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PANDA Fiber Sagnac Interferometer for Temperature Sensor Application

Tan Jun Wei[1], Lip Zhan Hong[1], Sulaiman Wadi Harun[2], Cheng Xiau San[1,*]

[1] School of Engineering, UOW Malaysia KDU University College, 40150 Shah Alam, Selangor, Malaysia
[2] Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

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ABSTRACT

Fiber Sagnac loop mirror has great potential for use in various application such as multi-wavelength laser source, strain and temperature sensors. This paper demonstrates an optical fiber temperature sensor based on two lengths of PANDA polarization maintaining fibers (PMFs) in a fiber Sagnac interferometer. The temperature sensing is based on the change of spectral spacing of the generated optical comb with the temperature difference between two PMFs. The performance of the system was characterized numerically and experimentally by measuring the spectral spacing when raising the temperature of one of the PMFs. A high temperature sensitivity up to 0.36 nm/°C is obtained, with detuning range of 43 nm. This makes it a good candidate for various in-field sensing application.

1. Introduction

Temperature sensors have been used for a variety of applications in fields such as medical applications, food processing, geological explorations, biological investigation, and different types of consumer devices [1-4]. Temperature monitoring technology such as thermocouple and infrared thermography are generally utilized for temperature sensing due to their ease of operation and mature preparation approach [5]. However, they are suffered by several limitation when operating in extremely harsh environments with high pressure, high temperatures and strong electromagnetic radiation [6,7]. The demand for developing optical temperature sensors has been drastically increased due to the benefits they offer over conventional technologies, such as compact size, effective in distant sensing, resistant to electromagnetic interference, and multiplexable [8,9].

To date, several approaches have been presented for temperature sensing including grating based optical fibers, fiber loop mirror of high birefringence fibers and hybrid fiber structure [10-19]. Each sensing configuration comprises different structures and sensing material to achieve high temperature sensitivity. Temperature monitoring using grating fibers can be achieved by demodulating the Bragg wavelength variation based on the change in refractive index of the fiber with the temperature [20]. Optical fiber-based temperature sensors with a hybrid fiber structure are

* *Corresponding author.*
E-mail address: xs.cheng@uow.edu.my

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based on the modal interference phenomenon of modes that occur in a multimode fiber. The hybrid fiber with different modes experiences the phase delay which the resonance wavelength can be shifted with respect to the variation in temperature [21]. Fiber loop mirror of high birefringence (Hi-Bi) fibers is widely employed as temperature sensor due to its simple fabrication and high temperature sensitivity. In fiber Sagnac interferometer, a 3 dB fiber coupler splits the incoming light into two directions before combining the two counter-propagating beams at the same coupler. The polarization-dependent mode propagation speed that is led along the loop serves as a proxy for the optical path difference [22]. The temperature dependence birefringence of the Hi-Bi fiber in the fiber Sagnac interferometer causes a phase difference between the two counter-propagating beams due to the thermal dependent tension across the core fiber. This results a shift in spectral spacing of the produced optical comb spectrum with the variation in temperature. Furthermore, it has been demonstrated that the stress induced Hi-Bi fibers, such as PANDA fiber and Bow-tie fiber, show much higher temperature sensitivity comparing with shape induced fiber [23].

In this paper, we presented a simple configuration of optical fiber temperature sensor based on two lengths of PANDA polarization maintaining fibers (PMFs) in a fiber Sagnac interferometer. The temperature sensing is based on the change of spectral spacing of the generated optical comb with the temperature difference between two PMFs. The spectral spacing detuning range and the temperature sensitivity of the fiber Sagnac interferometer was analyzed numerically and experimentally between temperature range from 30 – 150 degrees Celsius.

2. Methodology

Figure 1 shows the experiment setup of the optical fiber temperature sensor with a fiber Sagnac loop mirror. The Sagnac loop mirror was formed by a 2x2 3-dB coupler, a polarization controller (PC) and two lengths of PANDA type polarization maintaining fibers (PMF1 and PMF2). PMF1 and PMF2 has a length of 1.1 m and 0.9 m, respectively. The Sagnac interferometer operates by splitting the input beam into two beams with equal power by a 3-dB coupler. The two beams counter-propagated in the opposite directions and undergo interference. The two orthogonal components of travelling beam in the fast axis and slow axis may experience phase difference in the PMF [24]. Both PMFs in the Sagnac loop mirror were spliced together at an offset rotation of 90 degrees to the principal axis of the PMF. The PC was used to control the relative phase difference between two orthogonal polarization modes in such a way that the slow axis component interferes with fast axis component and produce the optical comb spectrum at the output of the 3-dB coupler. The output of the comb spectrum is measured by an optical spectrum analyzer (OSA: Yokogawa AQ6360B). A broadband source range from 1550 nm-1650 nm was launched into the Sagnac interferometer to produce the optical comb with equal spacing. The broadband source was an amplified spontaneous emission (ASE) source generated from 980 nm pumped Erbium doped fiber (EDF). The 15 m length of Erbium doped fiber has a cut-off wavelength at 890 nm and an absorption coefficient of 30 dB/m at 1530 nm.

