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# Temperature Performance of a Macrobending Single-Mode Fiber-Based Refractometer

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# Temperature performance of a macrobending single-mode fiber-based refractometer

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We present, theoretically and experimentally, an investigation of temperature dependence of a macrobending single-mode fiber-based refractometer utilizing a ratiometric scheme. The conventional scalar approximation method is utilized for predicting the temperature dependent loss of the proposed fiber refractometer. An all-fiber ratiometric measurement system is built to allow the comparison of modeled and measured results. Calculated and measured results for an SMF28 refractometer are in good agreement and confirm the effect of temperature on refractive index measurements. Both calculated and measured ratio responses monotonically change with temperature, which allows for a temperature correction process. © 2010 Optical Society of America

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## 1. Introduction

In recent years, a range of optical fiber-based refractometers have attracted enormous interest due to their wide applications in biotechnology sensing, e.g., for measurements of sugar content, protein concentration in the blood, and salinity of urine in the area of experimental medicine. Examples of fiber-based refractometers include a fiber Bragg grating-based refractometer [1,2], a fiber gap-based Fabry–Perot structure [3], a refractometer based on an abrupt taper Michelson interferometer [4], a refractometer based on a multimode-single-mode-multimode fiber core diameter mismatch [5] and a single-mode-multimode-single-mode fiber refractometer [6]. Generally these fiber-based refractometers have shown high sensitivities for refractive index (RI) measurements.

Our recent investigation on a macrobending standard single-mode fiber (SMF28) has shown that a bent fiber can be employed to develop an all-fiber edge filter [7] and RI sensor [8]. Such a macrobend fiber refractometer is attractive for use as a disposable RI sensor in biotechnology applications, where reuse of a sensor is not permitted. The disposable nature of the sensor arises from its low cost and ease of fabrication.

A key parameter for an RI sensor is measurement accuracy over a wide range of refractive indices. One of the main factors introducing inaccuracies in RI measurements is ambient temperature variation. It has been shown previously that temperature has a significant influence on the bending loss of macrobending fibers [9–11]. If a macrobend fiber refractometer is interrogated using a ratiometric intensity measurement system, then, normally, the ratiometric system is calibrated and the ratio response is obtained at a fixed temperature. However, a subsequent change in ambient temperature for the

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sensor can alter the ratio response and lead to inaccurate RI measurements.

For the Corning SMF28 fiber-based refractometer presented in Ref. [8], the sensor head consists of a single loop of coating-stripped macrobending fiber with a selected bending radius. If the bare bending fiber section is immersed in a liquid, the bending loss becomes a function of the liquid RI. By measuring the changes in macrobending loss, the RI of the surrounding liquid can be determined, assuming the measurement system is properly calibrated. In this paper a detailed investigation of the temperature dependence of an SMF28 fiber-based refractometer, and its effect on RI measurement using a ratiometric measurement scheme, is presented. In Section 2 a suitable theoretical model for predicting the temperature dependence of macrobending single-mode fibers is described. An experimental setup to measure the temperature induced ratio variation of the refractometer is described in Section 3. Results and discussion of temperature dependencies for the bent fiber based refractometer are presented in Section 4. Furthermore, we also propose and present a technique to extract the pure temperature dependent loss (TDL) of a fiber refractometer without the influence of the thermo-optic effect of the RI liquids.

## 2. Theoretical Background

When a bare-cladding fiber is immersed into a liquid, it can be considered an approximate equivalent of a fiber structure consisting of a core, cladding, and infinite coating layers. The expression for calculating the temperature dependent bend loss in fibers with single or multiple coating layers has been developed in [9] based on a conventional scalar approximation method, taking into account the thermo-optic coefficients (TOCs) of the multiple fiber layers.

In these studies, the parameters of Cargille RI oils with calibrated indices (with an RI tolerance of $\pm 0.0002$) were employed for simulation, and, subsequently, actual Cargille RI oils were also used in experiments. The corresponding refractive indices and TOCs of the oils at a wavelength of 1550 nm are listed in Table 1. Using these coefficients, the effect of temperature on the RI of the Cargille oils is taken into account in the simulation.

