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The Temperature Dependence of Polarization-Dependent Loss for a Macrobending Single-Mode-Fiber-Based Edge Filter

Pengfei Wang, Yuliya Semenova, Ginu Rajan, Thomas Freir, and Gerald Farrell

***Abstract*—The temperature dependence of polarization-dependent loss (PDL) for a macrobending standard single-mode fiber (SMF28) is investigated both theoretically and experimentally. The experimental results show an overall agreement with the proposed theoretical model over a temperature range from 0 °C to 70 °C. An SMF28-based edge filter is used as an example regarding temperature-dependent PDL performance. It is shown that the temperature variations have a significant influence on the polarization dependence of macrobending loss, and further impact on such a fiber bend loss edge filter used in a wavelength measurement application. It is also concluded that by using the proposed models, such a temperature-dependent birefringence can be beneficially predicted in bending fiber sensing applications.**

***Index Terms*—Edge filter, macrobending loss, polarization-dependent loss (PDL), single-mode fiber (SMF28), temperature dependence.**

I. INTRODUCTION

FIBER macrobending loss has been extensively investigated for applications in optical sensing and communication systems [1]–[4]. Recently, an edge filter based on macrobending standard single-mode fiber (SMF28) using multiple turns has been demonstrated for application in a rapid ratiometric wavelength measurement system [4], [5]. However, in the previously published investigations [6], [7], it was found that the fiber polymer coating layer(s), which provides a mechanical protection, has a significant influence on both the polarization and temperature dependence of macrobending loss as a result of the difference between the thermal expansion coefficients (TECs) and thermooptic coefficients (TOCs) of the coating layer (CPC6 acrylate polymer) and the fused silica cladding layer. Both polarization-dependent loss (PDL) and temperature-dependent loss (TDL) can affect the accuracy of wavelength measurement [6], [7], therefore a low polarization and temperature dependence in the macrobending loss transmission spectrum is a requirement for such an edge filter.

It is well known that the refractive index of an optical material depends on temperature and wavelength. In practice, temperature variations will alter the spectral response of the fiber edge filter, in comparison to the response used at the point of calibration, leading to inaccuracy in the measurement of wavelength. Furthermore, the influence of temperature variations can also change the polarization states of the bending fiber. Several theoretical models have been developed and presented in [6] and [7] for predicting the PDL/TDL influences on the spectral responses of bending SMF28. To the best of our knowledge, a correlation between the temperature and polarization dependence of macrobending loss in an SMF28 has not been addressed yet and is important for the development and complete characterization of a macrobending fiber-based edge filter.

In this letter, we study the temperature-induced variations in PDL of SMF28 both theoretically and experimentally. The operating temperature in our experiments is controlled within the range from 0 °C to 70 °C. The corresponding experimental results show a satisfactory agreement with the results of the theoretical modeling. The developed theoretical model offers a possibility of predicting the temperature-induced PDL of a macrobending standard SMF28 employed as an edge filter.

II. THEORETICAL MODELING

In previously published work [6], the theoretical formulation of bend loss of the SMF28 was refined for the transverse-electric (TE) and transverse-magnetic (TM) modes separately based on a scalar approximation method, which takes account of the respective boundary conditions at the interface between the fiber cladding and coating layer. Following the theoretical approximations and formulations in that reference and extending them for any two adjacent layers of fiber structure, given the continuous boundary conditions of the field, the adjacent fields for the TE mode can be expressed as (1), shown at the bottom of the next page, and the adjacent fields for the TM mode can be expressed as (2), shown at the bottom of the next page. Applying these boundary conditions, the bend loss coefficients, α_{TE} and α_{TM}, and the bend loss values, $\mathrm{BL}_{\mathrm{TE}}$ and $\mathrm{BL}_{\mathrm{TM}}$, of the TE and TM modes can be calculated. To characterize the polarization sensitivity of the bend loss, a PDL value can be calculated using the relationship $\mathrm{PDL} = \mathrm{BL}_{\mathrm{TE}} - \mathrm{BL}_{\mathrm{TM}}$.