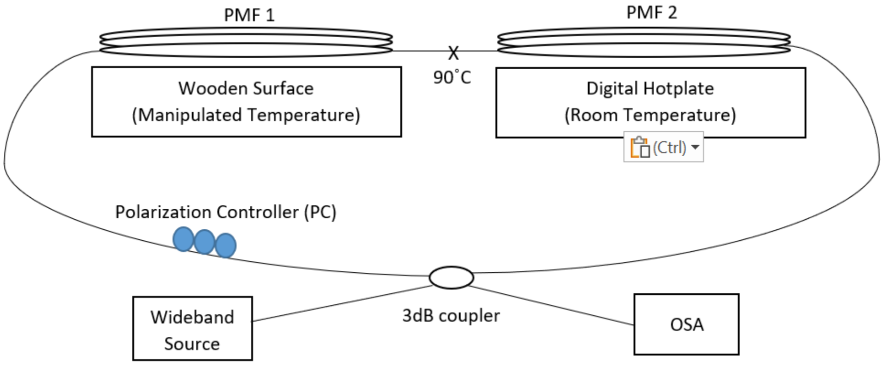

Fig. 1. Experiment setup of the optical temperature sensor with a Sagnac Interferometer

To introduce temperature difference between the two PMFs, one of the PMF was placed onto a hotplate which the temperature can be controlled from 30-150 degrees Celsius, while another PMF is fixed at room temperature. The PMF on the hotplate was wrapped with aluminum foil and covered with insulating sheets to ensure a consistent and uniform distribution of the temperature in the fiber. PMF is high birefringence fiber which is temperature dependence where the birefringence decreases with increasing of temperature due to the thermal dependent tension across the core fiber. The birefringence as a function of temperature, $\Delta n(T)$ can be calculated by a 2nd order polynomial model which is given by [25]:

$$\Delta n(T) = \Delta n(T_o) - b_1(T - T_o) - b_2(T - T_o)^2 \tag{1}$$

where b_1 = 2.55 × 10^{-7} °C^{-1} and b_2 = 1.5 × 10^{-9} °C^{-2} and $\Delta n(T_o = 30°C)$ = 4.02 × 10^{-4}. The birefringence as a function of temperature can be used to manipulate the spectral spacing of the optical comb generated in the Sagnac loop mirror. When the two PMFs are at different temperatures T_1 and T_2, thereby the spectral spacing can be written as:

$$\Delta\lambda(T_1, T_2) = \frac{\lambda^2}{\Delta n(T_2)L_2 \pm \Delta n(T_1)L_1} \tag{2}$$

where $L_2 > L_1$. The effective length of the two PMFs can be varied between $L_{eff} = L_2 - L_1$ and $L_{eff} = L_2 + L_1$ by adjusting the polarization controller that is incorporated in the Sagnac loop mirror. A rotation of 90 degree between the orthogonal components within the PMFs results a $L_{eff} = L_2 - L_1$ while a parallel orthogonal component gives a $L_{eff} = L_2 + L_1$. To investigate the temperature dependence of the spectral spacing of the fiber Sagnac interferometer, the temperature sensitivity of the system was evaluated with three difference cases. Firstly, the temperature of the longer PMF is manipulated while the shorter PMF is fixed at room temperature T_0. Then, the evaluation was repeated with the temperature of the shorter PMF is manipulated while the longer PMF was fixed. Lastly, only a single PMF with an effective length of $L_2 - L_1$ was used to provide comparative studies to the previous cases.

