Identifying hollow waveguide guidance in air-cored microstructured optical fibres

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Abstract: An analysis of leaky modes in real microstructured optical fibres fabricated specifically for photonic band gap guidance in an air core has been used to identify alternative guiding mechanisms. The supported leaky modes exhibit properties closely matching a simple hollow waveguide, uninfluenced by the surrounding microstructure. The analysis gives a quantitative determination of the wavelength dependent loss of these modes and illustrates a mechanism not photonic band gap in origin by which colouration can be observed in such fibres. These findings are demonstrated experimentally.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2280) Fibre design and fabrication; (060.2430) Fibers, single-mode; (160.5470) Polymers.

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1. Introduction

Microstructured optical fibres (MOFs) have been developed over the past six years, and their optical properties have attracted much attention. Currently, these fibres are fabricated from a range of materials, including pure silica [1], compound glasses [2] and polymers [3]. One particular sub-class of microstructured fibres, the photonic band gap (PBG) fibre, has received considerable attention, particularly because of its ability to guide light in air [4, 5, 6], which is instrumental for many applications such as gas sensing [7], enhanced Raman scattering [8], CO_2 laser guidance [9] or particle transport [10]. In addition, it could potentially provide a reduction of the fibre losses when material absorption is large [3, 9].

The bands of peak transmission found in the spectral response of PBG fibres is a distinctive feature caused by the Bragg reflection of light from the microstructure surrounding the central air core. Therefore colouration of the modes at the output of the fibre when illuminated by a very broadband or white-light source is a common first test for photonic band gap guidance [4, 5, 6]. However, it is important to understand all processes that can lead to colouration in optical fibres before any conclusions are drawn about the PBG nature of the guidance. A number of additional colouration effects in MOFs have already been observed and reported. Each has a unique origin unrelated to PBG effects, such as those associated with anti-resonant optical waveguides [11], fibre bending [1], and bending of MOFs with a depressed index core [12] or with an off-center core [13]. In this paper we identify and explain one additional mechanism by which colouration can arise in straight sections of air-cored MOFs. Unlike in the cited articles, the obtained transmission spectra are insensitive to the surrounding microstructure. That is, structural disorder results in the transmission properties of the MOF being dominated by the reflection of light off the first air/solid interface.

A number of guiding mechanisms are possible in air-cored microstructured fibres. Since guidance by total internal reflection is impossible in an air core fibre, the modes supported by the waveguide must be leaky. Confinement losses arise from partial reflections off air/solid interfaces and the leakage of light through the microstructure. Modes in hollow waveguides are also an example of such leaky modes, a detailed analysis of which can be found in [14]. They are legitimate eigen-solutions to the standard wave-equations for a waveguide consisting of simply one air hole in a uniform host material. Guidance is achieved only by partial reflection off the single air/material interface, commonly referred to as external reflection. When microstructure surrounds the air core the leaky mode solution describes the net reflection from the microstructured region. The MOF investigated here belongs to a common class of air-cored fibre where the features of roughly uniform size are air holes in a host material. Such fibres first demonstrated approximately 35% transmission through 30mm of fibre [4] and more recently a loss as low as 13dB/km has been reported [15].

2. Experimental observation

Air-cored PBG polymer fibres have been fabricated, and evidence of PBG guiding through short lengths of fibre has been observed [6]. Unfortunately, these initial results have proved difficult to reproduce, a fact that has been attributed to non-uniformities in the fibre structure, both in the transverse and longitudinal direction, which lead to a closing of the band gap [16].