In our previous work [7], it is clear that the single coating layer model, while it may be accurate for the theoretical prediction of bending loss at a fixed temperature of 20 °C, is not adequate for predicting the variation of bending loss with temperature. Therefore, the TDL models with a dual coating layer have been employed, which are in reasonable overall agreement with the experimental results. In the model, a bending single-mode SMF28 fiber with dual coating layers and an absorbing layer should be treated as a core–cladding–primary coating-infinite coating structure.

In Fig. 1, for a bending radius from 8 to 13 mm with a bending length of ten turns, the calculated PDLs at a wavelength of 1550 nm are shown for two different temperatures 0 °C and

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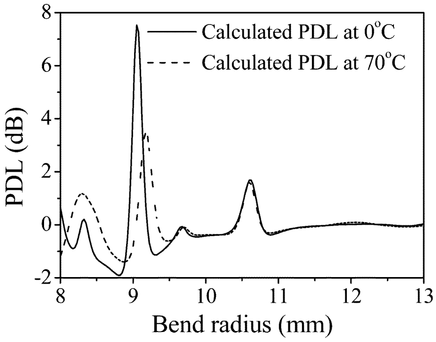


Fig. 1. Calculated PDLs for SMF28 fiber at temperatures of 0 °C and 70 °C, respectively.

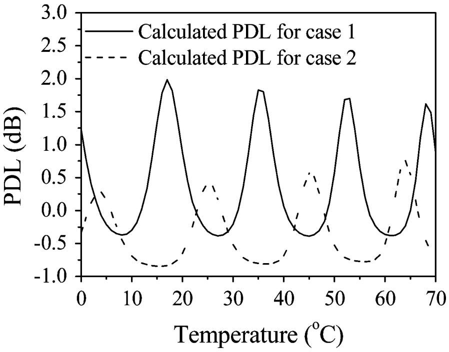


Fig. 2. Calculated PDLs versus different temperature for two fiber bend loss edge filters.

70 °C. The theoretical prediction was implemented by taking into account the corresponding TEC and TOC parameters of SMF28 fiber in the theoretical model described in [7]. From Fig. 1, one can see that for either of the operating temperatures, as the bend radius decreases, the PDL value does not increase monotonically but rather displays a number of peaks; e.g., the PDL for a bending radius of 9 mm is much higher (about two times) than that of 8 and 8.5 mm, so that in places the PDL actually decreases when the bend radius decreases. This effect is a result of a coherent coupling between the fundamental propagation mode and the so-called whispering-gallery modes (WGMs) which evolve at the cladding-coating and inner coating-outer coating interfaces. These WGMs have a significant effect not only on the bend loss but also on the PDL characteristics. Overall the theoretical modeling results support the conclusion that the PDL at each temperature is not a monotonic function of the bend radius, and the temperature dependence of the PDL at different bent radii displays significant variations in value and also changes sign.

Using the theoretical model above, it is possible to predict the impact of temperature variations on the PDL of an all-fiber-based edge filter sample. Using SMF28 as an example, two cases are considered: Case 1) a bending length of ten turns with a bending radius of 10.625 mm, and Case 2) a bending length of 20 turns with a bending radius of 10.125 mm. Both samples (Cases 1 and 2) have spectral responses suitable for application as edge filters in a ratiometric wavelength measurement system. The polarization-dependent performances as a function of ambient temperature for these two cases are plotted in Fig. 2. From the figure, both plots exhibit wave-like oscillations within the temperature range from 0 °C to 70 °C, consistent with the temperature dependence of macrobending loss presented in [7]. From Fig. 2, it also can be seen that the calculated PDL for Case 1 is larger than that of Case 2. One possible reason is that as shown in Fig. 1, the calculated PDL is very sensitive to bend radius at certain bending radii; given the same bending length in Fig. 1 of ten turns, the PDL at the bending radius of 10.625 mm is much larger than the PDL at the bending radius of 10.125 mm.

