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Study on fiber ring laser in sensing application with beat frequency demodulation

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ABSTRACT

A simple fiber ring laser is used for sensing based on beat frequency demodulation. Because of the absence of a mode selecting device, the mode spacings between multi-longitudinal modes in the laser can be large. Therefore, the beat frequency signals with high frequency are generated, and the high sensitivities will be achieved. In the experiment, six different beat frequency signals are studied and compared in strain sensing. Their sensitivities are in good agreement with theoretical predictions. The signal-to-noise ratios, 3-dB bandwidths, maximum measureable strains, stabilities, and their measurement accuracies are also measured and discussed. The fiber ring laser sensor system proposed is robust and cost-effective.

1. Introduction

Fiber lasers are very attractive in sensing application for their high signal-to-noise ratio (SNR), low-cost, and immunity to electromagnetic interference. In multiple modes fiber laser sensor systems, beat frequency demodulation technology is widely used, since it is cheap and stable [1,2]. The strain, temperature, load, bend, ultrasound and many other parameters can be detected by measuring the beat frequency signal (BFS) between two polarization modes of distributed feedback fiber lasers or distributed Bragg reflector fiber lasers [3–11]. However, the polarization of the fiber laser is not easy to be controlled. Thus, the appropriate BFS between the two polarization modes is a little difficult to be obtained. Recently, the multi-longitudinal mode fiber laser sensor was reported. The laser cavity is formed by a section of erbium-doped fiber (EDF), a section of single mode fiber (SMF) and two fiber Bragg gratings (FBGs) as reflectors [12]. In addition, one of the FBGs can be replaced by a coupler [13,14]. There are many longitudinal modes in the laser due to the long cavity. The strain, temperature and vibration can be measured by monitoring the BFS between two different longitudinal modes [12–14]. Moreover, if the BFS between polarization modes is also detected, dual-parameters measurement can be realized [2,15]. The measurement sensitivity of the multi-longitudinal mode fiber laser sensor is proportional to the frequency of the BFS, which means that the BFS with higher frequency has higher sensitivity. To obtain the BFS with high frequency, the mode spacing should be large. Traditionally, FBG is employed as reflector, and meanwhile, it also serves as mode selecting device in the laser cavity. The value of mode spacing is restricted by the bandwidth of FBG. Therefore, the sensitivity of the measurement is limited by the usage of FBG.

In this paper, a simple fiber ring laser for sensing application with beat frequency demodulation is proposed and studied. In the ring cavity, no reflector or mode selecting device is employed. As a result, there will be more longitudinal modes in the laser than in those using FBGs as reflectors. The BFS with high frequency can be achieved by beating two modes with large mode spacing, which will induce high sensitivity in the measurement. In the experiment, the BFSs obtained are as high as about 20 GHz. Six different BFSs of 1008 MHz, 2016 MHz, 4032 MHz, 7940 MHz, 12,980 MHz and 18,091 MHz are monitored and investigated as sensing signals, and their measured strain sensitivities are -0.62 kHz/$\mu\varepsilon$, -1.23 kHz/$\mu\varepsilon$, -2.46 kHz/$\mu\varepsilon$, -4.91 kHz/$\mu\varepsilon$, -8.04 kHz/$\mu\varepsilon$ and -11.12 kHz/$\mu\varepsilon$, respectively. The maximum measureable strains (MMSs), stabilities and measurement accuracies are also studied. In addition, the absence of a reflector or mode selecting device simplifies the system and increases its robustness in practical applications.

2. Principle

The ring cavity is shown in Fig. 1. It includes a wavelength division multiplexer (WDM), a section of EDF to supply enough gain for the multiple mode lasing, a section of SMF and a coupler.

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Multi-longitudinal mode laser is generated in the ring cavity, which can be written as

$$f_p = \frac{cp}{nL} \tag{1}$$

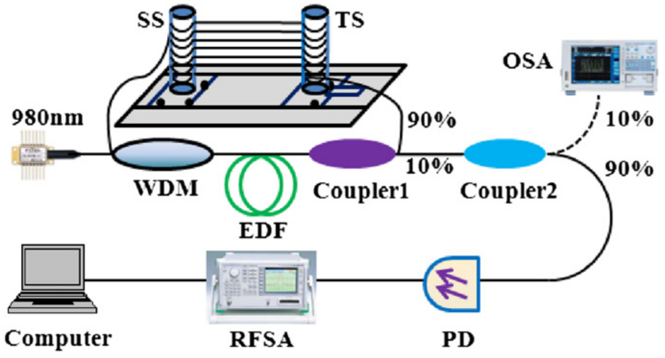

Fig. 1. Schematic configuration of the fiber ring laser sensor system.

