Innovative Sensor for Refractive Index monitoring based on a Plastic Optical Fiber side-polished in a 'V'-bent structure

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ABSTRACT

An innovative probe design, based on plastic optical fiber which has been designed around a side-polished fiber, bent into a 'V' shape, is reported. Such a probe offers an innovative approach to monitoring of the surrounding refractive index of the material under study. The underlying principle is that such a side-polished optical fiber configured in this way can give rise to an enhanced evanescent field. This structure, with the optical fiber slot, was used to fix the side-polished plastic optical fiber. As a result, the plastic optical fiber (POF) probe created this way has been optimized using different intersection angles, circular chamfer radius and different polished depths. The maximum sensitivity achieved with the use of this probe reaches 206.4 dB/Refractive Index Unit over the range of refractive index from 1.33 to 1.40. In the design, the half intersection angle, the circular chamfer radius and the polished depth were set to 30°, 1.12mm and 194.6 µm, respectively. Such a probe based on inexpensive plastic optical fiber has significant potential for a variety of low-cost, refractive index sensing applications.

Keywords: Plastic optical fiber, refractive index sensor, V-shaped groove, side-polished fiber.

1. INTRODUCTION

The use of the evanescent field around an optical fiber provides a simple, and easy to access approach to the characterization of the refractive index of a range of different chemicals used, for example, in a variety of applications which include healthcare, manufacturing, agriculture and security [1,2]. Plastic optical fibers (POFs) [3, 4] are routinely employed in a number of applications (being preferred to the more familiar silica fiber used in communications applications) for both delivering light and detecting local environments in evanescent-wave-based chemical sensors, taking advantage of their robustness, ease of optical coupling to and from the fiber and ready-operability of the sensor based on such fiber. Of the range of chemical sensors that have been developed in recent years, refractive index (abbreviated here to RI) sensing is important. Such a sensor for refractive index monitoring, designed around the use of plastic optical fiber, shows the advantages of immunity to electromagnetic interference, as well as potentially high sensitivity, fast response, ease of fabrication and operation, as well as compact size, operation in the visible spectral region, and inherent low-cost of fabrication, thereby enhancing commercial potential and flexibility for use in a range of different applications.

Plastic optical fiber (abbreviated here to POF) of the type discussed, designed with suitable geometries, can form the basis of evanescent-wave-based refractive-index sensors, even without removing the cladding. In general, such fibers can be locally modified to obtain high sensitivity in many different ways which include side polishing [3,4], heat treatment [3,5,6], chemical etching [7], surface chemical modification [8,9], use of insertion imperfections [10,11] and so on. The structural geometries of the POFs used are usually tapered [5], U-shaped [3,6], D-shaped [9,12] and side-hole [13], for example. Generally, the sensors designed and based on POFs are more useful for those methods that use intensity modulation, taking advantage of their multimode nature. Operating in the visible spectral region, the change in

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the light intensity in the sensor caused by the different refractive indices into which the fiber is inserted can readily be recognized and detected. However, one of the drawbacks of any light intensity-based detection scheme in an optical fiber sensor is that the measurement result may be susceptible to any intensity variations of the light source.

Herein, a different method to modify a POFs, designed to improve the sensitivity for refractive index monitoring in an evanescent wave-based sensor, is discussed. In this approach, the fiber used was bent into a V shape (with the help of a V-shaped structural element) into which the POF could easily be embedded, following which the top of V-bent fiber was then polished to a D-shape, to increase the impact of the evanescent wave effect. The mode propagation and loss characteristics of the sensor probe designed in this way have then been investigated and are reported in this work, where it has been shown that the sensing performance for refractive index was enhanced through a careful design process, involving experimentally optimizing its structural parameters.

2. PRINCIPLE OF OPERATION

The operational approach used in the side-polished V-bent plastic optical fiber sensor discussed herein has been based on attenuation of the total internal reflection effect seen. In general, in the sensor, the light rays follow curved paths in the core of the POF, and as a result of total internal reflection, refracted rays are coupled into the cladding. However, the light wave is not completely reflected, here into the fiber core. The light wave penetrates the surface of the cladding layer (a distance of approximately one wavelength), and propagates along the interface for a short distance, then finally returns to the core, where a decaying electromagnetic field (the evanescent field) was formed. This exponentially decaying field thus penetrates the medium under investigation, and which is in direct contact with the fiber, where the depth of the optical penetration effect can be expressed as [14]:

$$d = \frac{\lambda}{2\pi n_{co}\sqrt{\sin^2\theta - (\frac{n_{cl}}{n_{co}})^2}} \quad (1)$$

