Hollow core fiber with an octave spanning bandgap

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Abstract: We demonstrate that amongst all known lattices, a triangular arrangement of interconnected resonators generates the widest possible out-of-plane bandgap. A photonic bandgap fiber with an octave spanning transmission range is presented for the first time.

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1. Introduction

Hollow core photonic bandgap fibers (PBGFs) with tight mode confinement, low loss and ultralow nonlinearity have been paramount to the recent demonstration of highly efficient gas and liquid based nonlinear devices, high sensitivity gas spectroscopy cells and high energy soliton pulse delivery and compression [1]. The relatively narrow transmission bandwidth of commercially available PBGFs, typically around 100 nm at telecoms wavelengths, however, has severely limited their impact in ultra-wide bandwidth applications. Significant theoretical and experimental efforts have been therefore recently devoted to maximize the PBGF bandgap width. Numerical studies [2] have shown that a square lattice (SL) arrangement of holes generates a larger normalized bandgap width (W) than the more conventional triangular lattice of holes (TLH), where W is the ratio of the bandgap width along the air line to its central wavelength. From a fabrication point of view, the introduction of active pressurization control techniques has allowed a steady increase in the achievable air filling fraction, with a related increase in W. Fibers with a hole diameter to pitch ratio d/Λ close to 0.99 have been now recently demonstrated, generating W~33% and W~44% in a TLH [3] and SL [4] arrangement, respectively, which represent the widest bandgaps reported so far.

In this study we demonstrate that an improved cladding, based on a triangular lattice of rods (TLR) rather than holes, is able to generate significantly wider out-of-plane (OOP) bandgaps than any other known lattice. For the first time, we also show that a realistically achievable lattice is capable of generating an octave spanning (W=66%) OOP bandgap, enabling the simultaneous transmission of a laser frequency and its first harmonic. Finally, we demonstrate numerically that a realistic PBGF where such a periodic cladding surrounds a suitably constructed defect core would provide air guidance with sub-dB/m confinement loss over a spectral range of ~1000 nm in the near infrared.

2. Results – octave spanning bandgap

It is well known that for in-plane (IP) propagation, a square arrangement of holes is less effective than a triangular one in producing wide bandgaps [5]. It may seem at first surprising, therefore, that for OOP propagation the opposite conclusion holds, when SL and TLH are compared [2]. This however is a direct consequence of two effects. First, in real structures the resonant glass nodes generating the OOP bandgap need to be supported by an interconnection of thin struts. Strut-guided modes have the effect of narrowing down the bandgap [1], and therefore structures with a larger ratio of resonator diameter to strut thickness (D/T) tend to generate larger bandgaps. It turns out that a practically achievable SL has a larger D/T than the TLH. Second, the conventional TLH has a unit cell containing two resonating nodes. For IP propagation, the largest values of W are produced by periodic structures with the lowest number of resonators in the unit cell [6]. Therefore, one may expect that a triangular lattice arrangement

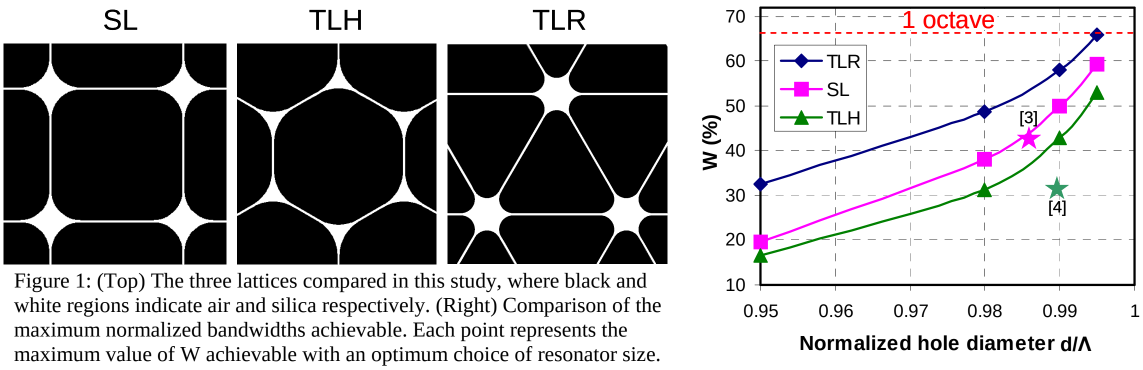

Figure 1: (Top) The three lattices compared in this study, where black and white regions indicate air and silica respectively. (Right) Comparison of the maximum normalized bandwidths achievable. Each point represents the maximum value of W achievable with an optimum choice of resonator size.

containing only one node per unit cell and with a very large D/T ratio, such as the TLR, would be able to outperform all other lattices and produce the widest OOP bandgaps.