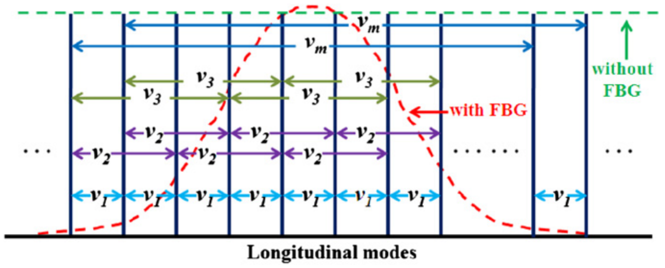

Fig. 2. Generation of BFSs between longitudinal modes.

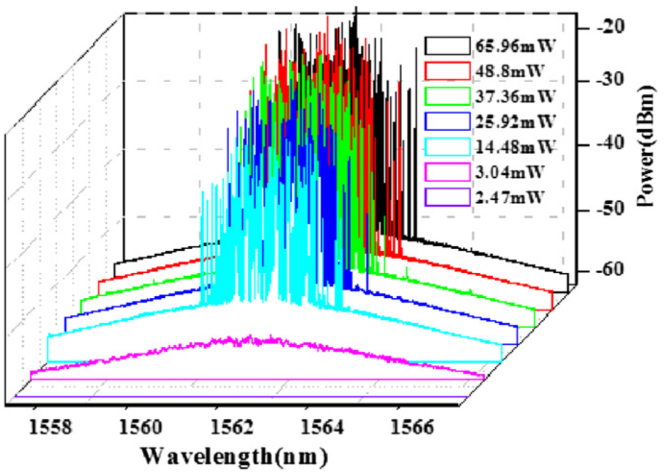

Fig. 3. Optical spectrum of the fiber ring laser under different pump powers.

where c is the light velocity in vacuum, p is the mode number, n is the effective refractive index, and L is the whole cavity length.

The BFS is produced by any two different longitudinal modes as shown in Fig. 2, and it is given as

$$\nu_N = \frac{(p-q)c}{nL} = \frac{Nc}{nL} \tag{2}$$

where q is another mode number, and $N=p-q$ is used to denote the beat frequency.

When the strain or temperature is applied on part of the laser cavity, the BFS will shift, which is given by [12,13]

$$\Delta\nu_N = -\frac{Nc}{nL}\left(\frac{\Delta L}{L}+\frac{\Delta n}{n}\right) = -\nu_N\,\frac{l}{L}(1-P_e)\,\Delta\varepsilon-\nu_N\,\frac{l}{L}\,(\alpha+\xi)\,\Delta T \tag{3}$$

where P_e is the strain-optic coefficient, α is the linear thermal expansion coefficient, ξ is the thermo-optic coefficient, and l is the length of the fiber used for strain or temperature sensing.

Theoretically, all of the BFSs can be chosen as sensing signals. However, it can be found from Eq. (3) that the high-frequency BFSs have higher sensitivities than low-frequency BFSs. According to Eq. (2) and Fig. 2, the frequencies of these BFSs are determined by mode spacings; therefore, to obtain high sensitivities, the mode spacings of the sensing signals we choose should be large. In traditional multi-longitudinal mode fiber laser sensor system, the mode spacings are restricted by the bandwidth of FBG, as shown in Fig. 2. In the sensor system presented in this paper, because of the absence of mode selecting device, large mode spacings can be achieved. Hence, there will be relatively high-frequency BFSs existing in the beat frequency spectrum, and high measurement sensitivities can be obtained.

3. Experiment and results

As an example, the fiber ring laser is used for strain measurement in the experiment. The experimental setup is shown in Fig. 1. The 980 nm pump source is launched into the ring cavity through the 980 nm port of the WDM. The EDF in the laser cavity is 0.75 m with the absorption coefficient of 16 dB/m at 1530 nm. Coupler1 is used to form the ring resonator. The laser from coupler1 is split into two parts by coupler2. One part of the output is sent into an optical spectrum analyzer (OSA), which is used to monitor the optical spectrum of the laser. The other part of the output of coupler2 is connected to a photodetector (PD) where the BFSs are produced. The BFSs are monitored by a radio-frequency spectrum analyzer (RFSA). Finally, the measured BFSs are sent into a computer for data processing. Part of the laser cavity with a length of about 9.2 m is rolled between two copper columns. One of the columns is fixed on a stationary stage (SS), and the other is fixed on a translation stage (TS). The strain applied on the laser cavity can be changed by tuning the TS.

