0.9-mm diameter holes from 22.0 dB/RIU for the single 0.9-mm diameter sensor, respectively, which agree well with the theory. The difference between the simulation and measured values also increases by the same factor. It means that the sensors with multiple holes especially need to have smoother hole surface to have negligible loss. Based on the above experimental observations, it can be concluded that we are able to obtain higher sensitivity with multiple-holes along the fiber axis. Table 1 shows the measured and calculated transmittance of single- and three-hole sensors for the liquids used in the experiments.

4. CONCLUSION

We proposed a high-sensitivity refractive index sensor structure in multimode POF with multiple in-line holes along the fiber axis. For proof of concept, we fabricated single- and multiple-hole sensors and measured sensitivity. For the case of single-hole sensors, sensitivity was measured to be 14.8 dB/RIU for the sensor with a 0.7-mm diameter hole and 22.0 dB/RIU for the one with a 0.9-mm diameter hole, respectively, in the refractive index range of 1.33–1.42. This result shows that the hole size increase leads to the sensitivity increase. To obtain higher sensitivity, multiple-hole sensors have been manufactured. For the case of three-hole sensors, sensitivity was measured to be 43.8 dB/RIU for the sensor with three 0.7-mm diameter holes and 62.9 dB/RIU for the one with 0.9-mm diameter holes, respectively. These values are about three times in logarithmic scale the sensitivities for the corresponding single-hole sensors, which agree with the theory. In conclusion, we have successfully demonstrated simple and compact high-sensitivity refractive index sensors by cascading in-line holes along the POF axis.

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BENT OPTICAL FIBER TAPER FOR REFRACTIVE INDEX MEASUREMENTS WITH TUNABLE SENSITIVITY

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ABSTRACT: *This letter presents experimental results of a refractive index sensor using a bent optical fiber taper. The approach of this sensor is based on an in-line Michelson interferometer implemented with a single mode tapered fiber with a cleaved tip end and changing tilt angle, enabling to tune its refractive index sensitivity. Several radii of curvature are tested and their refractive index sensitivities are analyzed for a refractive index range between 1.333 and 1.405. A clear enhancement of the sensor response is achieved at specific taper bending radii. A substantial improvement in the refractive index sensitivity, at values very close to distilled water, is obtained with a radius of curvature of 11 mm. A significant enhancement of the sensor response is also achieved for a refractive index close to 1.40 with a radius of curvature of 16.5 mm.* © 2015 Wiley Periodicals, Inc. Microwave Opt Technol Lett 57:921–924, 2015; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.28984

Key words: *optical fiber taper; Michelson interferometer; refractive index sensor; bending*

1. INTRODUCTION

Currently, it is well known that sensors based on optical fibers present several advantages in comparison with conventional technologies due to their special characteristics such as small size, immunity to electromagnetic interference, corrosion resistance and remote sensing capability. Refractive index (RI) sensors are very important for monitoring water quality in either industrial applications or environmental control [1, 2]. Many RI sensor configurations using optical fibers technology have been studied in the last years such as multimode tapered fibers [3], fiber–taper seeded long period grating (LPG) pair [4], multimode interference (MMI) devices [5], structures based in core diameter mismatches [6], Michelson interferometer using abrupt taper [7], core offset attenuators [8], in-line Mach–Zehnder interferometer setup by concatenating two single-mode fiber (SMF) tapers [9], and MMI based tapered fiber [10]. Most of those sensor configurations offer high sensitivity for RI close to 1.45 (RI of the fiber cladding), but present a relatively low sensitivity for RI close to distilled water (∼1.333), a range of interest for many chemical and biosensing applications.

In [9], it was reported a RI sensor using in-line Mach–Zehnder interferometer. The sensitivity for the RI range from 1.3324 to 1.35 was about 17.65 nm/RIU. The same authors tested an in-line Michelson interferometer for the same RI range, achieving ∼25.6 nm/RIU [11]. They also used a core-offset attenuator technique, and the RI sensitivity obtained was ∼32.95 nm/RIU.

