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Reduced Threshold of a Stimulated Four-Wave Mixing Process in an Optical Fiber

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Abstract. The possibility for all-optical control of the effective parametric Stokes gain was demonstrated in an optical fiber. For the first time the threshold reduction induced by the interference of two different four-wave mixing processes which share a common Stokes wave was used as a control mechanism.

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Because of their ability to maintain high intensities over large interaction lengths, optical fibres are extremely useful for frequency conversion of coherent radiation via various nonlinear processes. Among them are stimulated Raman and Brillouin scattering and four-wave mixing, second-harmonic generation, etc. [1]. Frequently two or more of these processes occur simultaneously and the understanding of their interaction is an important problem. In the present paper we treat the question how the dynamics of a stimulated four-wave mixing process (FWM) [2], pumped by a wave $P2$ with a given wavelength λ_{P2} is altered in the presence of a powerful optical wave $P1$ with substantially different wavelength λ_{P1}. We observed, for the first time, a reduction of the FWM threshold due to the nonlinear interaction of the $P1$ and $P2$ waves. This fact demonstrates a new possibility to actively and all-optically control a nonlinear conversion process in an optical fibre.

Experimental

Figure 1 shows the experimental setup. The source, on which it is based, was a Q-switched and mode-locked Nd:YAG laser operating at 1.06 μm. The Q-modulation and mode-locking frequencies were 700 Hz and 100 MHz, respectively. In order to eliminate any non-steady-state effects, the duration of the pulses was adjusted to 200 ps, while the duration of the pulse trains was 300 ns. After frequency doubling in a $LiIO_3$ crystal the first ($P1$) and second ($P2$) harmonics were divided by a Glan polarizer, sent over equal optical paths where their powers were independently controlled, and combined again in front of the fibre. The spectra of the fibre output were recorded by an optical spectrum analyzer (in the spectral region around 0.532 μm) or grating monochromator (around 1.06 μm). At $\lambda = 0.532$ μm, the normalized frequency parameter of the fibre was $V = 4.9$, while its core diameter and length were 4.5 μm and 80 cm, respectively. Because of the necessity to avoid the interference of nonlinear polarization rotation, we used a high birefringence ($B = 1.7 \times 10^{-4}$) fibre.

Figure 2 shows the output spectra in two cases: when the fibre was excited by $P2$ alone (lower curve) and when $P1$ and $P2$ were simultaneously launched (upper curve). The lower curve corresponds to a standard stimulated FWM of the mixed mode excitation type, i.e. the Stokes and one of the pump photons were propagating in the LP_{11} mode, while the anti-Stokes and the other pump photon in the LP_{01} mode. In agreement with the value of the V parameter the frequency shift was $\Omega \approx 330\ \mathrm{cm}^{-1}$. Because the fibre modes are not degenerate there are, in

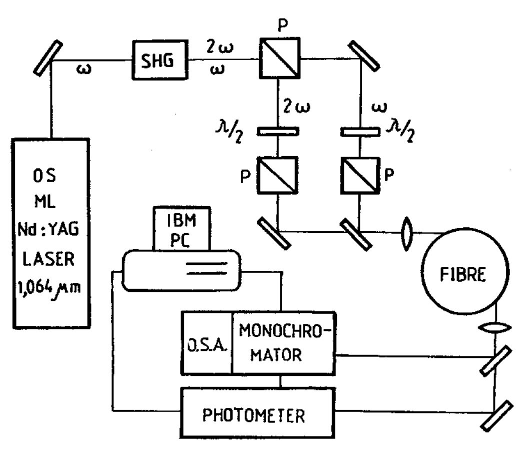

Fig. 1. Experimental setup

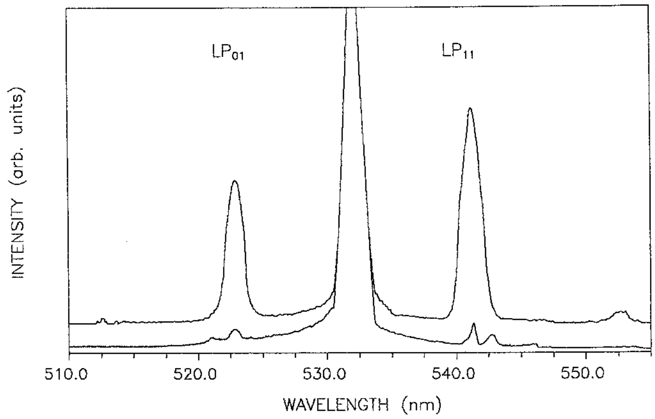

Fig. 2. Fibre output spectra without (lower curve) and with (upper curve) addition of *P*1

