Controlling Acousto-Optic Interactions in Photonic Crystal Fiber with Sub-Wavelength Core-Hole

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Abstract: The quasi-Raman interaction between confined acoustic phonons and light in PCF is strongly altered by the introduction of a sub-wavelength hole running axially through the core. Coupling calculations and forward scattering spectra illustrate the effect.

OCIS Codes: (060.2280) Fiber design and fabrication; (290.5830) Scattering, Brillouin.

1. Introduction

Tight simultaneous confinement of light and sound in the core of a photonic crystal fiber (PCF) was recently demonstrated, opening up new possibilities for improved all-fiber acousto-optic (AO) devices [1,2]. Other experiments demonstrated the ability of such fibers to suppress the optical interaction with phonons leading to higher stimulated Brillouin scattering (SBS) thresholds [3] and optimization of quantum-noise limited devices [4]. All these results relied on the ability to manipulate the acoustic eigenmodes through the micro-structure of the fiber cladding. In this paper we demonstrate how control of the acousto-optic interaction can be improved by introducing a tiny sub-wavelength bore in the center of the core of a highly-nonlinear PCF.

The central position of the hole strongly disturbs the optical and acoustic properties of the fiber. The sharp glass-air interface allows the build-up of intense evanescent optical fields within the hole [5]. Simultaneously, the strain induced by the acoustic eigenmodes is completely reshaped within the annular glass region. We show experimental evidence of such changes by the comparison of the forward scattering spectrum of such a fiber with that of a conventional highly-nonlinear solid-core PCF. To support these results we also present numerical modelling of the optical and acoustic modes of such fibers.

2. Results & discussions

We focused our investigations on two different fibers: a conventional highly-nonlinear PCF with a 1.78 μm solid-core (Fig. 1a, inset), and a highly-nonlinear PCF with a 1.68 μm core but with a centered ~350 nm bore (Fig. 1b, inset). In our setup we launched light from a linearly polarized CW laser (1550nm, 150kHz linewidth) at 45° with respect to the birefringence axis into the fibers. The polarization modulation induced by thermally excited phonons was measured using a polarization spectroscopy technique [6]. At the exit from the fibers, a polarizer converted polarization modulation into amplitude modulation, which was amplified in a low-noise EDFA and detected by a fast (~20 GHz) photodiode. Finally, the photocurrent was analysed with a radio frequency spectrum analyser. In order to avoid differences that could arise from the differing fiber losses, we ensured that both shared the same effective fiber length - about 8 meters. The experimental data together with SEM pictures of the tested fibers are shown in Fig. 1.

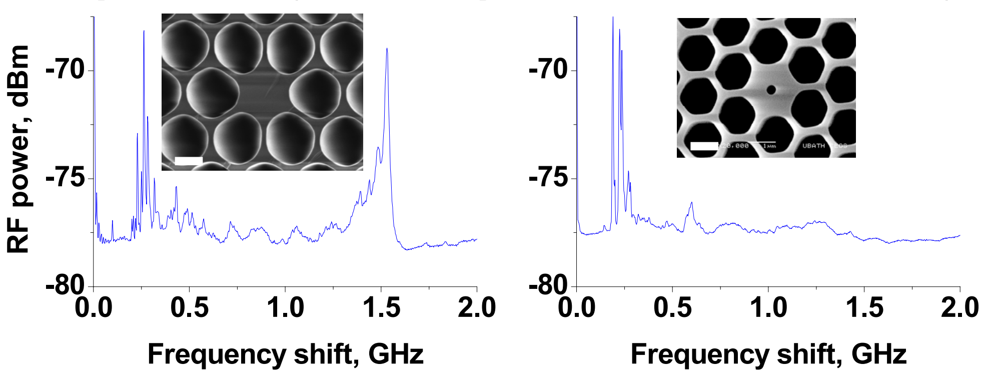

Figure 1: Depolarized forward scattering spectra for ~1.7 μm diameter core PCF; the thick white bars in the insets corresponds to 1 μm. Both spectra were measured using heterodyne detection. The vertical scale is logarithmic and both fibers shared the same effective length of 8 m. In a) one can identify a strong low frequency cladding resonances (~250 MHz) but also higher frequency ones at 1.53 GHz. In b), although the strongest low-frequency scattering of cladding resonances displays the same efficiency as in a), no peaks are observed at higher frequencies.

In Fig. 1 it can be seen that the strong core-trapped resonances in the conventional PCF (~ 1.5 GHz) were not apparent in the hole-core fiber, even though strong low-frequency cladding modes (~ 250 MHz) were detected in both fibers at roughly the same signal-to-noise ratios. As the core diameters of the fibers were almost the same, one would expect the same strength of scattering from the core resonances.

