Bidirectional High-speed Chaotic Communication System based on an All-optical Time-delay Feedback Loop

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Bidirectional high-speed chaotic communication system based on an all-optical time-delay feedback loop*

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Abstract: In this paper, a bidirectional high-speed chaotic optical communication scheme with physical layer encryption is proposed and studied theoretically. The external cavity optical feedback method is analyzed, an erbium-doped fiber amplifier (EDFA) is used to represent the all-optical delay feedback loop of the traditional external cavity, which can overcome the shortcomings of the traditional method such as lower precision and large equipment volume. And the bidirectional communication scheme is discussed, which just sets the encryption device at the transmitter, uses the correlation between the two encryption signals to decrypt, and cancels the decryption device at the receiver, which not only simplifies the experimental equipment, but also solves the problem that the receiver can't decrypt synchronously due to the channel damage in remote communication, and is easy to be applied in production and life. Finally, the simulation results show that the bit error rate is less than 10^{-5}, the bidirectional transmission of 10Gb/s information over 85km single-mode fiber is successfully realized.

Keywords: Optical chaotic, Time delays, Chaotic optical communication, Optical feedback

1. Introduction

The chaos theory was first proposed by the meteorologist Lorenz in 1963, and then in 1990, Pecora and Carroll [2] proposed and verified the chaos synchronization.

From then on, the chaos theory has been applied in the field of secure communication. In 1998, Van Wiggeren and Roy demonstrated a 10MHz back-to-back chaotic communication system with fiber lasers. In 2005, Argyris[3] et al. carried out field experiments in Athens and realized the encryption transmission rate of 1Gb/s on 120km optical fiber link, which opened a new era in the field of communication and ushered in a period of rapid development of chaotic secure communication. In 2010, Lavrovet[4] successfully realized the secure transmission of 10Gb/s differential phase-shift keying information over 100km optical fiber. In the same year, A.Argyris[5] improved the overall transmission capacity of the system through WDM technology, and achieved a transmission rate of 1.25Gb/s under the condition that the BER was below 10^{-12}.In 2017, Jianzhou Ai et al.[6] successfully transmitted 5Gb/s CAP-4 (carrier less amplitude/phase, Cap-4) signal and 10Gb/s OOK(on-off keying) signal by using a chaotic secure communication system based on the electro-optical time-delay feedback loop. In 2019, Longsheng Wanget realized the all-optical chaotic communication of 10Gb/s messages by enhancing the chaotic carrier bandwidth [7]. In the past two decades, researchers have continuously been proposing new solutions to improve the communication rate and transmission distance, which have been raised to 50Gb/s and 100km respectively.

In this paper, an all-optical bidirectional chaotic communication system based on all-optical time-delay feedback loop is proposed. Firstly, EDFA is designed in the all optical time-delay feedback loop to control the optical path of the external cavity precisely by changing the length of the fiber, which can overcome the traditional method’s disadvantages, such as the angle and length of the external cavity are difficult to be controlled, and then successfully produce chaotic waveforms. Then a bidirectional transmission communication scheme is presented, which can successfully recover the information sent by the other end in the local area. And the decryption equipment at both ends is cancelled, greatly simplifying the experimental equipment. Finally, the simulation results show that the BER is less than 10^{-5}, the bidirectional transmission of 10Gb/s information over 85km fiber can be realized. The performance of the communication system with time delays (TDS) mismatch at the transmitters is studied, which proves that the system has certain anti-interception ability.

2.Theoretical model

In the traditional external cavity optical feedback method (as shown in Fig. 1), the mirror reflects the light generated by the laser back to the active layer of the laser, disrupting the interaction between photons and carriers[8], and producing dynamically unstable chaotic sequence. In this method, the round-trip time of the light on the external cavity is the delay time of the chaotic sequence, but the length and angle of the external cavity are difficult to control, resulting in a larger device volume and higher requirements for device accuracy. Therefore, the traditional external cavity optical feedback method is improved here. An EDFA is used to replace the external cavity, an EDFA and an single-mode fiber are acted as an external feedback cavity. The external cavity can be controlled by changing the length of the erbium-doped fiber [9], which overcomes the disadvantages of the traditional scheme, reduces the demands for the equipment and is conductive to use in production and life.