The multi-longitudinal mode laser is produced when the pump reaches the threshold of 3.04 mW. The optical spectrum of the laser is

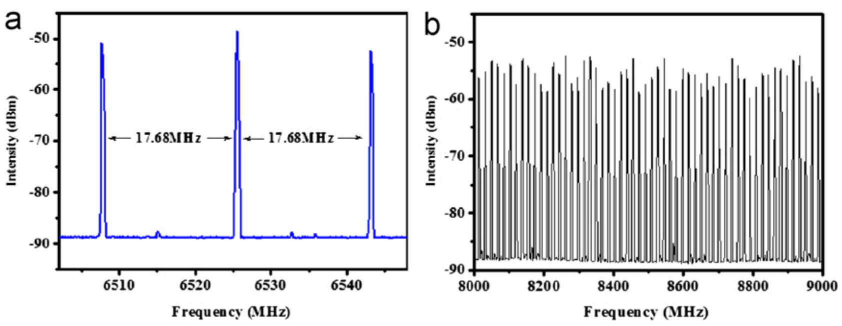

Fig. 4. Beat frequency spectrum: (a) from 6502 MHz to 6548 MHz and (b) from 8000 MHz to 9000 MHz.

shown in Fig. 3, from which we can find that the bandwidth of the laser is much wider than those with FBGs as reflectors [13,15].

The BFSs are generated by beating any two different modes in the PD. Because of the absence of mode selecting device, the mode spacings can be large, and high-frequency BFSs are achieved. Fig. 4 gives part of the frequency spectrum of the BFSs, which shows that there are many BFSs, with the frequency interval of 17.68 MHz, corresponding to the whole cavity length of 11.7 m. The BFSs obtained in the experiment are as high as about 20 GHz.

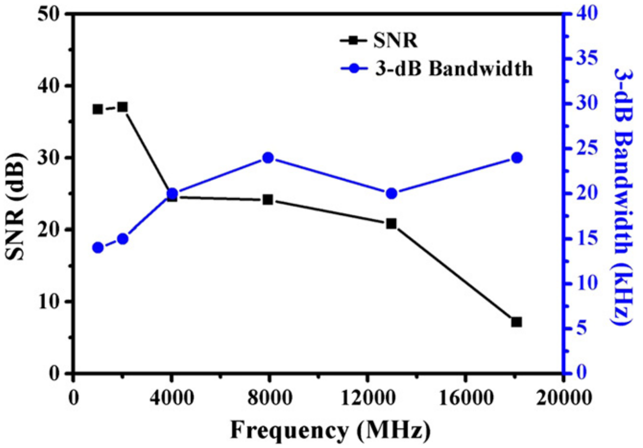

Fig. 5. SNRs and 3-dB bandwidths of sensing signals.

To study and compare the characteristics of these BFSs in sensing application, six different BFSs are chosen for monitoring from 0 to 20 GHz, randomly. The SNRs of the BFSs are high enough for the measurement, and the 3-dB bandwidths are all smaller than 25 kHz, as shown in Fig. 5. The relatively low SNRs at high frequency are caused by the response of PD. The SNRs of BFSs are significantly higher than those reported in Ref. [12]. When two FBGs are used as reflectors, there will be a mismatch between them, which brings more noise, leading to the degeneration of SNRs.

The strain responses of these BFSs are given in Fig. 6. Their measured strain sensitivities are −0.62 kHz/με, −1.23 kHz/με, −2.46 kHz/με, −4.91 kHz/με, −8.04 kHz/με and −11.12 kHz/με, respectively, which are in good agreement with the theoretical predictions of −0.62 kHz/, −1.24 kHz/με, −2.47 kHz/με, −4.87 kHz/με, −7.96 kHz/με and −11.1 kHz/με, respectively.

