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Two chaotic synchronizations in er-doped fiber lasers and their application in two-channel coding secure communications

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Abstract. A dual-ring erbium-doped fiber laser has nonlinear dynamic characteristics based on optical coupling interaction of lasing from the two laser rings and can send chaotic lasing to encode and mask an information to perform secure communication. Two independent groups of single-ring erbium-doped fiber lasers and a dual-ring erbium-doped fiber laser are used to construct two-channel chaos secure communication system while the synchronization's physical mathematical model is presented by using the "active-passive" chaotic synchronization method, where a dual-ring erbium-doped fiber laser is used as a transmitter and two independent groups of single-ring erbium-doped fiber lasers are used as two receivers. Our numerical simulation shows that these two receivers can synchronize with the transmitter respectively. A two-channel chaotic hidden encoding secure communications with a modulation frequency of 10kHz analog signal and a rate of 20kbit/s digital signal are numerically simulated respectively, which shows to have good decoding quality and strong security. The obtained result shows that the chaotic coding system can be well applied in chaotic two channel secure communications. The research results have an important reference value for optical multi-channel secure communication and network security.

1 Introduction

Chaos is a universal natural nonlinear phenomenon. Its basic characteristics are that it is very sensitive to initial conditions, its dynamics and change are random, and its long-term behaviour cannot be predicted [1-3]. At present, chaos and its coding have been used for secure communication [4-7]. Since Pecora and Carroll put forward "driving-response" chaotic synchronization method in the 1990s [1], chaos synchronization theory and its coding have developed rapidly. Chaos synchronization and its application in secure communication research presents exciting prospects [4-7].

At present, an erbium-doped fiber, as a mature laser source and optical amplifier, has been widely used in many fiber communication systems. As the metastable lifetime of erbium ions is 1-10ms and the power density of the fiber core is high, the laser can

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transition from continuous working state to self-pulsating or chaotic state. F. scancheez, et al. observed this nonlinear dynamic phenomenon and established a theoretical model of the two-coupled laser [4]. As chaotic laser synchronization is an important aspect of chaos laser research, especially its potential value in the field of optic secure communication, it has attracted great attention from people [5, 6]. Therefore, the research on chaotic laser synchronization of fiber lasers has attracted people's attention [4-7].

At present, the chaos synchronization of fiber lasers is mainly based on the "drive-response" synchronization method. In reference [2], the "drive-response" method is applied to realize the chaos synchronization of the dual-ring erbium-doped fiber lasers with two response systems with pulse modulation. Reference [5] shows that the synchronization of the chaos system of a group of dual-ring erbium-doped fiber lasers is realized. We presented that the "cross injecting reverse phase double ring active-passive" chaotic synchronization method and realized the two sets of independent erbium-doped fiber ring laser synchronizations with a dual-ring erbium-doped fiber laser [3, 5, 7].

This paper will present a "two-ring-two-ring 'active-passive'" chaotic synchronization method and put forward an "active-passive" chaotic erbium-doped fiber ring laser synchronization system. We can realize that the chaotic synchronizations of two sets of independent single-ring erbium-doped fiber laser with the dual-ring erbium-doped fiber laser. Then, a "two-ring-two-ring" chaotic hidden coding system is proposed for two channel secure communications.

2 The synchronous system and theoretical model

2.1 Model

The dual-ring erbium-doped fiber laser is composed of two coupled single-ring erbium-doped fiber lasers via using an optic coupler C_0, and its basic structure is shown in figures 1 and 2, where two optic wavelength division multiplexers (WDM) are used for pump input $I_{pa,b}$ and signal output $E_{a,b}$ form two laser rings a and b. The laser physics mode can be considered to simplify as a two-level laser system. Because of π /2 phase change showing after the laser' lasing passes through the optical coupler, the normalized inversion particle numbers and the dynamic behaviours of the output fields can be described as [4-7]:

