In-fiber modal Mach-Zehnder interferometer based on the locally post-processed core of a photonic crystal fiber

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Abstract: We demonstrate a novel, compact and low-loss photonic crystal fiber modal Mach-Zehnder interferometer with potential applications to sensing and WDM telecommunications. By selectively collapsing a ~1-mm-long section of a hole next to the solid core, a pair of modes of the post-processed structure are excited and interfere at its exit. A modulation depth of up to ~13 dB and an insertion loss as low as 2.8 dB were achieved. A temperature sensitivity of ~53.4 pm/°C was measured, making the device suitable for temperature sensing.

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References and links

1. Introduction

Since their first demonstration, photonic crystal fibers (PCFs) have made possible the development of new optical devices for a wide range of areas, such as sensing, metrology and optical communications [1]. These devices are a direct consequence of the unique optical properties of PCFs, which, in turn, derive from their distinct waveguide geometry. Recently, many PCF post-processing techniques have been developed [2–8], which has allowed for this geometry to be locally and permanently altered, thus enabling fiber structures that are optimized for specific goals. Among these structures are all-fiber Mach-Zehnder interferometers [6–17], in which orthogonal modes play the role of the interferometer’s branches. In recent years, PCF-based modal interferometers have been actively studied and proposed for a wide range of applications such as signal demodulation in optical communications [10] and strain [5–8,11–14], temperature [14,15], refractive index [13,16], pressure [13] and chemical [17] sensing. This type of interferometer has long been investigated in conventional fibers [18], with PCFs offering the advantage of a greater control over the characteristics of the excited modes and improved sensitivity to measurands, in the case of sensor applications.

Structural modifications in PCFs have been increasingly studied as means to enable interferometers in PCFs. In one case, a PCF was tapered and its holes locally collapsed to generate a section that supported several modes [6]. In most cases, however, the local fiber modifications are generated at the device input and output to induce coupling between the involved PCF modes. As with conventional fibers [18], long-period gratings have been employed to this end [8,9]. Another reported approach has been to locally collapse the holes of the PCF either at points along its length [8] or next to splices between the PCF and singlemode fibers [12,13,15,17] or other PCFs [7]. The complete microstructure collapse over some hundreds of micrometers along the PCF excites either cladding modes [8,10,11,13] or higher-order core modes [7,14,15,17] that interfere with the fundamental core mode. A similar effect can be obtained by radially offsetting the fibers to be spliced [10,11] or by splicing dissimilar fibers, thus allowing for the excitation of more than one core mode in the PCF [14]. In all reported cases either cladding modes, which are generally lossy, are exploited or the original PCF has to present a multimode core. Also, in most cases [7–17], the reported interferometers are tens to hundreds of millimeters long, which for sensing applications may limit the achievable spatial resolution.

A powerful and versatile PCF post-processing technique, to date not exploited for the development of Mach-Zehnder interferometers, was demonstrated by Witkowska et al. [4,5]. It produces structural modifications to the PCF by submitting different microstructure holes to distinct air pressure levels during a tapering process. Holes that are subjected to lower pressures tend to collapse during tapering, giving rise to solid regions that can either work as additional cores or modify the pre-existent core shape. The selective expansion of holes has also been demonstrated using a similar approach [19].

In this work we propose and demonstrate a low-loss, compact and robust all-fiber Mach-Zehnder interferometer, fabricated via a simplification of the technique proposed by Witkowska et al. [4,5]. In it, differential pressure and heat from the arc discharge produced by a fiber fusion splicer were used to locally collapse one hole next to the core, giving rise to an enlarged elliptical core. Light reaching the post-processed region naturally excites this core asymmetrically, thus exciting more than one mode. Therefore, the original core does not need to be multimode nor cladding modes need to be excited, which results in a robust interferometer design. Millimeter-long interferometers are demonstrated, which may be exploited for the development of discrete sensors with high spatial resolution.
2. Post-processing method

A longitudinal cut to the proposed interferometer based on a post-processed PCF is schematically shown in Fig. 1(a). At the post-processed region (circled) the core is formed by the original core and the collapsed channel. To achieve this geometry, we used a commercial PCF (Newport model F-NL-5/1040), the cross section of which can be seen in Fig. 1(b). It has a core diameter of 4.8 μm and a cladding hole diameter and pitch of 1.6 μm and 3.4 μm, respectively. One hole next to the solid core was locally collapsed using the following method. First, a ~1 μm outer diameter micropipette was employed to deploy a droplet of optical adhesive (Norland Products NOA73) at the entrance of the selected hole. The adhesive was subsequently cured with UV light, thus sealing the hole input. Then, all holes were collapsed at the opposite fiber tip by an electric discharge of an optical fiber arc fusion splicer.

