Temperature sensing based on chaotic correlation fiber loop ring down system

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Abstract: In this paper, we describe a novel temperature sensing system based on chaotic correlation fiber loop ring down technique. A fiber Bragg grating is introduced into the fiber loop cavity. The effect of temperature on the central wavelength of fiber Bragg grating is characterized by the ring down time of the autocorrelation coefficient of chaotic laser in the fiber loop cavity. The relationship between the autocorrelation coefficient ring down time of the chaotic laser and wavelength shifting of the fiber Bragg gratings induced by temperature is theoretically and experimentally analyzed. The sensitivity of 3.52ns/℃ is achieved in the proposed temperature sensing system with fiber cavity length of 6.05m. We also study the relationship between temperature and central wavelength of fiber Bragg grating by chaotic correlation fiber loop ring down system and receive the temperature sensitivity of 0.01nm/℃ of the FBG. This sensing method is not only simple and low cost, but also has the great potential applications for various industry and agriculture.

Keywords: Chaotic fiber laser; Temperature sensor; Chaotic autocorrelation coefficient; Fiber loop ring down; Fiber Bragg grating

1. Introduction

Temperature is one of the fundamental thermodynamic properties [1]. Temperature measurement is widely applied in various industries and agriculture, which is related to production safety, product quality, and service life of equipment [2, 3]. It is very important to measure the temperature accurately and real timely. The temperature sensing device in the present application is mainly electronic sensors, such as thermocouple and thermistors, which transforms temperature into electrical signals. The performances of electronic sensors are disturbed in high voltage and intense electromagnetic field [4]. With the development of optical fiber and laser technology, optical fiber sensors has emerged due to the electrical insulation of fiber itself and the inherent advantage of broadband. In recent years a variety of optical fiber temperature sensors have been proposed [5], such as distributed-temperature sensor [6, 7], optical fiber fluorescence temperature sensor [8, 9], reflective optical fiber temperature sensor [10, 11] and interferometric fiber temperature sensor [12, 13].

Fiber Bragg gratings (FBG) are excellent fiber optic sensing elements, and many physical parameters can be measured through it [14], such as temperature [15, 16], strain [17, 18], refractivity [19, 20], and magnetic field [21, 22]. FBGs are integrated into the light guiding core of the fiber. The wavelength encoded characteristic of FBG eliminates the problems of amplitude or intensity variations that plague many other types of fiber sensors. The FBG as fiber temperature sensing head occurs principally through the effect on the index of refraction [23]. At the present, the FBG-based temperature sensors are widely applied by measuring the shifts of the Bragg wavelength with change of temperature [24], and the demodulation is achieved in frequency domain. A new optical fiber sensor—fiber loop ring down (FLRD) sensor has been developed [25, 26]. FBG is introduced into fiber loop cavity to convert the measurement from wavelength change into the variation of ring down time, and the approach of demodulation is changed from frequency domain to time domain.

Fiber loop ring down system which consists of two optical couplers measures the ring down time of intensity of light in the fiber loop so that it can effectively minimize the impact of fluctuation of intensity of the injected pulse [27, 28]. The ring down time is both independent of excitation intensity, resulting in lower susceptibility to laser noise, and immune from external loss contributions, further improving sensitivity [29]. However, the fiber loop ring down sensing technology use the pulse laser as injected light [30.31], it is necessary to consider the contradiction between the length of fiber loop and the width and frequency of pulse for signal crosstalk [32], consequently the fiber cavity length is usually hundreds of meters , while the longer length of fiber loop can reduce sensing sensitivity of the fiber loop ring down sensing system.

