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# Curvature sensing with a hybrid-lattice hollow-core photonic crystal fiber

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**Abstract**—We report on curvature sensing measurements using a hybrid Kagomé-tubular hollow-core photonic crystal fiber. The sensing principle is based on bending-mediated resonant couplings between core and airy cladding modes achieved at specific curvature radii and wavelengths. We consider that our investigation identifies a promising use of hollow-core fibers in sensing, thus broadening the application framework of this family of fibers.

**Keywords**—fiber optics, photonic crystal fibers, hollow-core fibers, sensor, curvature

## I. INTRODUCTION

The research achievements on the technology of hollow-core photonic crystal fibers (HCPCFs) have been bountiful in recent years. Indeed, as HCPCFs now stand as the lowest loss fiber optics working from the ultraviolet to the infrared [1, 2], the impact of such development is expected to benefit a wide range of fields, both fundamental and applied, allowing this class of fiber optics to act as an enabling technology for the new steps in photonics.

The remarkable advances in the HCPCF field have greatly relied on the optimization of the fabrication procedures and the development of the fiber designs. In this context, a HCPCF design of particular interest is the so-called hybrid Kagomé-tubular (HKT) HCPCF [3], which displays a hybrid cladding structure formed by an inner cladding of untouched tubes (as in tubular-lattice HCPCFs) embedded into an outer Kagomé cladding. Such a structure allows allying effective single-mode operation to ultralow transmission loss thanks to the inner cladding capability of resonantly filtering the undesired core higher-order modes (HOMs) and the strong confinement power of the Kagomé outer cladding. This fiber architecture has achieved HOM extinction ratio values as high as 47 dB and loss figures as low as 1.6 dB/km at 1050 nm [3].

In this paper, we explore the application of a HKT HCPCF as a curvature sensor by assessing the resonant coupling between the core fundamental mode and the airy cladding modes due to bending. This approach has been theoretically studied previously using a different fiber design [4-6], however, the investigation we report herein is the first experimental study on the application of a HKT HCPCF

acting as a bending sensor. We understand that our demonstration widens the application scenario of HCPCFs in curvature sensing and, together with other approaches based on different HCPCF designs and methods [4-6], can be identified as a promising alternative for monitoring bend variations.

## II. CURVATURE SENSING WITH A HKT HCPCF

Fig. 1a shows the cross-section of the HKT HCPCF we use herein. Its structure exhibits an inner cladding formed by a set of six tubes connected to an outer Kagomé cladding. The inner cladding tubes have a thickness of 1.25  $\mu\text{m}$  and an internal diameter of 19.5  $\mu\text{m}$ . The struts that define the Kagomé structure are 850 nm thick, and the diameter of the fiber core is 33.5  $\mu\text{m}$ . Fig. 1b shows the transmission spectrum of a 2 m-long fiber between 770 nm and 1050 nm.

When a hollow fiber that displays a tubular lattice is bent, the alteration of the effective refractive index of the core mode due to bending can lead to phase-matching and subsequent resonant coupling to the airy modes supported by the tubular structure [7, 8]. In fact, this coupling is verified at specific curvature radii, typically referred to as critical radii,  $R_{cr}$ , which can be accounted by Eq. (1) for the situation in which one considers the coupling between the core fundamental mode and the fundamental mode of the cladding tubes, and a curvature made along the direction of one of the cladding tubes. In Eq. (1),  $D_{core}$  is the fiber core diameter,  $d_{in}$  is the inner diameter of the cladding tubes,  $\lambda$  is the wavelength, and  $u_{01} = 2.405$  is the first zero of the Bessel function  $J_0$  [7-9].

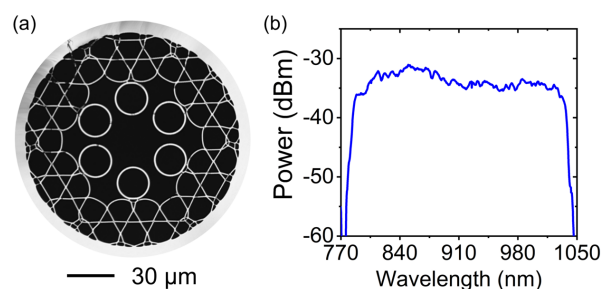


Fig. 1 (a) Cross-section of the HKT HCPCF and (b) its transmission spectrum between 770 nm and 1050 nm (fiber length: 2 m).

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$$R_{cr} = \frac{\pi^2 D_{core} d_{in}^2}{\lambda^2 u_{01}^2} \left[ 1 - \frac{d_{in}}{D_{core}} \right]^{-1} \quad (1)$$

Observation of Eq. (1) allows recognizing that if one bends the fiber with a radius  $R_{cr}$ , coupling between the modes in the core and cladding tubes will occur around a certain  $\lambda$ . As the loss of the cladding tubes' modes is larger than that of the core mode, one can expect a transmission dip to appear around such wavelength, corresponding to the situation in which the coupling between the modes has been verified. If, in turn, we alter the fiber bending radius starting from  $R_{cr}$ , we can expect the transmission dip to shift from its original position, thus allowing the platform to act as a curvature sensor.