In Equation (1) above, λ is the incident light wavelength, θ, the angle of incidence at the core-clad interface, n_{co}, is the core RI and n_{cl}, is the RI of cladding (medium forming the external environment). θ_c is the critical angle of the sensing section with respect to the normal on core-cladding interface and $\sin\theta_c = \frac{n_{cl}}{n_{co}}$. It can be seen from Eq. (1) that as θ approaches θ_c, the penetration depth increases, which results in the increase in evanescent absorption and hence the sensitivity of the POF sensor. When $n_{co} > n_{cl}$, the penetration depth increases with the increase of RI of the medium forming the external environment and the decrease of the incident angle, following which the light intensity decreases continuously, with the increase of the penetration depth.

In general, the evanescent field penetrates little into the external medium [10] and its interaction with the medium surrounding the fiber can be adjusted through modifying the cladding itself or bending of the fiber, which will create a variation in the output power received. This can then be observed as a function of the optical properties of the surrounding medium, which is being investigated.

In this paper, a new type of side-polished, V-bent, optical fiber sensor using a plastic material, designed to make more significant the interaction between the evanescent wave and the surrounding medium is discussed and results on its performance reported. A diagram of the side-polished, V-bent, structure, based on the use of POF used in this research is illustrated in Figure 1 and the influence on its performance in use in sensing of refractive index, with different design parameters of the V-bent structure and variations of the polished depth used, form the basis of this work discussed in this paper.

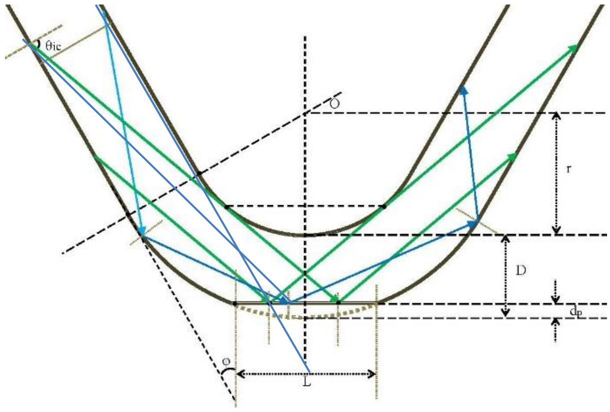


Figure 1. Schematic of the light propagation model of the side-polished V-bent POF sensor structure

3. EXPERIMENTAL DETAILS

3.1 Preparation of the POF Probe

The fiber used in this work was a commercially available fiber, a step-index type POF (Chunhui Science & Technology Co., Ltd, China). The material from which the core of the POF used was made was PMMA, with a diameter of 960µm, a RI of 1.49 and a thermo-optic (TO) coefficient of -1.15×10^{-4} /°C. In the fiber used, the cladding was made from a fluorinated polymer, of thickness 10 µm, a and a lower RI of 1.41 and a TO coefficient which was -3.50×10^{-4} /°C. A schematic of the side-polished, V-bent structure comprising the sensor is as shown as Figure 1. The side-polished area forms a circular arc whose length is L, and a depth of polishing is d_p. The macro-bending region is shown as a V-shaped structure, with a circular chamfer radius, r, and an intersection angle, 2φ. The sensor works on the principle of monitoring the propagation loss and the evanescent wave which comes from the side-polished structure where the light beam is affected in a reproducible way by the RI of the surrounding medium which has been evaluated. Therefore, through measuring the changes of the light as it propagates, the RI of the medium under investigation can be determined.

The V-shaped structures used, designed with different angles and circular chamfers, were 3D-printed and these were investigated. The polished POFs were embedded in the structure to create a very sensitive, compact and stable probe design for a range of applications, as shown in Figure 2. In addition, Figure 3 shows a picture of the V-bent structure with an optical fiber slot, different values of the intersection angle and the circular chamfer radius.

The side-polishing procedure is a simple one to use, in light of the fact that the soft polymer material comprising the fiber polishes easily. This procedure involves three different steps: fiber fitting, initial rough polishing and finally, fine grinding. In order to create the probe, first the POF was glued and fixed in that way into the optical fiber slot of the V-bent structure, as shown in Figure 2. Following that, a rough, abrasive paper was used first to create an approximate curved shape for the fiber being polished, and then a thinner gauge paper was used. This enabled a more precise grinding step to be undertaken, in order to obtain the desired smooth, polished surface. After the side-polishing process was completed, the polished geometric parameters were investigated, and their properties measured by using a microscope and a spiral micrometer.

