Modifying photonic crystal fibres

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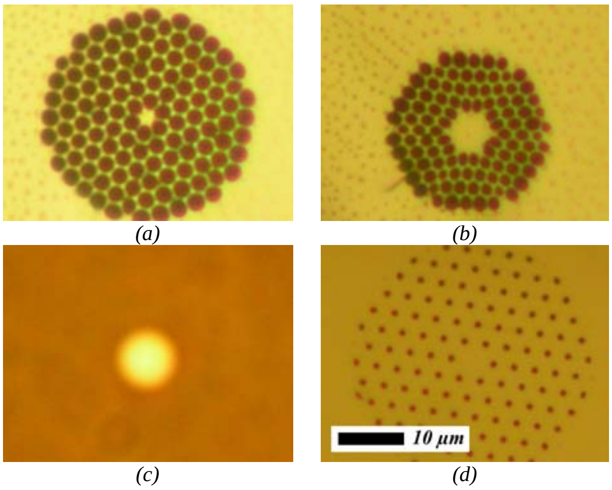
Abstract

We use controlled hole collapse in photonic crystal fibres to reduce the splice loss between dissimilar fibres. We also describe a hollow-core PCF as a support for a waveguide core made from silica aerogel.

Low-loss splices

Careful shrinking of the holes in a photonic crystal fibre (PCF) by repeated discharges in a fusion splicer reduces the effective core-cladding index step and expands the mode. This can reduce the splice loss between a PCF and a conventional single-mode fibre (SMF) with a different mode-field diameter (MFD) [1]. However, the process is not suitable for highly-nonlinear PCFs with very small MFDs and high air-filling fractions.

We made low-loss splices between a small-MFD PCF (PCF 1, Fig. 1(a), MFD = 1.7 μm) and fibres with much larger MFDs. Instead of shrinking all the PCF's holes, before splicing we completely collapsed two rings of holes around the core while keeping the rest. This expands the mode by enlarging the core.



(a) (b) (c) (d)

Fig. 1. End-faces of (a) PCF 1, (b) PCF 1 with two rings of holes collapsed, (c) SMF 1 and (d) PCF 3, to the same scale.

The holes were collapsed by blocking them with glue at one end of the fibre, supplying 3.5-4.0 bar nitrogen to the fibre end, and sweeping a small flame along part of the fibre [2]. The blocked holes collapsed to leave an enlarged core, Fig. 1(b). The sweep of the flame was progressively reduced to shrink the holes gradually over 1.5 cm, making the core size variation adiabatic: the loss of a typical entire transition was 0.12 dB. The fibre was cleaved and fusion-spliced to the conventional large-MFD fibre SMF 1 (Corning HI 1060, Fig. 1(c), MFD = 5.9 μm). After finding suitable splicer parameters, a series of nominally-identical splices was made.

A direct splice between PCF 1 and SMF 1 had 3.0 dB loss at $\lambda = 980$ nm, as expected for the MFD mismatch. In contrast, the total splice loss with expanded cores averaged 0.55 dB, the best of 20 attempts being 0.36 dB. Collapsing two rings of holes tripled the core diameter, a much better match to the SMF's core.

The average loss of similar splices to the large-MFD PCF 3 (Fig. 1(d), MFD = 5.4 μm) was 0.65 dB with a best case of 0.56 dB, though this required three rings of holes to be collapsed around the core of PCF 1.

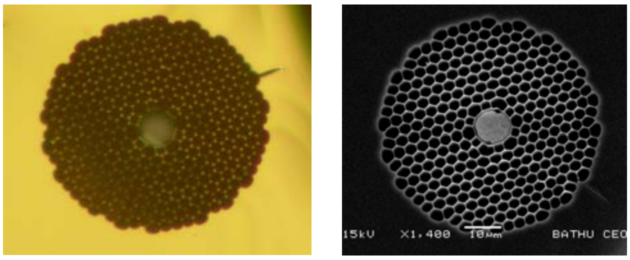
Aerogel-filled fibres

Silica aerogel is a highly-porous silica-air structure like a sponge but on a nanometre scale [3]. Rigid and with ultra-low refractive index, it behaves optically like "solid air". Its only use in fibre optics so far has been as a substrate for sub-micron tapered fibres [4]. However, it is reported to be 5 orders of magnitude more optically-nonlinear than solid silica [5].

We have successfully filled the core of a hollow-core PCF (HC-PCF) with aerogel. HC-PCFs confine light of certain wavelengths in an air core by means of photonic bandgaps in the cladding. They offer long interaction lengths between light and gases in the core [6]. They could therefore also offer long interaction lengths with silica aerogel and, as with gas-filled HC-PCFs, we may expect to see strong nonlinear and other effects. Aerogel could also act as an air-like host medium for dopants that cannot usually be put inside fibres.

