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Study of dual-directional high rate secure communication systems using chaotic multiple-quantum-well lasers*

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A scheme of synchronized injection multi-quantum-well (MQW) laser system using optical coupling-feedback is presented for performing chaotic dual-directional secure communication. The performance characterization of chaos masking is investigated theoretically, the equation of synchronization demodulation is deduced and its root is also given. Chaos masking encoding with a rate of 5 Gbit/s and a modulation frequency of 1 GHz, chaos modulation with a rate of 0.2 Gbit/s and a modulation frequency of 0.2 GHz and chaos shifting key with a rate of 0.2 Gbit/s are numerically simulated, separately. The ratio of the signal to the absolute synchronous error and the time for achieving synchronous demodulation are analysed in detail. The results illustrate that the system has stronger privacy and good performances so that it can be applied in chaotic dual-directional high rate secure communications.

Keywords: chaos, MQW laser, secure, dual-directional communication
PACC: 0545, 4265

1. Introduction

Chaotic communication is a promising technique which is used to improve security in communication.[1−4] All optical chaotic approaches have been used in high-speed and long-haul secure communications because all optical systems have a large bandwidth and low attenuation.[4−6] Many semiconductor laser systems have been proposed for chaotic optical secure communications.[7−11] These systems can be classified into three encoding types: chaos modulation (CMA), chaos shift keying (CSK) and chaos masking (CM).[12−14] Due to the random and complexity of chaotic waveform, such chaotic communication systems are very difficult to be attacked. Now, a lot of chaotic laser systems can be used only in single-directional communication.[7−12] Therefore, it is an important issue to investigate theoretically dual-directional chaotic communication. For better security, new chaotic communication systems will be further studied.

In this paper, a synchronized chaotic coupling-feedback system with graded-index separate confinement heterostructure (SCH) multi-quantum-well (MQW) lasers from the external injection light beams is presented for performing dual-directional secure communications. Because chaotic MQW laser has a high oscillation frequency and complex dynamics, the system will be of high bit-rate and of good security in secure communications.[10−14]

2. Theoretical model

2.1. Model

Figure 1 illustrates a synchronization model block of chaotic MQW lasers from external injection light beams.[9−14] The transmitter and the receiver each consist of master (M) laser and slave (S) MQW laser diodes (LDs). The M-LD output $E_{\rm m}\exp(-{\rm j}\omega_{\rm m}t)$ injecting S-LD, S-LD output $E_{\rm t}(t)\exp\{-{\rm j}[\omega_{\rm m}t+\varphi_{\rm t}(t)]\}$ can become chaotic state.[8,14] Synchronization can be achieved between the transmitter and the receiver by optical coupling-feedback. We can use the Lang–Kobayashi equations to describe the dynamics of S-LDs due to M-LDs light injection.[9−14]

$$\frac{{\rm d}E_t}{{\rm d}t}=\frac{1}{2}(G_{\rm t}-\gamma)E_{\rm t}+\frac{k}{\tau_L}E_{\rm m}\cos(-\varphi_{\rm t})+\frac{k}{\tau_L}f[E_{\rm r}\cos(\varphi_{\rm r}-\varphi_{\rm t})-E_{\rm t}],$$

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$$\frac{\mathrm{d}\varphi_\mathrm{t}}{\mathrm{d}t} = \frac{1}{2}\beta_\mathrm{c}(G_\mathrm{t}-\gamma) + \frac{k}{\tau_L}\frac{E_\mathrm{m}}{E_\mathrm{t}}\sin(-\varphi_\mathrm{t}) + \frac{k}{\tau_L}\frac{fE_\mathrm{r}}{E_\mathrm{t}}\sin(\varphi_\mathrm{r}-\varphi_\mathrm{t}) - \Delta\omega_\mathrm{m},$$
$$\frac{\mathrm{d}N_\mathrm{Bt}}{\mathrm{d}t} = \eta_\mathrm{i}\frac{\mathrm{I}}{q} - \gamma_\mathrm{BQ}N_\mathrm{Bt} + \gamma_\mathrm{QB}N_\mathrm{t},$$
$$\frac{\mathrm{d}N_\mathrm{t}}{\mathrm{d}t} = \gamma_\mathrm{BQ}N_\mathrm{Bt} - (\gamma_\mathrm{e}+\gamma_\mathrm{QB})N_\mathrm{t} - GV_\mathrm{p}E_\mathrm{t}^2, \tag{1}$$

