Short-pulse intracavity Raman laser

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We propose a new method for producing intense short laser pulses by using an intracavity Raman laser in an interlocking ring configuration with copropagating unidirectional pump and Stokes pulses. The temporal duration of the Raman output pulses is given by the difference between the round-trip times of the two cavities and therefore can be easily controlled and varied continuously. A theoretical model is described, and an analytic solution is presented.

Typically, short pulses are generated by mode locking[1] and optical phase-modulation–pulse-compression[2] techniques. In this Letter we describe a new technique based on the properties of intracavity Raman lasers.[3–6] The advantages of this technique include its relative simplicity, its provision for continuously adjustable pulse duration, and its high output intensity. Moreover, the frequency of the output pulse is tunable if the pump-laser frequency is tunable. If required, these output pulses can be further shortened by extracavity optical phase-modulation techniques.

Consider an intracavity Raman laser whose design is shown in Fig. 1. This laser contains independent pump and Stokes ring cavities whose copropagating and unidirectional pulses intersect in a Raman active medium. The pump ring cavity also contains its gain medium. The lengths of the two cavities are adjusted to differ by ΔL. A pump pulse and a small Raman seed pulse are initially injected into their respective cavities. Both injected pulses are shorter than their cavity trip times. By delaying injection of the pulse into the shorter cavity, the separation time between the pulses is reduced by $\Delta L/c$ on each round trip. As the pulses begin to overlap in the Raman cell, Raman conversion becomes possible. Once the threshold is reached, pump photons are converted to Stokes photons in the pulse-overlap region. Since only a fraction of the Stokes pulse is coupled out of the cavity, on successive round trips the intracavity Stokes pulse overlaps with a new unconverted and further amplified portion of the pump pulse of duration $\Delta L/c$ and generates an additional intense Stokes pulse of this same time duration. The intracavity pump pulse is successively shortened with each round trip by $\Delta L/c$. This narrowing of the pump pulse takes place from either its leading or trailing edge as fixed by the cavity lengths. The Stokes output consists of a train of pulses, each pulse of duration $\tau_{\rm out} = \Delta L/c$, separated by the Stokes cavity round-trip time. This train of Stokes pulses continues until the entire pump pulse is depleted and the intracavity Stokes energy has decayed.

To effect efficient Raman conversion over time $\tau_{\rm out}$, the response time of the Raman medium, T_2, should be small compared with $\tau_{\rm out}$. Otherwise, transient response of the medium reduces the Raman gain below the steady-state gain. Liquids, solids, and high-pressure gas media have sufficiently short T_2 times that picosecond pulses can be generated without entering the transient regime. Next we develop a quantitative model of the dynamics of these processes and present some numerical results.

Recently we presented a theoretical framework for understanding intracavity Raman conversion within a unidirectional ring laser and developed a model[6] constructed from well-known analytic solutions.[7] It is particularly important to have analytic solutions in the Raman medium for the case where the single-pass Raman gain is very large. When this occurs a sharp, nearly discontinuous, wave front develops, making numerical integration difficult if not impossible. In the calculations presented here we have taken the Raman and fundamental beams to be nearly collinear, allowing us to model the conversion process by using a plane-wave theory. More generally, the beams might be slightly off axis, in which case there is averaging over spatial fluctuations in the pump beam.[5,8]

An analytic form for the pulse propagation in the Raman cell can be determined if we assume that the polarization is in a steady state. This simplifies the first-order Maxwell equations for the fundamental and Stokes beams[9]:

$$\partial I_p/\partial x = -gI_pI_s, \tag{1}$$

$$\partial I_s/\partial x = \omega_s/\omega_p g I_s I_p. \tag{2}$$

Here I_i refers to the intensity of the ith beam, g is the

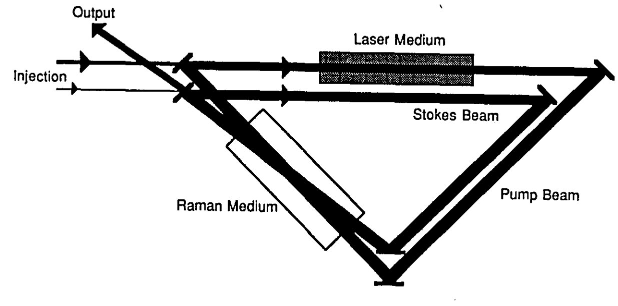

Fig. 1. Schematic of intracavity Raman ring laser.