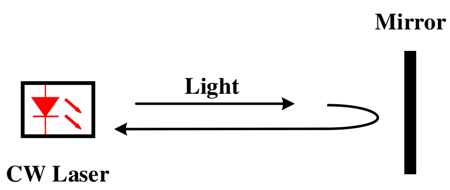

Fig. 1. Traditional external cavity optical feedback method.

In order to improve the traditional external cavity optical feedback method, a bidirectional chaotic communication system based on all-optical time-delay feedback loop is proposed shown in Fig. 2. The all-optical time-delay feedback loop used to generate chaotic signals, which is composed of a tunable delay line, an EDFA and a Bessel band-pass filter. The tunable delay line is matched with EDFA to flexibly adjust the optical path of the feedback loop. The Bessel filter causes the frequency-based phase shift to produce nonlinear signal distortion and minimizes the phase nonlinearity of the passband [9]. The light wave generated by CW Laser2 generates a chaotic signal after repeated iterations in the feedback loop. MZM1 modulates the binary information to be encrypted, the modulated signal is amplified and coupled with the chaotic carrier to complete the encryption operation. The encrypted information is divided into two channels by the beam splitter, one is left locally, and the other one enters the transmission channel through the circulator and is transmitted to the other end. Therefore, the receivers at both ends can receive the synchronous power error P1(t)-P2(t) of the two encrypted information. After taking the absolute value of the error and comparing it with the local information, the message sent by the other end can be recovered. In other words, bidirectional secure communication is realized.

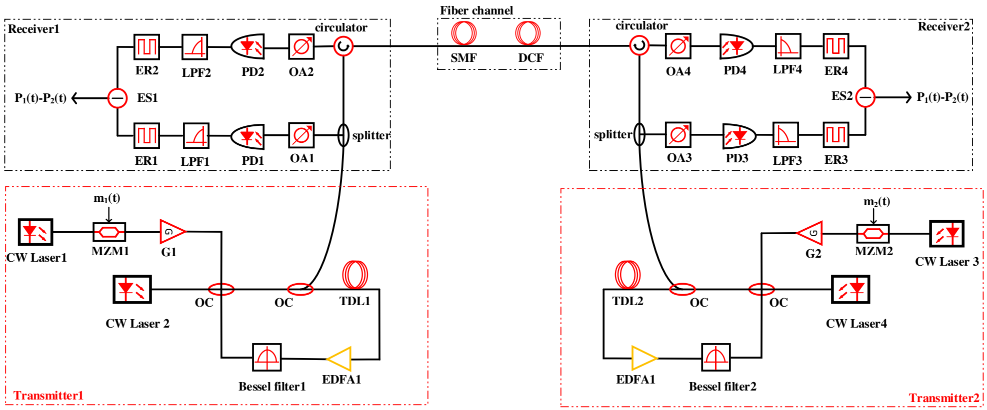

Fig. 2. Schematic diagram of chaotic communication system based on all-optical time-delay feedback loop

CW Laser: continue wave laser，MZM: Mach-Zehnder modulation，OC: optical coupler，TDL: tunable delay line，OA: optical attenuation，LPF: low pass filter，ER: electrical rescale，ES: electrical subtractor，DCF: dispersion compensation fiber.

Referred to the theory model of chaotic dynamics presented by A.R.Volkovskii, the system equations and the rate equation of the standard three-level laser are firstly derived [10] :

$$\frac{dq}{dt} = \left[V_a BN - \left(\frac{1}{\tau_c} \right) \right] q \text{，} \tag{1}$$

$$\frac{dN}{dt} = W_p\left(N_t - N\right) - 2BqN - \frac{N_t + N}{\tau_2} \ , \qquad (2)$$

