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Five-user, 1.25-Gbits/s per user, all-optical chaotic orthogonal multiplexing communications using semiconductor lasers

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ABSTRACT

In this paper, we numerically investigated the performance of chaotic orthogonal multiplexing communications using semiconductor lasers. The effect of injection rate from transmitter to receiver and wavelength spacing of transmitter lasers on chaotic synchronization is analyzed. The relationship between *Q*-factor and the number of users is also demonstrated. The results show that the proposed system can realize secure transmission of 1.25-Gbits/s message up to 5 users.

1. Introduction

Time-division multiplexing (TDM) and wavelength-division multiplexing (WDM) protocols are widely employed in modern fiber-optic communications. However, these protocols are not cryptographic hence there exist security issues. Since 1990s, there have been three types of secure protocols to resolve security issues of modern fiber-optic communications, namely, quantum communication [1], optical code division multiple access (OCDMA) [2], and chaotic optical communications [3]. Chaotic optical communications is a hardware encryption technology at the physical layer. For this encryption, the transmitter laser, subject to the external perturbation (e.g. external optical feedback), generates a noise-like chaotic optical carrier, which conceals the secure message. When the matched receiver laser can synchronize with the transmitter, the message decryption is realized by subtracting the output of the receiver from the compound signal (i.e. carrier plus message). Eavesdropping is impossible if eavesdropper (Eve) has no knowledge of the structure and parameters of transmitter.

During the past decade fruitful progress emerged, which accelerates the practical applications of chaotic optical communications [3–9]. One of the essential issues of the practical applications is multiplexing, in order to increase usage efficiency for fiber-optic links and being compatible of the present optical fiber communication networks. Consequently it is very important to transmit multiple messages from multiple users in single channel using chaotic optical communications. The orthogonality of double chaotic lights and their multiplexing communications have been investigated [10–13].

In this paper, we study the performance of orthogonal chaotic optical carriers and multiplexing communications of multiple users (up to five users). The effect of injection rate from transmitter to receiver and wavelength spacing of transmitter lasers on chaotic synchronization is analyzed. The relationship between *Q*-factor and the number of users is also demonstrated. The waveforms of decrypted messages for five users are shown.

2. Model

Fig. 1 shows the setup for multi-user chaotic orthogonal multiplexing communication utilizing semiconductor lasers. The chaotic carrier of transmitter LDT_i is generated by optical feedback. The message m_i is encrypted by chaos shift keying (CSK). The chaotic optical carriers with messages are combined by a combiner and then transmitted in the optical fiber channel. A splitter is arranged to split the compound signal from the fiber-optic channel into n beams. The ith beam injects the matched receiver LDR_i to generate synchronous chaotic carrier with the transmitter. An optical band-pass filter (OBPF) is utilized to filter the unmatched chaotic signals. The corresponding optical signals are converted into electronic signals by two photodetectors (PDs). The subtraction between the two electronic signals is sent to a low-pass filter (LPF) to decrypt the message m_i.

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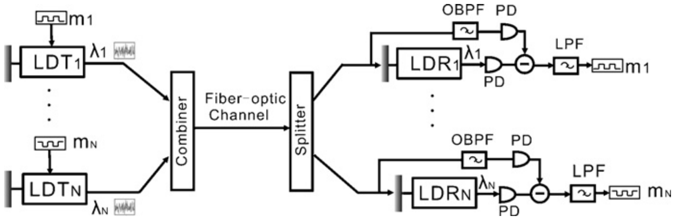

Fig. 1. Setup for multi-user chaotic orthogonal multiplexing communication utilizing semiconductor lasers. OBPF, optical band-pass filter; PD, photodetector; and LPF, low-pass filter.

Any pair of matched transmitter and receiver of the above setup can be described by the Lang–Kobayashi rate equations [14]:

$$\frac{\mathrm{d}E_T(t)}{\mathrm{d}t} = \frac{1}{2}(1+i\alpha)\left[\frac{G[N_T(t)-N_0]}{1+\varepsilon\left|E_T(t)\right|^2} - \frac{1}{\tau_P}\right]E_T(t) + k_T E_T(t-\tau_T)\exp(-i\omega_T\tau_T), \tag{1}$$

$$\frac{\mathrm{d}E_R(t)}{\mathrm{d}t} = \frac{1}{2}(1+i\alpha)\left[\frac{G[N_R(t)-N_0]}{1+\varepsilon\left|E_R(t)\right|^2} - \frac{1}{\tau_P}\right]E_R(t) + k_R E_R(t-\tau_R)\exp(-i\omega_R\tau_R) + \sum_{j=1}^{N} k_{\mathrm{inj}}^N E_T^N(t-\tau_{\mathrm{inj}}^N)\exp(-i(\omega_T^N\tau_{\mathrm{inj}}^N - (\omega_T^N-\omega_R)t)), \tag{2}$$

$$\frac{\mathrm{d}N_{\mathrm{T,R}}(t)}{\mathrm{d}t} = \frac{I_{\mathrm{T,R}}}{qV} - \frac{1}{\tau_n}N_{\mathrm{T,R}}(t) - \frac{G[N_{\mathrm{T,R}}(t)-N_0]}{1+\varepsilon\left|E_{\mathrm{T,R}}(t)\right|^2}\left|E_{\mathrm{T,R}}(t)\right|^2, \tag{3}$$

where T and R denote transmitter and receiver, respectively. E and N are the slowly varying complex electric field amplitude and the carrier density.