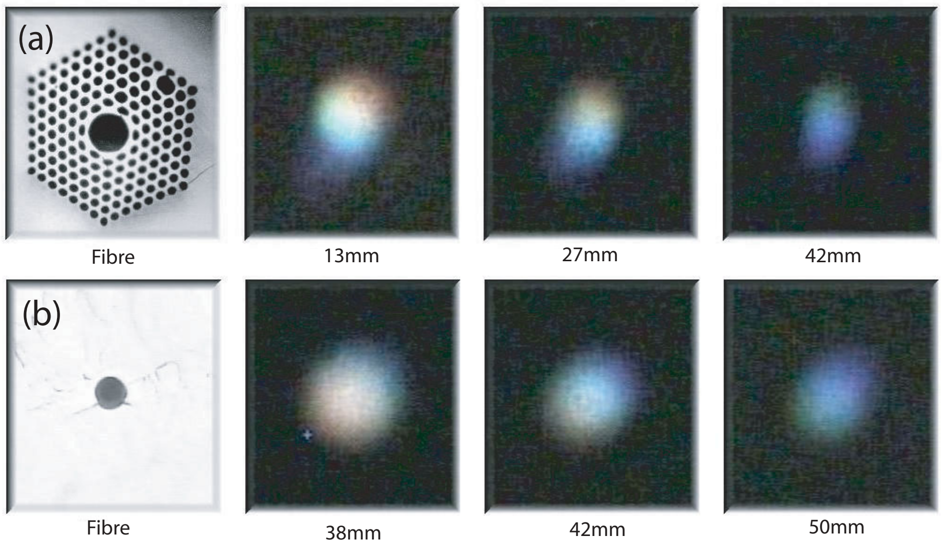

Fig. 1. Two polymer (PMMA) fibres. **(a)** PBG MOF with a 17.5μm core diameter, hole diameters of 4.3μm $\pm$ 7% and hole spacings of 6μm $\pm$ 5%. **(b)** Hollow waveguide with a 22μm core diameter. The three pictures next to the fibres show the length dependent output when diffuse white light is launched into the core.

Despite the absence of a PBG, colouration was still observed, as shown in Fig. 1. The first fibre has a 6-layer hexagonal structure similar to a PBG fibre, while the second is a simple single-hole hollow waveguide. The core sizes of these two fibres are comparable; 17.5μm for the PBG fibre and 22μm for the hollow waveguide, and both display similar characteristics. The three pictures next to the fibre images in Fig. 1 show the length-dependent output when diffuse white light is launched into the core by coupling with a multimode, high NA glass fibre. The shortest lengths show essentially white light transmission. Intermediate lengths show mixed colouration and blue transmission is observed around 45mm lengths. Longer lengths show no observable transmission in the core. The pictures are taken by cutting back one piece of fibre in both cases.

Quantitatively it can bee seen that the observation of colouration is very sensitive to the length of the fibre. Furthermore the same trend towards predominantly blue transmission is observed in both cases, suggesting that the surrounding microstructure may not contribute substantially to the dominant guiding mechanism. The intensity profiles closely resemble that of the common (Gaussian like) fundamental mode, motivating an analysis of the leaky modes supported by the waveguide in order to best describe the observed phenomena. This is presented in the following sections.

3. Identifying the dominant guiding mechanism

Since the confinement losses of various modes may differ by orders of magnitude it is convenient, although not strictly true, to attribute a particular guiding mechanism to the size of the confinement loss. Furthermore, since the power in the core decays exponentially, the length of

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a tested fibre is crucial in determining the dominant guiding mechanism responsible for the observed mode. Due to the considerable technical difficulty in fabricating microstructured fibres with sufficient uniformity along their length, the optical characterisation of fibres is often done with very short lengths, sometimes no more than a few centimetres. In such cases care must be taken when interpreting observation, since a number of guiding mechanisms are likely to contribute.

The measured optical transmission spectra for the MOF presented in Fig. 1(a) are given in Fig. 2 for 2 different core sizes. No sharp PBG transmission peaks are observed over this broad wavelength range, although some features are visible, which are relatively small when compared to the overall trend. These are mainly attributed to the wavelength dependent interaction of light with the surrounding microstructure.

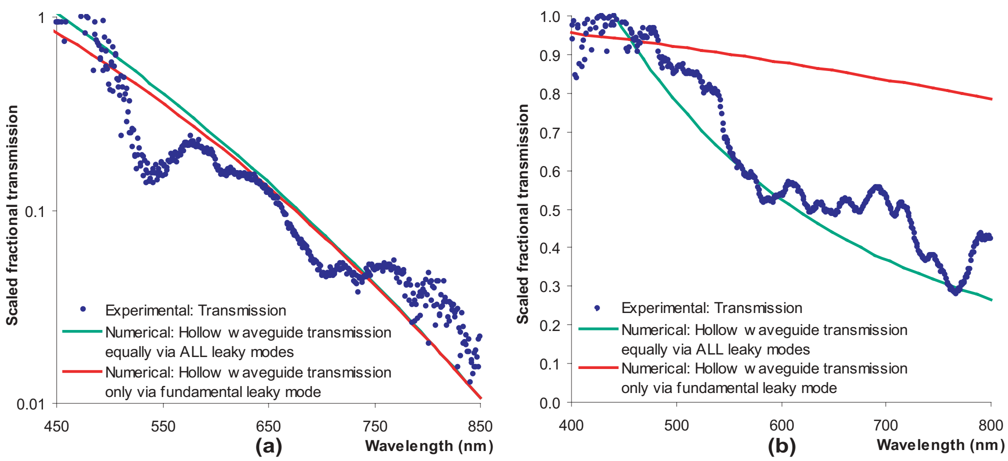

Fig. 2. A comparison of the measured transmission spectrum of two 13mm long pieces of air core MOF with the expected transmission for a hollow waveguide with equal diameter. The core diameters are **(a)** 17.5μm and **(b)** 48.0μm. The spectra have been normalised to a spectrum of the light source.