Chaotic laser has very broad bandwidth, high frequency and correlation properties due to its intrinsic randomness and has many great applications for fiber fault detection [33, 34], sensing [35, 36]. In this article, we investigate the fiber loop ring down temperature sensor based on the chaotic laser. The FBG as the sensor unit is incorporated into the fiber loop cavity and the autocorrelation coefficient ring down time of chaotic laser is utilized as sensing parameter. It allows shorter length of fiber loop owing to the extremely narrow bandwidth of autocorrelation curve [37]. The experimental scheme and principle of the fiber loop ring down temperature sensing system based on chaotic laser is described in section 2, followed by the experimental results and discussions which are given in section 3. Finally, the conclusion is presented in the section 4.

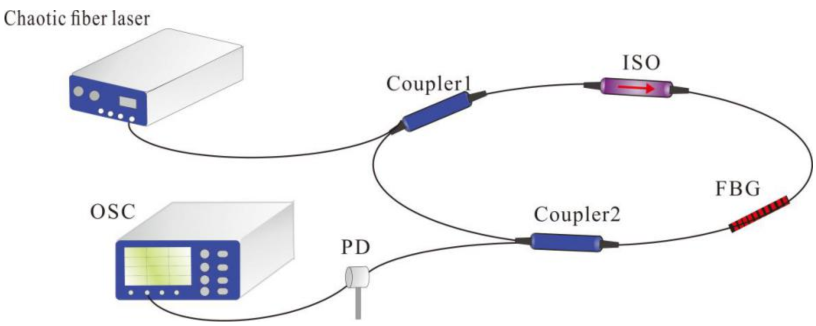
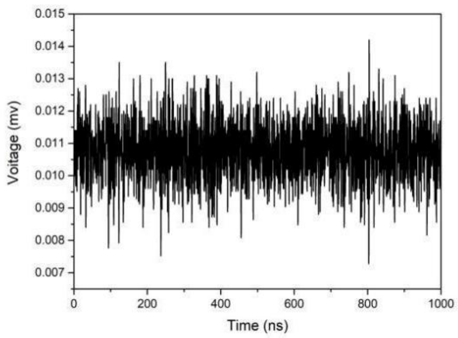


Fig.1. Schematic diagram of the FLRD temperature sensing system

2. Experimental setup and principle

The schematic diagram of the fiber loop ring down temperature sensing system based on chaotic laser is shown in Fig.1. The two standard 2x1 95:5 optical fiber couplers (coupler1 and coupler2), an isolator (ISO) and a FBG are connected to form the fiber loop cavity. The ISO ensures the unidirectional propagation of light. The FBG is used as the sensing head and the central wavelength of FBG is 1549.95nm with the quoted reflectivity of 12% and the FWHM of 0.25nm. The light from chaotic fiber laser is injected into the fiber loop cavity via 5% port of coupler1 and circulates in fiber loop cavity. The decayed light is coupled out of the fiber loop by 5% port of coupler2 and is detected by a photoelectric detector (PD). The output of the PD is measured by an oscilloscope (OSC).

In the experiment, the output power of chaotic fiber laser is 47mW. Fig.2 is the output characteristics of the wavelength tunable chaotic fiber laser. The time series of the chaotic fiber laser is presented in Fig.2 (a) and it shows that the chaotic laser has a noise-like time series. The spectrum of chaotic laser is shown in Fig.2 (b) and the central wavelength is 1550.21nm with the full width at half maximum (FWHM) of 0.25nm. Fig.2(c) depicts the autocorrelation curve of the time series of chaotic laser and shows that the autocorrelation curve of chaotic laser has the properties of delta-like-function and the FWHM of ~0.8ns. The autocorrelation curve of the decayed light of the output of 5% port of coupler2 is shown in Fig.2 (d). Multi-peaks are resulted from the multi-propagating and the transmission time delay of chaotic laser in the fiber loop cavity. The time interval between two adjacent spikes of 29.5ns shown in Fig.2 (d) is equivalent to the round trip time of the chaotic laser inside the loop and indicates that the length of fiber loop cavity in our experiment is 6.05 m. The chaotic autocorrelation coefficient peaks exponentially fitted is shown in Fig.2 (d) and the ring down time of 174.54 ns is obtained.



