Tunable diffraction and self-defocusing in liquid-filled photonic crystal fibers

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Abstract: We suggest and demonstrate a novel platform for the study of tunable nonlinear light propagation in two-dimensional discrete systems, based on photonic crystal fibers filled with high index nonlinear liquids. Using the infiltrated cladding region of a photonic crystal fiber as a nonlinear waveguide array, we experimentally demonstrate highly tunable beam diffraction and thermal self-defocusing, and realize a compact all-optical power limiter based on a tunable nonlinear response.

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1. Introduction

Periodic and nonlinear systems are the subject of intense studies in optics as well as other branches of physics. The discreteness and bandgap effects that appear in photonic lattices such as coupled waveguide arrays introduce new and unique opportunities for manipulating the flow of light, and nonlinearity offers the additional prospect of active control in such structures [1]. While design options in planar material systems are inherently limited, two-dimensional structures offer a whole range of transverse geometries with different symmetries and unique properties [2, 3, 4, 5, 6, 7, 8, 9, 10, 11] which broaden the perspectives for the study of discrete and nonlinear behavior of light. So far only a few physical systems have proved suitable for experimental studies of wave propagation in nonlinear media exhibiting periodicity in two transverse dimensions. These include (i) photorefractive optically induced lattices [2, 3, 4, 5, 6, 7], offering tunable index contrast ($\sim 10^{-4}$) and strong photorefractive nonlinearity, but requiring a bulky setup subject to real-time conditions; (ii) fs-laser written waveguide arrays [8, 9]; and (iii) multicore optical fibers [11]. The latter two offer excellent stability and structural regularity, but rely on highly specialized fabrication techniques and material systems that require large laser powers for the access to nonlinearity, and offer no dynamic tunability.

To fully explore the rich physics and technological potential of periodic and nonlinear optical media, it is desirable to identify accessible experimental platforms that combine the advantages of high quality fabricated structures with the attractiveness of tunability and strong nonlinearity. Photonic crystal fibers [12] (PCFs) are prime examples of fabricated two-dimensional microstructures which have recently become widely available. Typical PCFs are made entirely of silica and feature a periodic arrangement of air holes that extend along the length of the fiber. Filling the hollow sections of PCF structures with liquids, by use of capillary forces or pressure, allows for combining specific light guiding properties with strong material interactions for e.g. optical sensing [13, 14, 15], tunable devices [16, 17, 18, 19, 20], and enhancement of nonlinear effects [21, 22, 23].

In this work we suggest to use liquid-filled PCFs for the study of discrete and nonlinear light propagation in extended two-dimensional periodic systems. Conventional PCFs feature a

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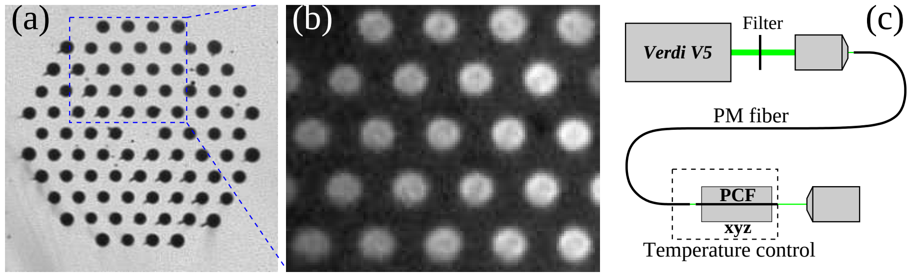

Fig. 1. Microscope images of (a) the photonic crystal fiber used in the experiment, and (b) section of fiber cladding after infiltration with a high index liquid. (c) Schematic of the experimental setup for coupling of light into the infiltrated PCF. PM – polarization maintaining fiber, *xyz* – 3D translation stage.

light guiding core defect surrounded by a periodic cladding structure, and as such do not represent fully periodic systems. However, the cladding structure itself, if sufficiently large, can be regarded as an extended periodic array that displays no structural defects [24]. We experimentally demonstrate strongly tunable beam diffraction in a triangular waveguide array created by infiltrating the cladding holes of a standard PCF with a high index nonlinear liquid, and employ the thermal nonlinearity of the liquid to achieve beam self-defocusing at higher light intensity. Based on the observed effects we devise a compact all-optical power limiter device with tunable characteristics.

