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Agus Hatta
Technological University Dublin, ahatta@tudublin.ie

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

Ginu Rajan
Technological University Dublin, ginu.rajan@tudublin.ie

Pengfei Wang
Technological University Dublin, pengfei.wang@tudublin.ie

J. Zheng
...n University

See next page for additional authors

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Analysis of temperature dependence for a ratiometric wavelength measurement system using SMS fiber structure based edge filters

A. M. Hatta[1*], Y. Semenova[1], G. Rajan[1], P. Wang[1], J. Zheng[2], G. Farrell[1]

[1]Photonics Research Centre, School of Electronic and Communications Engineering, Dublin Institute of Technology, Kevin Street, D8, Ireland
[2]College of Electronic Science and Engineering, Jilin University, 2699 Qianjin Street, 130012 Changchun, P.R. China

*Corresponding author. Address: Photonics Research Centre, School of Electronic and Communications Engineering, Dublin Institute of Technology, Kevin Street, D8, Ireland.
Tel: +35314024575
E-mail address: ahatta@dit.ie

Abstract Temperature dependence of an edge filter based on singlemode-multimode-singlemode (SMS) fiber structure is investigated numerically and experimentally. The experimental results and numerical results are in good agreement within an operational temperature range from 10 to 40 ^{o}C. It is found that the thermo-optic coefficient (TOC) has a more significant effect on the temperature dependence of an SMS edge filter compared to the thermal expansion coefficient (TEC). In the ratiometric wavelength measurement using two SMS edge filters, a small temperature variation can induce the ratio variation and in turn the wavelength measurement error. It is found the SMS edge filter's response to both wavelength and temperature is linear. It is proposed that self monitoring of temperature can be carried out using an updated ratiometric scheme. Self-monitoring of the temperature reduces temperature induced wavelength error to ± 10.7 pm at 1545 nm, regardless of the ambient temperature variation.

Keywords: temperature dependence, edge filter, multimode fiber

1. Introduction

Singlemode-multimode-singlemode (SMS) fiber structures have been demonstrated experimentally as an all-fiber implementation of a bandpass filter, an edge filter, a wavelength encoded temperature sensor and a strain and temperature sensor [1-5]. A SMS fiber structure is fabricated by splicing a specified length of a multimode fiber (MMF) with two singlemode fibers (SMF) at the ends of MMF. This configuration offers simplicity, an all fiber configuration, and a low cost.

Recently, we reported on the application of SMS fiber structures as edge filters for wavelength monitoring [2] and on the effect of misalignment of the SMF-MMF-SMF cores [3]. Wavelength measurement is essential for a fiber-Bragg-grating (FBG) based sensing system. Among the available schemes, an all-fiber ratiometric power measurement technique offers a simple configuration, competitive resolution and high speed measurement compared to an active scanning method. A ratiometric scheme converts the wavelength measurement into a signal intensity measurement. An all-fiber ratiometric wavelength monitor consists of a 3 dB fiber coupler with two outputs to which a fiber edge filter arm with a well defined spectral response and a reference arm are attached. Alternatively, two fiber edge filter arms with overlapping opposite slope spectral responses can be used. The use of two edge filters can increase the resolution of the measurement system [6]. Two fiber edge filters with overlapping and opposite slope spectral responses, a so-called "X-type spectral response" based on SMS fiber structure have been investigated numerically and experimentally [2].

The effect of temperature on the optical and mechanical properties of silica means that temperature changes could affect the spectral performance of devices based on an SMS fiber structure. An investigation has been carried out previously [7] on the peak wavelength shift of the transmission spectral response of an SMS structure due to temperature change and the reduction of this peak shift to a low value by temperature compensation. However in an edge filter based ratiometric wavelength measurement scheme, even low values of peak wavelength shift can still induce sufficient ratio variation to degrade wavelength measurement accuracy [8]. In this paper, we present an analysis verified by experimental results of the effect of temperature on the overall transmission response of a SMS structure used as an edge filter. In Section 2 we investigate the temperature dependence of an SMS based edge filter and find that there is a linear relationship between temperature and wavelength. Importantly there is also a linear response to temperature and this suggests that self monitoring of temperature is possible to reduce wavelength measurement error to a minimum, using an updated ratiometric system. This is presented in Section 3.

2. Temperature dependence in a SMS edge filter

It is useful to initially consider the design of the X-type spectral response SMS edge filters. In order to design an SMS fiber edge filter, a modal propagation analysis (MPA) for linearly polarized (LP) modes is used [1, 9]. A brief review of the design, fabrication and measurement of the X-type SMS edge filters can be found in [2]. A standard SMF type SMF28 and an MMF type AFS105/125Y are used with core/cladding diameters of 8.3/125 μm and 105/125 μm, respectively. Two lengths of MMF are chosen to provide the X-type SMS edge filters within a wavelength range 1530 to 1560 nm (typical for an FBG sensing), L_1 = 43.57 mm and L_2 = 42.63 mm for SMS-1 and SMS-2, respectively. The calculated and measured results for SMS edge filters are shown in Fig. 1. The measured results show a good agreement with the numerical results. The discrepancy between the calculated and measured results is most likely a consequence of splice insertion losses.

