Photonic crystal fiber modal interferometers for accurate refractometry

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ABSTRACT

We report on compact and simple refractive index sensors suitable for measuring indexes in the 1.320-1.432 range with high resolution. The devices are based on modal interference and consist of a stub of large-mode area photonic crystal fiber spliced to standard single mode fiber. In the splice regions the voids of the holey fiber are fully collapsed which allows the coupling and recombination of core and cladding modes. The devices are robust and highly stable over time. The interference patterns are observed in a broad wavelengths range. The devices operate in both reflection or in transmission mode.

Keywords: Photonic crystal fibers, modal interferometers, refractive index sensors, refractometers.

1. INTRODUCTION

Refractometry is important from both the scientific and technological point of views due to its numerous applications. On the one hand, the development of simple and compact refractometers is key for applications in industrial processing, quality control in food and beverage industries, etc. Refractive index sensors, on the other hand, are useful for studying different biological or chemical specimens. Optical fiber refractometers and refractive index sensors are attractive due to their small size, flexibility in their design, immunity to electromagnetic interference, network compatibility and the capability for remote and in-situ measurement. To design a functional optical fiber refractometer one needs to access the evanescent waves of the guided light without compromising the robustness of the device. In addition, an ideal refractometer or index sensor should be cost-effective and able to measure indices over a broad range with high resolution. Refractometers based on tilted Bragg gratings, long-period gratings, and some modal interferometers partially fulfill these conditions but they suffer from several drawbacks [1-11]. The fabrication, as well as the interrogation of Bragg and long period gratings (FBGs or LPGs), requires costly equipment. In addition, gratings are very sensitive to temperature, for example temperature fluctuations of just 1ºC shift the position of the gratings by several picometers. Modal interferometers are instead prone to drifts because they are susceptible to perturbations of the mode coupling conditions.

In this work we propose compact refractometers based on robust all-fiber modal interferometers fabricated via straightforward and well established fusion splicing. The device exploits the modal properties of photonic crystal fibers (PCFs) while the interrogation is carried out through conventional passive devices or pieces of standard optical fibers. The structure consists of a short piece of large mode area PCF, commercially known as LMA-8 (Crystal Fibre A/S, spliced to conventional single mode fiber (SMF). The fabrication of the device is simple, since it only involves cleaving and splicing processes that can be carried out in a standard fiber optics lab [12, 13]. The range of refractive indices that can be measured is quite broad, from 1.33 (aqueous environments) to 1.43 (biomolecules), with a resolution on the order of ~2.9×10^{-4}.

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2. DEVICE FABRICATION AND OPERATING PRINCIPLE

Photonic crystal fibers are characterized by a periodic pattern of microscopic voids that are present all along the fiber. The fabrication of interferometers with PCFs is therefore appealing. In our case a stub of PCF (LMA-8 Crystal Fiber) is fusion spliced to standard optical fiber (Corning SMF-28) with a conventional splicing machine (Fitel S122A). The diameter of the PCF is 125 μm which simplifies the aligning and splicing with the SMF-28. The splicing is carried out in such a way that the voids of the PCF get fully collapsed. However, this process introduces losses between 5 to 9 dB depending on the length of the collapsed region and the splicing conditions. After the splicing the PCF is cleaved with a standard cleaving machine so that the end of the PCF behaves as a mirror. Fig.1 shows the experimental set up and a micrograph of the PCF employed in drawing of the interferometer in reflection and transmission, and a diagram of the setup to interrogate it in reflection and transmission.

