Selective infiltration of photonic crystal fibres for waveguide arrays

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Photonic crystal fibres (PCFs) can be used as a platform for the study of periodic photonic structures as well as the novel linear and nonlinear physical effects associated with them. The cladding holes in these micro-structured fibres can be infiltrated with a liquid utilising capillary action. This can be prevented in selected holes through the prior blocking of one end, producing periodic photonic arrays in the shape of the infiltration, providing a customised array shape within a low defect, high quality PCF. The coupling pattern of guided light in an input hole redistributing to neighbouring infiltrated holes can be modified through thermo-optic relationships, which, together with non-linear effects resulting from high light intensity, enables the study of novel physical phenomena of both periodicity and non-linearity.

We developed a blocking procedure which, when applied to hexagonal ring Large Mode Area (LMA) PCFs, allowed a single row of holes to be infiltrated by an index matching oil with a well-defined thermal-optic relationship. With laser light guided into a single infiltrated hole and the sample maintained at $55 \pm 0.1^\circ\text{C}$, a linear discrete diffraction pattern was observed in the output intensity distribution, indicative of a one dimensional periodic photonic array.

The investigation of non-linear self trapping at a constant temperature produced results obscured by asymmetric linear coupling. Proposed alterations to the blocking procedure could allow for the formation of more complex infiltration patterns with novel coupling relationships and non-linear effects. Further development can lead to applications in bio-sensing and beam manipulation.

I. INTRODUCTION

Optical fibres have been almost universally deployed in the telecommunications industry for data transmission to take advantage of the bandwidth and low signal degradation that optical transmissions provide. However, the ability to manipulate these beams in a purely optical form has been limited, requiring a conversion of the optical signal to an electrical signal for manipulation, before becoming an optical signal again [1]. This has promoted research into optical beam control and manipulation. The novel effects of materials with periodic optical characteristics provide for such beam control possibilities.

A new type of optical fibre, known as photonic crystal fibre (PCF) has been recently developed [2]. These fibres are formed from a pre-form bundle of silica capillary tubes drawn out under heat. The resultant fibre is fused silica with a micro-structured array of holes as cladding around a core (core defect). There are many structural forms of PCFs

Fig. 1: Structures of photonic crystal fibres with (a) multiple cores, (b) close packed holes, (c) a hexagonal array and (d) a hollow core. Images adapted from [3].

[Fig. 1], and the type used in this experiment is a Large Mode Area (LMA) with a single solid core [Fig. 1(c)]. The holes are continuous through the length of the fibre and are open on each end, thus the holes generally contain air. The holes can be infiltrated with a liquid by immersing one end,

allowing the capillary force to draw up a column of liquid, displacing the air [3].

PCFs can function in a similar way to standard optical fibres, transmitting a signal through the core; however, most of the beam control possibilities come about from the effect of coupling. When light is injected into one of the infiltrated holes, the liquid, being of a higher refractive index than the surrounding glass, allows the hole to act as a waveguide, channelling the light along the length of the fibre [4].

At a glass-liquid boundary, light propagating in the liquid requires a field to extend into the glass to preserve the continuity of the electric and magnetic fields [3]. This is referred to as an evanescent field and decays exponentially with the transverse distance [Fig 2(a), x-axis] from the infiltrated hole. The rate of decay is dependent on the difference between the two refractive indices, the 'refractive index step'.

Fig. 2: (a) Coupling effect viewed along the propagation axis of (b) one dimensional, periodic array. (c) The transfer of light (arrows) only occurs between regions of similar refractive indices. Images adapted from [5].

The evanescent field reaches the next liquid channel, so the light field continuously couples to the surrounding waveguides along the length of the fibre [Fig. 2(a) z-axis]. With a small glass section between the holes and a small refractive index step, the transfer of power from one infiltrated hole to adjacent holes can be significant enough to distribute the input light throughout the waveguides, resulting in coupled channels. This is known as discrete diffraction.

Due to the light coupling only between the guiding regions of the fibre, PCFs with different cladding patterns will display different coupling patterns [6] [Fig. 2(c)].

