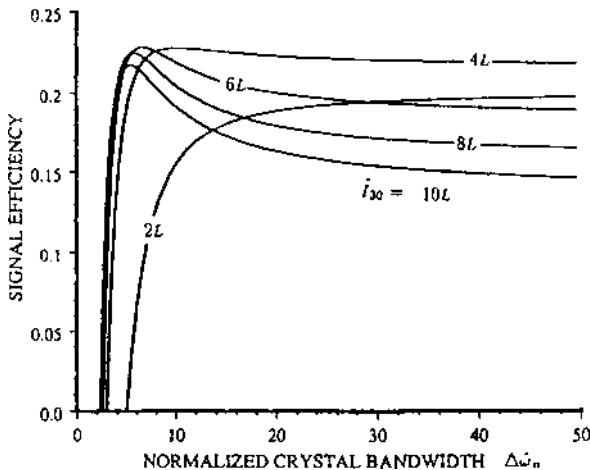
The primary effect of a finite  $\Delta\omega_n$  is a coupling of energy from near the peak of the pulse to its wings. The signal pulse width is narrower at larger values of  $\Delta\omega_n$ . At lower values of  $\Delta\omega_n$ , because the bandwidth cannot accommodate all of the frequencies comprising the pulse, appreciable energy is coupled from the pulse peak to the tails. This results in an increased signal pulse width.

Figure 44 shows that the net effect on signal efficiency is a high efficiency at intermediate bandwidths but low efficiency at small bandwidths. The peak of the efficiency curves in Fig. 44 may not be the best operating point since the pulses are not the shortest there.

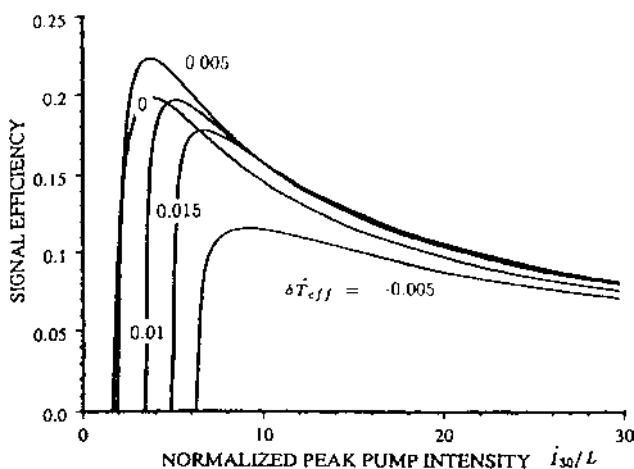
*Cavity bandwidth.* The cavity bandwidth  $\Delta\omega_c$  is also normalized to  $(\text{FWHM})^{-1}$ . It produces results similar to those due to  $\Delta\omega_n$ , but it affects the signal pulses symmetrically in time. This is because intracavity dispersive elements (e.g., étalons) modulate the cavity loss symmetrically in the frequency domain.

*Pump intensity.* As shown in Fig. 45, the signal efficiency is a maximum for the peak pump intensity near the steady-state threshold, for small positive cavity detuning. The calculations are accurate up to  $aI_{30} \sim 10L$  (Cheung and Liu's notation, i.e.,  $I_{p0} \sim 10I_{p,\text{th}}$  in the notation of this book). The signal output increases with increasing pump intensity, but at the expense of a decreasing efficiency and an increasing signal pulse width. For good efficiency and narrow pulse width, it appears that the best operation of the OPO is near its threshold.

*Conclusions.* Cheung and Liu draw some conclusions from their model relating to OPO design. The OPO design includes choices of output coupler



**Figure 44** Signal efficiency as a function of the normalized nonlinear crystal gain bandwidth for various normalized pump intensities (number of time above steady-state threshold) in a cw synchronously pumped singly resonant OPO. (From Ref. 46.)



**Figure 45** Signal efficiency as a function of the normalized pump intensity ratio (number of times above steady-state threshold) for various normalized cavity dephasing times in a cw synchronously pumped singly resonant OPO. (From Ref. 46.)

transmission, length and type of nonlinear crystal, and pump intensity. For good efficiency and narrow pulses, the OPO should be designed to operate with a peak pump intensity approximately two times the steady-state threshold value. For a given pump laser and nonlinear crystal, the choice of the output mirror transmission will set this parameter. An advantage of working near threshold is that the effect of pulse walk-off can almost be perfectly compensated by fine tuning the OPO cavity length. The choice of nonlinear crystal requires a trade-off in the *crystal length*  $L$ . The desire for a large nonlinear parameter  $a$  ( $\propto L^2$ ) for low threshold must be traded against the desire for a large gain bandwidth  $\Delta\omega_n$  ( $\propto L^{-1}$ ) for narrow pulses to optimize the design.

## VI. A BRIEF SURVEY OF DEVICES

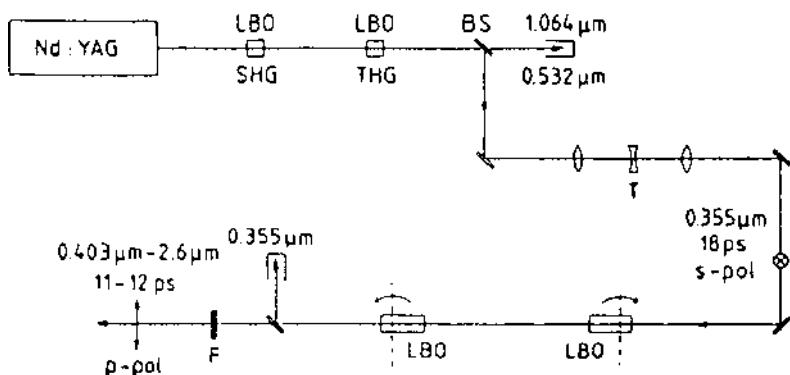
With the improvements in pump sources and nonlinear crystals, several new parametric devices have been reported in the past few years. This section presents a brief survey of devices that have appeared in the literature since 1988. These serve as illustrations of the principles and techniques of parametric devices, but no attempt has been made to give a complete survey of the literature. Devices reported prior to 1988 have been adequately described by other authors [7,47].

## A. OPGs and OPAs

For some applications, parametric superfluorescence and amplification are useful even without the advantages given by oscillation. These devices are simpler to align, and can still provide a stable, tunable output. They also serve well as experimental devices for the eventual development of OPOs using new nonlinear crystals.

A picosecond visible/near IR OPG/OPA system [27] is shown in Fig. 46. The system is pumped by 18 ps pulses at 355 nm obtained by frequency doubling the output of an actively and passively mode-locked Nd:YAG laser, then mixing the fundamental and second harmonic in a second LiB<sub>3</sub>O<sub>5</sub>(LBO) crystal. The UV pump beam is split off using a dichroic mirror and passes through a zoom telescope to adjust its intensity before pumping the LBO crystal of the OPG. This crystal generates a spectral continuum of signal and idler power that propagates to the second LBO crystal. The second crystal is separated from the first crystal by 50 cm to limit the solid angle of light collected and amplified. The signal and idler pulses are thus spectrally narrowed and amplified to the millijoule level. The residual pump energy is separated from the output by a dichroic mirror and filter. The output properties of this OPG/OPA system are given in Table 24.

A visible picosecond OPG/OPA system [37] is illustrated in Fig. 47. This system uses an LBO crystal for the OPG portion and a  $\beta$ -BaB<sub>2</sub>O<sub>4</sub>(BBO) crystal for the OPA stage. The pump beam at 355 nm is generated by a Nd:YAG mode-locked laser. The beam has a nearly Gaussian shape with 5 mm diameter and 0.7 mrad divergence. A portion of the beam split off from the main beam by mirror M1 (1 mJ) is focused with a 1 m focal length quartz lens into the LBO crystal, which was placed 10 cm in front of the focal point. The crystal is polished but uncoated and X, Y, Z cut ( $3 \times 3 \times 10 \text{ mm}^3$ ) for type I NCPM ( $\theta = \phi = 0^\circ$ ).



**Figure 46** Schematic diagram of an LBO based OPG/OPA system. (From Ref. 27.)

**Table 24** OPG/OPA Systems

| Pump laser                                                                                                  | Nonlinear crystal                                                                             | Output energy/<br>power | Conversion<br>efficiency<br>(%) | Tuning<br>range               | Line<br>width                 | Pulse<br>width | Ref. |
|-------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|-------------------------|---------------------------------|-------------------------------|-------------------------------|----------------|------|
| M-L Nd:YAG<br><br>3rd harm. (355 nm)<br>$\tau = 18$ ps<br>4.3 mJ/pulse                                      | LiB <sub>3</sub> O <sub>5</sub><br><br>(LBO)                                                  | ~ 1 mJ                  | 28                              | 403–2580 nm                   | ~ 20–1000<br>cm <sup>-1</sup> | 11–12 ps       | [27] |
| M-L Nd:YAG<br>3rd harm. (355 nm)<br>$\tau = 30$ ps, 10 Hz<br>4.8 mJ/pulse                                   | LiB <sub>3</sub> O <sub>5</sub><br>(LBO)<br>$\beta$ -BaB <sub>2</sub> O <sub>4</sub><br>(BBO) | 1.57 mJ<br>52 MW, peak  | 32.7                            | 416–482 nm                    | 0.15 nm                       | ~ 30 ps        | [37] |
| M-L Nd:YAG<br>3rd harm. (355 nm)<br>$\tau = 35$ ps 10 Hz                                                    | $\beta$ -BaB <sub>2</sub> O <sub>4</sub><br>(BBO)                                             | ~ 1 mJ                  | 30                              | 400–2000 nm<br>600–2500 nm    | ~ 0.2 nm                      | —              | [24] |
| M-L Er <sup>3+</sup> :YAG<br>(2940 nm)                                                                      | ZnGeP <sub>2</sub> (oeo)                                                                      | —                       | 3                               | 4–10 $\mu$ m                  | 30–540 cm <sup>-1</sup>       | —              | [32] |
| M-L Er <sup>3+</sup> :Cr <sup>3+</sup><br>:YSGG<br>(2790 nm)<br>$\tau = 100$ ps, 1–<br>2 Hz<br>2–4 mJ/pulse | ZnGeP <sub>2</sub> (oeo)<br><br>GaSe (eoo)                                                    | —                       | 17.6                            | 5.2–6.7 $\mu$ m               | 12 cm <sup>-1</sup>           | —              |      |
|                                                                                                             |                                                                                               | —                       | 1                               | 3.5–18 $\mu$ m                | 10–850 cm <sup>-1</sup>       | —              |      |
| Dye (605 nm)<br>$\tau = 190$ fs                                                                             | LiB <sub>3</sub> O <sub>5</sub><br>(LBO)                                                      | 3–4.5 mJ                | 10–15                           | 850–970 nm<br>1.6–2.1 $\mu$ m |                               | —              | [42] |

|                                                                                                                                               |                                                                                                                   |                                                           |                     |                                               |                             |                          |      |
|-----------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------|---------------------|-----------------------------------------------|-----------------------------|--------------------------|------|
| 30 $\mu$ J/pulse                                                                                                                              |                                                                                                                   |                                                           |                     |                                               |                             |                          |      |
| M-L Ti:sapphire                                                                                                                               | LiInS <sub>2</sub>                                                                                                | —                                                         | —                   | 4.8–9.0 $\mu$ m                               | —                           | 365–460 fs               | [61] |
| (800 nm)<br>$\tau$ = 200 fs, 1 kHz<br>200 $\mu$ J/pulse<br>(20-nJ white-light seed)                                                           | (LIS)                                                                                                             |                                                           |                     |                                               |                             |                          |      |
| M-L Ti:sapphire                                                                                                                               | $\beta$ -BaB <sub>2</sub> O <sub>4</sub> (BBO)                                                                    | 2.5–7.0 $\mu$ J                                           | 15–35 (quantum eff) | 865–1600 nm                                   | ~10–20 THz                  | 20–50 fs                 | [62] |
| 2nd harm.<br>(387.5 nm)<br>$\tau$ = 130 fs, 1 kHz<br>56 $\mu$ J/pulse<br>(white-light seed)                                                   |                                                                                                                   |                                                           |                     |                                               |                             |                          |      |
| Cr:forsterite regen amp (1250 nm)<br>$\tau$ = 175 fs, 1 kHz<br>63 $\mu$ J/pulse; and<br>2nd harm (625 nm)<br>8 $\mu$ J/pulse<br>(2-stage OPA) | HgGa <sub>2</sub> S <sub>4</sub> (type II)<br><br>HgGa <sub>2</sub> S <sub>4</sub> (type I)<br>AgGaS <sub>2</sub> | 0.2–1.1 $\mu$ J<br><br>0.1–0.8 $\mu$ J<br>0.2–0.5 $\mu$ J | 11<br><br>—<br>—    | 5–9 $\mu$ m<br><br>5–9 $\mu$ m<br>5–8 $\mu$ m | 0.570 $\mu$ m<br><br>—<br>— | 180–240 fs<br><br>—<br>— | [63] |
| M-L Ti:sapphire                                                                                                                               | MgO:LiNbO <sub>3</sub><br>(MLN)                                                                                   |                                                           |                     |                                               |                             |                          | [64] |
| (800 nm)<br>$\tau$ = 100 fs, 1 kHz<br>600 $\mu$ J/pulse                                                                                       |                                                                                                                   |                                                           |                     |                                               |                             |                          |      |

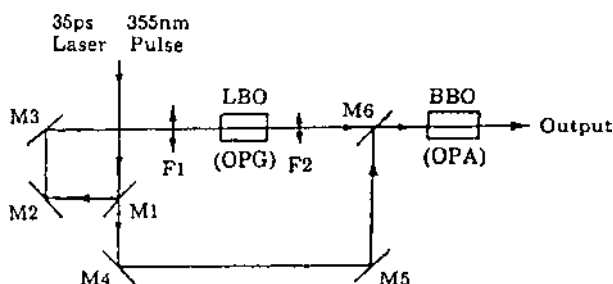
(continued)

**Table 24** Continued

| Pump laser                                                                                                    | Nonlinear crystal                                 | Output energy/<br>power | Conversion<br>efficiency<br>(%) | Tuning<br>range           | Line<br>width      | Pulse<br>width   | Ref. |
|---------------------------------------------------------------------------------------------------------------|---------------------------------------------------|-------------------------|---------------------------------|---------------------------|--------------------|------------------|------|
| (Nd:YVO <sub>4</sub> , 8- $\mu$ J,<br>1064-nm seed)                                                           |                                                   | > 10 $\mu$ J            | 40                              | 3.1–3.9 $\mu$ m           |                    | < 200 fs         |      |
| (InGaAs, > 1 W,<br>1064 nm seed)                                                                              |                                                   | 5 $\mu$ J               | 11                              | 3.5 $\mu$ m               |                    | 130 fs           |      |
| Ho:Tm:Er:YLF<br>(2.06 $\mu$ m)<br>$\tau$ = 50 ns<br>~35 mJ/pulse<br>(HeNe, 3-mW,<br>3.39- $\mu$ m seed)       | ZnGeP <sub>2</sub>                                | ~30 mW                  | —                               | 3.39 $\mu$ m              | —                  | —                | [65] |
| NIR OPG<br>(1.15–2.54 $\mu$ m)<br>$\tau$ = 120–140 fs<br>10–40 $\mu$ J/pulse                                  | ZnGeP <sub>2</sub>                                | —                       | 2.5                             | 2.5–10 $\mu$ m            | ~0.25–0.30 $\mu$ m | 75–200 fs        | [66] |
| M-L Ti:sapphire<br>2nd harm.<br>(395 nm)<br>$\tau$ = 150 fs, 1 kHz<br>130 $\mu$ J/pulse<br>(white-light seed) | $\beta$ -BaB <sub>2</sub> O <sub>4</sub><br>(BBO) | 5 $\mu$ J               | —                               | 550–700 nm<br>900–1300 nm | 98 nm<br>203 nm    | 6.2 fs<br>8.4 fs | [67] |
| M-L Ti:sapphire                                                                                               | $\beta$ -BaB <sub>2</sub> O <sub>4</sub>          | 2 $\mu$ J               | 20                              | White                     | 180 THz            | 7.2 fs           | [68] |

|                                                                                                                     |                                                                 |                                          |   |                                                                   |                       |         |      |
|---------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|------------------------------------------|---|-------------------------------------------------------------------|-----------------------|---------|------|
| 2nd harm.<br>(390 nm)<br>$\tau = 180$ fs, 1 kHz<br>10 $\mu$ J/pulse<br>(white-light seed)                           | (BBO)                                                           |                                          |   |                                                                   |                       |         |      |
| M-L Ti:sapphire<br>2nd harm.<br>(395 nm)<br>$\tau = 150$ fs, 1 kHz<br>100 $\mu$ J/pulse<br>(white-light seed)       | $\beta$ -BaB <sub>2</sub> O <sub>4</sub><br>(BBO)<br><br>Type I | 2–3 $\mu$ J                              | — | 550–690 nm                                                        | 2000 cm <sup>-1</sup> | < 20 fs | [69] |
| Nd:YAG<br>(1064 nm)<br>$\tau = 15$ ns, 10 Hz<br>< 45 mJ/pulse<br>(Yb fiber,<br>< 300-mW,<br>1074-nm seed)           | MgO:LiNbO <sub>3</sub><br>(MLN)                                 | 900 pJ<br>> 100 mW, peak<br><br>~ 2–4 mJ | — | $\lambda_s = 190 \mu m$<br>(1.6 THz)<br>$\lambda_i = 1.070 \mu m$ | < 200 MHz             | 3.4 ns  | [70] |
| Nd:YAG<br>(1064 nm)<br><br>$\tau = 15$ ns, 10 Hz<br>35 mJ/pulse<br>(Diode laser,<br>50-mW,<br>1066–1074-nm<br>seed) | MgO:LiNbO <sub>3</sub><br>(MLN)                                 | 1.3 mJ<br>> 200 mW, peak                 | — | 125–430 $\mu m$<br>(0.7–<br>2.4 THz)                              | < 100 MHz             | 4 ns    | [71] |

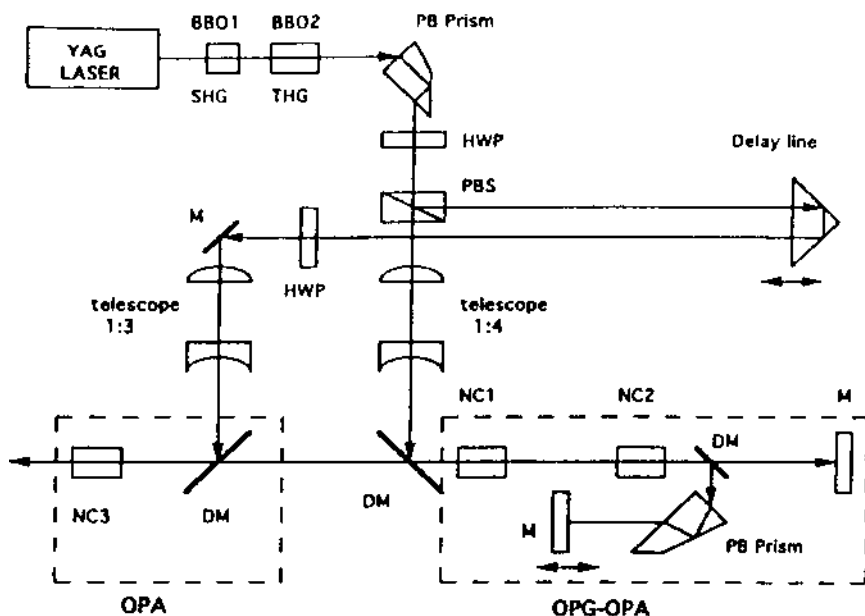
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**Figure 47** Schematic diagram of an LBO/BBO based OPG/OPA system. (From Ref. 37.)