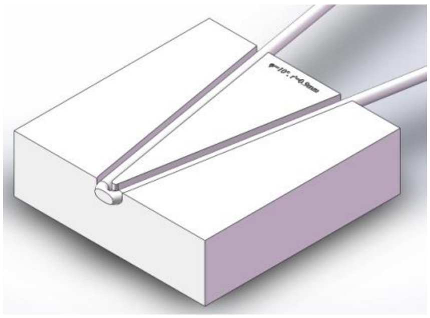


Figure 2. Schematic of the side-polished V-bent POF.

Figure 3.(a) Illustration of the V- bent structure (φ=30°, and r=1mm, 1.6mm, 2.1mm, 2.6mm, respectively). (b) Illustration of the V- bent structure (r=1, and φ=10°, 15°, 20°, 25°, 35°, 45°, respectively.

3.2 Experimental Setup

The experimental setup employed in this work to investigate the performance of the sensor is shown in Figure 4. This experimental arrangement allows the measurement of the transmission intensity of the POF probe, when tests were carried out on a glycerinum solution used as the sample medium. In order to overcome any possible influence of fluctuations in the light source used, the probe was required to be polished for a second time – then to obtain a reference signal output, as shown in Figure 4. Through a known variation of the concentration of the glycerinum solution investigated, RI values measured by Abbe refractometer (2WAJ, Shanghai Precision Instrument Co., Ltd) over the range from 1.330 to 1.403 were available. A SLD source (SLD-mCS-371-HP2-SM, Superlum), with a central wavelength of 840nm, was used to create a light beam (with the wavelength varying from 830nm to 850nm in the experiment). A Si-APD (APD110A, Thorlabs), with a spatial light input and a Si-APD (Fby photoelectric Technology Co. Ltd) with an optical fiber input, were used to monitor the intensity of the light signals from the reference output and the signal output respectively. These electrical signals, then acquired by the Digital Acquisition system (DAQ – USB6165, Thorlabs) were then ratioed, to allow correction for any light source fluctuations to be applied and thus to obtain a relatively stable effective signal. The experiment was undertaken in a room temperature (25 °C) environment.

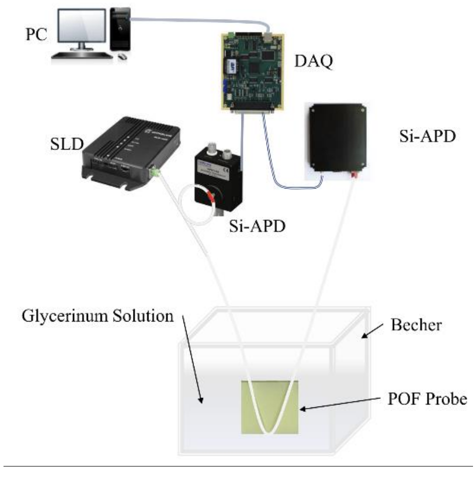


Figure 4 Schematic of the experimental setup used. SLD – superluminescent laser diode; Si-APD – silicon avalanche photodiode; DAQ – digital acquisition card; PC – computer

4. RESULTS AND DISCUSSION

4.1 Effect of the Circular Chamfer Radius and Polished Depth

In order to determine the influence of both the circular chamfer radius and the polished length on the performance of the probe, different V-shaped structures with a half intersection angle of 30° were used. The curvature radii of the circular chamfer of the V-shaped structures were set to 0.52 mm, 1.12 mm, 1.62 mm, and 2.12 mm respectively. Each of the V-shaped POF probes, with a specific circular chamfer radius, was polished little-by-little, then using these several sensing probes, with different depth of the polish were prepared. In the experiments carried out, the performance as a sensor of the different V-shaped POF probes (those probes not having the side polishing) and used to monitor the RI, was investigated as shown in Figure 5(a). As can be seen from the figure, when the circular chamfer radius, r, was 1.62 mm, the V-bent POF probe has an excellent RI sensing performance – illustrating that in that case, an excellent linear trend representing the sensing response to the external refractive index was monitored. The sensitivity is defined as shown below [15]:

$$S = \frac{d}{dn}[10log_{10}T(n)] \qquad (2)$$

where T(n) is the light transmittance in the probe. Here, the sensitivity is calculated in the scope of 1.33-1.3935. The resolution (R) of the presented sensor is further defined as [3]:

$$R = 3\sigma_a/S \qquad (3)$$

where σ_a is the standard deviation of transmittance when the POF sensor probe is exposed to the blank analyte (air). It should be noted that the POF sensor probes with different structural parameters have different σ_a. Before each test, the POF sensor probe should be thoroughly cleaned and dried with deionized water.

