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Carbon-nanotube-deposited photonic crystal fiber for refractive index sensing

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ABSTRACT

We present a novel fiber optic sensor based on the assembly of a thin film of carbon nanotubes (CNTs) onto a short length of photonic crystal fiber (PCF) which is spliced between two single mode fibers (SMFs). The assembly of the thin film was achieved via a simple and effective deposition method. The deposition of CNTs modified the sensing ability of the sensor, allowing it to work in the intensity encoding scheme, thus opening the sensor to the possibility of dual parameter sensing. The sensor exhibited a sensitivity of 36.1 dB/ RIU and 96.6 dB/ RIU within the ranges of 1.33-1.38 and 1.38-1.42 respectively.

Keywords: Fiber sensor, carbon nanotubes, photonic crystal fiber,

1. Introduction

Since its discovery in early 1996, Photonic Crystal Fibers (PCFs) have attracted a lot of research attention. Of particular interest is its application in the sensing field [1-14]. Various sensing configurations like tapering [2], using a polarization maintaining fiber [3], modifying the PCF into a sensor tip [4-6], using a fiber loop [7] and concatenating two PCFs [8], have been proposed to improve the sensitivity to temperature, strain and refractive index (RI) variations.

The conventional PCF sensor relies on wavelength encoding, where the sensor registers perturbations in the ambient environment through variations in wavelength of certain spectral features [9, 10]. Such a detection scheme is highly sensitive and not susceptible to fluctuations of the power source as long as the extinction ratio is high enough. However, it is prone to limitations from the free spectral range (FSR) of the spectrum. Such limitations would prevent the sensor from providing continuous real time measurements over the range of environmental perturbations.

In recent years, there has been an increase in the interest in the assembling of a thin film over the PCF being used as a sensor [11-14]. These coatings not only improve the sensitivity of the PCF sensors [11, 12], but also allow them to detect other forms of ambient environment perturbations like humidity [13, 14].

In this work, Carbon Nanotubes (CNTs) were used to assemble a thin film over a PCF sensor in a Mach-Zehnder Interferometer (MZI) configuration. A simple and effective airbrush technique was used to deposit the CNTs onto the PCF. The high RI of CNTs modified the entire sensing scheme and allowed for intensity encoding of variations in the ambient RI. This allows the sensor to be able to overcome the FSR limitations from conventional PCF sensors to detect a wider range of refractive indices (RIs) and also opens up the possibility of simultaneously measuring a second parameter through wavelength variations.

2. Fabrication of Sensor

The experimental setup is shown in Fig. 1. A 3 cm long PCF was spliced between two single mode fibers (SMFs). The PCF region was first treated with methanol to remove all impurities. CNT solution was prepared by sonicating CNT powder dispersed in Dimethylformamide (DMF) solution in a water bath. Light from an ASE source was coupled into the lead-in SMF and was subsequently interrogated at the lead-out SMF using an optical spectrum analyzer (OSA). The air brush technique was then

employed to evenly deposit a thin layer of CNTs onto the entire surface of the PCF. The spectrum was continuously monitored throughout the deposition process, as shown in Fig. 1. This allowed us to control the amount of CNTs to deposit onto the PCF so that a viable spectrum for sensing applications was still obtainable after the deposition process. The spectra for the PCF sensor in a RI environment of 1.0000 (air) before and after the deposition are shown in Fig 2.

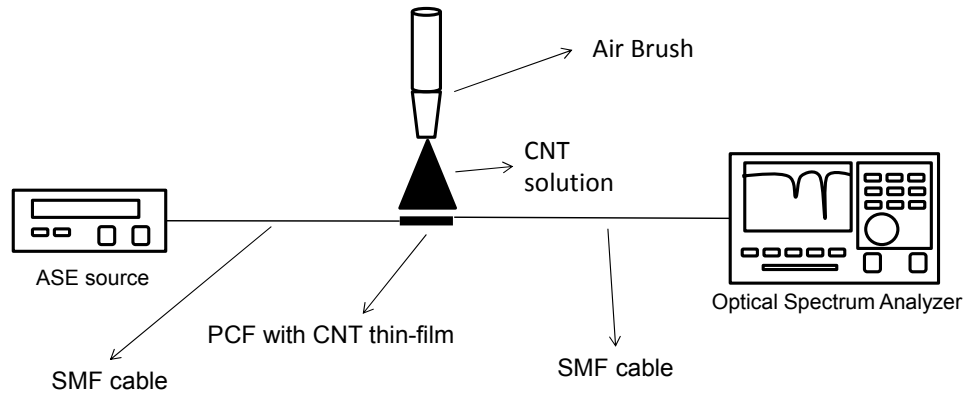


Fig. 1 Experimental setup for deposition of carbon nanotubes (CNTs) onto a PCF. The same setup is used for the refractive index (RI) sensing measurements after the coating of CNT thin-film.

