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Observation of self-focusing in optical fibers with picosecond pulses

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Self-focusing was observed at Raman frequencies, using picosecond pulses propagating in a large-core optical fiber of 100-μm diameter. For intense input pulses, a continuum of Stokes frequencies was generated in a small ring-waveguide structure. The ring diameter of 11 μm was about 10 times smaller than the beam diameter at low intensities. The ring structure was attributed to an induced-gradient-index profile arising from the nonlinear index of refraction.

Over the years, self-focusing of intense laser beams has been observed in many liquids and solids because of a radial change in the refractive index, namely, $n(\mathbf{r}) = n_0 + n_2E^2(\mathbf{r})$. Moving-foci and trap-waveguide models have been developed to explain the features of self-focusing in condensed media.[1] Self-focusing was first observed in liquids by Garmire *et al.*[2] in 1966 and in bulk glasses, using picosecond pulses, by Alfano and Shapiro[3] in 1970. In optical fibers, self-focusing could modify the waveguide structure and significantly change the propagation characteristics of intense pulses. Manifestations of self-focusing in optical fibers may have been previously observed,[4] but these have never been identified, to our knowledge. This Letter reports on the first experimental evidence for self-focusing of picosecond pulses propagating in an optical fiber. Self-focusing appears primarily at the Raman frequencies for which the effect of the nonlinear refractive index is enhanced by cross-phase modulation.

The experimental setup is shown in Fig. 1. A Quantel frequency-doubled mode-locked Nd:YAG laser produced 25-psec pulses at 532 nm. The laser beam was coupled into the optical fiber with a 10× microscope lens. A stable modal distribution was obtained with a Newport FM-1 mode scrambler. Images of the intensity distributions at the output face were magnified by 350× and recorded on photographic film. Average powers coupled into the fiber were measured with a power meter at the optical-fiber output. Narrow-band (NB) filters were used to select frequencies of the output pulses. The optical fiber was a commercial multimode step-index fiber (Newport F-MLD). Its core diameter was 100 μm, its numerical aperture 0.3, and its length 7.5 m.

Several magnified images of the intensity distributions that were observed at the output face of the fiber for different input pulse energies are shown in Fig. 2. The intensity distribution obtained for low pulse energies ($E < 1$ nJ) is shown in Fig. 2(a). It consists of a disk profile with a speckle pattern. The intensity distribution of the disk covers the entire fiber-core area. The disk diameter, measured by comparison with images of calibrated slits, is 100 μm, which corresponds to the core diameter. The characteristics of this fiber allow for the excitation of about 200,000 modes. The mode scrambler distributed the input energy to most of the different modes. The speckle pattern is due to the interference of these modes on the output face. Figure 2(b) shows the intensity distribution in the core for intense pulses ($E > 10$ nJ). At the center of the 100-μm-diameter disk image, there is an intense smaller (11-μm) ring of a Stokes-shifted frequency continuum of light. About 50% of the input energy propagated in this small-ring pattern. The corresponding intensities and nonlinear refractive indices are in the gigawattts per square centimeter and 10^{-6} ranges, respectively. For such intensities, there is a combined effect of stimulated Raman scattering (SRS), self-phase modulation (SPM), and cross-phase modulation (XPM) that generates the observed frequency continuum.[5] In Fig. 2(c), a NB filter selected the output light pattern at 550 nm. This clearly shows the ring distribution of the Stokes-shifted wavelengths. We observed such a ring distribution for a continuum of Stokes-shifted wavelengths up to 620 nm for the highest input energy before damage.

The small-ring intensity profile is a signature of self-focusing at the Raman wavelengths. First, the small ring is speckleless, which is characteristic of single-mode propagation. This single-mode propagation means that the guiding properties of the fiber are dramatically changed by the incoming pulses. Sec-

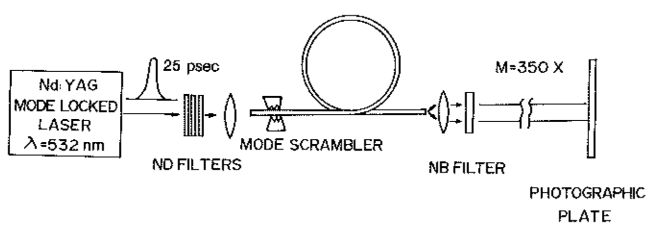

Fig. 1. Experimental setup.