$$\frac{d}{dt}E_a = -k_a(E_a + \eta_0 E_b) + g_a E_a D_a \tag{1}$$

$$\frac{d}{dt}D_a = -\left(1 + I_{pa} + E_a^2\right)D_a + I_{pa} - 1 \tag{2}$$

$$\frac{d}{dt}E_b = -k_b(E_b - \eta_0 E_a) + g_b E_b D_b \tag{3}$$

$$\frac{d}{dt}D_b = -\left(1 + I_{pb} + E_b^2\right)D_b + I_{pb} - 1 \tag{4}$$

where D_a and D_b are the particle numbers of the two laser rings a and b, respectively. g_a and g_b are the gain coefficients of two laser rings respectively. k_a and k_b are the loss coefficients of two laser rings, respectively. η_0 is the coupling coefficient of the optical coupler. The nonlinear dynamic behavior of dual-ring erbium-doped fiber laser is mainly caused to produce chaos by the nonlinear coupling effect of the coupling term of two laser rings. Therefore, aiming at this dynamic characteristic, then, a chaos synchronization system of “two-ring to two-ring ‘active-passive’” is proposed. Its two “passive” subsystems are composed of two independent single-ring erbium-doped fiber lasers. They have the same parameters as the ring a of the “active” system. The specific structure is shown in figure 2. The laser ring b of the “active” system injects into the ring a_i and the ring a_j of the "passive" system to obtain synchronization between the ring a of dual-ring erbium-doped fiber laser and two rings r_i and r_j. Thus, two groups of “two-ring-two-ring ‘active-passive’” chaotic synchronization system is composed of laser systems and device structures shown in figures 1 and 2. The dynamic behaviour of laser ring a_i of the “passive” system can be described by the following equation:

$$\frac{d}{dt}E_{ai} = -k_a(E_{ai} + \eta_0 E_b) + g_b E_{ai} D_{ai} \tag{5}$$

$$\frac{d}{dt}D_{ai} = -\left(1 + I_{pa} + E_{ai}^2\right)D_{ai} + I_{pa} - 1 \tag{6}$$

The dynamic behaviour of laser ring a_j of the “passive” system can be described as:

$$\frac{d}{dt}E_{aj} = -k_a(E_{aj} + \eta_0 E_b) + g_b E_{aj} D_{aj} \tag{7}$$

$$\frac{d}{dt}D_{aj} = -\left(1 + I_{pa} + E_{ai}^2\right)D_{aj} + I_{pa} - 1 \tag{8}$$

In fact, when there is no external chaotic laser injection, the laser output of the two independent single-ring erbium-doped fiber laser does not show any chaotic phenomenon, but it moves in a fairly stable state. Here, the “passive” laser subsystem in the stable state is driven to the chaotic state by the “active” chaotic system and finally realizes the chaotic synchronization with the “active” system. The “passive” subsystem rings ai and aj will achieve chaos synchronization with the “active” system ring a respectively, that is, two groups of independent single-ring erbium-doped fiber laser as two receivers can obtain two chaotic synchronizations with the dual-ring erbium-doped fiber laser as a transmitter.

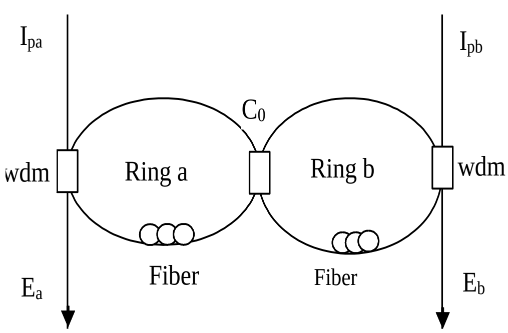


Fig. 1. The transmitter based on a erbium-doped fiber dual-ring laser as “active system”. I_{pa} and I_{pb} are pump light, C_0 coupler, wdm is the wavelength division multiplexer, E_a and E_b lasing fields output from ring a and ring b, respectively.

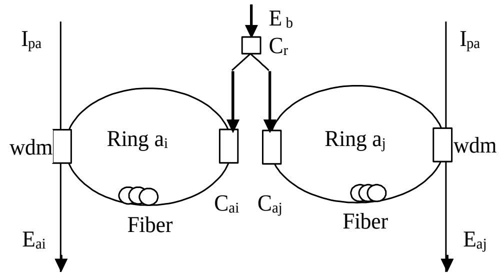
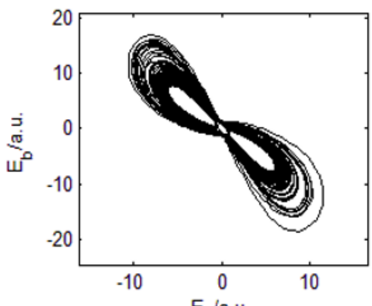


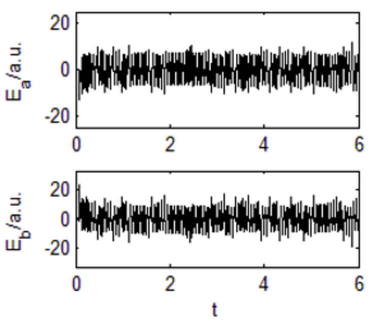
Fig.2. The two receivers based on two independent erbium-doped fiber ring lasers as "passive subsystems". C_r, Cai and Caj are the couplers, E_{ai} and E_{aj} lasing fields output from ring b_{ai} and ring a_j, respectively. E_b lasing field output from ring b.

