Stimulated-Raman-effect amplification of femtosecond light pulses in counterpropagating and copropagating pump beams

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(Submitted 15 October 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **46**, No. 10, 383–385 (25 November 1987)

Experiments reveal a preservation of the frequency modulation of picosecond laser pulses during stimulated-Raman-effect amplification in counterpropagating and copropagating pump beams. This fact is used as a basis for proposing a new method for amplifying femtosecond pulses. Gain values up to 41 dB have been achieved for 400–500-fs pulses (up to an energy on the order of a microjoule) at a repetition frequency of 1–30 kHz.

A problem of current importance in applied physics is that of generating and amplifying femtosecond-range laser pulses tunable over a broad spectral interval. The methods which make use of the generation of ultrashort pulses in dye lasers and nonlinear effects in optical fibers are capable of producing pulses of femtosecond length in the visible and near-IR spectral regions. Nevertheless, amplifiers for such pulses are presently available only for the visible range (near $\lambda \sim 0.6\ \mu$m); the amplifying medium in this case is a dye.[1]

In this letter we report the observation of the preservation of a linear frequency modulation of picosecond laser pulses during stimulated-Raman-effect amplification in glass optical fibers. On the basis of this result, we suggest some new methods for amplifying femtosecond-range pulses by means of counterpropagating and copropagating stimulated-Raman-effect amplification. One advantage of such amplifiers is that they are not restricted to a particular wavelength of the light, as in (for example) dye amplifiers; with a suitable pump they can operate in both the visible and near-IR spectral regions, i.e., over the entire range of transparency of glass optical fibers. Furthermore, the light beam exiting a fiber amplifier is a single-mode beam.

Stimulated-Raman amplification in an optical fiber has been studied previously in the microsecond, nanosecond, and picosecond ranges,[2–5] but the width of the stimulated-Raman-amplification line in fibers made of fused quartz is sufficient for amplifying pulses $\leqslant 100$ fs long.

The basis problem in the stimulated-Raman amplification of intense laser pulses in an optical fiber is the occurrence of a stimulated-Raman effect because of the pulse being amplified. This effect results in a conversion of the energy of the pulse being amplified into the energy of higher-index Stokes components and therefore hinders the amplification.[5] In an effort to prevent this harmful effect, we suggest amplifying femtosecond pulses which have first been subjected to a dispersive temporal broadening of several orders of magnitude. This approach would make it possible to lower the intensity of the light in the fiber by several orders of magnitude, to suppress the stimulated

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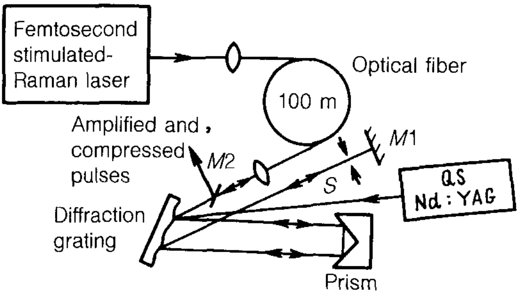

FIG. 1. Experimental layout for the counterpropagating stimulated-Raman amplification.

Raman effect, and to avoid other harmful nonlinear effects, e.g., self-focusing of the light and breakdown of the fiber. After amplification, the pulses are compressed to a femtosecond length in a dispersive delay line.

In the experiments which we are reporting here we used a synchronously pumped stimulated-Raman waveguide laser[6] as a source of femtosecond pulses of tunable wavelength. This laser produced a continuous train of pulses with a repetition frequency of 125 MHz, a length of 400–500 fs, and an energy ~1 nJ.

Figure 1 shows the layouts of the experiments on stimulated-Raman amplification in a counterpropagating pump beam. The laser beam is coupled into a single-mode fiber 100 m long, where the pulses are broadened in time to a length ~23 ps by virtue of the group-velocity dispersion of the fiber. The pump beam is coupled into the

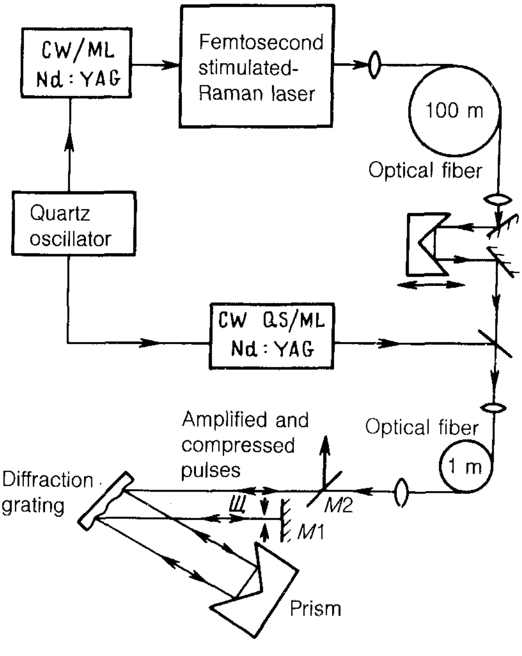

FIG. 2. Experimental layout for the copropagating stimulated-Raman amplification.