Fig. 1 Calculated and measured two edge filters X-type spectral response.

It is well known that there are two parameters which characterize the effect of temperature on the fiber, the thermal expansion coefficient (TEC) and the thermo-optic coefficient (TOC). The TEC characterizes the physical expansion or contraction of the material's volume, while the TOC characterizes refractive index change in response to temperature change. Using the TEC and TOC, the change in core radius (R), MMF length (L), and the refractive index (n) due to a temperature variation (ΔT), can be expressed, respectively, as

$$R_{(smf,mmf)_T} = R_{(smf,mmf)_0} + \alpha \cdot R_{(smf,mmf)_0} \cdot \Delta T \quad (1.a)$$

$$L_{(1,2)T} = L_{(1,2)0} + \alpha \cdot L_{(1,2)0} \cdot \Delta T \quad (1.b)$$

$$n_{(core,clad)_T} = n_{(core,clad)_0} + \xi \cdot n_{(core,clad)_0} \cdot \Delta T \quad (1.c)$$

where α and ξ are the TEC and the TOC, respectively.

To gain an insight into the effect of temperature changes on the transmission loss of a SMS based edge filter, we investigate experimentally and numerically the effect of temperature at a single wavelength. The experimental setup is built and is shown in Fig. 2. The SMS edge filter is attached to a thermoelectric Peltier cooler, which is controlled by a precision digital temperature controller (ITC 510, Thorlabs), while a digital resistance thermometer sensor probe is also attached to accurately measure the temperature.

Fig. 2 Schematic set-up for measuring the temperature dependence on the SMS edge filter transmission loss.

To calculate the temperature dependence of the transmission loss, we assumed α = $5\text{x}10^{-7}$ /^{o}C and ξ = $6.9\text{x}10^{-6}$ /^{o}C for both the SMF and MMF [7]. By using a MPA the transmission loss from 1540 to 1550 nm for the temperature of 10 and 40 ^{o}C is calculated and presented in Fig. 3(a). The measured results are also shown in Fig. 3(b). One can see both calculated and measured results for SMS-1 and SMS-2 show that an increase in temperature results in a spectral response shift to the higher wavelength as in [10, 11]. The change in transmission loss from the value at 20 ^{o}C is calculated for temperatures from 10 to 40 ^{o}C, at a wavelength of 1545 nm. The calculated and measured results for the transmission loss change over the temperature range for SMS-1 and SMS-2 are shown in Fig. 4. The calculated and measured results are in good agreement. From Fig. 4, it is also clear that the change in transmission loss for both SMS-1 and SMS-2 has a linear response with temperature. The transmission loss difference between 10 to 40 ^{o}C is 0.171 dB for SMS-1 and 0.134 dB for SMS-2.

Fig. 3 Transmission loss response at the temperature of 10 and 40 ^{o}C (a) calculation results (b) measurement results

Fig. 4 Transmission loss change as a function of temperature at a wavelength of 1545 nm for a reference temperature of 20 ^{o}C.

It is useful to analyze the separate contributions to temperature dependent effects of the TEC and TOC. The transmission loss change, relative to 20 ^{o}C, due to an increase in temperature is calculated for TEC only and then for TOC only and is compared to the contribution of both TEC and TOC taken together. As an example for SMS-1 at a wavelength of 1545 nm, the calculated transmission loss change due to a change in temperature for the contribution of TEC and TOC individually, and for the contribution of TEC and TOC together are shown in Fig. 5. It can be seen, with a change in temperature, the transmission losses for the TEC and TOC parameters have opposite slopes and thus induce opposite transmission spectral response shifts. However the TEC has a significantly lower contribution to the temperature dependence of the edge filter transmission loss compared to the TOC.

Fig. 5 Calculated transmission loss change due to temperature change for TEC, TOC separately and also for TEC and TOC together.

3. Temperature dependence in the ratiometric wavelength measurement system

To investigate the effect of temperature on the accuracy of wavelength measurement, the temperature dependence for a ratiometric wavelength measurement system, similar to that described in [2] using a pair of SMS structures as an X-type filters, is studied. The input signal from a tunable laser is split into two equal intensity signals using a 3 dB fiber coupler (see inset figure in Fig. 6). One of the signals passes through SMS-1 and the other passes through SMS-2. A dual channel power meter is placed at the ends of both arms. The two SMS edge filters are attached to the thermoelectric Peltier cooler. The ratio spectral response is measured from 10 to 40 ^{o}C within the wavelength range 1530-1560 nm. Fig. 6 shows the measured optical power ratio spectrum for several temperatures. The ratio response difference between 10 and 40 ^{o}C is 0.306 dB at a wavelength of 1545 nm (see inset graph in Fig. 6). The ratio change for a ± 5 ^{o}C temperature change is ± 0.051 dB. While this is a small change in ratio, the impact on wavelength accuracy is still significant. From the measured results it is estimated that a temperature variation of ± 5 ^{o}C at 20 ^{o}C induces a wavelength error of ± 67.4 pm at 1545 nm. This error is very significant as the inherent error in a ratiometric system due to noise and other non-temperature related effects can be less than 10 pm [2].

