文章编号:1000-2618(2003)03-00019-08

Numerical Calculations and Analyses of Mid-IR OPO Based on Periodically-poled Lithium Niobate

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Abstract: Quasi-phased-matching technique is a rapidly growing field due to recent advances in the fabrication of periodically-poled ferroelectric materials and is widely used in frequency conversion, such as optical parametric oscillation (OPO), difference frequency generation, sum frequency generation, and second harmonic generation. In optical parametric oscillation based on PPLN, the output wavelengths are conveniently tuned by changing operating temperature and the grating periods of periodically poled lithium niobate (PPLN). We program to calculate the output wavelengths of OPO pumped by wavelength at 1 064. 2nm with different grating periods of PPLN 28. 5 μm, 29. 0 μm and 29. 5 μm, while the operating temperature changes from 250K to 550K. The influences of PPLN periods on the signal wavelength of OPO under the condition of pump wavelength at 1064nm and operation temperature at 100 ℃ are analyzed in detail.

Key words: PPLN; OPO; temperature tuning

CLC number: O 437 **Document code**: A

Introduction

Nonlinear optical frequency conversion is very useful in generating coherent radiation where convenient laser sources are unavailable[1]. High power optical radiation propagating within a non-

收稿日期:2003-05-01
基金项目:国家自然科学基金资助项目(60278001)
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linear optical material can result in the generation of radiation at other frequencies. By making use of well developed laser, especially solid-state and diode laser in the near-IR, coherent light in the mid-IR, visible and UV spectral region can be generated by frequency conversation in a suitable nonlinear material. The utility of nonlinear optics has been predominately limited by the availability of suitable nonlinear optical materials[2]. Suitability of a material requires the simultaneous satisfaction of a number of conditions, including a significantly large nonlinearity, transparency at operating wavelengths, damage resistance and availability of high-quality crystals with dimensions of at least 1cm. Beyond the basic properties, the condition that eliminates most potential material from application is the requirement of phase-matching. Although quasi-phasing was invented shortly after the first nonlinear optical experiment, it was limited due to the lack of practical processing methods for fabricating materials with the micron-scale structures required for its implementation. Recent advances in the fabrication of periodically-poled ferroelectric materials have dramatically changed this situation[3]. The nonlinear optical approaches, such as optical parametric oscillation (OPO)[4-6], difference frequency generation (DFG)[7,8], sum frequency generation (SFG)[9] and second harmonic generation (SHG)[10] or combinations can be applied through the design of PPLN patterns and manufactured process to obtain the desired wavelength of output laser beam. PPLN is particularly suitable for the generation and customization of desired outgoing radiation wavelength of a laser beam according to its input conditions, such as the incoming source of radiation and its environmental temperature.

1 Quasi-phased match nonlinear optics[6]

Interaction through the nonlinear polarization of the medium gives rise to frequency components at the second harmonic, sum frequency, and difference frequency of input waves. In general three-wave interaction, the frequencies ω_1, ω_2, and ω_3 must meet the energy conversion criterion $\omega_1 + \omega_2 = \omega_3$. The phase of the fields is also important because the phase relationship determines the direction of power flow between the interacting waves. The conversion efficiency is determined by the extent of phase-matching. Dispersion in the material results in frequency-dependent phase velocities, leading to varied phase relationships. The variation per unit length is described by the phase velocity mismatch $\Delta\kappa = \kappa_3 - \kappa_2 - \kappa_1$, where $\kappa_j = \omega_j n_j / c (j = 1, 2, 3)$ is the wave vector of the corresponding wave with refractive index n_j. As shown in Fig. 1, when $\Delta\kappa \neq 0$, the phase changes as the wave propagates through the crystal, so the power oscillates between

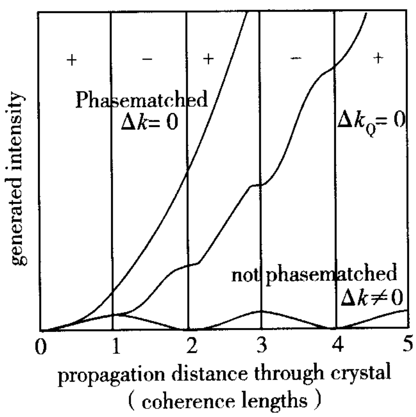

Fig. 1 Growth of generated wave for phase-matching, not phase-matching and quasi-phase-matching (QPM) interaction.