The crystal was placed in a precision temperature controlled heater with a thermocouple feedback system controlling temperature within 0.5%. The CPM type I BBO crystal ( $10 \times 8 \times 12 \text{ mm}^3$ ) was cut at  $28^\circ$ . Approximately  $350 \mu\text{J}$  of signal is injected into the OPA crystal after an adjustment of beam diameter to 5 mm with a 0.25 m focal length lens. This beam is combined collinearly with the 3.8 mJ pump beam at mirror M6. The output properties of this system are also summarized in Table 24.

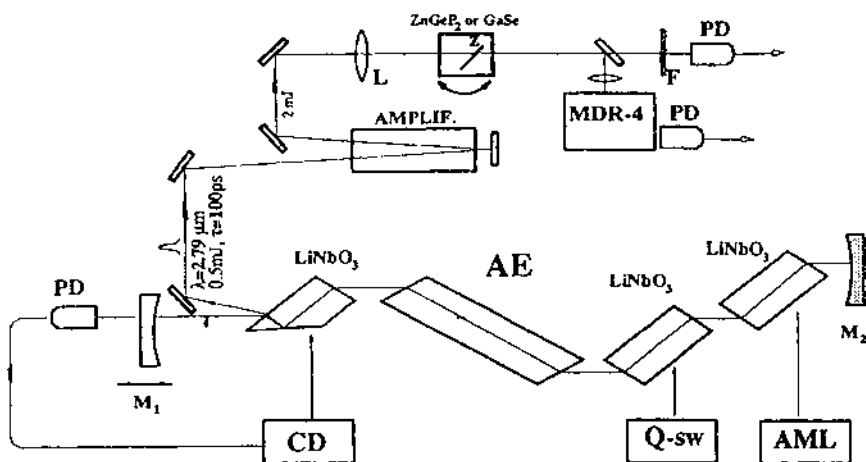
Another picosecond visible/near-IR system [24] employing BBO crystals is shown in Fig. 48. The third harmonic of an active-passive mode-locked Nd:YAG laser is generated by SHG and SFG using two BBO crystals. The *p*-polarized 355 nm beam of 35 ps pulses at 10 Hz is then split into two parts. One pumps a double-pass OPG/OPA stage, and the other, after an appropriate time delay, pumps a second OPA stage. The BBO crystals were cut at an internal angle of  $31^\circ$  between the surface normal and the optic axis for type I phase matching. The polished end faces were uncoated. Approximately 25–30% of the pump energy, controlled by a half-wave plate/polarizer combination, enters the OPG/OPA stage and generates a broad-band superfluorescence in the first BBO crystal. The second BBO crystal is situated about 20 cm from the first to collect the middle portion of the OPG beam. This crystal serves as a preamplifier as well as a spatial and spectral filter. Angle tuning of the two crystals is employed to select the signal frequency. Tilting the two crystals in opposite directions minimizes the pump and signal beam walk-off. A dichroic mirror separates the signal and residual pump, which are then fed back through the crystals for further amplification. The signal mirror can be replaced by a grating for further frequency and line width control. Finally, the amplified signal is sent through the single OPA stage for an amplification of about 10. The BBO crystals and grating for this system were mounted on rotation stages driven by computer-controlled stepper motors for synchronous rotation and frequency control. Output properties of this system are given in Table 24.



**Figure 48** Schematic diagram of a BBO based OPG/OPA system. Mirror M in dashed box at right replaceable with a grating. NCs = nonlinear crystals; DMs = dichroic mirrors; PB = Pellin–Broca prism, HWP = half-wave plate. (From Ref. 24.)

Figure 49 illustrates an IR OPG [32] utilizing ZnGeP<sub>2</sub> or GaSe nonlinear crystals. Pump lasers used with this system include actively mode-locked Er<sup>3+</sup>:YAG (2.94 μm) and Er<sup>3+</sup>:Cr<sup>3+</sup>:YSGG (2.79 μm) lasers. 100 ps pulses extracted from the laser cavity are further amplified to produce pulses in the millijoule level at 1–2 Hz. The high intensity pump beam (> 1 GW/cm<sup>2</sup>) was focused into the nonlinear crystals using CaF<sub>2</sub> lenses. For type I phase matched ZnGeP<sub>2</sub>, a 0.25 m focal length lens was used, while for type II phase matching, a 4 × telescope consisting of 10 and 2.5 cm focal length lenses was employed. In the case of GaSe, a 30 cm focal length spherical lens and a 4 cm focal length cylindrical lens combination was used. This focused the pump radiation mostly perpendicular to the (*k*, *z*) plane to avoid significant beam walk-off. The crystal parameters were as follows: type I ZnGeP<sub>2</sub> (θ = 47°, φ = 0°, 12 mm length), type II ZnGeP<sub>2</sub> (θ = 84°, φ = 31°, 42 mm length), type I GaSe (θ = 0°, φ = 90°, 12 mm length). Specific output properties of this OPG are again summarized in Table 24.

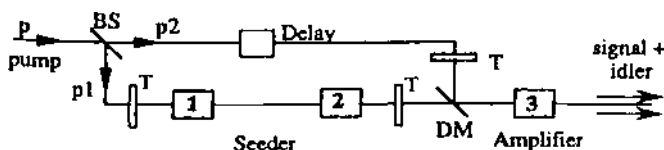
A femtosecond visible/near-IR OPG/OPA [42] is illustrated in Fig. 50. The 605 nm, 190 fs pump pulses were generated by a dye laser/amplifier system. The pump beam is split at the beam splitter, with 22% of its energy entering the OPG seeder section, which consisted of two 15 mm long NCPM LBO crystals.



**Figure 49** Schematic diagram of a ZnGeP<sub>2</sub>/GaSe based OPG system, AE = active laser element, AMPLIF = laser amplifier, AML = active mode-locker, CD = cavity dumper, PD = photodiodes, F = InAs filter, MDR-4 = monochromator. (From Ref. 32.)

The uncoated crystals are surrounded by a metal block embedded with a resistor driven by a constant current generator to heat the crystals. The pump beam in the seeder section is collimated to a spot diameter of approximately 300–350  $\mu\text{m}$  on the first crystal. The generated signal beam was collimated before injection into the OPA section, which consisted of another 15 mm uncoated NCPM LBO crystal. All beams propagated along the crystal X-axis. The pump beam was polarized along the Y-axis, and the signal and idler beams were polarized along the Z-axis ( $X, Y$ , and  $Z$  denote the principal axes of the crystal with  $n_Z > n_Y > n_X$ ). The output of this system is given in Table 24.

Since the latter half of the 1990s there has been a trend toward production of femtosecond pulses tunable in the near- and mid-infrared. Several systems have been based on a mode-locked Ti:sapphire pump, although a few other pump



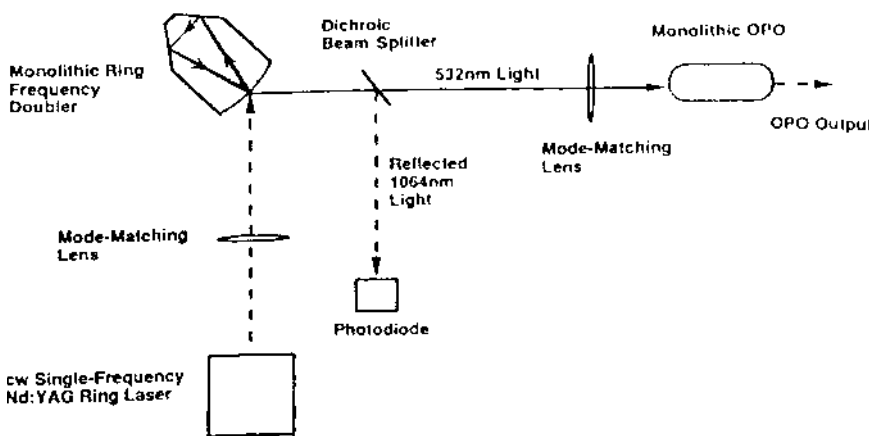
**Figure 50** Schematic diagram of an LBO based OPG/OPA system. BS = beam splitter, Ts = telescopes, Boxes 1,2,3 = 15 mm long LBO crystals, DM = dichroic mirror. (From Ref. 42.)

sources have appeared in the literature such as Cr:forsterite and Ho:Tm:Er:YLF systems. Examples of these are given in Table 24. There has also been great interest recently in the development of tunable pulsed terahertz sources. Two examples of these systems, using MgO:LiNbO<sub>3</sub> as the nonlinear medium, are included in Table 24.

## B. Continuous Wave OPOs

Most OPOs reported in the literature are pumped by pulsed or mode-locked lasers. However, improvements in pump sources, such as diode pumped solid state lasers with excellent spatial and single longitudinal mode control, and new nonlinear materials have allowed highly efficient cw OPOs with narrow line widths.

A doubly resonant cw OPO [34] is illustrated in Fig. 51. The OPO is monolithic and formed by polishing surfaces of 16 mm radius of curvature onto each end of a  $3 \times 3 \times 15$  mm MgO:LiNbO<sub>3</sub> crystal. The long axis of the crystal was parallel to the crystal X-axis. One end of the polished crystal was coated with a highly reflecting coating at 1064 nm, while the other (output) end was coated for 99.5% reflection at 1064 nm. The highly reflecting and output ends of the OPO had approximately 74% transmission at the pump wavelength, which was 532 nm obtained from a single frequency source shown in the figure. The monolithic ring resonator of MgO:LiNbO<sub>3</sub> produces the 532 nm pump beam when pumped by the fundamental of a single frequency Nd:YAG laser. The green output is then mode



**Figure 51** Schematic diagram of a monolithic MgO:LiNbO<sub>3</sub> based doubly resonant cw OPO system. (From Ref. 34.)

matched to the monolithic OPO by a focusing lens. Details of the output characteristics of this OPO are summarized in [Table 25](#).

The singly resonant OPO [48] of [Fig. 52](#) is pumped by a single frequency injection locked Nd:YAG laser producing a TEM<sub>00</sub> mode with a 20 kHz line width. This output is resonantly doubled to 532 nm in an external enhancement cavity containing a 6 mm long LBO crystal. Potassium titanyl phosphate (KTP) is used in the OPO cavity because of its large nonlinearity, low absorption at the signal and idler frequencies, large temperature-acceptance bandwidth, and high laser damage threshold. The 10 mm long KTP crystal was oriented for propagation along a crystallographic axis ( $\theta = 90^\circ$ ,  $\phi = 0^\circ$ ) with type II NCPM. The 532 nm pump beam propagates along the crystal X-axis with polarization along Y. Signal and idler waves are polarized along the Y- and Z-axes, respectively. The KTP crystal resides at the intracavity focus of a three-mirror standing wave resonator. The resonator consists of two 5 cm radius of curvature mirrors (M1, M2) and one flat mirror (M3). M2 is mounted on a piezoelectric transducer for fine adjustment of the cavity length. The incident angle on M1 is set at  $3^\circ$  to reduce astigmatism. All mirrors are highly reflecting ( $>99.9\%$ ) over the range of 970 nm to 1160 nm. The KTP crystal has dual-band antireflection coatings centered at 1090 and 532 nm. A Brewster angle LiNbO<sub>3</sub> prism is situated in the long leg of the cavity to spatially separate and dump the idler wave so that the cavity is truly singly resonant. A highly reflecting 25 cm radius of curvature mirror reflects the residual pump beam back through the crystal to lower the threshold. This mirror is mounted on a piezoelectric transducer to adjust the net phase for maximum gain and minimum threshold (see Section III.A and III.B for a discussion of a double-pass OPO). Salient features of this OPO are given in [Table 25](#).

Since the latter half of the 1990s there have been additional new sources used as pumps for cw OPOs, such as Nd:YVO<sub>4</sub>, Ti:sapphire, and GaAlAs diode systems. Examples of these are given in [Table 25](#).

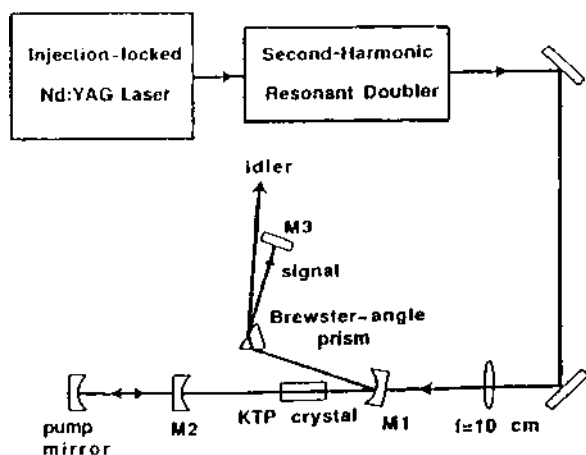
### C. Pulsed OPOs

This class of OPOs generally operates in the nanosecond pulse regime. Several of these devices have been reported in the literature since the late 1960s. A few examples dating from 1988 forward are cited here. Salient features of all the examples discussed are summarized in [Table 26](#).

One of the early pulsed OPOs employing a BBO crystal [23] is shown in [Fig. 53](#). The OPO is pumped by 355 nm, 6 ns pulses at a 30 Hz repetition rate. The beam, generated as the third harmonic from a seed-injected, Q-switched Nd:YAG laser, was spatially filtered to a Gaussian shape and prismatically separated from the fundamental and second harmonic before entering the OPO. The OPO cavity consisted of two flat mirrors separated by 3 cm and contained a single BBO

**Table 25** Continuous Wave OPO Systems

| Pump laser                                          | Nonlinear crystal          | Output power                     | Conversion efficiency (%) | Tuning range                                   | Line width | Ref. |
|-----------------------------------------------------|----------------------------|----------------------------------|---------------------------|------------------------------------------------|------------|------|
| Nd:YAG<br>2nd harm. (532 nm)<br>3.2 W               | KTiOPO <sub>4</sub> (KTP)  | 36 mW (signal)<br>1.07 W (idler) | 34.6                      | $\lambda_s = 1090$ nm<br>$\lambda_i = 1005$ nm | —          | [48] |
| Nd:YAG<br>2nd harm. (532 nm)<br>300 mW              | MgO:LiNbO <sub>3</sub>     | 104 mW                           | 38.3                      | 966–1185 nm                                    | —          | [34] |
| Nd:YVO <sub>4</sub><br>2nd harm. (532 nm)<br>220 mW | KTiOPO <sub>4</sub> (KTP)  | 10 mW                            | —                         | 1.7 GHz                                        | < 300 kHz  | [72] |
| GaAlAs MOPA<br>(845 nm)<br>500 mW                   | AgGaS <sub>2</sub>         | 2–3 mW                           | 2                         | $\lambda_s = 1267$ nm<br>$\lambda_i = 2535$ nm | —          | [73] |
| Ti:sapphire<br>(800 nm)<br>(Ar-ion pump, 14 W)      | KTiOAsO <sub>4</sub> (KTA) | 1.46 W                           | 85                        | 1.11–1.20 $\mu$ m<br>2.44–2.86 $\mu$ m         | —          | [74] |
| Nd:YVO <sub>4</sub><br>2nd harm. (532 nm)<br>1.2 W  | MgO:LiNbO <sub>3</sub>     | 10 mW                            | ~ 10                      | 788–1640 nm                                    | —          | [75] |



**Figure 52** Schematic diagram of a KTP based singly resonant cw OPO system. (From Ref. 48.)

crystal. The reflectance of the mirrors for the signal wavelength was 98% for the input mirror and 80% for the output mirror. The input and output couplers had a transmission of  $\geq 80\%$  at the pump and idler wavelengths. Three sets of mirrors were used to cover the entire tuning range. Two separate BBO crystals were used. Each was  $6 \times 6 \times 10 \text{ mm}^3$  in dimensions. One was cut at  $25^\circ$  while the other was cut at  $35^\circ$  to allow angle tuning over the entire wavelength range.