**Table 1. Refractive Indices and Thermo-Optic Coefficients of Cargille Oils at Wavelength 1550 nm at 25 °C**

| RI at 1550 nm ($\pm 0.0002$) | TOCs ($\times 10^{-4}$/°C) |
|---|---|
| 1.4586 | −3.92 |
| 1.4676 | −3.95 |
| 1.4766 | −3.98 |
| 1.4856 | −4.01 |
| 1.4946 | −4.04 |
| 1.5036 | −4.07 |
| 1.5126 | −4.09 |
| 1.5216 | −4.12 |
| 1.5306 | −4.15 |
| 1.5396 | −4.18 |

In order to gain a physical insight into the influence of temperature on RI measurements, the values of bend loss for a range of temperature and RI values were calculated for a refractometer with a bend radius of 7.7 mm at a wavelength of 1550 nm. In [8] it was shown that the use of an etched cladding fiber could improve RI sensitivity. Hence, in this work two fiber cladding diameters were employed, 125 $\mu$m for unetched fiber and 81 $\mu$m for etched fiber. The results of the calculations are presented in Figs. 1(a) and 1(b).

As shown in Fig. 1(a), if the temperature changes from 20 °C to 70 °C, significant changes occur in the bend loss spectral response of the unetched SMF28-based refractometer. For example, for measurements involving an RI equal to 1.46, the bend loss changes from 11.82 dB to 7.32 dB when the temperature changes from 20 °C to 70 °C, while, if measuring an RI equal to 1.56, the bend loss changes from 19.88 dB to 19.69 dB over the same temperature range. This temperature induced bend loss change

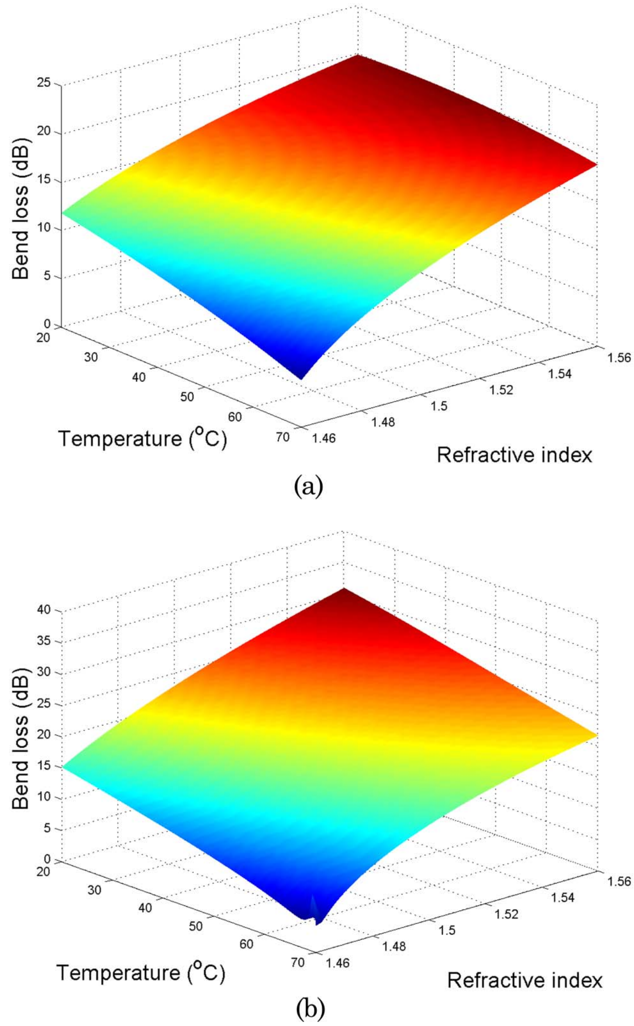



Fig. 1. (Color online) Calculated bend loss versus temperature (20 °C – 70 °C) and RI changes (1.46 – 1.56) for the bend radius of 7.7 mm. The cladding diameter is (a) 125 $\mu$m and (b) 81 $\mu$m; the operating wavelength is 1550 nm.

is referred to as TDL. The TDL behavior of the etched SMF28 fiber refractometer is shown in Fig. 1(b), where it is evident that the variations of bend loss induced by the changes of temperature are larger than that of the unetched fiber refractometer. As the changes in bend loss induced by temperature are of the same order of magnitude as those induced by RI change, there is clearly a temperature sensitivity issue.

