2009-01-01

A Macrobending Singlemode Fiber Based Refractometer

Pengfei Wang
Technological University Dublin, pwang@tudublin.ie

Yuliya Semenova
Technological University Dublin, yuliya.semenova@tudublin.ie

Qiang Wu
Technological University Dublin, qiang.wu@tudublin.ie

See next page for additional authors

Recommended Citation

Wang, P. et al (2009) A macrobending singlemode fiber based refractometer. *Applied Optics, Vol. 48, no. 31, pp.6044-6049. doi:10.1364/AO.48.006044*

Funder: IRCSET

A macrobending singlemode fiber based refractometer

Pengfei Wang[1], Yuliya Semenova[1], Qiang Wu[1], Gerald Farrell[1], Yunqiang Ti[2], Jie Zheng[2]

[1]Photonics Research Center, School of Electronic and Communications Engineering, Dublin Institute of Technology, Kevin Street, Dublin 8, Ireland;

[2]State Key Laboratory of Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Changchun 130012, P. R. China

E-mail: pwang@dit.ie

Abstract: A novel macrobending based all-fiber refractometer sensor with a simple optical configuration is proposed and investigated both theoretically and experimentally. The proposed fiber refractometer sensor consists of a single loop structure of bare macrobending standard singlemode fiber (SMF28) with a selected bending radius and reduced cladding diameter. The well-known scalar approximation theory is employed to theoretically predict the characteristics of the proposed fiber refractometer sensor. An approach to improve the resolution of the refractometer is presented, which shows that the refractometer with a reduced cladding diameter of 81 μm has an experimentally verified resolution of 5.75×10^{-5} for a refractive index range from 1.4586 to 1.5396 at the wavelength of 1550 nm.

Keywords: Macrobending loss, singlemode fiber, SMF28, refractometer sensor

1. Introduction

To date, a series of optical refractometers, such as Abbe and Rayleigh refractometers have been developed and utilized for measuring the refractive indices and concentrations of liquids in biotechnology applications, for example, for measurements of the sugar content, blood protein concentration and salinity of urine in the area of experimental medicine. Optical refractometers are also widely employed in chemical applications for measuring fluid concentrations for commercial liquids such as petrochemicals, antifreeze, cutting fluid and various industrial fluids.

Recent research has shown that optical fiber based sensors offer distinct advantages over conventional electronic sensors in a number of ways, such as immunity to electromagnetic interference, ease of fabrication and installation, safety in hazardous or explosive environments, high sensitivity and a long-distance remote measurement capability. A number of fiber refractometers have been presented to date, such as fiber Bragg grating based refractometer [1, 2], fiber gap based Fabry-Perot structure [3], a refractometer based on an abrupt taper Michelson interferometer [4], a refractometer based on multimode-singlemode-multimode fiber core diameter mismatch [5] and a singlemode-multimode-singlemode fiber structure refractometer [6]. Fiber based refractometers also offer the advantages of cost savings and the avoidance of possible contamination of the liquid by the refractometer. Here, as an alternative to previously presented fiber optic refractometers, a novel macrobending based bare fiber refractometer sensor is presented, with a simple configuration, easy fabrication process and competitive resolution.

In this paper, a thorough investigation of the proposed bare bending fiber based refractometer is presented both theoretically and experimentally, which includes: 1) modeling and experimental verification of the bending fiber based refractometer; and 2) improving the resolution for the refractometer, using a reduced cladding diameter. The agreement between theoretical and measured results indicates that the refractive index of the surrounding liquid can be reliably determined as a function of bend loss of the bare bending fiber sensor. The proposed fiber refractometer offers a much simpler configuration by comparison with existing waveguide/fiber-based optical refractometer sensors with the advantage of ease of fabrication, while retaining a competitive resolution.

2. Modeling and experimental verification of a bare bending fiber based refractometer

In 1978, H. Murakami et al [7] briefly investigated the bending loss behavior of a bent singlemode fiber, from which the coating had been stripped when the fiber was immersed in a liquid. They found that the bend loss varied with the refractive index of the liquid. Later, G. J. Veldhuis et al [8, 9] reported a simple macrobending integrated optical waveguide based refractometer sensor, which was fabricated by a chemical vapor deposition photolithography technique and chemical etching process.

In this paper, the proposed fiber refractometer sensor consists of a single loop structure of coating stripped bare macrobending fiber with a selected bending radius (see Fig.1). It utilizes the characteristics of fiber macrobending loss in the bare fiber section. If the bare bending fiber section is immersed in a liquid after the coating is removed, the bending loss becomes a function of the liquid refractive index. By measuring the changes in macrobending loss, the refractive index of the surrounding liquid can be determined.