To confirm this hypothesis, we extensively calculated the OOP bandgaps of realistic structures presenting TLR, SL and TLH periodic arrangements (Fig. 1). To efficiently model the extremely thin glass features of structures with d/Λ from 0.95 to 0.995, we employed a full vector finite element method (FEM) with Bloch boundary conditions and a non-uniform mesh. For each lattice and d/Λ we searched for the optimum resonator size producing the largest W. The results, shown in Fig. 1, confirm that for moderate values of d/Λ, typical of current commercial fibers, the bandwidth generated by the TLR is almost twice that of the conventional TLH. For more extreme $d/\Lambda = 0.995$, not unforeseeable with further improvement in the fabrication process, the TLR reaches the one octave limit, W = 66%, which is 10% and 25% wider than what is achievable with the best SL and TLH, respectively.

3. Results – PBGF with 1000 nm bandwidth

Next, we simulated the properties of a hollow core fiber based on the optimum $d/\Lambda = 0.995$ TRL cladding using a full vector FEM modal solver with perfectly matched layers. $\Lambda = 4.3$ µm was chosen to center the bandgap around 1500 nm; the core, formed by omitting 7 adjacent nodes, had a diameter of ~17 µm, and the optimum size of the resonating nodes was obtained by rounding the holes' corners with a radius $R = 0.066\ \Lambda$. Figure 2 shows the simulated results. The fiber exhibits a confinement loss below 1 dB/m in the spectral range 1035-2040 nm, and below 0.1 dB/km between 1050 and 1730 nm, indicating potentially useful bandwidths of 1000 nm for device applications and of 680 nm for telecoms transmission. The optimized core geometry prevents the existence of surface modes within the bandgap. The dispersion is anomalous at wavelengths longer than 1120 nm, and for central wavelengths sufficiently far from the bandgap edges, a negligible third order contribution is observed.

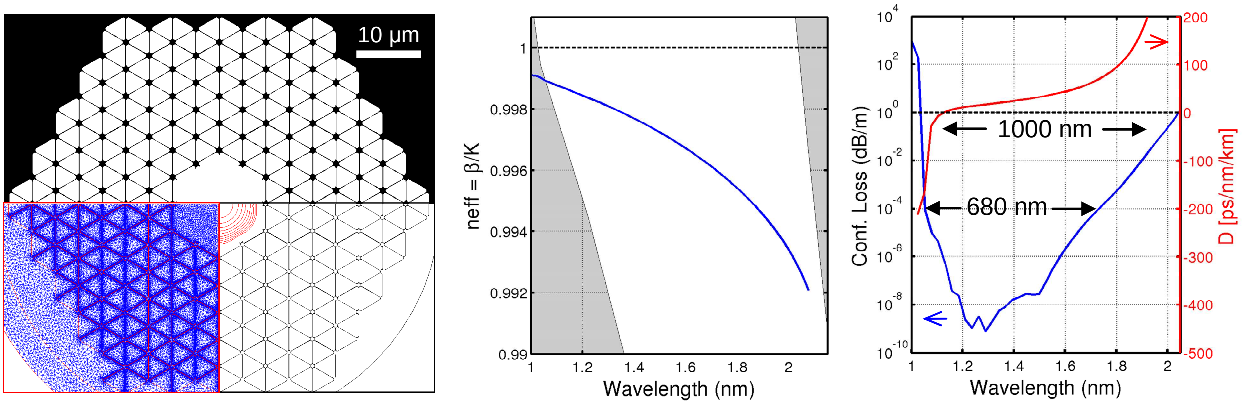

Figure 2: (Left) New TLR based PBGF structure (d/Λ=0.995, Λ=4.3 µm, D/T~ , 7 nodes missing in the core), mesh (7.5×10^5 degrees of freedom) and fundamental mode (1 dB contour lines); (Center) Effective index and bandgap; (Right) Confinement loss and dispersion of the fiber with 6.5 rings of nodes shown on the left.

4. Conclusions

We have studied a realistic lattice where resonating rods, rather than holes, are placed in a tightly packed triangular arrangement and are connected by ultra-thin struts. We found that this alternative lattice, denominated TLR, consistently generates wider OOP bandgaps for a given d/Λ than both SL and TLH. With extreme but not unrealistic air filling fractions, it allows the simultaneous air-guidance of an octave of frequencies. Although more challenging to realize than the conventional TLH, we believe that the TLR is still amenable to fabrication by a modified stack and draw procedure, and that its considerably wider bandgap is worth the additional fabrication effort. The proposed fiber has the potential to significantly accelerate progress in the areas of high energy ultrashort pulse generation, wide-band gas and liquid based nonlinear optical processes and, potentially, telecoms transmission.

5. References

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