Fig. 6 Measured ratio at different temperatures within the wavelength range. Schematic configuration of ratiometric wavelength measurement (inset figure). Temperature response at 1545 nm (inset graph).

Therefore in order to maintain accuracy when utilizing such SMS structures as edge filters, there are two possible solutions: i) use a packaging material for the SMS structure with a suitable TEC value which compensates for temperature induced changes in the SMS structure [7] or ii) actively monitor the filter temperature and correct the calibration as required (active temperature stabilization of the filter is possible but is more complex than monitoring). For the solution involving the use of a packaging material, a small un-compensated temperature drift due to a small mismatch in the TEC value of packaging material and the SMS can lead to a significant wavelength measurement error. For the temperature monitoring solution, from the inset graph in Fig. 6, the linear relation between the ratio and temperature shows that it is feasible to apply calibration correction. By knowing the operating temperature, the correction required to the calibrated ratio response over the whole wavelength range can be determined.

The linearity of the SMS edge filter's response to both wavelength and temperature potentially allows one to use the SMS structure to monitor its own temperature, with the added advantage that simultaneous measurement of the wavelength and temperature is possible if required. To implement a self-monitoring approach an updated ratiometric scheme is proposed as in Fig. 7. A 3 dB coupler and a power meter are added to the existing ratiometric scheme as in the inset figure in Fig. 6. The ratio $R_1 = P_{ref} - P_1$ and $R_2 = P_{ref} - P_2$ in dB are measured. The wavelength change, $\Delta\lambda$, and temperature change, ΔT, to the ratio change ΔR_1 and ΔR_2 can be expressed as:

$$\begin{bmatrix} \Delta R_1 \\ \Delta R_2 \end{bmatrix} = \begin{bmatrix} \alpha_1 & \beta_1 \\ \alpha_2 & \beta_2 \end{bmatrix} \begin{bmatrix} \Delta\lambda \\ \Delta T \end{bmatrix} = M \begin{bmatrix} \Delta\lambda \\ \Delta T \end{bmatrix}, \quad (2)$$

where $\alpha_{1,2}$ and $\beta_{1,2}$ are the matrix coefficients of M that correspond to the wavelength and temperature slopes respectively, which can be determined experimentally. Thus, the wavelength and temperature changes can be determined simultaneously from

$$\begin{bmatrix} \Delta\lambda \\ \Delta T \end{bmatrix} = M^{-1} \begin{bmatrix} \Delta R_1 \\ \Delta R_2 \end{bmatrix}, \quad (3)$$

where M^{-1} is an inverse matrix of M. The resolution of wavelength and temperature measurement can be determined from:

$$\begin{bmatrix} \delta(\Delta\lambda) \\ \delta(\Delta T) \end{bmatrix} = abs(M^{-1}) \begin{bmatrix} \delta(\Delta R_1) \\ \delta(\Delta R_2) \end{bmatrix} \quad (4)$$

where $\delta(\Delta R_{1,2})$ is the uncertainty in ratio measurement.

Fig. 7 Updated schematic ratiometric system to allow self-monitoring of temperature.

To determine the wavelength and temperature coefficients, pre-determined wavelength and temperature changes were applied separately to the ratiometric system. We measured the ratio R_1 and R_2 in the wavelength range of 1540 to 1550 nm at a fixed temperature of 10 ^oC as shown in Fig. 8(a). A smaller wavelength range is chosen to ensure a piece-wise linear response. The wavelength was then fixed at 1540 nm and the temperature was changed. Fig. 8(b) shows the ratio R_1 and R_2 with the respect to temperature changes at the wavelength 1540 nm. The measured ratios R_1 and R_2 have a good linear response with variations in wavelength and temperature. The coefficients $\alpha_{1,2}$ and $\beta_{1,2}$ can be obtained as a ratio slope with α_1 = -0.4588 dB/nm, α_2 = 0.331 dB/nm, β_1 = 0.0016 dB/^oC, and β_2 = -0.0076 dB/^oC. Assuming an uncertainty in ratio measurement of 0.003 dB, the estimated measurement resolution for wavelength and temperature are 9.8 pm and 0.8 ^oC, respectively. Without temperature self monitoring the temperature induced wavelength error will be high, eg. ± 67.4 pm for a 5 ^oC temperature variation. In practice much higher worst case ambient temperature variations could occur and induce even larger errors. Self monitoring of the temperature reduces the worst case temperature induced wavelength error to ± 10.7 pm at 1545 nm, regardless of ambient temperature variations, a value comparable to errors induced by noise and other sources.

