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Description
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Optical limiting properties of nonlinear multimode waveguide arrays

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Abstract: An experimental investigation of the transmission of multimode capillary waveguide arrays containing a liquid nonlinear absorber shows an enhanced nonlinear response relative to that found in a single waveguide and to the same length of bulk material. Comparison of the nonlinear response of arrays with different pitch to diameter (d/Λ) ratios confirm that both the intensity distribution within an individual waveguide and coupling between the elements of the array influence the overall nonlinear response.

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Waveguide arrays offer ways to control the flow of light that cannot be achieved in the bulk. They have proven to be important in areas ranging from the study of discrete physical systems [1-4] to practical applications such as optical networks [5] and imaging systems [6]. Much of the work on nonlinear waveguide arrays has involved waveguides with refractive nonlinearities. Arrays with nonlinear absorption are also of interest for certain applications because they can provide a longer effective path and enhanced response relative to bulk materials. For example, Khoo and his coworkers [7,8] showed that capillary arrays filled with nonlinear absorbers show promise for combining optical limiting and switching applications with an imaging function. Khoo, Diaz, and Ding [7] analyzed the intensity dependent transmission of capillary arrays filled with nonlinear absorbing materials. In this study, the arrays had an opaque cladding that eliminated any coupling between the array elements. The arrays were therefore sets of independent waveguides. Further, in modeling the response of the waveguides, a uniform radial intensity distribution within each waveguide was assumed.

We recently studied the energy dependent transmission properties of single liquid-filled, multimode, nonlinear capillary waveguides [9]. In order to accurately account for the observed transmission, it was necessary to include the effects of a non-uniform intensity distribution within the waveguides. Images of the light distribution at the exit face of the waveguides confirmed that the intensity profile was peaked near the center of the waveguides indicating only a subset of the waveguide modes are excited. This excitation of only a subset of the possible modes is expected from studies of linear multimode waveguides [10,11] where typically, the effective area illuminated is smaller than the actual waveguide core. In the nonlinear waveguides, this results in higher local fluences within the waveguide and an enhanced nonlinear response. In this Letter the studies of nonlinear capillary waveguides are extended to consider the intensity dependent transmission properties of arrays of nonlinear multimode capillary waveguides.

The capillary arrays were fabricated using the standard stack and draw technique [12] in which capillaries drawn from silica GE214 tubing (n = 1.462 at 532nm) are hand stacked to form a close-packed array. Three arrays with different packing fractions and inter-capillary separations were fabricated for this study. The capillary diameter, d, the pitch, Λ, and the diameter to pitch ratio, d/Λ, for three capillary arrays studied are summarized in Table 1.

| Array | d (µm) | Λ (µm) | d/Λ |
|-------|--------|--------|-----|
| Array 1 | 24 | 24 | ~1.0 |
| Array 2 | 17 | 18 | 0.94 |
| Array 3 | 17 | 25 | 0.68 |

Nonlinear waveguide arrays were formed by filling 1.8cm long samples of the capillaries with a 0.325 mM solution of bis[tri-(n-hexyl)siloxy]silicon-naphthalocyanine (SiNc) solutions in diocyl phthalate (n_d = 1.485). SiNc is a well-known nonlinear absorber [13-15] with excited state parameters that are known well enough to accurately model the energy dependence of the nonlinear transmission of a solution sample at 532nm with no adjustable...
parameters [16]. Once filled, the capillaries acted as highly multimode nonlinear waveguides with linear transmissions of approximately 45% at 532 nm. White light images of the three filled arrays are shown in Fig. 1 where the different spatial fill factors and capillary separations are apparent.