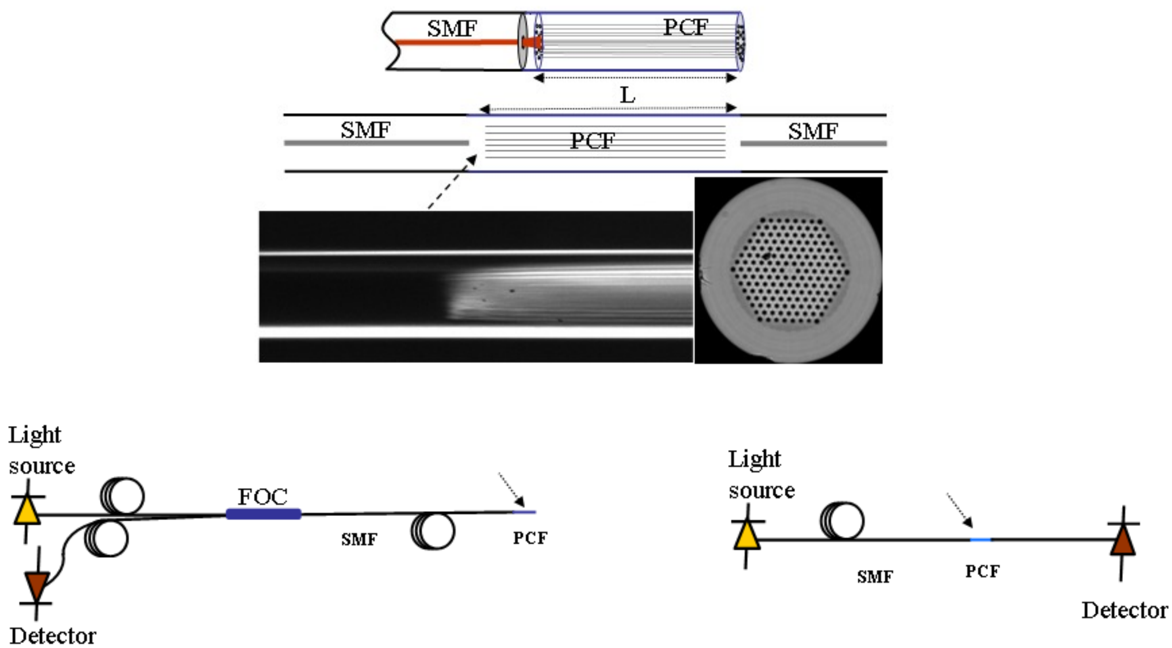
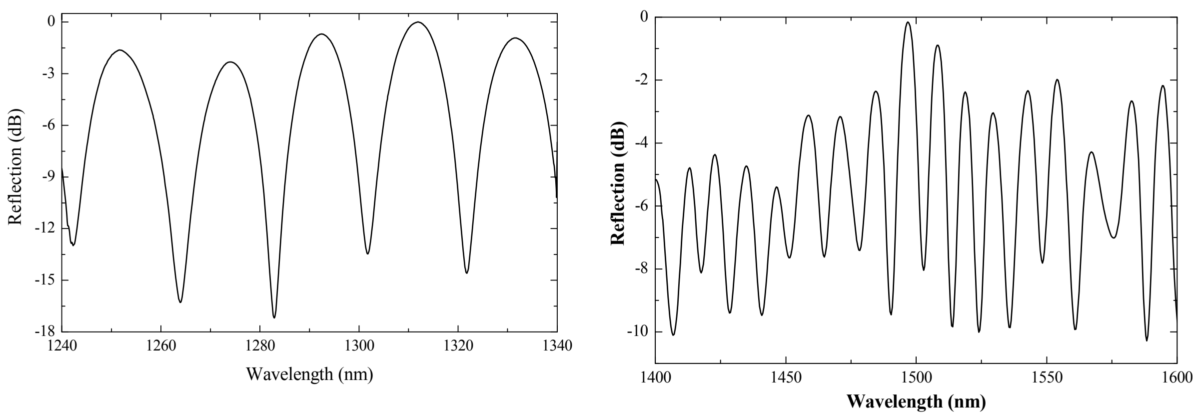


Figure 1. The drawing represents the interferometer in reflection and transmission. SMF stands for single mode fiber, PCF stand for photonic crystal fiber, FOC stand for fiber optic circulator. L is the length of the PCF. A micrograph of the PCF used in the experiments is shown. The diagram below shows the schematic of the experimental setup in reflection and transmission mode.

In a modal interferometer one needs an element or device that couples or excites two modes and one more to recombine them. In fiber-based interferometers those elements can be LPGs, misaligned splices, or the contracting and expanding zones of a taper. In our case the excitation and recombination of modes is carried out by a single splice in which the voids of the PCF are collapsed. The fundamental SMF mode begins to diffract -regardless the wavelength- when it enters the collapsed section of the PCF. Because of diffraction the mode broadens allowing the excitation of core and cladding modes in the stub of PCF [14]. Such modes propagate through the PCF until they reach the cleaved end from where they are reflected. When the reflected modes re-enter the collapsed region they are recombined in a SMF core mode. In case of transmission, after the PCF, the modes reach another solid piece of glass, i.e. the other end collapsed PCF region. They will thus further diffract and be recombined through the filtering of the subsequent SMF. The propagation constants of PCF core and cladding modes are different, in other words the modes propagate at different speeds. Thus, the modes accumulate a phase difference as they propagate over the PCF. The phase difference depends on the wavelength and also on the distance the modes travel. Thus if light from a broadband source is launched to the interferometer and reflected and transmitted light fed to a spectrum analyzer, a series of maxima and minima can be expected in the reflected and transmission spectrum.

