Optical limiting properties of nonlinear multimode waveguides

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Description
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Comments
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Optical limiting properties of nonlinear multimode waveguides

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An experimental investigation of the transmission of multimode capillary waveguides with a nonlinear absorber in the core shows an enhanced nonlinear absorption relative to the same length of bulk material. The results are consistent with partial mode filling within the cores of the waveguides. This study confirms the promising optical limiting capabilities of multimode nonlinear waveguides and implies that the mode structure should be considered in the design and evaluation of capillary array optical limiters.

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Nonlinear waveguides and arrays of such waveguides prove useful for both the study of fundamental physical phenomena and practical applications.1–4 Studies of nonlinear transmission in waveguides, mainly by Khoo et al.3–7 and He et al.8,9 have shown that capillary waveguide arrays filled with nonlinear materials have promise as optimal limiters. Useful nonlinear transmission properties with threshold energies as low as 0.1 µJ have been reported.4 In the previous studies a radially uniform light intensity distribution across the fiber that varied only with the distance along the fiber was usually assumed. There has been little investigation of the influence of the multimode nature of such waveguides on the nonlinear transmission properties.

In this Letter we present an experimental investigation of the energy-dependent transmission of a series of capillary waveguides filled with bis[tri-(n-hexyl)siloxy]silicon-naphthalocyanine (SiNc) solutions. SiNc is a well-known nonlinear absorber at 532 nm.10–12 The capillaries used in this study were 1.8 cm in length and consisted of fused silica (n = 1.462) filled with a 3.25 × 10⁻⁴ M solution of SiNc in dioctyl phthalate (n = 1.485). Core diameters ranged from 3.2 to 200 µm. When filled, the capillaries acted as highly multimode nonlinear waveguides. The transmission characteristics of these waveguides were measured as a function of incident energy by use of frequency-doubled Nd:YAG lasers. The lasers produced pulses at 532 nm that had an approximately Gaussian spatial and temporal intensity distribution. They were coupled into the capillary waveguides with a 10× microscope objective, and only the light that was confined to the core was collected with a second objective. Typical coupling efficiencies into the capillaries were 80% or more. The samples had a linear transmission of 45%.

Figure 1 shows the experimental relative transmission (open circles) as a function of input pulse energy for a capillary with 10-µm inner diameter by use of 7-ns pulses. At the intensities used, the dominant nonlinearity in SiNc is excited-state absorption and the transmission is fluence dependent. The experimental data in Fig. 1 were compared with the transmission calculated by numerical integration of a five-level sequential-absorption rate equation model for SiNc.13 The singlet and triplet excited-state cross sections are σₜ = 37 × 10⁻¹⁸ cm² and σᵣ = 112 × 10⁻¹⁸ cm², respectively.10–12 The ground-state cross section is σ₀ = 2.3 × 10⁻¹⁸ cm².10,11 The first excited-state lifetime and the intersystem crossing time are τ₁₀ = 1.6 ns and τᵣᵣₚₚ = 5.6 ns, respectively. Higher excited states have short lifetimes and no appreciable population in these experiments.10,11 These values are known to accurately account for the nonlinear absorption in bulk SiNc solutions.10 The temporal and spatial pulse shapes were modeled as Gaussian, and the beam diameter was assumed to be constant over the length of the capillary.

The dashed curve in Fig. 1 is the relative transmission calculated (Trel = T/Tlinear) for a SiNc sample with an assumed beam diameter of 10 µm, the same as the capillary diameter. The observed transmission...
decreases substantially faster and at lower incident energies than that calculated. The origin of the enhanced nonlinear absorption was identified by imaging the output of the fiber core onto a CCD array. This is shown in the inset in Fig. 1 for an input energy of 1.2 \( \mu \text{J} \). The observed light intensity distribution does not uniformly fill the waveguide. It is apparently distributed among only some of the waveguide modes so that the effective area illuminated is smaller than the actual core area. Independent experiments show that the \( n_2 \) for dioctyl phthalate at 532 nm is small and negative, so it is unlikely that self-focusing is responsible for the localization. To estimate the fraction of the core that is effectively illuminated, we used the beam diameter as the lone fitting parameter in the model. The solid curve in Fig. 1 is the transmission calculated for an effective beam diameter of 2.6 \( \mu \text{m} \). Since the light is confined to an area smaller than the cross-sectional area of the waveguide, the effective beam intensity and thus the nonlinear absorption are enhanced. This model is an approximation that does not take into account the waveguide boundary conditions.