fact, two closely spaced pairs of lines. The intensity of *P*2 in both of the cases was $I_2 \approx 3.5\,\mathrm{GW/cm^2}$, which was at the FWM threshold, while the intensity of *P*1 in the combined case was $I_1 \approx 10\,\mathrm{GW/cm^2}$. From the upper curve in Fig. 2 it is clearly seen that the addition of the 1.06 μm wave results in a substantial increment of the generated Stokes and anti-Stokes power. Except that, in the modified spectrum two new peaks, which can be attributed to cascade mixing, are observable at shifts $\approx \pm 2\,\Omega$.

We investigated also the dependence of the Stokes signal on the intensities of the two contributing pump waves.

The changes of the generated Stokes power with the second-harmonic intensity are shown in Fig. 3. The two curves correspond to the cases without (standard FWM: dashed line) or with (solid line) the addition of *P*1 with intensity $I_1 \approx 15\,\mathrm{GW/cm^2}$. It is seen that the contribution of *P*1 reduces the threshold and the saturation power, compared with the standard FWM case. We emphasize that for approximately one and the same *P*2 values the signal is below the detection limit and in the saturation regime, respectively, for these cases without and with *P*1 simultaneously launched.

Figure 4 shows the dependence of the Stokes signal on the *P*1 intensity I_1 for fixed *P*2 intensity $I_2 = 3.5\,\mathrm{GW/cm^2}$. In that case the curve can be characterized with an exponential growth, followed by a saturation range. This behavior, which is typical for the processes of stimulated scattering [3], suggests that the influence of *P*1 on the FWM pumped by *P*2 is based on another nonlinear mixing process which increases the effective Stokes gain.

The dependence of the anti-Stokes component on *P*1 and *P*2 are similar, although its intensity is lower, which can be explained with the Raman gain/loss contribution. The fact that in our experiments the nonlinear response was integrated over the pulse train, determines the qualitative character of the curves given above. We should point out also that the induced frequency shift [4] of the Stokes line due to cross-phase modulation between *P*2 and *P*1 was taking place and might have contributed to the saturation at high *P*1 powers. Nevertheless, we believe that the possibility to control the FWM threshold and the power of the Stokes and anti-Stokes components was demonstrated.

Discussion

We propose the following explanation of the observed effect. The *P*1 pump powers and the fiber length which we used were sufficient to induce high Raman gain. Hence a substantial Raman noise field develops at a frequency $\nu_{s1} \approx \nu_1 - \Omega$, although for such frequency shifts ($\approx 330\ \mathrm{cm^{-1}}$) the Raman gain coefficient is approximately 1/2 of its maximal value at $\approx 440\ \mathrm{cm^{-1}}$, where the stimulated Raman scattering is usually observed. Then,

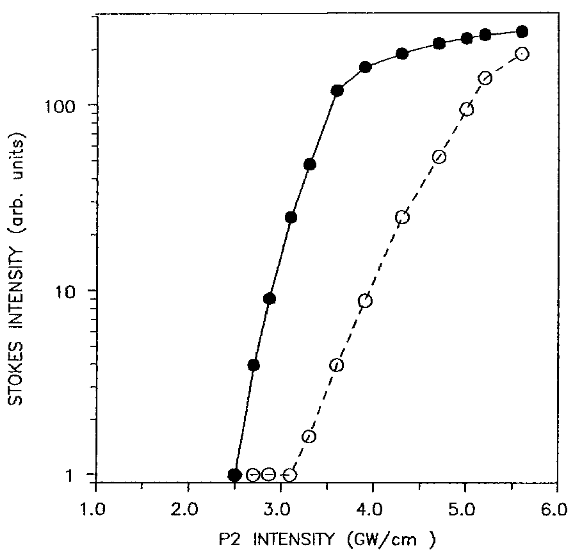

Fig. 3. Dependence of the generated Stokes ($\nu_{s2} \approx 18460\ \mathrm{cm^{-1}}$) power on the *P*2 intensity without (–o–) and with (——) addition of *P*1