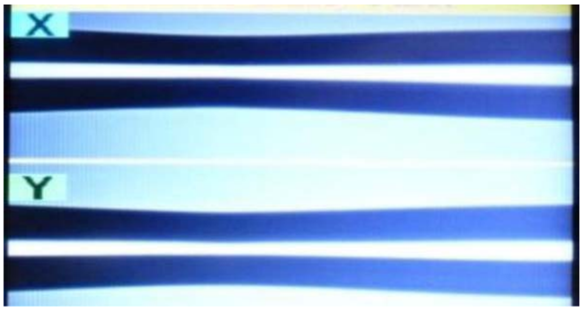

Figure 1 Photo of the taper after its fabrication in the splice machine. The X and Y photos are the taper's horizontal and vertical point of view, respectively. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

In [4], it was analyzed a hybrid configuration for RI sensor using LPG and an optical fiber taper. For RI values from 1.3333 to 1.3528, and using two LPGs only, the sensitivity was ~35.9 nm/RIU. However, the best result was obtained using the optical fiber taper between the two LPGs. The parameters used were taper length of 16 mm, minimum waist diameter of 38.75 μm and the distance between the two LPGs of 47.96 mm. In this particular case, the sensitivity was improved to ~184.6 nm/RIU.

An RI sensor using an SMF with an abrupt taper presented a very high sensitivity for RI close to distilled water achieving a sensitivity to RI changes of 1,197 nm/RIU for a range of 1.3333–1.3447 [2]. However, this approach used a very thin diameter of the taper waist (7 μm) and a taper length of 843 μm, resulting in a very fragile structure.

It was reported in [12], the utilization of bending as a technique to obtain good sensitivity to RI changes using a special high-bend loss SMF. The analyzed range of RI was 1.33–1.40 and the achieved sensitivity was 725.76 nm/RIU.

In this work, it is analyzed and demonstrated an RI sensor using a bent tapered single-mode optical fiber (BTOF). The BTOF sensor uses a tapered single mode-fiber with its cleaved tip end working as a Michelson interferometer [11] associated with bending the tapered region. This work investigates the role of bending in the enhancement of RI sensitivity. Many papers have examined this sensor configuration to measure RI changes. It was demonstrated good results for the RI range near the cladding RI value (~1.45). Conversely, this sensor generally presents poor sensitivity for the RI value near the distilled water. The goal of this work is to show the enhancement of the RI sensitivity in the region of distilled water when bending is used within the in-line Michelson interferometer.

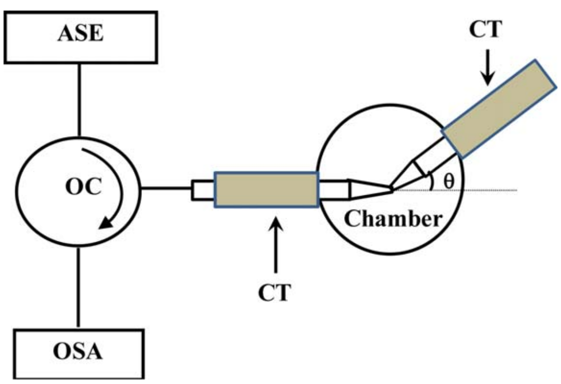

Figure 2 Schematic of the experimental setup. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

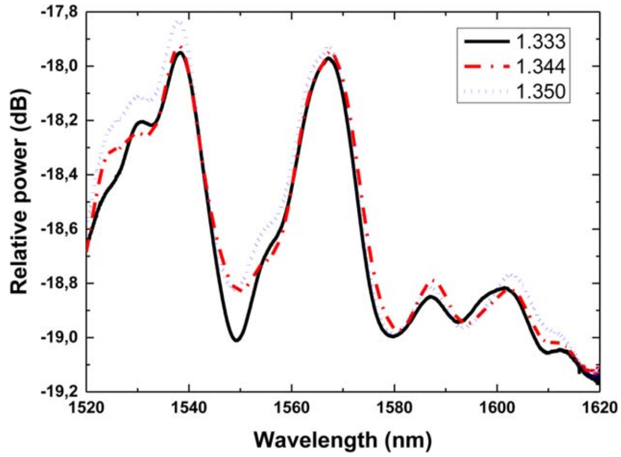

Figure 3 BTOF Spectra for RI values from 1.333 to 1.35 without bending the sensor. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