Where, q is the total number of photons, N is the number of particle inversions, N_t is the total number of particles, τ_2 is the lifetime of high-energy particles, τ_c is the lifetime of photons, and W_p represents the pump. Then, the normalization process is carried out to obtain:

$$\frac{d(2Bq\tau_2)}{d(t/\tau_2)} = \left[V_a BN\tau_2 - \frac{\tau_2}{\tau_c}\right]2Bq\tau_2 \ , \qquad (3)$$

$$\frac{d\left(N/N_t\right)}{d\left(t/\tau_2\right)} = -\left(1 + \tau_2 W_p + 2\tau_2 Bq\right)\frac{N}{N_t} + \tau_2 W_p - 1 \, , \qquad (4)$$

Let $I = 2Bq\tau_2$, $\tau = t/\tau_2$, $D = N/N_T$, $I_P = W_P\tau_2$, and we use g to denote $\tau_2 V_a BN_t$ and k to denote τ_2/τ_c. The simplified formula is as follows:

$$\dot{I}(\tau) = \left[gD(\tau) - k\right]I(\tau) \ , \qquad (5)$$

$$\dot{D}(\tau) = -\left[I_P + 1 + I(\tau)\right]D(\tau) + I_P - 1 \, , \qquad (6)$$

Then, the delay times $\tau_i^{'}$ are introduced into the formula, and considering that the system has two transmitters, the following equations are obtained. The differential equations formed by Equations (7) and (8) are the system equations of the all-optical bidirectional chaotic communication system.

$$\dot{I}_i(\tau) = g_i D_i(\tau) I_i(\tau) - k_i I_i\left(\tau - \tau_i^{'}\right) , \qquad (7)$$

$$\dot{D}_i(\tau) = -\left[I_P + 1 + I_i(\tau)\right]D_i(\tau) + I_P - 1 \, , \qquad (8)$$

The actual meaning of g and k are the loss coefficient and gain coefficient of the system feedback loop. The values of g and k are affected by the pumping intensity, the length and radius of the erbium-doped fiber, and i=1,2 are the subindices of different transmitters. In this bidirectional communication system, the decryption operation is performed by making the difference between the synchronized chaotic signals generated at both ends. Therefore, the encrypted bidirectional information transmission can be realized only when the hardware parameters of the two transmitters are perfectly matched.

The system performance was analyzed in the Optisystem software. Taking Transmitter1 as an example, the parameter values are selected. In order to make the simulation process have more practical reference value, the transmitting power of CW Laser1 is set as -70dBm, which is easy to achieve in practice, and the center frequency of the generated light wave is 1550nm. However, the transmission power of CW Laser2 should not be too large or too small. If it's too large, the information cannot be completely covered by chaotic signals, and if it's too small, useful information will be annihilated during long-distance transmission. Here, the value of CW Laser2 is set as -10dBm, and an amplifier with gain of 30dB is used to amplify the modulated light wave. In the all-optical time-delay feedback loop, the delay time of the total loop is set as 103ns. In order to realize encrypted bidirectional information transmission, chaotic signals on both sides must be synchronized, so Transmitter2 adopts the same parameters as Transmitter1, which will not be described here.

3. Results

It can be seen from Fig. 3, in the case of no information carrying, the signal generated by the transmitter shows chaotic behavior, and the high and low amplitude pulses are followed by each other. The phenomenon happened behind pulsating chaos is the occurrence of population inversion state for specific time and then instant release of energy in the form of chaotic pulse. As the energy stored during population inversion is not fully consumed in a single cycle, the remaining energy acts as a starting point for the next buildup of new pulse and hence the amplitude of every chaotic pulse becomes differently [11], so it generally shows noise-like characteristics and can effectively conceal the information. Thus, the third party can't steal the information at any point between the transmitter and the receiver, which improves the security of the communication system.

