

# Optical properties of solid-core photonic crystal fibers filled with nonlinear absorbers

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**Abstract:** A theoretical and experimental investigation of the transmission of solid-core photonic crystal fibers (PCFs) filled with nonlinear absorbers shows a sharp change in the threshold for optical limiting and in leakage loss as the refractive index of the material in the holes approaches that of the glass matrix. Theoretical calculations of the mode profiles and leakage loss of the PCF are in agreement with experimental results and indicate that the change in limiting response is due to the interaction of the evanescent field of the guided mode with the nonlinear absorbers in the holes.

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## 1. Introduction

Silica capillary waveguides, waveguide arrays, and photonic crystal fibers (PCFs) filled with solutions of chromophores [1–6] or amorphous silicon [7–9] are of great interest due to their potential for use in optical limiting and switching applications. In particular, the longer effective path length and additional spatial beam confinement in waveguide geometries lead to an enhanced nonlinear response relative to bulk materials when the waveguides are filled with nonlinear absorbers. Recently, it has been shown that the evanescent field in the propagating mode of a fluid-filled PCF can be used as a novel means to detect linear absorption of materials in the fiber holes [10,11], and to achieve optical limiting [12]. In this paper we discuss our experimental and theoretical investigation of optical limiting and leakage losses in solid-core PCFs filled with nonlinear absorbers.

## 2. Theoretical calculations

Figure 1 shows a white light image of the PCFs under investigation. The PCFs were composed of a solid silica glass core surrounded by four layers of holes in triangular lattice. The holes were approximately 1.4  $\mu\text{m}$  in diameter and the pitch (center-center hole spacing) was approximately 3.2  $\mu\text{m}$ .

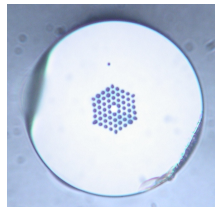


Fig. 1. Example of PCF used in this work.

Theoretical calculations of the mode profiles, mode energy distribution, and leakage loss were performed using the multipole method [13] and assuming an ideal PCF with similar dimensions to those described above. The calculations assumed that the holes of the PCF were filled with linear, non-absorptive solvents of various refractive indices. The results are consistent with those found by Agruzov *et al.* [14] for a PCF with somewhat different dimensions. Figure 2(a) shows the percentage of power carried by the portion of the optical mode that is propagating in the holes of the PCF (blue curve) as a function of the refractive index of the solvent in the holes. It is predicted that the power in the holes increases by almost an order of magnitude when the refractive index of the solvent increases from 1.440 to 1.455. This increase in solvent refractive index leads to a decrease in the refractive index contrast between the PCF core and the surrounding holes and is associated with an increase in the extension of the evanescent field into the holes. Figure 2(b) shows the calculated Poynting flux of the optical mode of the PCF as the refractive index of the solvent in the holes is increased. It is apparent that the distance the evanescent field extends outside the core

increases significantly as the refractive index of the solvent in the holes approaches that of the surrounding glass ( $n_{dsg} = 1.459$ ). It is expected that the effectiveness of a nonlinear absorber housed in the PCF holes will depend upon both the energy carried by and the extension of the evanescent field.

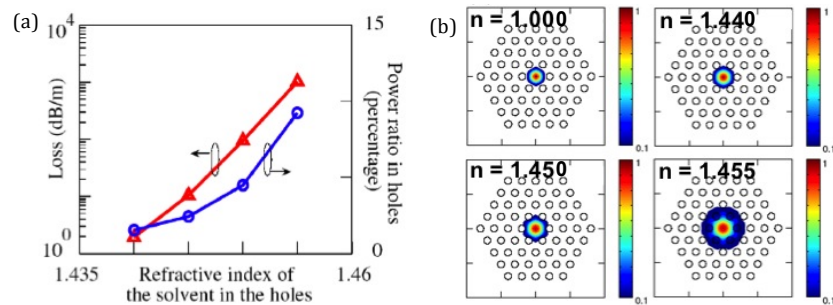


Fig. 2. (a) Leakage loss coefficient and power ratio in the holes vs. refractive index of the solvent in the holes for a PCF with the described geometry. (b) Optical mode profiles of a PCF filled with solvents having the refractive indices shown. The color contour plots represent the Poynting flux; red = large, blue = small flux. Figure 2(a) from Ref. 12.

