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Ultrastable in reflection photonic crystal fiber modal interferometer for accurate refractive index sensing

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A compact in reflection modal interferometer consisting of a stub of large-mode area photonic crystal fiber (PCF) spliced to standard fiber is presented. In the splice, the voids of the PCF are fully collapsed allowing so coupling and recombining PCF core and cladding modes. The interferometer is highly stable over time and can be used for different applications. The measuring of refractive index in the 1.33–1.45 range with high sensitivity is demonstrated. Sensing applications based on refractive index changes are also feasible. © *2008 American Institute of Physics*.

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The measuring, monitoring, or sensing of refractive index is of scientific and technological importance. Refractive index is a fundamental material property for which its accurate measuring is crucial in many cases. In chemical, food, or beverage industries, the monitoring of refractive index is part of the quality control. On the other hand, the detection of minute refractive index changes is crucial in biosensing. For example, molecular bindings, chemical, or biochemical reactions are manifested (and consequently detected) as refractive index changes.[1] Owing to the broad range of applications just mentioned, there is a growing interest on optical fiber refractive index sensors or refractometers. Those based on all-fiber interferometers[2–13] or resonators[1,14–16] are probably the most attractive ones since they offer high sensitivity, wavelength codified information (absolute detection), and in most cases broad measuring range. However, they have also some drawbacks. Some interferometers, for example, have complex design, are fragile, or are instable. Resonators on the other hand depend on critical alignments to couple light in and out of them, which makes resonators really instable. Here an in-reflection modal interferometer based on photonic crystal fibers (PCFs) is proposed for accurate refractometry. The fabrication of the device is simple since it only involves cleaving and splicing. The device is compact, robust, and highly stable over time. In addition, the range of refractive indices that can be measured is broad ranging from 1.33 (aqueous liquids) to 1.45 (index closed that of the fiber).

PCFs are characterized by a periodic pattern of microscopic voids that are present all along the fiber. The design of the PCF microstructure is what gives these fibers superior modal and guidance properties than those of conventional fibers.[17] 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 and 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. Figure 1 shows a micrograph of the PCF employed, a drawing of the interferometer, and a diagram of the setup to interrogate it. To interrogate the interferometer, light from a broad brand source is launched to the PCF through a fiber optic circulator or coupler. The reflected light from the cleaved end is fed to a high-resolution optical spectrum analyzer controlled by a personal computer.

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 long period gratings (LPGs), misaligned splices, or the contracting and expanding zones of a taper.[2–13] 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.[18,19] 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. The split-

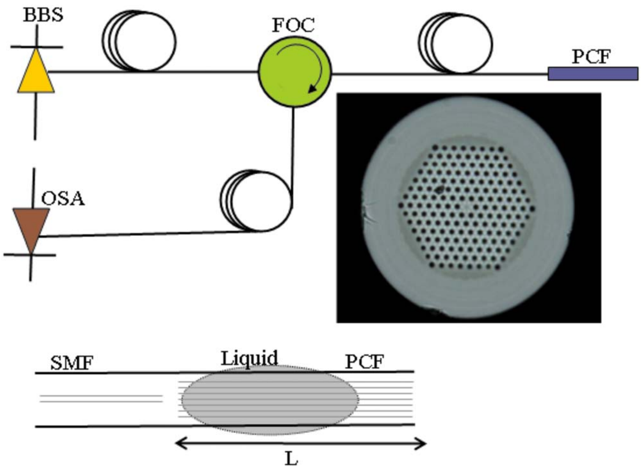

FIG. 1. (Color online) Schematic of the experimental setup. A micrograph of the PCF used in the experiments is shown. The bottom drawing represents the interferometer, being *L* the length of the PCF. BBS stands for broad brand source, FOC for fiber optic circulator or coupler, and OSA for optical spectrum analyzer.

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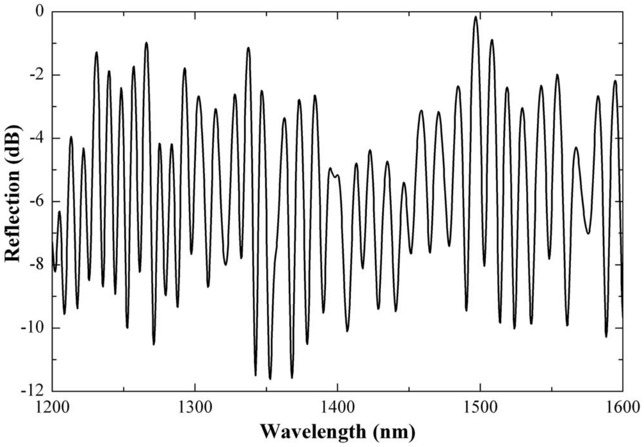

FIG. 2. Reflection spectrum of a device with $L=24$ mm over 400 nm.