## 3. Experiment Setup

To verify the theoretical model presented above, in the experiment a setup for measuring the TDL within different RI liquids was built, as shown in Fig. 2. A ratiometric RI measurement system was connected to a tunable laser with a wavelength range from 1500 to 1600 nm and to a personal computer, which can collect the output ratiometric signal after signal processing. A ratiometric measurement system is employed here, as it has the advantage that it can operate independently of source power variations, resulting in improved measurement stability and accuracy.

The coating-stripped bare SMF28 fiber is bent to form a small 360° loop, and it is used as a refractometer sensor head. Full contact between the refractometer and the RI liquid is ensured by full immersion of the sensor head in the liquid. The temperature of the RI liquid is controlled by a digital temperature controller connected to a heater. An accurate independent platinum resistance probe connected to a digital temperature display is immersed into the RI liquid for the purpose of temperature monitoring. Two photodiodes are employed at the ends of the reference arm and the arm containing the fiber refractometer to allow for measurement of the power ratio and, thus, extraction of the RI information.

Two SMF28-based refractometers with cladding radii of 125 and 81 $\mu$m with a measured resolution of $9.73 \times 10^{-5}$ RIU (RI unit) and $5.75 \times 10^{-5}$ RIU [8], respectively] are used in the experiments. The coating layers of SMF28 fibers were removed by using hot concentrated sulfuric acid ($H_2SO_4$, 95 wt. %, at a temperature of approximately 200 °C) to avoid potential defects of the cladding surface induced by a mechanical stripping process. The fiber sensor head is formed by creating a small 360° loop by inserting the fiber ends into a small 2 mm polymer tube. To fix the radius of the bending loops, the fibers inside the tube are glued, and this forms a stable macrobending fiber refractometer sensor head.

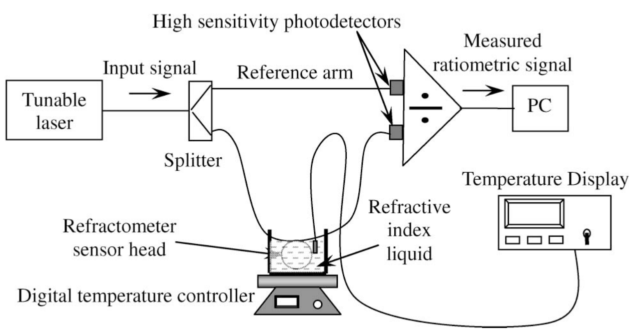



Fig. 2. Schematic of the ratiometric RI measurement system.

In order to prepare the fiber refractometer with an etched cladding diameter of 81 $\mu$m, both chemical etching of the cladding and subsequent fire polishing are undertaken, as described in Ref. [8]. The operating wavelength of the measurement system was 1550 nm, and both etched and unetched fiber refractometer heads had bending radii of approximately 7.7 mm. The TDL ratio response was measured at 2 °C intervals over a temperature range from 20 °C (room temperature) to 70 °C. The measured temperature range was limited by the properties of RI oils, which suffer from molecular degradation at temperatures above 70 °C.