The red curve in Fig. 2(a) shows calculations of the PCF leakage loss coefficient as a function of the refractive index of the solvent in the holes. It is predicted that the leakage loss coefficient will increase by nearly three orders of magnitude as the refractive index of the solvent in the holes increases from 1.440 to 1.455. Therefore, it is expected that there will be a significant decrease in the linear transmission of the PCF as the refractive index of the solvent in the holes approaches that of the glass matrix.

### 3. Experimental methods

In carrying out experiments, the PCFs were filled with solutions of bis[tri-(n-hexyl)siloxy] silicon naphthalocyanine (SiNC), a well known reverse-saturable absorber (RSA) [15–17]. SiNC was dissolved in mixtures of diethyl succinate (DES) ( $n_d = 1.420$ ) and dioctyl phthalate (DOP) ( $n_d = 1.485$ ) in order to tune the refractive index in the holes of the PCF. Waveguiding was achieved because the matrix of holes surrounding the solid core had an effective refractive index smaller than the solid core. The PCF samples were approximately 2.0 cm in length and the SiNC solutions had a concentration of approximately  $3.25 \times 10^{-4}$  mol/L.

Optical limiting of the samples was measured by use of a seeded, frequency-doubled Nd:YAG laser. The laser produced 4 ns pulses at 532 nm that had an approximately Gaussian spatial and temporal intensity distributions. The pulses were coupled into the solid core of the PCF using a combination of an iris and a  $4 \times$  microscope objective. The PCF output was imaged onto a sensor using a  $50 \times$  microscope objective. Theoretical calculations indicate that the optical mode of the PCF is well-confined to the solid-core and the first two surrounding rings of holes (see Fig. 2(b)), which is consistent with the experimentally observed mode profiles. Therefore, an iris was used to restrict the light incident on the sensor to that contained within the solid core and the first two rings of holes. Optical limiting of the SiNC-filled PCF samples was characterized by measuring the transmission of the samples as a function of incident energy. Transmission is defined as the ratio of the optical mode energy at the end of the PCF sample (before exiting the sample) to that at the beginning of the sample (just after coupling into the sample). Optical mode energies were determined by measuring the pulse energies upstream and downstream of the sample and then accounting for measured losses in the optical setup, the theoretically determined leakage loss (see Fig. 2(a)), and the calculated coupling efficiency.

#### 4. Results and analysis

Linear absorption spectra of SiNC in PCFs were measured in order to verify that there was an observable interaction between the evanescent field of the PCF optical mode and the SiNC solution. Measurements were done by coupling white light into the PCF samples and using a fiber spectrometer to characterize the PCF output. Figure 3(a) shows the linear absorption spectrum of a PCF sample filled with a  $n_d = 1.435$  solution of SiNC. The relative absorbance shown was found by normalizing the measured transmitted intensity of a PCF filled with SiNC solution with that of a PCF filled with a DOP/DES solution of the same refractive index. Figure 3(b) shows the spectrum of a  $1.6 \times 10^{-5}$  mol/L bulk solution (1 cm cell) of SiNC for comparison. The major features of the bulk SiNC solution spectrum are apparent in the PCF spectrum. This is consistent with absorption occurring via the evanescent field of the

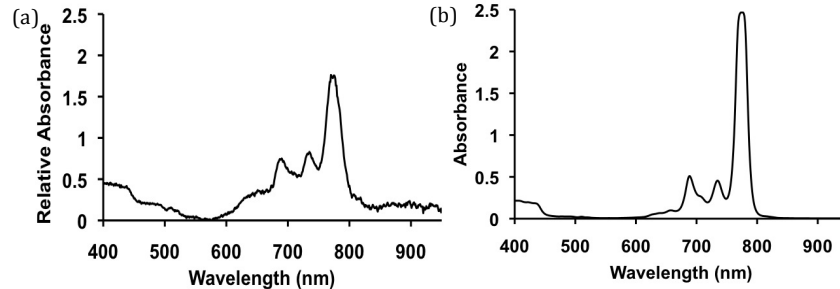


Fig. 3. (a) Linear absorption spectrum of white light traveling in a PCF sample filled with a  $n_d = 1.435$  solution of SiNC in DOP/DES. (b) Linear absorption spectrum of a  $1.6 \times 10^{-5}$  mol/L bulk sample (1 cm cell) of SiNC in DOP/DES.

