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Studying New-Generation Hollow-Core Fibers for Acousto-Optic Sensors

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Abstract— We demonstrate highly efficient modulation of a tubular lattice hollow core fiber by means of flexural acoustic waves. The acousto-optic parameters required for fluid sensing are numerically and experimentally investigated. The results point out high sensor's sensitivity to characterize fluid properties, such as refractive index, density, and viscosity.

Keywords—acousto-optic sensor, tubular lattice hollow core fiber, fluid sensing.

I. INTRODUCTION

All-fiber acousto-optic devices modulate the properties of optical fibers using tunable acoustic waves [1], [2], [3]. These devices are also used as sensors when the acoustic amplitude or period is changed by the medium surrounding the fiber [4], [5], [6], [7]. Additionally, optical fibers provide good resistance to characterize chemical and food substances. In cases requiring the temporal characterization of a fluid, such as viscosity, acousto-optic sensors provide linear response over a wide viscosity range [4], [5].

Fig. 1(a) illustrates the intended acousto-optic sensor setup, composed of a fluid container and a tubular lattice hollow core fiber (TL-HCF) fixed on a piezoelectric transducer (PZT) [7]. The PZT radially vibrates when excited at specific resonant frequencies and voltages, compressing, and extending the HCF. The resulting flexural acoustic wave modulates the HCF's power spectrum (P), as illustrated in Fig. 1(b). The induced bends couple power between the fundamental LP_{01} and a higher order mode LP_{1x} , modulating a notch in the spectrum with modulation depth η_1 . The fluid is further inserted in the container around the fiber and covering the HCF. The pressure forces applied by the fluid reduce the acoustic amplitude and the modulation depth, as illustrated in Fig. 1(c). Thus, the modulated spectrum allows obtaining a dynamic measurement of the changing fluid properties. In standard fibers-based sensors, however, the acoustic energy are mostly distributed over the fiber cladding, reducing the overlap with the optical modes. In contrast, the HCF's

geometry provides high overlap of the coupled optical modes and the acoustically modulated refractive index, which is promising to increase the sensor's sensitivity [8]. In addition, the new concept of the HCF-based sensor in Fig. 1(a) does not require the complex and costly techniques and facilities employed to produce the previously reported sensor's components, e.g., acoustic horn, fiber Bragg gratings (FBGs), and long period gratings (LPGs), which increase the device size, time response, and cost [4], [5].

Here, we numerically and experimentally demonstrate the modulation of a TL-HCF by means of flexural acoustic waves, corresponding to the preliminary stage of the sensor in Fig. 1(b). The acoustic and optical properties of the HCF are simulated employing the finite element method (FEM). The power and wavelength tuning of the acousto-optic device are evaluated. The results indicate a promising and highly efficient broadband tunable filter able to measure fluid properties, offering a simpler device compared to previous studies.

II. NUMERICAL AND EXPERIMENTAL STUDY

Fig. 2(a) shows the employed TL-HCF with 8 tubes with dimensions described in [1]. The HCF's cross section is

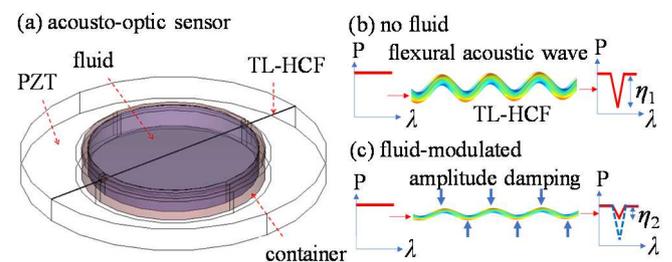


Fig. 1. Illustration of the (a) acousto-optic sensor [7] indicating the piezoelectric transducer (PZT), tubular-lattice hollow-core fiber (TL-HCF) and fluid. (b) The flexural acoustic wave induces a resonant notch in the HCF's transmission spectrum with modulation depth η_1 . (c) The fluid damps the acoustic wave amplitude changing the modulation depth to η_2 .