Both core sizes permit greater transmission at shorter wavelengths, resulting in predominantly blue colouration. Due to the similarities in transmission for both fibres shown in Fig. 1 a theoretical comparison is made with the expected transmission of a hollow waveguide with equal diameter. Since ray-optics approximations are invalid for the small core/cavity size of the hollow waveguide, the transmission spectrum was determined from the confinement losses of leaky-mode solutions. The diffuse (spatially incoherent) light source used here is expected to approximately equally excite every leaky mode supported by the waveguide [17]. Thus to simulate transmission though all leaky modes, 210 leaky modes were used in all the results presented. This number was convergent in the sense that exciting a greater number of modes did not significantly change the resulting transmission curve.

It is well understood that a large increase in reflectivity can occur at an interface as the glancing angle of incidence approaches zero degrees. Accordingly the large variation in confinement loss of modes supported by a hollow waveguide results from the effective reduction of the glancing angle at shorter wavelengths [14]. The numerical results over a broad spectral range for the hollow waveguide are superimposed in Fig. 2. It is clear that the hollow waveguide model correctly approximates the experimental data over orders of magnitude in transmission. A secondary finding is that the contribution to transmission of higher order leaky modes cannot be neglected when the core diameter is very large or the fibre length is short. In those cases the analysis provides better agrement with the experimental data when the higher order modes are taken into account.

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4. Comparison through numerical modelling

The Adjustable Boundary Conditions (ABC) method was recently developed [18] in order to accurately model the confinement loss of leaky modes in MOFs. This numerical method was used for the present calculations, where the radial basis function expansion first developed was replaced with a finite difference implementation, but the azimuthal expansion was retained. This alternative was adopted after it was found to give equally accurate results with less resource demand and in less computation time. The effective indices, n_{eff}, of the leaky modes are found in the complex plane and confinement loss is determined from its imaginary part using the standard expression; loss (dB/m) = $\frac{40\pi}{\lambda \ln(10)}\mathrm{Im}(n_{\mathrm{eff}})$, where λ is the free space wavelength.

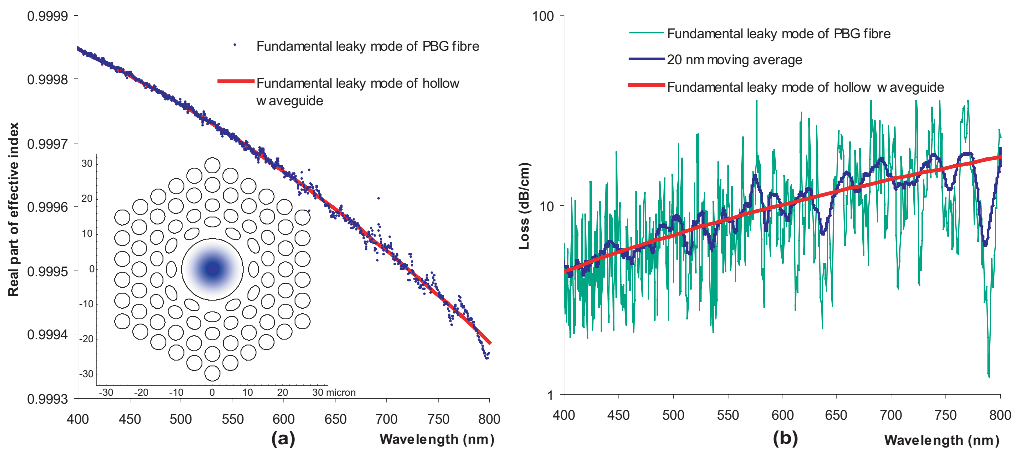

Fig. 3. Numerical propagation characteristics for the MOF shown in the inset - a 6-fold symmetric idealization of the fibre in Fig. 1 (a), including the measured ellipticity of the first ring of holes. The intensity profile of the fundamental (HE11 like) leaky mode solution is superimposed to demonstrate the similarity with experimental observation. **(a)** The real part of n_{eff} and **(b)** confinement loss are compared with the fundamental mode solution of the hollow waveguide model.