PCF optical mode. The PCF spectrum is not an exact replica of the bulk solution spectrum. Differences can arise because of variations in coupling efficiency due to sample-to-sample variations in the cleaved ends of the PCFs and perhaps by differences in dispersion of the PCF glass and the solution in the holes. Note that the relatively large excited state absorption cross-sections of SiNC allow these solutions to exhibit significant RSA at 532 nm where they have a relatively low linear absorbance [15–17].

Figure 4 shows the measured transmission of the PCF as a function of energy coupled into the optical mode for four different values of the SiNC solution refractive index,  $n_d$ . Optical limiting is indicated by the decrease in transmission with increasing optical mode energy for each value of  $n_d$ . It is also apparent that the magnitude of the optical limiting depends on the refractive index contrast between the glass and the solution in the holes. No optical limiting was observed for pure DOP/DES samples. The variation in transmission with  $n_d$  at low optical mode energy is consistent with theoretical calculations of the leakage loss as described below.

In order to discuss the observed variation of the PCF transmission with refractive index contrast, it is convenient to define a limiting threshold. In this paper, the threshold is defined as the input energy required to cause a 20% decrease in transmission. The observed threshold was largest for a SiNC solution refractive index of  $n_d = 1.435$  (pink data) and decreased as the SiNC solution refractive index approached that of the silica glass ( $n_{dsg} = 1.459$ ). The threshold was approximately 1000 nJ and 150 nJ for SiNC solution refractive indices of  $n_d = 1.445$  (blue data) and  $n_d = 1.450$  (green data), respectively. The observed transmission in Fig. 4 is consistent with the theoretical mode profiles, mode energy distribution, and PCF leakage loss shown in Fig. 2. The decrease in limiting threshold with increasing SiNC solution refractive index is expected from the increase in extension of the Poynting flux into the holes. As a greater fraction of the optical mode energy extends into the holes, there is a stronger interaction with the SiNC nonlinear absorber. In the case of a SiNC solution refractive index of  $n_d = 1.455$  (red data), the PCF core/hole refractive index contrast is small enough that the dominant effect is a large leakage loss as predicted in Fig. 2(b). The expanded scale in Fig.

4(b) shows that the maximum transmission observed was on the order of 1% and that the limiting threshold was less than 8.5 nJ.

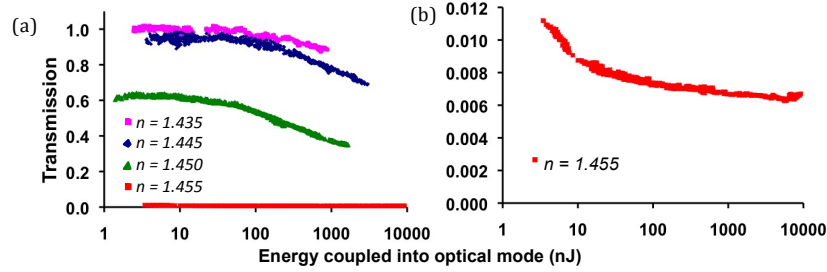


Fig. 4. (a) Transmission of PCF filled with solutions of SiNC in DOP/DES mixtures with refractive indices shown. (b) Expanded scale for the  $n = 1.455$  case from (a).

The theoretical leakage loss in Fig. 2(a) is related to the energies entering and exiting a PCF sample and is given by [18]:

