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Fiber Laser Temperature Sensor based on Sagnac Interferometer

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Abstract. A fiber laser temperature sensor which is based on Sagnac interferometer is proposed in this work. The fiber laser consists of an erbium-doped fiber amplifier for signal amplification and a Sagnac interferometer for signal filtering. The Sagnac interferometer is made of 30 cm polarization maintaining fiber (PMF) and it acts as the sensing head. Experimental results suggest that the temperature does affect the laser wavelength. As the temperature varies from 30°C to 41°C, the laser wavelength is shifted to the lower wavelength from 1596.5 nm to 1581.8 nm with the recorded sensitivity of 1.1965 nm/°C. The change of the laser wavelength with temperature validates the use of this fiber laser as the temperature sensor.

1. Introduction

In recent years, all-fiber optical sensors especially those with high sensitivity have gained great interest. Such a growing demand for fiber laser sensors stems from their advantages of simple structure, high sensitivity, high signal-to-noise ratio (SNR), and excellent stability [1]. Due to these advantages, fiber laser sensors have been successful in measuring temperature, strain, refractive index, vibration, twist, gas absorption and so on [2]. They have found applications in biomedicine, environmental monitoring, agricultural engineering, health monitoring and aeronautics [3].

Optical fiber sensors could be in the form of wavelength-modulated sensors, intensity modulated sensors and interferometric sensors. The mechanism for wavelength modulated sensors such as fiber Bragg grating (FBG) is based on the wavelength shift [4], [5]. Despite offering a wide dynamic range, the fabrication of the sensor head is rather complex. Intensity modulated sensors meanwhile work based on the change of the light intensity [6]-[8]. They are simpler in fabrication but prone to the instability due to the intensity fluctuation. As for interferometric sensors such as Mach-Zhender, Sagnac and Fabry-Perot sensors, the sensing function is obtained from the interference effect of propagating lights [9]-[14]. The interferometric sensors are basically more stable in comparison to intensity modulated sensors.

In this work, we demonstrate a temperature sensor using a reflective Sagnac loop in a fiber ring laser. The laser wavelength is found to have a linear relationship with temperature. As the temperature varies from 30°C to 41°C, the laser wavelength is shifted to the lower wavelength from 1596.5 nm to 1581.8 nm with the sensitivity of 1.739 nm/°C.

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2. Methodology

The experimental setup of the fiber ring laser for temperature detection is shown in Fig. 1. The ring laser consists of a custom-made erbium-doped fiber amplifier (EDFA), a reflective Sagnac loop filter and an output coupler. The EDFA comprises of a 10m erbium-doped fiber (EDF) which is pumped by a 980 nm laser diode through a wavelength division multiplexing (WDM) coupler. The 10m EDF provides optical amplification over the C-band region [15], [16]. Meanwhile, the reflective Sagnac loop is developed by a combination of a 50:50 coupler and a 30 cm polarization maintaining fiber (PMF). The Sagnac loop functions as a comb filter in which the spacing is influenced by the birefringence and length of the PMF. A 90:10 coupler is utilized to tap out 10% of the oscillating light for the laser output. Throughout the experiment, the output spectrum is captured using an optical spectrum analyzer (OSA) with a resolution of 0.05 nm.

Besides filtering, the Sagnac loop in this design also behaves as a temperature sensor head. In order to experience different temperatures, the sensor head is placed in a temperature chamber. As the temperature of the sensing head increases, the birefringence of the PMF in the Sagnac loop also changes as well. This consequently causes a shift of Sagnac loop transmission spectrum and ultimately a shift of laser wavelength.



Fig. 1. Experimental setup of fiber laser temperature sensor.

