Thermal Modulation of a Chaotic Fiber Laser by Using a Phase-Shifted Fiber Bragg Grating

Zhanwu Xie, Wenlong Zeng, Pengfei Li, Haitao Yan, and Daofu Han

***Abstract*—Thermal modulation of a chaotic fire laser by using a phase-shifted fiber Bragg grating (PS-FBG) is proposed. In this chaotic laser system, a double-ring resonator model is employed, leveraging the laser self-mixing method. Specifically, one of the rings serves as the laser resonator cavity, while the other ring acts as the cavity for injecting optical feedback. A PS-FBG is setting in the laser resonant optical path to select and limit the dominant frequency of laser signals. The laser system enters chaotic state through adjusting the intensities of optical feedback self-mixing. The temperature of the PS-FBG can be changed at 26–70 °C in stepping of 0.5 °C to control the chaotic laser. According to the experimental results, the chaotic signal has a highly sensitive dynamic response to the temperature change of PS-FBG. An easy method for dynamic modulation changes of chaotic laser signal is provided, the system has great potential application value in the FBG sensing, optical storage and information transfer of chaotic laser communication.**

***Index Terms*—Chaotic fiber laser, phase-shift fiber Bragg grating, thermal modulation.**

I. Introduction

Chaotic laser has received great attention in recent years due to its potential applications in chaos-based secure communication [1], chaotic radar [2], chaotic optical sensing [3], [4], random signal generation [5], [6], and chaos computing [7], and so on. Various schemes of optical chaos generation, external-cavity semiconductor lasers (ECSLs) [8], [9] and fiber laser feedback [10], [11] are mostly adopted. Chaotic laser is mainly generated by external light injection [12], optical feedback [13] or photoelectric feedback [14]. The external feedback light can be coherent light, non-coherent interference [15], [16], single feedback or double feedback [17], [18], and the reflection device can be a general plane mirror or grating [19], [20].

The laser can output a modulation variable chaotic state by changing the power of the pump laser or controlling the intensity and phase of the injection light (feedback light), which is still one of the key problems in the application of chaotic fiber laser that the chaotic state of chaotic fiber laser can be easily changed and the key parameters, such as: the bandwidth and time delay of the ghost laser signal can be adjusted. However, signal loading or control of chaotic laser signal is still the key part of chaotic laser transmission system, at present, there is a lack of clear information loading mode and device in the research of chaotic laser. Fiber Bragg grating (FBG) is one of the important passive components in optical communication system [21], [22]. It has the characteristic spectral reflection property, low loss and easy to be inserted into optical fiber system. However, there are few studies on the effective control of chaotic laser signals using the changes in optical properties of FBG.

In this work, the temperature change is used to control the optical characteristics of the phase-shift fiber Bragg grating (PS-FBG), and the PS-FBG modulates the generated signal of the chaotic laser system is proposed. The organic combination of PS-FBG and chaotic fiber laser system is realized. We have analyzed and tested the influence of the signal generated by the fiber grating chaotic laser system, and constructed the relationship between the temperature and the output of the chaotic fiber laser signal. The experimental results show that the chaotic fiber laser signal can be dynamically adjusted by using the reflection characteristics of the temperature modulated PS-FBG. This method provides a simple and low-cost dynamic modulation method for the output of the chaotic fiber laser signal, which makes a meaningful exploration for optical chaotic fiber laser communication, sensing and information processing.

II. Principle of the Chaotic Fiber Laser System

The diagram of chaotic fiber laser system is designed with two rings and shown as Fig. 1. We used a pump (PYOE-SM-976-D-600-0, Pmax is 600 mW, Pout is 78 mW) as seed source, and the output light of the pump incidences a wavelength division multiplexer (WDM). Next, the light through an erbium-doped fiber (EDF), a circulator (CIR) with a PS-FBG, which is placed in the temperature control equipment (DHG-9030A) with accuracy of 0.01 °C. In the experiment, the length of the EDF (OFS-GP980) was approximately 7.8 m. In addition, the polarization controller (PC) and optical coupler (OC) have contributed to the distribution of optical power within the system. Adjusting the PC to stabilize the system's output waveform as a single peak. Then, the light is divided into two parts by OC-1 (10%:90%). The part of 90% light is going into another OC (30%:70%). And

