Modulational instability of the propagation of the light from synchronously pumped parametric light sources in single-mode optical fibers

N. N. Akhmediev, G. I. Onishchukov, S. D. Ryabko, M. F. Stel'makh, and A. A. Fomichev
Moscow Physicotechnical Institute

(Submitted 14 April 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 11, 562–564 (10 June 1988)

The experimental achievement of a stimulated modulational instability in the propagation of light in optical fibers through the use of a single pump source is reported. Pulse trains with a repetition frequency ~ 0.15 THz and a length $\lesssim 500$ fs have been produced.

The "modulational instability" in the propagation of light in single-mode optical fibers is an increase in the amplitude modulation of an optical signal to the point that distinct ultrashort pulses are formed, during the joint operation of a phase self-modulation and a slight negative group-velocity dispersion.[1] A distinction is made between the "spontaneous" modulational instability, in which the process is nucleated by a slight fluctuational modulation of the light coupled into the single-mode fiber,[2,3] and the "stimulated" effect, in which there is a preliminary modulation of the amplitude of the light in the fiber (in particular, as a result of an interference of signals from different sources)[4] The repetition frequency of the ultrashort pulses in the case of the spontaneous modulational instability depends on the peak power of the light coupled into the fiber. The stimulated effect, in contrast, is interesting in that it permits one to actively control the shape and period of the ultrashort pulses by varying the shape of the preliminary amplitude modulation of the light coupled into the fiber.[5]

The theoretical papers have dealt with the stimulated modulational instability for an idealized spectral shape of the exciting source (one or several narrow equidistant components).[5] The spectrum of real laser sources, however, is quite different from the ideal models which have been treated theoretically. Our purpose in the present study was to determine whether it is possible to observe the stimulated modulational instability in a single-mode optical fiber through the use of a single, tunable, wide-band light source (a parametric light source) and to determine how the finite width of the modulation components and the presence of a pedestal in the spectrum influence the characteristics of the output pulses.

Synchronous pumping of the parametric light source, using a $Ba_2NaNb_5O_{15}$ crystal, is carried out with the second harmonic of the beam from a cw-pumped Nd:YAG laser in Q-switched operation with active mode locking (double modulation regime).[6] The parametric light source generated a train ~ 80 ns long of ultrashort pulses ~ 60 ps long. We used a fiber ~ 300 m long with a zero group-velocity dispersion at the wavelength 1.32 μm; the cutoff wavelength was 1.15 μm. The group-velocity dispersion in the single-mode optical fiber at the wavelength 1.36 μm was -3.3 ps·nm/km. It was difficult to carry out experiments over a wide spectral range because of a strong absorption band of hydroxyl groups at $\lambda = 1.44$ μm and some weaker absorption bands at the wavelengths $\lambda = 1.265$ μm and $\lambda = 1.34$ μm. Accordingly, the modulational instability was observed in the relatively narrow wavelength interval 1.355–1.37 μm at a peak power ~ 1 W of the light coupled into the single-mode fiber.

The light spectra were measured with an MDR-23 monochromator and a HEROS optical multichannel analyzer, with an averaging over $\sim 10^2$ trains of ultrashort pulses. The lengths of the pulses emerging from the fiber were measured by an automatic autocorrelator with collinear second-harmonic generation. The automatic data acquisition system made it possible to take temporal samples of length $\lesssim 10$ ns, corresponding to a given phase of the train, from the correlator signal. This system also made it possible to select fluctuations in the length and energy of the ultrashort light pulses from the parametric light source that entered the fiber. The results of the measurements were recorded only if the deviations of these parameters from their average values remained within specified limits (5% or 10%).

A distinctive feature of the light from the intermediate-frequency parametric light source used in this experiment is the presence of several modulation components, which initiate the self-modulation process in the fiber. Figure 1 shows an envelope of the spectrum of the light entering the single-mode fiber. The most prominent maxima

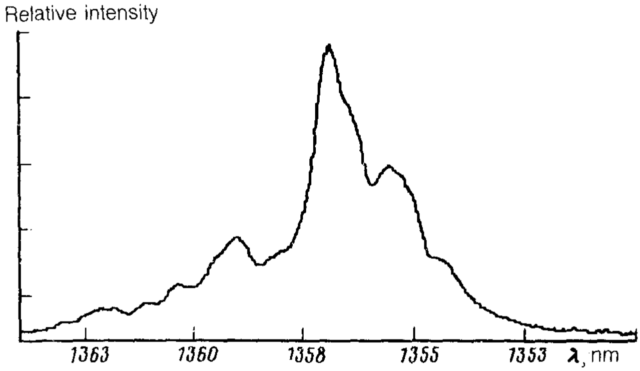

FIG. 1. Envelope of the spectrum of the light entering the single-mode optical fiber.

in the spectral modulation of the input signal are separated by ~2 nm; this figure corresponds to a period ~3 ps of the beats in the two frequencies taken separately. The presence of light from the parametric light source at the frequency equal to half the sum of these frequencies, on the other hand, leads to the formation of a train of pulses in the fiber which repeat at a period equal to twice the period of these beats.