Applications of PCFs

In terms of applications for PCF arrays, it is worthy to mention their potential use in light beam control and as compact bio-sensing devices.

Beam Control

When multiple strands of standard optical fibres are packed together for data transmission, separating material is added to prevent the signal from one strand impacting on the other. In PCFs, this ability to modify a signal by having other waveguides in close proximity can allow for beam routing, duplication and switching, enabling greater throughput, finer control or 'hardwired' passive controls compared with existing systems.

Fig. 3: (a) Theoretical coupling in a hexagonal array enabling beam splitting. (b) Simulation of optical logic gate using a linear network array, enabling beam routing (white intensity profiles added). Images adapted from [7,8].

Beam duplication or splitting can be achieved with an array. The coupling in a symmetrical array provides for identical outputs in holes the same distance from the input hole [Fig. 3(a)]. Under some refractive index step conditions, there is no residual light in the input hole and different array configurations can provide for various division ratios. Relative thermal expansion properties of liquids and silica allow for temperature tuning of the refractive index step, which in turn affects the splitting ratios. This fine control and ability to integrate a beam splitter into a fibre strand is more versatile than conventional, table mounted beam splitters.

These infiltrated arrays show two main properties allowing for sensing or switching possibilities; the expansion of the coupling effect under high temperatures and the contraction under high intensity light. These properties will be explained in-depth later, however they provide for ways of modifying the direction of a beam based on either external conditions (temperature) or the properties of the beam (intensity). A simple linear array could transmit light in the external holes for recombination, however at high intensities, the coupling contracts to

the input hole and the light is rerouted, providing a passive optical power limiter e.g. for laser surgery.

A possibility that requires a variety of cladding patterns is optical logic gates [Fig. 3(b)]. A laser beam incident at an angle over a number of holes in an array can cause the signal to transfer fully from one hole to an adjacent one, travelling across the network of holes. The path at junctions can be affected by the presence of other high intensity beams which impact on the optical properties of the array and decouple sections from the network. Thus the final beam path is affected by interactions with other beams, and a basic logic gate can be constructed. The theory behind these has already been developed with simulations [8] [Fig. 3(b)], and this could be matched by applications.

Bio-sensing

Bio-sensing possibilities for PCFs allow for the optical detection of biological or chemical traces in a compact sensor fibre package.

In standard spectroscopy, the volume of sample required is usually on the same order of magnitude as the optical path length [Fig 4(a), 1cm to 1mL]. An infiltrated PCF enables spectroscopic detection over a longer path length, allowing for more photon-liquid interaction and a higher absorption signal using far less liquid [Fig 4(b), 10km to 0.2mL]. This could be expanded to using coupling relationships for sample identification. A limited array PCF would benefit identification as theoretical models for two dimensional coupling assume a perfectly isotropic and infinite array with no core defect [7]. However, experimentally, these two dimensional arrays can lead to highly asymmetric coupling, which can lead to a greater variation between otherwise identical arrays. This should be lessened in a one dimensional array due to a more limited scope for impact of spacing irregularities and simpler coupling relationships with only two waveguides directly coupled to any third. This would make the distinction between the impact of normal structural irregularities and the identifying signal of the sample liquid.

PCFs are already being applied in bio-sensing applications [9] [Fig. 4(c)], with the use of a PCF for continuous flow, DNA specific capture and optical detection. DNA capture was provided by pre-treating a fibre with various polymers and chemicals. The optical detection utilises absorption from the central hollow core, however investigation could provide for a linked network with specific molecules

captured in each hole, allowing detection of many components though the changes to the coupling relationship. With more PCF structural options, more bio-sensing applications should become available.

Fig. 4: Bio-sensing applications of PCFs, such as absorption spectroscopy with a longer path length and decrease sample volume in (b) an infiltrated PCF compared to (a) a standard cuvette. (c) Lab-On-Chip DNA sensor using a fully infiltrated PCF. Images adapted from [9].

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Selective Infiltration

Although various designs of PCF can be created for specific applications, these often have a higher defect rate than commercially available fibres with high production volumes, have long lead times and are expensive. These defects can mask the identifying changes for sensing or can distort the signal in beam manipulation. If a waveguide pattern could be produced within the structure of a common PCF, both the low defect rate and array shape customisation can be achieved.

