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Temperature dependence of a macrobending edge filter based on a high-bend loss fiber

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Abstract: The temperature dependence of a macrobending bare fiber based edge filter is investigated both theoretically and experimentally. The fiber used is a high bend loss fiber, type 1060XP. The experimental results show a good agreement with the proposed theoretical model over a temperature range from 0 to 80°C. It is shown that the strong temperature dependence of a high-bend loss fiber has a significant influence on the performance of a fiber edge filter used in a wavelength measurement application. However it is also concluded that such a temperature dependent performance can be beneficially utilized in a fiber temperature sensing application.

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A singlemode bent fiber can provide a range of useful characteristics which can be utilized, for example, in novel fiber components such as sensors and edge filters [1-5] or used to enhance the operation of fiber lasers. Such bent fiber based components have the advantages of ease of fabrication and simplicity of interconnection to other fibers.

Recently, in an application involving an edge filter for rapid wavelength measurement, the macrobending loss of multiple turns of SMF28 fiber has been investigated theoretically and experimentally [4, 5] in order to optimize the structure. Such SMF28 based edge filter includes a splitter, a bending fiber based edge filter, a reference arm and two photodetectors. One splitter arm connects with the edge filter, while the other acts as a reference arm. Both arms are terminated in photodetectors to optical power levels. Given the wavelength dependence of bend loss, the ration of the measured power levels is a fraction of wavelength. Thus with a suitable calibration wavelength can be measured. However, in our previously published investigations [6,

7], it was found that the fiber polymer coating layer, which provides mechanical protection for the fiber, has a significant influence on both fiber bending loss and polarization dependent loss. For the fiber bend loss edge filter application, such coating layer(s) can also induce random variations throughout the measured transmission spectrum [8].

To obtain the desired transmission spectrum with a shorter fiber bend length for more compact structure, a type of bending loss sensitive fiber is desired, where the normalized frequency V should be lower. Furthermore, it was found that polarization dependent loss could reduce the precision of wavelength measurement. Therefore, in order to ensure accuracy in wavelength measurement, low polarization dependence for the fiber bending loss is required as well.

In terms of such requirements of optical fiber for fiber edge filter mentioned above, an optimized macrobending fiber edge filter based on a 1060XP fiber with single turn structure has been developed and presented [9]. 1060XP fiber is a high-bend loss fiber, originally developed for fiber laser applications. The fiber is stripped of its coating layer to remove the influence of the fiber coatings and has an optical absorption layer applied to the cladding. By comparison with SMF28 fiber presented previously [5], both theoretical and experimental results have shown that the 1060XP fiber based edge fiber can effectively remove the coating(s) induced influences mentioned above, and the bending loss of bare 1060XP fiber with absorbing layer can achieve a marginally better polarization dependent loss behavior than an equivalent SMF28 based edge filter, with the added benefit of a more compact physical structure (22 turns of SMF28 with radius for 11 mm by comparison with single turn of 1060XP with a bending radius of 10.5 mm for a typical edge filter). In the experiments, when a bare 1060XP fiber (bend radius is 10.5 mm, and the fiber length is single turn) is employed for ratiometric wavelength measurement, it is found that the system's resolution is approximately 10 picometer at 1550 nm when the fluctuation of the ratio caused by the noise of the photodetectors is approximately 0.002 dB.

In practice, in the experiments in [8] it was found that changes in temperature affected the measured bending loss. Upon investigation it was realized that because the bend loss of 1060XP is approximately two times more temperature sensitive than SMF28, so the spectral response of an edge filter based on 1060XP fiber would be more temperature dependent. Used in a wavelength measurement system, temperature changes could adversely affect the accuracy of the wavelength measurement system. There is a need therefore to properly quantify the temperature dependence of 1060XP fiber, to determine the extent of the effect on the spectral response of an edge filter so as to develop solutions such as active temperature control of the filter or ambient temperature feedback to adjust the calibration of the system as temperature changes. The temperature dependent properties of 1060XP bent fiber also suggest a possibility of designing and developing a novel temperature sensor based on a simple bending fiber structure, with the fiber bend loop optimized as an optical fiber probe with small bending radii.