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Table 1. Intracavity Raman Converter Parameters

Injected pump fluence, 0.282 J/cm^2
τ_{pulse} = 1.0 nsec
$\lambda_p = 7.50 \times 10^{-5}$ cm
$R_p = 0.9$
$R_s = 0.8$
$g = 4.08 \times 10^{-7}$ cm/W
$\sigma = 1.458 \times 10^{-20}$ cm^2
$\sigma_{ex} = 1.874 \times 10^{-21}$ cm^2
$n(x, t = 0) = 4.461 \times 10^{18}$ cm^{-3}
Raman-medium gain length, 23 cm
Pump gain length, 10 cm
Pump cavity length, 98.997 cm
Stokes cavity length, 97 cm
$\Delta L/c$ = 67 psec

Raman gain factor, and ω_p (ω_s) is the fundamental (Stokes) frequency. The group velocities of the two fields have been set equal, for simplicity, and dispersion has been neglected. The intensities $I_i(x, \tau)$ are functions of both distance in the Raman cell, x, and local pulse time, τ. The formal solutions to Eqs. (1) and (2) are

$$I_s(x, \tau) = I_s(0, \tau)\omega_s\phi(\tau)\exp[g\omega_s\phi(\tau)x]/(\omega_s\phi(\tau) + I_s(0, \tau)\{\exp[g\omega_s\phi(\tau)x] - 1\}), \quad (3)$$

$$I_p(x, \tau) = \omega_p\phi(\tau) - (\omega_p/\omega_s)I_s(x, \tau), \quad (4)$$

where $\phi(\tau)$ is the total photon flux, $\phi(\tau) = I_p(x, \tau)/\omega_p + I_s(x, \tau)/\omega_s$.

The propagation dynamics of the pump beam and the temporal dynamics of the excited-state population density in the pump gain medium (we consider a four-level laser with short lifetimes of the pump and terminal laser levels[10]) are given by the equations

$$\partial I_p/\partial x = (\sigma - \sigma_{ex})nI_p, \quad (5)$$

$$\partial n/\partial \tau = -\omega_p^{-1}\sigma n I_p - \tau_f^{-1}n. \quad (6)$$

Here σ and σ_{ex} are the stimulated-emission and excited-state absorption cross sections and τ_f is the lifetime of the excited-state population. Assuming that τ_f is large compared with the incident pulse duration, Eqs. (5) and (6) can be solved analytically.[11]

In the configuration modeled here, the input and output coupling for the pump and Stokes fields are located at mirrors positioned just after the Raman cell, $x = L_r$. The output intensity of the pump and Stokes beams is given by $(1 - R_p)I_p(x = L_r, t)$ and $(1 - R_s)I_s(x = L_r, t)$, respectively, where $R_p(R_s)$ is the mirror reflectivity for the pump (Stokes) wave. The boundary conditions for the fields that continue to propagate in the ring cavities are

$$I_p(x = L_r + \epsilon, t) = R_pI_p(x = L_r, t) + I_p^0(t), \quad (7)$$

$$I_s(x = L_r + \epsilon, t) = R_sI_s(x = L_r, t) + I_s^0(t), \quad (8)$$

where ϵ is an infinitesimally small number. $I_p^0(t)$ and $I_s^0(t)$ are the injected seed intensities that initiate the pump-laser amplification and Raman conversion processes. The initial conditions for propagation in the ring cavities are $I_p(x, 0) = I_s(x, 0) = 0$ and $n(x, 0) = n_{initial}$.

Using the form of the analytic solutions in the Raman and pump-laser regions coupled with their boundary conditions, it easy to piece together a complete solution for both fields over the entire propagation path.[6] Here we present results from modeling an alexandrite intracavity Raman laser with the parameters listed in Table 1. The gain medium corresponds to a strongly pumped alexandrite crystal ($n_{initial} = 0.3N$, where N is the active site concentration). The Raman gain medium corresponds to hydrogen gas at high pressure such that T_2 satisfies the steady-state approximation. A 20% output coupler is used for the Raman cavity. A fundamental pump pulse and a very weak Stokes seed pulse, with temporal intensity profiles $I_p^0(t) = At^2 \exp(-t/t_u)$ (1-nsec FWHM duration), are injected into their cavities, with the pump pulse advanced by 1-nsec relative to the Stokes seed. In Fig. 2 we plot the calculated Raman output intensity and the intracavity fundamental intensity at the end of the Raman gain medium versus time. The intensities are normalized to the maximum injected-beam intensity. The pump intracavity intensity builds with time during successive passes through the pump-laser gain medium until saturation of the gain takes place. On successive passes through the cavity, more of the leading edge of the fundamental pulse is converted into Stokes light until