A method to achieve this is the infiltration of only selected cladding holes within the PCF. The selective infiltration of a single row, a network of

holes [Fig. 5] or any desired geometry within a fibre has similar coupling properties to a fully infiltrated fibre in that custom shape; the un-infiltrated holes do not affect the overall liquid to liquid coupling relationship.

Fig. 5: The un-infiltrated face of a PCF (a) is completely infiltrated (b) creating an array of waveguides. Single line (c) or network (d) infiltrations provide for more application possibilities. Images adapted from [3].

A single line infiltration will act as a proof of concept of the procedure. This simple shape has been produced in structurally manufactured arrays, so provides well defined, expected, experimental coupling patterns. The selective infiltration array can be imaged under various input intensities and temperatures and compared with responses found by groups using other types of arrays. This serves as allows a method of judging the success of infiltrated structures in comparison to the fabricated arrays.

Fig. 6: Linear discrete diffraction through a 1D periodic array, (a) final output and (b) intensity profile. Images adapted from [5].

The primary identifying response of a manufactured line array, e.g. LiNbO_3 waveguide

array [5], is linear discrete diffraction [Fig 6(a), (b)]. At a critical, temperature dependent, propagation length, the central input waveguide is no-longer the peak intensity output. A symmetrical linear array will display two maximum peaks in the channels adjacent to the input hole, which contains an intensity minimum [10]. This is a distinctive and identifying feature of linear arrays, to be used for comparison with the coupling in selectively infiltrated PCFs while the non-linear expected result is dealt with in Section 4.

II. EXPERIMENTAL ARRANGEMENTS

Blocking

During infiltration, one end of the photonic crystal fibre is immersed in the sample liquid and the air contained within the cladding holes is displaced by the infiltrating column of liquid. Selective infiltration is achieved by the application of a viscous blocking liquid to one end of selected holes prior to immersion of the opposing end, thereby preventing the displacement of the contained air by liquid. The infiltration pattern produced is then the inverse of the pattern of blocked holes, the ‘blocking pattern’ [Fig. 7, setup].

The PCFs used consist of seven hexagonal rings of holes layered around a fused silica solid core (Crystal Fibre A/S LMA-15 and LMA-20) [Fig. 7, inset]. The cladding holes are approximately $4.8 \mu\text{m}$ and $6.3 \mu\text{m}$ in diameter with a periodicity (hole spacing) of approx. $9.8 \mu\text{m}$ and $13.2 \mu\text{m}$ for LMA-15 and LMA-20 respectively. Samples were cleaved by a fibre cutter to approx. four centimetres long to match the length of the fibre holder, although the process is applicable to various fibre lengths.

Fig. 7: Experimental arrangements for blocking. Inset of LMA-15 (left) and LMA-20 (right) samples used. The fibre samples are held vertically on a single axis translational stage. A 5x zoom microscope with

a long focal length and a camera is used to image the exposed face of the sample and the blocking process. Additional illumination to highlight the different optical properties of the blocked and unblocked holes allows the blocking pattern to be confirmed. The light is incident on the lower face of the sample, ‘back lighting’, and/or incident on the exposed sample face, ‘top lighting’. A ‘micropipette’ formed from a conventional optical fibre drawn through under heat and snapped is used for applying the blocking liquid. It is clamped onto a five axis translational stage to allow for fine spatial positioning of the pipette respective to the sample.

Fig. 8: Blocking procedure including (a) drop application and (b) drop formation

The blocking liquid was transferred from a drop on a glass slide to the micropipette, in a manner that produced a string of well-separated, small drops near the pipette tip [Fig. 8(a)]. The pipette is drawn through a drop of liquid, located at the edge of the glass slide, while the tip is bent upwards due to the angle the slide is held at [Fig. 8(b)].