Silica aerogel is made by sol-gel chemistry from a fluid precursor, a sol. We slowly drew sol made as in [3] into the 12 μm core of a HC-PCF by evacuating one end of the fibre and immersing the other end in the sol. The cladding holes had been collapsed at the ends with a splicer so only the core could accept fluid. The sol filled 1 m of the core in 45 min before turning into "wet" gel (the desired aerogel with its pores filled with methanol). The wet gel was left to age for 3 days.

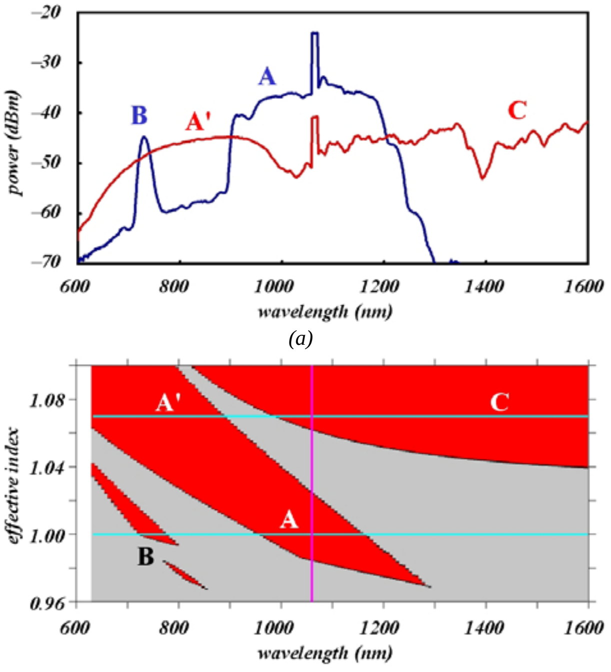
To avoid collapse of the silica network the methanol was removed by supercritical drying [3]. 20 cm lengths of filled uncoated fibre were placed in an autoclave made from stainless steel tube. This was pressurised to 80 bar with nitrogen and heated above 242°C to make the methanol supercritical. Pressure was then released over 1 hr at the high temperature, allowing gaseous methanol to escape diffusively along the fibre.



(a) *(b)*

Fig. 2. Optical (a) and scanning electron (b) micrographs of the HC-PCF endface with aerogel filling only the core.

The aerogel's physical properties were estimated from larger samples made in capillaries of 3 mm diameter. The density was 0.23 g/cm^3 and the refractive index was 1.07. The optical attenuation was 0.4 dB/cm at 1310 nm and (away from a water peak at ~1400 nm) proportional to $1/\lambda^4$ as expected for Rayleigh scattering.



(a)

(b)

Fig. 3. (a) Un-normalised transmission spectra of the unfilled (blue) and filled (red) fibres. (b) The cladding's photonic band structure, with bandgaps in red. The horizontal lines indicate the indicies of air (lower) and aerogel cores, and the vertical line at 1064 nm marks the residual pump from our supercontinuum source.

We are able to fill the fibre core with aerogel, leaving the other holes empty, Fig. 2. Transmission spectra of 15 cm of filled and unfilled fibre are shown in Fig. 3(a). Fig 3(b) is a plot of the photonic band structure of the cladding calculated using a fixed-frequency plane-wave solver [7]. The bandgaps in the unfilled fibre's spectrum match the simulation, including the feature marked B. The filled fibre has a shifted bandgap (A to A') and a broad range C of guidance by total internal reflection (not bandgap guidance) that is absent in the unfilled fibre, again as simulated. There is a water peak at ~1400 nm.

We believe this to be the first demonstration of waveguiding by an aerogel core. The loss evident in Fig. 3(b) includes coupling losses to the HC-PCF. Our aerogel was not optimised for attenuation, which would be as low as 0.06 dB/cm at 1550 nm if the transparency reported elsewhere was achieved [3].

Conclusions

We have reported two different ways in which an existing photonic crystal fibre can be modified to useful effect.

We demonstrated low-loss splicing of fibres with a substantial MFD mismatch, where the fibre with the smaller MFD is a PCF. Two rings of holes were collapsed to expand the core prior to splicing in an ordinary fusion splicer. Splice losses as low as 0.36 dB between fibres with MFDs of 5.9 and 1.7 µm were achieved.

We also demonstrated that silica aerogel can be formed in the core of a hollow-core PCF. The transmission spectrum exhibits the expected shift in the wavelengths of bandgap guidance, and guidance by total internal reflections (TIR) at other wavelengths becomes possible. It is notable that the effective index of a microstructured silica cladding is low enough to provide TIR guidance for such a low index core.

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