Square Lattice Hollow Core Photonic Bandgap Fibres

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Abstract *We propose a novel photonic bandgap fibre (PBGF) based on a square lattice cladding. The fibre presents a 20% wider bandgap than conventional triangular-lattice-based PBGFs and with a 9-cell core can be effectively single moded.*

Introduction

The possibility to guide light in the hollow core of a fibre by exploiting a photonic bandgap (PBG) in its 2D cladding has given rise to a number of novel applications including gas-based nonlinear optics, gas and liquid sensing and high power laser delivery. In the search for structures that provided the widest bandgap and the lowest loss, a large variety of periodic claddings have been studied and fabricated. The majority of research has focussed on studying alternative unit cells in the triangular lattice (TL, e.g. honeycomb, modified honeycomb and Kagome), which is also the best arrangement for closely packed circular capillaries. To the best of our knowledge, only a few isolated works to date have suggested the use of the alternative square lattice (SL), but they failed to identify any obvious advantage over the conventional TL [1,2]. From a first examination of the PBG for out-of-plane propagation in the SL, one discovers that square holes do not allow an air-crossing PBG, while circular holes present a 30-100% reduction in relative PBG width as compared to the same hole shape, arranged on a TL. However, by studying holes with shapes intermediate between these two extreme cases, we found that the width of the PBG crossing the air-line in a SL arrangement of holes can be up to 20% wider than achievable in a TL arrangement, and can reach up to 38% of the central wavelength for a realistic cladding structure. We therefore analyse the achievable optical properties of hollow fibres based on this optimised lattice and propose a fibre design that offers advantages in terms of PBG width and number of guided modes over the more conventional TL-based photonic bandgap fibres.

Out-of-plane PBG: comparing SL and TL

In order to systematically search for hole shapes that support a wider PBG across the air line (AL-PBG) we adopt a parameterisation that has been widely accepted to describe realistic holes in TL-PBGFs [3]. The four corners of a square hole with side *d* are rounded with circles of radius r1 (r1 = 0 → square; r1 = d/2 → circle). The resulting holes are regularly positioned on a lattice with a spacing of Λ. In Fig.1 we show the AL-PBG, normalised to its centre frequency, for values of r1 ranging from 0 to 1 and for d/Λ of 0.92, 0.95 and 0.98. The solid curves referring to the SL peak for values of r1/(d/2) between 0.4 and 0.6, roughly corresponding to the intermediate shape between a circle and square at the top of Fig. 1. The reason for this is that the main PBG opens between the M-point of bands 1 and 2, where the field is located in the corners of the unit cell, and the X-point of band 3 where light is localised in the thin struts between the corners. Therefore claddings with holes that allow thin struts on the four sides (increasing the minimum frequency in band 3) and at the same time large rods of glass at the corners (decreasing the maximum frequency in band 1 and 2) result in the largest PBGs.

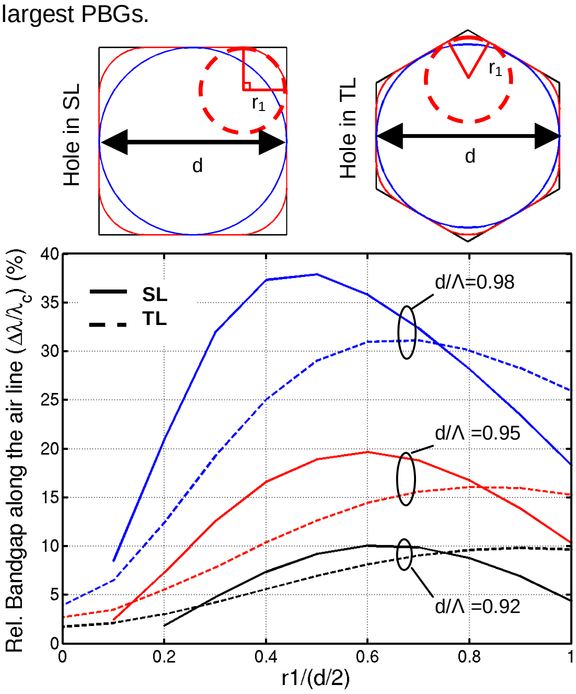

Fig.1 Relative bandgap width along the airline: comparison between square (solid) and triangular (dash) lattices for 3 values of d/Λ.

For comparison, the results of the same scan over holes with a similar parametrisation, but in the TL, are also shown. The AL-PBG for circular holes is wider in the case of the TL, however when one considers the fuller ranges of shapes as parameterised herein, then the SL is found to provide for larger AL-PBG widths - ~20% larger for the SL relative to the TL for fibres with d/Λ between 0.95 and 0.98. The effective numerical aperture, estimated from the gap maps [4] is quite similar for both lattices, reaching a maximum value of ~0.15-0.2 near the middle of the bandgap.