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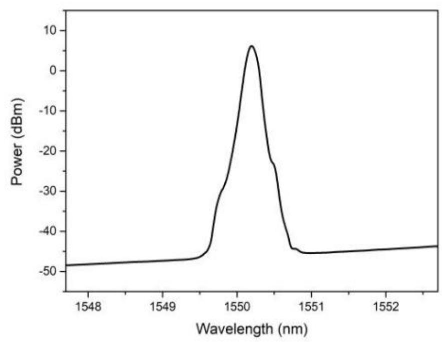

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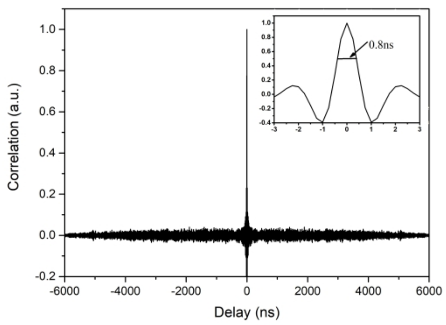

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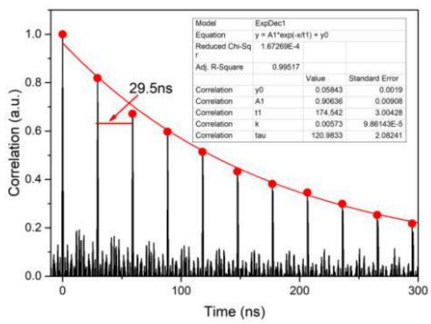


(d)

Fig.2. (a) Time series of chaotic fiber laser , (b) chaotic laser spectrum , (c) autocorrelation curve, and

(d) Autocorrelation curve of the decayed chaotic laser.

The demodulation principle of sensing system is based on the variation of overlap area of the spectrum of the FBG and chaotic laser. The mathematical expressions of spectrum $P(\lambda)$ of chaotic laser and the reflection spectrum $R(\lambda)$ of FBG can be found in our previous work [38].

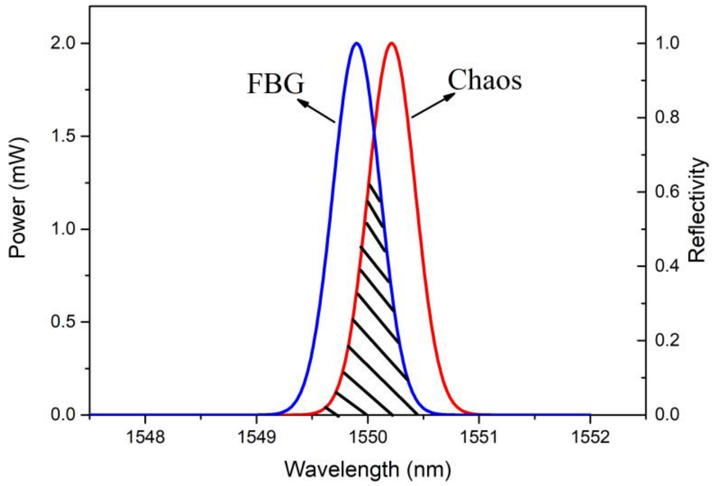


Fig. 3. Spectrum of chaotic laser and reflected spectrum of FBG.