A monolithic singly resonant OPO fabricated by specially polishing the ends of a  $\text{MgO:LiNbO}_3$  crystal [33] is shown in Fig. 54. The ends of the 2.5 cm long crystal were polished to 20 mm radii of curvature. One end was coated with a high reflectivity dielectric multilayer centered at 900 nm, while a 90% reflectivity coating at 900 nm was deposited on the other end to serve as the output coupler. In addition, a flat total internal reflection surface was polished to within 0.25 mm of the mirror axis. Thus the crystal could serve as a standing-wave resonator or an off-axis ring resonator, as shown in the figure. As illustrated in Fig. 55, the pump beam from a monolithic Nd:YAG nonplanar ring oscillator was amplified by several passes through a Nd:YAG slab before being frequency doubled by a temperature controlled  $\text{MgO:LiNbO}_3$  crystal. The acoustooptic modulator selected the pulse width. 500 ns pulses were frequency doubled to 532 nm, and this radiation was focused into the OPO to a beam waist of  $37 \mu\text{m}$ . The oven heated the OPO crystal to its phase matching temperature of  $107^\circ\text{C}$ . The output signal and residual pump waves were then separated by a dichroic mirror.

An OPO with tunable output available in the UV portion of the spectrum [21] is shown in Fig. 56. This OPO was pumped with the fourth harmonic of

**Table 26** Pulsed OPO Systems

| Pump laser                                                                                                                    | Nonlinear crystal                              | Output energy/power    | Conversion efficiency (%) | Tuning range                   | Line width                  | Pulse width | Ref. |
|-------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------|------------------------|---------------------------|--------------------------------|-----------------------------|-------------|------|
| Q-Sw. Nd:YAG<br>3rd harm., 355 nm<br>$\tau = 6$ ns, 30 Hz<br>30 mJ/puls                                                       | $\beta$ -BaB <sub>2</sub> O <sub>4</sub> (BBO) | 4.7 mJ 140 mW, avg.    | 24                        | 412–2550 nm                    | < 3 GHz                     | 2.5 ns      | [23] |
| Nd:YAG (amplified<br>monolithic<br>nonplanar ring<br>oscillator)<br>2nd harm., 532 nm<br>$\tau = 500$ ns, 3 Hz<br>140 W, peak | MgO:LiNbO <sub>3</sub><br>monolithic           | —                      | 35                        | 834–958 nm<br>1.2–1.47 $\mu$ m | $\sim 0.7$ cm <sup>-1</sup> | < 500 ns    | [33] |
| Q-Sw. Nd:YAG<br>4th harm., 266 nm<br>$\tau = 9$ ns                                                                            | $\beta$ -BaB <sub>2</sub> O <sub>4</sub> (BBO) | —                      | —                         | 330–1370 nm                    | —                           | —           | [21] |
| Q-Sw. Nd:YAG<br>3rd harm., 355 nm<br>$\tau = 9$ ns                                                                            | $\beta$ -BaB <sub>2</sub> O <sub>4</sub> (BBO) | 7 mJ                   | 50                        | 420–2300 nm                    | 0.03 nm                     | —           | [49] |
| Injection-seeded<br>XeCl, 308 nm<br>$\tau = 10$ ns, 1 Hz<br>25 mJ/pulse                                                       | urea                                           | 3.8 mJ                 | 37                        | 537–720 nm                     | —                           | 4–6 ns      | [30] |
| Q-Sw. Nd:YAG<br>2nd harm., 532 nm<br>$\tau = 12$ ns<br>25 mJ/pulse                                                            | $\beta$ -BaB <sub>2</sub> O <sub>4</sub> (BBO) | 1 mJ<br>80 kW,<br>peak | 10                        | 940–1220 nm                    | —                           | —           | [25] |
| Injection-seeded                                                                                                              | $\beta$ -BaB <sub>2</sub> O <sub>4</sub> (BBO) | $\sim 2$ mJ            | > 10                      | 354–2370 nm                    | $\sim 1.5$ –10.5 nm         | 4–12 ns     | [22] |

(continued)

**Table 26** Continued

| Pump laser                                                                                                          | Nonlinear crystal                     | Output energy/power | Conversion efficiency (%) | Tuning range                  | Line width                  | Pulse width | Ref. |
|---------------------------------------------------------------------------------------------------------------------|---------------------------------------|---------------------|---------------------------|-------------------------------|-----------------------------|-------------|------|
| XeCl, 308 nm<br>$\tau = 10$ ns, 1 Hz<br>25 mJ/pulse                                                                 |                                       |                     |                           |                               |                             |             |      |
| Q-Sw. Nd:YAG<br>1064 nm<br>$\tau = 15$ ns, 540 Hz<br>22 mJ/pulse<br>cw Color Center<br>(seed)<br>(1500 nm)<br>20 mW | LiNbO <sub>3</sub>                    | 3 mJ                | > 10                      | 1500 nm (locked)              | 120 MHz                     | 9.5 ns      | [50] |
| Q-Sw. Nd:YAG<br>1064 nm<br>10 Hz<br>150 mJ/pulse                                                                    | LiNbO <sub>3</sub>                    | > 4 mJ              | 7.6–9.9                   | 2.5–4.0 $\mu$ m               | $\leq 0.2$ cm <sup>-1</sup> | —           | [51] |
| Q-Sw. Nd:YLF<br>2nd harm., 523 nm<br>$\tau = 16$ ns<br>300 $\mu$ J/pulse                                            | LiB <sub>3</sub> O <sub>5</sub> (LBO) | 6 $\mu$ J           | 45 (internal)             | 924–1208 nm                   | —                           | ~ 12 ns     | [39] |
| Q-Sw. Nd:YAG<br>2nd harm., 532 nm<br>$\tau = 6$ ns, 10 Hz                                                           | KTiOPO <sub>4</sub> (KTP)             | 3 mJ                | 12                        | 700–900 nm<br>1.3–2.2 $\mu$ m | 0.02 cm <sup>-1</sup>       | ~ 3.5 ns    | [52] |
| Q-Sw. Nd:YAG                                                                                                        | KTiOPO <sub>4</sub> (KTP)             | 21.4 W              | ~ 35                      | 2153 nm (signal)              | ~ 6 nm                      | —           | [76] |

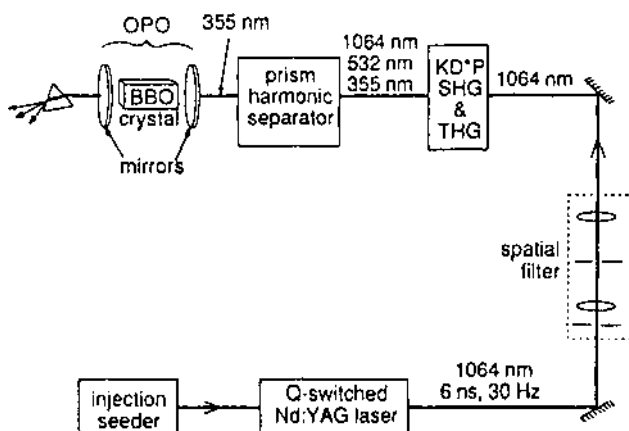
|                                                                                                               |                                                |                                                                                        |                               |                                               |                  |              |      |  |
|---------------------------------------------------------------------------------------------------------------|------------------------------------------------|----------------------------------------------------------------------------------------|-------------------------------|-----------------------------------------------|------------------|--------------|------|--|
| 1079 nm<br>6.22 kHz<br>62 W                                                                                   |                                                |                                                                                        |                               |                                               | 2166 nm (idler)  |              |      |  |
| Q-Sw. Nd:YAG<br>1064 nm<br>$\tau = 9.6$ ns, 10 Hz<br>4.5 mJ/pulse                                             | KTiOPO <sub>4</sub> (KTP)                      | 275 $\mu$ J                                                                            | $\sim 6, 11 \pm 4$<br>(slope) | 1570–1647 nm<br>(signal)<br>> 3000 nm (idler) | $\sim 3$ nm      | —            | [77] |  |
| Q-Sw. Nd:YVO <sub>4</sub><br>1064 nm<br>$\tau = 8.5$ ns, 5 kHz<br>5 $\mu$ J/pulse                             | KTiOPO <sub>4</sub> (KTP)                      | 0.4 $\mu$ J                                                                            | $\sim 8\%$                    | 1535 nm (signal)<br>3.47 $\mu$ m (idler)      | —                | 7.5 ns       | [78] |  |
| Q-Sw. Nd:YAG<br>1064 nm<br>$\tau = 17.5$ –22.5 ns,<br>100 Hz<br>100–130 W                                     | KTiOAsO <sub>4</sub> (KTP)                     | $\sim 30$ –35 W                                                                        | $\sim 32$                     | 1534.7 $\pm$ 0.6 nm<br>(signal)               | 0.6 nm           | —            | [79] |  |
| Q-Sw. Nd:YAG<br>1064 nm $\tau = 16$ ns,<br>10 Hz 60 mJ/pulse<br>cw Yt-doped fiber<br>(seed)<br>1070 nm, 90 mW | LiNbO <sub>3</sub>                             | 6.3 mJ (idler,<br>unseeded)                                                            | $\sim 11$ –13 (idler)         | 1068–1075 nm<br>(idler, unseeded)             | 200 MHz (signal) | 8 ns (idler) | [80] |  |
|                                                                                                               |                                                | 7.2 mJ (idler, seeded)<br>0.23 nJ (signal,<br>unseeded)<br>0.14 nJ (signal,<br>seeded) |                               | 194 $\mu$ m (signal)                          |                  |              |      |  |
| Q-Sw. Nd:YAG<br>3rd harm., 355 nm                                                                             | $\beta$ -BaB <sub>2</sub> O <sub>4</sub> (BBO) | $\sim 1$ mJ (signal)                                                                   | —                             | $\sim 500$ –680 nm                            | < 300 MHz (DRO)  | —            | [81] |  |

(continued)

**Table 26** Continued

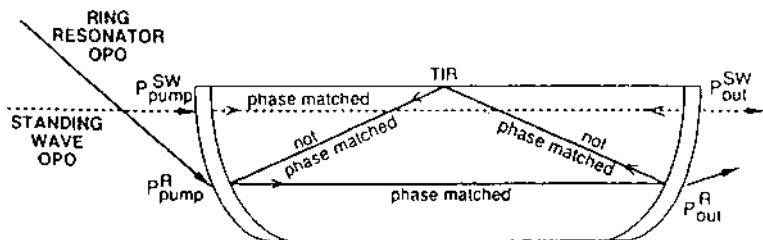
| Pump laser                                                                                                              | Nonlinear crystal                              | Output energy/power | Conversion efficiency (%) | Tuning range                                                  | Line width                                                                                      | Pulse width | Ref. |
|-------------------------------------------------------------------------------------------------------------------------|------------------------------------------------|---------------------|---------------------------|---------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------|------|
| $\tau = 20$ ns, 12.5 Hz<br>50 mJ/pulse                                                                                  |                                                |                     |                           |                                                               |                                                                                                 |             |      |
| Q-Sw. Nd:YAG<br>2nd harm., 532 nm<br>$\tau = 5$ ns, 10 Hz<br>12 mJ/pulse                                                | $\beta$ -BaB <sub>2</sub> O <sub>4</sub> (BBO) | 37.6 mJ (signal)    | 5.3                       | 745–890 nm (signal)<br>1.32–1.86 $\mu$ m (idler)              | 145 nm (signal)<br>540 nm (idler)                                                               | —           | [82] |
| Q-Sw. Er,Cr,T-<br>m:YSGG<br>2.93 $\mu$ m<br><br>$\tau = 100$ –110 ns,<br>10 Hz<br>10 mJ/pulse<br>LiNbO <sub>3</sub> OPO | ZnGeP <sub>2</sub> (ZGP)                       | 1.2 mJ (signal)     | 12.8–14.7<br>(idler)      | 3.9–12.4 $\mu$ m (type I)<br>4–10 $\mu$ m (type II)           | 6.5 cm <sup>-1</sup> (type I)<br>1.5 cm <sup>-1</sup> (type II)                                 | —           | [83] |
| 2.55 $\mu$ m (idler)<br>$\tau = 12$ ns<br>12 mJ/pulse                                                                   | ZnGeP <sub>2</sub> (ZGP)                       | 0.5 mJ (idler)      | 4                         | 3.4–10.5 $\mu$ m (idler,<br>gap in 4.7–5.6 $\mu$ m<br>region) | 38 cm <sup>-1</sup> ( $\sim 0.1$ cm <sup>-1</sup><br>with intracavity<br>grating<br>and etalon) | —           | [84] |

|                                                                                                       |                          |                     |                            |                                                             |                                   |                |      |
|-------------------------------------------------------------------------------------------------------|--------------------------|---------------------|----------------------------|-------------------------------------------------------------|-----------------------------------|----------------|------|
| Nd:YAG, 1064-nm pump<br>$\tau = 15$ ns,<br>90 mJ/pulse                                                |                          |                     |                            |                                                             |                                   |                |      |
| Tm:YLF-pumped<br>Ho:YAG<br>2.09 $\mu$ m<br><br>$\tau < 29$ ns. 10 kHz<br>0.95 mJ/pulse, 33 kW<br>peak | ZnGeP <sub>2</sub> (ZGP) | 4.2 W, avg (signal) | 53 (signal) (85,<br>slope) | $\lambda_s = 3.8$ $\mu$ m                                   | 170 nm (signal)                   | 26 ns          | [85] |
|                                                                                                       |                          | 2.1 W, avg (idler)  | 37 (idler) (44,<br>slope)  | $\lambda_i = 4.65$ $\mu$ m                                  | 260 nm (idler)                    |                |      |
| Q-Sw. Nd:YAG<br>1064 nm<br>$\tau = 12$ –100 ns,<br>10 Hz<br>40 mJ/pulse                               | AgGaS <sub>2</sub> (AGS) | 372 $\mu$ J (idler) | 3.1–4.9                    | 3.9–11.3 $\mu$ m (idler)<br>1.17–1.46 $\mu$ m (sig-<br>nal) | $\sim 1$ cm <sup>−1</sup> (idler) | —              | [86] |
| BBO OPO<br>565–590 nm<br>$\tau = 5$ ns,<br>4.5 mJ/pulse<br>7-ns, 355-nm<br>Nd:YAG<br>pump             | 2A5NPDP                  | 300 $\mu$ J (idler) | 3–4.5 (idler)<br>8 (total) | 1300–1500 nm<br>(idler)<br>1000 nm (signal)                 | 3.5 nm (idler)<br>2 nm (signal)   | $\sim 1$ –2 ns | [87] |

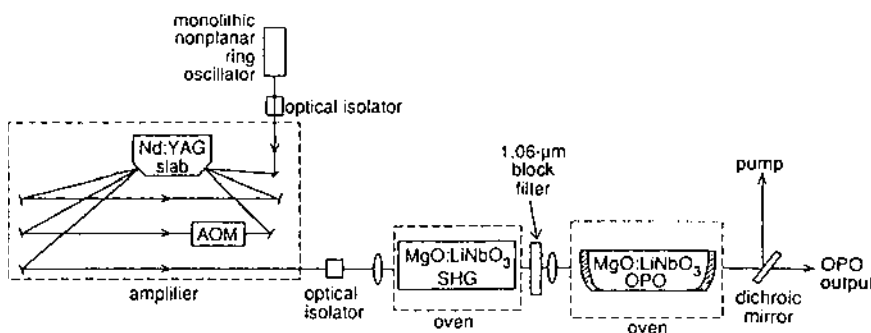


**Figure 53** Schematic diagram of a 355 nm pumped BBO based pulsed OPO system. (From Ref. 23.)

a Q-switched Nd:YAG laser. This beam had a diameter of 1.6 mm, a pulse duration of 9 ns, and a wavelength of 266 nm. The type I BBO crystal was cut at  $39.1^\circ$  with a  $12 \times 6 \text{ mm}^2$  aperture and a 20.5 mm interaction length. The 55 mm long cavity, corresponding to a 75 mm optical length, consisted of two flat highly reflecting mirrors for the signal wavelengths, and two  $45^\circ$  incident highly reflecting ( $>98\%$  at 266 nm) pump beam steering mirrors. These mirrors transmit at all wavelengths of interest longer than 300 nm and obviate the need for the OPO mirrors to be transparent at the pump wavelength. The pump steering mirrors were set at Brewster's angle with respect to the cavity axis. The extraordinary pump beam was *s*-polarized and the ordinary signal and idler beams were *p*-polarized to take advantage of the high transmission of the pump mirrors at the Brewster's angle. Five pairs of OPO reflectors were used to cover the entire tuning range of the OPO.