The blocking process involved the pipette being aligned parallel to a line of cladding holes and then lowered onto the fibre face, covering a partial line per application. To prevent covered holes reopening, the blocking liquid must not readily infiltrate into the cladding holes while still forming suitably sized drops. Castor oil was found to be suitable. A red dye suspension was added to provide additional absorbance and scattering, further distinguishing the blocked and unblocked areas.

Infiltration

For infiltration, <0.1mL of infiltrating liquid is drawn into a 3 mL syringe, which is then positioned upside down. The unblocked end of the fibre sample is inserted into the liquid reservoir in the syringe tip and left to stand for approx. 20 minutes. In the blocked holes, the liquid rises a short distance before the pressure of the air being compressed within the hole prevents further capillary rise. After infiltration, the fibre is cleaved at both ends to remove the blocking tip and the immersed tip, resulting in a 2cm long selectively infiltrated sample.

Fig. 9: Temperature dependence for index matching oils, $n=1.47$ (grey) and $n=1.48$ (black) with a reference line of fused silica (light grey) [11].

The infiltrating liquids used are index matching oil $n=1.4700\pm0.0002$ and $n=1.4800\pm0.0002$, (Cargille Labs Series A-certified refractive index liquids) which have a well defined, linear relationship between the refractive index and temperature [11], as shown in Fig. 9.

The higher refractive index of the liquids allows the infiltrated holes to act as waveguides, and the different thermo-optic coefficients of the liquid and glass [Fig 9, slopes] allows the refractive index step to be decreased by increasing the temperature of the fibre. This promotes the coupling of light between the holes and is utilised in the following section.

Coupling

The infiltrated samples are mounted in two grooved brass plates within an oven, temperature controlled to $\pm 0.1^\circ\text{C}$ [Fig. 10, inset]. Light of 532nm wavelength from a Verdi V-5 laser is injected into a single hole in the PCF sample via a single mode, polarisation maintaining input fibre, with a mode of approx. $5\mu\text{m}$. The input fibre can be moved independently of the infiltrated samples, which allows the incident light to be injected in a single hole, given the comparable mode and cladding hole sizes. Covering this is a thermally insulated oven

cover with a glass window pressed on the output end of the samples [Fig 10, inset]. A drop of the infiltrated liquid is placed on the input-sample butt-couple and on the sample-glass contact to ensure minimum imaging and coupling losses.

Fig. 10: Experimental arrangements for coupling measurements. The inset displays the oven covering as white lines with the input fibre tube (left) and PCF sample (right). Images adapted from [3].

The output light is collected by an imaging lens and then split into beams to both a CCD camera and through a pin-hole mask to a power meter. The imaging lens was adjusted so the pin-hole mask exclusively transmitted light from the input channel to be measured by the power meter. Sequential images of the coupling intensity distribution were taken at various temperatures and laser power levels to investigate the linear and non-linear effects. The input hole was also varied to minimise the impact of edge effects and lattice defects.

III. RESULTS

Blocking technique

The blocking technique was successfully developed to allow for the formation of a one dimensional infiltration pattern within the cladding hole lattice of photonic crystal fibres. This method is repeatable and scales from larger (LMA-20) to smaller (LMA-15) fibre samples.

The reliability with which the blocking pattern was replicated in the infiltration is high, although additional, undesired infiltrations do occur [Fig 11(d), bottom left]. These were usually sufficiently displaced from the infiltrated line to

produce only a negligible impact on the coupling pattern.

Fig. 11: LMA-20 sample. Fibre blocked with red dyed castor oil for single line infiltration, shown (a) top lit and (b) back lit. The same fibre infiltrated with $n=1.48$ oil is shown (c) top lit and (d) back lit.

A visual inspection of the infiltration pattern under a microscope produced false positives, when excess liquid on the cleaved face partially infiltrates a hole, and false negatives, when the infiltrated liquid receded too far back into the hole to be identified. This resulted in different infiltration patterns when each end is viewed under a microscope. As the coupling process is less affected by these end effects, it was necessary for each sample to be put through the coupling setup to determine the successful blocking of a sample and the validity of new patterns or techniques.