$$\frac{E_B}{E_A} = kC10^{-\alpha L/10}. \quad (1)$$

$E_A$  and  $E_B$  are the energies measured by the detectors upstream (A) and downstream (B) from the sample,  $k$  is a measured constant that accounts for the losses in the optics between the sample and the detectors,  $C$  is the coupling efficiency for the sample,  $L$  is the length of the sample, and  $\alpha$  is the leakage loss coefficient in dB/m. A cutback method for measuring  $C$  and  $\alpha$  independently could not be used on the fluid-filled PCFs in our sample geometry. Rather, a substitution method was employed using several 1.5 cm, 2 cm, and 4 cm long PCF samples filled with various pure DOP/DES mixtures. At low energy, the transmission of the PCFs filled with SiNC/DOP/DES solutions, shown in Fig. 4, was within experimental uncertainty of those filled with pure solvent. This is expected since the linear absorption coefficient of SiNC is small at this wavelength.  $E_A$  and  $E_B$  were measured for each sample and used to determine the average and standard deviation of the energy ratio for each length. The average energy ratios for solvent refractive indices of 1.435 and 1.440 were consistent with measurements done on capillary waveguides having essentially zero leakage loss. Therefore, the ratios at these refractive indices were used as a baseline for zero leakage loss in the PCFs. This allowed the average coupling efficiency for the samples with these refractive indices to be calculated resulting in  $C = 0.47 \pm 0.06$ .

As a first approximation, it was assumed that the samples filled with all other DOP/DES mixtures had this same value for  $C$  on average. Under this assumption, Fig. 5 compares the experimental leakage loss coefficient (blue circles) to the theoretical values (red triangles).

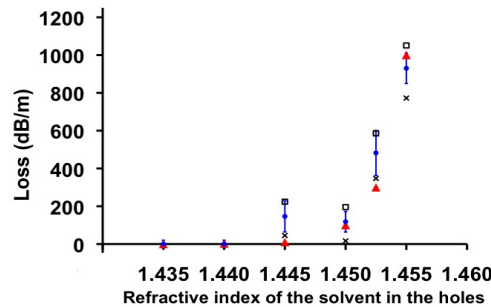


Fig. 5. Experimental (blue circles) and theoretical (red triangles) leakage loss coefficient vs. refractive index of the solvent in the holes. The blue circles assume an average coupling coefficient of 0.47. The crosses and squares are the experimental values assuming an average coupling efficiency of 0.25 and 0.75, respectively.

The error bars are best estimates primarily from the sample-to-sample variations in coupling efficiency. In order to get an idea of the uncertainty in the average experimental leakage loss coefficient due to uncertainties in average coupling efficiency we changed the assumed average coupling efficiency from 0.47 (blue circles) to 0.25 (crosses) and 0.75 (squares). These coupling efficiencies correspond to a typical range observed in capillary waveguides. It is apparent that the average experimental leakage loss coefficient is sensitive to uncertainties in average coupling efficiency, but in all cases the trend in the experimental data follows the same general trend seen in the theoretical values.

## 5. Conclusions

A theoretical and experimental examination of the transmission of a solid-core PCF filled with solutions of SiNC in DOP/DES solvents shows that the nonlinear absorption and hence the optical limiting threshold depends on the refractive index contrast between the core and the material in the holes. Experimentally, we observed a sharp decrease in the optical limiting threshold as the refractive index of SiNC solutions in the holes of silica glass ( $n_{dsg} = 1.459$ ) PCFs were varied from 1.435 to 1.455. Theoretically, multipole method calculations of the optical mode profiles of a solvent-filled, silica PCF showed that this same increase in the solvent refractive index (decrease in the refractive index contrast) is associated with an increase in the extension of the evanescent field into the PCF holes resulting in nearly an order of magnitude increase in the energy carried by the evanescent field. It is reasonable to conclude that the experimental decrease in observed limiting threshold with refractive index contrast is due to the greater interaction of the optical mode with the SiNC solution via the evanescent field.

As the core/hole refractive index contrast approaches zero, the leakage losses increase until the PCFs no longer act as waveguides. Experimentally, the linear transmission was near 50% for a refractive index contrast of about 0.01 and dropped to near 1% when the refractive index contrast was less than about 0.004. This was consistent with theoretical calculations that predicted an exponential increase of the leakage loss coefficient with a decrease in refractive index contrast.

This work shows that a substantial improvement in the optical limiting threshold in a solid-core PCF waveguide can be achieved by optimizing the refractive index contrast between the core and a nonlinear material in the holes. For the PCF hole configuration studied here, the optimum contrast is on the order of 0.015. Further reduction in contrast leads to a rapid drop-off in the linear transmission of the PCF because of the rapidly increasing leakage loss. However, it is possible that modification of the PCF geometry could reduce the leakage loss while maintaining a low limiting threshold.

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