In order to investigate whether the suppression of the core-trapped resonances scattering was due to the bore we performed numerical simulations for the optical and acoustic modes of this structure using the finite element method (FEM). The optical modes were calculated using a full-vectorial FEM code based on isoparametric edge elements considering 4 complete rings of air-holes as the fiber cross-section, whereas for the acoustic modes we used a cross-section with one complete ring of air holes as a plane-strain problem in FEMLAB, which is a good approximation as long as one is concerned only with Raman-like (cut-off) acoustic modes. Given the acoustic strain field, a straight-forward calculation leads to the induced permittivity perturbation [7]. The spatial overlap between the optical fields and the permittivity perturbation is a crucial parameter in the acousto-optic interaction. In Fig. 2 we show the calculated density plots of these quantities to point out the strong changes induced in the optical and acoustic modes due to the presence of the small bore in the core. Fig. 2a and 2b represent the amplitudes of the electric field horizontal component of the HE_{11}–like mode for the holey-core PCF and the solid-core, respectively. The strain-induced permittivity changes ($\Delta\varepsilon_{xx}$) are shown in Fig. 2c and 2d. One can see, by comparison of Fig. 2a and 2c with Fig. 2b and 2d, that the inner bore induces significant changes in the optical modes and in the perturbed permittivity. One interesting feature in Fig. 2a and 2c is that perturbed permittivity changes sign over a loop around the bore, while the optical mode remains positive. This could lead to reduced AO coupling. Further numerical investigation of the actual AO coupling coefficient and its dependence on the size of the geometrical features should provide additional understanding of the suppression of the high-frequency resonances.

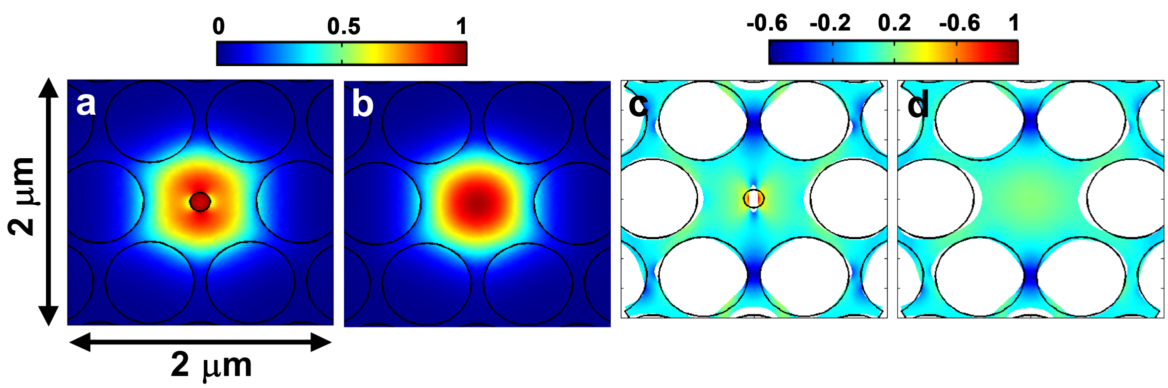

Figure 2: Calculated optical modes and permittivity perturbation. (a),(b) show the amplitude of the electric field horizontal component of HE_{11}–like modes of the hole-core and solid-core PCF, respectively. The color scale is in arbitrary units but ensures that the optical modes carry the same optical power. (c),(d) show the calculated amplitude of the permittivity perturbation ($\Delta\varepsilon_{xx}$) induced by the acoustic strain in the hole-core and solid-core PCF, respectively. The distorted shape corresponds to the structural motion of the fibers. The color scale is in arbitrary units and the acoustic modes were normalized to have the same vibrational energy.

3. Conclusions

The presence of a sub-wavelength hole running down the axis of a PCF core represents a new degree of freedom for controlling acousto-optic interaction. In the fiber investigated, strong suppression of core-trapped acoustic resonances was observed. Numerical modelling indicates that the changes arise from the redistribution of both optical and acoustic energy within the PCF core.

4. Acknowledgements

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5. References

[1] Dainese, P. et al. "Raman-like light scattering from acoustic phonons in photonic crystal fiber," Opt. Express **14**, 4141-4150 (2006).
[2] Beugnot, J. C., et al. "Experimental observation of core guided acoustic wave Brillouin scattering in photonic crystal fibres," in ECOC 2006.
[3] Dainese, P. et al. "Stimulated Brillouin scattering from multi-GHz-guided acoustic phonons in nanostructured photonic crystal fibres". Nature Physics **2**, 388 - 392 (2006).
[4] Elser, D. et al. "Reduction of guided acoustic wave Brillouin scattering in photonic crystal fibers". Phys. Rev. Lett. **97**, 133901 (2006)
[5] Work done in a collaboration between CePOF and the University of Bath – submitted for publication.
[6] Shelby, R. M., Levenson M. D., and Bayer P. W. "Guided acoustic-wave Brillouin scattering". Phys. Rev. B. **31**, 5244–5252 (1985).
[7] A. Yariv and P. Yeh, Propagation and control of laser radiation (John Wiley & Sons, 1984), Chap. 9.