Finally, the setup shown in Fig. 2 was used to pressurize and locally heat the PCF. The PCF end with a single sealed hole was fixed to the tip of a syringe, which in turn was connected to an air compressor. This assembly was attached to a computer-controlled motorized uniaxial translation stage with a repeatable incremental movement of 0.8 μm. A section of the fiber, located a few centimeters from its end, was positioned at the fiber fusion splicer and the air compressor was turned on, producing a pressure increase of ~5 bar in all holes except the sealed one. The fiber splicer then produced an arc discharge that locally heated the PCF. The sealed hole, with a lower internal pressure then collapsed generating a solid region. The arc current, arc duration and air pressure were chosen so as to collapse only the sealed hole, while all other holes kept approximately their original dimensions.

This procedure allowed a channel length of ~200 μm to be collapsed. The motorized translation stage was then used to axially displace the PCF by 150-180 μm before the procedure was repeated. Individually post-processed regions were, therefore, stitched together, which made possible to obtain control over the device length. We observe that this method can be regarded as a simplification of the technique described in [4,5], in which fiber tapering is not necessary (because the required fiber modification is sufficiently small) and a conventional fiber fusion splicer replaces the flame as a heat source. After cleaving both fiber tips, the post-processed PCF was optically characterized.
3. Interferometer structure and analysis

When the mode of the original PCF reaches the modified region it ceases to be a waveguide mode, becoming a superposition of modes of the new structure. As the cross section of the original PCF core overlaps with only one half of that of the modified core, excitation of a few low order modes is achieved. These modes then evolve independently with different propagation constants. At the end of the post-processed region, if the accumulated phase difference is a multiple of $2\pi$, the original transverse intensity distribution is recovered and light can couple back into the pristine PCF core. Otherwise, part or all the light is lost to the cladding. The two limits of the modified core then naturally act as efficient beam splitters and combiners, resulting in low interferometer insertion losses.

Considering, for simplicity, that only two modified-core modes are excited and that $\Delta n$ is their modal index difference, the wavelengths for which recoupling to the original core is achieved are given by [12]

$$\lambda_m = \frac{\Delta n L}{m},$$

with $L$ being the interferometer length and $m = 1,2,3\ldots$ The expected transmission spectrum then presents a modulation with a period

$$\Delta \lambda = \frac{\lambda^2}{\Delta n L}.$$ (2)

If a $\Delta n$ of the order of $10^{-2}$ is assumed, as reported in other interferometers that use PCF core modes [15], a spectral periodicity of ~100 nm can be expected for $\lambda = 1 \mu m$ $L = 1 \text{mm}$.

4. Device characterization

The post-processed PCF was characterized with the setup shown in Fig. 3, in which the radiation from a commercial infrared (800-1700 nm) supercontinuum light source (Toptica FFS-Cont) was coupled to one end of the PCF via an objective lens, being collected at the opposite end with another objective lens and a singlemode fiber (SMF) connected to an optical spectrum analyzer (OSA).

![Fig. 3. Experimental setup for optically characterizing the post-processed PCF.](image)

The transmission spectrum obtained with a post-processed PCF with a 1.5-mm-long collapsed hole is shown in Fig. 4(a). As expected, a modulated spectrum was obtained, presenting a 17-nm periodicity and a modulation depth of up to 9.5 dB. A single periodicity was observed to dominate over the whole measured spectrum (from at least 900 to 1600 nm), which indicates that two modes are preferentially excited within the interferometer. With the use of Eq. (2) a modal index difference of ~$4 \times 10^{-2}$ is calculated, which is of the same order of magnitude of those found in some other PCF interferometers that use core modes [15]. As in [15], the relatively high value of $\Delta n$ may indicate that one of the coupled modes is beyond its cutoff, but presents a sufficiently low loss along the short device length. Indeed, the modulation depth was observed to reduce for longer wavelengths (in some cases 0.5-dB depth observed at 1550 nm), for which the mode would be further away from cutoff.
Figure 4(b) shows the transmission spectrum of a post-processed PCF with half the collapsed length (0.75 mm). As expected, a longer modulation period is observed (~31 nm), which is reasonably close to the 34-nm period expected from Eq. (2) and the calculated $\Delta n$. The improved modulation depth of 12.7-dB with the shorter interferometer is consistent with the assumption that the higher order mode is beyond cutoff but may also be related to the limited axial homogeneity of the collapsed hole obtained with the stitching technique.