It should be noted that the estimated wavelength error above is based on the matrix coefficients α and β at a fixed temperature of 10 ^oC and a fixed wavelength of 1540 nm, respectively. However, detailed experimental results have shown that there is a variation of matrix coefficients α and β with temperature and wavelength. For the temperature range from 10 to 40 ^{o}C and a wavelength range from 1540 to 1550 nm the measured matrix coefficients variations are α_1 = -0.46 ± 3.19x10^{-4} dB/nm, α_2 = 0.33 ± 1.42x10^{-3} dB/nm, β_1 = 1.68x10^{-3} ± 1.42x10^{-4} dB/^{o}C, and β_2 = -7.63x10^{-3} ± 7.48x10^{-4} dB/^{o}C. The calculated results are comparable with matrix coefficient variations thus: α_1 = -0.51 ± 1.66x10^{-3} dB/nm, α_2 = 0.34 ± 2.16x10^{-3} dB/nm, β_1 = 3.24x10^{-3} ± 9.77x10^{-4} dB/^{o}C, and β_2 = -5.08x10^{-3} ± 9.74x10^{-4} dB/^{o}C. The measured and calculated matrix coefficients show a good agreement. Discrepancies could be attributed to the small wavelength dependent response of the 3 dB couplers used in the measurement and the accuracy of TEC and TOC coefficients used in the calculation. These matrix coefficients variations can increase the error measurement as described in [12]. Self temperature monitoring is still feasible if an artificial neural network (ANN) approach as in [13-15] is used rather than the inverse matrix approach above. The ANN can model the nonlinear or linear relationship between the input and output data using several neurons with nonlinear transfer functions. By using sufficient neurons, the ANN can learn the relationship between the input and output data. Therefore the relationship between $\{\Delta\lambda, \Delta T\}$ and $\{R_1, R_2\}$ can be modelled more accurately by using an ANN and it has been reported that the use of ANN can increase the measurement accuracy compared to the inverse matrix approach above [13-15].

Fig. 8 (a) wavelength coefficients at the temperature of 10 ^{o}C (b) temperature coefficients at the wavelength of 1540 nm.

4. Conclusion

An analysis of the temperature dependence of a ratiometric wavelength measurement scheme using SMS fiber structure based edge filters has been carried out. We have investigated numerically and experimentally the effects of temperature on the transmission loss of a dual SMS edge filter. The experimental results are in good agreement with the numerical results. It is found that the TOC makes a more significant contribution to the temperature dependence of an SMS edge filter compared to the TEC. The linearity of the SMS edge filter's response to both wavelength and temperature potentially allows one to use the SMS structure to monitor its own temperature using an updated ratiometric scheme, with the additional advantage of simultaneous measurement of the wavelength and temperature if required. It is demonstrated a self-monitoring of the temperature reduces temperature induced wavelength error to ± 10.7 pm regardless of the ambient temperature variation. It is also noted that using an artificial neural network could improve accuracy still further.

Acknowledgment

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Figure Captions

Fig. 1 Calculated and measured two edge filters X-type spectral response.

Fig. 2 Schematic set-up for measuring the temperature dependence on the SMS edge filter transmission loss.

Fig. 3 Transmission loss response at the temperature of 10 and 40 ^{o}C (a) calculation results (b) measurement results.

Fig. 4 Transmission loss change as a function of temperature at a wavelength of 1545 nm for a reference temperature of 20 ^{o}C.

