Propagation characteristics of high-power ultrashort light pulses in multimode optical fibers

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(Submitted 18 July 1981; resubmitted 24 August 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **34**, No. 7, 391–395 (5 October 1981)

Parametric nonstationary SRS and other nonlinear effects in fiber lightguides (FLG) have been investigated. A redistribution of the energy of picosecond light pulses among the modes of the FLG has been detected. The conditions for the soliton regime of propagation of the higher-order Stokes SRS components in the zone near the FLG axis are discussed.

PACS numbers: 42.80.Mv, 42.65.Cq

A nonlinear conversion of laser radiation is achieved in fiber light-guides (FLG) at an anomalously low light-flux power at the FLG input; this opens up the prospect of studying the nonlinear-conversion mechanism of high-power radiation in a broad range of energies of the exciting pulses. In our work we have investigated experimentally for the first time the nonlinear processes that develop in an FLG excited by ultrashort light pulses. The time-dependent characteristics of the light pulses were analyzed by means of an "Agat" electron-optical camera with a time resolution of 2–3 psec. The experimental apparatus has been described elsewhere.[1]

Figure 1 shows microphotograms of the time sweep of the pump pulses at the input of the multimode FLG ($\lambda = 532$ nm, $\Delta t_p = 35$ psec, and $P_p \sim 100$ kW) and at the output of the FLG for a diameter $d = 50$ μm of the quartz core and an FLG length $l = 5$ m and the time sweep of the ninth Stokes SRS component at an Si-O bond vibration of ~460 cm^{-1} of the core material of the FLG for $l = 100$ m. It can be seen

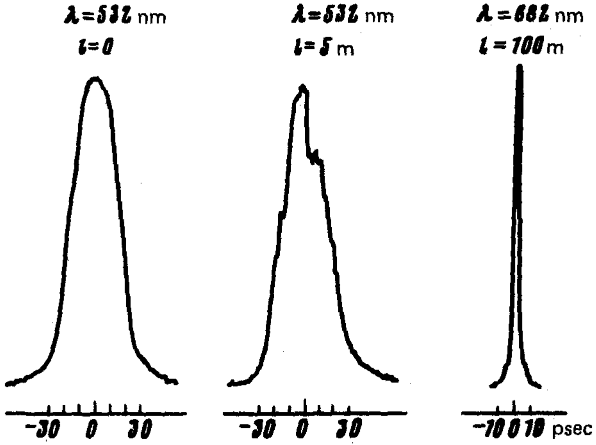

FIG. 1. Microphotograms of pump pulses at the input ($l = 0$) and output ($l = 5$ m) of FLG and of the ninth Stokes SRS component ($l = 100$ m).

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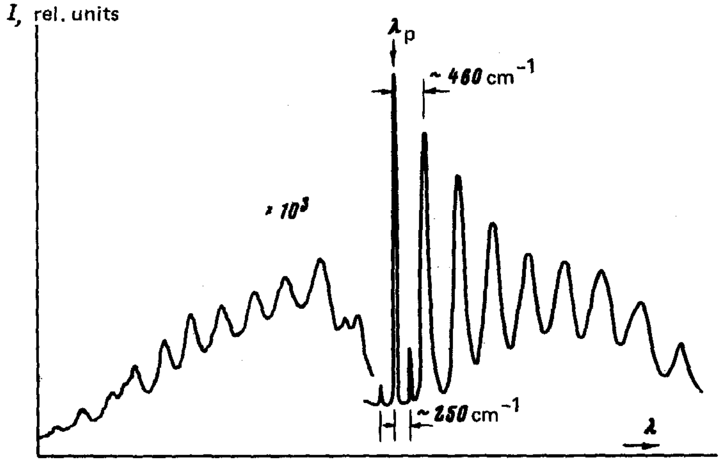

FIG. 2. Microphotogram of the converted-radiation spectrum in FLG.