The transmission of these waveguide arrays was measured as a function of incident energy using a seeded, frequency-doubled Nd:YAG laser. The laser produced 7ns pulses at 532nm that had an approximately Gaussian spatial and temporal intensity distribution. The pulses were coupled primarily into a single waveguide near the center of each array using a 10X microscope objective. A second microscope objective was used to image the output face of the array onto either an energy sensor or a CCD camera. An iris was used to select which waveguides in the array were imaged onto the sensor and camera. The measured coupling efficiencies into the entire array were typically 75%. The total transmission of the array was measured as a function of input energy. Coupling between the waveguides was observed even at low incident energies. For array 1, where there is very little separation between the individual waveguides, only ~15% of the energy coupled into the array appears at the output of the waveguide that was initially excited. The fraction at the output of the excited waveguide for array 2 was ~60% and for array 3 it was ~75%.

Figure 2 shows the relative transmission ($T_{rel} = T/T_{linear}$) for each array as a function of incident energy. In this graph, the total energy transmitted by the array is shown as a function of total energy coupled into the array. Array 3 exhibited the lowest onset of nonlinear transmission. This is reasonable since in this array a greater fraction of energy remains confined to the excited waveguide. Since the energy is confined to the smallest area it produces the greatest nonlinear response.

![Figure 2](image-url)

Fig. 2. Total transmission of the array as a function of incident energy for the nonlinear capillary arrays. Green– Array 1; Pink– Array 2; Blue– Array 3. Red line is a model of the transmission of a single capillary with approximately the same open area as the arrays.

The observed onset of nonlinear transmission in the different arrays varies with the fraction of energy that remains in the excited waveguide. In array 1, with the largest pitch to diameter ratio, more of the light is coupled into other waveguides reducing the nonlinear response. Figure 2 shows that array 2 provides nearly the same nonlinear response as array 3 even though the spatial fill factor is much larger ($d/\Lambda = 0.94$) than array 3 where $d/\Lambda = 0.68$. 

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Both have a significantly better nonlinear response than array 1 with a spatial fill factor close to unity (d/Λ = ~1.0).

In all cases the arrays demonstrate a substantially lower threshold for nonlinear response compared to what would be expected for a single capillary with an open area approximately equivalent to the capillary arrays (red line). This line is calculated from a model of the transmission of a single capillary with approximately the same size open area as the entire capillary array. The transmission was calculated by numerical integration of the five-level sequential absorption rate equation model for SiNc that can accurately fit the transmission as a function of incident energy in bulk SiNc solutions. The singlet and triplet excited-state cross-sections are \( \sigma_s = 37 \times 10^{-18} \text{cm}^2 \) and \( \sigma_t = 112 \times 10^{-18} \text{cm}^2 \) respectively [13-15]. The ground-state cross section is \( \sigma_0 = 2.3 \times 10^{-18} \text{cm}^2 \) [13,14]. The first excited-state lifetime and the intersystem crossing time are \( \tau_{10} = 1.6 \text{ns} \) and \( \tau_{isc} = 5.6 \text{ns} \). Higher excited states have short lifetimes and no appreciable population in these experiments. 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.

Figure 3 shows the relative transmission of the specific waveguide that was excited for each array. In each case the relative transmission is smaller than that in Fig. 2. In order to obtain an estimate of the fraction of the waveguide that is effectively illuminated in the array, we used the beam diameter as a fitting parameter in the model described above. The solid lines in Fig. 3 are the calculated transmission assuming an effective beam diameter of 14µm for array 1, 10µm for array 2, and 8µm for array 3. These effective beam diameters are significantly smaller than the measured waveguide diameters given in Table 1. This is consistent with our previous studies of single multimode capillary waveguides where we found that the light was confined to an area smaller than the cross sectional area of the waveguide leading to an enhancement of the effective beam intensity and the nonlinear absorption [9].
In order to investigate the possibility of nonlinear coupling between the waveguides in an array, the output energy of individual waveguides of array 2 were measured as a function of energy coupled into the array. The results are shown in Figs. 4(a) and 4(b). The set of blue data points are data for the excited waveguide while the green and red points are for an adjacent and a next nearest waveguide, respectively. The pink curve is the total transmitted energy for the entire array. At low incident energies, approximately 60% of the energy output from the entire array is found in the excited waveguide while approximately 3% and 1% of the energy output from the entire array are found in the adjacent and next nearest waveguide, respectively. The solid straight lines in Fig. 4(a) show the expected transmitted energy if the transmission and coupling were to remain constant at their low energy values.