The Sagnac loop structure together with the circulator is shown in Fig. 2. The Sagnac loop consists of a 3-dB coupler and a PMF as the birefringent element. The mechanism of the Sagnac loop as the temperature sensor is as follows; the input light firstly enters the 3-dB coupler via the circulator. In the 3-dB coupler, the signal is split into a clockwise and anti-clockwise direction. These two light beams then pass through the PMF and they get a phase difference due to the birefringence of the PMF. When the two light beams recombined at the output port of the 3-dB coupler, the interference spectrum can be formed. The phase difference ϕ is given by

$$\phi = 2 \pi B L / \lambda \tag{1}$$

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where, *B* is the birefringence of the PMF, *L* is the length of the PMF, and λ is the wavelength of the input light. The output transmission spectrum at the circulator is a periodic function of the wavelength, which is stated as [11]

$$T = (1 - \cos \phi)/2$$
 (2)

If $\phi = 2 \pi m$, the transmission spectrum will reach its maximum intensity. Here, *m* is an integer. A change in the phase can be induced by either changing the PMF length ΔL or the birefringence ΔB which is stated as

$$\phi' = 2 \pi (B + \Delta B) (L + \Delta L) / \lambda$$
(3)

As the PMF is not strained, therefore $\Delta L \ll L$ and Eqn (3) can be reduced to

$$\phi' = 2 \pi (B + \Delta B) L / \lambda \tag{4}$$

Resulting from the change of phase, the phase difference $\Delta \phi$ is defined as

$$\Delta \phi = \phi' - \phi = 2 \pi \Delta B L / \lambda \tag{5}$$

which contributes to the shifting of the transmission spectrum. That mean, shifting of the transmission spectrum of Sagnac loop can be induced by changing the temperature of the PMF.



Fig. 2. Sagnac loop configuration

3. Results and discussion

The threshold power of the laser is firstly investigated. The threshold power is defined as the amount of EDF pump power at which the laser output power increases significantly. Figure 3 shows the change of laser output power as compared to the input pump power. In this investigation, input pump power increases from 0 mW to 80 mW with a step of 5 mW. An optical power meter is used to measure the laser output power. It can be seen from Fig. 3 that the threshold pump power is above 20 mW and beyond it, the output power increases linearly with the pump power. Based on the curve fitting, the recorded laser efficiency is x%.

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The evolution of the laser output spectrum with input pump power is then examined. Figure 4 shows the output spectrum as the pump power increases from 0 mW to 80 mW with a step of 5 mW. In this observation, the temperature is set at 33°C. Based on Fig. 4, it is observed that the laser spectrum starts to appear at 25 mW. That mean, the input pump power from 0 mW to 20 mW is not enough to generate the laser output spectrum



Fig. 3. Laser output power with a variation of pump power



Fig. 4. Laser output spectrum with a variation of pump power

The behavior of the laser output spectrum as the temperature changes is then explored. Figure 5 illustrates the change of the output spectrum as the temperature sensor head is varied from 30°C to 41°C with a step of 1°C. In this observation, the pump power is fixed 200 mW. It is noticeable from Fig. 5 that the laser output spectrum shifts to the shorter wavelength with increasing temperature. When the temperature is set to 30°C, the laser wavelength is at 1570.69 nm and it shifts to the shorter wavelength at 1556.88 nm as the temperature is fixed at 41°C. The blue-shift of the laser wavelength with increasing temperature is due to the change of the PMF birefringence in the Sagnac loop. The birefringence change

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modifies the interference effect between the clockwise and anti-clockwise light, leading to the blue-shift of the laser output spectrum.

Figure 6 meanwhile plots the laser output wavelength as a function of temperature. It is evident that the laser output wavelength shifts linearly as temperature increases from 30°C to 41°C. Linear fitting is also done to the data in Fig. 6 and the slope of the linear line is found to be 1.1965 nm/°C. This slope basically represents the temperature sensitivity of this fiber laser sensor.



Fig. 5. Laser output spectrum with a variation of temperature



Fig. 6. Laser output wavelength with a variation of temperature

4. Conclusion

In summary, a fiber laser temperature sensor based on Sagnac interferometer is presented. The fiber laser consists of a Sagnac interferometer working as a signal filter and EDFA for signal amplification. The sensing head is made of 30 cm PMF. Based on experimental results, it is evident that temperature indeed affects the laser wavelength. As the temperature varies from 30°C to 41°C, the laser wavelength experiences a blue-shift from 1596.5nm to 1581.8nm. The recorded sensitivity for this fiber laser sensor is 1.1965 nm/°C.

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