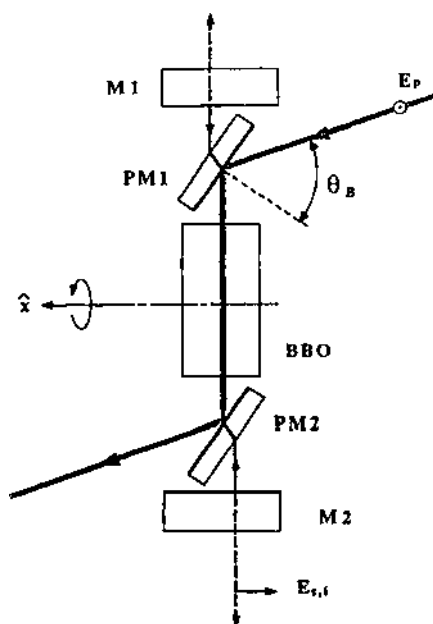


**Figure 54** Monolithic MgO:LiNbO<sub>3</sub> singly resonant OPO. (From Ref. 33.)

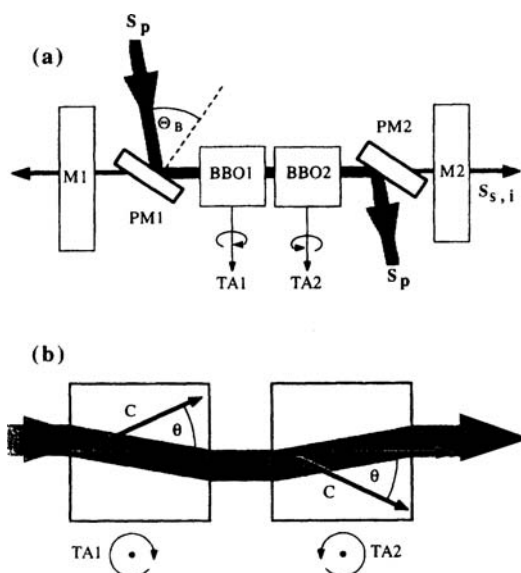


**Figure 55** Schematic diagram of a monolithic  $\text{MgO:LiNbO}_3$  based pulsed OPO system. (From Ref. 33.)

A two BBO crystal version of the above OPO [49] is shown in Fig. 57. The purpose of the two crystals is to compensate for the relatively large walk-off angle in BBO, which limits the efficiency. The first crystal (BBO1), with an aperture of  $10 \times 10 \text{ mm}^2$  and an interaction length of 11.5 mm, is cut for type I



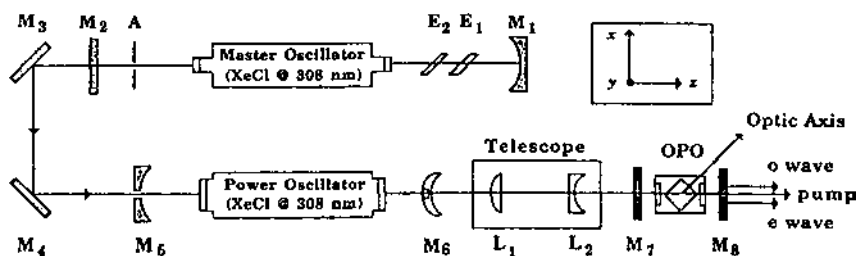
**Figure 56** Schematic diagram of a 266 nm pumped BBO based pulsed OPO system. PM1 and PM2 = pump steering mirrors. (From Ref. 21).



**Figure 57** Schematic diagram of a 355 nm pumped two BBO crystal based pulsed OPO system. PM1 and PM2 = pump steering mirrors, TA1 and TA2 = crystal tuning axes. (From Ref. 49.)

phase matching with an angle of  $30.2^\circ$  between the entrance face normal and the optic axis. The second crystal is  $10 \times 10 \times 9.5 \text{ mm}^3$  and cut at  $29.3^\circ$ . These crystals reside on separate rotation stages and are arranged with their optic axes at twice the phase matching angle relative to one another. In this manner the walk-off of the pump beam in the first crystal is compensated in the second crystal to improve the conversion efficiency, as illustrated in the figure. Tuning is accomplished by rotating both crystals. The pump steering mirrors in this experiment consisted of standard high reflectors ( $>98\%$ ) at the 355 nm pump wavelength. Cavity mirror M1 was a standard, low damage threshold, broadband dielectric high reflector ( $>90\%$  over 480–700 nm). For line width narrowing, this reflector was replaced with a 1,800 groves/mm grating blazed at  $26.7^\circ$ , with the groves perpendicular to the signal wave polarization. Mirror M2 was a 50% output coupler. All mirrors transmitted  $>90\%$  of the infrared idler waves to ensure singly resonant operation. The cavity length was 55 mm.

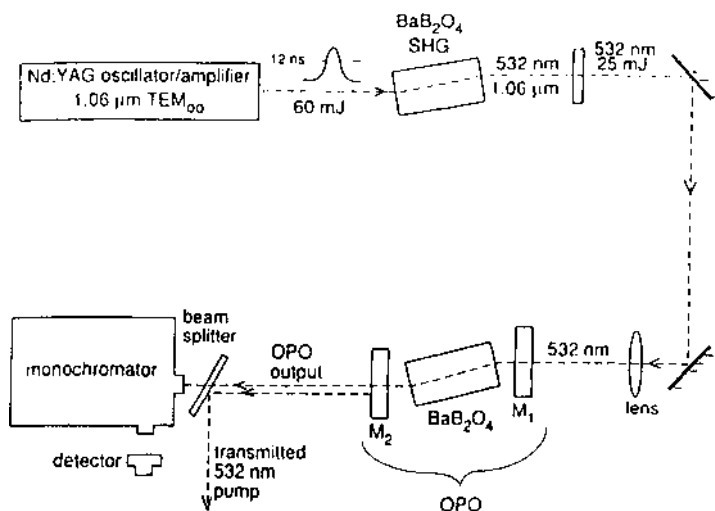
A visible OPO pumped by a XeCl excimer laser [30] is illustrated in Fig. 58. The pump laser emits 10 ns, 1 Hz repetition rate pulses at 308 nm. The beam was linearly polarized with a rectangular cross-section. It was compressed by a Galilean telescope to an approximately  $1 \times 2.5 \text{ mm}^2$  cross-section before entering the OPO as an ordinary wave. The nonlinear medium was type II single crystal of



**Figure 58** Schematic diagram of a 308 nm pumped urea based pulsed OPO system. A = aperture, Es = étalons. (From Ref. 30.)

urea with a 15 mm length and  $12 \times 10 \text{ mm}^2$  aperture. The crystal was polished on its (110) entrance and exit faces, then immersed in a cell containing *n*-hexane for index matching. The cell had uncoated quartz windows. The crystal was mounted near the  $90^\circ$  phase matching angle to minimize walk-off. Flat dichroic mirrors were chosen for the cavity mirrors with high reflectance ( $>95\%$ ) over 500–600 nm. The mirrors also had a transmittance of  $>95\%$  at the pump wavelength and were antireflection coated on the back surfaces at 308 nm. The physical length of the OPO cavity was 54 mm.

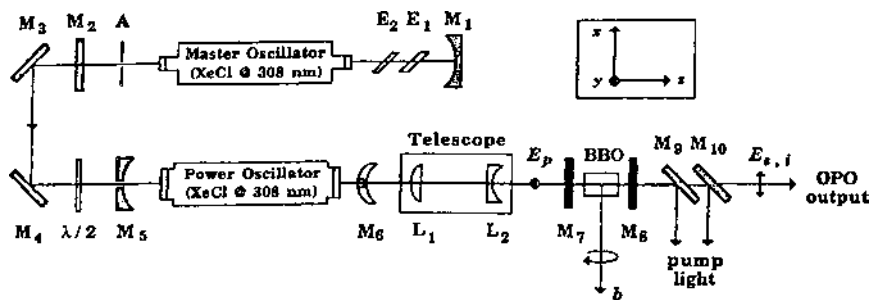
A BBO OPO pumped by a visible source for near IR output [25] is shown in Fig. 59. The pump wavelength was 532 nm, obtained from frequency doubling



**Figure 59** Schematic diagram of a 532 nm pumped BBO based pulsed OPO system. (From Ref. 25 © IEEE 1989.)

the fundamental output of an amplified TEM<sub>00</sub> mode Q-switched Nd:YAG laser. The 12 ns fundamental was converted to the second harmonic with 50% internal energy conversion efficiency in a 6.8 mm long BBO crystal. This green beam was then weakly focused into the OPO at a position that could be adjusted to achieve maximum gain. The OPO consisted of a simple two flat mirror resonator of 25 mm length. The mirror reflectances at the signal wave were 90% and 76%. The BBO crystal inserted in the OPO cavity was 9 mm long with its optic axis oriented at 20° with respect to the surface normal. The parallel end faces were polished and uncoated.

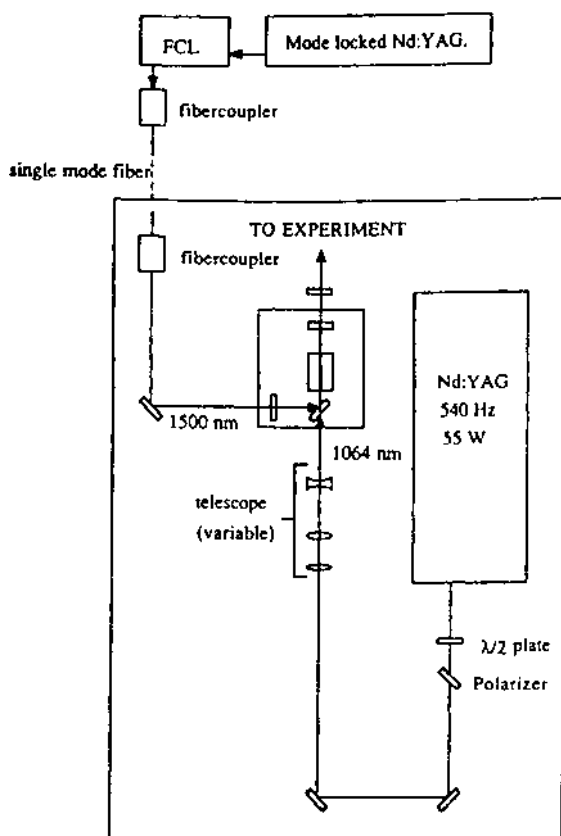
Excimer lasers are potentially useful pump sources for OPOs operating throughout the ultraviolet, visible, and near-infrared spectral region because of a variety of available UV pump wavelengths that allow relatively high efficiency and the potential for higher average power compared to frequency tripled Nd:YAG lasers. Figure 60 illustrates such a UV-NIR OPO system [22]. Because of the wide bandwidths associated with excimer lasers, this particular configuration employs a master oscillator/power oscillator combination to obtain high pump energy with a narrow linewidth. Line narrowing étalons and a spatial filter are used in the master oscillator to obtain a relatively spectrally pure seed signal, which is injected into the power oscillator. Spectral purity of the 308 nm pump energy (10 ns pulses at a 1 Hz repetition rate) from the power oscillator was better than 0.25 cm<sup>-1</sup>. Polarization is controlled by a half-wave plate prior to the power oscillator to yield an extraordinary beam to pump the OPO. The emerging pump beam had a cross-section of 1 × 2.5 cm<sup>2</sup>, which was compressed by passing through an 8 × Galilean telescope to 1.2 × 3 mm<sup>2</sup> before being launched into the OPO. The OPO consisted of a BBO crystal situated between a pair of flat dichroic mirrors separated by 28 mm. The crystal was cut for type I phase matching at a nominal internal propagation angle of 32° with respect to the optic axis. The crystal measured 12 mm in length with a 6 × 8 mm<sup>2</sup> aperture. The faces were



**Figure 60** Schematic diagram of a 308 nm pumped BBO based pulsed OPO system. A = aperture, E<sub>s</sub> = étalons. (From Ref. 22 © IEEE 1990.)

polished but uncoated, and the crystal was mounted on a precision rotation stage for angle tuning. Three sets of dichroic mirrors were needed to cover the entire tuning range. The mirrors had a high reflectance of 90–95% over the signal wavelength ranges (320–370 nm, 420–480 nm, and 500–600 nm) and were highly transmitting at 308 nm.

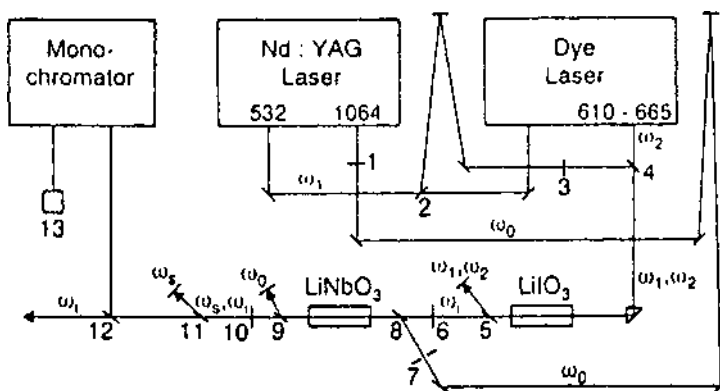
Many applications of OPOs require a high average power system, since efficiency and signal-to-noise ratio typically scale with repetition rate. Figure 61 illustrates a high average power injection seeded OPO [50]. The pump laser is a single longitudinal mode Q-switched Nd:YAG laser producing 15 ns pulses at a 540 Hz repetition rate. After propagating over 6 m, the spectrally pure (120 MHz bandwidth) pump beam is imaged onto the OPO cavity with a zoom telescope. The OPO is seeded with a cw single mode 1500 nm color center laser.

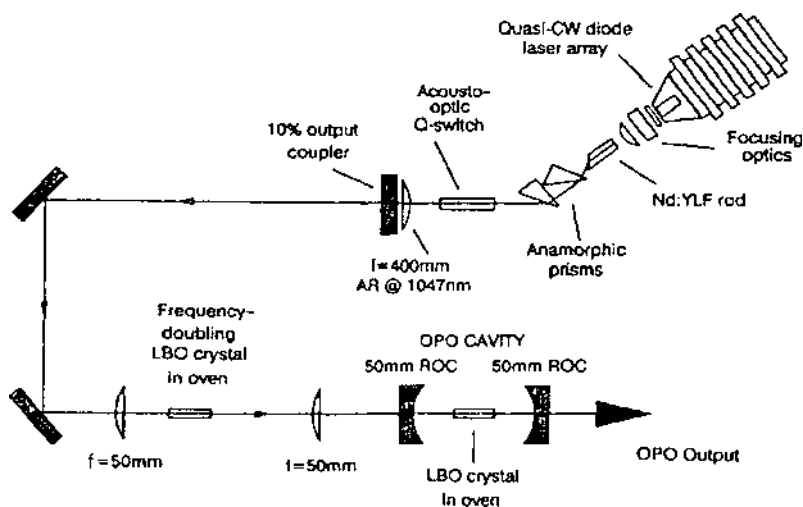


**Figure 61** Schematic diagram of a 1064 nm pumped LiNbO<sub>3</sub> based pulsed OPO system with injection seeding at 1500 nm. FCL = color center laser. (From Ref. 50.)

The L-shaped OPO cavity consists of three dielectric mirrors and a  $\text{LiNbO}_3$  crystal ( $10 \times 10 \times 50 \text{ mm}^3$ ) as the nonlinear medium. The two input couplers are highly reflecting at 1500 nm, while the output coupler has a 50% reflectance at this wavelength. A piezoelectric transducer is applied to one of the input couplers to match the cavity modes to the seed frequency. The nonlinear crystal resides in a brass oven stabilized near  $35^\circ\text{C}$  and mounted on a rotation stage.

A doubly resonant OPO utilizing an LBO crystal [39] is shown in Fig. 63. The pump source is a diode pumped Nd:YLF laser that is frequency doubled to 523.5 nm in an LBO crystal. The 16 ns pump pulses at 523.5 nm are then

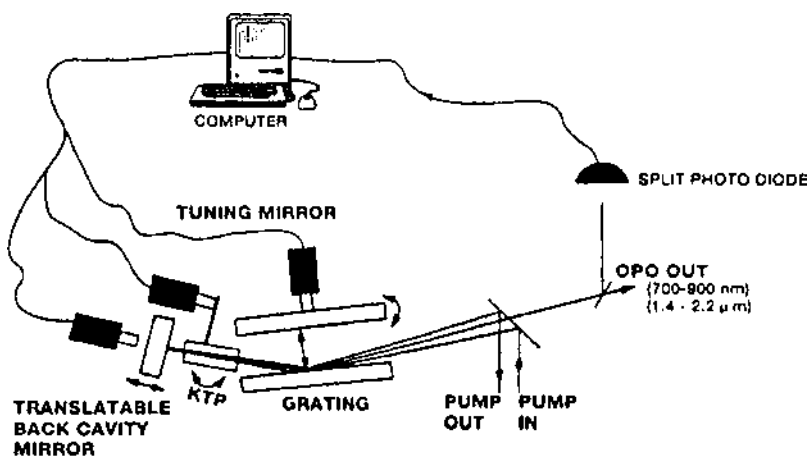




**Figure 63** Schematic diagram of an all-solid state, 523.5 nm pumped LBO based pulsed OPO system. (From Ref. 39.)

focused by a 50 mm focal length lens to a spot size of approximately  $15\text{ }\mu\text{m}$  inside the LBO crystal situated in the OPO cavity. The crystal length (12 mm) to confocal distance ratio was nearly optimum at a value of 2.84. The LBO crystal was placed at the intracavity focus of the resonator, which consisted of two 50 mm radius of curvature mirrors. Both mirrors were highly reflecting at 1047 nm and antireflection coated at 523.5 nm. Both  $3 \times 3\text{ mm}^2$  faces of the  $\text{LiNbO}_3$  crystal were antireflection coated at both 1047 nm and 523.5 nm. The crystal, cut for type I NCPM in the  $X$ - $Y$  crystal plane ( $\theta = 90^\circ$ ,  $\phi = 0^\circ$ ), was placed in an oven with tuning accomplished by varying the temperature over a range of 156–166 °C.

