Optimizing Hollow Core Fibers for Stable Interferometry

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***Summary*—We present a hollow core fiber (HCF) with optimized thickness of coating and silica glass, calculate its thermal sensitivity including the effect of coating and compare it with earlier-reported HCFs. We experimentally demonstrate the optimized HCF with thermal phase sensitivity as low as 1.64 rad/K/m, which is 30 times below that of the standard single mode fiber.**

Keywords*— *Hollow-core fibers; Thermal sensitivity; Fiber interferometry

I. Introduction

Hollow core fibers (HCFs) propagate light through a central air (or vacuum) filled hollow core surrounded by a microstructure that enables light guiding even when the fiber is bent or coiled [1]. Guiding light in the hollow core rather than silica glass (as in traditional single-mode fibers, SMFs) has many advantages. For example, the phase of the light propagating through HCF changes with temperature up to 30 times less [2], which is of interest in many metrology applications that use optical fibers, e.g., for time and frequency transfer or for fiber interferometry. Here, we refer to this property as thermal sensitivity, i.e., HCF have a thermal sensitivity up to 30 times lower than SMF. Recently, improved HCF design and fabrication resulted in HCF attenuation as low as 0.174 dB/km [3], which is comparable to a typical SMF.

HCF thermal sensitivity can, however, degrade due to the protective fiber coating, typically made from acrylate polymer. Besides degrading the thermal sensitivity, coatings also have viscoelastic properties which introduce a time delay between the ambient temperature change and the light phase change, making compensation for temperature changes challenging.

To address this, we previously fabricated a 189 µm outer diameter HCF with only 10 µm coating thickness and demonstrated that the coating's viscoelastic properties effects on the fiber thermal sensitivity were strongly suppressed, especially when compared to a standard dual-coated fiber [2].

Here, we present experimentally an improved thinly-coated HCF. We significantly increased the silica glass jacket thickness to improve mechanical robustness, increasing the fibres outer diameter to ~300 µm. This is also expected to lower the fibre's acoustic sensitivity due to larger amount of glass as compared to HCF reported in [2][4]. Preliminary characterization of this optimized HCF is also shown here.

II. HCF Design and Fabrication

Thermal sensitivity of a coated HCF is mainly given by the thermal expansion coefficient α and Young's modulus E of the silica glass and coating [5]:

$$\alpha_{coated\ fib} = \frac{\alpha_{silica}E_{silica}A_{silica}+\Sigma_i(\alpha^i{}_{coating}E^i{}_{coating}A^i{}_{coating})}{E_{silica}A_{silica}+\Sigma_i(E^i{}_{coating}A^i{}_{coating})}, \quad (1)$$

where A denotes the cross-section area.

Fig. 1a shows the cross-section of the previously reported HCF [2] with silica outer/inner diameter of 185/70 µm and coating thickness of 10 µm. Here, we consider α_{silica}= 0.38 ppm/K [6], $\alpha_{coating}$= 180 ppm/K and Young's moduli of 72.5 GPa (silica) and 35 MPa (coating) [7][7]. Eq. 1 then gives $\alpha_{coated\ fib}$ of 0.40 ppm/K, which is 5% more than for a fiber without any coating (0.38 ppm/K). Considering the bendability of the fiber and limitations of our fiber draw equipment, we decided to draw an HCF with outer diameter of 300 µm and an internal structure similar to the previous design, i.e., a 70 µm micro-structure inner diameter. The coating thickness was 20 µm, due to fabrication constraints. These parameters were put into Eq. 1 giving $\alpha_{coated\ fib}$ of 0.41 ppm/K, which is very similar to our earlier design. The cross-section of the fabricated HCF is shown in Fig. 1b. Besides the geometry difference, there are fewer inner tubes in here-reported HCFs, which was reported to achieve lower loss [8].

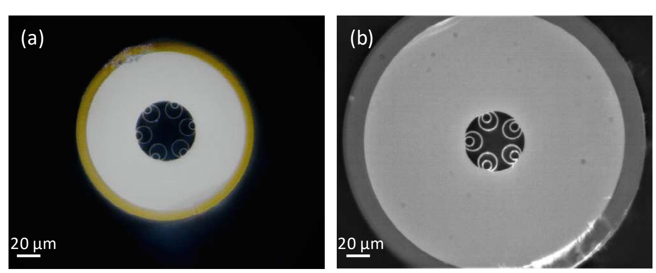

Fig. 1. Microscopy photograph of the cross-section of two thinly-coated hollow core fibers, (a) early version [2], (b) here-reported version.

III. EXPERIMENT AND RESULTS

To evaluate the thermal sensitivity of the fabricated HCF, we used experimental set-up shown in Fig. 2. A 39 m length of HCF (slightly longer than used in [2], where 24 m was used) was coiled in 14 cm diameter and spliced into a Mach-Zehnder interferometer (MZI) made of a 2×2 input coupler and a 3×3 output coupler. The 3×3 output coupler enables unambiguous phase change extraction including its sign [8]. The residual SMF in both branches were of the same length (within ±0.5 cm) to suppress the influence from the thermal sensitivity of SMF pigtails. We put the interferometer into a thermal chamber and placed a thermistor in the center of the coiled HCF under test. The light source was a narrow linewidth laser (RIO Orion from NuFern, emitting at 1558 nm), frequency-locked to a carrier-envelope offset (CEO) stabilized optical frequency comb to eliminate laser carrier frequency drift, which ensures the measured phase response is only due to the phase change in the fibers inside the interferometer rather than a drift in the central laser frequency.