and

$$\frac{\mathrm{d}E_\mathrm{r}}{\mathrm{d}t} = \frac{1}{2}(G_\mathrm{r}-\gamma)E_\mathrm{r} + \frac{k}{\tau_L}E_\mathrm{m}\cos(-\varphi_\mathrm{r}) + \frac{f}{\tau_L}[E_\mathrm{t}\cos(\varphi_\mathrm{t}-\varphi_\mathrm{r}) - E_\mathrm{r}]$$
$$\frac{\mathrm{d}\phi_r}{\mathrm{d}t} = \frac{1}{2}\beta_\mathrm{c}(G_\mathrm{r}-\gamma) + \frac{k}{\tau_L}\frac{E_\mathrm{m}}{E_\mathrm{r}}\sin(-\varphi_\mathrm{r}) - \Delta\omega_\mathrm{m} + \frac{f}{\tau_L}\frac{E_\mathrm{t}}{E_\mathrm{r}}\sin(\varphi_\mathrm{t}-\varphi_\mathrm{r})$$
$$\frac{\mathrm{d}N_\mathrm{Br}}{\mathrm{d}t} = \eta_\mathrm{i}\frac{\mathrm{I}}{q} - \gamma_\mathrm{BQr}N_\mathrm{Br} + \gamma_\mathrm{QB}N_\mathrm{r},$$
$$\frac{\mathrm{d}N_\mathrm{r}}{\mathrm{d}t} = \gamma_\mathrm{BQ}N_\mathrm{Br} - (\gamma_\mathrm{er}+\gamma_\mathrm{QB})N_\mathrm{r} - G_\mathrm{r}V_\mathrm{p}E_\mathrm{r}^2, \tag{2}$$

where the subscripts t and r indicate the transmitter and the receiver, respectively. E and φ are the amplitude and phase of the field. Both N and N_B are the carrier numbers in the barrier region and the active region, respectively. E_m is the amplitude of the injection light and k is the injection coefficient, where we take $E_\mathrm{m} = 0.2529\,E_\mathrm{s}$ in this paper. f is the coupling-feedback coefficient. $G = [(\Gamma g_0 v_\mathrm{g})/(1+E^2/E_\mathrm{s}^2)] \times \lg\{(N+N_\mathrm{s})/(N_\mathrm{th}+N_\mathrm{s})\}$ is the nonlinear mode gain where v_g is the group speed of photon in laser cavity, g_0 is the gain constant, $\Gamma = V/V_\mathrm{p}$ is the mode confinement coefficient with the laser cavity volume V and the laser mode volume V_p, $N_\mathrm{s} = n_\mathrm{s}V$ is the parameter of logarithmic gain with its density n_s, $N_\mathrm{th} = n_\mathrm{th}V$ is the carrier number at transparency with its density n_th. E_s is the optical field amplitude at saturation with saturation photon number P_s. E and E_s are normalized by $E = (P/V_\mathrm{p})^{1/2}$ and $E_\mathrm{s} = (P_\mathrm{s}/V_\mathrm{p})^{1/2}$. $\gamma_\mathrm{p} = v_\mathrm{g}(\alpha_\mathrm{m}+\alpha_\mathrm{int})$ is the total photon loss with the group speed v_g, α_m is the cavity loss, α_int is the internal loss. $\Delta\omega_\mathrm{m}$ can be regarded as frequency detuning between external injection light and output light. $\tau_L = 2n_\mathrm{g}L/c$ is the round-trip time in the cavity with a length L, c is the speed of light in vacuum, $n_\mathrm{g} = c/v_\mathrm{g}$ is the group refractive index. η_i is the internal quantum efficiency. I is the drive current. q is the unit charge. β_c is the optical linewidth gain factor. γ_BQ is the loss of carriers from the SCH region to the quantum wells, and γ_QB is the loss of carriers escaping from the active region to the SCH layer. $\gamma_\mathrm{e} = A_\mathrm{nr}+B(N/V)+C(N/V)^2$ is the total carrier loss in the active layer, A_nr is the nonradiative recombination rate, B is the radiative recombination coefficient, and C is the Auger recombination coefficient. With suitable parameters, if absolute value $|E_\mathrm{t}-E_\mathrm{r}| \to 0$, $|\varphi_\mathrm{t}-\varphi_\mathrm{r}| \to 0 \to 0$, $|N_\mathrm{t}-N_\mathrm{r}| \to 0$ and $|N_\mathrm{Bt}-N_\mathrm{Br}| \to 0$, the receiver will be synchronized with the transmitter.