3. RESULTS AND CONCLUSIONS

Figure 2(a) shows the reflection spectrum around 1300 nm of an interferometer in which the length of the PCF was only 12 mm. Note the truly sinusoidal pattern and the high fringe contrast that reaches 13 dB. From the interference pattern shown in Fig. 2(a) it can be concluded that only the core and a cladding mode participate in the interference. Figure 2(b) shows the reflection spectrum at longer wavelengths of a device fabricated with 24 mm of PCF. In this case the fringes become closer but the fringe contrast diminishes and the pattern is more irregular. The later indicates that several cladding modes participate in the interference. The results shown in fig. 2(a) and (b) demonstrate the broad wavelength range in which the interferometers can operate. This is posible since the splitting and recombining elements (a collapsed region in the vicinity of the splice) do not depend on the wavelength and are identical.



2 (a) 2 (b)

Figure 2. Reflection spectra of two devices, one with L = 12 mm and the other with L = 24 mm at different wavelengths.

In addition to the above features a high stability over time was expected since the splice is permanent. It does not degrade over time or with temperature. The stability of an interferometer or resonator is important for sensing applications since one measure the position of the interference or resonance peaks. In our case the drift in the interference was extremely small. Figure 3 shows the drift in the interference pattern as a function of time of a large device of 8 cm. The behavior of our interferometers at different temperatures was also studied by putting them on a hotplate capable of heating the interferometers from room temperature to 250 ºC. The interference patterns shifted to longer wavelengths as the temperature increased. The thermal sensitivity was found to be in the 6-8 pm/ ºC range.

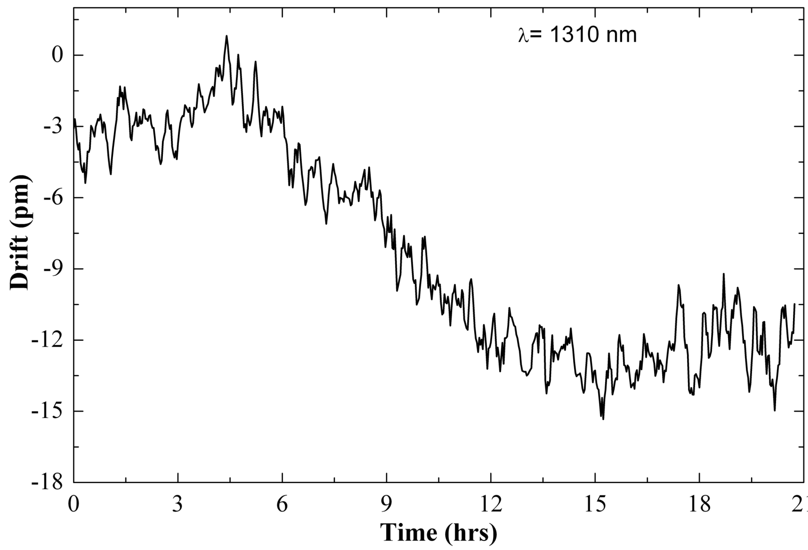


Figure 3. Drift as a function of time observed in an interferometer fabricated with 8 cm of PCF.

It is important to point out that our approach for refractive index sensing with PCFs is different than those based on tapers, diffraction, Bragg or long period gratings reported so far. In some of these approaches the measure of the indexes is carried out by filling the PCF voids with the liquids of interest. Although the sensitivity may be higher with this techniques infiltrating the voids of a PCF with liquids and positioning them on the grating is not a simple task. The cleaning of the PCF voids which is important for reusable devices is neither simple. The evanescent waves of cladding modes reach the external surface of the PCF thus making possible the interaction with liquids or layers. In this way the interaction is solely with the cladding mode since the core mode is isolated. Thus, by depositing a liquid on the PCF surface the propagation constant of the cladding modes can be modified. This is turn causes a change in the phase difference giving rise to a shift of the interference pattern. Figure 4 shows the shift measured for several indexes in an interferometer fabricated with 19 mm of PCF in reflection [15] whereas figure 5 shows shift measured for several indexes in an interferometer fabricated with 17 mm of PCF in transmission [16]. Cargille oils with calibrated indexes were used in the experiments.