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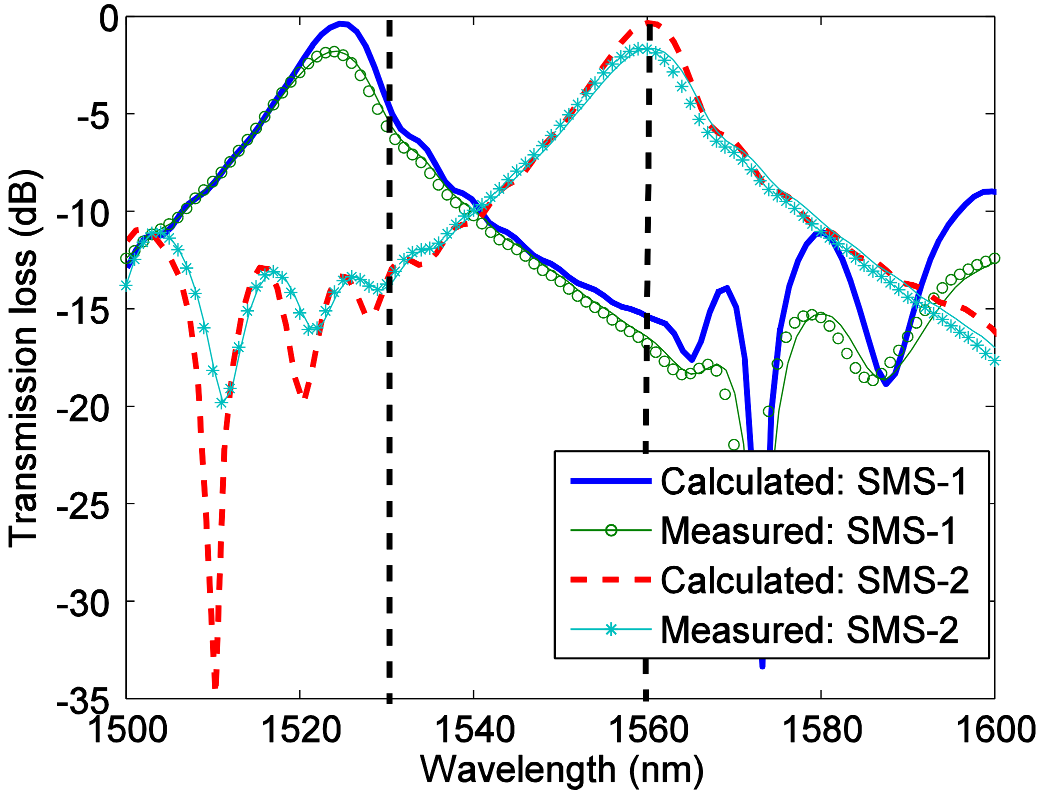

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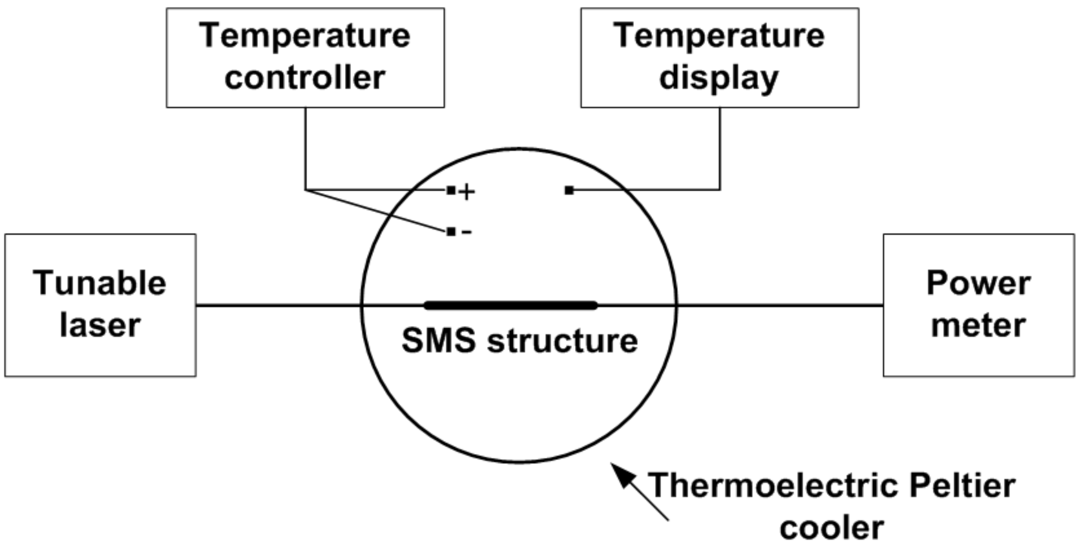

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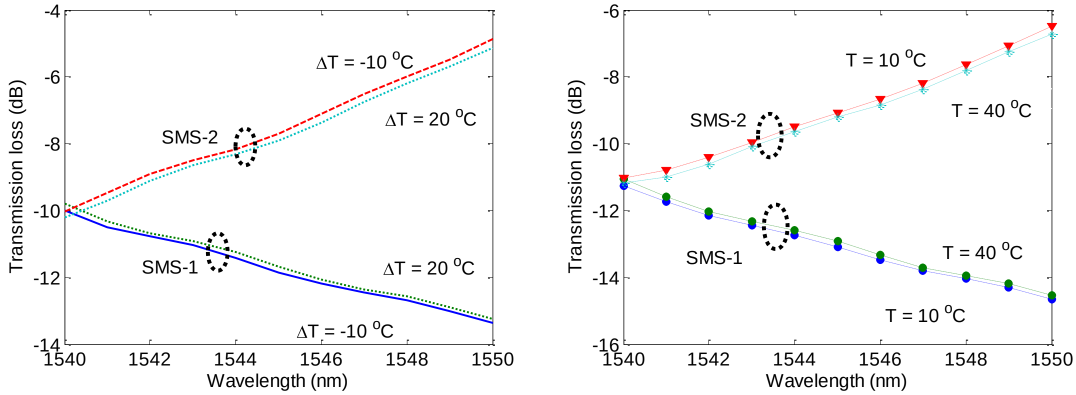