Theoretical models for predicting the macrobending loss in singlemode fibers can be categorized into two types: 1) the models originally developed by D. Marcuse [10] which treated the bending fiber as a fiber core-infinite cladding structure; 2) models for a bending fiber with a fiber core-cladding-infinite coating structure, encompassing a number of theoretical approaches and corresponding experimental investigations presented in Refs. [11-14]. These models considered the impact of the whispering-gallery mode (WGM) caused by the reinjected field arising at the cladding-coating interface. In this paper, the liquid under test is treated as an infinite coating for the bare bending fiber section; therefore, a simulation technique utilizing a scalar approximation method (for a fiber core-cladding-infinite coating structure) presented in Ref. [14], is employed to simulate and predict the proposed fiber refractometer sensor.

As a design example, a standard Corning singlemode fiber (SMF28) is chosen and the parameters of the fiber are the same as those presented in Ref. [14]. Given that the refractive index of the fiber core is 1.4504 at a wavelength of 1550 nm, the measurable minimum liquid refractive index is limited by the refractive index of the fiber core and thus must be greater than 1.4504. It is well known that refractive indices of most petrochemicals lie in the range of 1.46~1.56, such as glycerol (1.47), turpentine (1.475), lubricating oils for automobiles (1.50) and clove oil (1.53). For the purpose of this study therefore the desired refractive index range of the proposed bent fiber refractometer is defined as 1.46 to 1.56. The calculated bending losses versus bending radii and refractive index of SMF28 singlemode fiber refractometer sample are presented in Fig. 2, where the proposed operating wavelength is 1550 nm.

In Figure 2, the simulated bending losses are calculated using the scalar approximation method, which can predict the light propagation through the whole bending fiber structure. The eigenmodes within the fiber bending section are determined by the refractive index of the liquid under test and the fiber bending radius, thus the bending loss is affected correspondingly. Fig. 2 shows the relationship between bending loss and refractive index. For some bending radii the bending loss is relatively insensitive to refractive index changes, for example for a bending radius circa 10 and 12 mm. Such bend radii are clearly unsuitable for use in a refractometer. However bending radii in the vicinity of 7.7 and 9 mm demonstrate a strong quasi-linear relationship between bend loss and refractive index and thus these bending radii are suitable for use on refractive index sensing. In particular for a bending radius circa 7.7 mm, one can see that the discrimination range (the difference in bend loss between an refractive index of 1.46 and 1.56) of the bending loss characteristic is the largest over the whole realizable bending radius range from 7 to 12 mm. Beyond 12 mm the refractometer sensitivity is too low, while below 7.5 mm, the risk of bare silica fiber breakage by excessive mechanical stress is too high.

To obtain the greatest sensitivity to changes in refractive index, the desired bending radius should lie in the vicinity of 7.7 mm. Therefore, bending losses as a function of measurable refractive index range around the bending radii of 7.7 mm are considered. It is also clear from Fig. 2 that there is a one-to-one relationship between the bending loss and measureable refractive index when the bending radius varies around 7.7 mm. The bending loss curve at a bending radius of 7.7 mm shows the largest discrimination range from 10.71 to 20.99 dB, which is quasi-linear over the desired refractive index range.

It is well known that the resolution of a commercial optical powermeter is about 0.01 dB and the resolution of a fiber refractometer can be estimated as:

$$\text{Resolution} = \frac{\text{Measureable RI range}}{\text{Discrimination range}} \times \text{Resolution of detector} \qquad (1)$$

Therefore a bending fiber refractometer sensor with a bend radius of 7.7 mm has an estimated theoretical resolution of 9.73×10^{-5}.

To verify the proposed model, experiments were carried out employing a standard SMF28 singlemode fiber. The polymer coating layers of SMF28 fiber were stripped by a hot concentrated sulfuric acid (H_2SO_4, wt >95%, at a temperature circa 200^{o}C). The fiber sensor head is formed by creating a single 360^{o} loop by inserting the fibre ends into a small 1 mm polymer tube. To fix the radius of the bending loop, the junction of the fiber inside the tube is glued. This forms a stable macrobending fiber refractometer sensor head. The fiber bend radius used was 7.7 mm and the basic structure of the experimental setup is shown in Fig. 3.

The broadband source launches the light into an external tunable filter, which can guarantee a tunable 3-dB bandwidth as 1 nm and the tuning wavelength range is from 1530 to 1570 nm. The bending fiber based refractometer sensor head is connected to the tunable filter and a power meter, in which the bend loss changes for the fiber sensor can be measured and the power meter is acquired by a computer.