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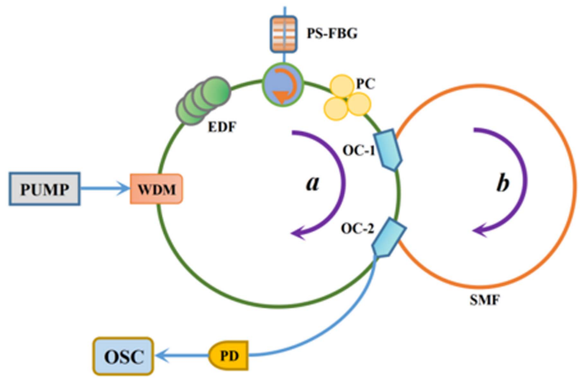

Fig. 1. Diagram of chaotic laser system with two rings.

the 70% light is feedback into the WDM. These optical devices form the first ring-a, which is a stable erbium-doped fiber laser. Another part of 10% light by the OC-1 go into another fiber, and the other end of the fiber connects to OC-2, which is forming the second ring-b. The part of 30% light separated by the OC-2 is converted into an electrical signal by a photoelectric detector (PD). The electrical signal is observed by an oscilloscope (OSC Tektronix DPO 7254C).

According to this system, when light is injected into the first ring-a, the laser will work stably. Then through the action of optical feedback and delay feedback, the system enters the chaotic state. And 30% of the OC-2 optical output is guided to the OSC. Light from ring-a is loaded into the second ring-b through OC-1, then light from ring-b that through delayed feedback is injected into ring-a. It forms a chaotic laser, and it circulates back and forth. We put the PS-FBG in a thermostat, then adjust the temperature of the thermostat. The oscilloscope is used to measure the sequence diagram of the chaotic fiber laser system with different temperatures after the temperature is stable.

Based on the Lang-Kobayashi rate equations [11], if this chaotic fiber laser system has no PS-FBG, it can be represented by a slowly varying electric field E and the average carrier number N, and it can be shown in the following formula:

$$\frac{dE}{dt} = \frac{1}{2}\cdot(1+i\alpha)\left(G(t)-\tau_p^{-1}\right)\cdot E + \eta\cdot E(t-\tau)\cdot\exp\left[-i(\omega\tau+\phi)\right] \quad (1)$$

$$\frac{dN}{dt} = J - N\cdot\tau_N^{-1} - G(t)\cdot|E|^2 \quad (2)$$

where $\alpha = \frac{g(N-N_0)}{1+\varepsilon|E|^2}$ is the optical gain, g represents the small-signal gain coefficient, N_0 represents the threshold carrier number, ε is the saturation coefficient. $G(t)$ is the gain coefficient, τ_p is the photon lifetime, η is the feedback strength, τ is the time-delay signature of optical feedback, φ is the phase of the laser field, J is the injection carrier rate and τ_N is the carrier lifetime.

The PS-FBG has a very narrow spectral linewidth, which can reduce the link noise and make it easier to realize the conversion of optical and electrical signals. Since the PS-FBG adds optical feedback in the first ring-a, the amount of phase shift, reflection coefficient and central reflection wavelength of PS-FBG all affect the (1) above. We set the phase shift amount to φ_0, the reflection coefficient to η_0, the central reflection wavelength to λ_0 of the PS-FBG. The time-delay signature of the reflection of the center wavelength λ_0 is the $\tau(\lambda_0)$, so the (1) can be revised as:

$$\frac{dE}{dt} = \frac{1}{2}\cdot(1+i\alpha)\left(G(t)-\tau_p^{-1}\right)\cdot E + \eta_0\cdot\eta\cdot E\left(t-\tau-\tau(\lambda_0)\right)\cdot\exp\left[-i(\omega\tau+\varphi+\varphi_0)\right] \quad (3)$$

In addition, if we just take the effect of temperature change on center wavelength into consideration, the variation of the wavelength of the FBG can be expressed as (4),

$$\frac{\Delta\lambda}{\lambda_0} = (\alpha+\xi)\Delta T \quad (4)$$

where λ_0 is the center wavelength of PS-FBG, $\Delta\lambda$ is the change of the center wavelength, α is the thermal expansion coefficient of the fiber material, ξ is the thermal optical coefficient of the fiber, and ΔT is the temperature variation.

At this point, the variation of wavelength $\lambda(T)$ with temperature can be substituted into the (3) to replace the steady-state center wavelength λ_0.