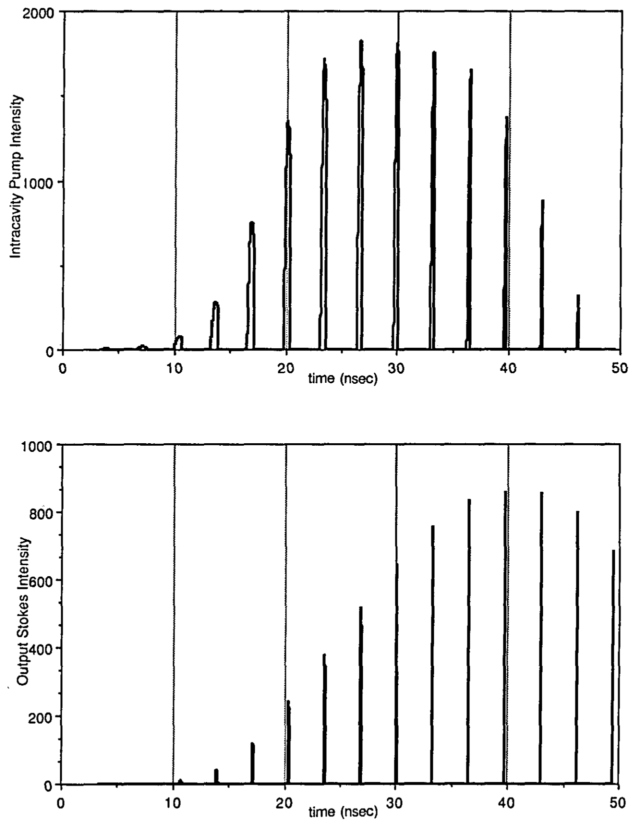

Fig. 2. Output Raman intensity and intracavity pump intensity (at the end of the Raman cell) versus time. The intensities are normalized to the peak intensity of the injected beam. The results are obtained by using the data tabulated in Table 1.

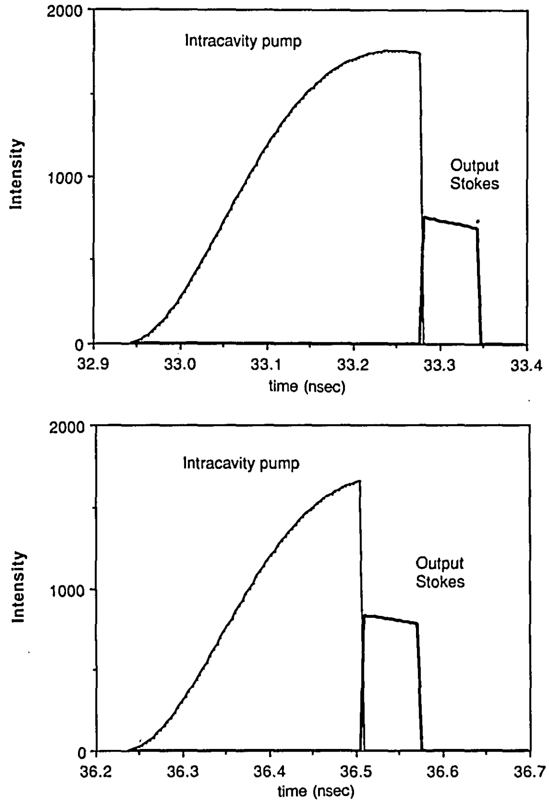

Fig. 3. Blowup of regions of Fig. 2 near 33 and 36 nsec.

the entire fundamental beam is consumed. The peak intensity of the last several intracavity pump pulses decreases because only the trailing of the pulse remains and the pump laser's gain has been depleted. The intracavity Stokes pulse continues to circulate in the cavity for many cavity lifetimes even after the pump has been totally depleted. Figure 3 shows a blowup of the intracavity pump and output Stokes pulses in the time regimes near 33 and 36 nsec. The output Stokes pulse durations are nearly equal to the difference in the cavity round-trip times, $\Delta L/c = 67$ psec, and the time between output pulses is nearly equal to the Stokes cavity time, 3.23 nsec. The intensities of the Stokes output pulses are fairly uniform. Successive shortening of the intracavity pump pulse owing to the Raman conversion is apparent.

In conclusion, we have described a new class of intracavity Raman lasers capable of generating trains of intense, controlled-duration short pulses. Pulse duration is controlled simply by adjusting the difference between the pump and Stokes cavity lengths. Output pulse duration is limited by the dephasing time of the Raman medium, i.e., the inverse Raman bandwidth. Liquid, solid, and high-pressure gaseous Raman media have sufficiently short dephasing times that picosecond duration pulses should be obtainable. Because of averaging over the transverse-mode structure of the pump beam in the Raman gain medium,[8] it should be possible to generate a nearly single spatial-mode Stokes output by using multimode pump lasers. Moreover, intracavity Raman conversion is advantageous in obtaining high quantum conversion efficiency into shifted frequencies and extracting energy efficiently from low-emission cross section gain media.[5] When the intracavity Raman laser is used as a (nonlinear) output coupler for a low cross section (high-energy storage) gain medium, the flux in the pump-laser cavity can build up to a set maximum level before the output coupling turns on. Thus, the Raman laser acts as both a power limiter and output coupler for the pump laser, permitting energy extraction to take place under more efficient high-fluence conditions without the risk of optical damage.

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