Cargille refractive index oils with calibrated indices (~ ±0.0002) were used in the experiments. The corresponding refractive indices of the oils at wavelengths of 589.3 nm and 1550 nm are listed in Table 1:

The results are presented as the difference in bend loss by comparison with the bend loss at the starting refractive index of 1.4586. This approach is used to eliminate the effect of unavoidable experimental losses, such as splice insertion loss, so as to allow for more useful comparisons between theoretical and experimental results. The difference in bend loss of bare SMF28 fiber with a bend radius of 7.7 mm at a wavelength of 1550 nm is calculated, the fundamental theory is based on the theoretical model presented in Ref. [14]. In Fig. 4, it is shown that the modeled bend loss difference results at a bend radius of 7.7 mm (solid line) demonstrate a strong monotonic increase from a start refractive index (1.4586@1550nm) to an end refractive index (1.5306@1550nm). The experimental results of SMF28 fiber refractometer as a function of the refractive indices range from 1.4586@1550nm to 1.5306@1550nm are also presented in Fig. 4 as well (hollow circle points). The measured resolution is circa 9.89×10^{-5}. From the Fig. 4, one can also see that there is an acceptable agreement between the solid line and experimental data. The perceptible discrepancy between the experimental and theoretical results may be caused by the limited physical accuracy of the achieved bend radius, as from Fig. 2, one can see that the bend loss is very sensitive to the bend radius in the vicinity of 7.7 mm and in practice it is difficult to control the bend radius precisely. To verify this, the calculated results at a bend radius of 7.67 mm (dashed line) are presented in Fig. 4 as well, from which one can see that the calculated results show a much better agreement with the measured results, supporting the premise that the discrepancies in Fig 4 are due to small experimental errors in the setting of the bend radius.

3. Improving the resolution for the fiber refractometer sensor

One way to maximize the sensitivity of this refractive index sensor is to select a bend radius with the highest slope change between bend loss and refractive index. To improve the sensitivity still further it is possible to reduce the fiber cladding diameter. From the developed models based on the scalar approximation method for predicting macrobending losses of singlemode fibers [11-14], it was known that the bending losses depend not only on specific bending radii, but also on the fiber cladding radii. In addition, decreasing the cladding diameter will also have the beneficial effect of reducing the bending induced mechanical stress on the fiber. It should be noted that in practice one possible experimental approach to achieving a reduced fiber cladding diameter is chemical etching of the fiber using HF acid.

Assuming a bending radius at 7.7 mm, there is a need to find an appropriate fiber cladding diameter with an improved sensitivity using a simulation model. In Fig. 5, the calculated bending losses versus cladding radii and refractive index for a SMF28 singlemode fiber based refractometer are presented, where the bending radius is defined at 7.7 mm, and the wavelength is 1550 nm. From Fig. 5, one can see that the bending loss is a strong function of refractive index and shows a quasi-linear relationship between the bending loss and the liquid refractive index when the cladding diameters are close to 67, 81, 93 and 104 μm, etc.

In Fig. 5, one can also see that the discrimination range of the bending loss at the cladding diameter of 67 μm is the largest by comparison with the other cladding diameters. Moreover, the discrimination range with a cladding diameter of 67 μm is significantly better than that of the initial results shown in Fig. 4. The calculated discrimination range of a bending fiber based refractometer sensor with a cladding diameter of 67 μm is 16.69 dB, which ranges from 14.43 dB to 31.12 dB, better than the other cladding radii. Using the formula (1) presented above, for the improved refractometer the estimated resolution is 5.99×10^{-5}, which is significantly better than the resolution of 9.73×10^{-5} presented in Section II, for a fiber with a conventional 125 μm cladding diameter.

To verify our proposed theoretical model presented in Figure 5, the fiber bending region of samples was immersed in an aqueous solution of hydrofluoric acid (HF, ~40%), yielding a diameter cladding reduction rate of circa 1.8 μm/min, measured by a precise digital screw micrometer. After the chemical etching process, the HF acid remaining on the samples had been made neutral by a weak alkaline solution, such as an aqueous solution of sodium bicarbonate (wt~5%), and the samples were carefully cleaned in an ultrasonic bath. The surface of samples has been examined by using a microscope, and it was found that the surface defects exist on the etched SMF28 fiber section (see Figure 6a). During the etching process, we found that the roughness of the cladding surface defects depends on the HF acid concentration and the etching time, etc.

The surface defects will significantly influence on the measured bend loss results, thus the etched samples with rough surfaces cannot be employed for the refractometer sensing at this stage. In order to mitigate the effect of the defect on the surface of etched cladding, all samples were fire-polished by a pure H_2 flame at the temperature of circa 1250^{o}C, which is a transition temperature of the silica material. Figure 6b shows a microscope image of the fire-polished fiber surface, from which one can see that the fire polishing process significantly reduces the severity of the surface defects, and forms a spotless surface state.