2.2 Synchronization result

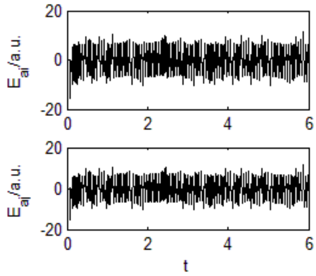
Due to the nonlinear coupling effect of coupling terms in dual-ring erbium-doped fiber laser, the laser field dynamics can show chaos under certain conditions. The parameters of laser system are listed as: The normalized parameters of the laser system set as I_{pa}=4, I_{pb}=4.1, k_a=k_b=1000, η_0=0.22, g_a=4750, g_b=10500, and time unit presents ms. Figure 3 shows that the transmitter outputs, and the transmitter synchronizes with two receivers. Figure 3 (a) is that the transmitter laser shows a chaotic attractor, which means the dual-ring erbium-doped fiber laser moves in a chaotic state. Figure 3 (b) shows that two laser rings of the transmitter ouput two chaotic lasing, these laser are used as a chaotic carrier and a drive lasing. The chaotic carrier can be used to encoding an information and the drive lasing is used to drive two receivers to obtain synchronization between the transmitter' ring a and laser ring a_i and laser ring a_j of two receivers, respectively. Figure 3 (c) shows two lasing waveforms from two ring a_i and a_j of the receivers. We find that two lasing waveforms from two ring a_i and a_j show the same change behaviour as that of the transmitter' ring a after 1 ms. Which implies that two chaotic synchronizations have realized between the transmitter' ring a and laser ring a_i and laser ring a_j of two receivers, respectively. Figure 4 (c) shows two chaotic synchronizations between the transmitter' ring a and laser ring a_i and laser ring a_j of two receivers after 1 ms, where (E_a-E_{ai})=0 after 1 ms. The result of the our calculation is that (E_a-E_{ai})=0, (E_a-E_{aj})=0 and (E_{ai}-E_{aj})=0 after 1 ms, which implies that two chaotic synchronizations have realized between the transmitter' ring a and the laser ring a_i and laser ring a_j of two receivers, and another chaotic synchronization has realized between two laser ring a_i and laser ring a_j, where insets show E_a=E_{ai} and E_{ai}=E_{aj}.



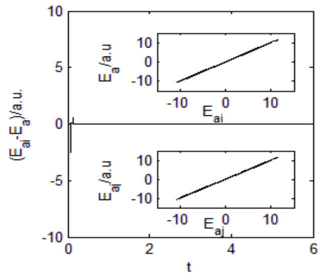
(a) Chaotic attractor



(b) Laser' rings a and b output, respectively.



(c) Ding ai and ring aj output, respectively.



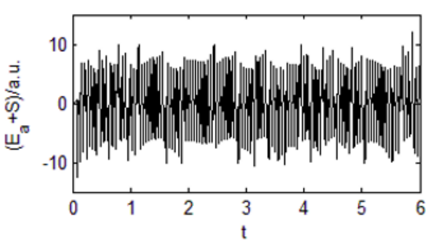
(d) Synchronization

Fig. 3. The transmitter output, two receivers output, and the transmitter synchronizes with two receivers.

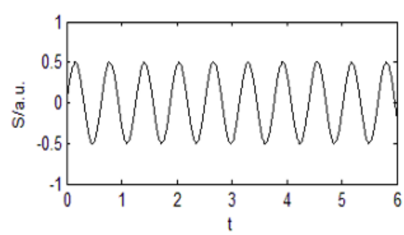
3 Coding and secure communications

We know that the laser chaotic attractor is composed of infinite dense and different phase space trajectory. It is found the performance of the laser chaotic wave with the characteristics of complex disorder and randomness. And its long time behaviour is not predictable, and its signal has a wide spectrum like noise. The above chaotic features are used I chaotic secure communication.