## 4. Results and Discussion

The theoretical and experimental macrobending loss ratios are presented in Fig. 3(a) for an unetched fiber refractometer with a radius of 7.7 mm, for a temperature range from 20 °C to 70 °C and an RI range from

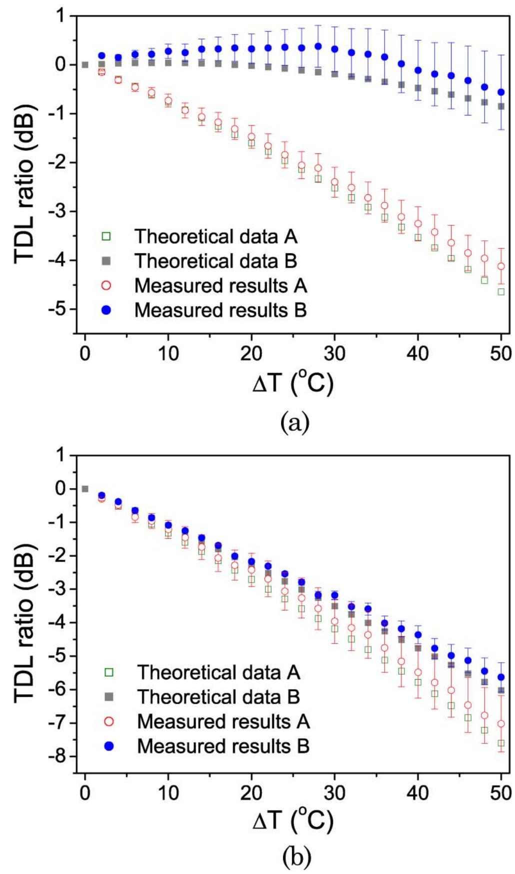



Fig. 3. (Color online) Calculated and measured TDL ratio responses as a function of the difference of temperature from 20 °C to 70 °C at a wavelength of 1550 nm, when the cladding diameter is (a) 125 $\mu$m and (b) 81 $\mu$m. (Theoretical data: theoretically calculated results for the RI liquid: A, RI = 1.4586 at 25 °C; and B, RI = 1.5396 at 25 °C. Measured results: measured results with the error bars for the RI liquid: A, RI = 1.4586 at 25 °C; and B, RI = 1.5396 at 25 °C.)

1.4586 to 1.5396. Figure 3(b) presents the theoretical and experimental TDL ratio response for an etched fiber refractometer over the same temperature range. Error bars are shown on all measured data, and from the figures one can see that there is a good overall agreement between the calculated and experimental data.

The error bars used are derived from a consideration of the major sources of error in the experiments. The accuracy of the vernier caliper employed in the experiments is $\pm 0.01$ mm. It was previously shown [8] that given the accuracy of the vernier calipers and minute mechanical changes to the fiber loop over time, an experimental variation up to $\pm 0.03$ mm on the bend diameter can be expected for a fiber refractometer. Errors also arise from the limited accuracy of the TOC values of the liquids ($\pm 0.0002$). The error bars in Figs. 3(a) and 3(b) take into account the effect of the accuracy of the bend diameter and also the accuracy of the TOCs of the RI liquids. Other perceptible minor discrepancies between the experimental and theoretical results may be caused by minute differences between the temperature of the fiber and temperature measured by the reference thermometer sensor probe, for example, those resulting from a convection induced liquid flow.

To better illustrate and evaluate the influence of temperature on an SMF28 fiber-based refractometer over the entire RI range from 1.4586 to 1.5396 at a wavelength of 1550 nm, theoretically calculated and experimentally measured differences between bending loss at 20 °C and 70 °C, as functions of the RI ranging from 1.4586 to 1.5396, are presented in Fig. 4 for refractometers with cladding diameters of 125 $\mu$m and 81 $\mu$m, respectively.

From Fig. 4(a), one can see that the experimentally measured difference in the bend loss between 20 °C and 70 °C over an RI range from 1.4586 to 1.5396 shows a monotonically increasing characteristic, which matches the calculated results well. Also, it can be found from the figure that the average slope of the calculated TDL ratio is 46.91 dB/RIU, and the average slope of measured TDL is 43.95 dB/RIU.