To better illustrate the bend loss behavior presented in Fig. 5, the theoretical results for two samples are presented in Figure 7 at 1550 nm for two different cladding diameters, 67 and 81 μm, where both of the samples have bend radii of 7.7 mm. Once again the results are presented as the difference in bend loss by comparison with the bend loss at the starting refractive index of 1.4586. The experimental results with/without the fire polishing process are also presented in the figures. From Figure 7 (a) and (b), it is clear that the calculated bend loss differences as a function of refractive index model are in reasonable agreement with the measured results for the samples with the fire polished surfaces (hollow circle points).

The measured refractive index resolutions that can be estimated are 5.88×10^{-5} and 5.75×10^{-5} for the refractometer sensor with a cladding diameter of 67 and 81 μm, respectively. As mentioned previously the surface roughness of the fiber cladding is a function of the etching time and HF acid concentration. Achieving a fiber diameter of 67 μm requires a longer etching time than that for 81 μm and the result is an increased surface roughness, manifested as a larger discrepancy between measured and theoretical results without fire polishing as can be seen from Fig. 7 (*a*) and (*b*). The samples with a 67 μm cladding give an average discrepancy of 4.624 dB between the calculated (solid line) and measured results (star points), significantly larger than 1.844 dB of the sample with an 81 μm cladding.

Based on the marginally better resolution and a reduced level of surface defects during the etching process, a fiber diameter of 81 μm is proposed as a better solution.

4. Conclusion

In conclusion, we have presented and investigated a novel all-fiber macrobending refractometer sensor for measuring the unknown refractive index of a liquid sample. The well-known scalar approximation method for predicting the macrobending loss of singlemode fiber has been utilized for numerical simulation. A standard singlemode fiber-SMF28 has been employed for verifying the numerical models presented. The agreement between the theoretical and experimental results confirms that the refractive index of the surrounding liquid can be determined as a function of bend loss of the bare bending fiber, with an estimated theoretical refractive index resolution of 9.73×10^{-5}. By reducing the cladding diameter of the sensor, an improved measured resolution of 5.75×10^{-5} over a measureable refractive index range from 1.4586 to 1.5396 (at the wavelength of 1550 nm) can be achieved, for a cladding diameter of 81 μm.

5. Acknowledgement

The support of the Irish Research Council for Science, Engineering and Technology (IRCSET) is gratefully acknowledged.

The research was partially supported by the National Natural Science Foundation of China (No. 60577008, 60777038), the China-Ireland Science and Technology Collaboration Research Fund and the International cooperation project (No.20070708-3) of Jilin Provincial Science & Technology Department of China.

References

1. W. Liang, Y. Y. Huang, Y. Xu, R. K. Lee, and A. Yariv, “Highly sensitive fiber Bragg grating refractive index sensors,” App. Phys. Lett. 86, pp. 151-122 (2005).
2. A. N. Chryssis, S. M. Lee, S. B. Lee, S. S. Saini, and M. Dagenais, “High sensitivity evanescent field fiber Bragg grating sensor,” IEEE Photon. Technol. Lett. 17, pp. 1253-1255 (2005).
3. T. Wei, Y. Han, Y. Li, H-L. Tsai and H. Xiao, “Temperature-insensitive miniaturized fiber inline Fabry-Perot interferometer for highly sensitive refractive index measurement.” Opt. Express, Vol. 16, No. 8, pp. 5764-5769 (2008).
4. Z. Tian, S. S-H. Yam and H-P. Loock, “Refractive index sensor based on an abrupt taper Michelson interferometer in a single-mode fiber.” Opt. Lett., Vol. 33, No. 10, pp. 1105-1107 (2008).
5. J. Villatoro and D. Monzón-Hernández, “Low-cost optical fiber refractive-index sensor based on core diameter mismatch.” J. Lightwave Technol., Vol. 24, No. 3, pp. 1409–1413 (2006).
6. Q. Wang and G. Farrell, “All-fiber multimode-interference-based refractometer sensor: proposal and design.” Opt. Lett., Vol. 31, No. 3, pp. 317-319 (2006).
7. Y. Murakami and H. Tsuchia, “Bending losses of coated single-mode optical fibres,” IEEE J. Quant. Electron., Vol. QE-14, No. 7, pp. 495-501 (1978).
8. G. J. Veldhuis and P. V. Lambeck, “Highly-sensitive passive integrated optical spiral-shaped waveguide refractometer,” Appl. Phys. Lett., Vol. 71, No. 20, pp. 2895–2897, 1997.
9. G. J. Veldhuis, L. E. W. van der Veen, and P. V. Lambeck, “Integrated optical refractometer based on waveguide bend loss,” J. Lightwave Technol., Vol. 17, No. 5, pp. 857–864, 1999.
10. D. Marcuse, “Curvature loss formula for optical fibers,” J. Opt. Soc. Am., Vol. 66, No. 3, pp. 216-220 (1976).
11. I. Valiente and C. Vassallo, “New formalism for bending losses in coated single-mode optical fibres,” Electron. Lett., Vol. 25, No. 22, pp. 1544-1545 (1989).
12. H. Renner, “Bending losses of coated single-mode fibers: a simple approach,” J. Lightwave Technol., Vol. 10, No. 5, pp. 544-551 (1992).
13. L. Faustini and G. Martini, “Bend loss in single-mode fibers,” J. Lightwave Technol., Vol. 15,

No.4, pp. 671-679 (1997).