2. EXPERIMENTAL SETUP

The experiments were carried out to analyze the refractive index sensitivity of the BTOF sensor acting as a Michelson interferometer. The fiber-taper Michelson interferometer consists of an uncoated section of SMF fiber between a taper (i.e., a small region of the fiber with reduced cladding diameter), and its cleaved end. The taper couples a fraction of the core light to the cladding modes, which are propagating along the cavity until the tip end, then they are reflected back to the taper again by the cleaved end, which acts as a partial mirror. This generates interference fringes in the reflected optical signal. The phase between the cladding (LP_{nm}) and core (LP_{01}) modes traveling in the cavity with length L in the Michelson interferometer is approximately expressed as [11]:

$$\Delta\phi = \frac{4\pi\Delta n_{nm}L}{\lambda} \tag{1}$$

where Δn_{nm} is the effective refractive index difference between the two modes and λ is the wavelength of the traveling light.

The process of tapering a fiber is to reduce its diameter by heating and pulling the fiber ends. There are some options of heat sources to be used in the fabrication of fiber-tapers. In this work, the fiber-taper was fabricated using an electronic arc provided by a fusion splice machine used to heat the fiber while its end is elongated. The fabricated fiber-taper is showed in Figure 1. The length and minimum waist diameter of this taper are around 430 μm and 98 μm, respectively. The resulting cavity length, that is, the length from the taper waist to the fiber tip end is about 20 mm.

As can be seen in Figure 2, the fiber with the taper is inserted into two capillary tubes, leaving the taper and the region near it free to be bent, and exposed to refractive index changes. This bent section is placed in contact with liquids of different refractive indices through a small chamber.

Once the sensor sensitivity to the RI variation must be analyzed as a function of the taper bent angle, it is important to relate the angle of curvature of the tilted sensor to its radius of curvature. The following equation was used [13]:

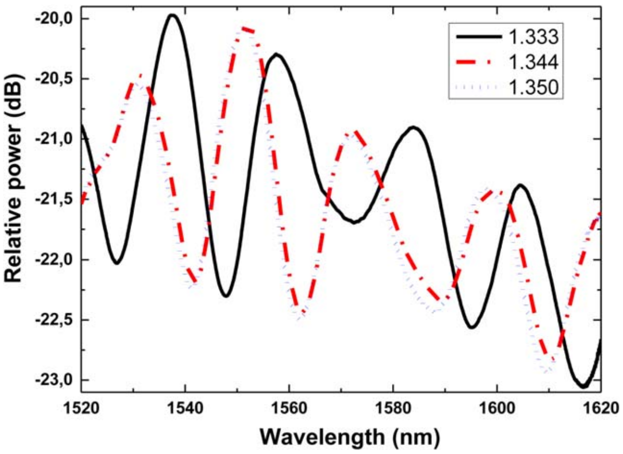

Figure 4 BTOF Spectra for RI values from 1.333 to 1.35 and a radius of curvature of 11 mm (99°). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

$$R_c = \frac{360\, L_{\text{bent}}}{2\pi\theta} \tag{2}$$

where, R_c is the radius of curvature, L_{bent}, is the length of the fiber section submitted to bending and θ is the angle of inclination relative to the middle of L_{bent}.

The experimental setup illustrated in Figure 2 consists of an ASE source with a bandwidth ranging from 1520 to 1620 nm used to illuminate the BTOF through the optical circulator (OC). The optical signal is reflected back from the cleaved tip end of the BTOF and by means of the OC is directed to the optical spectrum analyzer.

3. RESULTS AND DISCUSSION

The analysis of the sensor sensitivity was performed using three peaks of the recorded interferometric spectra and computing the wavelength shift of the fringe pattern as a function of the refractive index changes. It is taken an average of those wavelength shifts and then those average values are taken into account to calculate the RI sensitivities. The spectra obtained when the sensor was subjected to RI values of 1.333, 1.334, and 1.350 for the case with no bending can be observed in Figure 3. It can be noted that the sensitivity for the straight sensor is low as the acquired spectra are very similar for the three different values of RI.