We studied a range of waveguides with different core diameters. The intensity distribution observed was not radially uniform in any capillary. Table 1 gives the experimental core diameter compared with the best-fit diameter for the nonlinear transmission observed. In all but a 200-\( \mu \text{m} \)-core-diameter capillary the effective area illuminated was smaller than the physical diameter of the core. In a 200-\( \mu \text{m} \) capillary, apparently enough modes are excited so that the core diameter is approximately the same as the effective beam diameter. In a 75-\( \mu \text{m} \) capillary the intensity distribution was irregular, and in the three smaller capillaries the intensity distribution observed at the exit of the capillary was peaked in the center.

The lowest thresholds for nonlinear transmission were observed for the smaller-diameter fibers. Figure 2 shows the experimental relative transmission (open circles) as a function of input pulse energy for a 3.2-\( \mu \text{m} \)-inner-diameter capillary with 5-ns pulses. The nonlinear absorption threshold, where \( T_{\text{rel}} = 0.5 \), was ~3 nJ, and a transmission of 5% or less was observed for input energies as low as 100 nJ. The solid curve in Fig. 2 is the calculated transmission for an effective beam diameter of 2 \( \mu \text{m} \). The inset in Fig. 2 shows the output energy distribution of the core for an input pulse energy of 60 nJ. Even in this small-diameter capillary, the light does not uniformly fill the waveguide but is confined to a subset of the available modes.

The excitation of a restricted set of modes is well known in linear waveguides.\textsuperscript{14–16} Several studies in linear waveguides show that, under so-called restricted launch conditions, only a set of low-order modes are excited and propagate along the length of the optical fiber. It is reasonable that this effect also plays a role in nonlinear multimode waveguides. The results include increased energy density and enhanced nonlinear response in the capillary waveguide.

We also recorded the beam profile at the exit of the capillary waveguides at different input energies.

<table>
<thead>
<tr>
<th>Actual Capillary Inner Diameter (( \mu \text{m} ))</th>
<th>Effective Beam Diameter (( \mu \text{m} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>75</td>
<td>28</td>
</tr>
<tr>
<td>10</td>
<td>2.6</td>
</tr>
<tr>
<td>6.3</td>
<td>2.6</td>
</tr>
<tr>
<td>3.2</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 2. Transmission of a 3.2-\( \mu \text{m} \)-inner-diameter SiNc-filled capillary by use of 5-ns pulses. The open circles are the experimental data points. The solid curve is a theoretical calculation assuming a constant beam diameter of 2 \( \mu \text{m} \). Inset, energy distribution within the waveguide core for an input energy of 60 nJ.

Fig. 3 shows the light intensity distribution at the exit face of the core of a 3.2-\( \mu \text{m} \)-diameter capillary filled with SiNc at several incident energies as high as 100 nJ. The intensity profile observed is strongly peaked near the center of the capillary.

Fig. 3. Energy distribution within the core of a 3.2-\( \mu \text{m} \)-inner-diameter SiNc-filled capillary for input pulse energies of (a) 400 pJ, (b) 4 nJ, (c) 60 nJ, and (d) 100 nJ.
with a near-Gaussian shape at all energies. The distribution of energy within the core varies little over the energy range observed even at energies where the transmission is less than 5% because of the nonlinear absorption. This is markedly different from bulk nonlinear absorbers. In a bulk sample a Gaussian input becomes a flattop output under conditions of strong nonlinear absorption, because the energy is preferentially absorbed from the center of the beam where the fluence has a maximum. In the capillary waveguide the beam profile remains constant and peaked in the center even with strong nonlinear absorption. It is likely that the waveguide boundary conditions contribute to this effect. However, a theoretical model for nonlinear absorption that includes the waveguide boundary conditions is not available to our knowledge.

The distribution of energy into the waveguide modes could be altered by off-axis coupling of the input pulses. However, off-axis coupling led to a decrease in the coupling efficiency into the waveguide. In linear multimode waveguides the intensity distribution within a waveguide is dependent on launch conditions. Similarly, in the nonlinear case we expect that the energy distribution in the waveguide modes, and consequently the nonlinear response, will depend on the launch conditions.

In summary, we reported the nonlinear transmission properties of highly multimode nonlinear waveguides consisting of silica capillaries filled with a solution of SiNc. An enhanced nonlinear response arises because the light does not uniformly fill the waveguide but appears to be distributed among the allowed modes so that the effective area illuminated is smaller than the actual core area. The smallest-diameter capillaries showed lower threshold for nonlinear transmission than had been previously reported. We observed that the intensity distribution within the nonlinear waveguide remains nearly Gaussian even under conditions of strong nonlinear absorption. We conclude that the influence of the mode structure of the nonlinear waveguides should be considered in the design, evaluation, and modeling of capillary array optical limiters.

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References