14. Q. Wang, G. Farrell, and T. Freir, “Theoretical and experimental investigations of macro-bend losses for standard single mode fibers,” Opt. Exp., Vol. 13, No. 12, pp. 4476-4484 (2005).
15. Q. Wang, G. Farrell, T. Freir, G. Rajan and P. Wang, "Low-cost Wavelength Measurement based on a Macrobending Single-mode Fiber," Optics Letters, Vol. 31, No. 12, pp. 1785-1787, 2006.
16. Q. Wang, G. Rajan, G. Farrell, P. Wang, Y. Semenova and T. Freir, "Macrobending fiber loss filter, ratiometric wavelength measurement and application," Measurement Science and Technology, Vol. 18, pp. 3082-3088, 2007.

Figure Captions:

Fig. 1 Schematic of macrobending singlemode fiber based refractometer sensor.

Fig. 2 (Color online) Calculated bend losses versus bend radius and refractive index for SMF28 singlemode fiber based refractometer, where the operating wavelength is 1550 nm.

Fig. 3 Schematic of the experimental setup for refractive index sensing

Fig. 4 Calculated and measured differences of bending losses as a function of refractive index for bending radii in the vicinity of 7.7 mm, where the operating wavelength is 1550 nm.

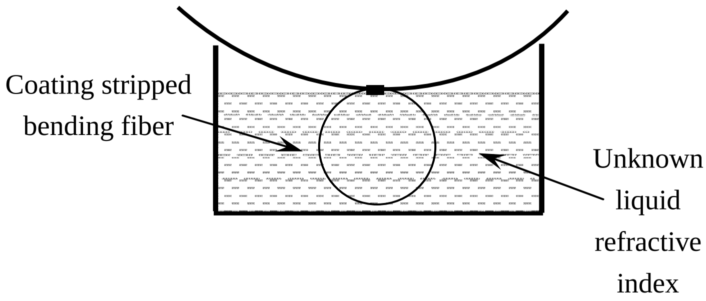
Fig. 5 (Color online) Calculated bending loss versus cladding radii and refractive index for SMF28 singlemode fiber based refractometer, the bending radius is 7.7 mm, and the wavelength is 1550 nm.

Fig. 6 Microscope images of etched bare SMF28 fiber: (a) after the chemical etching process (calibration bar is 40 μm), surface defects visible; (b) after the fire polishing process, surface quality improved (calibration bar is 80 μm).

Fig. 7 Calculated and measured the differences of bend losses as a function of refractive index at a bending radius of 7.7 mm, where the wavelength is 1550 nm and the cladding diameter is (a) 67 and (b) 81 μm.

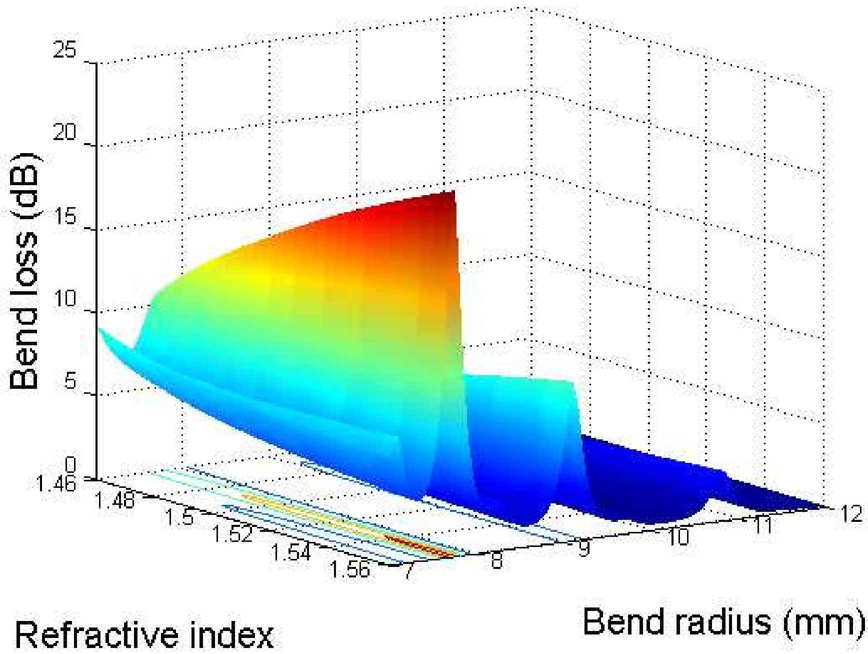
Table Captions:

Table 1: Specified refractive indices of Cargille oils at wavelengths of 589.3 nm and 1550 nm, at the temperature of 25^{o}C.



