Light amplification due to nonlinear interaction of counterpropagating waves in a single-mode optical fiber

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The nonlinear interaction of counterpropagating waves from two YAG lasers in a single-mode optical fiber has been studied experimentally. The first Stokes component ($\lambda = 1.12\,\mu$m) of the signal laser is amplified by a factor of more than 50 as a result of the interaction. Along the time scale, the signal wave is split into peaks less than 5 ps wide.

1. The nonlinear processes which occur in single-mode optical fibers have recently attracted considerable research interest. The motivations are the large variety of physical processes which lead to nonlinear conversions of the frequency of light (phase self-modulation, stimulated Raman scattering, stimulated Brillouin scattering, and four-wave processes) and the extensive opportunities for converting the temporal characteristics of light.

The exponential nature of the amplification of the Stokes components of stimulated Raman scattering is known to lead to an effective contraction of the pulses of these components.[1] It was shown[2] in 1976 that when a single-mode optical waveguide is excited by counterpropagating pulses from two lasers, the amplification of the signal Stokes wave due to the counterpropagating pump wave is accompanied by a significant shortening of the signal pulse, due to the preferential amplification of its front. Since then, however, there have been only a few papers on this topic,[3,4] and the only topics which have been discussed have dealt with the amplification of the signal wave. Its temporal characteristics have not been studied. It is thus extremely interesting to study the temporal and spectral characteristics of a signal wave amplified in a counterpropagating field.

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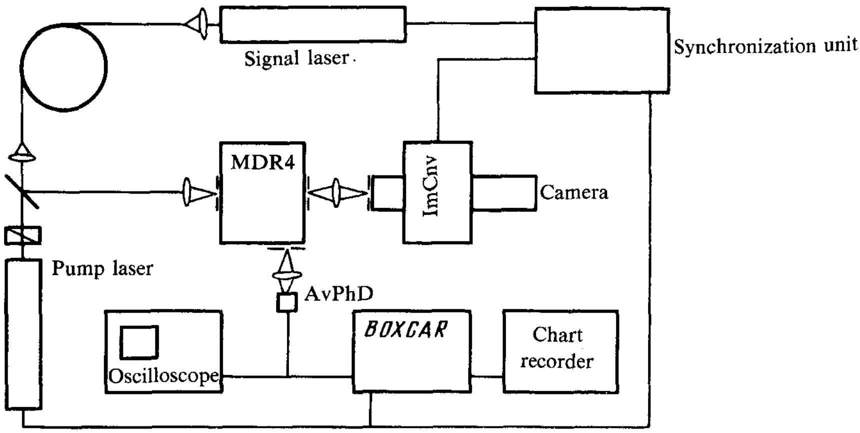

FIG. 1. The experimental apparatus.

2. The experimental arrangement is shown in Fig. 1. The beam from the yttrium aluminum garnet (YAG) signal laser, in Q-switched operation with simultaneous mode locking (the wavelength is 1.064 μm, the pulse length is 150 ps at a train length of 250 ns, the repetition frequency is 700 Hz, and the peak power is 100 kW), is coupled into the single-mode fiber (the core diameter is 8 μm; the difference between the refractive indices of the core and cladding is 3×10^{-3}; the cutoff wavelength is 1 μm; and the length is 100 m), in which stimulated Raman scattering is excited. The

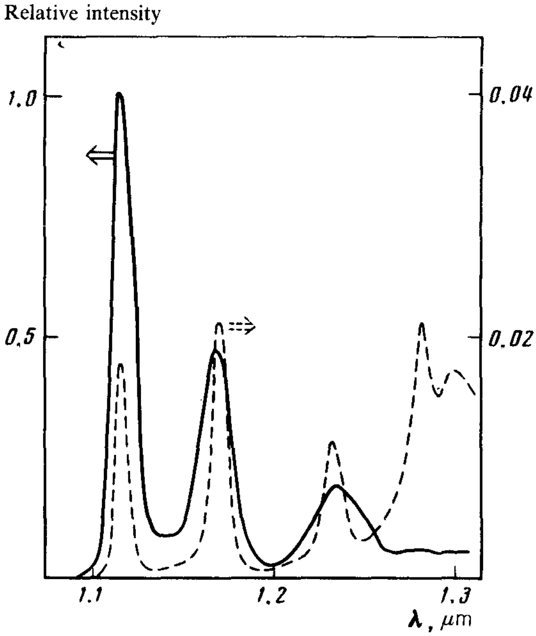

FIG. 2. Spectrum of the stimulated Raman scattering initiated by the signal pulse. Dashed line—pump laser off; solid line—pump laser on.