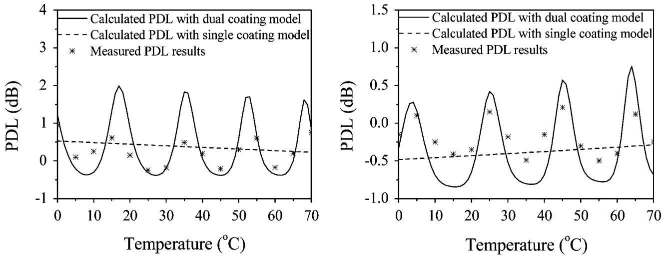
III. EXPERIMENTAL VERIFICATION AND DISCUSSION

To verify the results calculated above, an experimental setup was used as shown in [7]. The SMF28 fiber is wrapped over a series of precisely dimensioned metal mandrels, with each mandrel providing a different usable diameter. The beginning and end of the bending fiber section is fixed by a two-part epoxy to ensure mechanical stability. A tunable laser (TL) and an optical spectrum analyzer (OSA) are employed as a source of light and detector and a polarization controller (PC) is added between the TL and bending fiber to change the polarization states of input signals. The bending loss value for the TE and TM modes can be estimated from the OSA while tuning the PC. Both the bending fiber with an outer absorbing layer and mandrel were bonded to a semiconductor thermo-electric Peltier cooler (STPC) and a heat sink by a silica-based thermally conductive adhesive. The STPC is controlled by a digital temperature controller, while a digital resistance thermometer sensor probe is attached to the mandrel to accurately measure the temperature.

The experiment is carried out by measuring the PDL of the two edge filter samples, Cases 1 and 2, over a range of temperatures from 0 °C to 70 °C with 5 °C increments. Both calculated and measured results are plotted in Fig. 3(a) and (b). As a comparison, the calculated temperature-dependent PDL with single coating is also presented in Fig. 3(a) and (b). It is clear

$$\left\{\begin{array}{l} D_q(\zeta)B_i[X_q(x_q,\zeta)]+H_qA_i[X_q(x_q,\zeta)]=D_{q+1}(\zeta)B_i[X_q(x_{q+1},\zeta)]+H_{q+1}A_i[X_q(x_{q+1},\zeta)] \\ \frac{1}{n_q^2}\{D_q(\zeta)B_i'[X_q(x_q,\zeta)]+H_qA_i'[X_q(x_q,\zeta)]\}=\frac{1}{n_{q+1}^2}\{D_{q+1}(\zeta)B_i'[X_q(x_{q+1},\zeta)]+H_{q+1}A_i'[X_q(x_{q+1},\zeta)]\} \end{array}\right. \tag{1}$$

$$\left\{\begin{array}{l} D_q(\zeta)B_i[X_q(x_q,\zeta)]+H_qA_i[X_q(x_q,\zeta)]=D_{q+1}(\zeta)B_i[X_q(x_{q+1},\zeta)]+H_{q+1}A_i[X_q(x_{q+1},\zeta)] \\ D_q(\zeta)B_i'[X_q(x_q,\zeta)]+H_qA_i'[X_q(x_q,\zeta)]=D_{q+1}(\zeta)B_i'[X_q(x_{q+1},\zeta)]+H_{q+1}A_i'[X_q(x_{q+1},\zeta)] \end{array}\right. \tag{2}$$



(a) (b)

Fig. 3. Calculated and measured macrobending loss results for temperature ranging from 0 °C to 70 °C at the wavelength of 1550 nm, the bending radius is (a) $10.5 + 0.125$ mm with a bending length of 10 turns (circa 667.59 mm); (b) $10 + 0.125$ mm with a bending length of 20 turns (circa 1272.35 mm).

also that the single coating layer model, while it may be accurate at predicting PDL at a fixed temperature of 20 °C, is not adequate for predicting the variation of PDL with temperature. From both figures, one can see that the calculated PDLs using a dual-coating layer model are in reasonable agreement with the experimental results. Wave-like variations exist in both the modeled and measured temperature-dependent PDL results which can be explained as follows: In the theoretical model, the primary coating has a finite thickness and the secondary coating is assumed to be infinitely thick. Hence radiation entering the primary coating from the cladding is partially reflected at the first interface between the cladding and the primary coating layer and again at the interface between the primary and secondary coating layers. The finite thickness of the primary coating layer combined with the refractive index differences on either side comprises a simple Fabry–Pérot (F-P) interferometer. Hence as the index/thickness of the primary coating varies with temperature, the fraction of the incident radiation from the cladding that is transmitted into the primary coating will vary periodically, which further results in the periodicity of the PDL spectral response and the oscillations in the PDL curves in Fig. 3 for both the modeled and experimental results. In the theoretical model with a single-coating layer, the fiber coating is assumed to be infinitely thick and hence the radiation entering the coating layer from the cladding propagates away from the fiber without any subsequent reflection. The monotonic behaviour of the single coating layer results in Fig. 3(a) and (b) are a confirmation that no F-P cavity is formed in this case.