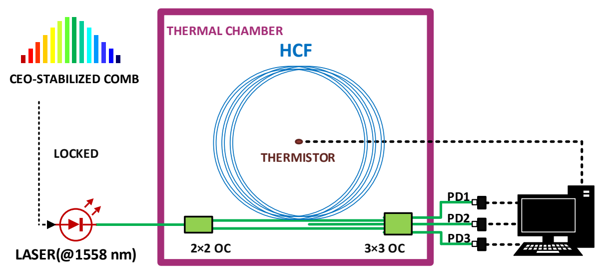

Fig. 2. Measurement set-up used to characterize thermal sensitivity of the manufactured thinly-coated HCF. CEO-stabilized comb: carrier envelope offset stabilized optical frequency comb; OC: optical coupler; PD: photodetector.

We first stabilized the temperature at 26^{O}C, then increased it to 40^{O}C, and kept it at this temperature for several hours. We recorded the temperature inside the chamber, and power at the three output photodiodes, which we used to retrieve the phase changes [8], Fig. 3a. Subsequently, we processed these data into a phase-temperature plot, which is shown in Fig. 3b.

From Fig. 3b, we see that the thermal response of HCF shows a linear relationship between accumulated phase change and temperature, which can be well fitted with a linear curve, which is also shown in Fig. 3b. Analyzing Fig. 3a and b suggests that the viscoellastic coating influence is strongly suppressed. For example, it would have introduced a phase drift at the end of the experiment, where the temperature is constant (Fig. 3a), as the viscoellastic coating would keep relaxing. This would have also resulted in a change in the slope of the curve shown in Fig. 3b towards the end of the experiment. The linear fit of Fig. 3b gives HCF thermal sensitivity of 1.64 rad/K/m, which is in line with our expectations.

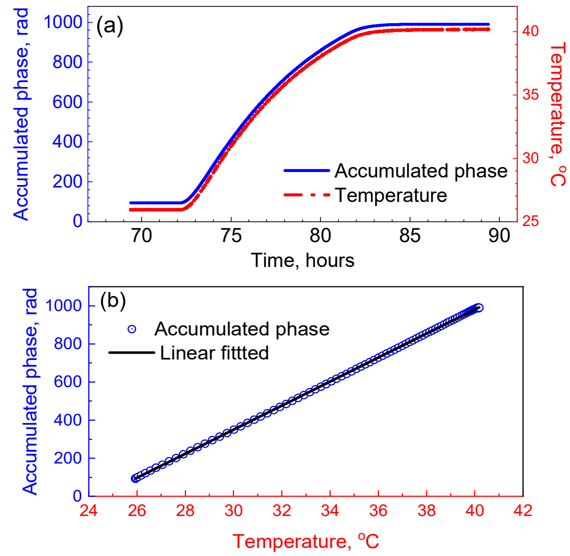

Fig. 3. Phase change of here-reported HCF in response to change in the temperature. (a) recorded over time and (b) extracted phase-temperature plot showing linear dependence with its slope corresponding to thermal sensitivity.

IV. CONCLUSIONS

We showed an HCF with optimized thickness of coating and glass, showing it to have a linear thermal response of the accumulated phase change. The thermal sensitivity as low as 1.64 rad/K/m was obtained in the temperature range of 26 – 40 ºC. Despite being thicker than standard fibers used today, it is still flexible to be easily coiled. At the same time, applied coating of a modest thickness should provide good mechanical strength. We believe this fiber to be of interest in many fiber interferometry scenarios, in which small and linear thermal response is strongly desired.

REFERENCES

[1] F. Poletti, "Nested antiresonant nodeless hollow core fiber," *Optics express*, vol. 22, no. 20, pp. 23807-23828, 2014.

[2] B. Shi *et al.*, "Thinly coated hollow core fiber for improved thermal phase-stability performance, " *Optics Letters*, vol. 46, no.20, pp. 5177-5180, 2021.

[3] G. T. Jasion *et al.*, "0.174 dB/km hollow core double nested antiresonant nodeless fiber (DNANF)," in *2022 Optical Fiber Communications Conference and Exhibition (OFC)*, 2022: IEEE, pp. 1-3.

[4] M. Pang *et al.*, "Detection of acoustic pressure with hollow-core photonic bandgap fiber," *Optics express*, vol.17, no. 13, pp. 11088-11097, 2009.

[5] V. Dangui *et al.*, "Phase sensitivity to temperature of the fundamental mode in air-guiding photonic-bandgap fibers, " *Optics Express*, vol. 13, no. 18, pp. 6669-6684, 2005

[6] G. K. White, "Thermal expansion of reference materials: copper, silica and silicon," *Journal of Physics D: Applied Physics*, vol. 6, no. 17, pp. 2070, 1973.

[7] https://focenter.com/wp-content/uploads/documents/AngstromBond---Fiber-Optic-Center-AngstromBond-DSM-3471-3-14-UV-Cure-Fiber-Re-Coating-(1Lt)-Fiber-Optic-Center.pdf

[8] G. K. Alagashev *et al.*, "Impact of geometrical parameters on the optical properties of negative curvature hollow-core fibers." *Laser Physics*, vol. 25, no. 5 pp. 005101, 2015.

[9] K. Koo, A. Tveten, and A. Dandridge, "Passive stabilization scheme for fiber interferometers using (3×3) fiber directional couplers," *Applied Physics Letters,* vol. 41, no. 7, pp. 616-618, 1982.