First demonstration of opposing thermal sensitivities in hollow core fibers with open and sealed ends

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It has been shown that both the output phase and propagation time of an optical signal propagating through a length of hollow core optical fiber (HCF) drifts with changes in environmental temperature significantly less than in conventional optical fibers. In all earlier experimental studies, however, the simplifying assumption was made that the thermo-optic effect of air was negligible. In this paper we present the first experimental demonstration that the air inside a HCF core can make an appreciable contribution to the fiber’s thermal sensitivity with the performance depending whether the fiber is open to the atmosphere, or sealed at both ends (e.g. spliced to solid fiber pigtails as is quite often the case in practice). We measure both the sensitivity of the accumulated phase as well as the signal propagation time for both open and sealed HCF and show that these are opposite in sign. Most importantly we show that the thermal sensitivity contribution from the air inside an open HCF has the opposite sign to the effect of fiber elongation (which is otherwise the dominant effect responsible for the overall thermal sensitivity of HCF). We then go on to show that these two effects can be used to balance each other out in order to achieve zero thermal sensitivity for both accumulated phase and propagation time. We demonstrate this property experimentally over a large spectral range.

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The signal propagation time through an optical fiber (referred to as ‘delay’ or ‘latency’) as well as the phase accumulated during the propagation vary due to environmental changes (temperature, vibrations, etc.), which is undesirable in a host of applications. For example, accumulated phase variations are highly problematic in all applications requiring interferometers – some of the most precise instruments that exist today (e.g., for use in metrology, fiber gyroscopes [1], gravitational wave detectors [2], etc.), and propagation delay variations are a major concern in applications requiring highly accurate time synchronization of (data) signals, e.g., for future 5G networks [3].

The temperature sensitivity of propagation time through an optical fiber is commonly characterized by the Thermal Coefficient of Delay (TCD):

, (1)

where  is the propagation time, *T* is the temperature, and *ng* the fiber mode group refractive index.

For accumulated phase, , we define the thermal phase sensitivity as:

(2)

where *neff* is the fiber mode (phase) effective index, and  is the wavelength. In Eqs. (1) and (2), the first term on the right-hand side represents contributions from changes in the group and phase indicies respectively (which are mostly due to the thermo-optic effect in silica glass), while the second terms relate to the thermally-induced fiber elongation ( and , respectivelly).

It has been shown that the thermo-optic effect in silica glass provides the dominant contribution to *TCD* and *S* in standard solid-core optical fibers [4], making them relatively sensitive to temperature. In HCFs, the light propagates primarily through air in which the thermo-optic effect is significantly weaker than in silica and the impact of this becomes comparable or smaller than that due to thermally-induced elongation. We elaborate on this later, as the interplay between the two effects is the main subject of our paper.

Over the entire transparency window of silica glass (i.e. from 400 to 2000 nm) with refractive index *n*, [5] and it can be shown that when neglecting the thermal sensitivity of air is always positive in any HCF at any wavelegth. Considering that silica glass has [5] it follows from Eq. (2) that *S*is always positive, which makes it impossible to achieve zero phase sensitivity (*S=0*). Interestingly, the situation is different for [6], at least for photnic bandgap HCFs in which becomes negative at wavelengths near the long-wavelength bandgap edge [6], making it possible to achieve *TCD = 0* (from Eq. (1)) in this wavelength range. Reaching *TCD = 0*, however, requires the local chromatic dispersion of the fiber to be about 80 ps/nm/km [6], which may be detrimental for some (e.g. telecomms) applications.

In the previous discussion, we neglected the thermal properties of air. However, as more than 99% of the light can propagate in air within a HCF [7], the temperature-induced change in *neff* and *ng* depends crucially on the thermal properties of the air and, as we show later, this cannot be always neglected. For a sealed HCF, the air inside the fiber keeps its volume (neglecting the small volume change due to HCF expansion [6]), while for an open HCF, the air inside will essentially maintain the pressure of the surroundings. In this paper, we show that this results in significantly different thermal behavior in HCFs that have open or sealed ends. Interestingly, for the open HCF case, this behavior allows full thermal insensitivity (in terms of both, *S*and TCD) to be achieved.

For simplicity, we consider dry, CO2-free air behaving like an ideal gas, atmospheric pressure, and an operating wavelength of 1550 nm. Using data from [8], we plot the phase refractive index of air *nair* in a sealed (constant volume) and open (constant pressure) HCF for various temperatures, Fig. 1(a). In our further analysis, we make an approximation that . At first, it may seem surprising that *nair* in a sealed HCF is almost insensitive to temperature while it is very temperature sensitive for an open HCF. This occurs because the density of the air inside a sealed HCF remains virtually constant with increasing temperature whilst for an open fiber, hotter air molecules escape from the fiber ends, maintaining the pressure but reducing the air’s density and thus its refractive index.