In this work, the sensitivity is shown in the figure to reach 32.425 dB/RIU. Following that, the sensing performance achieved when monitoring the value of the RI of the different V-shaped sensing probes, designed with different polished lengths, was investigated and the results are illustrated in Figure 5(b)-(e). As can clearly be seen from the figure (Figure 5(b)-(e)), for a probe with a certain circular chamfer radius, the response could be seen to vary with the polished depth. Table 1 shows the results from the experiments carried out and thus comparison of the results shown also in Figure 5(b)-(e).

Evaluating these results in detail, for the probe designed with a value of r=0.52 mm, the optimum response (in the index range from 1.330–1.3935) was seen to occur when the polished depth, d_p, was given by 80.2 μm. Here the sensitivity reached 150.334 dB/RIU. For the probe designed with r=1.12 mm, the best response was seen when the polished depth, d_p, was set to 194.6 μm, and here the maximum sensitivity achieved was 179.796 dB/RIU. In another case, where the value of r=1.62 mm, and the polished depth, d_p, was 219 μm, the maximum sensitivity was then 162.784 dB/RIU. Looking at the results overall, the optimum sensitivity for such a probe design was 308.755 dB/RIU, and the best resolution was 3.249×10^{-6}, where r=2.12 mm and the polished depth, d_p, was 372.2 μm. However, the linearity seen in this case was not very good. Further, because of the large propagation loss seen, the output signal and the signal-to-noise ratio were both considerably smaller than in other cases.