Therefore, when the ambient temperature of the PS-FBG changes, the chaotic state of the chaotic fiber laser will be changed, and the output signal will be changed accordingly. In order to obtain the spectral signal variation of chaotic fiber laser, the self-correlation function [23] is used to analyze the signal of this system, which is shown as follows:

$$C(\Delta t) = \frac{\langle(I(t)-\langle I(t)\rangle)\rangle\langle(I(t+\Delta t)-\langle I(t+\Delta t)\rangle)\rangle}{\sqrt{\left\langle(I(t)-\langle I(t)\rangle)^2\right\rangle\left\langle(I(t+\Delta t)-\langle I(t+\Delta t)\rangle)^2\right\rangle}} \quad (5)$$

In the (5), I(t) is the intensity of output light for the chaotic fiber laser system and $I(t)=|E(t)|^2$, Δt is the delay time $I(t+\Delta t)$ relative to $I(t)$, and $\langle\cdot\rangle$ means averaging over time.

III. Experimental Measurements and Discussion

In the chaotic fiber laser system, the length of fiber in ring-b is 1 meter (including 1 m SMF28e optical fiber, the OCs input and output length of 1 m, a total of 3 m), and the PS-FBG is placed in the reflex circuit of ring-a. The PS-FBG has a center wavelength of 1550.012 nm, a 3-dB bandwidth of 1.1456 nm, an adjacent side-mode suppression ratio of approximately 16 dB, reflectivity greater than 99.9%, and a linewidth of 210 MHz. To verify the stability and reliability of this system, we use an optical spectrum analyzer (OSA, AQ6370D) to test the output light of the 30% of the OC-2, and the optical spectrum can be recorded and observed. We conducted the test in the temperature range of 26–70 °C in stepping of 0.5 °C. Fig. 2(a) shows the system output waveform at different temperatures with the different temperature, and the center wavelength is 1549.8006 nm, 1549.8817 nm, 1549.9655 nm, 1550.0500 nm, 150.1311 nm, 1550.2146 nm, and 1550.2641 nm at 26 °C,

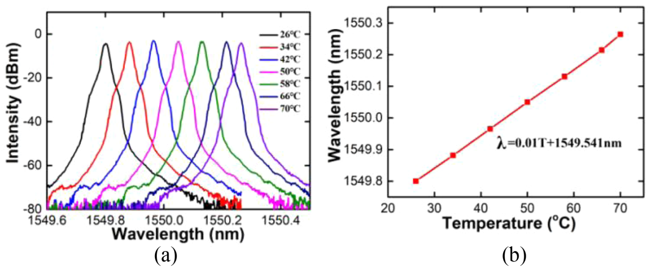

Fig. 2. (a) System output waveform at different temperatures. (b) the fitting linear relationship.

34 °C, 42 °C, 50 °C, 58 °C, 66 °C and 70 °C, respectively. The center wavelength is red-shifted with the temperature increasing, and the waveform profile of PS-FBG central wavelength is almost no change. The fitting linear relationship between the center wavelength of system output waveform and temperature is shown as Fig. 2(b). There is a good linear relationship between the shift of the center wavelength and the temperature variation. The above results prove the stability and reliability of this chaotic fiber laser system.

As is shown in Fig. 1, we used a PD and an OSC instead of optical optical spectrum analyzer to record the electrical signals of the above information. The data underwent self-correlation processing, resulting in time sequence diagrams, autocorrelation plots, and phase portraits at different temperature conditions. The results are depicted in Fig. 3.

It can be observed in Fig. 3 that the chaotic laser output state of the system is changed obviously at different temperatures. At 26 °C, the system entered a chaotic state, the sequence diagram is disorganized, the corresponding self-correlation graph is a comb-shaped function similar to the Delta function. And the phase diagram represents the attractor graph, which shows the form of infinite outward expansion. At 34 °C, the self-correlation diagram and phase diagram are similar to those at 26 °C, but the attractor trajectories and the period of self-correlation graph are different. The amount of information contained in the system is different at different temperatures. That has a great impact on information storage and communication sensing. It can be seen from 42 °C, 50 °C, 58 °C and 66 °C that the graph further verifies the previous statement. Different temperatures contain extremely rich data, and the temperature can be used as signal uploading device or a secret key for chaotic secure communication, which has a good prospect in chaotic communication system. The timing chart of the above experimental structure also shows that, there is a process for the steady state to change into chaotic state, and our experiment is just in this process. Beyond this range, the disturbance will be large, and this chaotic laser system can be kept in chaotic state. At 70 °C, it is observed that the timing diagram of the system is in a period-like state and the attractor moves towards a certain point inside the ellipse. So the temperature variation of PS-FBG to control of chaotic laser is realized.

