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Hollow-Core Antiresonant Fibers with a Twist
Alessio Stefani, Richard Lwin, Alexander Argyros and Simon Fleming
Institute of Photonics and Optical Science (IPOS), School of Physics, The University of Sydney, NSW 2006, Australia
alessio.stefani@sydney.edu.au

Abstract: Antiresonant hollow-core guiding fibers are investigated. By using this guiding mechanism and a flexible polymer (polyurethane) we also demonstrate how we can realize a twistable (and un-twistable) hollow-core fiber and we investigate its properties.
OCIS codes: (060.2280) Fiber design and fabrication; (160.5470) Polymers; (050.5745) Resonance domain.

1. Introduction
Antiresonant hollow-core fibers have attracted a lot of interest in the past years. This is mostly due to the good guiding properties despite the simple structure [1,2]. Such fibers have been now fabricated in many materials and for various frequency regimes [2,3]. During about the same period of time, twisting of photonic crystal fibers (PCFs) has also found increasingly more interest because of the unique properties of the excited modes [4]. So far, twisting of only solid core fibers has been reported. Moreover, because of the material used (silica) and the fabrication techniques, the fibers realized had twist imparted during fabrication and thus fixed and neither tunable nor reversible.

We report not only on a simple way to realize a hollow-core twisted fiber, but also of a fiber with tunable and reversible twist. This has been possible by combining the mechanical properties of polyurethane and the guidance obtained by the simple antiresonant tube lattice fibers. We tested the realized fibers in the THz spectral region where the long wavelengths allow for larger structures and so easier fabrication. Moreover, we use a time domain system that allows us to measure the electric field, and the effective refractive index of the propagating waves.

2. Antiresonant fibers
The fiber structures investigated consist of six tubes, arranged in a hexagonal array. The transmission properties and a picture of three fibers are shown in Fig. 1. Two different materials have been used for the fibers here presented: poly(methyl methacrylate) (PMMA) and polyurethane (PU). PMMA is a lot more flexible than silica [3], but still quite rigid when the size of the tubes is in the order of millimeters. Polyurethane, instead, is much more flexible and can be bent even in rods of the centimeter level. The PU fiber was also drawn to a smaller size to prove the ability of scaling such structure by fiber drawing. The fibers exhibit the transmission typical of antiresonant fibers [1] and the spacing of the transmission minima is consistent with the thickness of the layers.

![Fig. 1. Transmission spectra through 10 cm of the antiresonant fibers and photograph images of the fibers cross-section. The thickness of the tubes is ~300 µm for the PMMA antiresonant fiber (top), ~250 µm for the small PU antiresonant fiber (middle), and ~500 µm for the larger PU fiber (bottom).](image)

We also analyzed the spectral features as function of the time delay of the fibers to obtain information about the effective index and the dispersion of such waveguides. Fig. 2 shows the spectrograms of the reference pulse, of the PMMA antiresonant fiber and of the larger of the PU fibers. As it is possible to see, the low frequency components of the fibers experience a larger dispersion compared to the higher frequency components. This is probably related to the larger mode and overlap with the material. Interestingly, we also measured this behavior being stronger in the tube lattice fibers (negative curvature) compared to simple suspended-tube antiresonant fibers (not shown here).
3. Twisted hollow-core antiresonant fiber

The large PU fiber was then used to demonstrate a simple method to realize a twisted hollow-core fiber and to do it in a reversible manner. The fiber was fixed on one end (where the light was coupled in the fiber), while the other end was progressively rotated counter clockwise, inducing a twist in the tube structure and subsequently clockwise to return to the initial position. Fig. 3 shows a section of the fiber before twisting and at maximum twist and the transmission spectra at different twisting and untwisting steps. The maximum twist rate was of about 0.89 rad/cm.

Two main spectral features changes can be observed with twist: the central frequency of the band at lower frequency is blue-shifting while maintaining the same transmitted power; and the high frequency transmission dip (ca. 0.9 THz) is red shifting and the transmission at higher frequencies is decreasing. The shift of the transmission band and of the dip could be explained by a change in effective index due to the twist. While the loss of transmission could be attributed to coupling to cladding modes, typical of twisted PCFs and of long period grating structures.

To confirm the behavior, we analyzed the spectrogram of the different twisted stages which showed an overall increase of the effective index with increasing twist and an increasing dispersion towards the low frequency.

4. Conclusions

We showed a simple way of making a twisted hollow-core fiber that can also be tuned in twist rate. Moreover, we investigated the dispersion properties of antiresonant fibers both twisted and not. We will continue the investigation by looking at the field distribution of the modes, comparing the results to theory and simulations and we aim at scaling the structure down in size and therefore in wavelength.

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References