In this letter, the temperature dependent loss (TDL) behavior for the key edge

filter parameters, baseline loss and discrimination range, for a 1060XP based edge filter are investigated and presented. The investigation involves both theoretical modeling of TDL and experimental verification. The theoretical numerical modeling shows a good agreement with the measured results for the TDL of bent 1060XP fiber with a correction factor (namely, the wavelength dependent effective bend radius, which is employed to achieve good agreement between the modeled results and the experimental results due to the fiber bending stress) of 1.298 at a wavelength of 1550 nm.

In previously published work [9], for a fiber bend loss edge filter application, the bare cladding fiber was coated with an absorbing layer. Analytically this is approximately equivalent to a fiber structure with an infinite cladding and the expression for calculating the fiber bend loss coefficient with an infinite cladding has been expressed by Marcuse in Ref. [10]. Furthermore, in the theoretical model, the so-called effective bend radius (correction factor) presented in previously published papers [11-13] has been utilized in the calculated model of bending loss to fit the experimental results.

For the silica material used in the fiber, the physical expansion or contraction of the material's volume in response to temperature changes is characterized by silica's thermal expansion coefficient (TEC).

The refractive index of an optical material depends on temperature and wavelength. For silica material, when the ambient temperature changes the consequent refractive index variations of the silica glass material, caused by lattice deformation of its matrix structure are characterised by the thermo-optic coefficient (TOC). Therefore, in the theoretical modelling which is based on the scalar approximation method developed by Marcuse [10], both TEC and TOC are accounted for in the calculated prediction for bending loss.

For 1060XP singlemode fiber, the corresponding parameters are shown in Table I:

Previously, the presented fiber bend loss edge filter [4, 5] utilized for a measurable wavelength range from λ_1 to λ_2, provides a strong monotonically increasing wavelength dependent attenuation range, which can be defined as discrimination range, the power difference between a given lower start wavelength λ_1 (at which the attenuation value is the so-called baseline loss) and an end wavelength λ_2. These two parameters, baseline loss and discrimination range, can be used to effectively evaluate the performance of a fiber edge filter.

To gain an insight into the influence of temperature on the baseline loss (bend loss at 1500 nm) and discrimination range (the difference of bend loss between 1500 and 1600 nm), the calculated baseline loss and discrimination range as a function of different bend radii at a temperature of $0\,^{o}C$ and $80\,^{o}C$, is presented in Fig. 1.

In relation to the choice of temperature range, it is accepted that such a wide temperature range would be very rare in a wavelength measurement system, typically used in an ambient environment. However as mentioned above, since there are potential temperature sensing applications, where wider temperature ranges could be expected, the temperature end-points throughout the investigation were chosen to

match the maximum temperature range possible in the experimental setup available, that is 0°C to 80°C.

As shown in Fig. 1, one can see that if the temperature changes from 0°C to 80°C, significant changes occur in both baseline loss and discrimination range, with a consequent impact on the spectral response of a 1060XP based edge filter. For example, for a selected bend radius of 10.5 mm [9], the baseline loss changes from 5.785 dB to 4.604 dB, and the discrimination range changes from 18.48 dB to 15.698 dB when temperature changes from 0°C to 80°C.

