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Performance analysis of dense wavelength division multiplexing secure communications with multiple chaotic optical channels

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ABSTRACT

The performance of dense wavelength division multiplexing secure communications with multiple chaotic optical channels is numerically analyzed in this paper. Taking the multiplexing of three chaotic optical channels as an example, we investigate the effects of second-order dispersion coefficient and nonlinear coefficient of fiber, channel spacing, message amplitude and bit rates on chaotic synchronization and multiplexing communications. Chaotic synchronization quality and *Q*-factor of the recovered message decrease with the increasing fiber length. A 1.25 Gbits/s non-return-to-zero (NRZ) sequence can be securely transmitted up to 60 km under the influence of the other two chaotic optical channels. Compared with the fiber dispersion, the cross-phase modulation is the primary factor which deteriorates the quality of communications. The results also show that the quality of communications is unlimited to the channel spacing as long as chaotic synchronization can be maintained. In addition, the effect of the amplitude of encrypted message on *Q*-factor and the confidentiality is demonstrated.

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1. Introduction

There has been growing interest in chaotic optical communications since it is a hardware-based encryption on the physical layer [1–9]. In this technique, the message is hidden within a noise-like chaotic optical carrier generated by a transmitter. The parameters of the receiver are well matched with those of the transmitter to achieve chaotic synchronization. The message is decrypted by subtracting the output of the receiver from the encrypted transmitted signal. For the eavesdropper, she is unable to decrypt the message without any knowledge of the structure and parameters of the transmitter because she only obtains the random signal from the channel. Up to now, there have been many fruitful publications over the past decade on chaotic optical communications [10–13]. Sánchez-Díaz et al. examined the performance of chaotic optical communications using one-to-one single fiber-optic channel. The results show that the quality of chaotic synchronization and chaotic communications degrade with the increasing length of dispersion shifted fiber [14]. Argyris et al. successfully implemented a real-world chaotic optical communications for transmission rate of 1 Gbits/s, and bit error rate of 10^{-7} in 120 km single fiber channel [15]. Photonic integrated circuits for chaotic optical communications are designed and fabricated in a single chaotic optical channel [16].

At present, conventional optical wavelength division multiplexing (WDM) has been realized in order to exploit the tremendous bandwidth of fiber. Therefore WDM for chaotic optical communications should be realized for practical application. This issue includes two aspects: WDM between chaotic optical channel and conventional optical channel, and WDM with multiple chaotic optical channels. For the former, Zhang et al. numerically studied the DWDM transmission between chaotic optical channel masking 1 Gbits/s secure message and conventional optical channel carrying 10 Gbits/s message [17]. The DWDM transmission distance can be up to 80 km when the channel spacing is 0.8 nm. Argyris et al. showed the corresponding experimental results [18]. Note that the bit rate for the message masked by chaotic optical channel is 1.25 Gbits/s. The bit error rate of this communication setup can be reduced to the order of 10^{-12} when forward error correction (FEC) encoding technique is applied. However, there has been little research that demonstrates the DWDM transmission with multiple chaotic optical channels.

In this paper, the performance of dense wavelength division multiplexing (DWDM) transmission with three chaotic optical channels, unlike chaotic optical communications using single channel [14], is analyzed. The results show that cross-phase modulation (XPM) effect is more effective to degrade the quality of DWDM transmission than dispersion of fiber. The channel spacing has no effect on the chaotic optical DWDM even when the channel spacing reduces to 0.2 nm.

2. Model and parameters

The setup for DWDM transmission with chaotic optical channels is shown in Fig. 1. The chaotic optical carrier of transmitter LDT_j with central wavelength λ_j is generated by optical feedback. The secure message

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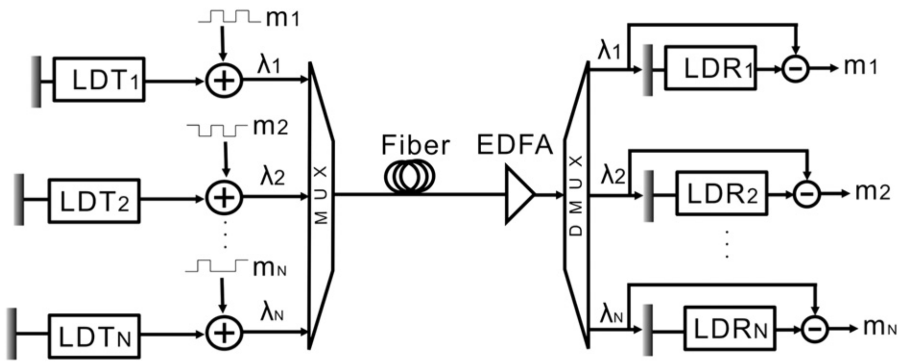

Fig. 1. Schematic diagram for DWDM transmission with chaotic optical channels.

m_j is hidden in the chaotic optical carrier by chaos masking (CMS). All the chaotic optical carriers with different secure messages in them are combined to one compound optical signal by a wavelength division multiplexer (MUX). Then the optical signal is transmitted through the fiber link. An Erbium-doped fiber amplifier (EDFA) is assigned to compensate the optical power loss caused by the long-haul fiber link. A wavelength division demultiplexer (DMUX) is utilized to separate all the combined chaotic optical signals. At the receiver side, the message m_j is decrypted by subtracting the output optical power of receiver LDR_j from the chaotic optical signal from the jth channel.