For the etched fiber case from Fig. 4(b), one can see that the relationship between the TDL ratio response and RI measured for the cladding diameter of 81 $\mu$m is nonmonotonic and nonlinear, although simulated results maintain satisfactory agreement with the experimental data. The nonlinear variations over the entire RI range presented in Fig. 4(b) are most likely caused by the difference in sign between the positive TOC of silica and the negative TOC of Cargille oils, as evident from Table 1. Additionally, the experimental results in both Figs. 3 and 4 are influenced by the limited resolution of the temperature sensor employed in the experiments and small variations of the temperature of the hot plate.

To examine the influence of the thermo-optic effect of the RI liquids on the fiber refractometer TDL ratio, the TDL of the fiber refractometer can be divided into two parts: (i) a TDL induced by the TOC and thermal expansion coefficients (TEC) of fiber material itself and (ii) a TDL induced by the thermo-optic effect of the Cargille oil liquids. Thus the total TDL ratio can be expressed as follows:

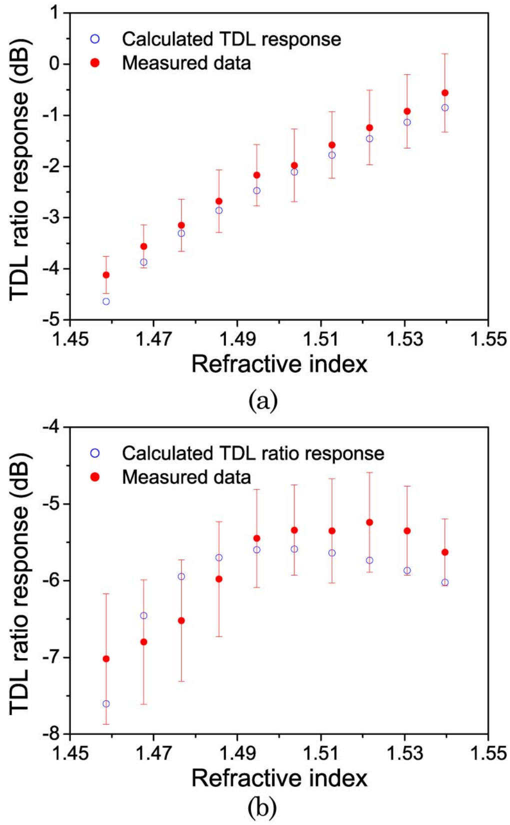



Fig. 4. (Color online) Calculated and measured TDL ratio response (with the error bars) between 20 °C and 70 °C as a function of RI (with an interval of 0.009) at a wavelength of 1550 nm, when the cladding diameter is (a) 125 $\mu$m and (b) 81 $\mu$m.

$$\mathrm{TDL}_{\mathrm{fiber}} + \mathrm{TDL}_{\mathrm{liquids}} = \mathrm{TDL}_{\mathrm{total}}, \tag{1}$$

where $\mathrm{TDL}_{\mathrm{fiber}}$ is the TDL of fiber caused by the TOC and TEC of fiber materials, $\mathrm{TDL}_{\mathrm{liquids}}$ is the TDL induced by the thermo-optic effect of the Cargille oils, and $\mathrm{TDL}_{\mathrm{total}}$ is the total TDL ratio measured at the photodetectors. In general, the TDL between two temperatures $X$ °C and $Y$ °C (where $Y$ °C $>$ $X$ °C) is defined as

$$\mathrm{TDL} = \mathrm{Loss}_{Y\,^{\circ}\mathrm{C}} - \mathrm{Loss}_{X\,^{\circ}\mathrm{C}}. \tag{2}$$

The key issue is how to separate the wanted TDL of the fiber from the measured TDL, which includes that of the liquid. The technique proposed is to generate measured TDLs for two liquids, at two temperatures relative to 20 °C. By careful selection of the liquid RI values and temperatures, it is possible to extract the TDL of the fiber alone.

The generalized basis for this approach is as follows. Eqs. (1) and (2) above are extended to a set of equations, as shown in Eqs. (3)–(7) for two temperatures $X$ °C and $Y$ °C, where $Y$ °C $>$ $X$ °C.