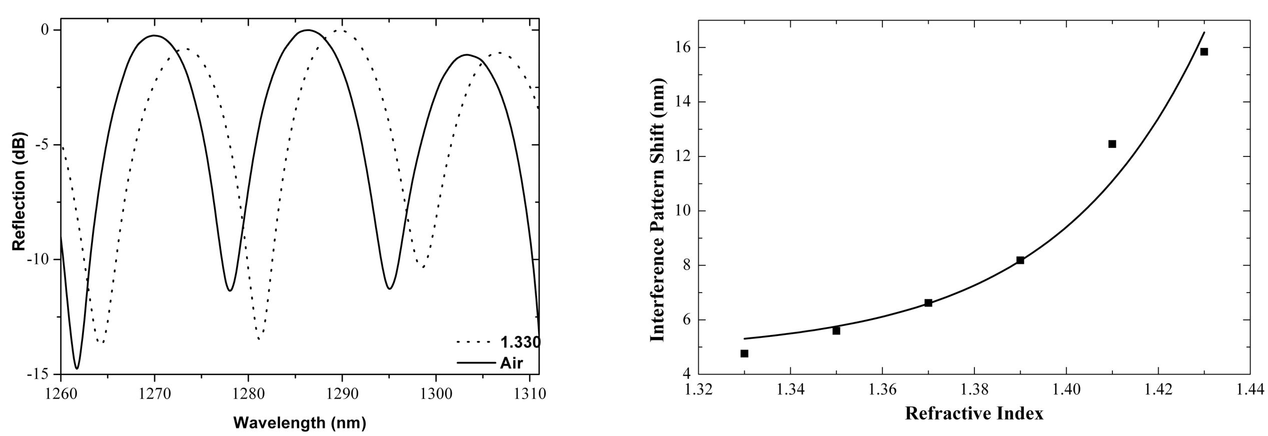


Figure 4. Shift of the interference pattern as a function of the external refractive index observed in a device fabricated with 19 mm of PCF. The squares are experimental data and the continuous line is a fitting to the data. The measurements were carried out at 1300 nm.

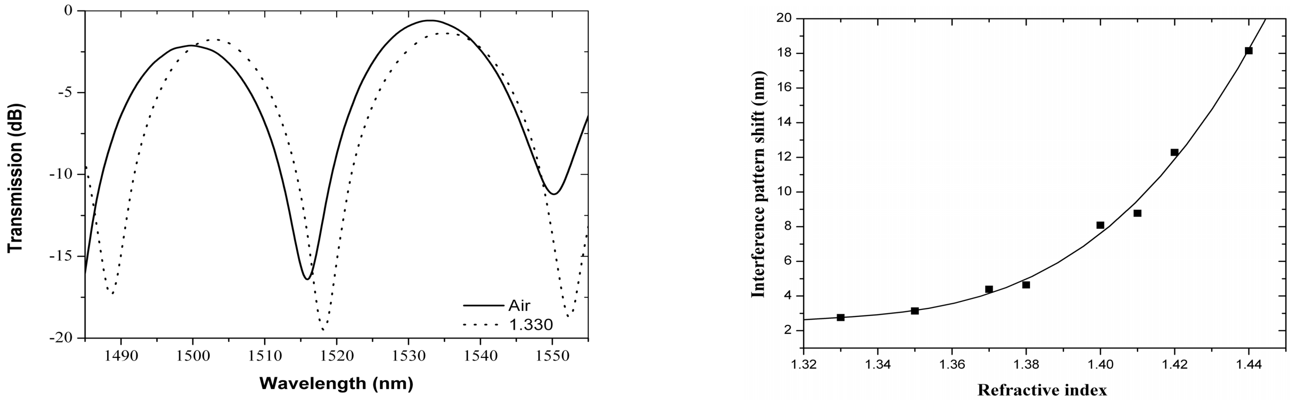


Figure 5. Shift of the interference pattern as a function of the external refractive index observed in a device fabricated with 17 mm of PCF. The squares are experimental data and the continuous line is a fitting to the data.

Only one drop of oil was deposited on the PCF, close to the splice (see Fig. 1), thus avoiding the infiltration of sample into their voids. Between consecutive measurements the fiber was cleaned with acetone and then dried to ensure similar conditions in each measurement. It can be observed from the figure that the shift of the interference pattern increases exponentially as the external index gets closer to that of the fiber.

In conclusion a modal PCF interferometer that operates in reflection and transmission was proposed. The fabrication of the device consists of splicing a stub of PCF with standard optical fiber. The device exploits the modal properties of PCFs but the interrogation is carried out with widely available optical fibers and components. The performance, stability, and refractometric applications of our interferometers were studied. In terms of stability of the device, the device is very much stable in both reflection and transmission. It is to be noted here that a smaller device shows much better stability in either mode of operation. Therefore the results are comparable for both modes of operation. In transmission, the operating wavelength range of the interferometer is an order of magnitude larger than that in reflection. In transmission, the interferometer can operate between 1200-1700 nm whereas in reflection the operating range is limited by the use of fiber optic circulator (FOC), i.e. about 50 nm. The measuring of refractive index in the 1.330-1.430 range was demonstrated.

Acknowledgements

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