In Fig. 3(a) is shown the overall trend of chromatic dispersion for the modelled MOF as compared to the hollow waveguide. The two trends are in excellent agreement over a broad wavelength range apart from small deviations due to Kramer-Kronig like features that are simultaneous with dominant peaks in confinement loss. In Fig. 3(b) the overall trend in confinement loss is enhanced by using a 20nm smoothing, which is expected to simulate experimental effects such as the finite resolution of the optical spectrum analyser (10nm) and random perturbations from the idealized microstructure, whose effects are difficult to quantify. Structural disorder of only $4-8\%$ in the range of hole positions and radii has been shown to completely close a typical PBG [16]. This places stringent tolerances on the fabrication of MOFs that have not been reached here. It is clear that the spectral features of this MOF are especially narrow in the visible wavelength range (i.e., $<$ 3% of the central wavelength) and the authors are convinced that structural disorder has destroyed any evidence of PBG guidance in the fibres tested.

5. Reference charts for air-core waveguides

This section provides useful reference charts in Fig. 4 for identifying hollow waveguide type guidance in air-cored MOFs.

Although it is known [14] that the loss of each mode is proportional to λ^2/D^3, the combined losses of all the modes are provided in Fig. 4. It shows that a range of λ/D and lengths exist where the guidance of light in the hollow waveguide is dominated by transmission properties of the fundamental mode. In this regime one can then expect the intensity distribution of the

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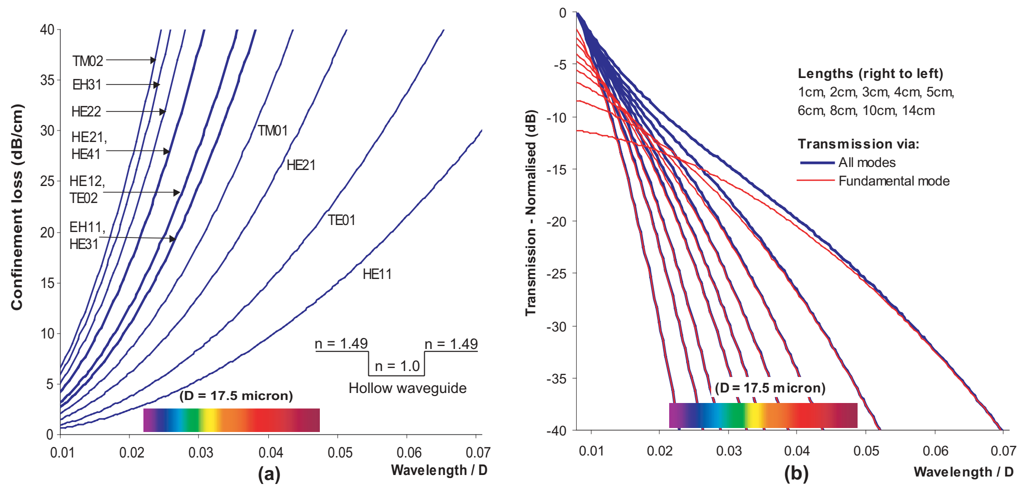

Fig. 4. Transmission characteristics for hollow waveguides. **(a)** Mode dependent confinement loss of the 13 least lossy leaky modes and **(b)** overall transmission via all leaky modes for various fibre lengths. A colour bar indicates the visible spectrum range for the core diameter ($D = 17.5\mu$m) of the MOF in Fig. 1 (a).

transmitted light to appear similar to that of a typical fundamental mode. Such is the case of the MOF considered in Fig. 2(a) with core diameter 17.5μm and length of 1.3cm. While outside this regime the results reveal that the blue colouration is enhanced by considering the loss contributions of higher order modes, as experimentally demonstrated using a core diameter of 48.0μm in Fig. 2(b). Roughly speaking, Fig. 4 indicates that in order to confirm PBG guidance in fibres with core diameters smaller than 40μm, a length larger than 50cm is required for the full attenuation ($>$ 40dB) of hollow waveguide modes.

6. Conclusions

The predominantly blue colouration of light transmitted though real air-cored microstructured optical fibres was examined and compared with hollow waveguide guidance in short lengths of fibre. Experimental and theoretical spectral trends have been presented to identify the core interface reflection as the main guiding mechanism. This was understood using the wavelength dependent confinement loss of the leaky modes supported by the fibre. A full numerical simulation of the microstructured fibre demonstrated that the experimental test is incapable of resolving the narrow photonic bandgap features of the fibre with structural disorder.

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