Coating stripped
bending fiber
Unknown
liquid
refractive
index

Fig. 1



25
20
15
10
5
0
Bend loss (dB)
1.46
1.48
1.5
1.52
1.54
1.56
7
8
9
10
11
12
Refractive index
Bend radius (mm)

Fig. 2

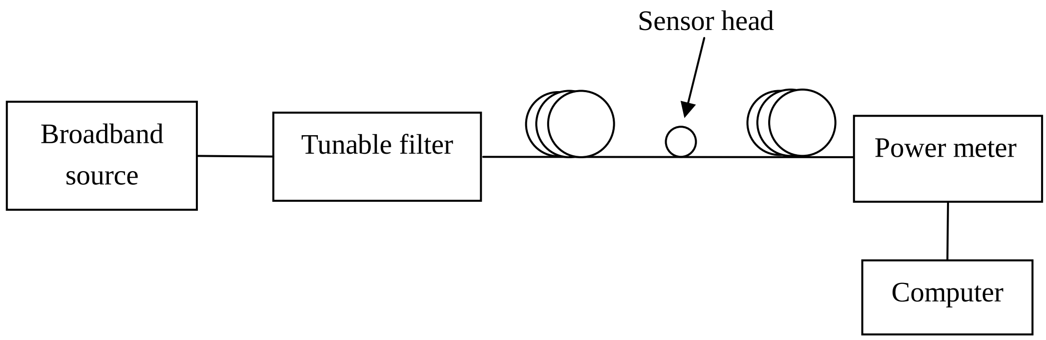

Sensor head
Broadband source
Tunable filter
Power meter
Computer

Fig. 3

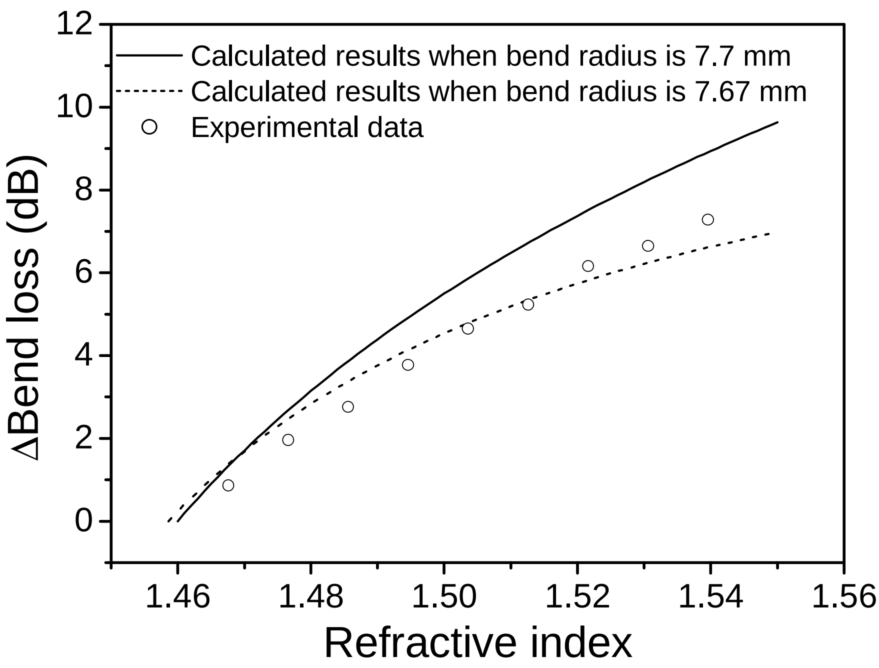

Calculated results when bend radius is 7.7 mm
Calculated results when bend radius is 7.67 mm
Experimental data
ΔBend loss (dB)
Refractive index
0
2
4
6
8
10
12
1.46
1.48
1.50
1.52
1.54
1.56