2. Experimental setup

The experiment is performed in a 20 mm long piece of commercially available silica PCF (Crystal Fibre LMA-15). An optical microscope image showing the cross section of the fiber is depicted in Fig. 1(a). The cladding region consists of 84 air holes of diameter $d = 5\mu$m arranged around the fiber core in a triangular pattern with inter-hole distance (pitch) $\Lambda = 10\mu$m. By use of capillary forces the air holes are filled with castor oil, which has a refractive index ($n = 1.48$) slightly higher than that of silica ($n = 1.46$). This results in the creation of a two-dimensional array of high index waveguides [17, 18] as shown in Fig. 1(b). The PCF sample is placed inside a temperature controlled oven (HC Photonics TC038) which can be stabilized to $\pm 0.1^{\circ}$C over a wide temperature range, allowing for precise thermo-optic tuning of the infiltrated castor oil.

Light from a Verdi-V5 continuous-wave laser ($\lambda = 532$nm) is coupled into the central channel of the PCF waveguide array by use of a single-mode polarization maintaining (PM) fiber [Fig. 1(c)]. The mode field diameter of the PM fiber (Newport F-SPA) is 3.6μm which provides a good match to the fundamental mode of the infiltrated waveguides. A drop of castor oil is applied between the input fiber and the PCF in order to further enhance the butt-coupling efficiency. After propagation through the sample, the output beam is imaged by a microscope objective. A thin glass plate is placed in contact with the end of the PCF to ensure good imaging of the near field. Neutral density filters mounted between the laser and the PM fiber allow for controlling the beam power.

3. Tunable linear diffraction

At room temperature the refractive index step between the glass and the infiltrated castor oil is $2 \cdot 10^{-2}$, and the cladding waveguides forming the triangular array shown in Fig. 1(b) are strongly multi-mode (the V parameter is 7.2) and decoupled from each other. By exploiting the large thermo-optic coefficient of the castor oil (measured to be $-3 \cdot 10^{-4}$K^{-1}), it is possible to

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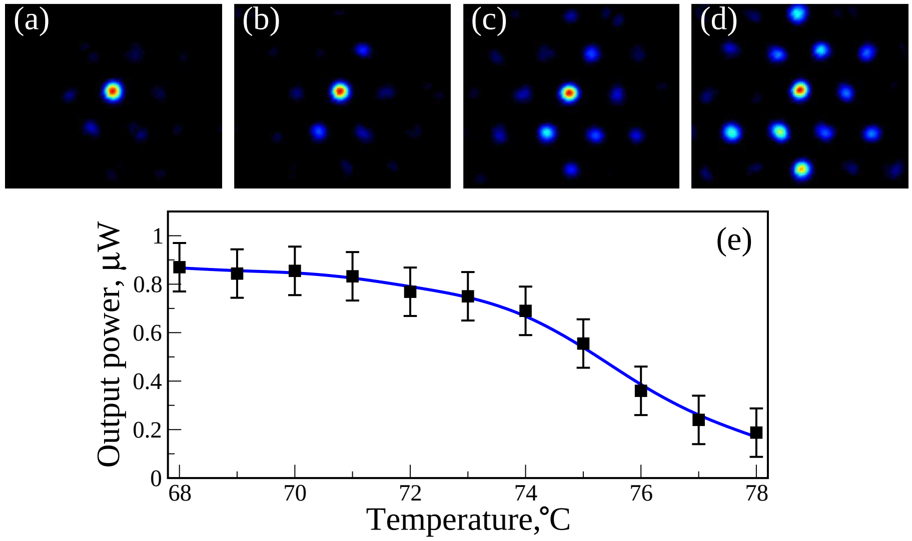

Fig. 2. (a-d) Linear output intensity distribution at temperature 72, 73, 74, and 75 °C, respectively. (e) Output power at the central lattice site measured as a function of temperature.

decrease the refractive index step to below $2\cdot10^{-3}$ by heating the fiber to above $\sim 70\,^\circ$C. In this regime, the waveguides become single-mode ($V < 2.4$), and the coupling between neighboring sites through evanescent mode field overlap is significantly increased. Light which is coupled into the central waveguide at the fiber input is thus enabled to tunnel into the surrounding lattice sites, leading to beam broadening in the form of *discrete diffraction* [1, 11]. The coupling length is numerically found to be $\sim 1\,$cm for an index step of $2.3\cdot10^{-3}$ corresponding to $V = 2.4$.