At the spectral range shown in Figs. 4(a) and 4(b), the measured modulation depth is suitable for both sensing and filtering applications, comparing favorably with those observed in a number of reported PCF interferometers [7,9,11,13,14] (the highest reported depths are of the order of 18 dB [10]). Figure 4(c) shows an optical image of light as it couples out from another PCF, which was cleaved at the modified region. It is seen that light is guided both via the original core and via the collapsed hole.

In order to test the axial homogeneity of the collapsed hole, a 10-mm-long post-processed sample was produced. Figure 5 shows optical microscope images of the cross section of this sample, cleaved at two different points along the modified region. It can be observed that the selected hole next to the solid core (red arrow) appears completely collapsed in Fig. 5(a) while in Fig. 5(b) it is not totally closed. Another hole next to the core (blue arrow) also appears almost closed, which was not a desired feature. In fact, Fig. 4(c) was obtained with this PCF sample and with the cross section shown in Fig. 5(a) at the output. It can be seen in Fig. 4(c) that, indeed, a second hole adjacent to the core also carries an optical intensity that is higher than that of the surrounding holes.

The optical transmission spectrum of the 10-mm-long sample (not shown) exhibits a lower modulation depth (~2 dB) and a less regular periodicity. Although the lower depth is in line with the assumption that one of the coupled modes is beyond cutoff, and agrees with the result reported in [14], both these spectral features are also believed to be a consequence of the lack of axial homogeneity. Work is under way to improve the post-processing system, but for high homogeneity the flame-brushing technique may be necessary. In any case, the interferometer is observed to present a better performance for short post-processed lengths, for which the use of the splicer is demonstrated to be suitable.
4.1-Insertion loss

The insertion loss of the modified PCF structure was determined around a wavelength of 1550 nm by tuning an external cavity semiconductor laser to one of the interferometer transmission maxima and by measuring its power in the PCF after and, subsequently, before the post-processed region. Measured losses mounted to ~2.8 dB, which are significantly lower than those of most PCF interferometers, as insertion losses of up to ~9-10 dB have been reported [7,10,15,17]. The low insertion loss, together with compactness, are the main achievements of our device. Further loss reduction may be possible if its axial homogeneity is improved.

4.2-Temperature dependence

In order to test the interferometer applicability to sensing, the temperature dependence of the transmission spectrum was characterized. To this end a modified PCF sample with a 1.5-mm collapsed length was placed on a Peltier element and temperature was varied in the 24°C to 42°C range. A fiber Bragg grating written on a conventional fiber was placed on the Peltier next to the PCF to provide a reference for the temperature measurements. Figure 6(a) shows some obtained transmission spectra around a single transmission peak. Figure 6(b) shows the corresponding peak wavelength position dependence on temperature, from which a sensitivity of ~53.4 pm/°C can be observed. This sensitivity is, in absolute value, about four times that of a fiber Bragg grating and ~7 times that of other PCF-based interferometers [14,15]. As in other reported PCF interferometers [14,15], a blue shift is observed, rather than the red shift expected from silica’s positive thermo-optic coefficient. In Eq. (1) both $L$ and $\Delta n$ depend on temperature, with $\Delta n$ varying both because of the change in silica’s refractive index and because of modal redistribution in the air-silica structure [14]. The negative sign of the temperature sensitivity indicates that the latter effect dominates. Note that any parameter that affects $L$ or $\Delta n$, such as strain and pressure [12,13], can, in principle, be sensed.

5. Conclusions

A new kind of all-fiber modal Mach-Zehnder interferometer was proposed and demonstrated, which is based on a solid-core PCF with a short section of a hole next to the core collapsed. When light reaches the modified section, two waveguide modes are preferentially excited, thus composing two interferometer branches. A 1.5(0.75)-mm-long device presented a spectral modulation with a periodicity of 17 (31) nm and a depth of ~10 (~13) dB. This depth can possibly be increased by improving the post-processing method but is already comparable to those of other PCF modal interferometers. The device’s compactness and low loss (2.8 dB) are its main assets. Applications to sensing and WDM communications are envisaged.

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