To test the operation of the sensing scheme studied here, we used the experimental setup depicted in Fig. 2a. With the aid of alignment mirrors (M1 and M2) and a coupling lens (L1), light from a supercontinuum source (SC) has been coupled to the HKT HCPCF. To subject the fiber to different bending conditions, we used a system comprising a fixed wall and a movable platform connected to a motorized translation stage (Fig. 2a). By suitably placing the HKT HCPCF in between the walls and by moving the motorized translation stage, we could controllably alter the fiber bending radius while monitoring the fiber transmission spectrum in an optical spectrum analyzer (OSA).

Fig. 2b shows the transmission spectra of the HKT HCPCF corresponding to the situation in which it was not bent (reference, black dashed line), and for the cases that it has been bent at representative bend radii. By examining the plot shown in Fig. 2b, we see that the bend application generated a transmission dip, whose spectral position shifted as we altered the fiber bending conditions, as we could predict from Eq. (1). The shadowed region in Fig. 2b highlights the spectral region where the transmission dip arising from the bend-mediated coupling between the core and cladding modes occurred. Zoom in this spectral region (between 900 nm and 975 nm) is shown in Fig. 2c for better visualization of the dip shifting due to the bending conditions alterations (as indicated by the red arrows in Fig. 2b and 2c).

Fig. 2d exhibits as blue circles the wavelength corresponding to the minimum of the resonance seen in Fig. 2c as a function of the absolute value of the critical radius variation ( $|\Delta R_{cr}| = |R_{cr} - R_{cr0}|$ , with  $R_{cr0} = 4.45$  cm). Also, Fig. 2d displays as a dashed black curve the expected trend of the wavelength variation as a function of  $|\Delta R_{cr}|$  that we can calculate from Eq. (1) using the geometrical parameters of the fiber we used herein, *i.e.*,  $d_{in} = 19.5$   $\mu\text{m}$  and  $D_{core} = 33.5$   $\mu\text{m}$ . Observation of Fig. 2d informs that the measured  $|\Delta R_{cr}|$  values agree with the corresponding ones predicted by Eq. (1). Additionally, although the dependence of the resonance spectral position on  $|\Delta R_{cr}|$  is not linear, one can linear fit the experimental data so as to estimate our device's sensitivity. The dotted red curve in Fig. 2d stands for the linear fit of the experimental data ( $R^2 = 0.9995$ ) from which we can estimate a sensitivity of  $(7.97 \pm 0.06)$  nm/mm.

### III. CONCLUSIONS

We described the application of a HKT HCPCF in curvature sensing measurements. To do so, one assessed the bend-induced coupling between the fiber core and cladding modes at specific bending radii and evaluated the resonance shifting as the fiber bending radius was varied. This allowed us to demonstrate a curvature sensor with a sensitivity of  $(7.97 \pm 0.06)$  nm/mm. We believe that the method we studied herein

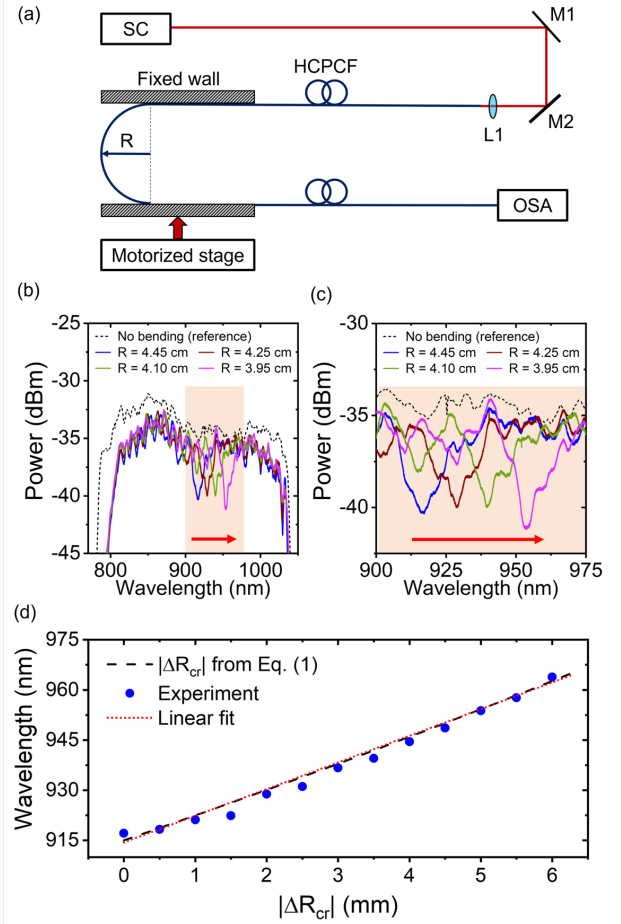


Fig. 2 (a) Representation of the experimental setup. SC: supercontinuum source; M1 and M2: mirrors; L1: lens; OSA: optical spectrum analyzer. (b) Transmission spectra of the unbended fiber (reference, dashed black line) and for representative bend radii (fiber length: 2 m). (c) Zoom between the wavelengths of 900 nm and 975 nm. (d) Resonance wavelength as a function of the absolute value of the critical radius variation ( $|\Delta R_{cr}|$ ). The dashed black curve corresponds to the  $|\Delta R_{cr}|$  calculated from Eq. (1) and the dotted red line is the linear fit of the experimental data.

affords an alternative means for the realization of curvature sensing using optical fiber-based platforms.

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