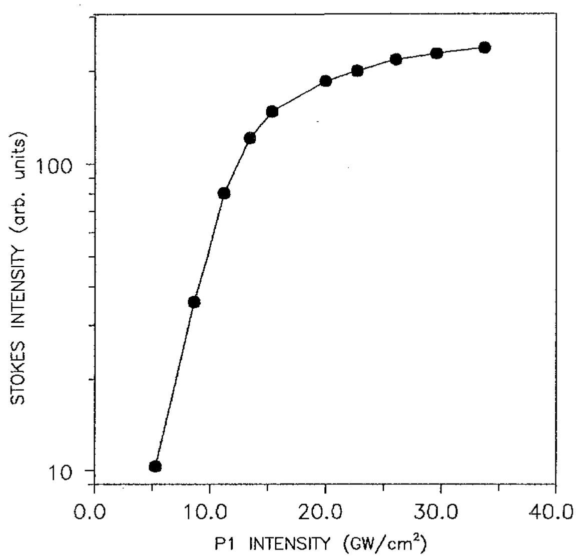

Fig. 4. Dependence of the generated Stokes ($\nu_{s2} \approx 18460\ \mathrm{cm^{-1}}$) power on the *P*1 intensity

when the strong pump waves $P1$ and $P2$ with frequencies ν_1 and ν_2 copropagate in the fibre, two additional four-wave mixing processes take place. Their energy balances are $\nu_1-\nu_{s1}=\nu_2-\nu_{s2}$ and $\nu_1-\nu_{s1}=\nu_{a2}-\nu_2$, where $\nu_{s2}\approx 18\,460\ \mathrm{cm}^{-1}$ and $\nu_{a2}\approx 19\,120\ \mathrm{cm}^{-1}$ are the frequencies of the registered Stokes and anti-Stokes lines (see Fig. 2).

The contribution of the basic stimulated FWM process (the one pumped by $P2$) to the Stokes and anti-Stokes components is the usual exponential amplification [5]

$$I_{s2,a2}\sim\exp\{L[\gamma^2 I_2^2-(k_2/2)^2]^{1/2}\}, \qquad (1)$$

where k_2, γ, and L are the resultant mismatch of the process, the gain coefficient, and the length of the fiber, respetively [1]. In the presence of exact phase-matching, which is the case, this process is the main source of Stokes gain.

Exact phase-matching of the two additional processes, connected with $P1$, is not possible and $\gamma^2 I_1 I_2 \ll k_{s1,a1}$, where $k_{s1,a1}$ are resultant mismatches of the processes. Consequently, their contribution to the visible Stokes and anti-Stokes components can be written as [5]

$$I_{s2,a2}=I_{s1}\gamma^2 I_1 I_2 L^2\left(\frac{\sin(k_{s1,a1}L/2)}{(k_{s1/a1}L/2)}\right)^2. \qquad (2)$$

Obviously, the amplification described by the latter expression is relatively weak and the significance of $P1$ is mainly in the increased "seeding" for the basic process. However, if the gain described by (1) is near the threshold value $G_{thr}\approx 16$ [3], then the additional processes might have substantial influence on the generated visible power. They can transfer the basic process from the spontaneous, sub-threshold regime to the stimulated (and even saturated) regime.

In the same time the IR wave at ν_{s1} experiences only the weak gain of the second process. The latter fact explains why we did not observe any influence of $P2$ on the IR output spectrum.

Because of the relatively long pulses (200 ps) and the short coherence length of the additional four-wave mixing process, the influence of group-velocity mismatch between $P1$ and $P2$ is negligible in our case.

Our estimations indicate that similar threshold reduction can be obtained for the stimulated Raman scattering process also. Moreover, the interfering process except FWM can be a three wave mixing process, too. Obviously, the mutual influence of the various coexisting third-order nonlinear processes in an optical fibre needs further treatment.

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