FBG is equivalent to a narrow band filter, one part of the light is back-reflected and the other is forward-propagated. The partially back-reflected of the chaotic laser induces the transmission loss of the chaotic laser when the chaotic laser is injected into the fiber loop cavity. The shadow area shown in Fig.3 is related to the transmission loss of chaotic laser which is incurred by FBG in the fiber loop, and the formulation of the loss B can be expressed as:

$$B = \frac{\int_{-\infty}^{\infty} R(\lambda)P(\lambda)d\lambda}{\int_{-\infty}^{\infty} P(\lambda)d\lambda} \tag{1}$$

Substituting mathematical expressions of $P(\lambda)$ and $R(\lambda)$ into Eq. (1) and integrating the results over wavelength, we can obtain:

$$B = R_B\sqrt{\frac{\alpha_1^2\alpha_2}{\alpha_1+\alpha_2}}\exp[-\frac{(\lambda_0-\lambda_B)^2}{\alpha_1+\alpha_2}]. \tag{2}$$

$$\Delta\lambda_B = \eta\lambda_B \bullet \Delta T. \tag{3}$$

Where η is the temperature sensitivity coefficient of the FBG, ΔT is the change of temperature. The central wavelength of FBG shown in Eq. (3) would change when the temperature change. Thus the transmission loss B also changes and it cause the change of the autocorrelation coefficient ring down time in the fiber loop cavity. The ring down time τ of chaotic correlation coefficient for the sensing system is given by [37]:

$$\tau = \frac{nL}{c(A+B)}. \tag{4}$$

Where n, L, c and A are fiber refractive index, fiber loop length, light speed in vacuum and inherent loss of fiber loop, Substituting Eq.(2) into Eq.(4) and the ring down time is:

$$\tau = \frac{nL}{c} \bullet \frac{1}{A + R_B\sqrt{\frac{\alpha_1^2\alpha_2}{\alpha_1+\alpha_2}}\exp[-\frac{(\lambda_0-\lambda_B)^2}{\alpha_1+\alpha_2}]}. \tag{5}$$

The relationship between ring down time (τ) and central wavelength (λ_B) shift of FBG incurred by temperature is established.

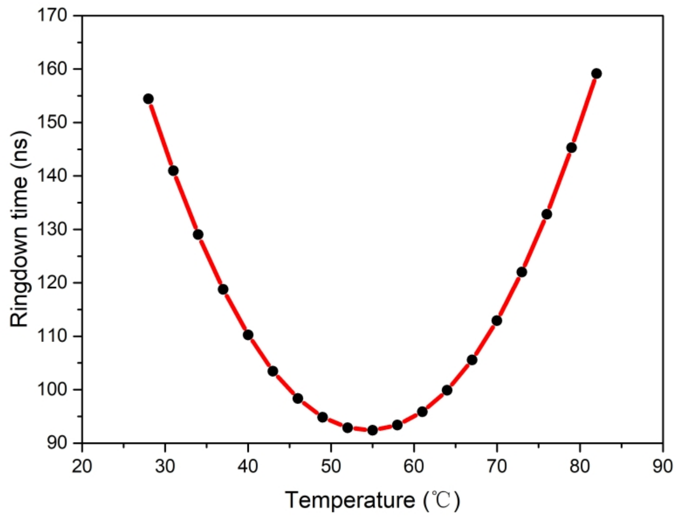
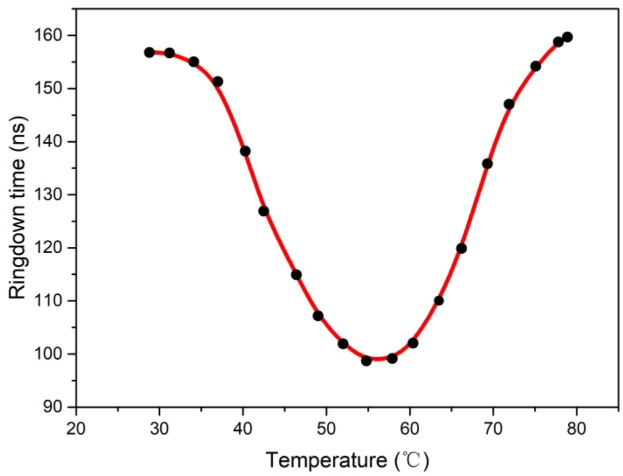


Fig.4. The simulation of the ring down time with the change of temperature.