The discrepancies between the calculated temperature-dependent PDLs and measured results could be caused in the first instance by the scalar approximations made in the calculation. The calculation of polarization dependence for an SMF28 includes some approximations. For example, to consider the polarization dependence of bend loss caused by the coating layers, the boundary conditions at the interface between the cladding and coating layers in the calculation of the bend loss need to be treated separately for the TE and TM mode and using the conventional definition, the PDL can be calculated by the difference between the simulated TE and TM modes, thus the calculated PDL results inherit the approximations of the scalar approximation theory. Secondly, in the model the interface between the cladding and coating layers is approximated as a plane. The limited dimensional accuracy of each bend radius, set by the accuracy of the mandrel diameter is also a source of error, which is compounded by the fact that, as was shown in earlier and in Fig. 1, the calculated PDL is very sensitive to temperature at certain bending radii. Finally, the temperature step of 5° was utilized in the experiments in order to ensure reasonable experimental durations. Using a smaller temperature step could improve the agreement between calculated and measured results.

Overall, it is clear that temperature variations will significantly impact the PDL, and will further influence the accuracy of wavelength measurements. Our theoretical method can be used to evaluate the PDL performance of a fiber macrobending-based edge filter as a function of ambient temperature. Moreover, PDL and its temperature dependence can significantly influence light transmission properties for any simple bending fiber structure such as, for example, bending fiber loops utilized for sensing applications as polarization interferometers or fiber gyroscopes. The general agreement between calculated and measured results suggests that this model could be used for analysis and evaluation of performance of such devices, improving their temperature stability and facilitating the development of new types of fiber sensors.

IV. CONCLUSION

In this letter, the temperature-dependent PDL characteristics of a macrobending standard SMF28 have been studied theoretically and experimentally. A theoretical model based on a scalar approximation method has been presented. Corresponding experimental verifications have been carried out and the acceptable agreement between the simulated and measured results indicate that the developed model can be utilized for predicting the temperature-induced variations of PDL for an SMF28 with a dual coating.

REFERENCES

[1] R. Morgan, J. S. Barton, P. G. Harper, and J. D. C. Jones, "Temperature dependence of bending loss in monomode optical fibres," *Electron. Lett.*, vol. 26, no. 13, pp. 937–939, 1990.

[2] F. M. Haran, J. S. Barton, S. R. Kidd, and J. D. C. Jones, "Optical fibre interferometric sensors using buffer guided light," *Meas. Sci. Technol.*, vol. 5, no. 5, pp. 526–530, 1994.

[3] S. H. Nam and S. Yin, "High-temperature sensing using whispering gallery mode resonance in bent optical fibers," *IEEE Photon. Technol. Lett.*, vol. 17, no. 11, pp. 2391–2393, Nov. 2005.

[4] Q. Wang, G. Farrell, and T. Freir, "Study of transmission response of edge filters employed in wavelength measurements," *Appl. Opt.*, vol. 44, no. 36, pp. 7789–7792, 2005.

[5] Q. Wang, G. Farrell, T. Freir, G. Rajan, and P. Wang, "Low-cost wavelength measurement based on a macrobending single-mode fiber," *Opt. Lett.*, vol. 31, no. 12, pp. 1785–1787, 2006.

[6] Q. Wang, G. Rajan, P. Wang, and G. Farrell, "Polarization dependence of bend loss for a standard singlemode fiber," *Opt. Express*, vol. 15, no. 8, pp. 4909–4920, 2007.

[7] P. Wang, Y. Semenova, and G. Farrell, "Temperature dependence of macrobending loss in all-fiber bend loss edge filter," *Opt. Commun.*, vol. 281, pp. 4312–4316, 2008.