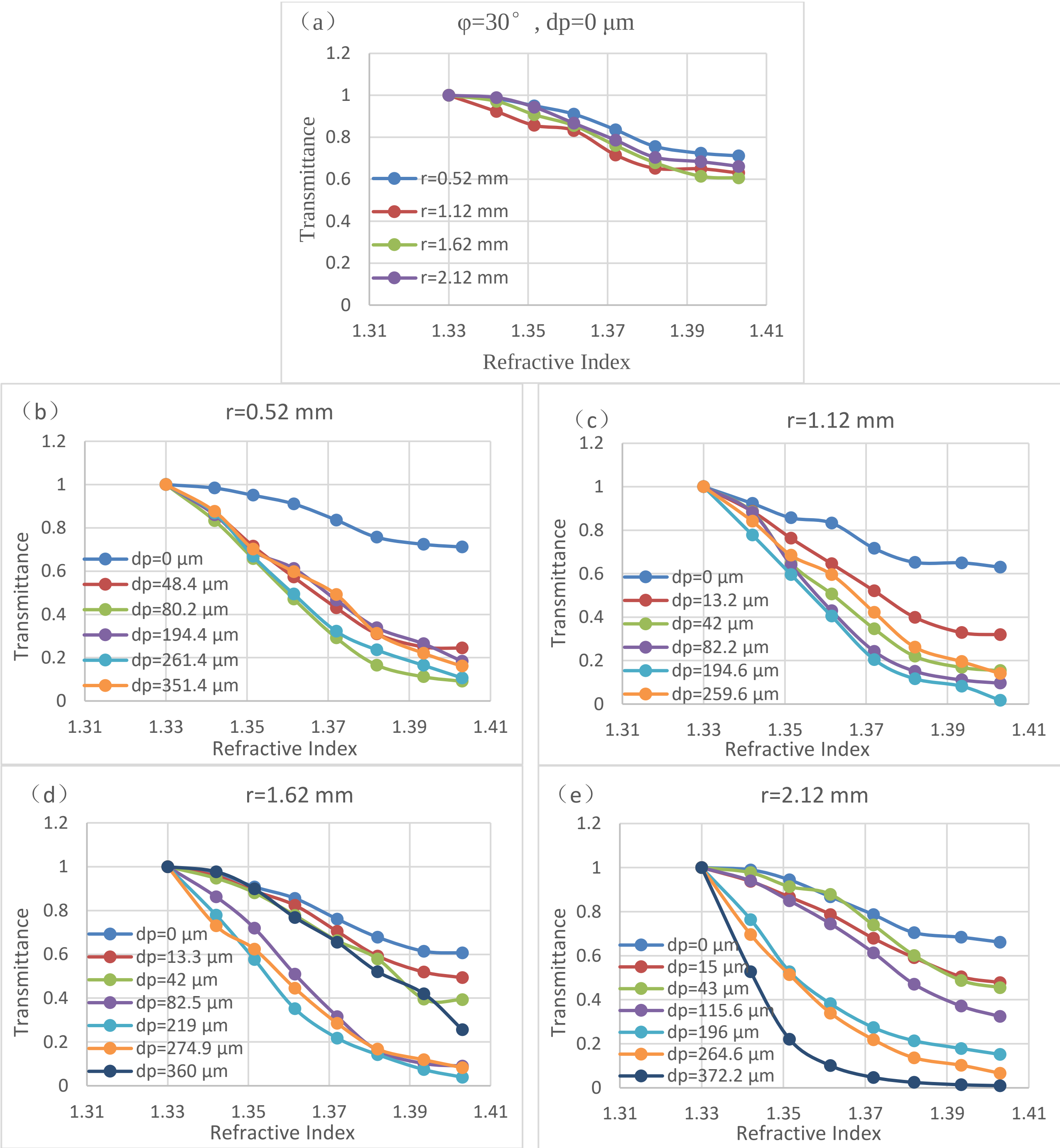


Figure 5. Illustration of the effect of the circular chamfer radius of the V-bent POF probe, with half the intersection angle (φ=30°) on the RI sensing performance. (a) The polished depth, d_p= 0 μm. In the cases (b)-(e), the effect of the different side-polished V-bent POF probe designs used, monitoring the RI sensing performance is shown, where the circular chamfer radius was given by 0.52 mm,1.12 mm,1.62 mm, and 2.12 mm in (b)-(e), respectively.

Circular chamfer radius (mm)	Half the intersection angle (°)	Polished depth (μm)	Maximum sensitivity (dB/RIU)	Resolution (RIU)

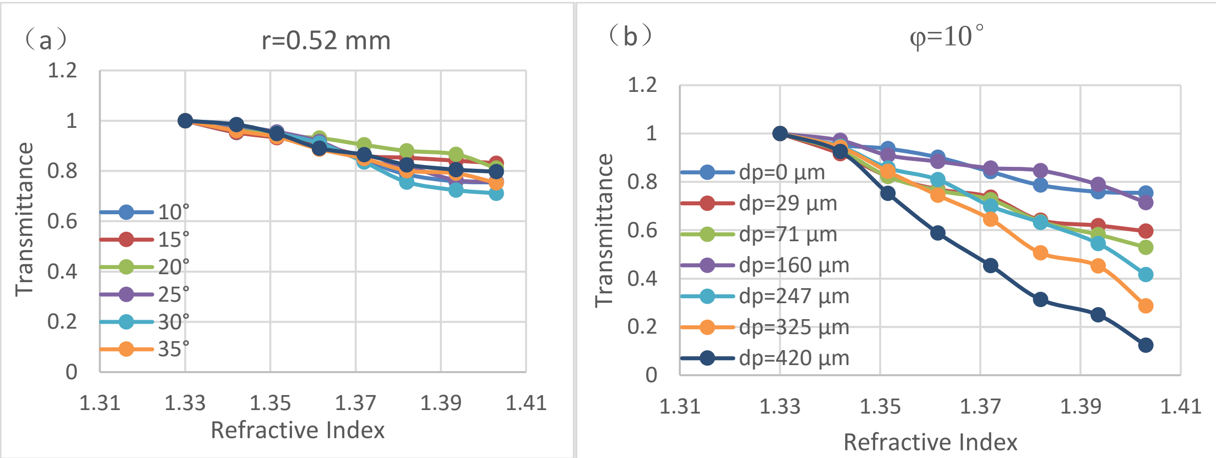
0.52	30	80.2	150.334	6.673×10^{-6}
1.12	30	194.6	179.796	5.579×10^{-6}
1.62	30	219	162.784	6.163×10^{-6}
2.12	30	372.2	308.755	3.249×10^{-6}

Table 1. Summary and comparison of the results from the data shown in Figure 5 (a)-(e).