that the duration Δt_{9S} of the Stokes-component pulse is reduced considerably compared with the value of Δt_p, and the pump pulse acquires a distinct structure, which is determined primarily by the quantities l and P_p, after passage through the FLG. For $l \geqslant 20$ m the pump pulse is spread out into wide, structured bands with $\Delta t_p = 0.7$–1 nsec, whereas the values of Δt_S are nearly constant as l varies from 5 to 100 m. We note that the total number of Stokes SRS components in the FLG was 22–24 and was limited by the region of large linear losses in the quartz FLG near $\lambda \approx 1.3$ μm. The tendency of the Δt values of the Stokes SRS components to decrease as their number is increased can be seen from the example of 1–3 components for $l = 5$ m, whose Δt value amounts to 17 ± 3, 10 ± 3, and ~3 psec, respectively. The Δt values of the higher-order Stokes SRS components are restricted by the maximum time resolution of the "Agat" instrument. The Δt value of the first anti-Stokes SRS component at the same values of P_p and $l = 100$ m is equal to ~350 ± 50 psec.

The spectrum of the converted radiation is shown in Fig. 2. The intense light continuum in the 420 to 510 and 550 to 1000-nm regions is caused by the phase self-modulation (PSM) of the light waves, which was previously observed for nanosecond excitation in the visible region in an FLG only in the Stokes region.[2] The observed efficient conversion of the pump radiation into the light continuum and into a series of Stokes and anti-Stokes SRS components is attributable, in our opinion, to the high power of the radiation for nanosecond SRS conversion and to the realization of the conditions for parametric interaction of the light waves in the FLG.[1] The narrow lines in the Stokes and anti-Stokes regions at a distance of ~250 cm^{-1} from the pump line correspond to conversion of the pump radiation in the stimulated four-photon mixing process.[3]

Figure 3 shows photographs of the mode content of the pumping radiation and the higher-order Stokes SRS components in the FLG. It can be seen that the converted radiation propagates in the form of an HE_{1m} mode, whereas the pump radiation from the FLG output for large P_p has a complicated mode structure with a large