In order to verify the feasibility of the sensing approach, the simulation of the sensing system is carried out. The central wavelength and peak power of chaotic laser is set to 1550.21nm and 2mW respectively. The central wavelength of FBG and the peak reflectivity are taken to 1549.950nm and 12% respectively. Take the length of fiber loop L=6.05m and fiber refractive index n= 1.464 for the simulation. The central wavelength of FBG is changed at the interval of 0.03nm according to the Eq. (5). Fig.4 shows the relationship between the ring down time and temperature. According to the Eq. (3) and (5), the temperature measurement and the change of central wavelength of the FBG can be achieved simultaneously by the ring down time of autocorrelation coefficient.

3. Experimental results and discussion

In the experiment, the laser wavelength was tuned to 1550.21nm, which is 0.26nm away from the central wavelength of FBG. A thermo-tank with the highest operation temperature of 300℃ and the resolution of 0.1℃was used to control temperature of FBG, the FBG was placed loosely in the thermo-tank to ensure no bend and strain on FBG, meanwhile there is an electronic thermometer to monitor the actual temperature of FBG. Fig.5 (a) shows the ring down time of autocorrelation coefficient vary as the temperature and it indicates the variation process of overlap area of spectrum of FBG and chaotic laser. The temperatures is set in the range of 28.8℃-78.9℃. The ring down time of autocorrelation coefficient varied from 156.71ns to 98.72ns and back to 158.75ns corresponding to increase of temperature. The ring down time approximately is a constant when temperatures were lower than 34.1℃ and higher than 77.8℃ due to there is no interaction between FBG and chaotic laser. Fig.5(b) shows the response of temperature sensor in range of 34.1℃-52℃, the sensor presents a good linear response to the change of temperature and the sensitivity is 3.23ns/℃. Fig.5(c) shows the response of temperature sensor in range of 60.4℃-77.8℃ and the sensitivity of 3.52ns/℃. A gap between the two fitted intervals is attributed to the excessive optical loss caused by FBG [24]. Fig.5(b) and (c) show the temperature sensor has the operation scope of 35.3℃ approximately. The ring down time at each temperature mentioned above was the average of five events and the measurement was performed after each individual temperature was stable. The error bars of the five events are shown in the Fig.5 (b) and Fig.5(c) and the standard deviation of the ring down time measured is kept within 2 ns. This indicates the fiber loop ring down sensing system has great stability. The sensing system can have different temperature measurement regions when the chaotic laser wavelength is set to other values.



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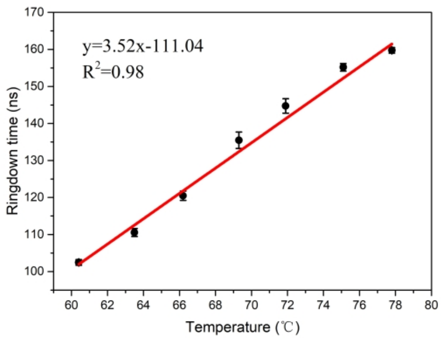

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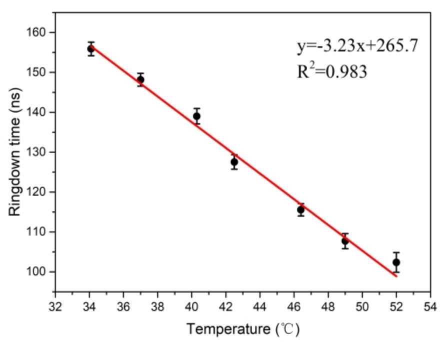


(c)

Fig.5. Ring down time versus temperature. (a) The change of ring down time in 28.8℃-78.9℃. (b) The change of ring down time in 34.1℃-52℃. (c) The change of ring down time in 60.4℃-77.8℃.