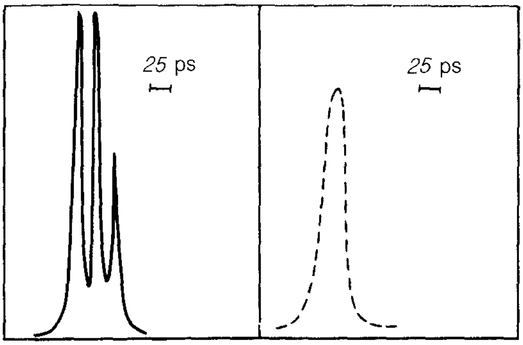

FIG. 3. Shape of the pulse at the frequency of the first Stokes component of the signal laser. Dashed line—pump laser off; solid line—pump laser on.

dashed line in Fig. 2 is the spectrum of the stimulated Raman scattering initiated by the signal laser. The pump beam from a second YAG laser, also in Q-switched operation, is coupled into the exit end of the fiber. The length of the output pulses from this laser is 100 ns. A digital delay line is used to arrange the "collisions" of the pump and signal pulses at various points along the fiber. The maximum gain of the Stokes components of the signal pulse is reached when the waves meet near the exit end of the fiber (the "exit end" from the standpoint of the signal laser). The solid line in Fig. 2 shows the spectrum of the stimulated Raman scattering of the amplified signal wave. As a detector we use a germanium avalanche photodiode with a resolving time on the order of 500 ps. It can be seen from these results that the first Stokes component is amplified by a factor of at least 50, and its spectral half-width more than doubles. The amplification of the Stokes components of higher orders is by a slightly lower factor.

The temporal characteristics of the amplified Stokes components are measured with an image converter camera operating in a line sweep mode with a maximum resolving time of 5 ps (Ref. 5).

The dashed line in Fig. 3 shows the shape of the signal light pulse, measured with the image converter camera, at the frequency of the first Stokes component in the absence of the pump wave; the solid curve shows the same pulse after amplification in the counterpropagating wave. It follows from these results that the signal pulse has undergone a temporal "splitting" into peaks less than 5 ps wide. The same sort of typical splitting was observed for the other Stokes components, but the number of peaks and their heights decrease significantly as we move into the IR region. A similar picture is observed in a fiber of the same type, but 25 m long. The gain for the signal pulse is lower, but its structure is similar to that shown in Fig. 3.

3. The temporal splitting seen in the Stokes pulses seems to contradict the well-known preferential amplification of the front of such pulses. In this connection, the physical picture which arises in the nonlinear interaction of counterpropagating waves in a single-mode optical fiber apparently takes the following form in this case. The amplification due to the interaction of counterpropagating waves occurs because the intense pump wave excites the medium, and if the time of the interaction is chosen in such a way that the Stokes wave excited by the pump wave has not yet developed from the spontaneous noise, the excitation will remove the Stokes signal pulse. As a result of this nonlinear interaction, there is a preferential amplification of the front of the pulse, and if the amplification is sufficiently large, the pulse will become shorter, despite the intramode dispersion and phase self-modulation. There is essentially a contraction of the pulse. If the energy in the pump wave is high enough, the intensity of the contracted Stokes signal pulse may exceed a certain threshold, and this pulse will be the pump for a Stokes component of higher order. As a result of this process of stimulated Raman scattering, a gap will form at the center of the signal pulse, and the length of the "fragments" will decrease. During the subsequent amplification, the fragment at the front will again be amplified to the critical level and split in two as a result of stimulated Raman scattering. The process will continue in this fashion until the Stokes signal pulse leaves the fiber.

4. Our experiments on the counterpropagating interaction of waves in a single-mode optical fiber have revealed the conversion of 150-ps pump pulses ($\lambda = 1.064$ μm) in a train of peaks less than 5 ps long at the frequency of the first Stokes component ($\lambda = 1.12\ \mu$m). The length of the amplified Stokes pulses is relatively insensitive to the length of the initial signal pump pulse.

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[1]N. Blombergen, Usp. Fiz. Nauk **97**, 307 (1969).
[2]Lin Chinlon and R. H. Stolen, Appl. Phys. Lett. **29**, 428 (1976).
[3]M. Nakazawa, M. Tokuda, Y. Negishi, and N. Uchida, J. Opt. Soc. Am. **B1**, 80 (1984).
[4]M. Nakazawa, T. Nakashima, and S. Seikai, J. Opt. Soc. Am. **B2**, 515 (1985).
[5]V. I. Lozovoĭ *et al.*, Kvant. Elektron. (Moscow) **7**, 2063 (1980) [Sov. J. Quantum Electron. **10**, 1200 (1980)].

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