For a single RI liquid, we can write

$$\mathrm{Loss}_{\mathrm{total}}^{X\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{total}}^{20\,°\mathrm{C}} = \mathrm{TDL}_{\mathrm{total}}^{X\,°\mathrm{C}} = \mathrm{TDL}_{\mathrm{fiber}}^{X\,°\mathrm{C}} + \mathrm{TDL}_{\mathrm{liquids}}^{X\,°\mathrm{C}}, \quad (3)$$

$$\mathrm{Loss}_{\mathrm{total}}^{Y\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{total}}^{20\,°\mathrm{C}} = \mathrm{TDL}_{\mathrm{total}}^{Y\,°\mathrm{C}} = \mathrm{TDL}_{\mathrm{fiber}}^{Y\,°\mathrm{C}} + \mathrm{TDL}_{\mathrm{liquids}}^{Y\,°\mathrm{C}}, \quad (4)$$

$$\mathrm{Loss}_{\mathrm{fiber}}^{X\,°\mathrm{C}} + \mathrm{Loss}_{\mathrm{liquids}}^{X\,°\mathrm{C}} = \mathrm{Loss}_{\mathrm{total}}^{X\,°\mathrm{C}}, \quad (5)$$

$$\mathrm{Loss}_{\mathrm{fiber}}^{Y\,°\mathrm{C}} + \mathrm{Loss}_{\mathrm{liquids}}^{Y\,°\mathrm{C}} = \mathrm{Loss}_{\mathrm{total}}^{Y\,°\mathrm{C}}. \quad (6)$$

Assume now that there are two different Cargille oil liquids, RI1 and RI2, at temperatures of $X\,°\mathrm{C}$ and $Y\,°\mathrm{C}$, respectively; then, using Eqs. (3) and (4)

$$\mathrm{TDL}_{\mathrm{fiber}}^{X\,°\mathrm{C}} + \mathrm{TDL}_{\mathrm{RI1}}^{X\,°\mathrm{C}} = \mathrm{TDL}_{\mathrm{total1}}^{X\,°\mathrm{C}} = \mathrm{Loss}_{\mathrm{total1}}^{X\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{total1}}^{20\,°\mathrm{C}}, \quad (7)$$

$$\mathrm{TDL}_{\mathrm{fiber}}^{Y\,°\mathrm{C}} + \mathrm{TDL}_{\mathrm{RI2}}^{Y\,°\mathrm{C}} = \mathrm{TDL}_{\mathrm{total2}}^{Y\,°\mathrm{C}} = \mathrm{Loss}_{\mathrm{total2}}^{Y\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{total2}}^{20\,°\mathrm{C}}, \quad (8)$$

where $\mathrm{Loss}_{\mathrm{fiber}}^{X\,°\mathrm{C}}$ and $\mathrm{Loss}_{\mathrm{fiber}}^{Y\,°\mathrm{C}}$ are the fiber bending loss caused by the TEC and TOC of fiber silica material at temperatures of $X\,°\mathrm{C}$ and $Y\,°\mathrm{C}$, respectively; $\mathrm{Loss}_{\mathrm{RI1}}^{X\,°\mathrm{C}}$ is the fiber bending loss caused by the thermo-optic effect of liquid RI1 at a temperature of $X\,°\mathrm{C}$; $\mathrm{Loss}_{\mathrm{RI2}}^{Y\,°\mathrm{C}}$ is the fiber bending loss caused by the thermo-optic effect of liquid RI2 at a temperature of $Y\,°\mathrm{C}$; and $\mathrm{Loss}_{\mathrm{total1}}^{20\,°\mathrm{C}}$ and $\mathrm{Loss}_{\mathrm{total2}}^{20\,°\mathrm{C}}$ are the measured reference bending losses at a temperature of 20 °C for the liquid RI1 and RI2, respectively. From Eqs. (5) and (6), we have

$$\mathrm{Loss}_{\mathrm{fiber}}^{X\,°\mathrm{C}} + \mathrm{Loss}_{\mathrm{RI1}}^{X\,°\mathrm{C}} = \mathrm{Loss}_{\mathrm{total1}}^{X\,°\mathrm{C}}, \quad (9)$$

$$\mathrm{Loss}_{\mathrm{fiber}}^{Y\,°\mathrm{C}} + \mathrm{Loss}_{\mathrm{RI2}}^{Y\,°\mathrm{C}} = \mathrm{Loss}_{\mathrm{total2}}^{Y\,°\mathrm{C}}. \quad (10)$$