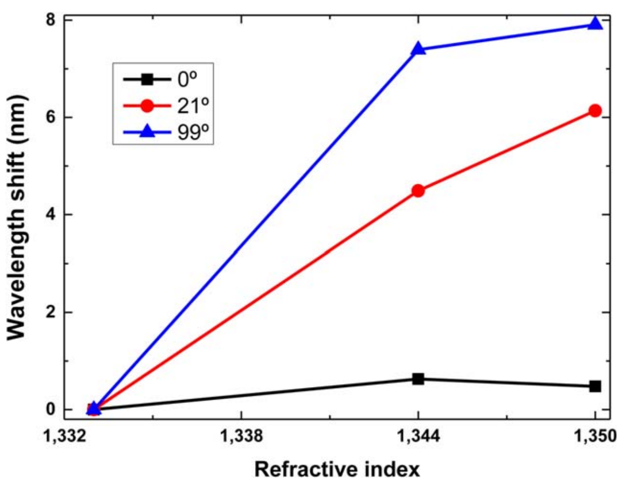

Figure 5 Average of the wavelength shift as a function of RI for three tilt angles: 0°, 21° and 99°. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

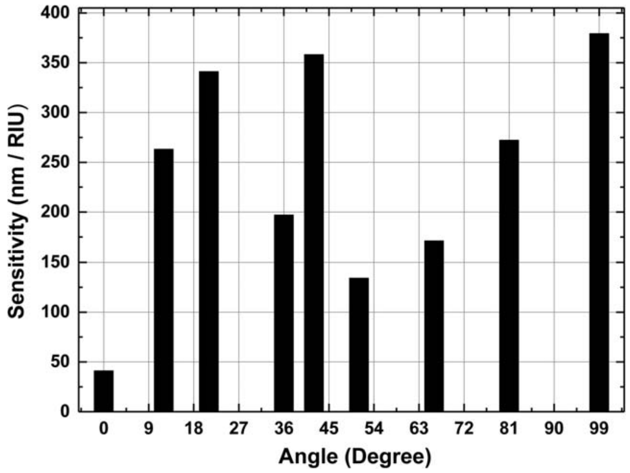

Figure 6 Sensitivity to RI changes from 1.333 to 1.35 as a function of tilt angle

It was tested the behavior of the sensor response at certain radii of curvature. It can be observed in Figure 4 the spectra for a RI range from 1.333 to 1.35 when the taper is bent at a radius of curvature of 11 mm.

The wavelength shift due to RI changes (from 1.333 to 1.35) can be seen in Figure 5 for three radii of curvature, which are, infinite (0°), 51.8 mm (21°) and 11 mm (99°). The best response occurs at $R_c = 11$ mm

The sensitivity of the sensor, which is the average wavelength shift per refractive index unit (nm/RIU), is presented in Figure 6 for the range of RI from 1.333 to 1.350 for all angles of inclination analyzed. It can be seen that for zero angle (no bending case), the sensitivity is very low, ~41nm/RIU. The highest sensitivity is attained for a tilt angle of 99° ($R_c = 11$ mm) with ~378.73 nm/RIU. However, a similar sensitivity is also achieved at much smaller angle values with 358.36 nm/RIU and 341.38 nm/RIU for tilt angles of 42° ($R_c = 25.9$ mm) and 21° ($R_c = 51.8$ mm), respectively. Therefore, it is possible to obtain an improved response relative to the