4. Discussions

Fig. 7 shows that the sensitivities of these BFSs increase linearly with frequency, as expected. The usage of high-frequency BFSs for sensing can improve the measurement sensitivity. However, to avoid the crosstalk between BFSs, the maximum frequency shift of a certain signal cannot be larger than the frequency interval. As the frequency interval is fixed, the MMSs for these BFSs are not the same, and they are given in Fig. 7. It should be mentioned that the calculated MMSs only make sense to high-frequency BFSs. Since, for low-frequency BFSs, the

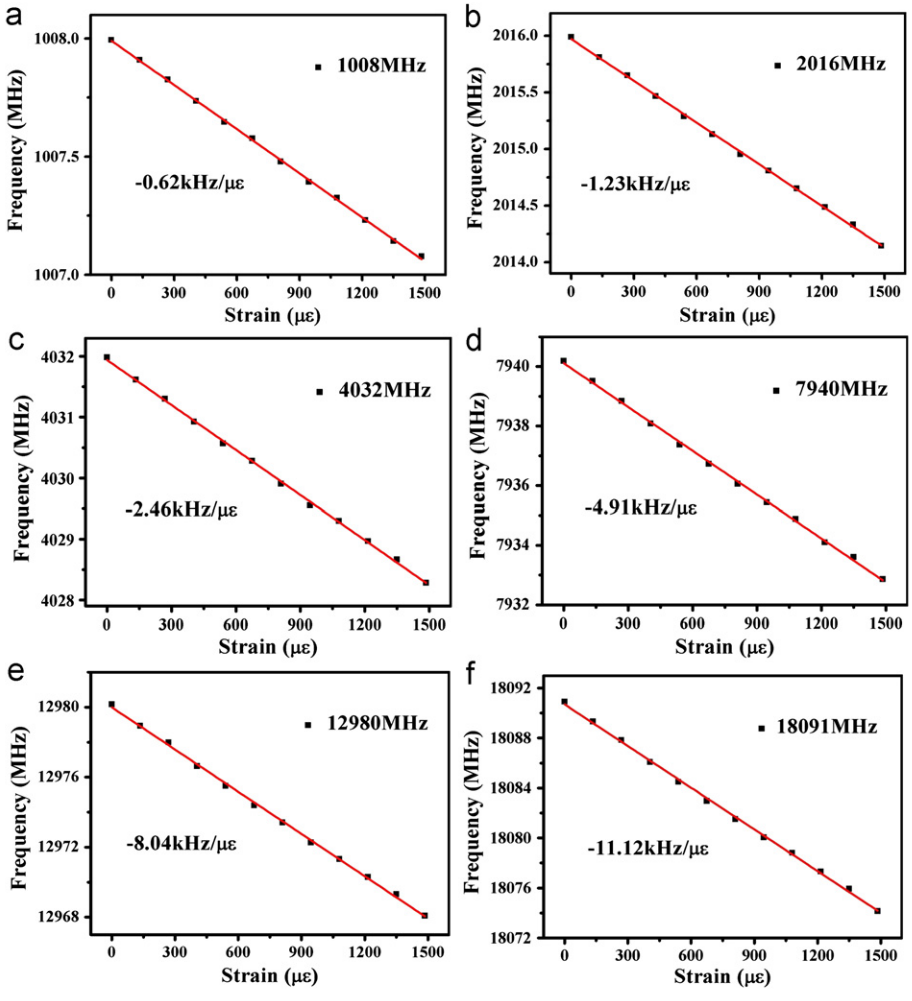

Fig. 6. Strain responses of sensing signals.

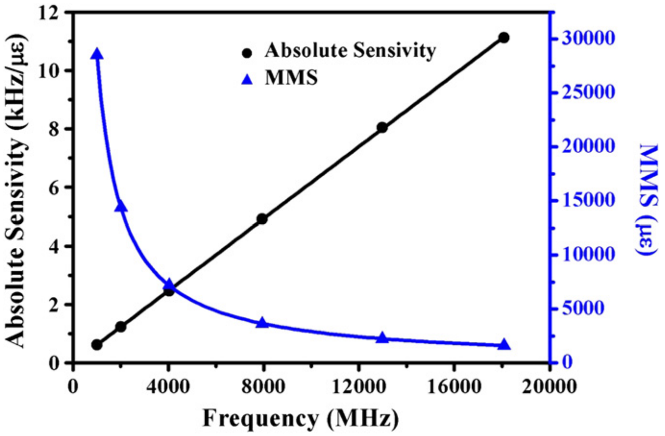

Fig. 7. Absolute sensitivities and MMSs of sensing signals.