Without the introduction of wavelength dispersing elements in the cavity or injection seeding, the line width of a pulsed OPO can vary over a range of a few wave numbers to several hundred wave numbers and can vary as a function of output wavelength. An OPO that achieves single-frequency line widths of  $0.02\text{ cm}^{-1}$  over its tuning range [52] is illustrated in Fig. 64. The resonator consists of a back mirror, a grating, and a tuning mirror. The 1800 grooves/mm holographic grating had deep modulation for optimum diffraction efficiency and was placed in the cavity at a grazing angle ( $\sim 88^\circ$ ) with respect to the cavity axis. The tuning mirror was set to retroreflect the first order diffracted beam, and both the signal and the idler coupled out of the cavity by the zero order specular reflection of the grating. The pump beam was obtained by doubling the output of a 10 Hz, injection seeded, single



**Figure 64** Schematic diagram of a single-frequency, 532 nm pumped KTP based pulsed OPO system. (From Ref. 52.)

longitudinal mode Nd:YAG laser. The 532 nm pulses were 6 ns wide, and the beam was reduced to a 1.3 mm diameter by a 1.8:1 telescope before pumping the KTP crystal of the OPO. The crystal resided in a 5 cm cavity (corresponding to a free spectral range of  $0.1 \text{ cm}^{-1}$ ), which was kept as short as possible to optimize efficiency and longitudinal mode discrimination. Tuning over short ranges ( $< 7 \text{ cm}^{-1}$ ) could be accomplished by rotating the tuning mirror alone. For longer tuning scans, the mirror and the KTP crystal had to be rotated simultaneously. Two KTP crystals were used. Both were  $7 \times 7 \times 15 \text{ mm}^3$  in size. The crystals were cut for type II phase matching in the X-Z crystal plane with orientations of  $\theta = 54^\circ$ ,  $\phi = 0^\circ$  and  $\theta = 65^\circ$ ,  $\phi = 0^\circ$ . Both were antireflection coated at the pump wavelength (532 nm) and the resonated wavelengths (700–900 nm).

Since the latter half of the 1990s there has been a virtual explosion of development in pulsed OPO systems. This includes new nonlinear crystals and new pump sources, including other OPOs. There has also been considerable interest in the development of tunable sources in the near and mid-infrared spectral regions. Examples are given in [Table 26](#).

#### D. Synchronously Pumped OPOs

Several areas of research, such as studying carrier dynamics in semiconductors and performing time domain vibrational spectroscopy of molecules, require ultrashort optical pulses. Extending these types of optical sources into new

wavelength regions, including the IR, has provided a motivation for the development of synchronously pumped OPOs. This section describes some of the activities in this area. Some features of the OPOs discussed are included in [Table 27](#).

The first reported OPO synchronously pumped with femtosecond pulses at  $10^8$  Hz [53] is depicted in [Fig. 65](#). The OPO is situated within the cavity of a colliding pulse mode-locked (CPM) dye laser. This CPM laser was modified in the following way. The output coupler was replaced with a high reflector, a new intracavity focus was formed with the introduction to two 20 cm radii of curvature mirrors (for pumping the OPO), and the existing quartz prism pairs were separated by an additional 14 cm to compensate for the group velocity dispersion at 620 nm (pump wavelength) introduced by the nonlinear OPO crystal (KTP). The hydrothermally grown KTP was cut for type II phase matching at normal incidence, with single layer  $\text{MgF}_2$  antireflection coatings on both faces. This crystal was placed in the new intracavity CPM focus, and tuned by rotating about a horizontal axis perpendicular to the CPM beam. The OPO cavity was formed into a ring by two 10 cm radii of curvature mirrors and two flat mirrors. One flat mirror was mounted on a piezoelectric transducer for fine adjustments of the cavity length. Three of the mirrors were highly reflecting over 820–920 nm, while the one flat mirror acted as a 1% output coupler. The ratio of signal to pump confocal parameters was less than one. Group velocity dispersion and pulse walk-off between signal and pump in the KTP resulted in consistently broader pulses than those of the CPM pump laser.

A dispersion compensated system to correct for these effects [54] is shown in [Fig. 66](#). The cavity is nearly identical with that of [Fig. 65](#), but a set of prisms and cavity length stabilization electronics have been added. The prisms (P) were equilateral, uncoated SF-14 flint glass, mounted for minimum deviation, which is approximately Brewster's angle in the near-IR. The prism separation was approximately 20 cm. By varying the amount of glass intercepted by the signal beam, the net cavity group velocity dispersion could be adjusted to zero for any wavelength. To minimize long-term drift of the pulse width caused by acoustic noise and other room fluctuations, the cavity length was actively stabilized. This was done by monitoring light leaking through one of the cavity mirrors. Such light was diffracted off a grating and incident on two photodiodes, with their difference signal typically set near zero. A change in the cavity length would produce a monotonic shift in the output spectrum. The error signal detected by the combination of the two photodiodes was fed back to the mirror transducer through a high-grain amplifier to compensate actively for the cavity change. This system was then able consistently to achieve transform limited 105 fs output pulses.

A 76 MHz synchronously pumped OPO in an external cavity [55] is shown in [Fig. 67](#). The ring resonator was formed with two highly reflecting 20 cm radii

**Table 27** Synchronously Pumped OPO Systems

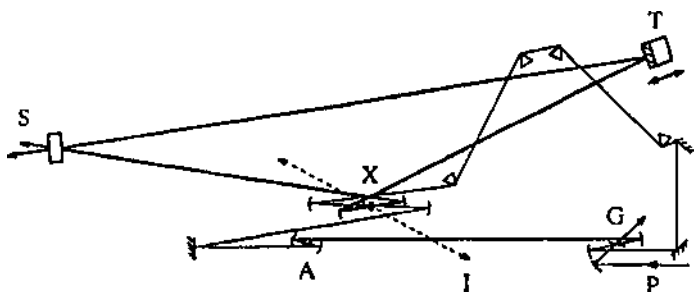
| Pump laser                                                                                      | Nonlinear crystal         | Output energy/power | Conversion efficiency (%) | Tuning range                                   | Line width     | Pulse width   | Ref. |
|-------------------------------------------------------------------------------------------------|---------------------------|---------------------|---------------------------|------------------------------------------------|----------------|---------------|------|
| CPM dye (R6G)<br>620 nm<br>intracavity<br>$\tau = 170$ fs, 100 MHz                              | KTiOPO <sub>4</sub> (KTP) | 2 mW, avg.          | —                         | 820–920 nm<br>1.9–2.54 $\mu$ m                 | —              | 220 fs        | [53] |
| CPM dye (R6G)<br>620 nm<br>intracavity<br>GVD<br>compensation<br>$\tau = 170$ fs, 100 MHz       | KTiOPO <sub>4</sub> (KTP) | 2 mW, avg.          | —                         | 720–4500 nm                                    | —              | 105 fs        | [54] |
| CPM dye (kiton red/malachite green)<br>645 nm<br>$\tau = 150$ fs, 76 MHz<br>280 mW, avg.        | KTiOPO <sub>4</sub> (KTP) | 30 mW, avg.         | 13 (internal)             | 1.2–1.34 $\mu$ m                               | —              | 220 fs        | [55] |
| M-L Nd:YLF<br>2nd harm.,<br>523 nm<br>$\tau = 15$ ps,<br>325 MHz<br>570 mW, avg.<br>123 W, peak | KTiOPO <sub>4</sub> (KTP) | 10–40 mW, avg.      | $\sim 7$                  | $\lambda_s = 1020$ nm<br>$\lambda_i = 1075$ nm | $\sim 09$ nm   | —             | [56] |
| M-L Nd:YLF<br>2nd harm.,<br>523 nm                                                              | KTiOPO <sub>4</sub> (KTP) | 42 mW, avg.         | 16                        | 1.002–1.096 $\mu$ m                            | $\sim 0.77$ nm | $\sim 1.5$ ps | [19] |

|                                                                                                                |                                       |                                        |               |                                                  |                                                        |                    |      |
|----------------------------------------------------------------------------------------------------------------|---------------------------------------|----------------------------------------|---------------|--------------------------------------------------|--------------------------------------------------------|--------------------|------|
| $\tau = 2$ ps,<br>125 MHz<br>~ 300 mW, avg.<br>~ 101 kW, peak                                                  |                                       |                                        |               |                                                  |                                                        |                    |      |
| Q-Sw. M-L Nd:YLF<br>2nd harm.,<br>523 nm<br>$\tau = 55$ ps, 182 MHz<br>$\tau_{\text{env}} = 105$ ns,<br>500 Hz | LiB <sub>3</sub> O <sub>5</sub> (LBO) | —                                      | 20 (internal) | 652–2650 nm                                      | ~ 1–11 nm                                              | —                  | [57] |
| M-L Nd:YAG<br>3rd harm., 355 nm<br>$\tau = 9$ ps,<br>~ 130 MHz<br>$\tau_{\text{env}} = 600$ ns,<br>2 mJ/pulse  | LiB <sub>3</sub> O <sub>5</sub> (LBO) | —                                      | 26 (internal) | 452–690 nm                                       | —                                                      | 6 ps               | [28] |
| M-L Ti:Al <sub>2</sub> O <sub>3</sub><br>765 nm<br><br>$\tau = 110$ fs,<br>76 MHz<br>800 mW, avg.              | KTiOPO <sub>4</sub> (KTP)             | 185 mW, avg.                           | —             | 1.2–1.34 $\mu\text{m}$<br>1.78–2.1 $\mu\text{m}$ | —                                                      | 62 fs<br>(ext com) | [58] |
| M-L Ti:Al <sub>2</sub> O <sub>3</sub><br>$\tau = 125$ fs,<br>90 MHz<br>2.5 W, avg.                             | KTiOPO <sub>4</sub> (KTP)             | 115 mW                                 | 55            | 1.2–1.37 $\mu\text{m}$<br>1.8–2.15 $\mu\text{m}$ | —                                                      | 57 fs              | [59] |
| Q-Sw. M-L Nd:YAG<br>2nd harm.,<br>532 nm<br>$\tau = 100$ ps, 100 MHz<br>$\tau_{\text{env}} = 230$ ns           | LiB <sub>3</sub> O <sub>5</sub> (LBO) | ~ 180 mW, avg sig<br>~ 100 mW, avg idl | 30            | 800–1700 nm                                      | 0.14 nm no grating<br>0.01 nm grating<br>(80 mW, avg.) | ≤ 100 ps           | [41] |

(continued)

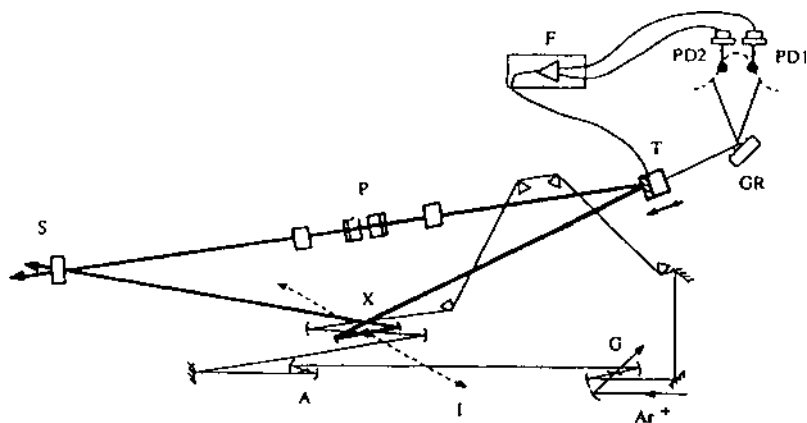
**Table 27** Continued

| Pump laser                                                                                                      | Nonlinear crystal                              | Output energy/power                            | Conversion efficiency (%) | Tuning range                                        | Line width | Pulse width | Ref.    |
|-----------------------------------------------------------------------------------------------------------------|------------------------------------------------|------------------------------------------------|---------------------------|-----------------------------------------------------|------------|-------------|---------|
| 600 mW, avg.<br>M-L Nd:YLF<br>2nd harm.,<br>523 nm<br>$\tau = 2$ ps<br>290 mW, avg.                             | LiB <sub>3</sub> O <sub>5</sub> (LBO)          | 78 mW, avg.                                    | 27                        | 800–1500 nm                                         | ~ 1.5 nm   | 1.5 ps      | [40,60] |
| M-L Nd:YLF<br>2nd harm.,<br>527 nm<br>$\tau = 35$ ps, 76 MHz<br>5.6 W, avg.                                     | LiB <sub>3</sub> O <sub>5</sub> (LBO)          | 1.6 W, avg.                                    | 55                        | 740–930 nm (signal)<br>1220–1830 nm (idler)         | 0.06 nm    | 22 ps       | [88]    |
| M-L Ti:Al <sub>2</sub> O <sub>3</sub><br>800 nm<br>$\tau = 50$ fs<br>2 W, avg.                                  | $\beta$ -BaB <sub>2</sub> O <sub>4</sub> (BBO) | 13 nJ                                          | —                         | 570–600 nm                                          | —          | 30 fs       | [89]    |
| M-L Ti:Al <sub>2</sub> O <sub>3</sub><br>765 nm<br>$\tau = 26$ fs,<br>80 MHz<br>800 mW, avg.                    | KTiOPO <sub>4</sub> (KTP)                      | 55 mW, avg.                                    | —                         | ~ 1.2 $\mu$ m                                       | 53 nm      | 34 fs       | [90]    |
| Q-Sw. M-L Nd:YAG<br>2nd harm.,<br>532 nm<br>$\tau = 145$ ps, 1 kHz<br>$\tau_{\text{env}} = 260$ ns<br>5 W, avg. | AgGaS <sub>2</sub> (AGS)                       | 750 Mw, (signal, avg.)<br>350 mW (idler, avg.) | 19 (26, slope)<br>7       | 1.4–1.9 $\mu$ m (signal)<br>2.6–4.4 $\mu$ m (idler) | —          | —           | [91]    |

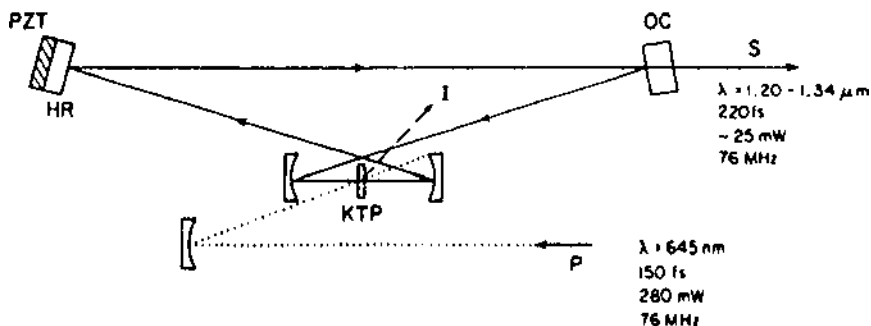


**Figure 65** Schematic diagram of an intracavity KTP based OPO synchronously pumped by a CPM laser. Signal wave (S) beamline is bolded. I = idler beam, X = KTP crystal, T = piezoelectric transducer P = Ar ion laser pump beam, G = dye gain jet, A = dye saturable absorber jet. (From Ref. 53.)

of curvature mirrors, one highly reflecting plane mirror, and a flat 2% output coupler. The flat high reflector was mounted on a piezoelectric transducer for fine-tuning the cavity length. A 1.5 mm thick KTP crystal, cut for type II phase matching and antireflection coated at 1300 nm on both faces, was mounted on a rotation stage at the intracavity focus. The pump source was a dispersion



**Figure 66** Schematic diagram of an intracavity KTP based OPO synchronously pumped by a CPM laser, with prism compensated group velocity dispersion (GVD) and actively stabilized cavity length. Signal wave (S) beamline is bolded. I = idler beam, X = KTP crystal, T = piezoelectric transducer, P = GVD compensation prism sequence, G = dye gain jet, A = dye saturable absorber jet, GR = grating PDs = photodiodes, F = feedback circuit. (From Ref. 54.)

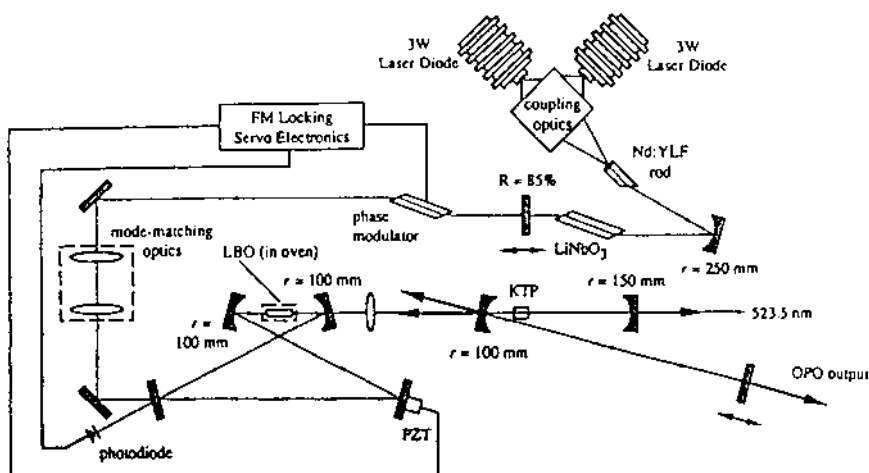


**Figure 67** Schematic diagram of a 654 nm external synchronously pumped KTP based OPO. P = pump, S = signal, I = idler, HR = high reflector, PZT = piezoelectric transducer, OC = output coupler. (From Ref. 55.)

compensated hybridly mode-locked dye laser producing 150 fs pulses at 645 nm. The pump beam was focused onto the KTP crystal noncollinearly with the signal beam (typically at  $1.7^\circ$ ) to compensate partially for beam walk-off. The output signal wavelength was tuned by rotating the KTP crystal.