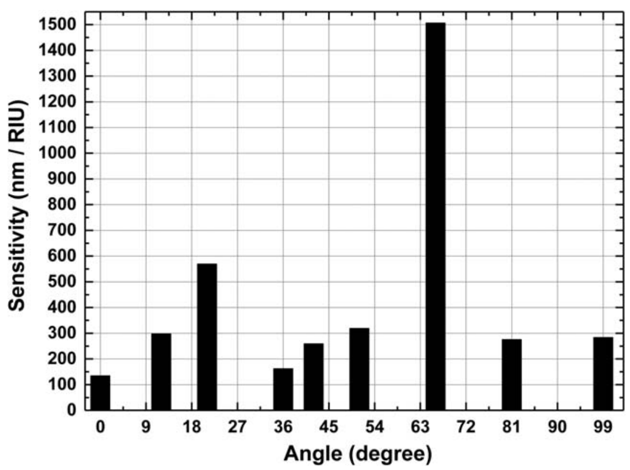

Figure 7 Sensitivity to RI changes from 1.397 to 1.405 as a function of tilt angle

straight sensor, just by tuning the inclination angle. Certainly, it is desirable to avoid bending the sensor at very large angles due to the risk of breaking.

When it is considered a RI value close to 1.40 (1.397–1.405) the sensitivity is enhanced from 134 nm/RIU for the no bending case to ~1506 nm/RIU with $R_c = 16.5$ mm (66°) which corresponds to an increase in the sensitivity compared to the straight device by a factor of 11. At smaller bending angles (21°/ $R_c = 51.8$ mm) lower enhancement is observed, ~568.7 nm/ RIU, representing about four times improvement in comparison to the not bent sensor. A summary of these results are depicted in the Figure 7.

It is realized through the results, the oscillatory nature of the RI sensitivity of the analyzed interferometric sensor. In [14], it was reported numerical results for the bent in-line Mach–Zehnder interferometer RI sensor based on SMF with two concatenated tapers. The numerical results reported in that paper presented also a similar oscillatory RI sensitivity as a function of the bending.

A possible explanation is that bending the taper allows that more energy from core mode couples to higher radial order modes what contributes to increase of RI external ambient sensitivity. However, the increase in bending also transfers more energy from core mode to azimuthal modes and much energy is lost and does not recouple to the core mode, contributing to decrease the RI sensitivity. Thus, the relationship between coupling and recoupling among radial and azimuthal modes helps to explain the oscillatory nature of the RI sensitivity.

The results presented in this letter demonstrated the great potential of the BTOF sensor to enhance the RI sensitivity. It is possible to choose the appropriate radius of curvature according to the range of RI to be measured. It is worthy to mention the great improvement in the sensitivity for RI values very close to distilled water what is a hard task for a sensor based on standard SMF.

4. CONCLUSION

The results confirmed the great enhancement of the BTOF sensitivity for RI values close to distilled water as well as for RI values near 1.40, when the sensing taper is subjected to bending. For RI values very close to distilled water (1.333–1.35) the sensitivity was about 41 nm/RIU for the straight BTOF and 378.73 nm/RIU for the bent sensor at $R_c = 11$ mm. Similar sensitivities can also be achieved at even smaller bending angles. Thus, it is clear that a tunable sensitivity can be obtained by means of choosing a bending angle. For RI values close to 1.40 the sensitivity was 134 nm/RIU without bending and 1506 nm/ RIU at $R_c = 16.5$ mm. In this work, it was demonstrated the great potential of the BTOF to obtain an optimized RI sensor for RI values close to distilled water.

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CONTINUOUSLY TUNABLE BAND-NOTCHED ULTRAWIDEBAND ANTENNA

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ABSTRACT: *A compact coplanar wave guide -fed elliptically tapered ultrawideband (UWB) antenna with a tunable narrow rejection band of 0.195 GHz with tunable range (5.07–5.83) GHz is presented. The proposed antenna consists of elliptically tapered patch, elliptically tapered and truncated ground plane to achieve the UWB bandwidth. A quarter wavelength stubs loaded with a varactor diode has been used to tune the notched band. The proposed antenna has been fabricated on low cost FR4 substrate with dimensions as (24 × 30 × 1.524) mm³. Both the frequency domain as well the time domain performance characterization have been carried out and discussed.* © 2015 Wiley Periodicals, Inc. Microwave Opt Technol Lett 57:924–928, 2015; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.28990

Key words: *elliptically tapered ultrawideband antenna; tunable notched band; quarter wave stub; varactor diode; system fidelity factor*