Design of air guiding fibres

Merging several holes together to create a suitable central defect allows air guidance for a number of modes. The main PBG in the SL occurs at a lower normalised frequency than in the TL (between bands 2→3 in SL and bands 4→5 in TL), with the consequence that a smaller Λ is required to achieve a PBG centred at the same wavelength. As a result, we expect a larger number of rings of holes to be required in the SL to obtain a low modal confinement loss (CL). To confirm this trend and to simulate the optical properties of SL-PBGFs, we use a full vector Finite Element Method (FEM) modal solver. Extensive calculations confirm that for lower values of d/Λ, more than 10 rings of holes and large core sizes are needed to achieve a confinement loss of less than 1 dB/m. The number of required rings of holes however decreases rapidly as d/Λ becomes larger.

As an example, we present in detail the properties of a fibre with d/Λ = 0.98, r1/(d/2) = 0.4 (air filling fraction of 87%) and a 16-cell core. A pitch of Λ = 2.8 μm generates a bandgap centred around 1540 nm (Fig. 2(a)) which extends along the air line from 1250 nm to 1830 nm, corresponding to a normalised width of ~38%. 7 rings of holes are adequate to maintain the CL below 1 dB/m and 0.1 dB/m over more than 500 nm and nearly 400 nm respectively. Any additional ring of holes roughly reduces the CL by one order of magnitude.

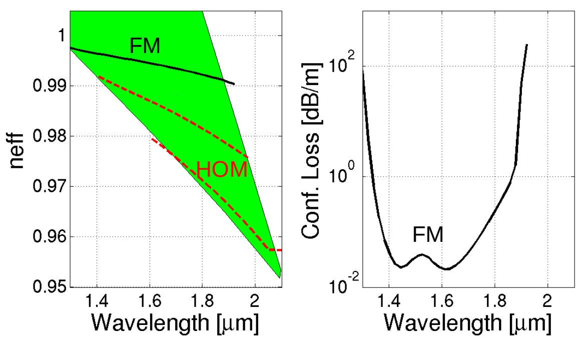

Fig.2 (a) Gap map of the cladding and effective index of the air guided modes of the 16-cell core fibre; (b) confinement loss of the FM of a fibre with 7-rings.

The fibre presents an effective area of 50-60 μm^2 and a percentage of power in the air core greater than 95%. Using an established technique for suppressing surface modes, we designed the core in such a way as not to perturb the glass rods at the intersection between 4 adjacent holes. Such a design and the superposed intensity profile of the fundamental mode (FM) are shown in Fig. 3 (left). We have also simulated fibres with a perfectly square core, and observed that, as expected, surfaces modes localised in the truncated rods appear inside the bandgap, giving rise to anti-crossings with the FM at certain wavelengths.

The FM is Gaussian-like at the centre of the fibre, and becomes square-like only at the -20dB intensity level. The fibre however is not strictly single moded. Similarly to a 7-cell core TL-PBGF, additional higher order modes (HOM) are also guided in the core with a similar confinement loss as the FM.

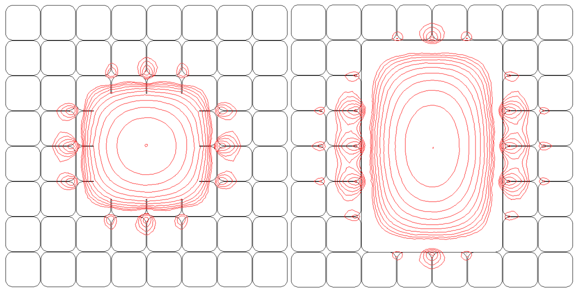

Fig.3 2dB contours of the FM of a 16 and 24 cell core PBGF with d/Λ = 0.98, r1/(d/2) = 0.4 and Λ/λ = 1.8.

An effectively single mode fibre can be obtained by reducing the core dimension, e.g. with only 9 missing cells. From density of modes considerations, the number of guided modes in this lattice with a square core consisting in 9, 16, 25, 36 and 49 missing holes is estimated to be 4.1, 7.3, 11.4, 16.5 and 22.4 respectively. This compares with 11.8 and 19.6 for a 7 and 19-cell core TL-PBGF respectively, and highlights the increased granularity offered by the SL due to the smaller Λ. Note that the FM of the 9-cell core fibre presents a similar confinement loss to the 16-cell one, provided that an additional ring of holes is added. The 4 degenerate HOMs however, are guided close to the bandgap edge and their CL is ~25dB worse than the FM throughout the PBG, allowing the fibre to behave as effectively single moded.

Note also that fibres with rectangular cores, such as the one shown in Fig. 3 (right), may be useful for a number of device and beam delivery applications.

Conclusions

We have demonstrated for the first time that hollow core fibres based on the SL can offer advantages over the more conventional TL fibres. Square holes with rounded corners allow AL-PBGs up to 20% wider than those achievable with current TL PBGFs. We have provided a physical explanation for the ultra-wide PBG obtained, which we believe can be used to achieve even larger bandgaps for both lattices. We studied the properties of PBGFs obtained with a SL and proposed a fibre that can be effectively single moded and presents a wider bandgap than is possible in the TL.

References

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