Fig. 1(b) shows the thermo-optic coefficient of air (calculated from the data in Fig. 1(a)). For the sealed HCF, it is negligible as compared to the effect of the HCF elongation ( [5]), meaning that the thermal properties of a sealed HCF are dominated by . For an open HCF, the situation is very different. Interestingly, the thermo-optic coefficient of the air is negative (Fig. 1(b)), having an opposite sign to that of the thermally-induced fiber elongation, so the two effects (partially) cancel each other out. At room temperature, has a slightly larger magnitude, but at temperatures above 107 OC, it becomes smaller than the fiber expansion, Fig. 1(b). This results in the interesting prediction that an open HCF should have a negative Sat temperatures below 105 OC; be completely insensitive to thermal changes near 107 OC (as the two effects completely cancel each other out), and becomes positive above this temperature. In what follows we verify these predictions experimentally. It is worth mentioning that the same prediction can also be made for the TCD (which, rigorously speaking, requires taking the chromatic dispersion of air into account, Eq. (1)).

The experimental set-up we used to measure both accumulated phase and signal delay sensitivity is shown in Fig. 2. The HCF was a 210-µm dimeter, 19-cell-design photonics bandgap HCF [7] with acrylate coating (outer diameter of 360 µm). To seal the fiber ends, we spliced them to a core-less solid-code fiber, which was about 1-2 mm long. We used a 4 m long fiber sample coiled with a 10 cm bend diameter and placed it along with a thermometer (resolution of 0.1 OC) between two metallic plates attached to two TEC heaters/coolers. The fiber under test was put into one arm of a free-space balanced (both arms of almost equal length) Mach-Zehnder interferometer. The interference pattern (interferogram) was recorded using an optical spectrum analyzer (OSA). The data acquisition and signal processing was different for measuring the accumulated phase changes and signal delay changes, which we explain in more detail below.



Fig. 1. (a) Refractive index of air and (b) its thermo-optic coefficient inside an open-ended (red dash) and sealed (black solid) HCF. The dash-dotted line shows where the thermo-optic coefficient of air has equal magnitude to .





Fig. 2. (a) Experimental setup (HCF sealed or open to the ambient atmosphere). (b) Sample of measured interferogram: the entire bandwidth is used to extract the spectral phase and delay is calculated as its derivative. For phase change calculation, spectral shift of interference pattern observed over 5 nm bandwidth and recorded as a function of temperature.

For accumulated phase change, we set the delay in the interferometer to obtain spectral interference fringes with a period of about 1 nm at the wavelength of interest (e.g., 1555 nm). Subsequently, we measured the spectrum over a limited spectral width (5 nm) and recorded changes in the interference pattern. As the interference pattern changed by over many tens of periods during the measurement, we needed to record data over short temporal intervals (hence the limited spectral width of the measurement) in order not to miss any interference pattern movement by one or more spectral periods. During the measurement we increased the TEC currents in steps (which resulted in a temperature change of about 10 OC) and always waited (~15 min) in between steps until the temperature stabilized (ensuring uniform temperature change cross the HCF sample).

The relative optical length change with temperature for open and sealed HCFs is shown in Fig. 3. Each point represents a change in the interference pattern by one spectral period (for relativelly fast changes) or a change by half the spectral period (for relativelly slow changes). The resulting Sis shown in Fig. 3 (as numbers above the curves) and in Fig. 4. The sealed HCF shows a relatively linear change of optical path length with temperature with a slope close to that expected simply from thermally-induced elongation (0.55 ppm/OC [8]). This is in line with our previously-published results [9]. For the open HCF, at room temperature, but this gets smaller as the temperature is increased, reaching zero around 113 OC and becoming positive at higher temperatures, see Figs. 3 and 4. As suggested earlier (Fig. 1(b)), this is due to being counter-balanced by air escaping from the HCF. Fig. 1(b) predicts that these two effects cancel each other out at 107 OC, which is close to the experimentaly-obtained value of 113 OC. Apart from being in very good agreement, this also suggests that we can use a simple model to predict Sin an open HCF: S + . For example, at T = 25 OC, this gives (Fig. 1): S 0.55 - 0.87 = -0.32 ppm/OC, which is very close to the value that we measured experimentally (-0.38 ppm/OC, Figs. 3 and 4).



Fig. 3. Relative optical path length change for sealed (squares) and open (circles) HCF. The numbers shown are the slopes of the curves, corresponding to S(in ppm/OC).  = 1560 nm.

We were curious as to how *S*changes over the HCF transmission window, especially close to the zero sensitivity temperature. As the interference pattern only changed very slowly we could sweep the measurement over a very large spectral range (which takes long time) without running the risk of missing a shift by more than one interference fringe in between any two scans. From this measurement, Fig. 5, we see that Schanges very little over the entire spectral window measured (by ±-0.01 ppm/OC over the wavelength range1520 - 1620 nm).