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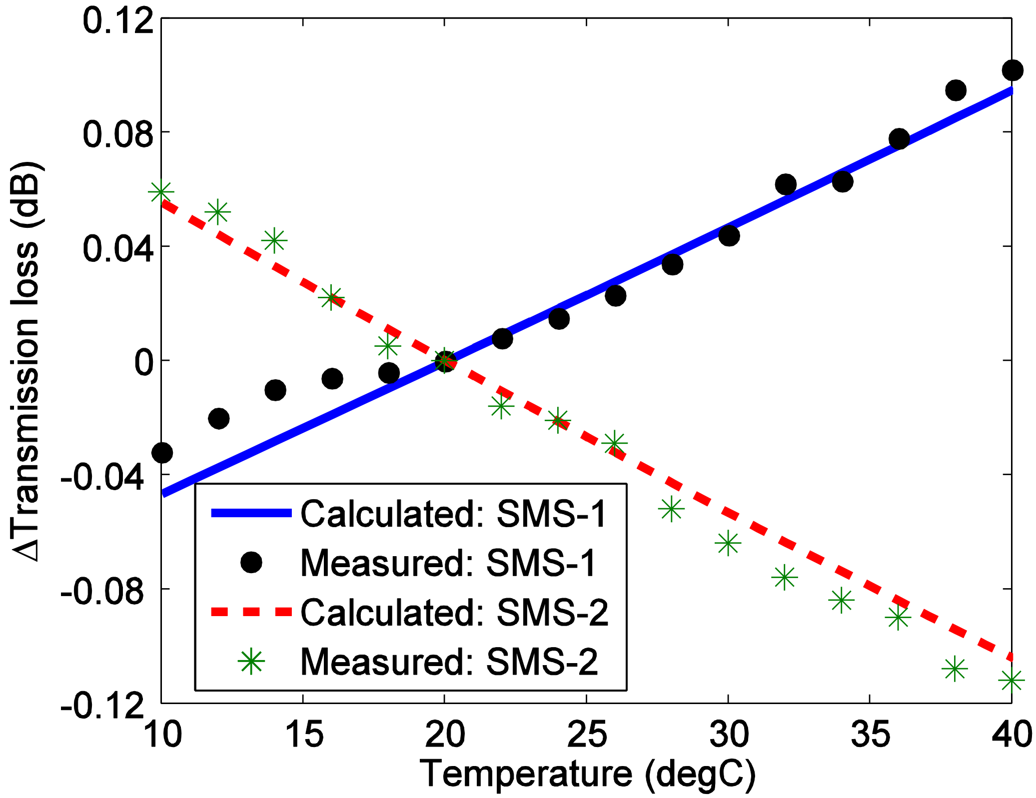

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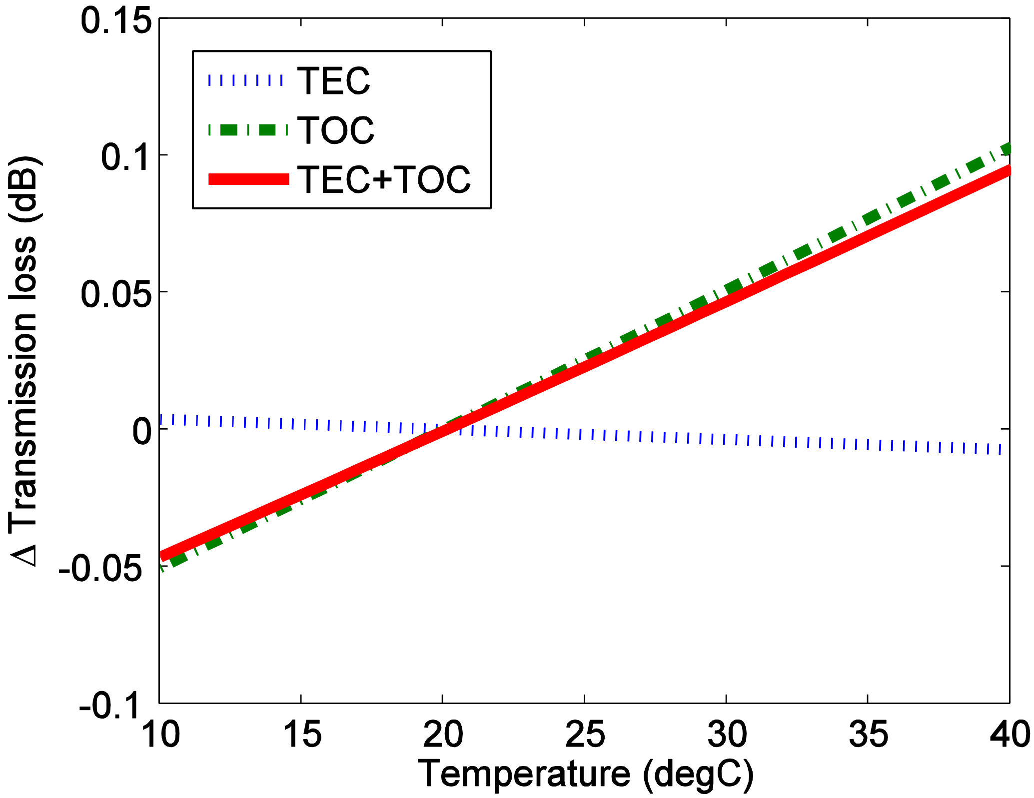