Using Eqs. (7)–(10), we can write

$$\mathrm{Loss}_{\mathrm{fiber}}^{X\,°\mathrm{C}} + \mathrm{Loss}_{\mathrm{RI1}}^{X\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{total1}}^{20\,°\mathrm{C}} = TDL_{\mathrm{total1}}^{X\,°\mathrm{C}}, \quad (11)$$

$$\mathrm{Loss}_{\mathrm{fiber}}^{Y\,°\mathrm{C}} + \mathrm{Loss}_{\mathrm{RI2}}^{Y\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{total2}}^{20\,°\mathrm{C}} = TDL_{\mathrm{total2}}^{Y\,°\mathrm{C}}. \quad (12)$$

The values of $\mathrm{TDL}_{\mathrm{total1}}^{X\,°\mathrm{C}}$ and $\mathrm{TDL}_{\mathrm{total2}}^{Y\,°\mathrm{C}}$ can be measured by the photodetectors. Assuming it is possible to select RI liquids and temperatures $X\,°\mathrm{C}$ and $Y\,°\mathrm{C}$ such that the bend loss of liquid RI1 at a temperature of $X\,°\mathrm{C}$ is equal to the bend loss of liquid RI2 at a temperature of $Y\,°\mathrm{C}$, then $\mathrm{Loss}_{\mathrm{RI1}}^{X\,°\mathrm{C}} = \mathrm{Loss}_{\mathrm{RI2}}^{Y\,°\mathrm{C}}$. Taking this equality into account, and by taking the difference between Eqs. (11) and (12), then

$$\mathrm{Loss}_{\mathrm{fiber}}^{Y\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{fiber}}^{X\,°\mathrm{C}} + \mathrm{Loss}_{\mathrm{RI2}}^{Y\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{RI1}}^{X\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{total2}}^{20\,°\mathrm{C}} + \mathrm{Loss}_{\mathrm{total1}}^{20\,°\mathrm{C}} = \mathrm{TDL}_{\mathrm{total2}}^{Y\,°\mathrm{C}} - \mathrm{TDL}_{\mathrm{total1}}^{X\,°\mathrm{C}}. \quad (13)$$

The terms $\mathrm{TDL}_{\mathrm{total1}}^{X\,°\mathrm{C}}$, $\mathrm{TDL}_{\mathrm{total2}}^{Y\,°\mathrm{C}}$, $\mathrm{Loss}_{\mathrm{total1}}^{20°C}$, and $\mathrm{Loss}_{\mathrm{total2}}^{20°C}$ are all measurable, leaving the term $\mathrm{Loss}_{\mathrm{fiber}}^{Y\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{fiber}}^{X\,°\mathrm{C}}$, which is the TDL of the fiber between the temperatures $X\,°\mathrm{C}$ and $Y\,°\mathrm{C}$, independent of the TDL of the liquids.

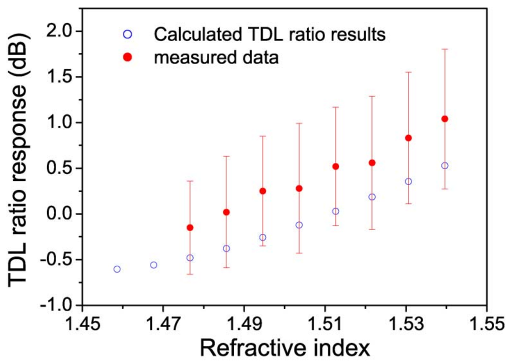
As an example of the use of this technique, as shown in Table 1, the Cargille RI liquid of 1.5036 at 25 °C has the TOC value of $-4.07 \times 10^{-4}\,°\mathrm{C}^{-1}$. At a temperature of 70 °C, the RI value decreases to 1.4853, which is very close to the RI liquid of 1.4856 at a temperature of 25 °C. Thus we have satisfied the condition above that the RI values of two different liquids are the same at two different temperatures. In this example, this means $\mathrm{Loss}_{\mathrm{RI1}}^{25\,°\mathrm{C}} \approx \mathrm{Loss}_{\mathrm{RI2}}^{70\,°\mathrm{C}}$, so that the pure TDL of the fiber refractometer ($\mathrm{Loss}_{\mathrm{fiber}}^{70\,°\mathrm{C}} - \mathrm{Loss}_{\mathrm{fiber}}^{25\,°\mathrm{C}}$) between 25 °C and 70 °C can be obtained using Eq. (13).