We randomly selected two groups of temperatures, 38.5 °C and 44.5 °C, and only increased by 0.1 °C of PS-FBG. Through further calculation, we obtain two groups of chaotic laser signal

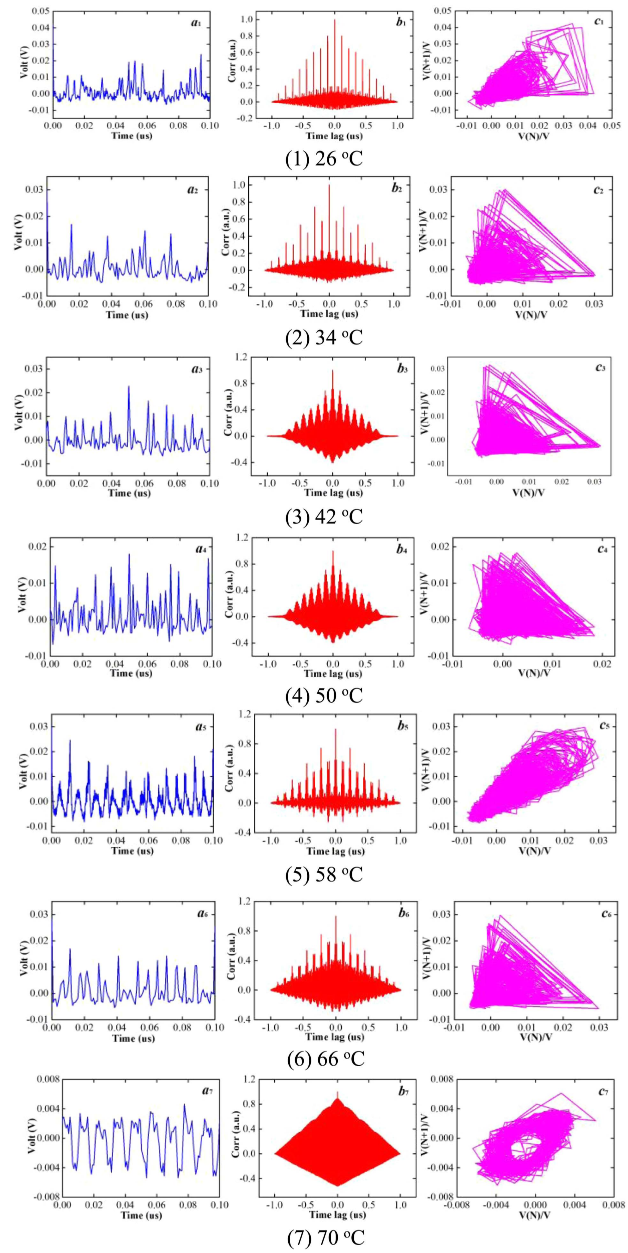

Fig. 3. Equence diagram, self-correlation diagram, and phase diagram with different temperature.

diagrams. The results are shown in Fig. 4. The two groups of temperature data are listed, which are 38.5 °C and 38.6 °C (Fig. 4(1a) and (1b)), 44.5 °C and 44.6 °C (Fig. 4(2a) and (2b)), respectively. According to the experimental results, when the temperature is only changed by 0.1 °C, the chaotic laser signal is corresponding to the small increase. Compared with the initial state in the Fig. 4(1a) and (2a), the state of the chaotic fiber laser system has great changes in the Fig. 4(1b) and (2b). A higher filling factor indicates a more dispersed system state and a stronger chaotic nature. It is shown that the chaotic laser signal generated by our system has a discriminable and highly sensitive dynamic response to temperature variation.