Fig 4. (a). Output energy vs. input energy for Array 2. Pink – entire array; blue – excited waveguide; green – nearest neighbor waveguides; red– next nearest neighbor waveguides. Solid lines are calculated for linear transmission assuming constant coupling efficiency. (b). Images of the spatial distribution of the intensity at the output face of Array 2. The intensities in the nearest neighbor and next nearest neighbor waveguides are much lower than in the central, excited waveguide. The false color scales have been adjusted to show the distribution in each type.
In Fig. 4(a) the nonlinear response is largest within the central waveguide that is excited, undoubtedly because the fluence is largest here. The effective transmission of the other waveguides begins to decrease at approximately the same input energy. This is reasonable since nonlinear absorption in the central waveguide means there is less light to be coupled into the peripheral waveguides. As the input energy is increased further the effective transmission of the peripheral waveguides begins to increase. In the case of the next nearest neighbor waveguides, the effective transmission goes above that observed at low input energies. This is evidence for a nonlinear coupling between the waveguides at large input energies. This nonlinear coupling causes a larger fraction of energy to be coupled into the peripheral waveguides at large input energies. Further evidence of this can be inferred from the nonlinear transmission observed in the central waveguide at large input energies. The transmission of this waveguide asymptotically approaches a limiting value at large input energy. Nonlinear coupling provides a second mechanism that contributes to the reduction of intensity in this waveguide. The central waveguide behaves like an ideal optical limiter [17].

Images of the exit face of this capillary waveguide array at different input energies were recorded with a CCD camera. Figure 4(b) shows such an image for array 2. In this image, the intensity of the central, excited guide is much larger than that in the peripheral guides. To show the light distribution across a range of intensities, a different false color scale is used for each ring of waveguides. A symmetric beam is observed in the central waveguide with a beam diameter that is significantly smaller than the waveguide diameter. This is consistent with the results for single multimode waveguides. The observed beam diameter is qualitatively consistent with the calculations to account for the observed transmission in Fig. 3. In the waveguides accepting energy, the intensity is not uniform; it appears to be distributed randomly among a relatively few modes.

In summary we have measured the nonlinear transmission properties of three nonlinear multimode capillary waveguides arrays with different pitch to diameter ratios. In each of the arrays the nonlinear response is greater than that expected for a uniformly illuminated waveguide. Images of the output face show that for each waveguide in the array, the light is confined to an area smaller than the cross sectional area of the waveguide. Since the effective beam diameters are significantly smaller than the measured waveguide diameters, the effective beam intensity and the nonlinear absorption are enhanced in waveguide arrays just as they are in single waveguides.

We surveyed the effect of increasing the spatial fill factor of the arrays and altering the coupling between the elements by changing the pitch to diameter ratio of the individual waveguides. An array with \( d/\Lambda = 0.94 \) had a larger spatial fill factor but nearly the same nonlinear response as one with \( d/\Lambda = 0.68 \). Evidence for nonlinear coupling between the array elements was observed in the \( d/\Lambda = 0.94 \) array where the fraction of light in next nearest neighbor waveguides increased with increasing intensity. For the array with \( d/\Lambda = 1.0 \), the nonlinear response is reduced compared to the other arrays, presumably because the coupling is too large and the light is rapidly distributed among several waveguides.

We conclude that both the intensity distribution within a single waveguide and nonlinear coupling between the waveguides influence the observed nonlinear response. The influence of the mode structure and the coupling between the waveguides should be considered in the design, evaluation, and modeling of optical limiter arrays.

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