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

$$k_{\mathrm{T,R}} = \frac{1}{\tau_{\mathrm{in}}}\frac{(1-r_0^2)r_{\mathrm{T,R}}}{r_0}, \tag{4}$$

$$k_{\mathrm{inj}} = \frac{1}{\tau_{\mathrm{in}}}\frac{(1-r_0^2)r_{\mathrm{inj}}}{r_0}. \tag{5}$$

In order to simplify the numerical simulation, the ideal channel is chosen. The other parameters and their values used in the numerical simulation are listed in Table 1.

Table 1
The parameter values used in the numerical simulation.

Symbol	Parameter	Value
V	Volume of the active region	150 μm^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%
$r_{\mathrm{T,R}}$	Reflection rate of external mirror	1%
l	External cavity length	15 cm
N_{th}	Carrier density at threshold	9.9×10^5 μm^{-3}
N_0	Carrier density at transparency	4×10^5 μm^{-3}
G	Gain coefficient	2.125×10^{-3} μm^3 ns^{-1}
ε	Gain saturation coefficient	3×10^{-5} μm^3
α	Linewidth enhancement factor	5.5
I_{th}	Threshold current	12 mA
q	Charge quantity	1.6×10^{-19} C

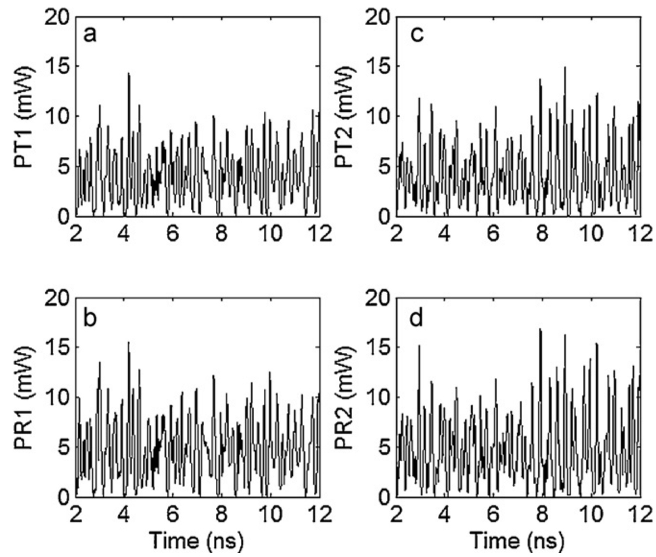

Fig. 2. Time traces for the optical powers of the transmitters and receivers.

3. Orthogonality of double users

Concerning to chaotic optical communications, the orthogonality means that matched transmitter and receiver can maintain synchronization while the unmatched ones are nonsynchronous. We first examine the orthogonality of double users. The central wavelengths of the transmitters for the two users are 1550.12 nm and 1551.72 nm, respectively. The injection rate from transmitter to receiver is $r_{\mathrm{inj}} = 0.8$. Fig. 2 shows the time traces for the optical powers of the transmitters and receivers. In order to further show the chaotic synchronization, Fig. 3 exhibits the corresponding correlation plots. As can be seen, the points for optical powers of matched transmitter and receiver (PT1 and PR1, PT2 and PR2) concentrate on the diagonal. However, the unmatched pairs of lasers (PT1 and PR2, PT2 and PR1) are nonsynchronous because the points scatter in Fig. 3(b) and (d). Accordingly two chaotic optical carriers can be orthogonal.

We further investigate the effect of wavelength spacing of transmitter lasers and injection rate on chaotic synchronization for double users. The central wavelength of user #1 is set to 1550.12 nm. The initial central wavelength of user #2 is 1550.22 nm

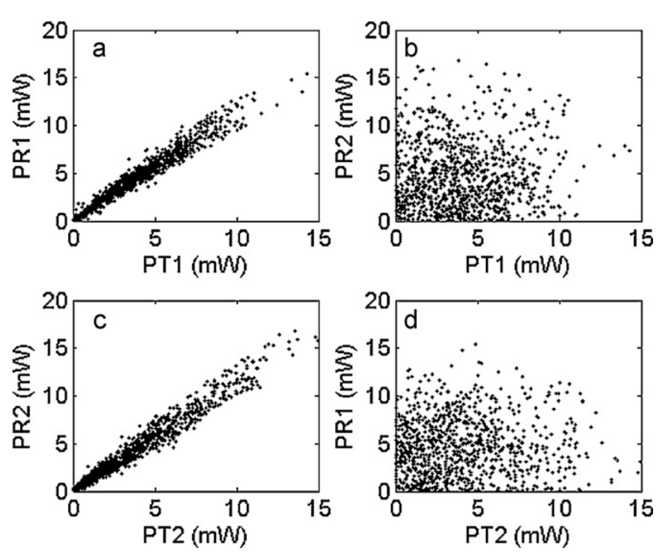

Fig. 3. Correlation plots for optical powers of the transmitters and receivers.