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More complex blocking geometries may also be formed using this blocking method. Multiple parallel

infiltrated lines; either adjacent or separated by blocked regions is a trivial extension of the single line process. Closed, hollow shapes, such as rings or boxes, have been attempted but were not successful due to it being energetically unfavourable for a drop to be situated on the very tip of the micropipette. As the blocking liquid spreads along the length of the pipette where it touches the fibre, fine control is lost. This is not an issue when a whole line is to be blocked but prevents controlled, partial line blocking. This same problem exists for two dimensional networks. The formation of simple solid shapes, such as solid triangles or trapezoids should avoid this problem and be feasible with minor modifications to the procedure. Multiple rotations of the sample in the fibre holder would be required to bring the next flat edge into a region the pipette can reach without crossing the shape.

Temperature response

For the successful formation of periodic arrays within PCFs, utilising selective infiltration, the coupling output must match that produced by similar, fabricated arrays. In this case, the single line infiltration should display similar linear discrete diffraction as seen in LiNbO_3 waveguides [5] [Fig. 6(a)]. This coupling is indicative of an extended, symmetrical, one dimensional array with a small refractive index step and a single input site excitation.

At temperature up to 53°C , the refractive index step between the glass and the infiltrated liquid keeps the input beam contained to the input hole [Fig. 12, 53°C]. From an initial refractive index step of $\Delta n = 0.011$ ($n_{\text{oil}} = 1.470$, $n_{\text{glass}} = 1.459$) at 25°C , the refractive index step decreases by approx. $-3.83 \cdot 10^{-4}^\circ\text{C}^{-1}$ for every degree above 25°C due to the disparity in thermo optic coefficients; $-3.95 \cdot 10^{-4}^\circ\text{C}^{-1}$ for oil [4] and $-1.2 \cdot 10^{-5}^\circ\text{C}^{-1}$ for glass [9].

As the temperature is elevated, the lower refractive index step reduces the rate at which the evanescent field between the infiltrated holes decays and allows more energy to be coupled outwards; however the peak intensity remains at the input site [Fig. 12, 54°C]. It is worth noting that the size of the cladding holes in the LMA-20 allows the propagation of non-fundamental modes. These modes couple ‘faster’ than the fundamental mode, resulting in two or more intensity lobes per infiltrated hole at the edge of the fundamental mode coupling.

At $55.0 \pm 0.1^\circ\text{C}$, a symmetrical intensity distribution with two peak intensity lobes adjacent to the input hole is produced. This is indicative of linear discrete diffraction [Fig. 12, 55°C]. The low refractive index step allows almost all of the light to be coupled away from the central, input channel. This clearly matches the output of fabricated linear arrays from other groups [Fig. 6(a)].

Fig. 12: Coupling intensity distribution for a single line infiltration of $n=1.47$ in a LMA-20 sample over a 53°C to 57°C temperature range at constant input power. Input hole circled.

As the temperature is increased further, the beam continues to spread through the array [Fig. 12, 56°C and 57°C]; however the symmetry is quickly lost due to the edge effects of the array extending further to the left than to the right.

A single line infiltration within a photonic crystal fibre has been shown to display linear discrete diffraction in a manner characteristic of a one dimensional periodic photonic array. The irregularity and edge effects in the array mainly affect the symmetry at higher temperatures when the refractive index step is smaller. This allows the beam to spread out further through the array, leading to more coupling relationships and a greater potential for irregularities to cause asymmetrical coupling. However, the general validity of this

approach for small array extensions is supported by the results.

IV. NONLINEARITY

Optical systems dealing with low light intensity are considered to be linear to a first order approximation and to follow the principle of superposition [12]. The system response at any intensity can then be broken down into a sum of response seen at lower levels. Necessarily, the optical properties of the propagation medium are independent of the input power, so a transmitted beam has no effect on the transmission material, hence it does not affect light propagating through the same region.

However, when light of a high intensity propagates through a medium, the large scale interactions between photons and the atoms of the material causes localised changes to the optical properties of the media [4]. In this way, the first order approximation falls down and the system is considered to be non-linear; the act of transmitting light impacts on light propagating through the same region, allowing a sustained beam to self-modulate.