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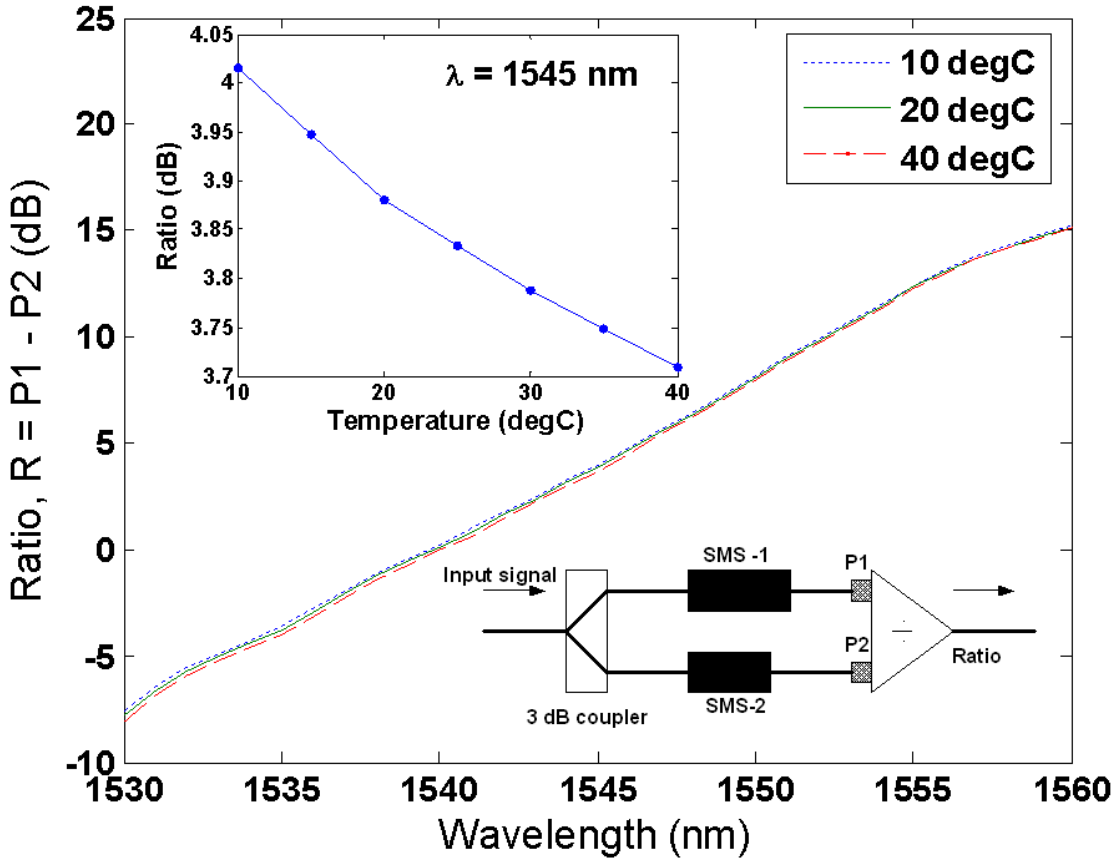

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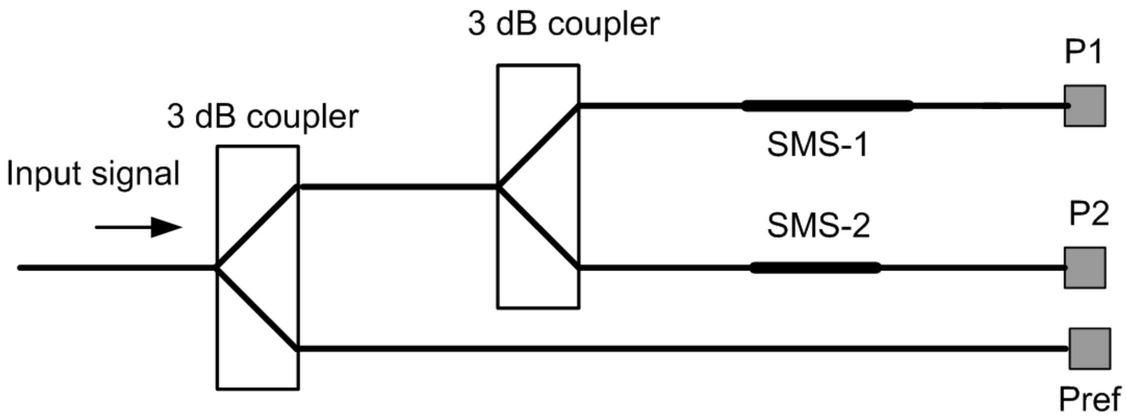