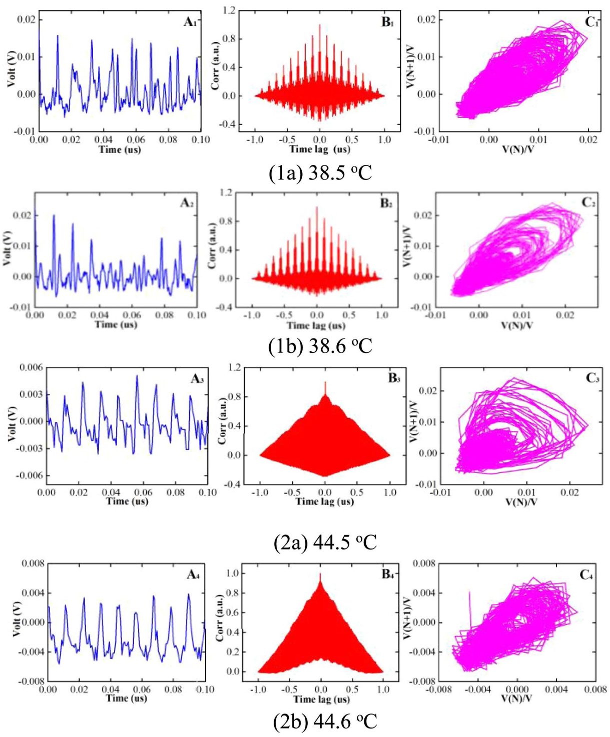

Fig. 4. Equence diagram, self-correlation diagram, and phase diagram with 0.1 °C different temperature of PS-FBG.

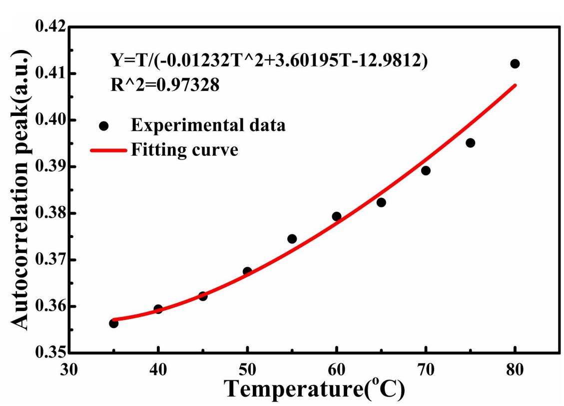

Fig. 5. Variation of the peak value of the autocorrelation peak with temperature.

In order to analyze the influence of changed temperature of the PS-FBG with the chaotic signal. We tested and collected the laser chaos signal at 35–80 °C with a step size of 5 °C, and computationally acquired the correlation diagram. The fourth correlation peak from $\Delta t = 0$ in the autocorrelation diagram is selected, we performed curve fitting to the temperature and correlation coefficients. The result is shown in Fig. 5.

As can be seen in the Fig. 5, the peak of the fourth autocorrelation peak shows an upward trend with the temperature increased, it shows that the autocorrelation peak of the chaotic signal increases with the temperature of the environment of the PS-FBG. The increase of the peak value indicates the similarity of the chaotic signal between the preceding and posterior cycles, that is, the complexity of the chaotic signal decreases. The reason is that when the temperature changes, causing the drift of the PS-FBG center wavelength, making the center wavelength drift of the PS-FBG, thus the phase information changes in the transmission light path, which will lead to the delay and dispersion in the whole link. Thus, the chaotic signals detected by PD also contain different information.

Temperature is the basic parameter for any environment, because of the uniqueness of temperature, the system's chaotic laser has a positive influence on the sensing, storage and expression with temperature information. So we plan to further research the practical application of chaotic lasers, such as synchronization chaos, communication secret key, etc.

IV. Conclusion

In this paper, an easy modulation of a chaotic laser signal by PS-FBG with changed temperature variation had been proposed and demonstrated. The signal output during the temperature process of 26–70 °C in stepping of 0.5 °C has been explored. According to the experimental results, the chaotic laser signal is obviously occurred modulation changes with the changed temperature of PS-FBG, a change 0.1 °C of PS-FBG can lead to a strong change of the chaotic laser system signal. At this point, it can be considered that the next chaotic period has just arrived. It proved that this chaotic fiber laser system had a discriminable and highly sensitive dynamic response to the temperature change of PS-FBG, and thermal modulation of a chaotic fiber laser by using a PS-FBG is provided, which brings uploading method and device of chaotic laser signal. The system has great potential application value in the sensing, optical storage and information transfer of chaotic laser communication.

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