In this work, the TDL value is defined as an absolute value of the difference in bend loss between 0°C and a temperature of T^oC, where T can vary from 0°C to 80°C, thus:

$$TDL = \left| BL_{T^oC} - BL_{0^oC} \right| \qquad (2)$$

Choose the 1060XP fiber as an edge filter example and one bending radius is considered. The TDL of bending bare 1060XP fiber with a bend radius of 10.5 mm at a wavelength of 1550 nm is calculated based on the theoretical model presented in Ref. [10]. In Fig. 2, it is shown that the modeled TDL results (Plot A) demonstrate a strong monotonic increase from a start temperature (0°C) to an end temperature (80°C). For a SMF28 fiber base edge filter [8], it is found that the TDL display several strong periodical bending loss response at different bend radii due to whispering gallery modes (WGMs) effects guided at cladding-coating interface, whereas for bare 1060XP fiber presented in Fig. 2, it is clearly that the TDL changes monotonically over the measured temperature range from a start temperature (0°C) to an end temperature (80°C), such TDL performance is significantly different with that of coated SMF28, this indicates that temperature variations induced periodical bending loss response of coated fiber is mainly caused by coatings, and the striped bare fiber with absorbing layer has effectively reduced the impact of WGMs.

In order to verify the theoretical model for TDL, an experimental setup for measuring TDL was developed and is shown in Fig. 3. The bending fiber was connected to a tunable laser and an optical spectrum analyzer. The tunable laser has an output power of 0 dBm. The bare 1060XP fiber section coated with an absorbing layer (acrylic based material) is bent to form a small 360° bend, and is mounted on a thermoelectric Peltier cooler using a two-part epoxy to improve mechanical stability. The measured bend radius is 10.5 mm. The Peltier cooler is controlled by a digital temperature controller (ITC 510, Thorlabs), and a digital platinum resistance thermometer sensor probe is attached to the Peltier cooler to accurately measure the temperature.

The TDL of the 1060XP fiber was measured for a bending radius of 10.5 mm at a wavelength of 1550 nm. The experimental TDL results of 1060XP as a function of the temperature range from 0 to 80°C are presented in Fig. 2 (Plot B).

In Fig. 2, one can also see that there is a good agreement between the calculated (Plot A) and experimental data (Plot B). The perceptible divergence between the experimental and theoretical results may be caused by: 1) the limitations of the absorbing layer on the surface of the bare fiber where the absorbing layer does not

absorb all the radiation lost at the bend at the fiber cladding-air interface, leading to WGMs effects, such WGMs can recouple to the propagating mode in the fiber core and can result in wavelength dependent interference effects, further results in the perceptible quasi-periodic behavior of the measured results in Fig. 2. Further investigation using different absorbing layer materials is ongoing; 2) minute discrepancies between the temperature of the fiber and the reference thermometer sensor probe, for example those resulting from ambient airflow.

To better illustrate and evaluate the temperature influence of a macrobending-based 1060XP fiber edge filter as a wavelength measurement application over the whole wavelength range from 1500 to 1600 nm, the theoretical and experimental macrobending loss differences between 0°C and 80°C over the wavelength range from 1500 to 1600 nm for a designed bend radius of 10.5 mm are presented in Fig. 4. The correction factors determined at 10 nm intervals over the wavelength range of interest between 1500 and 1600 nm are used in the TDL theoretical model. As shown in Fig. 4, one can see that there is very good match between the calculated and experimental data. The experimental TDL data shows a monotonically increasing characteristic which matches the proposed theoretical predictions well. The measured TDL is about 1.19 dB/turn at a wavelength of 1500 nm and is circa 4.02 dB/turn at a wavelength of 1600 nm.

In conclusion, based on a scalar approximation theory, we have studied and investigated the temperature dependence of bare macrobending 1060XP fiber theoretically and experimentally, for an all-fiber bending loss edge filter application. The experimental results show a good agreement with the proposed theoretical model. For 1060XP fiber based edge filter, it is clear that temperature variations will significantly impact the accuracy of wavelength measurements. Our method can be used to evaluate the performance of a fiber macrobending based edge filter as a function of ambient temperature for high-speed wavelength measurements and also for fiber-based temperature sensing applications.

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Figure captions

Fig. 1 Calculated baseline loss and discrimination range at 0°C and 80°C, for a fiber

length of one turn, with correction factors of 1.308 @1500 nm and 1.336@1600 nm.