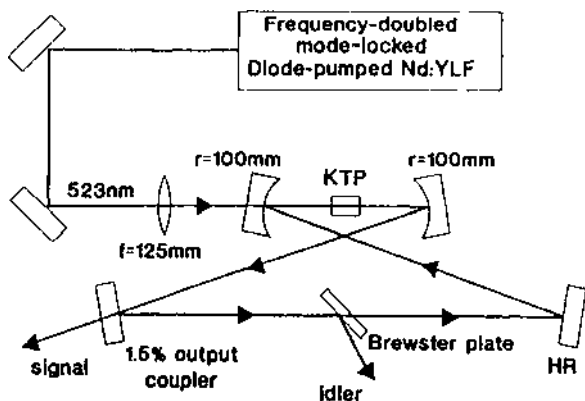
Many synchronously pumped OPOs are pumped with Q-switched mode-locked lasers to achieve the peak powers required for singly resonant OPOs. The finite pulse trains obtained are not optimal for all applications. The configuration shown in Fig. 68 illustrates a doubly resonant OPO pumped by a lower power but longer train of pulses from a cw mode-locked laser [56]. The pump was an FM mode-locked Nd:YLF laser, frequency doubled in an external cavity to produce a continuous train of mode-locked pulses at 523.5 nm at a repetition rate of 353 MHz. The width of each pulse was approximately 15 ps. The OPO folded cavity resonator was formed by a concave 15 cm radius of curvature mirror, a 10 cm radius of curvature folding mirror and a flat output coupler. All cavity mirrors were highly reflecting ( $>99\%$ ) over a range of 1020–1200 nm with  $>99\%$  transmittance at 523.5 nm. The OPO cavity length was set at twice the length for synchronous pumping by the Nd:YLF laser. This was done to match the cavity confocal parameter close to that for minimum threshold. The nonlinear crystal was a  $3 \times 3 \times 5 \text{ mm}^3$  KTP crystal, cut for collinear type II phase matching at normal incidence. Both faces of the crystal were broad band antireflection coated with a center wavelength of 1064 nm.

The requirement for simultaneous resonance of the signal and idler waves places stringent constraints on the pump laser and OPO cavity and often results in poor amplitude and frequency stability. The problem associated with pumping a singly resonant oscillator with cw mode-locked lasers is one of weak pump power. It is possible to overcome this limitation if higher-energy pump pulses are



**Figure 68** Schematic diagram of 523.5 nm synchronously pumped KTP based OPO. PZT = piezoelectric transducer. (From Ref. 56.)

short enough. Such a system pumped with picoseconds pulses [19] is illustrated in Fig. 69. The laser was a frequency doubled, self-starting additive-pulse mode-locked Nd:YLF laser pumped by a diode laser. The peak power at 532 nm was about 1.1 kW in 2 ps pulses. The OPO cavity was in a ring configuration with two 10 cm radius of curvature mirrors 99.7% reflecting at 1047 nm, and highly transmitting (90%) at the 523 nm pump wavelength. One flat high reflector was



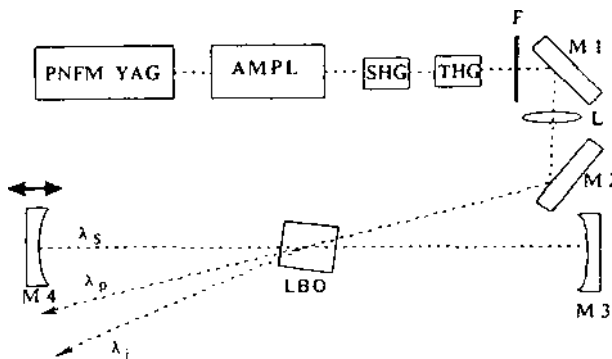
**Figure 69** Schematic diagram of 523.5 nm synchronously pumped KTP based OPO. (From Ref. 19.)



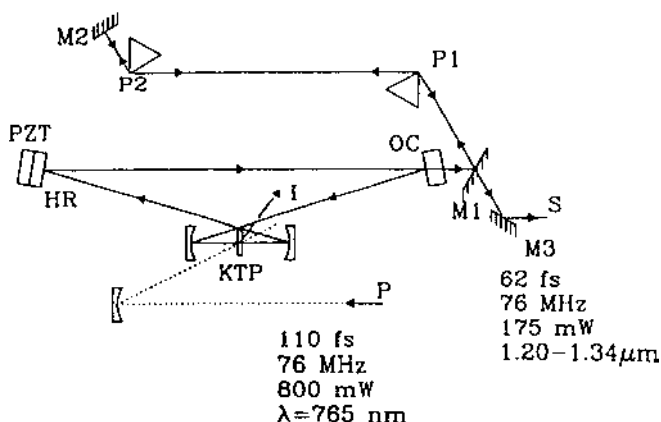
the 650–800 nm signal wavelength range and were  $>85\%$  transmitting at the pump wavelength. The pump beam was focused to a spot radius of approximately  $15\text{ }\mu\text{m}$  so that the pump confocal parameter was matched closely to that of the signal. A 12 mm long LBO crystal with a  $3\times 3\text{ mm}^2$  aperture was located inside an oven and placed at the intracavity focus. Both faces of the crystal were antireflection coated at 523.5 nm and 1047 nm. The crystal was cut for noncritical type I phase matching in the  $XY$  plane, with the surface normal along the  $X$ -axis.

Another LBO based system pumped in this case in the UV [28] is illustrated in Fig. 71. The output of a passive negative feedback mode-locked Nd:YAG laser was amplified in a three-stage Nd:YAG amplifier, and the third harmonic at 355 nm was obtained using a pair of KDP type II crystals. The result was a beam of 355 nm pulses with single pulse width of 9 ps. This beam was focused by a 1 m focal length lens into a  $5\times 5\times 10.5\text{ mm}^3$  LBO crystal, at an angle of  $35\text{ mrad}$  with respect to the resonator axis. The crystal was cut for type I phase matching ( $\theta = 90^\circ, \phi = 39^\circ$ ). The resonator consisted of two identical spherical mirrors, with radii of curvature of 1 m and high reflectance ( $>99\%$ ) over 405–690 nm. The beam waist for this confocal resonator had a diameter of  $400\text{ }\mu\text{m}$  and was closely matched to the pump waist diameter.

High repetition rate, ultrashort pulse CPM pumped systems are particularly suited for high signal-to-noise ratio time resolved spectrometry. The femtosecond dye pump lasers have some undesirable features, though, including high maintenance, poor mode quality, and delicate operation. The recently developed Kerr lens mode-locked Ti:sapphire lasers offer potentially dramatic improvements for pumping these types of OPOs. An OPO pumped with this type of laser [58] is illustrated in Fig. 72. The pump produces 110 fs pulses at a 76 MHz repetition rate with nearly 1 W of average power at 765 nm. The output of this



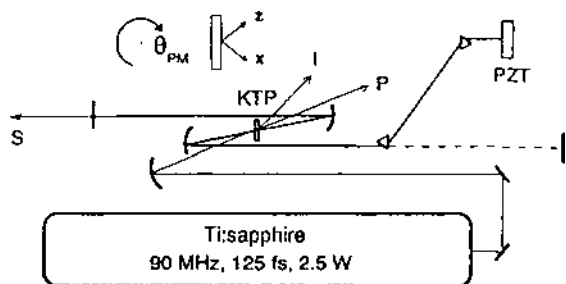
**Figure 71** Schematic diagram of 355 nm synchronously pumped LBO based OPO. (From Ref. 28.)



**Figure 72** Schematic diagram of Ti:sapphire synchronously pumped KTP based OPO. P = pump, S = signal, I = idler, HR = high reflector, PZT = piezoelectric transducer, OC = output coupler, Ps = prisms. (From Ref. 58.)

laser is tunable between 720 nm and 1000 nm, with peak powers that can exceed 100 kW, crucial for pumping singly resonant OPOs. The OPO in Fig. 72 is a ring resonator type. A 1.5 mm thick KTP crystal, antireflection coated at 1300 nm, was cut for type II phase matching ( $\theta = 67^\circ$ ) with propagation in the XZ plane and mounted at the intracavity focus of the resonator. The cavity consists of two highly reflecting 20 cm radius of curvature mirrors, a plane high reflector, and a 2% output coupler. The plane high reflector is mounted on a piezoelectric transducer for fine-tuning the cavity length. The high intracavity intensity produces self-phase modulation within the crystal, which leads to chirped pulses. Thus a pair of SF4 equilateral prisms are used to compress the pulses to a 62 fs width.

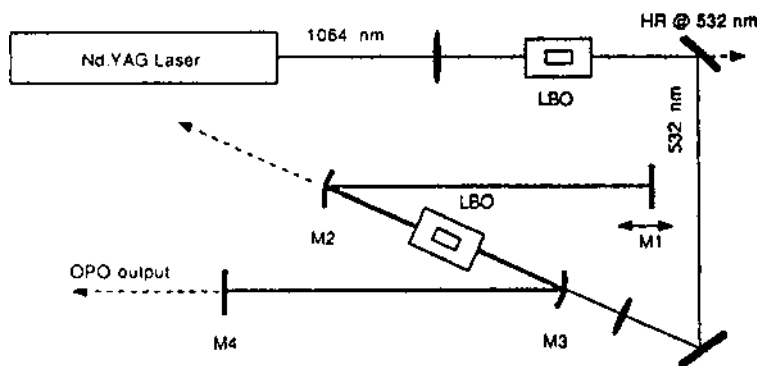
Another example of a Ti:sapphire synchronously pumped OPO [59] is given in Fig. 73. This self-mode-locked laser produced 125 fs pulses at a 90 MHz repetition rate with 2.5 W of average power when pumped with a 15 W argon ion laser. The Ti:sapphire laser was focused into a 1.15 mm KTP crystal using a 15 cm radius of curvature mirror. The crystal was cut for type II phase matching at  $\theta = 47.5^\circ$  and  $\phi = 0^\circ$  and antireflection coated at 1300 nm with  $\text{MgF}_2$ . The linear OPO cavity was formed using two 10 cm radius of curvature mirrors aligned for oscillation in the XZ-plane of the crystal to provide compensation for walk-off between the pump and signal beams. Two flat mirrors, one a 1% output coupler and the other mounted on a piezoelectric transducer for fine cavity length adjustment, completed the cavity. To compensate for group velocity dispersion, which puts a chirp on the signal pulses, an SF-14 prism pair was inserted in



**Figure 73** Schematic diagram of Ti:sapphire synchronously pumped KTP based OPO. P = pump, S = signal, I = idler, HR = high reflector, PZT = piezoelectric transducer. (From Ref. 59.)

the cavity as shown in the figure. The OPO output wavelength could be tuned by adjusting the cavity length, changing the pump wavelength, or rotating the KTP crystal.

A temperature tuned, synchronously pumped OPO [41] is illustrated in Fig. 74. The pump in this case was the frequency doubled output of a Q-switched mode-locked Nd:YAG laser, producing a 230 ns train of 23 mode-locked pulses at 532 nm. The singly resonant OPO was formed with two 30 cm radius of curvature mirrors that were >99% reflecting at the signal wavelengths, and two flat mirrors with reflectances of >99% and approximately 75% for the output coupler. An LBO crystal in a temperature- controlled oven was placed at the intracavity focus. The crystal had dimensions of  $2.5 \times 3 \times 15 \text{ mm}^3$  and was cut for NCPM. The pump beam was focused to a  $170 \text{ }\mu\text{m}$  spot inside the crystal and

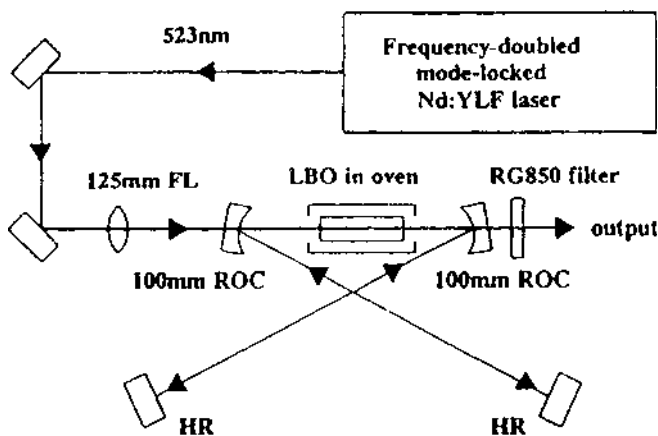


**Figure 74** Schematic diagram of 532 nm synchronously pumped LBO based OPO. Output coupling mirror M4 replaceable with a Littrow grating. (From Ref. 41.)

closely matched to the focal spot of the signal beam. To achieve a narrow line width, the output coupler was replaced with an 1800 grooves/mm Littrow grating. The first order diffracted beam was retroreflected by a flat mirror, and the zero order diffraction provided the output coupling.

Another temperature tuned OPO based on an LBO nonlinear crystal [40,60] is shown in Fig. 75. This OPO was pumped with the second harmonic of a mode-locked Nd:YLF laser, with 2 ps pulse and peak power of 1.3 kW. The linear OPO cavity was formed with mirrors taken from a commercial Ti:sapphire laser (Spectra-Physics 3900). They were coated to be highly reflecting ( $>99.9\%$ ) over 800–1000 nm and highly transmitting ( $>96\%$ ) at 523 nm. They also had high transmittance (80–90%) over the 1100–1400 nm range. One flat high reflector was mounted on a micrometer-driven translation stage for coarse cavity length adjustment, while the other was mounted on a piezoelectric transducer for fine cavity length control. The  $3 \times 3 \times 12 \text{ mm}^3$  LBO crystal was cut for type I NCPM and antireflection coated on both faces at 1047 nm and 523 nm. The crystal was mounted in an oven to control the temperature between ambient and  $200^\circ\text{C}$  with a stability of  $\pm 1^\circ\text{C}$ , for tuning the output wavelength, and placed at the intracavity focus where the resonated mode had a waist of  $26 \mu\text{m}$  radius. The pump beam was focused through a 125 mm focal length lens to a  $16 \mu\text{m}$  waist within the LBO crystal.

The latter half of the 1990s has witnessed a continued interest in the development of synchronously pumped OPO systems. Several additional examples are included in [Table 27](#).



**Figure 75** Schematic diagram of 523.5 nm synchronously pumped LBO based OPO. (From Ref. 60.)

## E. Systems with Quasi-phase-matched Materials

Recently, a phenomenal amount of work has been directed toward the development of parametric systems based on quasi-phase-matched (QPM) materials. These efforts have benefited from the achievement of periodic poling of nonlinear crystals, which was extended from earlier work on periodic poling in waveguides. QPM materials offer distinct advantages. Since the restrictions of birefringent phase matching are removed, propagation along a principal crystal axis becomes feasible, where the largest nonlinear coefficients can be selected without the problems of beam walk-off. This results in highly efficient frequency conversion at modest pump energies and high pulse repetition frequencies. In turn, it reduces the likelihood of optical damage particularly for nanosecond pump sources. In fact, the high efficiency allows for the consideration of small, compact pump sources such as microchip lasers. Tuning in QPM-based systems can be achieved by recording multiple grating periods in the poled crystals. Fan-out gratings can also be employed. Temperature control provides a further tuning mechanism and also prevents photorefractive damage in periodically poled lithium niobate (PPLN), which is the most common QPM crystal. Recent work has also demonstrated the utility of other periodically poled materials.

QPM materials have been employed in OPG/OPA systems, cw OPOs, pulsed OPOs, and synchronously pumped OPOs. Several examples are summarized in [Tables 28–31](#).

## VI. SUMMARY AND SOME PRACTICAL CONSIDERATIONS

OPOs make very attractive all solid-state sources of continuously tunable radiation, from the UV to long wave infrared (LWIR). In the visible and near-IR they are replacing dye lasers, which tend to be both messy and cover only a small spectral range without a dye change. Already, commercially available OPOs provide spectral coverage from 410 nm to 2400 nm using a single type I BBO crystal pumped by the 355-nm third harmonic of a Nd:YAG laser. It may be remarked that with type I phase matching there is small gap near the degeneracy point (710 nm) that does not exist for type II phase matching. OPOs using the noncritically phase-matched (NCPM) KTP have become popular as a source of eye-safe 1.57- $\mu\text{m}$  radiation for such applications as military training exercises and for wire avoidance for helicopters. OPOs are also very attractive for mid-infrared (MIR) and LWIR radiation sources for such applications as lidar and military countermeasures. For applications requiring continuous tunability in the 3–5  $\mu\text{m}$  atmospheric window, the holmium laser-pumped  $\text{ZnGeP}_2$  (ZGP) OPO has proved to be very useful [139].