4.2 Effect of the Intersection Angle and Polished Depth on the Sensor Performance

To investigate the influences of both the intersection angle and polished length, on the performance of the probe as a RI sensor, a series of different V-shaped structures, with a circular chamfer radius of 0.52 mm, was fabricated and investigated. The half-intersection angles of the V-shaped structure were given by 10°, 15°, 20°, 25°, 30°, 35°, and 40° respectively in the different sensors. When the half-intersection angle of the V-shaped structure was set to 10°, the POF was polished bit-by-bit, then the sensing probes having different depths of the polish used were prepared. The RI sensing performance of the different V-shaped sensing probes, without side polishing, was measured and is illustrated in Figure 6(a). As can be seen from Figure 6(a), when the circular chamfer radius r was 0.52mm, the V-bent POF probes without side polishing showed a lower, and indeed similar, performance for the better monitoring of the value of the refractive index. Next, the probe performance of the different V-shaped sensing probes prepared with different polished lengths, was investigated, as shown in Figure 6 (b)-(h) below. As illustrated in these figures (6 (b)-(h)), for probes with a certain intersection angle, the response was observed to vary with the polished depth. Table 2 shows a summary of the comparison of the results obtained from analysis of Figure 6 (b)-(h).

Looking more closely at the results obtained, for the probes where φ=10°, the best response (in the RI range 1.330–1.3935) was seen to occur when the polished depth, d_p, was 420 μm and here the sensitivity reaches 96.9 dB/RIU. However, the propagation loss of the probe, with a polished depth of 420 μm, was sufficiently large that the output signal was diminished, affecting in a negative way the signal-to-noise ratio. For the probe where φ=15°, the best response was seen when the polished depth, d_p, was 60 μm and the maximum sensitivity was given by 108.002 dB/RIU. The maximum sensitivity for all these probes investigated was 323.329 dB/RIU, and the best resolution was 3.140×10^{-6}, while the value of φ=35° and the polished depth, d_p, was 113 μm – however in this case the linearity seen was not particularly good.