Fig. 4

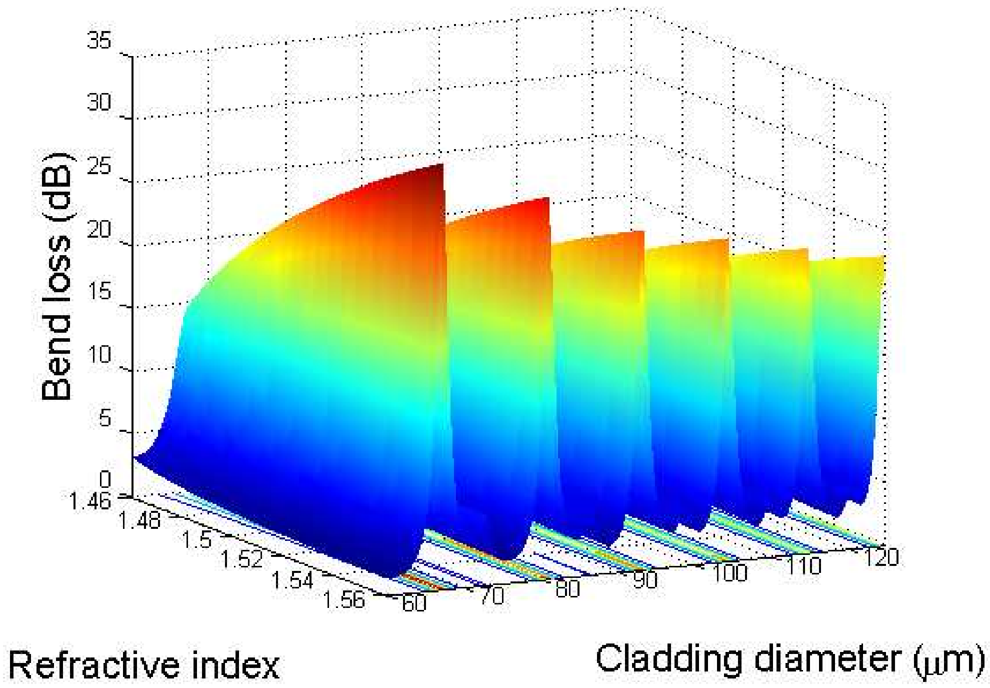

35
30
25
20
15
10
5
0
Bend loss (dB)
1.46
1.48
1.5
1.52
1.54
1.56
60
70
80
90
100
110
120
Refractive index
Cladding diameter (μm)

Fig. 5

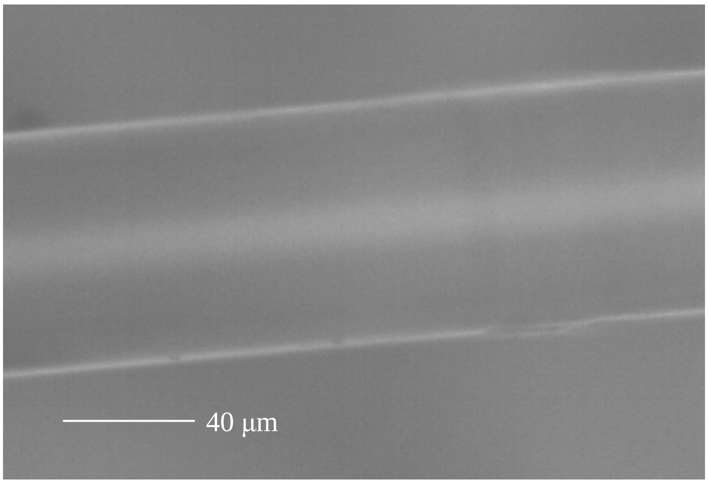


Fig. 6(a)