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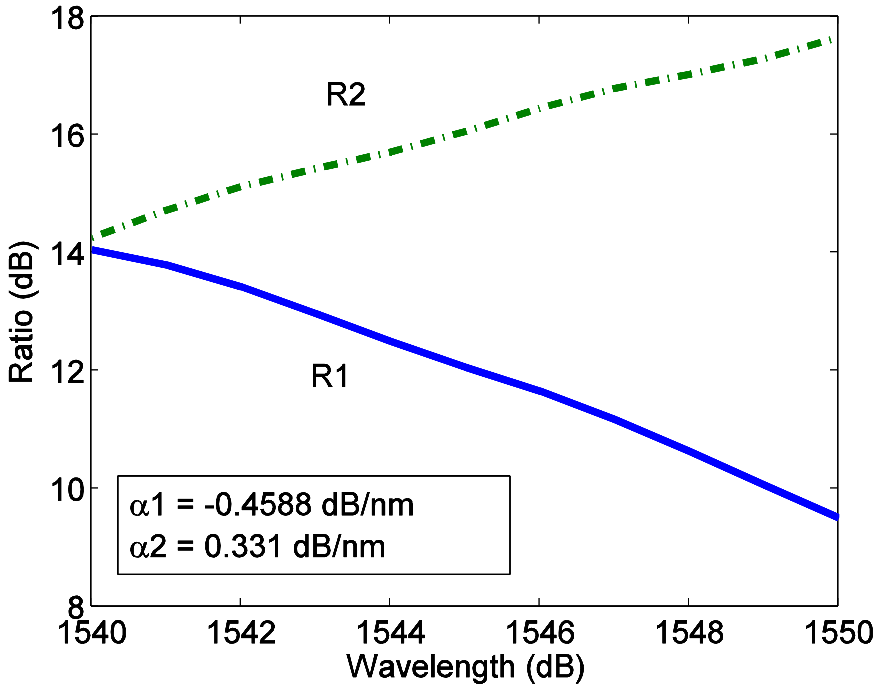
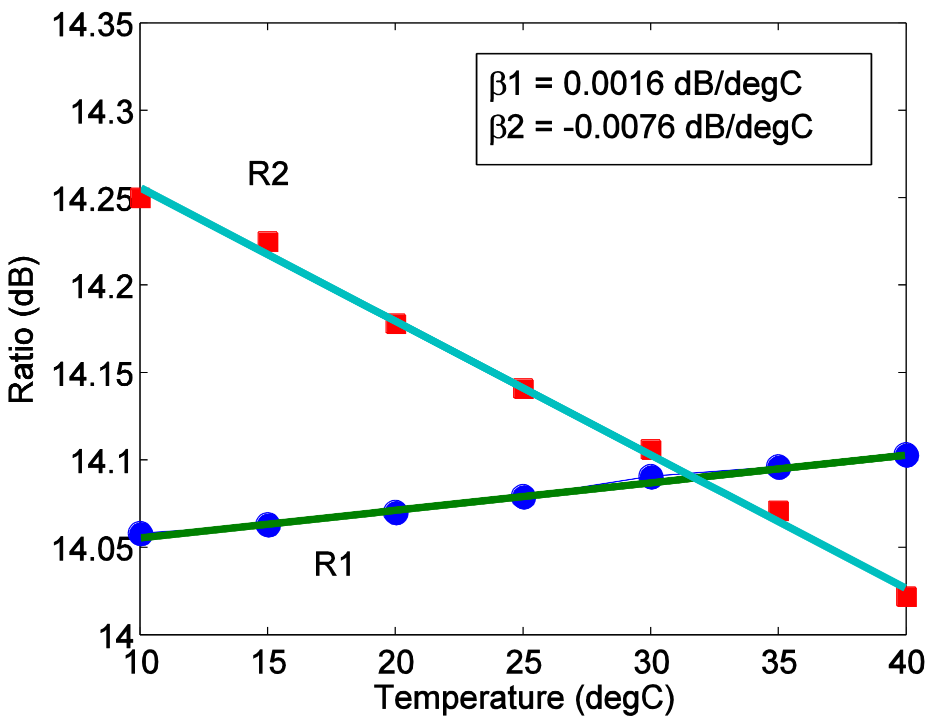


(a)



(b)

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