Fig. 2 Calculated (Plot A) and measured (Plot B) TDL for a temperature range from 0 to 80°C at a wavelength of 1550 nm with a bending radius of 10.5 mm and a single fiber turn.

Fig. 3 Experimental setup for measuring the TDL of a bent 1060XP fiber.

Fig. 4 Calculated and measured temperature dependence between 0 and 80°C as a function of wavelength (with an interval of 10 nm), for an edge filter with a bend radius of 10.5 mm and a single turn of fiber.

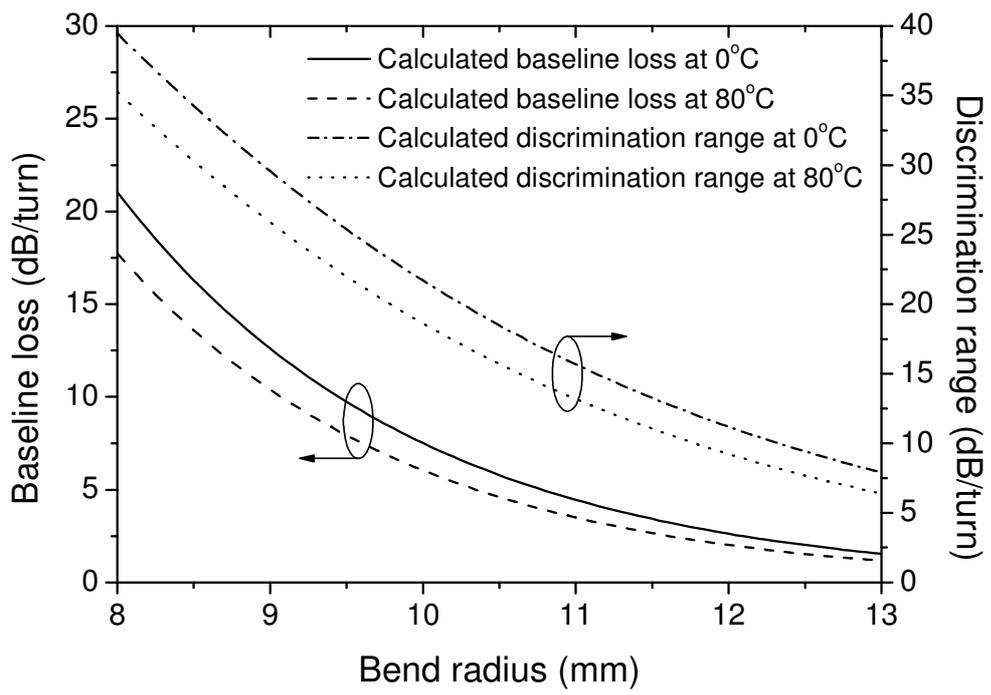## Table Caption

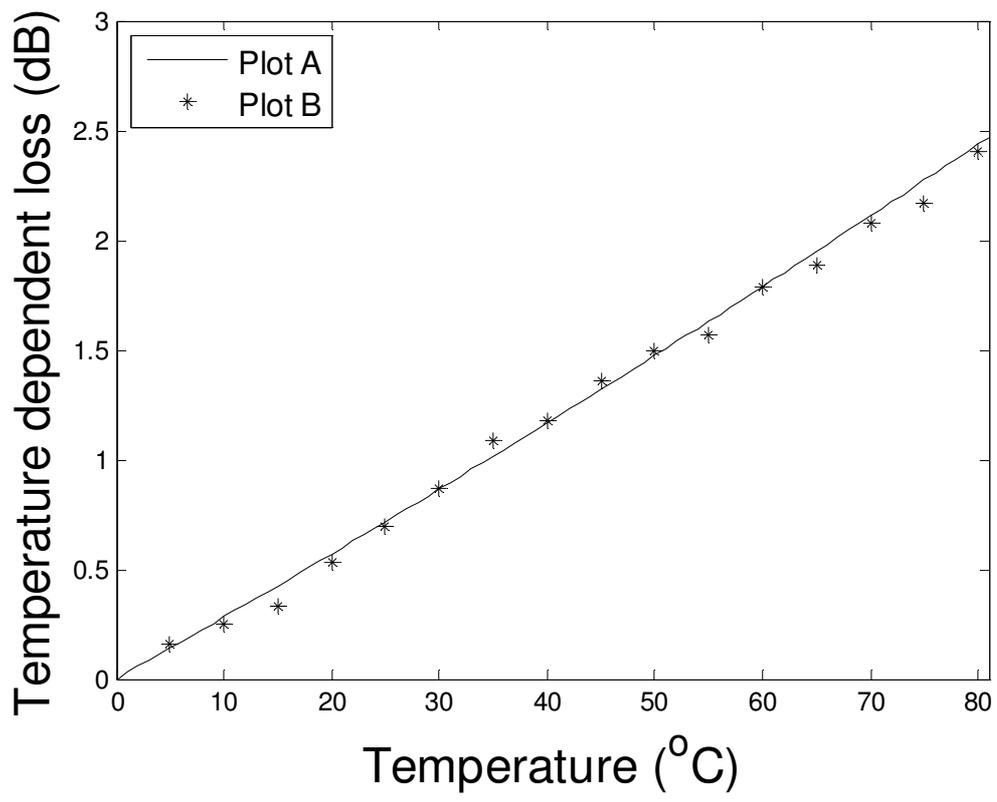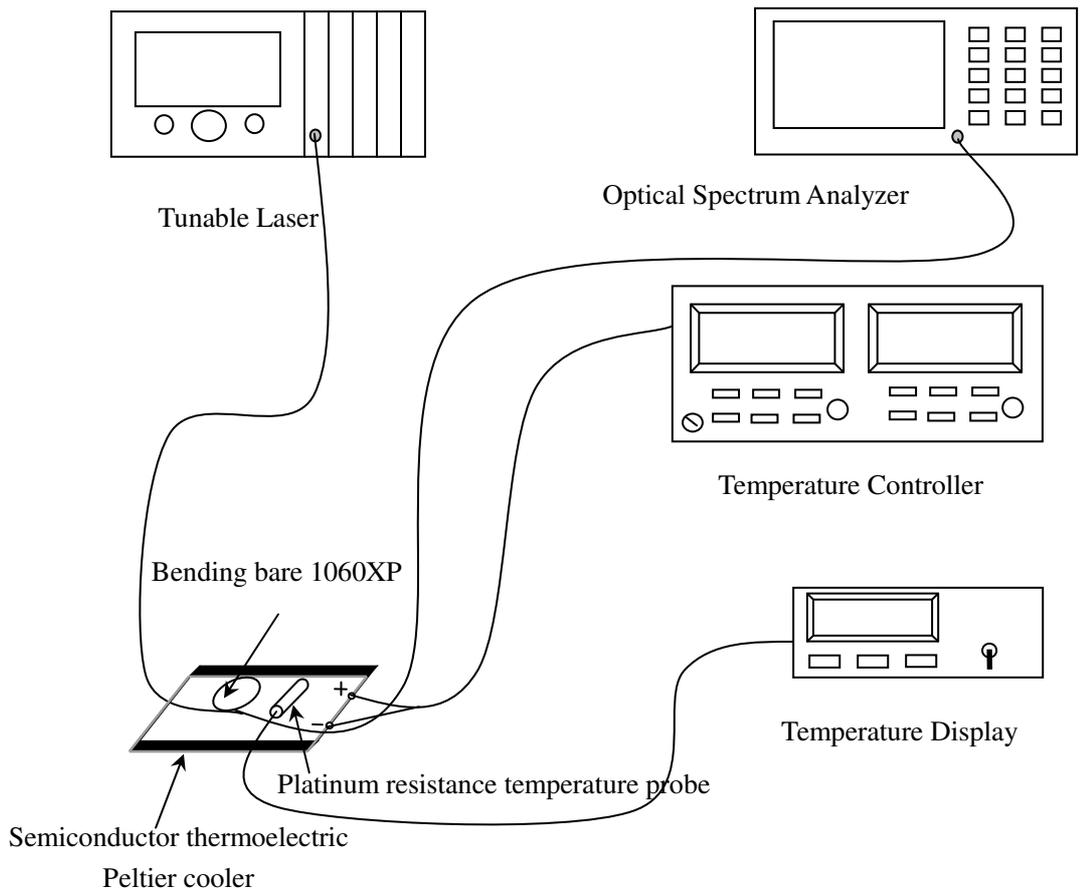TABLE I: PARAMETERS OF THE 1060XP FIBER;