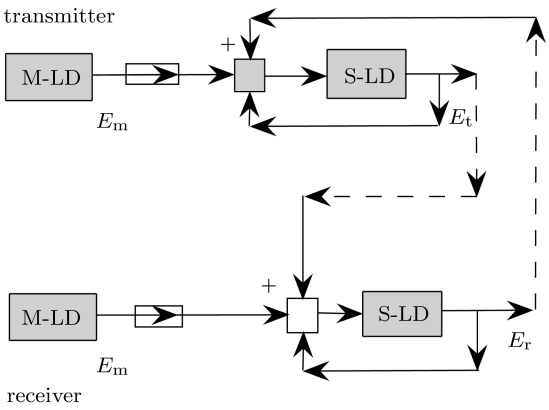


Fig.1. Schematic synchronization model block. The upper is the transmitter and the lower is the receiver. M-LD denotes the master laser, S-LD represents the slave laser with an feedback pith, $\boxed{\rightarrow}$ denotes the optical isolator, $\square$ represents the coupler.

2.2. Synchronization equation

Subtracting Eq.(2) from Eq.(1), a synchronization equation is obtained as

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}(E_\mathrm{t}-E_\mathrm{r})\\(\varphi_\mathrm{t}-\varphi_\mathrm{r})\\(N_\mathrm{Bt}-N_\mathrm{Br})\\(N_\mathrm{t}-N_\mathrm{r})\end{pmatrix}=\begin{pmatrix}F_1(E_\mathrm{t},\varphi_\mathrm{t},N_\mathrm{Bt},N_\mathrm{t},E_\mathrm{r},\varphi_\mathrm{r},N_\mathrm{Br},N_\mathrm{r})\\F_2(E_\mathrm{t},\varphi_\mathrm{t},N_\mathrm{Bt},N_\mathrm{t},E_\mathrm{r},\varphi_\mathrm{r},N_\mathrm{Br},N_\mathrm{r})\\F_3(E_\mathrm{t},\varphi_\mathrm{t},N_\mathrm{Bt},N_\mathrm{t},E_\mathrm{r},\varphi_\mathrm{r},N_\mathrm{Br},N_\mathrm{r})\\F_4(E_\mathrm{t},\varphi_\mathrm{t},N_\mathrm{Bt},N_\mathrm{t},E_\mathrm{r},\varphi_\mathrm{r},N_\mathrm{Br},N_\mathrm{r})\end{pmatrix}, \tag{3}$$

where the functions of F_1, F_2, F_3 and F_4 can be found in Eqs.(1) and (2). It is an essential condition for chaotic secure communication that the transmitter and the receiver have the identical parameters. Hence, Eqs.(1) and (2) have the same unmoving points, and ensures $E_0 = E_{\mathrm{r}0}, \varphi_0 = \varphi_{\mathrm{ro}}$, $N_{\mathrm{B}0} = N_{\mathrm{Br}0}$, $N_0 = N_{\mathrm{r}0}$, $G_0 = G_{\mathrm{r}0}$ and $\gamma_{\mathrm{e}0} = \gamma_{\mathrm{er}0}$. For the receiver or the transmitter, let $E_\mathrm{r}(t) = E_{\mathrm{r}0} + \delta E_\mathrm{r}(t)$, $\varphi_\mathrm{r}(t) = \varphi_{\mathrm{r}0} + \delta\varphi_\mathrm{r}(t)$, $N_{\mathrm{Br}}(t) = N_{\mathrm{Br}0} + \delta N_{\mathrm{Br}}(t)$, and $N_\mathrm{r}(t) = N_{\mathrm{r}0} + \delta N_\mathrm{r}(t)$, then we will obtain

$$G_\mathrm{r}(N_{\mathrm{r}0}+\delta N_\mathrm{r}, E_{\mathrm{r}0}+\delta E_\mathrm{r}) \approx G_{\mathrm{r}0}(N_{\mathrm{r}0}, E_{\mathrm{r}0}) + G_{\mathrm{r}N_\mathrm{r}}\delta N_\mathrm{r} + G_{\mathrm{r}E_\mathrm{r}}\delta E_\mathrm{r},$$