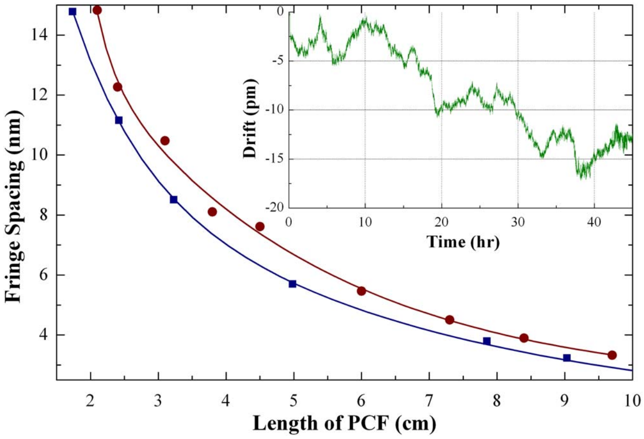

FIG. 3. (Color online) Average fringe spacing as a function of the length of the PCF measured in the 1250–1350 nm range (squares) and 1500–1600 nm range (dots). The continuous lines are fittings to the experimental data. The inset shows the average shift of the interference pattern at 1300 ± 50 nm as a function of time of a device with $L=5$ cm collected over 45 h.

ting and recombination of the modes is carried out by the same splice, which helps to improve the device performance. 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 broad band source is launched to the interferometer and the reflected light fed to a spectrum analyzer, a series of maxima and minima can be expected in the reflected spectrum.

Figure 2 shows the reflection spectrum of an interferometer in the 1200–1600 nm wavelength range in which the length of the PCF was 24 mm. Note the sinusoidal pattern, the high fringe contrast, and the broad wavelength range in which the interferometers operate. This is possible since the splitting and recombining elements (a collapsed region in the vicinity of the splice) do not depend on the wavelength and are identical. From the interference pattern shown in the figure, it can be concluded that more than two modes participate in the interference. The average fringe spacing as a function of the length of PCF at two wavelength windows is shown in Fig. 3. The fringe spacing in this type of interferometers decreases exponentially with the length of PCF. Note that interference patterns with periods below 5 nm can be obtained with compact devices thanks to the fact that light travels twice the PCF.

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 monitors the position of the interference or resonance peaks.[1–16] The inset of Fig. 3 shows the drift as a function of time of an interferometer fabricated with 5 cm of PCF. The graph was obtained by leaving the interferometer isolated on a holographic table and by tracking the position of the interference peaks every 30 s. A fiber Bragg grating interrogator (I-MON 400E-USB Ibsen Photonics) with 10 pm resolution was used to track the position of the interference peaks in time. The results shown in the figure demonstrate the ultrahigh stability over time of our interferometers. The behavior of our interferometers from room temperature to 250 °C was also studied. The interference patterns shifted to longer wavelengths as the temperature increased. The thermal sensitivity was found to be in the 6–8 pm/°C range.

After the characterization of the interferometers, we proceeded to exploit their applications for refractive index sensing. Note that 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. In Fig. 4, we show the interference patterns of a device with $L=19$ mm when the external medium was air and a liquid with refractive index of 1.390. The shifts measured with different indices are summarized in the same figure. The interference pattern shifts were measured by monitoring the positions of the maxima and minima in the 1250–1340 nm range. Cargille oils with calibrated indices were used in the experiments. Only one drop of oil was deposited on the PCF, close to the splice. Because of surface tension, the liquid spread out

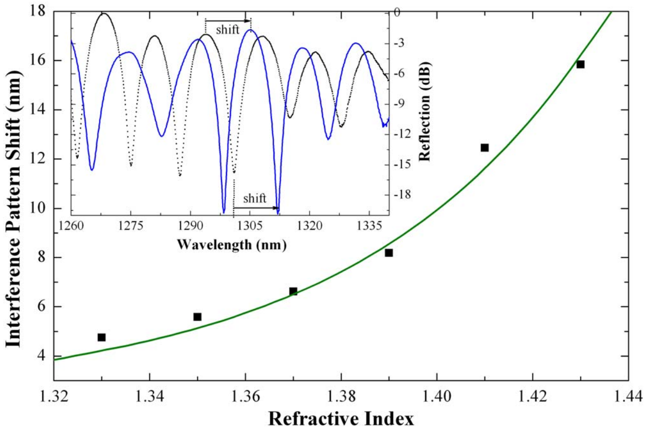

FIG. 4. (Color online) Shift of the interference pattern as a function of the external refractive index observed in a device fabricated with 19 mm of PCF. The squares are experimental data and the continuous line is a fitting to the data. The inset shows the interference patterns around 1300 nm of the device immersed in air and in a liquid with index of 1.390.

along the length of the PCF thus covering about two thirds of the photonic fiber, see Fig. 1. We set up the interferometers with a slight inclination to avoid the infiltration of sample into the PCF 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 Fig. 4 that the shift of the interference pattern increases exponentially as the external index gets closer to that of the fiber. In this regard, our interferometer behaves in a similar manner to those based on LPG. From the figure, the average refractive index resolution can be estimated. By assuming that a shift of 20 pm can be resolved, then the resolution is 1×10^{-4}, which is similar to that of commercial refractometers. In the region of higher indices (above 1.39) the estimated resolution reaches 7×10^{-5}. It seems possible to improve the resolution with longer devices.

It is important to point out that our approach for refractive index sensing with PCFs is different than those based on tapers,[4] diffraction,[20] Bragg or LPGs (Refs. 21–24) reported so far. In some of these approaches, the measure of the indices is carried out by filling the PCF voids with the liquids of interest.[20–22] 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.[21,22] The cleaning of the PCF voids, which is important for reusable devices, is neither simple.

In conclusion, a modal PCF interferometer that operates in reflection 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, only a single circulator or a coupler is required. The performance, stability, and refractometric applications of our interferometers were studied. High stability over time was observed in the devices. The measuring of refractive index in the 1.33–1.45 range was demonstrated. The interferometer can be coated with variable index films or biolayers for which it can be useful for chemical or biosensing applications. In these types of applications, refractive index changes over time are important to monitor.

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