Fig. 1

Fig. 2

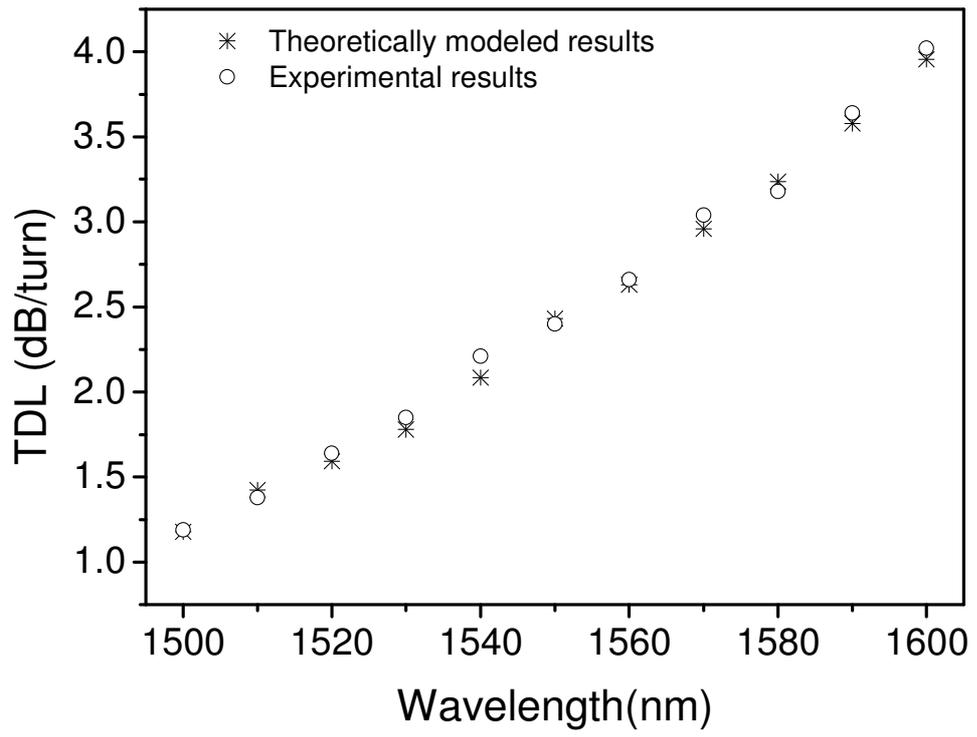Tunable Laser

Optical Spectrum Analyzer

Temperature Controller

Bending bare 1060XP

+
−

Temperature Display

Semiconductor thermoelectric
Peltier cooler

Platinum resistance temperature probe

Fig. 3

Fig. 4

TABLE I: PARAMETERS OF THE 1060XP FIBER;

1060XP fiber	Core	Cladding
Diameter (μm)	5.3 ± 0.5	125 ± 0.5
TEC α (K^{-1})	$\sim 5.5 \times 10^{-7}$	—
TOC β (K^{-1})	$\sim 1.1 \times 10^{-5}$	$\sim 1 \times 10^{-5}$