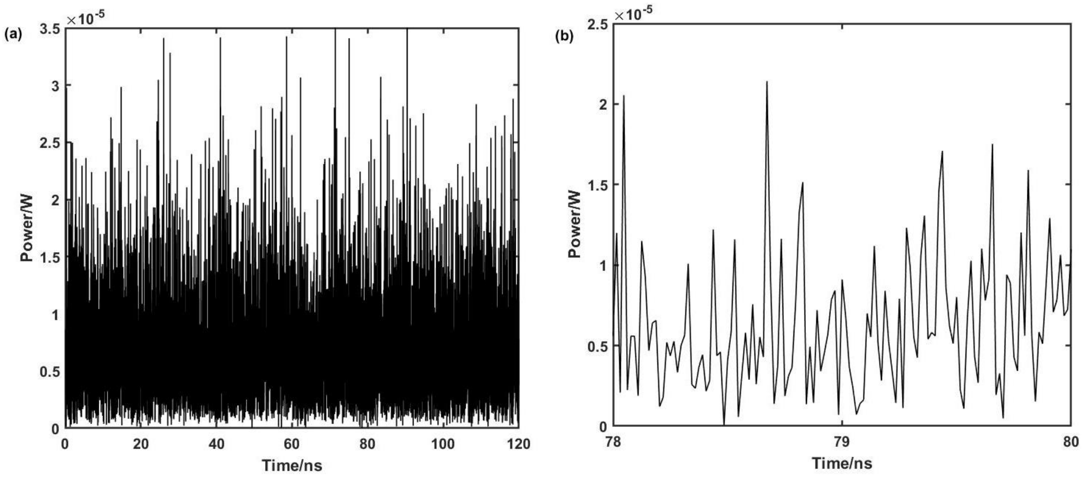

Fig. 3.(a) Chaotic waveform; (b) Zoomed figure of chaotic waveform.

Subsequently, we input two groups of zero-returned binary information m_1 and m_2 into the system. The introduction of information will disturb the synchronization state of the two transmitters, making the output waveform of both ends constantly switch between synchronous and asynchronous [12]. Only when the same symbols are transmitted at both ends at the same time, the output waveforms can be kept synchronized. If the two ends transmit different symbols, the waveforms at both ends show an asynchronous state. Encrypted information is transmitted to the other end through the channel and subtracted from the local encrypted information to obtain the synchronous power error $P_1(t)$-$P_2(t)$ of the two waveforms. After taking the absolute value of the error, the encrypted information can be recovered by performing the XOR operation with the local information. The specific steps of decryption are shown in Table 1. The time domain diagram obtained during the simulation process is shown in Fig. 4, which is consistent with the theoretical value in Table 1, confirming that the system has the capability of bidirectional transmission.

Table.1. Digital demonstration of decryption steps.

$m_1(t)$	0 1 0 0 1 0 0 1 1 1 0 1 1 1 0 1

$m_2(t)$	0 1 1 1 1 0 0 0 1 0 1 1 0 0 1 0
$\lvert P_1(t)-P_2(t)\rvert$	0 0 1 1 0 0 0 1 0 1 1 0 1 1 1 1
$m_1(t)\oplus\lvert P_1(t)-P_2(t)\rvert$	0 1 1 1 1 0 0 0 1 0 1 1 0 0 1 0
$m_2(t)\oplus\lvert P_1(t)-P_2(t)\rvert$	0 1 0 0 1 0 0 1 1 1 0 1 1 1 0 1