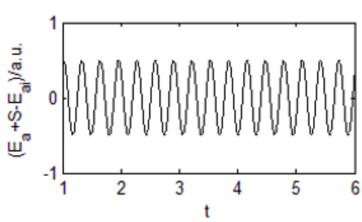
Here, a two-ring-two-two chaotic hidden coding system for two-channel secure communication is constructed, and its basic structure is very similar to the synchronous system based on the system shown in figures 1and 2. And the transmitted information S(t) is directly added to the chaotic carrier E_a, and the modulated information is emitted together with the chaotic carrier, that is, the modulated formation is hidden in the chaotic wave, so it is difficult to separate the information from the chaotic waveform when the outside world does't understand the laser parameters as secret agreements. When the receiver and transmitter achieve their chaotic synchronization, the information signal S(t) can be demodulated by subtraction.



(a) A chaotic wave maskes an inforamation.



(b) An inforamation signal.

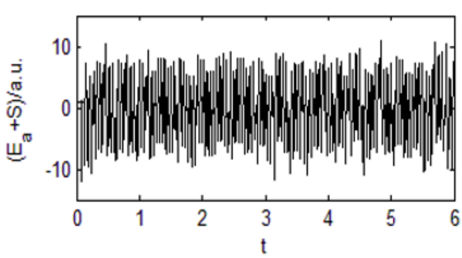


(c) Synchronization demodulatiom.

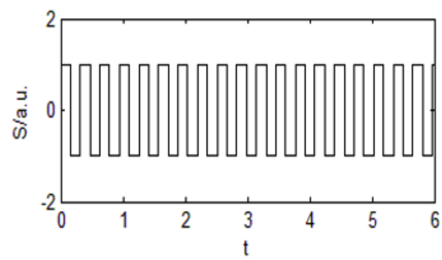
Fig. 4. Chaotic coding for secure communication.

When the ring a_i is used as the receiver, and the sinusoidal signal S(t) is used to directly add to the chaotic wave E_a to be modulated to transmit to the receiver a_i. As such an analog signal secure communication can realize. This coding result shows in figure 4, where the amplitude of the analog signal sets as the value 0.1 and its frequency set as the value 1.59 kHz. Figure 4 (a) shows that the analog signal hides in the chaotic wave E_a. We find that the chaotic carrier masks the information signal so that the outside personnel is indecipherable for this communication. So this system can be used for secure communication to enhance communication security. Figure 4 (b) shows a modulated information signal. Figure 4 (c) shows a result of synchronization demodulation using subtraction, this is, $(E_a+S-E_{ai})=S+E_a-E_{ai}=S$. In this way, the encoding and decoding of chaos hiding of an analog signal is achieved in this channel secure communication.

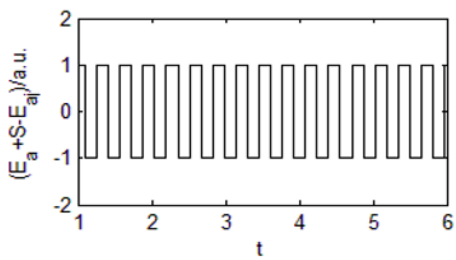
When the ring a_j is used as the receiver, and a digital signal S(t) is used to be modulated to directly add to the chaotic wave E_a to transmit to the receiver a_j. Such a digital secure communication in another channel can be performed. The result of a chaotic digital encoding and decoding is shown by figure 5, where a digital information signal rate is 20kbit/s and its amplitude shifts in the value 1 or 0. Figure 9 (a) shows a digital signal hiding in the chaotic wave E_a. Due to the chaotic carrier masking the information signal, the outside personnel is indecipherable for this communication. So this system can be used to enhance communication security. Figure 9 (b) is the information signal. Figure 9 (c) shows that an demodulated information signal by subtraction, this is, $(E_a+S-E_{aj})=S+E_a-E_{aj}=S$. In this way, the encoding and decoding of chaos hiding of a digital signal is achieved in this digital secure communication channel.



(a) A chaotic wave maskes an inforamation.



(b) An inforamation signal.



(c) Synchronization demodulatiom.

Fig. 5. Chaotic digital coding for secure communication.

4 Conclusion

This article applied “two-ring–two-ring ‘active-passive’” chaotic synchronization method, realized two sets of independent single-ring erbium-doped fiber lasers synchronizing with a dual-ring erbium-doped fiber laser. The chaotic coding and decoding of the system can be performed successfully. The system can be widely used in a multi-channel chaotic secure communication. And it has an important application value for information security and secure communication.

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