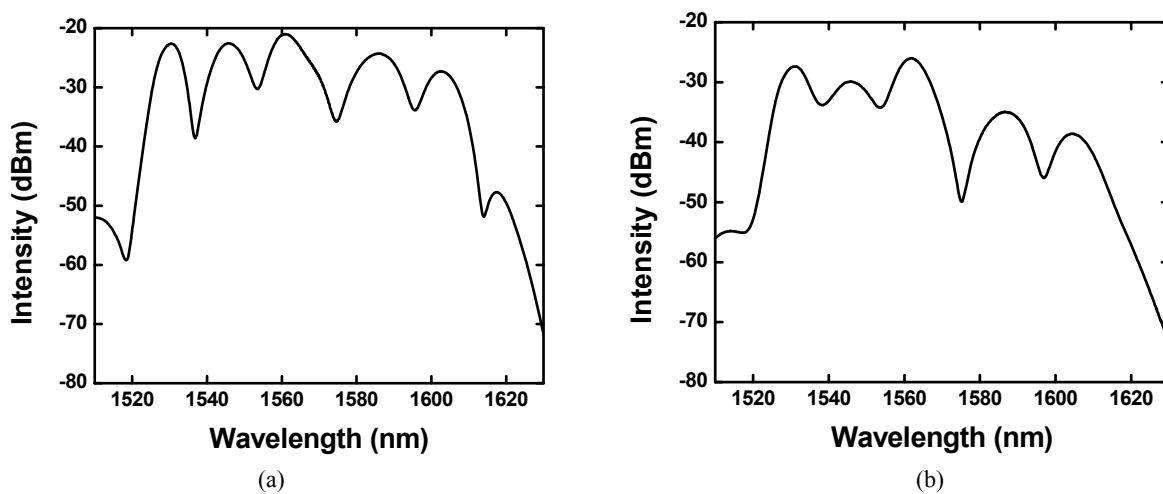


Fig. 2 Spectra of PCF in a RI environment of 1.0000 (air) (a) before and (b) after deposition of CNTs.

Fig. 2(a) shows the spectrum before deposition. The spectrum displays clear distinct dips at different wavelengths. The post-coated spectrum is shown in Fig. 2(b). As can be seen, the extinction ratios of the dips at wavelengths lower than 1575.28 nm have decreased while that of those at the wavelengths of 1575.28 nm and above has increased. The coated spectrum also experienced a slight power decrease of approximately 8 dB which could be attributed to differences in input power on both occasions and the absorption or the coupling out of certain power from the propagating modes in the PCF due to the coating.

3. Experimental Results and Discussion

Sucrose solution of different concentrations (and hence different RI) was used as the test solution. The experimental setup was similar to that shown in Fig. 1, except that the PCF was placed over a glass slide. The RI of approximately 1 ml of each solution was measured by a digital refractometer (Kruss DR201-95) with a resolution of 0.0001. The solution was then dropped on the PCF section. Care was taken to ensure that the entire PCF section was immersed in the solution for an accurate measurement of the RI. All measurements were carried out in an indoor environment at a constant temperature of 23 ± 0.1 °C to avoid any temperature induced errors in the results. The spectral changes were recorded on the OSA. At the end of each trial, the sensing element was thoroughly rinsed with de-ionized water and left to dry. Care was taken to ensure that the original spectrum in air was obtained (Fig. 2(b)) before the next measurement was carried out.

The spectral dip at 1575.28 nm (see Fig. 2(b)) was chosen to measure the variations in intensity resulting from the different solutions since it displayed the highest extinction ratio. Fig. 3(a) shows the variations in intensity for each solution used. As can be observed, the dip increases in intensity as the RI of each solution increases. There is a clear and distinct change in intensity of the dip for each RI measurement. Fig. 3(b) shows a plot of the intensity of the spectral dip with each RI measurement. The sensor was found to vary nonlinearly within the 1.33 to 1.42 RI range. This is in line with previous works which have shown that the relationship between the intensity and refractive index is nonlinear [15]. A sensitivity of 36.1 dB/RIU was obtained for the lower RI region from 1.33 to 1.38, and a sensitivity of 96.6 dB/RIU was obtained for the upper RI region from 1.38 to 1.42.