图1 相位匹配、不匹配和准相位匹配情况下的增益比较

them and there is no active generation. The coherence length is the distance where the accumulated phase mismatch is π and the power flow reverses direction.

The power of pump light is efficiently transferred to the generated field as the wave propagates through the crystal when the interaction is phase-matched ($\Delta\kappa = 0$). As we know, phasematching is typically realized by using the birefringence of the materials to offset the dispersion. The refractive indices of a crystal can be changed to some extent by temperature and by the angle between the propagation direction and the crystal axis. However, there are limited fortuitous materials meeting the phase-matching condition.

In OPO based on PPLN, frequency conversions involve interactions between three different light beams with vacuum wavelengths λ_p , λ_s , and λ_i , which are the pump, the signal and the idle wavelength respectively. They are constrained by the following energy conservation equation:

$$\frac{1}{\lambda_s} + \frac{1}{\lambda_i} = \frac{1}{\lambda_p}, \qquad (1)$$

The highest conversion occurs at the center of the phase-matching peak, where the phase mismatch in a first-order QPM interaction, Δk , is given by the following equation[11]:

$$\Delta k = 2\pi\left(\frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} - \frac{n_i}{\lambda_i} - \frac{1}{\Lambda}\right). \qquad (2)$$

where n_p is the extraordinary refractive index at the pump wavelength, n_s and n_i are the corresponding qualities for the signal and the idle waves, respectively. Λ represents the grating period of PPLN.

2 Periodically poled lithium niobate

Lithium niobate (LN) has been a historically significant material for optical parametric oscillators (OPO) since the first Czochralski growth of large boules at Bell Laboratories in 1965. PPLN fabrication methods are electric-field poling technique first demonstrated by Yamada et al. of Sony Corporation in 1992[3].

In some sense, PPLN serves nonlinear optics as silicon serves the microelectronics industry—— it is a well-developed generic substrate material, from which a variety of devices can be fabricated.

Through poling, the higher nonlinear index of the bulk material, d33, can be employed for second order non-linear frequency conversion. Normally, PPLN exhibits a 4.5 fold increase in an effective nonlinear coefficient when comparing to the birefringently phase-matched lithium niobate. Therefore, the high efficiency in such frequency conversion can easily be obtained since the conversion efficiency of PPLN is directly proportional to the square value of the effective nonlinear coefficient.

An OPO structure containing PPLN is shown in Fig. 2. Tuning in OPO can be accomplished by adjusting the temperature, angle, and grating period. The operating

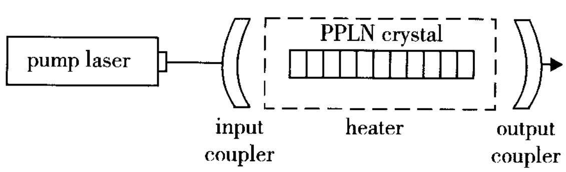

Fig. 2　OPO structure　　图 2　OPO 结构示意图

point of a QPM OPO is determined by the simultaneous solution of the energy conservation and momentum conservation (phase matching) conditions. Temperature-tuned PPLN OPO[11] and angle-tuned difference frequency generation have been demonstrated[12], but tuning by adjusting the grating vector is the most distinctive method since it is unique to QPM devices.

3 Analysis of output wavelength of OPO

PPLN is very useful to configure an OPO which can tune the output wavelength easily. It is a good route to get versifying sources to meet various requirements due to the large span of spectrum.

3.1 Phase matching

A set of interaction wavelengths is chosen, and the QPM period required for phase-matching at the desired operating temperature is calculated. The temperature is then allowed to deviate from this optimum value. The phase mismatching equation (2) can be rewritten as the following:

$$\Delta k(T) = 2\pi\left(\frac{n_3(T,\lambda_3)}{\lambda_3} - \frac{n_2(T,\lambda_2)}{\lambda_2} - \frac{n_1(T,\lambda_1)}{\lambda_1} - \frac{1}{\Lambda(T)}\right). \quad (3)$$

The period required for QPM is calculated by setting the phase mismatch in Eq.(3) equal to zero. Because the PPLN devices are manufactured and sold at room temperature, thermal expansion needs to be accounted for in relating the QPM period at the operating temperature to the QPM period at room temperature.