**Table 28** QPM-Based OPG/OPA Systems

| Pump laser                                                                                                          | Nonlinear medium <sup>a</sup>                                    | Output energy/power | Conversion efficiency (%) | Tuning range                                                              | Line width            | Pulse width | Ref. |
|---------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|---------------------|---------------------------|---------------------------------------------------------------------------|-----------------------|-------------|------|
| Q-Sw Tm, Ho: YLF<br>2.051 $\mu\text{m}$<br>$\tau = 50\text{ ns}$ ,<br>50 Hz<br>7 mJ/pulse<br>180 mW, avg.           | PPLN (50 mm)<br>$\Lambda = 25.5\text{--}28.7\text{ }\mu\text{m}$ | 30 mW               | 16.7                      | 3.4–5.2 $\mu\text{m}$                                                     | —                     |             |      |
| Q-Sw Nd:YAG<br>1064 nm<br>$\tau = 2.6\text{ ns}$ ,<br>120 Hz<br>650 $\mu\text{J}$ /pulse                            | PPLN (50 mm)<br>$\Lambda = 28.5\text{--}29.9\text{ }\mu\text{m}$ | $\sim 8\mu\text{J}$ | $\sim 8$                  | 6820–6220 $\text{cm}^{-1}$ (signal)<br>2580–3180 $\text{cm}^{-1}$ (idler) | 0.05 $\text{cm}^{-1}$ | 2.5 ns      | [93] |
| Q-Sw Nd:YAG<br>2nd harm.,<br>532 nm<br>$\tau = 2.5\text{ ns}$ ,<br>1.1 kHz<br>90 $\mu\text{J}$ /pulse<br>97 mW avg. | PPLN (50 mm)<br>$\Lambda = 10.1\text{--}13\text{ }\mu\text{m}$   | 12 mW, avg.         | 23                        | 637–593 nm                                                                | 0.15–0.32 nm          | —           | [94] |
| Alexandrite,<br>diode seed<br>786 nm<br>$\tau = 0.5\text{ ns}$<br>5 mJ/pulse                                        | PPLN (5 mm)<br>$\Lambda = 19.5\text{ }\mu\text{m}$               | 1 mJ                | 20                        | 1550 nm                                                                   | —                     | 680 fs      | [95] |
| Er-doped fiber                                                                                                      | PPLN (20 mm [2])                                                 | 50 nJ               | $\sim 39$                 | 1.31 $\mu\text{m}$                                                        | 1.5 nm                | 2.7 ps      | [96] |

|                                                                                                                                                     |                                                                                               |                                                                |                                        |                                                                                              |                               |        |      |
|-----------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|----------------------------------------------------------------|----------------------------------------|----------------------------------------------------------------------------------------------|-------------------------------|--------|------|
| 2nd harm.,<br>676 nm<br>$\tau = 2$ ps,<br>1.6 MHz<br>10 pJ/pulse<br>diode seed,<br>1.31 m $\mu$                                                     | $\Lambda = 18.3, 18.7 \mu\text{m}$                                                            |                                                                |                                        |                                                                                              |                               |        |      |
| Q-Sw Nd:YAG<br>1064 nm<br>$\tau = 15$ ns,<br>1 kHz<br>750 $\mu\text{J/pulse}$                                                                       | PPLN (5 cm [2])<br>$\Lambda = 29.75 \mu\text{m}$<br>$\Lambda = 29.7\text{--}30.1 \mu\text{m}$ | 180 $\mu\text{J}$ (signal)<br>60 $\mu\text{J}$ (idler)         | —                                      | $\lambda_s = 1.6 \mu\text{m}$<br>$\lambda_i = 3.3 \mu\text{m}$<br>18 $\text{cm}^{-1}$ tuning | 0.08 $\text{cm}^{-1}$ (idler) | —      | [97] |
| Q-Sw Nd:<br>YAG<br>1064 nm<br>$\tau = 5$ ns,<br>20 Hz<br>3 mJ/pulse<br>Er-Yb:glass<br>seed<br>1554 nm,<br>6 mW avg.                                 | PPKTN (15 mm)<br><br>$\Lambda = 35.6 \mu\text{m}$                                             | 0.61 mJ (signal)<br><br>0.15 mJ (idler)<br>71 mJ (signal, OPA) | 38 (total OPG)<br><br>3.1 (total, OPA) | 1544–1559 nm (signal)<br><br>1554 nm                                                         | 0.65 nm                       | —      | [98] |
| M-L II:sapphire<br>800 nm<br>$\tau = 80\text{--}100$ fs,<br>1 kHz<br>600 $\mu\text{J/pulse}$<br>Nd:YVO <sub>4</sub> , 8-<br>kW peak<br>1064-nm seed | PPKTN<br>10 mm<br>$\Lambda = 27.5 \mu\text{m}$                                                | 5 $\mu\text{J}$ (idler)                                        | 40 (internal)                          | 3.8 $\mu\text{m}$ (idler)                                                                    | $\sim 0.2 \mu\text{m}$        | 210 fs | [99] |

<sup>a</sup> PPLN = periodically poled lithium niobate; PPKTN = periodically poled KTN (KTiOPO<sub>4</sub>).

**Table 29** QPM-Based Continuous Wave OPO Systems

| Pump laser                                      | Nonlinear medium <sup>a</sup>                                       | Output power      | Conversion efficiency (%) | Tuning range                                                        | Line width                        | Ref.  |
|-------------------------------------------------|---------------------------------------------------------------------|-------------------|---------------------------|---------------------------------------------------------------------|-----------------------------------|-------|
| AlGaAs diode 810 nm<br>75 mW                    | PPLN (50 mm)<br>$\Lambda = 21.0\text{--}22.4\text{ }\mu\text{m}$    | 4.6 mW (idler)    | 6.5                       | 1.06–1.19 $\mu\text{m}$ (signal)<br>2.58–3.44 $\mu\text{m}$ (idler) | —                                 | [100] |
| InGaAs diode 924 nm<br>2.25 W                   | PPLN (33 mm)<br>$\Lambda = 26.0\text{ }\mu\text{m}$                 | 200 mW (idler)    | 9                         | 2.11 $\mu\text{m}$ (56 GHz tuning)<br>5 MHz (idler)                 | < 1 MHz (signal)                  | [101] |
| Nd:YAG 1064 nm<br>3.7 W                         | PPLN (2.5 cm)<br>$\Lambda = 30.34\text{--}30.66\text{ }\mu\text{m}$ | 450 mW (idler)    | 12                        | 2.9–3.25 $\mu\text{m}$                                              | 140 MHz                           | [102] |
| InGaAs MOPA 925 nm<br>2.5 W                     | PPLN (38 mm)<br>$\Lambda = 26.0\text{--}26.6\text{ }\mu\text{m}$    | 480 mW (idler)    | 19                        | 1.55–1.70 $\mu\text{m}$ (signal)<br>2.03–2.29 $\mu\text{m}$ (idler) | < 1 MHz (signal)<br>5 MHz (idler) | [103] |
| Nd:YVO <sub>4</sub> 2nd harm.,<br>532 nm<br>5 W | PPLN (53 mm)                                                        | ~ 200 mW (signal) | ~ 7 (signal)              | 917–988 nm (signal)                                                 | —                                 | [104] |
|                                                 | $\Lambda = 6.5\text{ }\mu\text{m}$                                  | ~ 430 mW (idler)  | ~ 14 (idler)              | 1151–1267 nm (idler)                                                |                                   |       |
| Nd:YAG<br>1064 nm<br>11 W                       | PPLN (50 mm)                                                        | 400 mW            | ~ 4                       | 1.53–1.62 $\mu\text{m}$                                             | < 6 MHz                           | [105] |
| Nd:YVO <sub>4</sub><br>1064 nm<br>1 W           | $\Lambda = 29.1\text{ }\mu\text{m}$ (fan-out)                       |                   |                           |                                                                     |                                   |       |
|                                                 | PPLN (50 mm)                                                        | ~ 295 mW (total)  | ~ 68 (total)              | 1.446–1.604 $\mu\text{m}$ (signal)                                  | —                                 | [106] |
|                                                 | $\Lambda = 28.5\text{--}29.9\text{ }\mu\text{m}$                    |                   |                           | 3.158–4.024 $\mu\text{m}$ (idler)                                   |                                   |       |

|                                                                      |                                                                  |                                  |                                      |                                                                     |           |       |
|----------------------------------------------------------------------|------------------------------------------------------------------|----------------------------------|--------------------------------------|---------------------------------------------------------------------|-----------|-------|
| Diode<br>810 nm<br>100 mW (signal mode)<br>400 mW (multi mode)       | PPLN (19 mm)<br>$\Lambda = 21.0\text{--}22.4\text{ }\mu\text{m}$ | 5 mW (signal)<br>39 mW (signal)  | 5 (signal mode)<br>9.75 (multi mode) | 1.15–1.25 $\mu\text{m}$ (signal)<br>2.31–2.66 $\mu\text{m}$ (idler) | —         | [107] |
| Nd:YAG<br>2nd harm., 532.26 nm<br>450 mW                             | PPLT (25 mm)<br>$\Lambda = 7.3\text{--}10.7\text{ }\mu\text{m}$  | 60 mW                            | 22 (total)<br>1167–1733 nm (idler)   | 768–978 nm (signal)                                                 | < 160 kHz | [108] |
| InGaAs MOPA<br>925 nm<br>2.3 W                                       | PPLT (35 mm)<br>$\Lambda = 27.3\text{--}27.9\text{ }\mu\text{m}$ | 244 mW                           | ~ 11                                 | 1.55–2.3 $\mu\text{m}$                                              | < 10 MHz  | [109] |
| Nd:YAG<br>2nd harm., 532 nm<br>93 mW                                 | PPKTP (10 mm)<br>$\Lambda = 9.00\text{ }\mu\text{m}$             | ~ 6.5 mW (total)                 | ~ 8                                  | 1037–1093 nm                                                        | —         | [110] |
| Nd:YLF 2nd harm.,<br>532 nm<br>200 mW                                | PPKTP (9 mm)<br>$\Lambda = 9.55\text{ }\mu\text{m}$              | 10 mW (idler)                    | 5 (idler)                            | 769.1–763.4 nm<br>(signal)<br>1639.2–1665.7 nm (idler)              | ~ 10 MHz  | [111] |
| Ti:sapphire 840 nm<br>2.2 W (intracavity<br>OPO)<br>Ar ion pump, 8 W | PPRTA (4.5 mm)<br>$\Lambda = 30\text{ }\mu\text{m}$              | 270 mW (idler)<br>930 mW (total) | 43 (total)                           | 2.53–3.26 $\mu\text{m}$ (idler)<br>1.13–1.27 $\mu\text{m}$ (signal) | —         | [112] |

<sup>a</sup> PPLN = periodically poled lithium niobate ( $\text{LiNbO}_3$ ); PPLT = periodically poled lithium tantalite ( $\text{LiTaO}_3$ ); PPKTP = periodically poled KTP ( $\text{KTiOPO}_4$ ).

**Table 30** QPM-Based Pulsed OPO Systems

| Pump laser                                                                                                                           | Nonlinear medium <sup>a</sup>                                                                 | Output energy/power                          | Conversion efficiency (%)  | Tuning range                                                         | Line width           | Pulse width | Ref.  |
|--------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|----------------------------------------------|----------------------------|----------------------------------------------------------------------|----------------------|-------------|-------|
| Q-SW. Nd:YAG<br>1064 nm<br>$\tau = 20$ ns, 1 kHz<br>3.2 mJ/pulse<br>external-cavity diode<br>laser seed, 1.5 $\mu$ m,<br>500 $\mu$ W | PPLN (17 mm)<br><br>$\Lambda = 29$ $\mu$ m                                                    | 338 $\mu$ J (idler)                          | 15.4                       | 3.22–3.7 $\mu$ m                                                     | 158 MHz              | 4 ns        | [113] |
| Q-SW. Nd:YAG<br>1064 nm<br>$\tau = 120$ ns, 1–5 kHz<br>1 mJ/pulse                                                                    | PPLN (40 mm)<br><br>$\Lambda = 29.3$ & 29.5 $\mu$ m<br>(DAST crystal for<br>DFG of 2 signals) | 270 $\mu$ J (total)<br><br>(53 fJ of<br>DFG) | $\sim 8$                   | 1.529 and 1.546 $\mu$ m<br><br>(120–160 $\mu$ m, THz<br>wave by DFG) | $\sim 0.1$ $\mu$ m   | —           | [114] |
| Q-SW. Nd:YAG<br>1064 nm<br>$\tau = 28$ ns, 3 kHz<br>0.8 mJ/pulse                                                                     | PPLN (2) (50 mm)<br><br>$\Lambda = 28.5$ –29.9 $\mu$ m,<br>$\Lambda = 30.0$ –31.2 $\mu$ m     | 250 $\mu$ J<br>(signal)                      | 25                         | 1450–1950 nm                                                         | 0.3 $\text{cm}^{-1}$ | —           | [115] |
| Q-SW. Nd:YAG<br><br>1064 nm<br>$\tau = 120$ ns, 1 kHz<br>1.6 W, avg.                                                                 | PPLN (18 mm)<br><br>$\Lambda = 30$ $\mu$ m                                                    | $\sim 260$ mW,<br>avg.                       | $\sim 16$ (18.5,<br>slope) | 1.533–1.589 $\mu$ m                                                  | —                    | —           | [116] |
| Q-SW. Nd:YAG<br><br>1064 nm<br>$\tau = 3.5$ ns, 30 Hz<br>300 $\mu$ J/pulse                                                           | PPLN (10 mm)<br><br>$\Lambda = 26$ –31.5 $\mu$ m                                              | $\sim 80$ $\mu$ J,<br>(signal)               | $\sim 27$                  | 1.475–1.7 $\mu$ m<br>(signal)                                        | $\sim 1$ –30 nm      | 3 ns        | [117] |

|                                                                                                                                                                     |                                                                                                 |                         |                                           |                                                                        |                                              |   |       |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------|-------------------------------------------|------------------------------------------------------------------------|----------------------------------------------|---|-------|
| Nd:YAG, 1064 nm<br>1.2-W diode<br>pump, or Nd:YVO <sub>4</sub> ,<br>1064 nm 2-W diode<br>pump<br>(monolithic OPO<br>design,<br>with LiTaO <sub>3</sub><br>Q-switch) | PPLN (11 mm)<br>$\Lambda = 30\text{--}31.2$                                                     |                         |                                           |                                                                        |                                              |   |       |
|                                                                                                                                                                     | 8.7 $\mu\text{J}$ , 1 kHz<br>(YAG pump)<br>5.9 $\mu\text{J}$ , 5 kHz (YVO <sub>4</sub><br>pump) | —                       | 1540–3440 nm                              | —                                                                      | 11.4 ns (YAG)<br>1.65 ns (YVO <sub>4</sub> ) |   | [118] |
| Er-doped fiber 2nd<br>harm., 780 nm<br>$\tau = 45$ ns, 300 Hz<br>60 $\mu\text{J}$ /pulse                                                                            | PPLN (20 mm)<br>$\Lambda = 19\text{--}20.5$ $\mu\text{m}$                                       | $\sim 2$ $\mu\text{J}$  | $\sim 6$ (signal)<br>( $\sim 10$ , slope) | 945–1450 nm<br>(signal) 1690–<br>4450 nm (idler)                       | —                                            | — | [119] |
| Er-doped fiber<br>1.545–1.56 $\mu\text{m}$<br>$\tau = 60$ ns, 500 Hz<br>150 $\mu\text{J}$ /pulse                                                                    | PPLN (50 mm) $\Lambda = 32.4\text{--}$<br>33.2 $\mu\text{m}$                                    | 8 $\mu\text{J}$ (idler) | 18                                        | 2.55–2.7 $\mu\text{m}$<br>(signal) 3.65–<br>3.96 $\mu\text{m}$ (idler) | —                                            | — | [120] |
| Q-SW. Nd:YAG 1064 nm<br>$\tau = 5.1$ ns, 10 Hz<br>150 mJ/pulse                                                                                                      | PPKTP (10 mm) $\Lambda 35.0$ $\mu\text{m}$<br>(cylindrical)                                     | —                       | —                                         | 1517–2040 nm<br>(signal) 2220–<br>3560 nm (idler)                      | —                                            | — | [121] |
| Q-SW. Nd:YAG 2nd<br>harm., 523 nm<br>$\tau = 5$ ns, 20 Hz<br>0.5 mJ/pulse                                                                                           | PPKTP (8 mm) $\Lambda = 12.77$ $\mu\text{m}$                                                    | 1.79 mJ                 | 50 (signal)                               | 631–641 nm                                                             | 0.3 nm                                       | — | [122] |
| Q-SW. Nd:YAG 1064 nm<br>$\tau = 5$ ns, 20 Hz<br>16.2 mJ/pulse                                                                                                       | PPKTP (8 mm) $\Lambda = 37.8$ $\mu\text{m}$                                                     | 7 mJ (total)            | 45 (total)                                | 1715–1745 nm<br>(signal) 2803–<br>2726 nm (idler)                      | $\sim 15$ nm (signal)                        | — | [123] |

(continued)

**Table 30** Continued

| Pump laser                                                                                                                                  | Nonlinear medium <sup>a</sup>                        | Output energy/power                                         | Conversion efficiency (%)                    | Tuning range                                           | Line width                                   | Pulse width                            | Ref.  |
|---------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|-------------------------------------------------------------|----------------------------------------------|--------------------------------------------------------|----------------------------------------------|----------------------------------------|-------|
| Q-SW. Nd:YAG 2nd harm., 523 nm<br>$\tau = 5$ ns 1.5 mJ/pulse                                                                                | PPKTP (10 mm)<br>$\Lambda = 9.01$ $\mu$ m            | —                                                           | 13 (idler, axial Bessel beam)<br>(27, total) | 931–1241 nm (total)                                    | —                                            | —                                      | [124] |
| Q-SW. Nd:YAG 1064 nm<br>$\tau = 5$ ns, 20 Hz<br>4.5 mJ/pulse                                                                                | PPKTP (2) (15 and 20 mm)<br>$\Lambda = 38.5$ $\mu$ m | 1.8 mJ (total)                                              | 50                                           | 1.8–2.5 $\mu$ m                                        | —                                            | —                                      | [125] |
| Q-SW. Nd:YVO <sub>4</sub> 1064 nm, $\tau = 5.5$ ns,<br>1 kHz 800 $\mu$ J/pulse<br>Q-sw. Nd:YAG 1064 nm $\tau = 20$ ns,<br>10 Hz 65 mJ/pulse | PPRTA (7 mm)<br>$\Lambda = 40.2$ $\mu$ m             | 45 $\mu$ J (signal)<br>11 $\mu$ J (idler)<br>17 mJ (signal) | 6 (signal) 26                                | 1577sfhnm (signal)<br>1577 nm (signal)                 | $\sim 7$ –11 nm                              | —                                      | [126] |
| M-L Ti:sapphire<br><br>780–910 nm<br>$\tau = 1.5$ ps, 81 MHz<br>1.5 W, avg.                                                                 | PPRTA (8 mm)<br><br>$\Lambda = 30$ $\mu$ m           | 320 mW (signal)<br>113 mW (idler)                           | $\sim 25$ (signal)<br>$\sim 9$ (idler)       | 1.062–1.112 $\mu$ m (signal)<br>3.35–5 $\mu$ m (idler) | $\sim 3$ nm (signal)<br>$\sim 35$ nm (idler) | 714 fs (signal)<br>$\sim 1$ ps (idler) | [127] |

<sup>a</sup> PPLN = periodically poled lithium niobate (LiNbO<sub>3</sub>); PPKTP = periodically poled KTP (KTiOPO<sub>4</sub>); PPRTA = periodically poled RTA (RBTiOAsO<sub>4</sub>).