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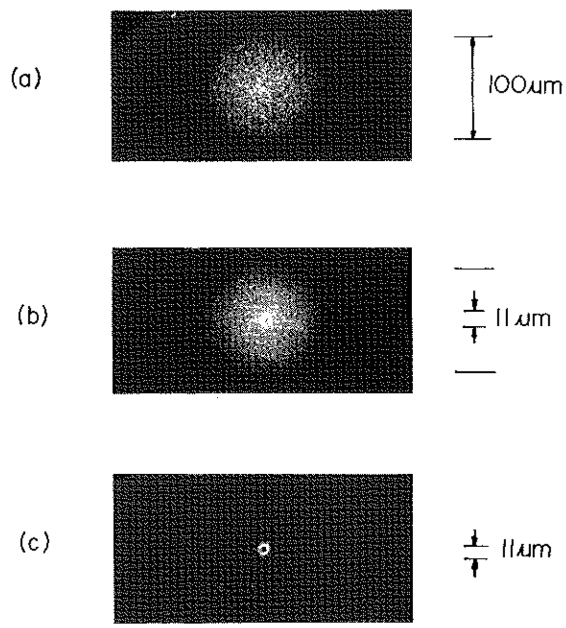

Fig. 2. Images of the intensity distributions at the optical-fiber output: (a) input pulses of low energies ($E < 1$ nJ), (b) input pulses of high energies ($E > 10$ nJ), (c) same as (b) with an additional NB filter centered at 550 nm. ($M = 350\times$).

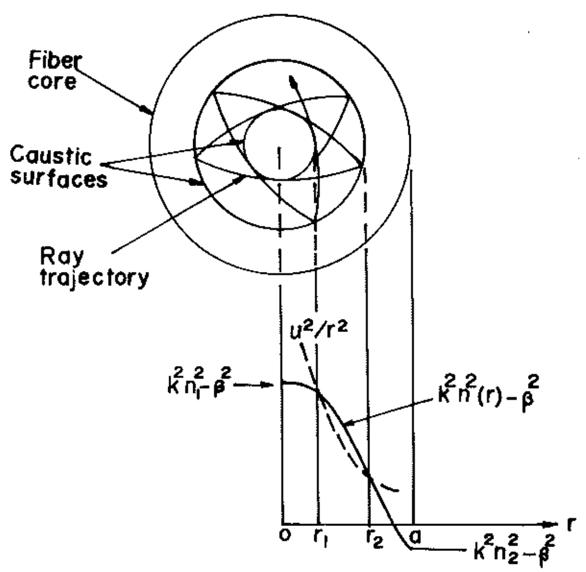

Fig. 3. Cross-sectional projection of a skew ray in a gradient-index fiber and the graphical representation of its mode solution from the WBK method.[10] The field is oscillatory between the turning points r_1 and r_2 and is evanescent outside this region.

ond, SRS, SPM, and XPM occur only in the ring structure, i.e., where the maximum of input energy has been concentrated. Our experimental results may be explained by an induced-gradient-index model for self-focusing. For high input energies, the Gaussian beam induces a radial change of the refractive index in the optical-fiber core. The step-index fiber becomes a gradient-index fiber, which modifies its light-guiding properties. There is further enhancement of the nonlinear refractive index at Raman frequencies because of XPM.[6,7] Thus Stokes-shifted light propagates in a well-marked induced-gradient-index fiber. The ray-propagation characteristics of a gradient-index fiber[8–10] are shown schematically in Fig. 3. The cross-sectional view of a skew-ray trajectory in a graded-index fiber is shown. For a given mode u, there are two values for the radii, r_1 and r_2, between which the mode is guided. The path followed by the corresponding ray lies completely within the boundaries of two coaxial cylindrical surfaces that form a well-defined ring. These surfaces are known as the caustic surfaces. They have inner and outer radii, r_1 and r_2, respectively. Hence Fig. 3 shows that skew rays propagate in a ring structure that is comparable with the one shown in Fig. 2(c). This seems to support the induced-gradient-index model for self-focusing in optical fibers.

In summary, we have observed self-focusing of Raman picosecond pulses in optical fibers. Experimental results may be explained by an induced-gradient-index model of self-focusing. A detailed theoretical model for self-focusing in optical fibers needs to be developed. An immediate application of our observation could be single-mode propagation of high-bit-rate optical signals in large-core optical fibers.

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