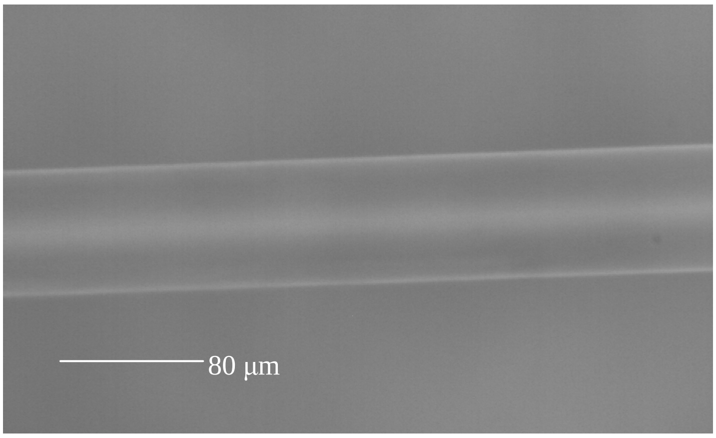
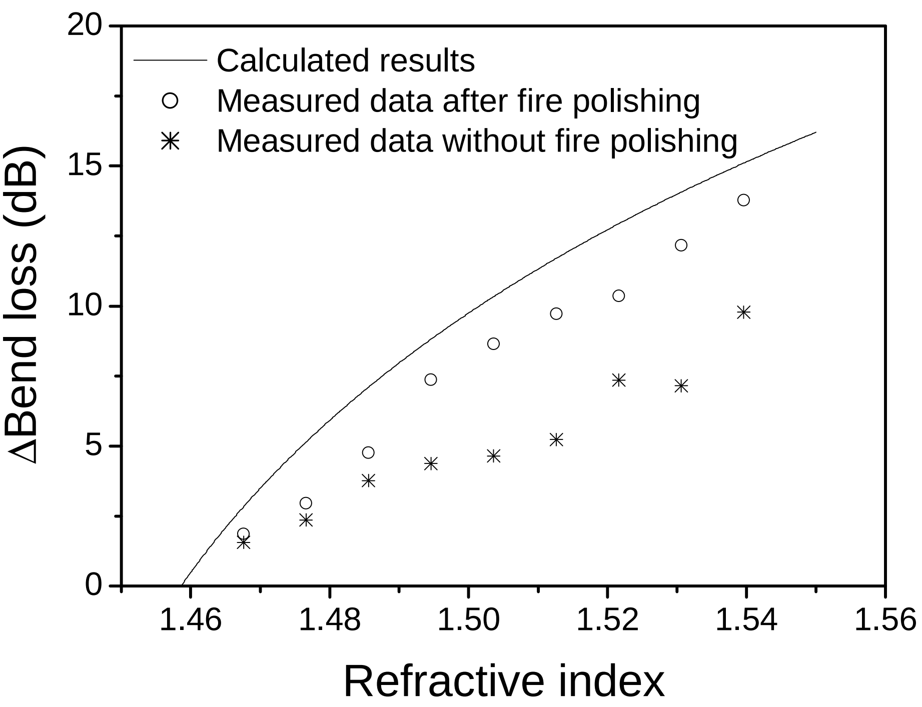
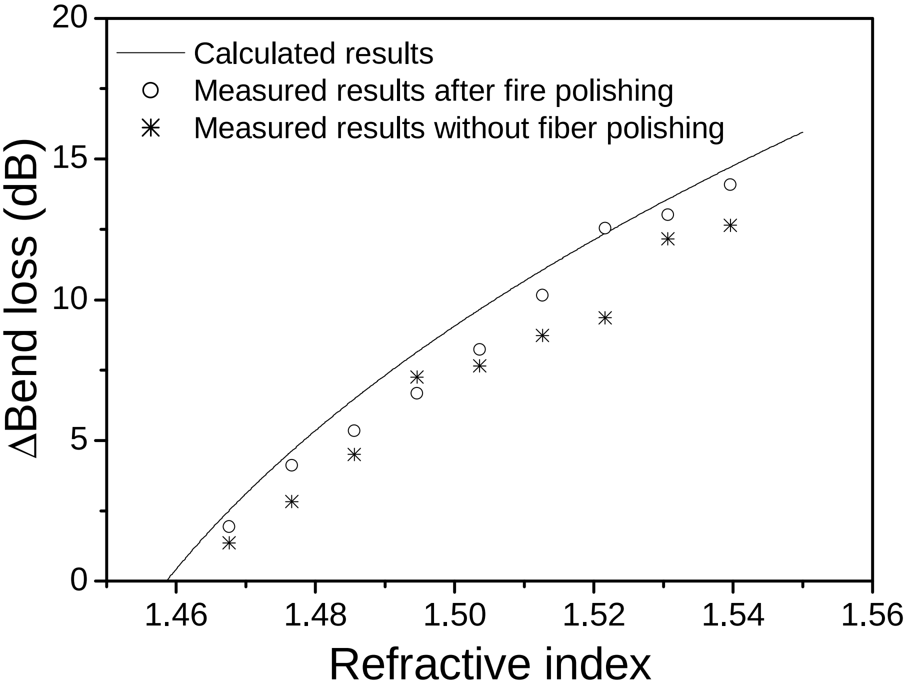


Fig. 6(b)



Calculated results
Measured data after fire polishing
Measured data without fire polishing
ΔBend loss (dB)
Refractive index
0
5
10
15
20
1.46
1.48
1.50
1.52
1.54
1.56

Fig. 7(a)



20
15
10
5
0
ΔBend loss (dB)
Calculated results
Measured results after fire polishing
Measured results without fiber polishing
1.46
1.48
1.50
1.52
1.54
1.56
Refractive index

Fig. 7(b)

Table 1: Specified refractive indices of Cargille oils at wavelengths of 589.3 nm and 1550 nm, at the temperature of 25^{o}C.

Refractive indices@589.3 nm	**Refractive indices@1550 nm**
1.47	1.4586
1.48	1.4676
1.49	1.4766
1.50	1.4856
1.51	1.4946
1.52	1.5036
1.53	1.5126
1.54	1.5216
1.55	1.5306
1.56	1.5396