3. Results

The broadband amplified spontaneous emission (ASE) spectrum which cover 50 nm bandwidth from 1550 nm to 1600 nm was used to verify the temperature characteristics of the Sagnac interferometer. One of the PMF (PMF1) in the Sagnac interferometer was used as the temperature sensitive medium, while another PMF (PMF2) act as the reference medium. The temperature dependence birefringence causes a phase difference between the two counter-propagating beams which results a shift in spectral spacing of the transmission spectrum. The temperature of longer PMF (PMF1) was raised from 30°C to the maximum limit of the digital hotplate 150°C, as PMF2 was fixed at 30°C. Figure 2 shows the output spectrum of the Sagnac interferometer at various temperatures of PMF1. The spectra spacing of the transmission spectrum was observed to increase from 32 nm to 75 nm when the temperature of PMF1 rise from 30°C to 150°C. The slight difference in the composition of the PMF structure causes different thermal expansion rates which induce a change in PMF birefringence when it detects a different temperature. The birefringence reduces as the temperature increases according to Eq. (1). Eq. (2) describes that the spectral spacing increases with the reduction of birefringence, which explains the increment of the spectral spacing when the longer PMF is heated.

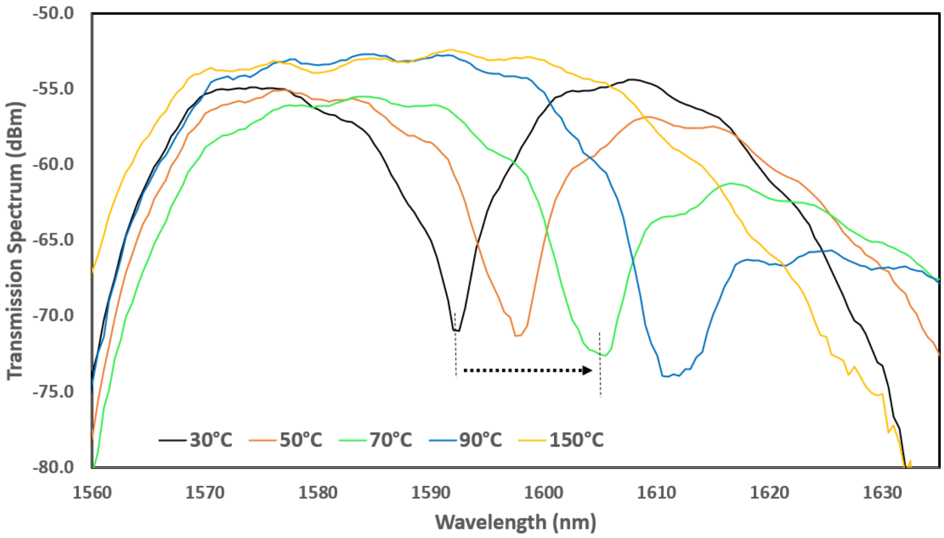

Fig. 2. Output Spectra of the Sagnac interferometer at various temperatures of the longer PMF

To investigate the effect of the PMF lengths on the performance of the fiber Sagnac interferometer, the detuning range for the Sagnac interferometer was numerically calculated with various combinations of PMF length. The detuning range for this work was defined as the range of spectral spacing when the temperature of one of the PMF varies from 30°C to 150°C. Figure 3 shows the detuning range of the Sagnac interferometer with various combinations of PMF length, where the length of one of the PMF was fixed at 1 m, another PMF length was manipulated from 0.5 m to 2.1 m. It was observed that the highest detuning range of 83 nm is obtained when both lengths of PMF are set to be closer at around 1.1 m and 1m, respectively. A higher detuning range within the same temperature range reflects the higher sensitivity of a sensor.

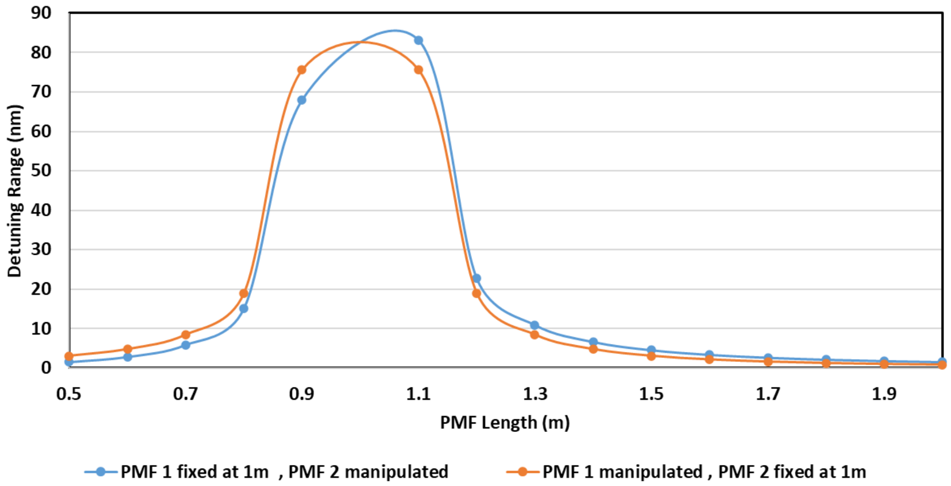

Fig. 3. Detuning range of the Sagnac interferometer with various combinations of PMF length