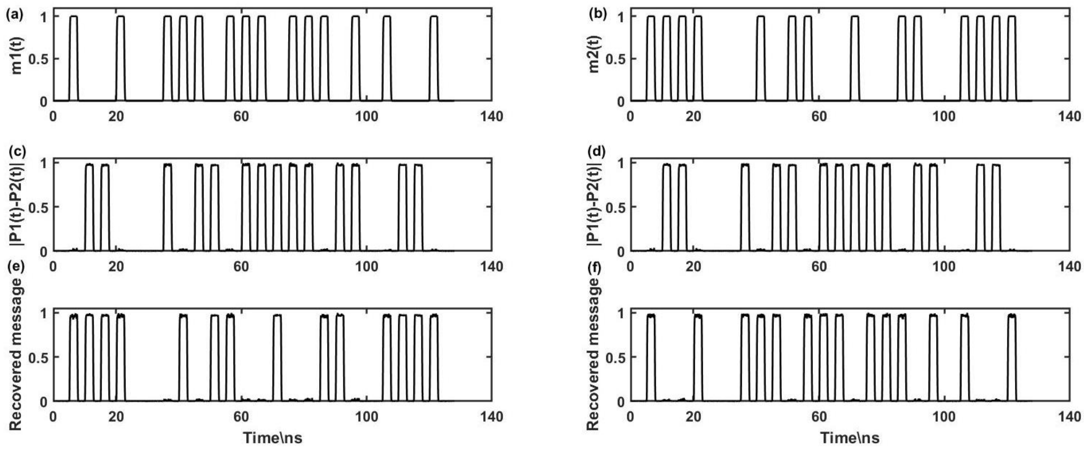

Fig. 4.(a) Information $m_1(t)$; (b) Information $m_2(t)$; (c) The absolute value of the synchronization power error received by Receiver1; (d) The absolute value of the synchronization power error received by Receiver2; (e) Information recovered by Receiver1; (f) Information recovered by Receiver2.

Under the condition of ensuring that the system can achieve bidirectional transmission, the relationship between transmission distance and BER is further studied. The information transmission rate at both ends is set at 1Gb/s to obtain the curve of distance and BER shown in Fig. 5. With the increase of transmission distance, the BER continues to increase. When the transmission distance is increased to 100km, $\log_{10}(BER)=-6.7269$, the BER meets the minimum communication requirement of less than 10^{-5}. However, when the transmission distance continues to increase to 120km, the BER is lower than 10^{-5} due to the introduction of too many interference signals during the transmission process of encrypted information. In this case, the eye diagram is shown in Fig. 6. There is chaotic and no obvious "eye" shape in the eye diagram, so the information cannot be decrypted effectively. Therefore, when information is transmitted at a rate of 1Gb/s, the maximum transmission distance that can be achieved is 100km.

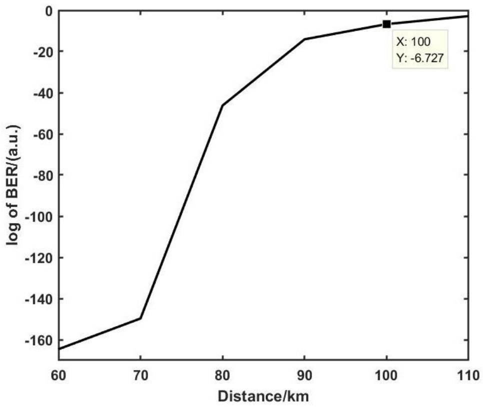

Fig. 5. Relationship between distance and BER at 1Gb/s.

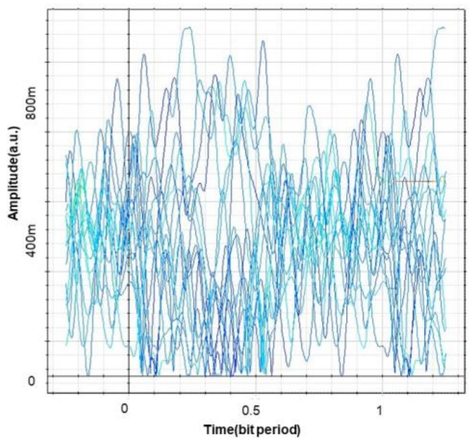

Fig. 6. Eye diagram when transmission distance is 120km.

As usual, the information transmission rates commonly used in optical fiber communication are 10Gb/s and 40Gb/s, which are much higher than the 1Gb/s set in the above simulation process, the relationship between transmission speed and BER is studied to make the simulation more practical, in order to reserve space for the increase of BER accompanied by rate growth, the transmission distance is set as 85km in combination with the data in Fig. 6. And we get the curve of transmission speed and BER as shown in Fig.7(a) after multiple simulations. When the transmission speed is 10Gb/s, the minimum requirement of communication BER is met. Therefore, under the condition that the BER is less than 10^{-5}, the bidirectional information transmission of 10Gb/s on 85km optical fiber is successfully realized. The eye diagrams at different transmission rates are show in Fig. 7(b), 7(c) and 7(d). With the increase of the speed, the height of the eye opening gradually decreases. When the transmission distance is increased to 13Gb/s, the quality of the eye diagram is seriously affected, and it is almost impossible to accurately recover the encrypted information.