Figures 2(a-d) show the measured output intensity distribution for single site input excitation when the temperature is increased from 72 through 73, 74, and 75 °C, respectively. A considerable amount of light is seen to escape from the central site as the system is heated. The output pattern observed at 75 °C [Fig. 2(d)] features a central dominating peak while light in the neighboring waveguides form a lower intensity distribution resembling a hexagonal star. At higher temperatures the waveguide coupling is further increased, and as a result the strongly diffracting beam reaches the boundaries of the periodic structure [cf. Figs. 1(a) and 1(b)], and the triangular symmetry is broken. Apart from such boundary effects, small irregularities of the structure (due to nonuniform hole size and separation, or variations in the composition or infiltration of the waveguide liquid) are expected to significantly compromise symmetric diffraction and lead to disorder and randomness effects [10, 11]. Indeed, even for beams confined within the periodic structure, some degree of disorder and coupling asymmetry is always observed in the experiment. Typical output profiles [Fig. 2(a-d)], however, resemble the discrete diffraction pattern predicted by theory and observed previously in triangular lattices [7, 9, 11].

The tunable beam diffraction can be used for dynamically controlling optical attenuation [16], as illustrated in Fig. 2(e) which shows the measured output transmitted through the central waveguide as a function of fiber temperature. The measurement was done by imaging the output beam onto a spatial filter blocking all but the central part of the beam.

4. Nonlinear defocusing

Next we investigate how the thermal defocusing nonlinearity of castor oil affects beam propagation in the waveguide array. Because of the large and negative thermo-optic coefficient inherent

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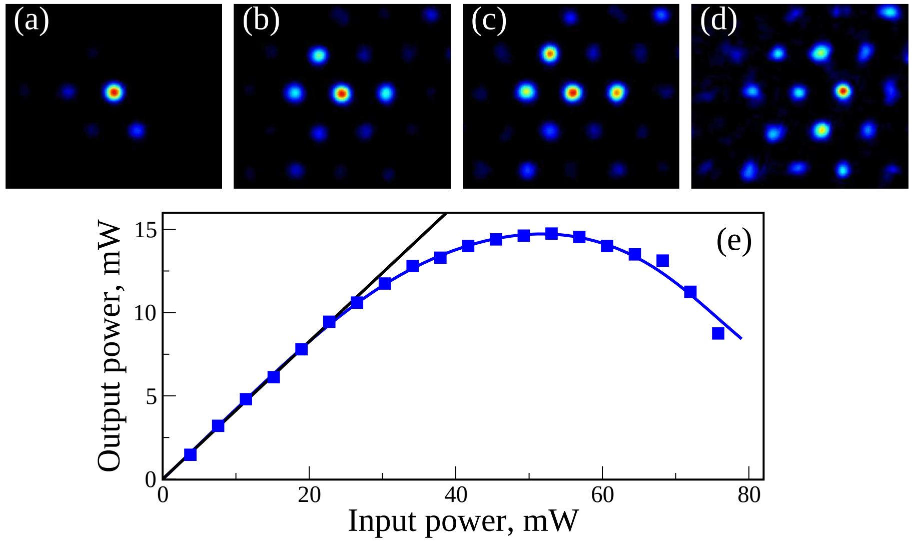

Fig. 3. (a-d) Output intensity distribution at 74 °C for increasing laser power; (a) corresponds to linear propagation. (e) Output power measured at the central lattice site versus input beam power for weakly absorbing sample.

to most liquids, heating produced by partial absorption of the propagating beam translates into a significant decrease of the refractive index at higher light intensity. Introducing absorbent dye into the liquid before infiltration allows for increasing the thermal nonlinear response [19].

Figures 3(a-d) show the measured output intensity distribution for increasing laser power, when the externally controlled temperature is fixed at a level corresponding to weak linear coupling, in this case 74 °C. Figure 3(a) corresponds to low power linear propagation. The thermal nonlinear response causes increased diffraction or *self-defocusing* of the probe beam, eventually spreading over most of the structure as the laser power is increased [Figs. 3(b-d)]. As a consequence, the output power in the central waveguide decreases relative to the input power, giving rise to a nonlinear power characteristic as shown in Fig. 3(e). Two regimes of propagation can be identified: at low laser power the dependence is linear to a very good approximation, but above 25 mW input power the nonlinear defocusing increasingly limits the optical throughput, and the output power eventually drops after reaching a maximum at about 52 mW input power.