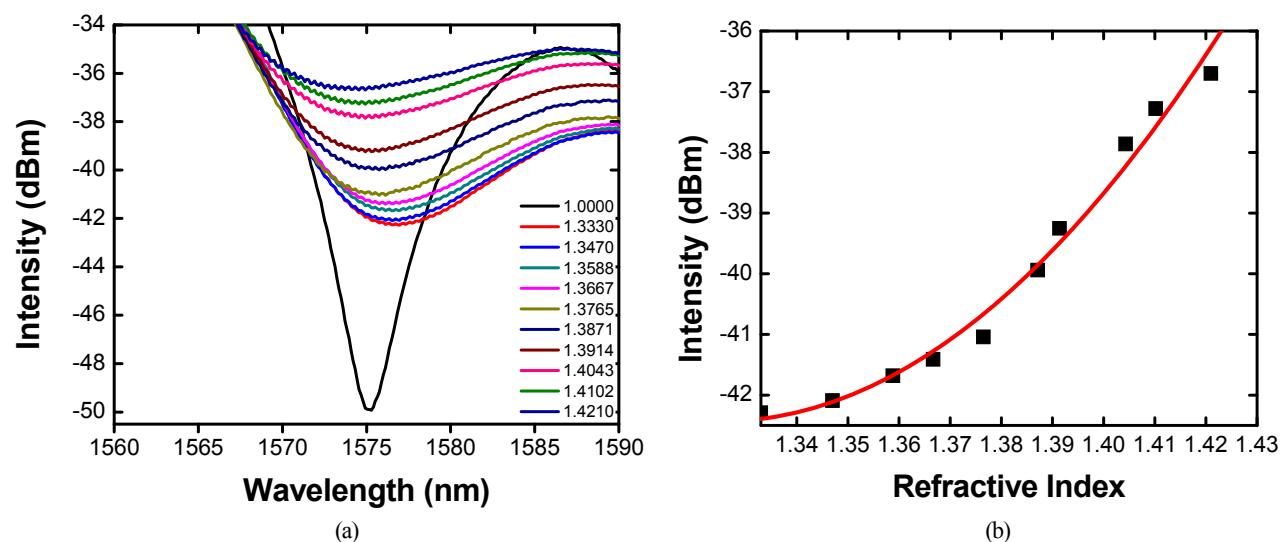


Fig. 3 (a) Variation of intensity of the spectral dip at 1575.28 nm with different RI. (b) Plot of intensity against refractive index for the CNT coated PCF.

Since the sensor encodes variations in RI with in its intensity, it is theoretically possible to measure a second perturbation to the sensor through wavelength encoding. A perturbation like strain, which has been shown to stimulate a wavelength shift in the spectrum [9], can be concurrently or individually measured. This would increase the sensors attractiveness as conventional sensing schemes are only able to detect strain or RI changes individually but not concurrently. By using intensity encoding, the sensor has also gained immunity to FSR limitations as compared to the conventional PCF sensors. However it will also experience the drawbacks of intensity based sensors like power fluctuations, which can be overcome by using better resolution equipment, using highly stable light sources, or employing better demodulation techniques. Lower running costs can be attained with this scheme if a band pass filter is used to filter the sensor from 1565 nm to 1585 nm and a power meter used to measure the intensity of light at the output end, which removes the need for an OSA.

4. Conclusion

In conclusion, we have presented a novel optical fiber PCF-MZI sensor which uses a CNT thin film to modify the sensing of a PCF fiber. The fabrication scheme is simple and does not require specialized equipment which makes it cost effective. The sensor exhibited a sensitivity of 36.1 dB/ RIU for a RI range of 1.33-1.38 and a sensitivity of 96.6 dB/ RIU for the RI range of 1.38-1.42. By using intensity to encode the variations in RI, wavelength encoding can be used to measure a second environmental perturbation, allowing dual parameter measurements, which is one of the directions for future works. Apart from that, the effects of film thickness and PCF length on the sensitivity will also be explored.

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