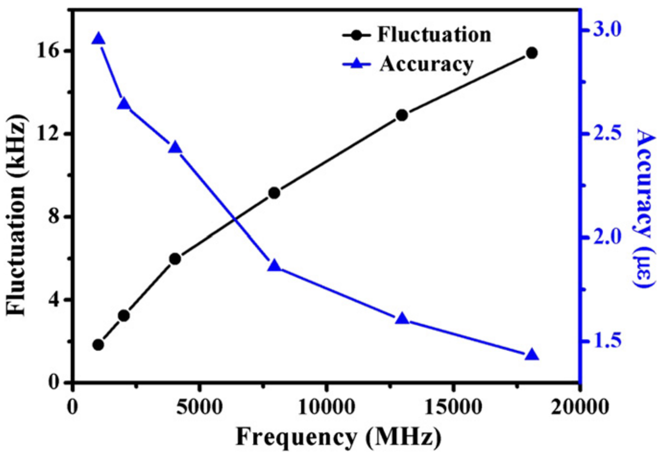

Fig. 8. Maximum fluctuations and measurement accuracies of sensing signals.

calculated MMSs cannot be reached because of the upper strain limit of fiber. According to Fig. 7, we can find that the high-frequency BFSs have higher sensitivities, but smaller MMSs than low-frequency BFSs. Thus, there is a trade-off between the sensitivity and MMS in the selection of sensing signal. The selection should depend on practical requirements and available equipments. Note that if the whole length of the laser cavity is decreased, the frequency interval will be larger, and the MMS for a certain BFS will be increased.

The stabilities of these chosen sensing signals are measured every 10 min for 1.5 h and given in Fig. 8. It shows that high-frequency signals have larger fluctuations than low-frequency signals. In our opinion, there are mainly two reasons. Firstly, the performance of PD is degraded at high frequency. Secondly, the high-frequency BFSs have higher sensitivities than low-frequency BFSs; thus, they are more sensitive to environmental disturbance. In the experiment, the fiber ring laser sensor is exposed in the air. Especially, part of the laser cavity is just coiled and put on the table. If the sensor is well packed and protected from the environmental disturbance, the stabilities of these sensing signals can be improved. According to the fluctuations and sensitivities of BFSs, we can achieve the measurement accuracies, and they are shown in Fig. 8. Despite the larger fluctuations of high-frequency BFSs, they still have higher measurement accuracies than those of low-frequency BFSs, due to their higher sensibilities. It can also be found that the measurement accuracies of high-frequency BFSs are higher than those reported in Refs. [4,5,12]. In the experiment, the lower path of the cavity is not used for sensing, due to the fusion splices between EDF and SMF. In practical application, if the fusion splices are packaged, the whole cavity can be used for sensing. Hence, the sensitivities are improved, and higher measurement accuracies will be obtained, accordingly.

A certain BFS $\Delta\nu_N$ is the summation of many beat signals as shown in Fig. 2. When a certain beat signal with the frequency of $\Delta\nu_N$ disappears because of mode hopping, other beat signals with the frequency $\Delta\nu_N$ are still generated. Therefore, the BFS $\Delta\nu_N$ still exists, and the measurement depends on the frequency shift of BFS, which cannot be changed by mode hopping; as a result, the mode hopping has little effect on the measurement.

No specially designed or fragile component is used in the system, which makes the sensor robust and low-cost. In addition, beat frequency demodulation is employed, that avoids complex optical and electronic signal processing. Moreover, if a specialized demodulation equipment or circuit based on monitoring the frequency shifts of the BFSs is produced, the cost, size and weight of the demodulation system can be further reduced, since the electronic technology is relatively mature and cost-effective, nowadays.

5. Conclusion

In summary, we have presented a robust and simple-structure fiber ring laser sensor system. Because of the absence of mode selecting device, high-frequency BFSs can be obtained, and the usage of high-frequency BFSs as sensing signals improves the measurement sensitivities and accuracies. Furthermore, the SNRs, 3-dB bandwidths, MMSs, and stabilities of these BFSs with different frequencies are measured and investigated. The sensor system provides many alternative sensing signals with different characteristics for different practical requirements and available equipments. It shows its promising applications in geological monitoring, temperature monitoring, hydrophone, and so on.

Acknowledgments

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