We now demonstrate how this nonlinear power characteristic can be combined with the independent thermal control of the linear properties, discussed in the previous section, to achieve a tunable all-optical power limiter. Figure 4(a) shows the nonlinear power characteristic traced for a range of different temperatures with the top and bottom curves corresponding to 73 and 77 °C, respectively. We point out that beam self-defocusing is observed for all temperatures in the experiment, i.e. regardless of the strength of the linear coupling in the array. However, the linear slope of the characteristic curve at low input power is seen to drop for increasing temperature [Fig. 4(a)], in agreement with our characterisation of the linear properties [Fig. 2(e)]. Correspondingly, the maximum output power in the nonlinear regime also varies with temperature, and can be tuned externally as shown in Fig. 4(b).

We note that a photoinduced degradation of the oil leading to increased absorption and stronger nonlinearity was observed for long exposure at high laser power. This effect, however, was found to have no qualitative effect on our results. Any significant degradation was avoided in our measurements by limiting the high power exposure time.

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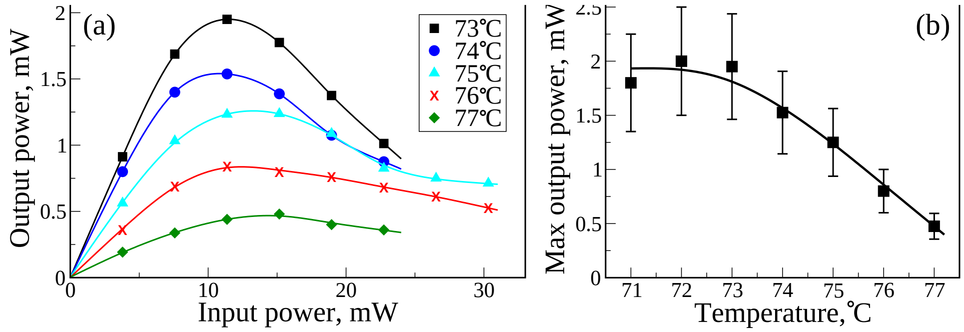

Fig. 4. (a) Output versus input power at the central lattice site measured at different temperatures for moderately absorbing sample. (b) Corresponding maximum output power as a function of temperature.

We also note that the strong defocusing observed in the experiment [Fig. 3] could indicate a high degree of nonlocality associated with the thermal nonlinear response. That is, heat produced in the input waveguide diffuses throughout the structure and may substantially increase the temperature and waveguide coupling in the entire array, rather than detuning only a single waveguide. This idea is supported by the fact that the defocusing behavior is observed for any input position in the array, regardless of boundary and disorder effects and the strength of the linear coupling. In disordered arrays a local nonlinear response, on the other hand, can lead to both beam localization and spreading, depending on input position [10]. We believe that a characterization of the temporal dynamics of the system could shed further light on the possible effect of nonlocality, as e.g. transitory beam self-localization in the form of a nonlinear defect mode (or discrete soliton) [1, 2] may happen on a short time scale before thermal equilibrium is reached.

5. Conclusions

We have demonstrated a novel liquid-filled PCF platform for the study of discrete and nonlinear light propagation in two-dimensional periodic systems. We have experimentally demonstrated thermal control of linear diffraction and nonlinear self-defocusing in a triangular waveguide array, and realized tunable all-optical power limiting. The spatial control of light is enabled by the combined effects of discreteness, strong material tunability and nonlinearity, and does not rely on any architectural light guiding core defects as in the case of conventional PCF structures.

The use of commercially available fabricated microstructures in combination with liquid infiltration avoids the need for specialized high-precision fabrication procedures [11], and provides high tunability and nonlinearity at moderate laser powers while taking advantage of a simple and compact experimental setup. We anticipate that the increasingly broad range of PCF structures available will stimulate further efforts in applying them in discrete nonlinear optics. The long propagation lengths that are accessible in fiber-based discrete systems could even allow for experimental studies of combined spatial and temporal nonlinear effects and thus pave the road for future demonstrations of spatiotemporal control of light.

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