The optical Kerr effect, whereby the local refractive index of the propagation medium becomes a function of light intensity at high input levels, is of particular interest in this experiment. In most liquids, the effect is ‘negative’ [4], an inverse relationship between refractive index and intensity [Fig. 13(a)]. This occurs due to the localised heating effect from the absorbance of energy from transmitted light. The thermal expansion of the liquid decreases the refractive index at a rate given by the thermo-optic coefficient.

As the laser beams have a non-homogenous intensity profile, the refractive index encountered will vary across the beam. The speed of light propagation varies inversely with refractive index so a plane wavefront will be distorted by the different speeds. For a Gaussian cross-sectional beam, the central, peak intensity light is sped up relative to the edges, resulting in the ‘self-defocusing’ of a plane wavefront [Fig 13(b)]. A wave peak thus broadens faster from nonlinearity than occurs due to linear diffraction.

Fig. 13: (a) Kerr effect causing the refractive index of the propagating medium (grey) to change and (b) a self-defocusing effect on plane waves in a bulk nonlinear medium. A spatial soliton is formed from nonlinear self-trapping in a periodic structure, shown along (c) the propagation axis with (d) the final output and (e) intensity profile. Images adapted from [3,5].

However, when high intensity light is transmitted through material with a negative thermo-optic coefficient in a periodic photonic array, a distinct phenomenon is displayed, whereby the wavefront is prevented from dispersing, see Fig. 13(c-e) in contrast to Fig. 6. This occurs when the refractive index of the input hole is reduced by the Kerr effect, leaving the waveguide surrounded by higher refractive index regions. These act as Bragg reflectors, confining the beam to the input channel and preventing the light coupling out. The ‘self-trapping’ effect produces a spatial soliton [6] which, due to their non-dispersing, self-reinforcing propagation, are highly applicable for signalling, transmission, and beam control.

In PCFs, the confinement of the input light to small cladding holes allows high light intensities to be achieved with moderate laser power levels. The coupling relationship in these fibres can be ‘tuned’ both thermally through linear discrete diffraction and optically through non-linear self trapping.

The relatively high thermo-optic coefficient of the infiltrating liquid [11] and the sensitivity of the coupling to a small change in temperature, [Fig 12, 54°C-55°C] made a strong thermal non-linear response expected for moderate input power. However, investigations into self-trapping were hindered by difficulties in re-producing a selectively infiltrated fibre with reasonably symmetrical coupling. Asymmetrical coupling relationships

obscure the contraction of the wavefront in the move from linear discrete diffraction to self-trapping. Refinement of the blocking and infiltration procedure should allow for further investigation of nonlinear effects in such infiltrated fibres.

V. CONCLUSIONS

Photonic crystal fibres provide a low cost, 'tuneable' platform for the study of multiple aspects of periodicity. Liquid infiltration allows for simple modification of the refractive index step as well as investigation of sample liquids. Non-linear responses can be achieved using lasers of moderate power levels. The key to the investigation is determining the relationship between thermal or optical inputs and expected intensity outputs. Although commercially available PCFs are low in defects, the impact of slight variations in hole positions, as well as the core and edge effects, results in complicated coupling relationships in fully infiltrated fibres. Limited infiltration can reduce the impact of lattice irregularities, simplifying the determination of particular cause for small changes to the coupling output.

Selective infiltration was achieved for a single line of holes within hexagonal ring, solid core PCFs (LMA-15, LMA-20). Thermal tuning produced the one-dimensional linear discrete diffraction seen in individually fabricated waveguide arrays. Identification of a nonlinear self trapping response through a contraction of the coupling at elevated input levels was made problematic by asymmetric linear coupling. A 1D array contained within an optical fibre package with a liquid medium that can be varied provides for greater bio-sensing and beam control applications than standalone, fabricated arrays with a defined transmission medium.

The blocking methodology developed provides a basis from which other non-trivial infiltration patterns can be produced after slight modifications to the process. Geometries with novel coupling relationships can be investigated in the linear and non-linear input regions utilising the test bed developed for this report. The ability to modify the shape, composition and refractive index step of periodic arrays, within a standard PCF structure, should encourage the development of further applications.

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