opposite end of the fiber after reflection from a diffraction grating (the pump beam is produced by a cw-pumped Nd:YAG laser with active Q switching, with $\lambda = 1.064$ μm, with a pulse length of 60–90 ns, and with a repetition frequency up to 30 kHz). The pump pulses have a temporal substructure instead of being smooth, in order to prevent the occurrence of stimulated Brillouin scattering in the fiber. The depths to which the pump beam penetrates into the fiber is determined by the occurrence of the copropagating stimulated Raman effect from the spontaneous noise; at a pump power of 1.2 kW, this penetration depth is 2 m. The stimulated-Raman amplification of the signal pulses occurs in this part of the fiber. At an energy of 1 nJ of the signal pulses, we achieve a gain by a factor ranging from 10 to 200 over the tuning interval from 1.09 to 1.12 μm. The fiber used in these experiments did not conserve the polarization. Our calculations show that the use of a polarization-conserving fiber would make it possible to raise the gain in the counterpropagating stimulated Raman effect to $\sim$3000. The amplified pulses are compressed in a dispersive delay line using a diffraction grating, a rectangular prism, and mirrors $M1$ and $M2$. For spectral selection, we use an adjustable slit S in the arrangement.[6,7] The length of the pulses compressed after amplification is 500–650 fs (Fig. 3a), providing evidence of a preservation of the frequency modulation of the pulses in the course of the stimulated Raman amplification.

Figure 2 shows the experimental layout for the copropagating stimulated-Raman amplification. The pump beam in this case is a beam from a cw-pumped Nd:YAG laser with active mode locking and Q switching. The repetition frequency of the Q-switching pulses ranges up to 1 kHz; the length of the mode-locking pulses is 50 ps;

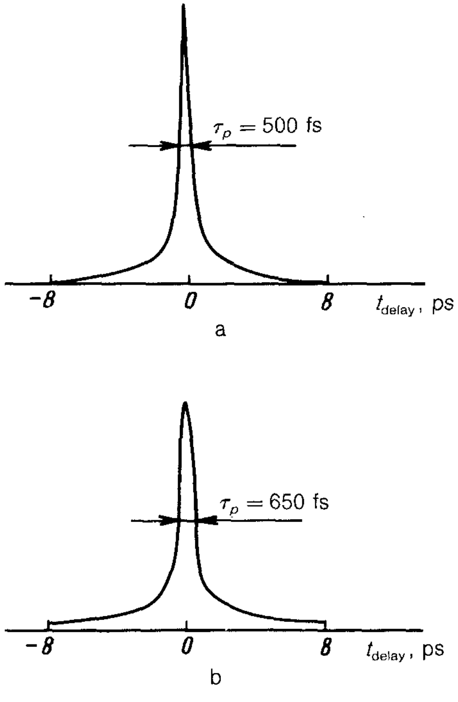

FIG. 3. Autocorrelation function of the compressed pulses. a—In the experiments on counterpropagating stimulated-Raman amplification; b—in the experiments on copropagating stimulated-Raman amplification.

and the peak power is 0.75 mW. The acoustooptic mode-locking devices of these lasers are supplied power from a common quartz oscillator in order to achieve a temporal synchronization of the pump and stimulated-Raman-laser pulses (Fig. 2). The pulses from the stimulated-Raman laser are subjected to a dispersive broadening to ≈ 23 ps in a first fiber 100 m long and then amplified in a second fiber 1 m long in the field of the pump beam. When pulses with an energy of 0.02 nJ are coupled into the fiber, we achieve a gain up to 1.5×10^4, i.e., up to an energy of 0.3 μJ. The power of the pump pulses in this case is 150 kW.

The amplified pulses are compressed to a length of 600–700 fs (Fig. 3b) in a dispersive delay line, in the same manner as in the experiment on the counterpropagating stimulated-Raman amplification.

A theoretical model for the methods proposed here for stimulated-Raman amplification of femtosecond light pulses and an analysis of the limiting capabilities of these methods will be published in separate papers.

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Translated by Dave Parsons