In order to evaluate the repeatability of the experiment, we carried out the temperature measurement at five different times, the error bars of measurements are shown in Fig.6. The standard deviation of ring down time was kept within 2ns, it shows that the sensing system has good repeatability.

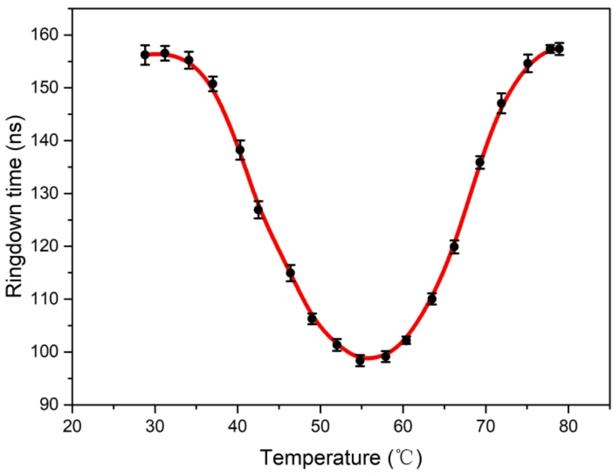
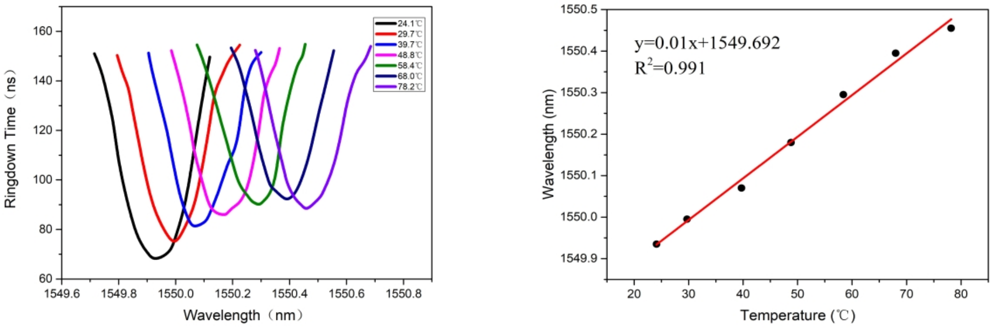


Fig.6. The results of five experiments at different times

We further demodulated the central wavelength of FBG at different temperatures through the change of the ring down time. Under the condition of invariable in the temperature, the dependence of ring down time versus wavelength of chaotic laser can be obtained by tuning the wavelength of chaotic laser with a step of 0.02nm. The temperature is changed from 24.1℃ to 78.2℃, we can obtain the relationship between the ring down time of autocorrelation coefficient and the wavelength of chaotic laser at different temperature shown in Fig.7(a). The results show that these curves have the same FWHM and the lowest point of each curve is different due to the shape of reflection spectrum of FBG changing with increasing temperature. The wavelengths corresponding to the lowest point of each curve represents the central wavelength of FBG at the temperature at the moment. The central wavelength of FBG is then plotted as a function of temperature shown in Fig.7(b), and the fitted line has a slope of 0.01nm/℃ which is consistent with theoretical value.



(a) (b)

Fig.7. (a) The curves of ring down time respect to chaotic wavelength at different temperatures; (b) Central wavelength of FBG versus temperature.

4. Conclusions

A chaotic correlation fiber loop ring down temperature sensor is reported. The sensing system uses chaotic laser as the input of the fiber loop cavity, a FBG as the sensing unit and the ring down time of autocorrelation peak of chaotic light as the sensing parameter. This proposed technique significantly simplifies the section of light source of sensing system and allows a shorter length of fiber loop. The temperature measurement results show a good linear response and demonstrate a sensitivity of 3.52ns/℃, and the temperature sensitivity of FBG is 0.01nm/℃ was attained. This new approach of FLRD system should be useful in practical temperature sensing application.

Acknowledgments

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