Overall, it is clear that temperature variations will significantly impact the accuracy of a bent fiber-based refractometer. Our theoretical method can be used to evaluate the TDL performance of a macrobending fiber-based refractometer as a function of ambient temperature. Moreover, given that both calculated and measured TDL ratio responses show a monotonic variation with the temperature [Fig. 3], the influence of temperature can be mitigated by a suitable temperature correction process, where the temperature of the liquid under test is monitored.

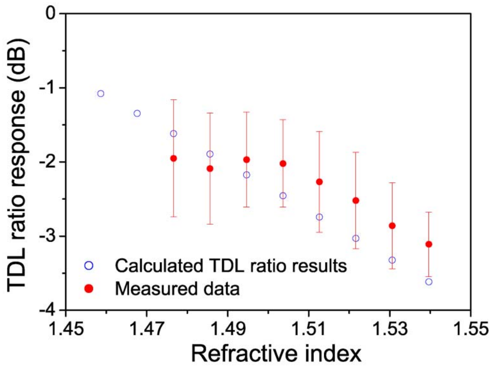
From both Figs. 4(a) and 5(a) it can be observed that the TDL ratio response of the unetched fiber refractometer, as a function of measured RI, shows a monotonic response over the temperature range of 20 °C to 70 °C [Fig. 4(a)] and from 25 °C to 70 °C [Fig. 5(a)]. The TDL ratio response of the unetched fiber refractometer without the influence of the thermo-optic effect of RI liquids is significantly less than that of the etched fiber refractometer presented in Fig. 5(b). This linear and small TDL response for the unetched fiber refractometer can be exploited for temperature correction of RI measurement.

However, for the case of the etched fiber refractometer, the TDL response varies in a parabolic fashion over the entire RI measurement range, as shown in Fig. 4(b), and the range of the TDL change is significantly higher, as presented in Fig. 5(b). Such characteristics will make temperature correction more difficult to implement.

Finally, the general agreement between calculated and measured results suggests that the model could have broader applications for the analysis, design, and evaluation of performance of fiber sensor devices, including their temperature sensitivity and facilitating the development of new types of fiber sensors.




(a)




(b)

Fig. 5. (Color online) Calculated and measured TDL ratio response (with error bars) between 25 °C and 70 °C as a function of RI (with an interval of 0.009) at a wavelength of 1550 nm, when the cladding diameter is (a) 125 $\mu$m and (b) 81 $\mu$m. Both modeled and measured results are corrected without the influence of the thermo-optic effect of RI liquids (see text for detail).

## 5. Conclusion

In this paper, the effect of temperature on measurements of RI by a system based on a macrobending SMF28 refractometer has been studied theoretically and experimentally. An effective theoretical model based on a scalar approximation method has been presented. Corresponding experimental verifications, involving a ratiometric RI measurement system, have been carried out; the acceptable agreement between the simulated and measured results indicates that the developed model can be utilized for predicting the temperature dependent performance of a bent fiber-based refractometer. Additionally, the error induced by the thermo-optic effect of Cargille RI liquids has been discussed and taken into account. The monotonic nature of the temperature dependence of the proposed fiber refractometer means that it is feasible to correct for changes in ambient temperature by monitoring the temperature of RI liquids and correcting the ratio response.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