**Table 31** QPM-Based Synchronously Pumped OPO Systems

| Pump laser                                                                                        | Nonlinear medium <sup>a</sup>                                                               | Output energy/-<br>power                   | Conversion efficiency<br>(%)                 | Tuning range                                                    | Line width | Pulse<br>width | Ref.  |
|---------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|--------------------------------------------|----------------------------------------------|-----------------------------------------------------------------|------------|----------------|-------|
| M-L Ti:Al <sub>2</sub> O <sub>3</sub><br>790 nm $\tau$ = 175 fs,<br>110 MHz 1 W,<br>avg.          | PPLN (0.8 mm)<br>$\Lambda$ = 19.75 $\mu$ m                                                  | 20 mW, avg. (signal)                       | $\sim$ 5                                     | 1.4 $\mu$ m (signal)                                            | —          | 220 fs         | [128] |
| M-L InGaAs oscil<br>lator–amplifier<br>927 nm $\tau$ = 20 ps,<br>2.488 GHz 1 W,<br>avg.           | PPLN (38 mm)<br>$\Lambda$ = 26.0–26.6 $\mu$ m                                               | 5 mW, avg. (signal)<br>78 mW, avg. (idler) | < 1 (signal)<br>$\sim$ 9 (idler) (13, slope) | 1531–1737 nm<br>(signal)<br>1986–2350 nm (idler)                | 1 nm       | 7.8 ps         | [129] |
| M-L-Ti:Al <sub>2</sub> O <sub>3</sub><br>840 nm $\tau$ = 45 fs,<br>84.5 MHz 1 W,<br>avg.          | PPLN (aperodic) (1 mm)<br>$\Lambda$ = 22.96 $\mu$ m, avg.<br>21.89–23.55 $\mu$ m, max chirp | 5–10 mW, avg.                              | —                                            | 2.7–3.7 $\mu$ m (idler)                                         | > 500 nm   | 53 fs          | [130] |
| M-L-Ti:Al <sub>2</sub> O <sub>3</sub><br><br>800 nm<br>$\tau$ = 100 fs,<br>86 MHz, 1.5 W,<br>avg. | PPLN (1 mm)<br><br>$\Lambda$ = 20.5-22 $\mu$ m                                              | 90 mW, avg. (signal)                       | 12                                           | 0.975–1.54 $\mu$ m<br>(signal)<br><br>1.67-4.55 $\mu$ m (idler) | —          | 140 fs         | [131] |
| M-L Ti:Al <sub>2</sub> O <sub>3</sub><br><br>810 nm<br>$\tau$ = 100 fs,<br>84 MHz, 1.5 W,<br>avg. | PPLN (1 mm)<br><br>$\Lambda$ = 16.0–20.0 $\mu$ m                                            | 14.4 mW, avg.<br>(idler)                   | —                                            | 910–1080 nm (signal)<br><br>2.8–6.8 $\mu$ m (idler)             | —          | $\sim$ 150 fs  | [132] |
| M-L Nd:YLF                                                                                        | PPLN (19 mm)                                                                                | 300 mW, avg.<br>(signal)                   | 30                                           | 1.6–1.9 $\mu$ m (signal)                                        | —          | $\sim$ 3 ps    | [133] |

(continued)

**Table 31** Continued

| Pump laser                                                                                                    | Nonlinear medium <sup>a</sup>                                      | Output energy/-<br>power                                      | Conversion efficiency<br>(%)        | Tuning range                                                                     | Line width              | Pulse<br>width     | Ref.  |
|---------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|---------------------------------------------------------------|-------------------------------------|----------------------------------------------------------------------------------|-------------------------|--------------------|-------|
| 1064 nm $\tau = 4$ ps,<br>120 MHz 1 W,<br>avg.                                                                | $\Lambda = 30\text{--}30.4\text{ }\mu\text{m}$                     | 200 mW, avg.<br>(signal)                                      | 22                                  |                                                                                  | —                       | $\sim 250$ fs      |       |
| M-L Nd:YAG<br>1064 nm<br>$\tau = 100$ ps,<br>76 MHz<br>16 W, avg.                                             | PPLN (12 mm)<br><br>$\Lambda = 29.75\text{ }\mu\text{m}$           | 3.3 W, avg. (idler)                                           | $\sim 20$ (idler)                   | $\lambda_s = 1.5\text{ }\mu\text{m}$<br><br>$\lambda_i = 3.5\text{ }\mu\text{m}$ | —<br><br>—              | —                  | [134] |
| M-L Nd:YLF<br>1064 nm 1 W, avg.                                                                               | PPLN (19 mm)<br>$\Lambda = 21\text{--}24\text{ }\mu\text{m}$       | 10 mW, avg. (idler)                                           | —                                   | 5.3–6.3 $\mu\text{m}$ (idler)                                                    | —                       | —                  | [135] |
| M-L Ti:Al <sub>2</sub> O <sub>3</sub><br><br>835–1000 nm<br>$\tau = 800$ fs,<br>80.5 MHz 250–<br>980 mW, avg. | PPLN (6 mm)<br><br>$\Lambda = 21\text{--}22.4\text{ }\mu\text{m}$  | 280 mW, avg.<br>(signal)<br><br>$\sim 60$ mW, avg.<br>(idler) | 35 (signal)<br><br>$\sim 9$ (idler) | 1.004–1.040 $\mu\text{m}$<br>(signal)<br><br>3.9–5.98 $\mu\text{m}$ (idler)      | $\sim 7$ nm<br>(signal) | 0.4 ps<br>(signal) | [136] |
| M-L Yd:YAG<br><br>1030 nm<br>$\tau = 600$ fs,<br>35 MHz<br>11 W, avg.                                         | PPLT (22 mm)<br><br>$\Lambda = 28.3\text{--}29\text{ }\mu\text{m}$ | 2.3–2.7 W, avg.<br>(signal)                                   | $\sim 30$                           | 1429–1473 (signal)<br><br>3425–3670 nm (idler)                                   | 3–4 nm<br>(signal)      | 700–900 fs         | [137] |
| M-L Ti:Al <sub>2</sub> O <sub>3</sub><br><br>758 nm $\tau = 215$ fs,<br>76 MHz 650 mW,<br>avg.                | PPKTP (7 mm)<br><br>$\Lambda = 24\text{ }\mu\text{m}$              | 140 mW, avg.<br>(signal)                                      | 22                                  | 1000–1235 nm (sig-<br>nal)                                                       | —                       | 330 fs             | [138] |

<sup>a</sup> PPLN = periodically poles lithium niobate (LiNbO<sub>3</sub>); PPLT = periodically poles lithium tantalite (LiTaO<sub>3</sub>); PPKTP = periodically poles KTP (KTiOPO<sub>4</sub>).

Lidar (light detection and ranging) applications have great need for a continuously tunable coherent radiation source for the LWIR 8–12- $\mu\text{m}$  atmospheric transmission window. Many chemical species have distinguishing signatures in this window. Traditionally, the  $\text{CO}_2$  laser has been used in this region. The  $\text{CO}_2$  laser carries the advantage of large energies and high efficiency. The disadvantage is that the  $\text{CO}_2$  laser emits only discrete lines over a limited spectral range and is, therefore, not able to meet lidar needs. The OPO, although a much weaker source, is able to cover the entire 8–12  $\mu\text{m}$  range continuously. A number of different OPO schemes are able to generate tunable radiation in this range. Some of these schemes involve two-stage OPOs while others attempt parametric generation in a single step. So far no one scheme has emerged as the clear winner for lidar applications.

For lidar applications in both the visible and IR, the following factors enter into consideration:

1. Spectral coverage
2. Energy per pulse
3. Peak power
4. Pulse repetition frequency (PRF)
5. Spectral bandwidth
6. Output beam quality ( $M^2$ )
7. Beam stability during tuning
8. Pump laser maturity
9. Ease of system operation

In designing an OPO, a number of practical issue must be considered. These are outlined below.

## A. Pump Laser Issues

The availability of a suitable pump laser is one of the most important considerations in designing an OPO. Currently, the Nd:YAG laser is the most mature commercially available laser. Typically it provides Q-switched, nanosecond pulse-width output at 1064 nm. The Nd:YAG output, along with its harmonics at 532 nm, 355 nm and 266 nm, have been very popular pump sources for OPOs from the UV to the IR. A summary of some examples of the use of the Nd:YAG laser and its harmonics being used as a pump for OPO generation are:

- 266 nm pumping BBO, LBO,  $\rightarrow 0.32 \mu\text{m}$  to  $1.6 \mu\text{m}$
- 355 nm pumping BBO, LBO  $\rightarrow 0.4 \mu\text{m}$  to  $2.5 \mu\text{m}$
- 532 nm pumping KTP, KTA, BBO  $\rightarrow 0.68 \mu\text{m}$  to  $2.5 \mu\text{m}$
- 1.064  $\mu\text{m}$  pumping KTP, KTA, PPLN,  $\text{AgGaS}_2 \rightarrow 1.5 \mu\text{m}$  to  $10 \mu\text{m}$

1.064  $\mu\text{m}$  pumping tandem OPOs (e.g., KTA + AgGaSe<sub>2</sub>)  $\rightarrow$  1.5  $\mu\text{m}$  to  $> 14 \mu\text{m}$

The 2- $\mu\text{m}$  Ho laser, pumped by a diode array-pumped thulium laser, has emerged as a promising pump for MIR [139] and LWIR [140,141] OPOs. The 2.8- $\mu\text{m}$  Er:Cr:YSGG laser has also been used as a pump for OPOs in the same range [142]. Many other lasers, ranging in pulse widths from femtoseconds to continuous wave as described in Section V, have also been successfully used to pump OPOs.

## B. Crystal Issues

The first requirement for an OPO crystal is, of course, phase-matching, which may be normally type I or II. Type II, generally speaking, gives higher dispersion and thereby leads to narrower linewidths for the OPO output. Type I provides greater tunability, but leads to wider linewidths, specially near the degeneracy point.

Another consideration is beam walk-off among the waves of differing polarizations inside the crystal. This problem is less severe when the beam diameters are large, but can limit the interaction length for smaller diameter beams. The problem of beam walk-off is alleviated when the propagation is along, or perpendicular to, a crystal axis [the so-called noncritical phase matching (NCPM)] at the expense of output wavelength choices. The introduction of QPM materials (e.g., PPLN) has helped alleviate the walk-off problem since phase-matched propagation may be along a crystal axis.

Absorption at any of the three waves can reduce the effective OPO again. In terms of sensitivity, absorption at the resonated wave is most serious followed by that at the pump.

Crystal damage long prevented OPOs from gaining acceptance as a viable source of tunable radiation. The development of damage-resistant KTP and BBO crystals and isomorphs changed the situation. For MIR and LWIR, the development of ZGP crystals has been very important. New developments of QPM materials also alleviates this problem because the larger nonlinear coefficients utilized lower the pump threshold.

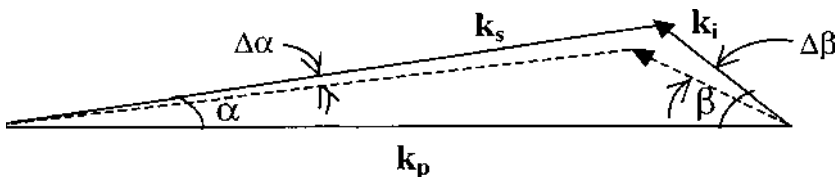
## C. Resonator Issues

Which wavelength to resonate in an OPO is an important question. In principle, either of the two wavelengths produced in the parametric process may be resonated while the other is generated to balance the energy and momentum with pump. Traditionally, because of the easier availability of optical coatings, it is the shorter wavelength that is resonated regardless of which wavelength is of interest.

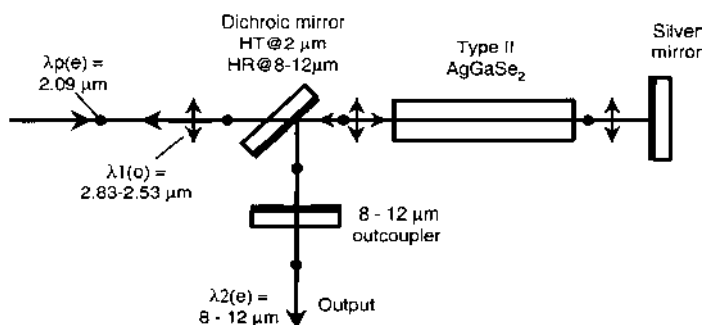
Such a choice, however, is not always wise [141], especially when the longer wavelength is the one desired. This is especially true when the beam quality is important (e.g., for remote sensing). One reason is that the resonator Fresnel number,  $w^2/L\lambda$  (where  $w$  is the beam radius,  $L$  the resonator length, and  $\lambda$  the resonated wavelength), becomes smaller when the longer wavelength is resonated. A second reason is that a small divergence of the shorter wavelength leads to a large divergence of the longer wavelength (shorter wave-vector) even for a diffraction-limited pump, as shown in Fig. 76. Third, when the pump phase front is not diffraction-limited, its imperfections are carried by the nonresonated beam.

*Optical coatings.* The presence of three wavelengths in the resonator simultaneously requires rather demanding trichroic optical coatings. First of all, the crystal must be coated with trichroic anti-reflection (AR) coatings. For a simple two-mirror SRO cavity, one desires the input mirror to be highly transmissive (HT) for the pump and highly reflective (HR) for the signal and the idler. The outcoupler is typically HR for the pump, a partial reflector for the signal and should be HT for the idler. Such coatings are often difficult to make, especially when OPO tuning is to be done over a large range. Sometimes one may get around the problem by taking advantage of the polarization differences among the waves. A judicious use of a polarizer in the resonator and/or an L-shaped resonator cavity can reduce demands on the coatings.

*Tuning issues.* In most OPO cavities, the output beam(s) position translates as the crystal is rotated for turning the output wavelength. This can be a major problem in remote sensing applications. Further, when the phase matching is not exactly collinear, as is the case with most double pump pass cavities, the nonresonated beam would steer as well as translate. Figure 77 shows a design that alleviates the output beam movement [141]. In this design, the output is taken from the rear of the resonator, whereas the beam translation occurs only at the silver (front) mirror.



**Figure 76** The phase matching condition means that any angular spread in the longer wave vector will cause a much bigger angular spread in the shorter wave vector (longer wavelength).



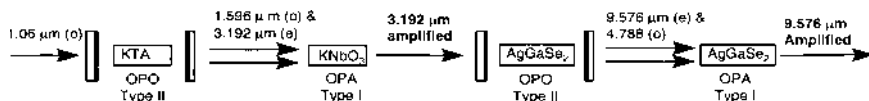
**Figure 77** The Ho-laser pumped 100-Hz OPO achieved more than 40% quantum slope conversion efficiency,  $M^2$  of 2.3, and a stationary beam during scanning.

## D. Energy Conversion Efficiency Issues

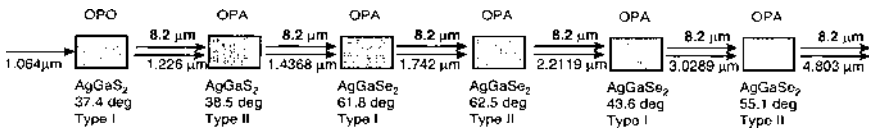
Apart from the quantum conversion efficiency (i.e., fraction of pump photons converted), one also must contend with the quantum defect, which becomes especially severe, for example, in converting the  $1.064\text{ }\mu\text{m}$  wavelength to  $8\text{--}12\text{ }\mu\text{m}$  LWIR. For every LWIR photon generated, nine-tenths of the pump photon energy goes into the photon that is wasted. Schemes have been proposed to convert the energy of the would-be wasted photons into desired photons. The so-called “greater-than-100%” quantum conversion efficiency was demonstrated experimentally in PPLN generating MIR photons.

*A 2-for-1 scheme.* This scheme utilizes the more energetic photon in the OPO process as a pump for OPA/DFG to derive a second photon of the desired wavelength. This may be done either interactively or external to the resonator cavity. The intracavity DFG was used in the PPLN experiment mentioned above.

*A 9-for-1 photon concept* [143]. This concept, (shown Fig. 78) was presented by Allik et al. The KTA OPO generates photons at wavelengths of



**Figure 78** The first OPO and OPA combination seeks to generate three photons at  $3.192\text{ }\mu\text{m}$  starting from one initial  $1.064\text{ }\mu\text{m}$  photon. The subsequent OPO and OPA containing  $\text{AgGaSe}_2$  strive to generate three-for-one photons at  $9.576\text{ }\mu\text{m}$ .



**Figure 79** An example of how an idler of desired wavelength may be amplified by successive stage OPAs using signal wavelengths from a previous stage.

$1.5 \times$  and  $3 \times$  the pump wavelength. The type I OPA then seeks to add two more photons at the longer wavelength for each shorter wavelength photon destroyed.

*Cascaded OPO/OPA concept* [144]. The idea here is to effect amplification of the LWIR photons using the otherwise wasted photons produced in each previous stage (see Fig. 79).

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