It is worth mentioning that similar results are expected for any geometry of silica-based HCF, since the observed effects result purely from the interplay between elongation of the HCF (determined by the properties of the silica glass) and the thermo-optic properties of air.

Subsequently, we characterized the signal delay. To measure it, we balanced the two interferometer paths at a wavelength of 1610 nm and then changed the temperature in 10 OC steps and for each temperature saved the entire interferogram (1440 - 1630 nm). By locating the spectral positions of constructive and destructive interference we then extracted the spectral phase. The signal delay through the fiber was calculated as the first derivative of the spectral phase. Details of this method can be found in [6].



Fig. 4. Phase sensitivity S calculated from data shown in Fig. 3c for sealed (squares) and open (circles) HCF.  = 1560 nm.



Fig. 5. Phase sensitivity Sfor open HCF at its zero sensitivity point (at  = 1560 nm) measured over the1500-1620 nm spectral range.

Figs. 6 and 7 show the difference in signal delay at various temperatures as compared to the delay measured at 15 OC obtained for sealed (Fig. 6) and open HCF (Fig. 7), respectively. The TCD calculated from the data in Figs. 6 and 7 is shown in Fig. 8. For clarity, only the most interesting results are shown: the temperature-averaged value for closed HCF and values for 20 OC (room temperature) and 110 oC (close-to-zero sensitivity temperature) for open HCF. For the sealed HCF, our results are similar to those we published previously [10] with a zero TCD point at the long-wavelength edge of the bandgap and relatively uniform TCD (fiber-elongation-dominated, over the majority of the bandgap (as predicted in [6] for this fiber and shown in [11]). However, as predicted by our earlier analysis presented here, the result is very different for open HCF, see Figs. 7 and 8. The TCD has an opposing sign as compared to the sealed HCF over the a large proportion of the bandgap and reaches values close to zero around 110 OC over a relatively broad wavelength range, Fig. 8.



Fig. 6. Normalized propagation delay for sealed HCF measured at various temperatures in respect to delay measured at 15 OC. Zero TCD occurs around 1610 nm.



Fig. 7. Normalized propagation delay for open HCF measured at various temperatures in respect to delay measured at 15 OC.

Finally, we also claculated the chromatic dispersion (for various temperatures) from the derivative of the delay, see Fig. 9. Values for open-end and sealed fiber were similar, so for the sake of simplicity we show the result of the sealed HCF only. We see that the largest change is observed at the long wavelength edge. This change is directly-related to the TCD properties and in particular the occurence of the zero TCD, as we have discussed in detail in [6].



Fig. 8. TCD calculated from the data in Figs. 6 and 7. For closed HCF (dash-dot, blue) the average value over the temperature range 15-115 OC is shown. For open HCF, the data for T = 20 OC (solid, black) and 110 OC (dashed, red) is shown. At 110 OC, close-to-zero TCD occurs for open HCF over the 1460-1560 nm spectral range.



Fig. 9. Chromatic dispersion at three temperatures for sealed HCF. The short-wavelength edge of the bandgap is shifts at a rate of -16 pm/OC, while the long wavelength edge shifts by 45 pm/OC, meaning the bandgap center shifts by ~29 pm/OC.

In conclusion, we have measured the phase and delay sensitivity of air filled HCF under open and sealed conditions. Regarding the phase sensitivity, sealed HCF behaves as previously-published. However, we show here for the first time that open HCF exhibits very different and interesting behavior – with negative phase thermal sensitivity at room temperature but with its value crossing zero (zero sensitivity) at a temperature of 113 OC. This suggests zero thermal sensitivity HCF can be made, e.g., by drilling holes from the side periodically (as demonstrated, e.g., in [12]). We expect the zero sensitivity temperature could be tuned (e.g., moved to room temperature) by controlling the density of the air inside the HCF, for example through ambient pressure control. Close-to-zero sensitivity is observed aross almost the enitre transmission window with a very weak spectral dependence (e.g., at 113 OC, it is within ±0.01 ppm/OC over 100 nm bandwidth).

Furthermore, we also complemented our phase measurements by measuring the sensitivity of signal delay to temperautre (characterized by the TCD) in HCF. In this instance, it is important to mention that the fiber used was a photonic bandgap HCF, which we previously-demonstrated has a zero crossing TCD at the long-wavelength bandgap edge. The sealed fiber behaved as previously-demonstrated (although the new measurements presented here were carried over a wider temperature range and with more data points). The zero TCD point lies between 1606 and 1620 nm over 15-115 OC temperature range. For open HCF, the TCD behaved similarly to the phase sensitivity and was dominated by the negative temperature sensitivity the refractive index of air at constant pressure (physically, air molecules escape from the fiber core as the fiber is heated up, reducing the refractive index of air inside the HCF). Thus, as opposed to selaed HCF, open HCF can be used to simultaneously obtain both zero phase and time delay sensitivity.

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