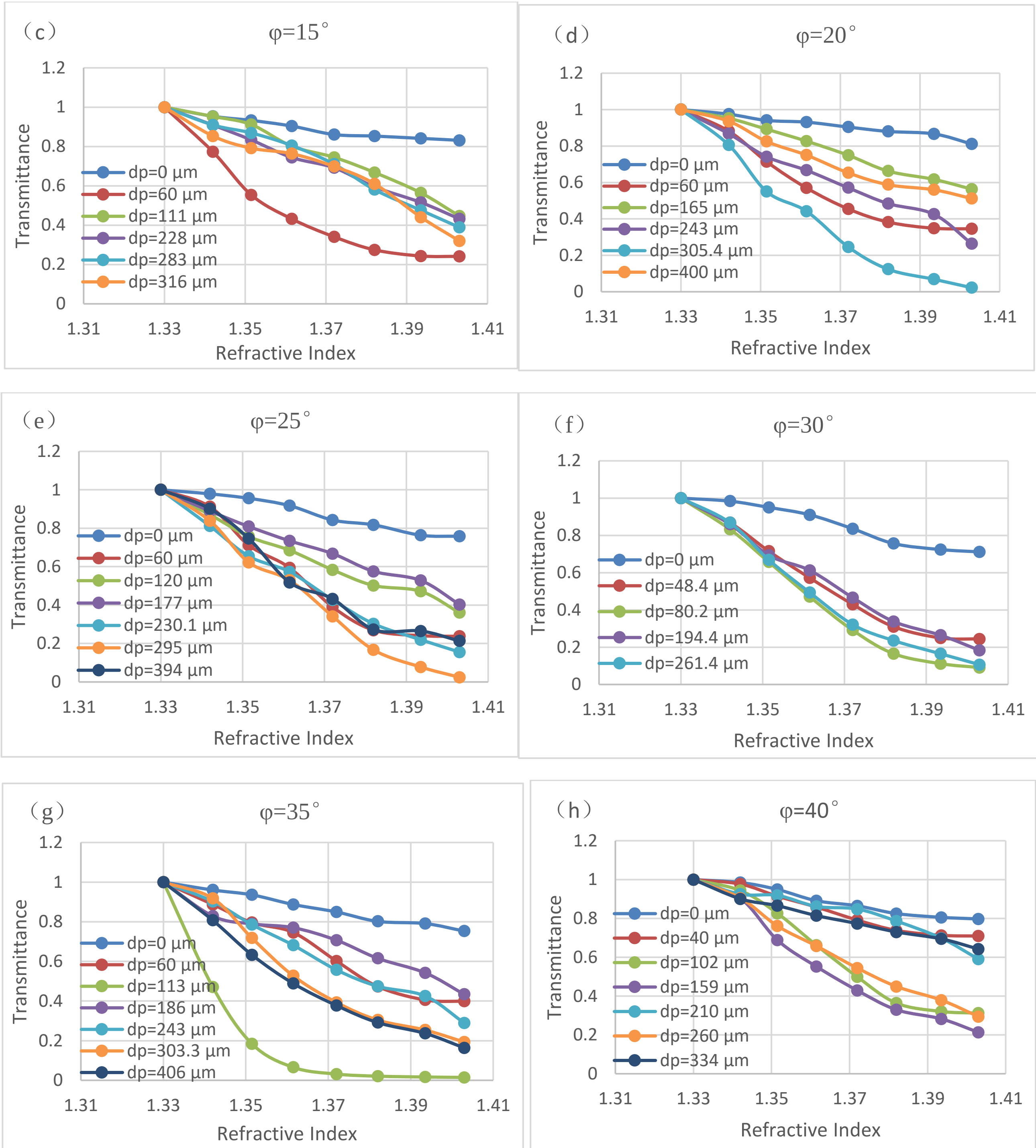


Figure 6. The effect of the intersection angle of the V-bent POF probe with circular chamfer radius of 0.52 mm, for the probe performance as an RI sensor. (a) the depth of polish, d_p= 0 μm. (b)-(h) shows the effect of the different side-polished V-bent POF probes in terms of RI sensing performance, where the half-intersection angle was given by 10°, 15°, 20°, 25°, 30°, 35°, and 40° respectively.

Circular chamfer radius	Half the intersection angle	Polished depth	Maximum sensitivity	Resolution

(mm)	(°)	(μm)	(dB/RIU)	(RIU)
0.52	10	420	96.9	1.035×10^{-5}
0.52	15	60	108.002	9.566×10^{-6}
0.52	20	305.4	174.687	5.760×10^{-6}
0.52	25	295	149.651	6.744×10^{-6}
0.52	30	80.2	150.334	6.743×10^{-6}
0.52	35	113	323.329	3.140×10^{-6}
0.52	40	159	92.702	1.147×10^{-5}

Table 2. Summary and comparison of the results illustrated in Figure 6 (a).

5. CONCLUSION

This paper has discussed the design and performance of a series of refractive index sensors, designed around using a V-shaped side-polished polymer optical fiber (POF), where the work done shows an analysis of the important factors influencing the sensitivity of the V-bent sensor probe developed which were investigated. Characteristics such as the polished depth, the intersection angle and the circular chamfer radius of the V-shaped structure have been examined (and the best chosen), to provide the optimum device sensitivity. A series of experiments on the RI sensing performance of the various probes which were fabricated has been carried out and the results obtained show that the different V-shaped POF probes, without side polishing, have a lower (and similar) performance as a refractive index sensor. When the half-intersection angle of the V-shaped structure was set to 30°, the polished depth that leads to the maximum sensitivity of the probe increases, with the increase of the circular chamfer radius. The best probe performance was seen with the probe which showed the maximum sensitivity (of 179.796 dB/RIU), where the circular chamfer radius was 1.12 mm and the polished depth was 194.6 μm. When the circular chamfer radius was 0.52 mm, the maximum sensitivity of the V-bent POF sensors studied was seen to vary with the change of the intersection angle and the depth of the polish used. The optimal probe design was established from the results obtained to be the sensor with a maximum sensitivity of 174.687 dB/RIU, in which the half-intersection angle was 20° and the polished depth was 305.4 μm. For comparison with the sensitivity of the refractive index sensor in paper [3], the sensitivity value of 174.687 dB/RIU can be transformed into 1685.6%/RIU which is higher than the sensitivity 1541%/RIU in [3]. The design of the system has shown that immunity to any intensity fluctuations in the light source used is a feature of the system. Overall, the design is simple, easy to fabricate and thus low cost for the measurement of RI over the range 1.33 to 1.4 discussed in this work.

Future work will continue to investigate the design – in particular to explain the relationship between the sensitivity and the circular chamfer radius, the half-intersection angle and the polished depth – with a view to its optimization, underpinning this process with theoretical analysis.

6. ACKNOWLEDGMENTS

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