The dynamical characteristics of each pair of transmitter and receiver in the above setup can be described by the well-known Lang–Kobayashi rate equations for single longitudinal mode semiconductor laser as follows [19]

$$\frac{dE_{T,R}(t)}{dt} = \frac{1}{2}(1+i\psi)\left[\frac{G\left[N_{T,R}(t)-N_0\right]}{1+\varepsilon\left|E_{T,R}(t)\right|^2}-\frac{1}{\tau_P}\right]E_{T,R}(t) + k_{T,R}E_{T,R}(t-\tau)\exp(-i\omega\tau)+k_{inj}E_{ext}(t), \tag{1}$$

$$\frac{dN_{T,R}(t)}{dt} = \frac{I_{T,R}}{qV}-\frac{1}{\tau_n}N_{T,R}(t)-\frac{G\left[N_{T,R}(t)-N_0\right]}{1+\varepsilon\left|E_{T,R}(t)\right|^2}\left|E_{T,R}(t)\right|^2, \tag{2}$$

where E and N are the slowly varying complex electronic field amplitude and the carrier density in the laser cavity. The subscripts T and R denote transmitter and receiver, respectively. ω is the angular frequency of the free-running laser. E_{ext} is the electronic field amplitude injected into the receiver.

The feedback coefficient $k_{T,R}$ and the injection coefficient k_{inj} from transmitter to receiver are defined as follows

$$k_{T,R} = \frac{1}{\tau_{in}}\frac{\left(1-r_0^2\right)r_{T,R}}{r_0}, \tag{3}$$

$$k_{inj} = \frac{1}{\tau_{in}}\frac{\left(1-r_0^2\right)r_{inj}}{r_0}. \tag{4}$$

The other parameters and their values used in the numerical simulation are listed in Table 1.

The propagation of the jth chaotic optical signal in fiber can be described by the coupled nonlinear Schrödinger equation (NLSE)

$$i\frac{\partial E_j}{\partial z} = -\frac{i}{2}\alpha E_j+\frac{\beta_2}{2}\frac{\partial^2 E_j}{\partial t^2}-\gamma\left(\left|E_j\right|^2+2\sum_{k=1,k\neq j}^{N}\left|E_k\right|^2\right)E_j, \tag{5}$$

where E_j and E_k are the slowly varying complex electronic field amplitude of the jth channel and kth channel. α is the loss coefficient. β_2 is the second-order dispersion coefficient. γ is the nonlinear coefficient. The fiber used in this paper is non-zero dispersion shifted fiber (NZ-DSF, ITU-T G.655) and the corresponding typical parameters are $\alpha = 0.2$ dB/km, $\beta_2 = 5.1$ $ps^2 \cdot km^{-1}$, $\gamma = 1.5$ $W^{-1} \cdot km^{-1}$.

3. Generation of chaotic optical carriers

To test the performance of DWDM transmission with multiple chaotic optical channels, we choose three channels as an example during the following sections of this paper. We set the external cavity length of the three chaotic transmitters 15 cm, 30 cm, and 45 cm in order to differentiate the waveforms of the chaotic carriers. According to ITU-T G.692 on channel spacing of DWDM, the central wavelengths of the three transmitters are 1550.12 nm, 1550.92 nm, and 1551.72 nm. Therefore the channel spacing is 0.8 nm. The other parameters of the three transmitters are the same, which have been listed in Table 1. Fig. 2 shows the optical spectra of the transmitters operating in free-running states (without optical feedbacks) and chaotic states (with optical feedbacks). The optical spectrum of chaotic state is broader than that of free-running state due to the coherence collapse caused by optical feedback. However, the three optical spectra of chaotic transmitters are still not overlapped for channel spacing of 0.8 nm (100 GHz).

4. Chaos synchronization

The waveform of chaotic optical carrier can be varied through fiber link. Thereby the chaos synchronization between the transmitter and receiver is changed. Fig. 3 presents the waveforms and correlation plots of transmitter and receiver connected by the second channel. The waveforms of the other two pairs of semiconductor lasers vary similarly to what we present here. As can be seen from Fig. 3(a), (b), and (d), the chaos synchronization between transmitter and receiver is well maintained after 10-km fiber transmission. The output of receiver injected by the chaotic carrier after 60-km fiber

Table 1
The parameter values used in the numerical simulation.

Symbol	Parameter	Value
V	Volume of the active region	1.5×10^{-16} m^3
τ_n	Carrier lifetime	2 ns
τ_P	Photon lifetime	2 ps
τ_{in}	Round-trip time in the internal laser cavity	9 ps
r_0	Reflection rate of the laser facet	30%
$r_{T,R}$	Reflection rate of external mirror	0.6%
N_{th}	Carrier density at threshold	1.5×10^{24} m^{-3}
N_0	Carrier density at transparency	10^{24} m^{-3}
G	Gain coefficient	2×10^{-12} m^3/s
ε	Gain saturation coefficient	3×10^{-23} m^3
ψ	Linewidth enhancement factor	4.5
I_{th}	Threshold current	18 mA
r_{inj}	Injection ratio	60%
q	Charge quantity	1.6×10^{-19} C

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