The PPLN crystal expands in the propagation direction, and the grating period increases correspondingly. The length l of crystal at temperature T is normalized to the length of 298K according to the following formula[13]

$$l = l_{298K}[1 + \alpha(T - 298) + \beta(T - 298)^2]. \quad (4)$$

where α and β are the expansion coefficients which can be found in the reference[13]. Refractive index n is given as[14]

$$n_0^2(\lambda,T) = 4.9130 + \frac{1.173\times10^5 + 1.65\times10^{-2}T^2}{\lambda^2 - (2.12\times10^2 + 2.7\times10^{-5}T^2)^2} - 2.78\times10^{-8}\lambda^2. \quad (5)$$

$$n_e^2(\lambda,T) = 4.5567 + 2.605\times10^{-7}T^2 + \frac{0.970\times10^5 + 2.7\times10^{-2}T^2}{\lambda^2 - (2.01\times10^2 + 5.4\times10^{-5}T^2)^2} - 2.24\times10^{-8}\lambda^2. \quad (6)$$

In equations (4), (5) and (6), the temperature T is the absolute temperature in degrees Kelvin.

3.2 Calculation results

The phase-matching condition can be altered by changing any one of the following quantities: the wavelength of one of the input lasers, the temperature of the PPLN crystal, and the angle of the PPLN crystal with respect to the laser beams. Using equations (1), (3), (4) and (6), the period required for QPM according to the desired output wavelength around mid-IR is calculated in this paper, shown in Fig. 3. Because the PPLN devices are manufactured at room temperature, thermal expansion needs to be considered in relating the PPLN period at the operating temperature to the period at room temperature. Pump wavelength λ_p is 1 064. 2 nm, while operating temperature of PPLN is 100℃.

3. 2. 1　Wavelength tuning by PPLN grating period

Fig. 4 shows the influences of PPLN periods on the signal wavelength of OPO under the condition of pump wavelength at 1 064 nm and operation temperature at 100℃ in detail. Desired output wavelength can be obtained by means of selecting correct PPLN grating period even under the same pump. The output wavelengths can be tuned by changing the PPLN grating periods. For example, the fan-out pattern provides a convenient way of covering broad spectral regions completely[14].

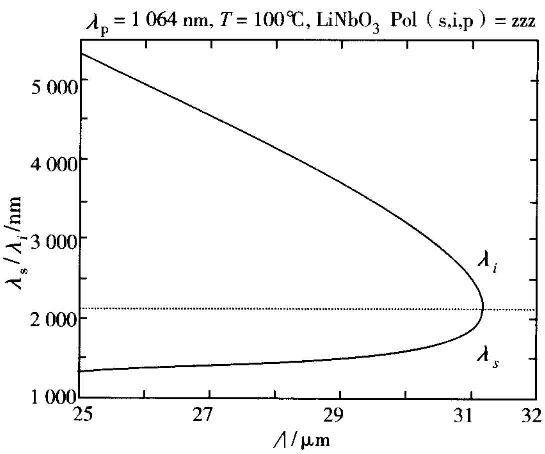

Fig. 3　Signal and idle wavelengths depending on the PPLN periods for an OPO pumped by a Nd: YAG laser

图3　工作温度为100℃，Nd: YAG 激光泵浦的 OPO 信号光和空闲光与 PPLN 周期的关系

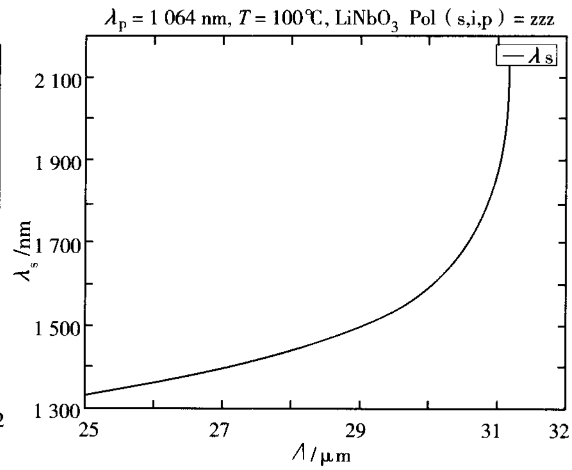

Fig. 4　Influences of PPLN periods on the signal wavelength of OPO

图4　泵浦波长为 1 064. 2 nm，工作温度 100℃，PPLN 周期对信号光波长的影响

3. 2. 2　Wavelength tuning by adjusting operation temperature

Signal and idle wavelengths can be tuned by adjusting operation temperature as long as the phase matching equation (3) is zero. Because the extraordinary indices of refraction have a complex relationship with their wavelengths and the temperature of PPLN, we can not resolve equation (3) directly. We programmed by means of Matlab. 6. 5 to obtain the data solution, and the flow chart of the program is shown in Fig. 5. When $\triangle k$ is smaller than a setting value close to zero, $\triangle k$ is regarded as zero. Using the method of successive approximation, we can find $\triangle \lambda_s$ in response to the change of temperature ΔT.