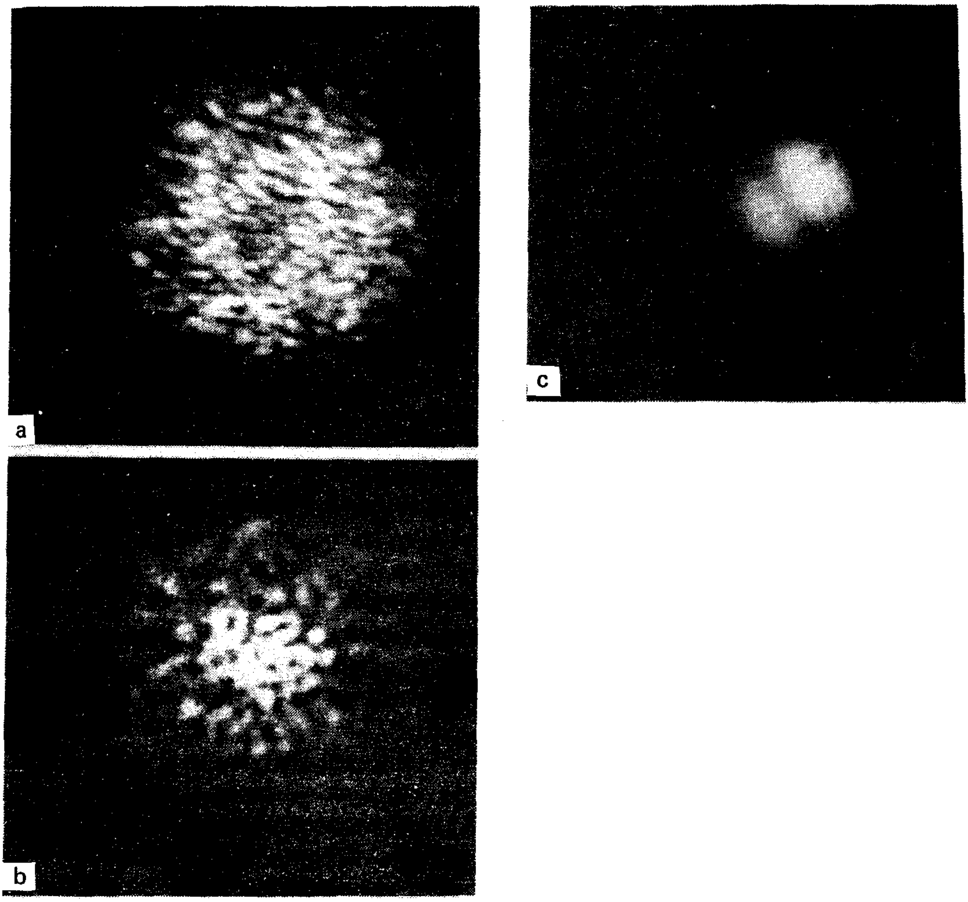

FIG. 3. Mode distribution of radiation from the FLG output. a–Pumping without nonlinear conversion ($P_p \sim 1$ kW), b–pumping under radiation self-focusing conditions ($P_p \sim 100$ kW), c–ninth Stokes SRS component ($P_p \sim 100$ kW).

energy concentration in the modes near the axis.

We assume that the conversion of the pump radiation in a multimode FLG into SRS components occurs under the conditions for the self-focusing of this radiation in the lower FLG modes near the axis (Fig. 3b). Such a concentration of energy in the modes near the axis is responsible for the subsequent quasi-single-mode propagation of the converted radiation. The quasi-single-mode propagation of light pulses in the given multimode FLG is also indicated by the generation of radiation in it during the stimulated four-photon mixing process, which is realized only in an FLG with about ten modes.[3] However, excitation of the anti-Stokes SRS components is possible if the conditions for spatial synchronism for the wave vectors of the interacting light waves are satisfied; as a result, the radiation of the anti-Stokes SRS components propagates outside the axial zone in many FLG modes, and the values of Δt for the anti-Stokes components (and for the pumping radiation in the higher modes) are determined by the modal and intermodal dispersion processes.

The results of a measurement of the Δt values of the higher Stokes SRS components in the FLG merit special attention. At a sufficiently large P_p value we observed the generation of more than ten Stokes components at $l = 5$ m. For a length $l = 100$ m and an analogous P_p value, the value of Δt for the quasiunimodal light-pulse propagation is determined by the dispersion of the FLG material (~50 psec in our case); however, the results of the measurement of the Δt values of the higher Stokes components give the values $\leqslant 15$ psec. In our opinion, the dispersive spreading of the pulses of the Stokes SRS components is compensated for in the axial zone of this FLG because of the introduction of a nonlinear correction in the refractive index and because of the appearance of a stable wave packet—a soliton. In the visible region of the spectrum (for positive dispersion of the FLG), according to the data of a theoretical analysis,[4] the soliton regime for passage of the light pulse is realized in an FLG with a radially inhomogeneous refractive index of the core, which, according to Ref. 4, is determined by the FLG fabrication technique; however, in our case it is determined by the nonlinear-conversion conditions of the pump pulse in the multimode FLG. In addition, we do not rule out the possibility of coherent fluctuations of the populations of the interacting levels[5] of the higher SRS components in the FLG; this can be established by analyzing the time parameters of the higher anti-Stokes components during their collinear propagation together with the waves of the corresponding Stokes SRS components. The formation of a soliton in a single-mode FLG for light pulses in the negative-dispersion region of the FLG ($\lambda \geqslant 1.35$ μm) has been recently demonstrated in Ref. 6.

In summary, the self-action of high-intensity laser radiation in a multimode FLG changes its propagation conditions, for which a self-compression of the ultrashort light pulses is possible at the frequencies of the Stokes SRS components. Detailed experiments using recording devices with a subpicosecond time resolution will make it possible to determine the characteristics of nonstationary SRS conversion of laser radiation in multimode FLG and to evaluate the prospects for transmitting information along the SRS components in FLG designed for fiber-optic communication lines.[7]

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Translated by Eugene R. Heath
Edited by S. J. Amoretty