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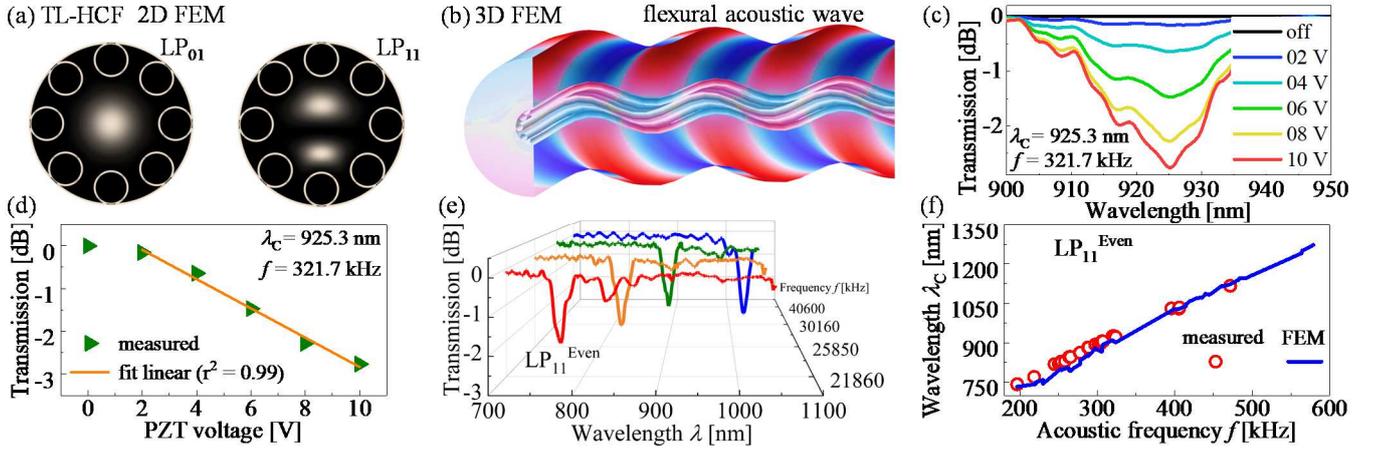


Fig. 2. (a) 2D FEM simulated power profile of the modes LP_{01} and LP_{11} in the TL-HCF. (b) 3D FEM simulation of a flexural acoustic wave in the TL-HCF. (c) Unmodulated (off) and modulated spectra with voltage up to 10 V. (d) Voltage response at $\lambda_c = 925.3$ nm and $f = 321.7$ kHz. (e) Samples of the modulated spectra showing the wavelength tuning of the mode LP_{11}^{Even} and its total (f) measured-simulated spectral-frequency response from $f = 196$ to 579 kHz [8].

modeled employing the FEM-based COMSOL Multiphysics and the methodology described in [8]. The effective refractive indices, n_{01} and n_{11} , of the modes, LP_{01} and LP_{11} , are respectively computed for the wavelength range of $\lambda = 743 - 1355$ nm (Fig. 2(a) shows the simulated power profile of these modes in the HCF).

The 2D HCF's modeled geometry is further extruded along 7.7 cm to generate a 3D fiber component [8]. The fiber is further excited by a sinusoidal force in the frequency range of $f = 196 - 579$ kHz, and the acoustic period Λ is computed. Fig. 2(b) shows an arbitrary flexural acoustic wave simulated in the HCF. The resonances' center wavelength, λ_c , is calculated using the phase matching relation, $\lambda_c = (n_{01} - n_{11})\Lambda$, considering the computed parameters from the 2D and 3D simulations. The experimental setup and characterization of the modulated TL-HCF is described in [1]. Fig. 2(c) shows the HCF's measured modulated spectrum for a voltage range from 0 to 10 V at $f = 321.7$ kHz (the PZT is off at 0 V). The voltage response at $\lambda_c = 925.3$ nm is shown in Fig. 2(d). Note that the modulated power scales almost linearly with voltage. Fig. 2(e) shows the modulated resonance corresponding to the mode LP_{11}^{Even} (the HCF supports the even and odd LP_{11} modes due to birefringence [1][3]). Fig. 2(f) shows the tuning of λ_c with increasing frequency, indicating good agreement between the measured and simulated results.

Overall, our study shows that the HCF's high modulation performance is mainly caused by the reduced silica content in the fiber and by the strong overlap of the coupled modes in the air core. Additionally, the large air core increases the strain and modal superposition with the acoustic wave in the cladding. Further advance might suggest the characterization of the modulated HCF interacting with fluids (next stage of the sensor's development in Fig. 1(c)). Changes in the modulation depth and spectral-frequency response caused by the fluid properties are expected. It might enable the fabrication of the acousto-optic sensor in Fig. 1(a), which does not require acoustic horns, gratings, or mirrors, resulting in a simpler, fast, and compact device.

III. CONCLUSION

We have investigated the interaction of a TL-HCF with flexural acoustic waves. The silica reduction and strong modal overlap in the HCF enhance the modulation depth. It indicates that changes in acoustic amplitude caused by a varying fluid parameter might be measured by monitoring the modulation depth. In addition, the HCF's modal parameters provide an almost linear broadband spectral tuning, which might be useful to overcome fluid absorption bands limiting devices based on permanently inscribed LPGs [5]. The results indicate higher modulation strength in TL-HCFs than in the standard optical fibers. The demonstrated HCF's acousto-optic features are promising to increase the sensor's sensitivity, offering great potential to measure fluid properties such as viscosity and refractive index in industrial applications.

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