According to the discussion above, the operation temperature fluctuation of PPLN causes output wavelength shifts due to the changes of length of PPLN and refractive index of materials. The width of PPLN grating period will change due to the expansion coefficient of materials when the operation temperature fluctuates. The output wavelength changes at the same time. Fig. 6 shows the output wavelength shift when operation temperature is in the range of 250 K to 550 K under the condition that PPLN periods are 28.5μm, 29.0μm and 29.5μm respectively. The output wavelength shifts longer with the increase of PPLN grating period. In the three situations, the largest shift of wavelengths is reached for PPLN period of 29.5μm.

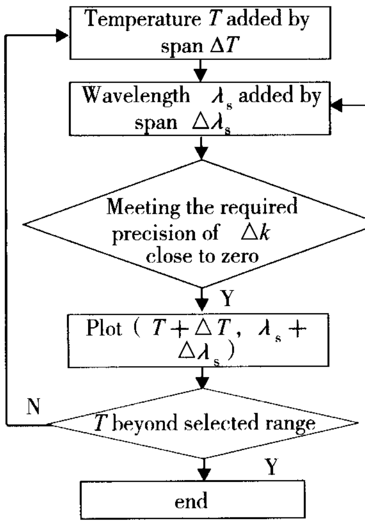

Fig. 5 Flow chart for finding the relationship between signal wavelength and operating temperature

图5 计算信号光和工作温度关系的程序流程图

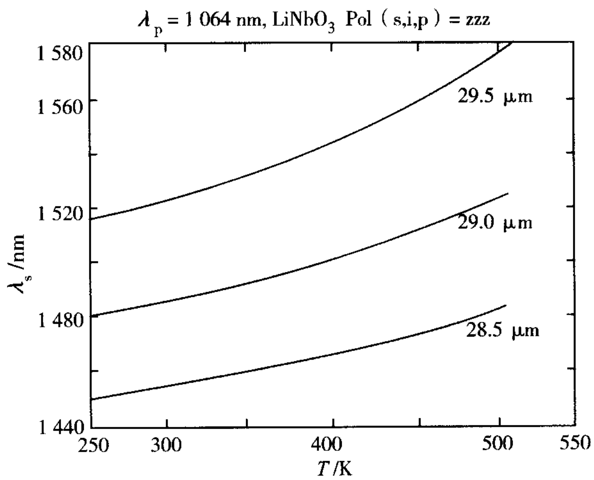

Fig. 6 Temperature tuning curves with different PPLN grating periods

图6 PPLN周期分别为28.5 μm，29.0 μm和29.5 μm，1064.2 nm波长泵浦时信号光的温度调谐

Conclusion

PPLN has advantages over standard LN for OPO applications due to quasi-phase-matching features. It is found that output wavelength of OPO based on PPLN is conveniently tuned by the PPLN grating period and operating temperature. More useful laser sources can be obtained by using this important characteristic. Another benefit of using PPLN is that it has extraordinary polarization for the long-wavelength idler, which is unavailable in birefringently phase-matched LN OPO's. There are other characteristics, for example, the large gain resulting from the large effective nonlinear coefficient and no-walk-off, which helps to offset the damage limitations by enlarging the operating range between the oscillation threshold and surface damage limit.

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基于PPLN中红外OPO数值计算与分析

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摘　要：准相位匹配技术因周期性极化晶体的制备技术的提高而迅速发展，广泛用于光学参量振荡、差频、和频和二次倍频等频率变换．基于周期性极化铌酸锂晶体的中红外光学参量振荡器的输出波长，可通过改变PPLN的工作温度和周期便捷调谐．作者编程计算了PPLN周期分别为28.5 μm、29.0 μm和29.5 μm时，泵浦波长为1 064.2 nm，工作温度从250 K至550 K下的输出波长．分析了PPLN的周期在100 ℃情况下对信号光波长的影响．

关键词： 周期性极化晶体；光学参量振荡产量器；调谐
中图分类号： O 437 **文献标识码：** A

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