Figures 2 and 3 show the correlation functions of the light leaving the fiber in the cases of permissible deviations of ± 5% and ± 10%, respectively, of the energy of the second harmonic of the parametric light source from the average value. In the former case we can clearly see a period ~6 ps in the correlation function (a repetition frequency ~0.15 THz). An increase in the scatter of the parameter values of the light in the fiber to ± 10% leads to an increase in the scatter in the pulse repetition period, which is expressed in the disappearance of the periodic modulation of the correlation function. The contrast of the correlation function is 2.8 at a zero delay and ~1.5 at delays exceeding the pulse length. The reason for these results is that the train of

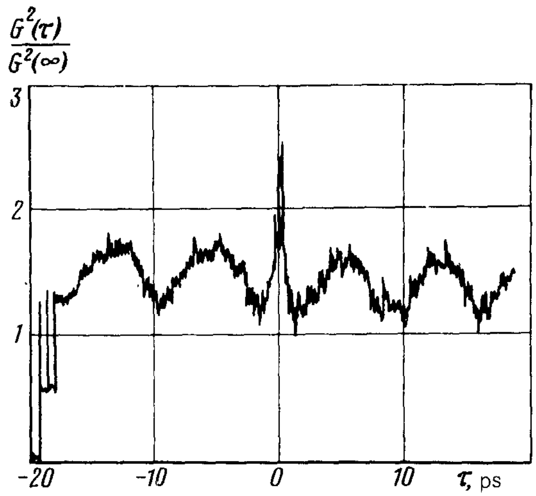

FIG. 2. Correlation function of the light leaving the fiber in the case in which ± 5% deviations are permitted in the energy of the second harmonic from the parametric light source.

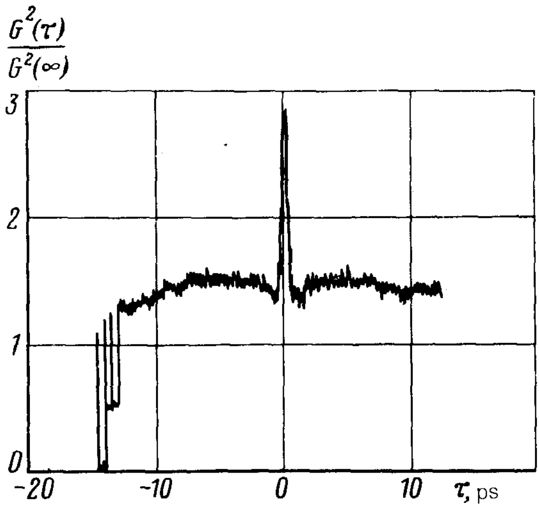

FIG. 3. Correlation function of the light leaving the fiber in the case in which ± 10% deviations are permitted in the energy of the second harmonic from the parametric light source.

pulses with a fluctuating repetition period is averaged. The lengths of the individual pulses are $\lesssim 500$ fs in either case. Following Ref. 5, we can show that the period (T) of the light pulses at the exit from the fiber is given by

$$T = \alpha \left(\frac{n_0 \mid D \mid \lambda^3 s}{2c^2 \mu_0 n_2 P} \right)^{1/2} ,$$

where α is a correction factor[3] $\sim 0\ 8$ for the self-modulation of the pulses of finite length, n_0 is the refractive index of quartz, D is the group-velocity dispersion, s is the cross-sectional area of the optical mode in the fiber, c is the velocity of light, μ_0 is the permeability of free space, n_2 is the nonlinear refractive index of quartz, and P is the peak power of the light coupled into the fiber. For the parameter values corresponding to our experiments, the period $T = 6$ ps is realized at a peak optical power ~ 0.5 W, which corresponds in order of magnitude to the experimental data. The pronounced scatter in the period of the pulses leaving the fiber which we observed in these experiments is apparently a consequence of a competition among various modulation components in the output spectrum from the parametric light source. A slight modulation of the spectrum and an incomplete coherence of the pulse $(\Delta\nu \times \tau \sim 15)$ also make the period of the ultrashort pulses far more sensitive to fluctuations in the power from the pump source. Eliminating these effects in an arrangement using a parametric light source as a pump source will require a greater regularization of the modulation of the spectrum and the formation of this spectrum in the form of several equidistant narrow components.

The fact that the period of the pulses leaving the fiber is the same as that of the preliminary modulation due to the given shape of the spectrum, on the one hand, and the values $\gtrsim 10$ found for the "off-duty factor" of the output light, on the other, are evidence that a stimulated modulational instability with a preset modulation period occurred in these experiments (in the case of a spontaneous effect, the off-duty factor is usually smaller; cf. Refs. 2 and 3 with Ref. 4)

In summary, we have shown that it is possible to achieve a stimulated modulational instability through the use of a single wide-band light source, even with a shallow modulation of the spectrum.

[1]A. Hasegawa and W. F. Briman, IEEE J. Quantum Electron. **QE-16**, 694 (1980).
[2]M. J. Potasek, Opt. Lett. **12**, 921 (1987).
[3]K. Tai, A. Hasegawa, and A. Tomita, Phys. Rev. Lett. **56**, 135 (1986).
[4]K. Tai, J. E. Jewel, and A. Hasegawa, Appl. Phys. Lett. **49**, 236 (1986).
[5]N. M. Akhmediev, V. M. Eleonskiĭ, and N. E. Kulagin, Zh. Eksp. Teor. Fiz. **89**, 1542 (1985) [Sov. Phys. JETP **62**, 894 (1985)].
[6]A. A. Fomichev, Izv. Vyssh. Uchebn. Zaved., Fiz. **48**, 2325 (1984).

Translated by Dave Parsons