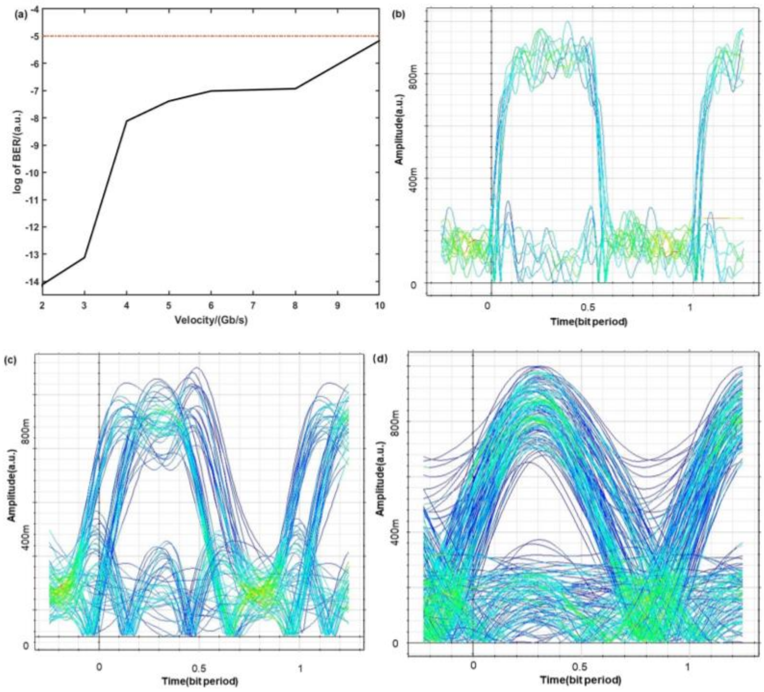

Fig. 7. (a) Curve diagram of transmission speed and bit error rate; (b) Eye diagram at 1Gb/s; (c) Eye diagram at 5Gb/s; (d) Eye diagram at 13Gb/s;

Next, the performance of the system when the two transmitters are TDS mismatch is further analyzed. We continue to maintain the transmission distance of 85km and the transmission rate of 10Gb/s, by adjusting the delay time of the TDL at either end, and obtain the following curve graph of TDS mismatch degree and the normalized BER. It can be seen from the Fig.8, due to the mismatching of TDS, the BER of recovered information increases sharply, resulting in a great discount on the quality of the information. The greater the degree of mismatch, the less successful the information can be recovered. That is to say, the system has a certain ability to resist interception. As long as the third party cannot reconstruct the completely correct chaotic dynamics system, the information will not be able to steal to ensure the security of communication.

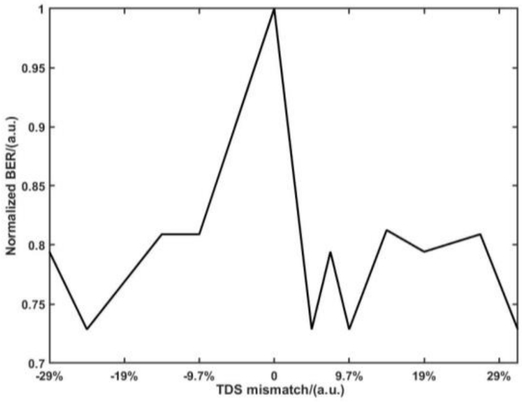

Fig. 8. Curve of TDS mismatch degree and the normalized BER.

4. Conclusions

This paper proposes an all-optical bidirectional chaotic communication system, which overcomes the problems of poor security and low transmission efficiency in the traditional secure communication system. In this scheme, an all-optical time-delay feedback loop is designed by using EDFA to improve the traditional external optical cavity method, which produces chaotic waveforms successfully, and it solves the problem of high equipment requirements in the traditional scheme, which is easy to be applied on a large scale. On this basis, a bidirectional transmission scheme is proposed to improve the efficiency of information transmission. Under the condition that BER is less than 10^{-5}, the bidirectional information transmission rate of 10Gb/s on 85km optical fiber is finally achieved successfully. The anti-interception ability of the system is also verified by studying the mismatch degree of TDS at the transmitters, which proves the security of the system, and it provides a new idea for the research of subsequent chaotic generation schemes.

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