The temperature dependence of the spectral spacing of the fiber Sagnac interferometer was evaluated with three difference cases. Firstly, the temperature of the longer PMF (T_1) was manipulated while the shorter PMF was fixed at room temperature. Then, the measurement was repeated with the temperature of the shorter PMF (T_2) manipulated while the longer PMF was fixed. Lastly, only a single PMF with an effective length of $L_2 - L_1$ was used to provide comparative studies to the previous cases. Figure 4 compares the spectra spacing against temperature increment between the experimental results and analytical estimation for the three different cases. The experimental results are in good agreement with the analytical estimation. The spectra spacing measurements was taken by measuring the width of the semi-cycle within the wavelength 1580 nm which the analytical calculation of the spectral spacing was also based on 1580 nm in Eq. (2). It was observed that the spectra spacing of the fiber Sagnac interferometer can be increased (reduced) by heating the longer (shorter) PMF. The spectra spacing detuning range for the first two cases were 43 nm and 25 nm respectively when T_1 and T_2 are manipulated separately in each case of the experiment. Meanwhile, for the case when a single PMF was used, only a slight increment around 4.12 nm of spectra spacing detuning range was detected within the temperature range from 30-150 degrees Celsius. These results show that the temperature of the longer PMF should be manipulated during the measurement in order to obtain the maximum detuning range of the output comb spacing. Table 1 displays the temperature sensitivity comparison of the fiber Sagnac interferometer among three different cases. Fiber Sagnac interferometer with dual-segment of polarization maintenance fibers demonstrates higher temperature sensitivity compared to fiber Sagnac interferometer with single-segment PMF. A maximum of 43 nm spectral spacing detuning range was obtained by heating the longer PMF in the configuration. This is corresponding to a temperature sensitivity of 0.36 nm/˚C.

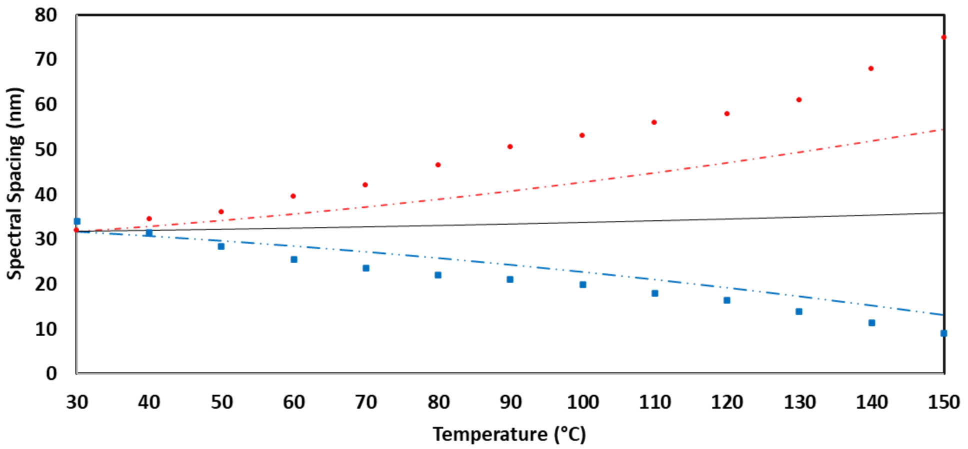

Fig. 4. Comparison of spectra spacing against temperature increment between experimental results and analytical estimation

Table 1
Comparison of temperature sensitivity between single-PMF configuration with the dual-PMF Sagnac Interferometer configuration

Case	Spectral Spacing detuning range (nm)	Temperature sensitivity (nm/°C)
Single-PMF Sagnac Interferometer	4.12	0.03
Dual-PMF Sagnac Interferometer (Heating Longer PMF)	43.00	0.36
Dual-PMF Sagnac Interferometer (Heating Shorter PMF)	25.00	0.21

4. Conclusions

The feasibility of a Sagnac interferometer based on two segments of PANDA PMF for high temperature sensitivity measurement is demonstrated. The temperature sensing is based on the change of spectral spacing of the generated optical comb with the temperature difference between two PMFs. High temperature sensitivity up to 0.36 nm/°C has been achieved, with maximum detuning range of 43 nm. The experiment shows that the Sagnac interferometer provides wider detuning range and greater temperature sensitivity by heating the longer PMF. Hence this makes it a good candidate for various in-field sensing applications.

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