and

$$\gamma_{\mathrm{er}}(N_{\mathrm{r}0}+\delta N_\mathrm{r}) \approx \gamma_{\mathrm{er}0}(N_{\mathrm{r}0}) + \gamma_{\mathrm{er}N_\mathrm{r}}\delta N_\mathrm{r},$$

where

$$\begin{aligned}
G_{\mathrm{r}E_\mathrm{r}} &= \frac{\partial G_\mathrm{r}}{\partial E_\mathrm{r}}|_{N_\mathrm{r}=N_0,\ E_\mathrm{r}=E_0} = (\Gamma g_0 v_\mathrm{g})\frac{-2E_0/E_\mathrm{s}^2}{(1+E_0^2/E_\mathrm{s}^2)^2}\log\frac{N_0+N_\mathrm{s}}{N_\mathrm{th}+N_\mathrm{s}} = G_\mathrm{E},\\
G_{\mathrm{r}N_\mathrm{r}} &= \frac{\partial G_\mathrm{r}}{\partial N_\mathrm{r}}|_{N_\mathrm{r}=N_0,\ E_\mathrm{r}=E_0} = (\Gamma g_0 v_\mathrm{g})\frac{1}{(1+E_0^2/E_\mathrm{s}^2)}\frac{1}{N_0+N_\mathrm{s}} = G_\mathrm{N},\\
\gamma_{\mathrm{er}N_\mathrm{r}} &= \frac{\partial \gamma_\mathrm{r}}{\partial N_\mathrm{r}}|_{N_\mathrm{r}=N_0} = \frac{B}{V}+2C\frac{N_0}{V^2} = \gamma_\mathrm{eN}.
\end{aligned}$$

Equation 3 yields the first-order approximate synchronization equation

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\delta(E_\mathrm{t}-E_\mathrm{r})\\\delta(\varphi_\mathrm{t}-\varphi_\mathrm{r})\\\delta(N_\mathrm{Bt}-N_\mathrm{Br})\\\delta(N_\mathrm{t}-N_\mathrm{r})\end{pmatrix}=\begin{pmatrix}B_{11}&A_{12}&A_{13}&A_{14}\\A_{21}&B_{22}&A_{23}&A_{24}\\A_{31}&A_{32}&A_{33}&A_{34}\\A_{41}&A_{42}&A_{43}&A_{44}\end{pmatrix}\begin{pmatrix}\delta(E_\mathrm{t}-E_\mathrm{r})\\\delta(\varphi_\mathrm{t}-\varphi_\mathrm{r})\\\delta(N_\mathrm{Bt}-N_\mathrm{Br})\\\delta(N_\mathrm{t}-N_\mathrm{r})\end{pmatrix}, \tag{4}$$

where

$$\begin{aligned}
A_{11} &= \frac{1}{2}(G_0-\gamma+E_0G_\mathrm{E})-\rho_\mathrm{f}, & A_{21} &= \frac{1}{2}\beta_\mathrm{c}G_\mathrm{E}-\frac{\rho_\mathrm{m}}{E_0^2}\sin(-\varphi_0),\\
A_{12} &= \rho_\mathrm{m}\sin(-\varphi_0), & A_{22} &= -\frac{\rho_\mathrm{m}}{E_0}\cos(-\varphi_0)-\rho_\mathrm{f},\\
A_{13} &= 0, & A_{23} &= 0,\\
A_{14} &= \frac{1}{2}E_0G_\mathrm{N}, & A_{24} &= \frac{1}{2}\beta_\mathrm{c}G_\mathrm{N},
\end{aligned}$$

$$\begin{aligned}
A_{31} &= 0, & A_{41} &= -2G_0V_\mathrm{p}E_0 - V_\mathrm{p}E_0^2G_\mathrm{E},\\
A_{32} &= 0, & A_{42} &= 0,\\
A_{33} &= -\gamma_\mathrm{BQ}, & A_{43} &= \gamma_\mathrm{BQ},\\
A_{34} &= \gamma_\mathrm{QB}, & A_{44} &= -\gamma_{\mathrm{e}0}-\gamma_\mathrm{QB}-N_0\gamma_\mathrm{eN}-V_\mathrm{p}E_0^2G_\mathrm{N},
\end{aligned}$$

$$B_{11} = A_{11}-\rho_\mathrm{f}, \quad B_{22} = A_{22}-\rho_\mathrm{f}, \quad \rho_\mathrm{k} = f/\tau_L, \quad \rho_\mathrm{m} = kE_\mathrm{m}/\tau_L.$$

Equation (4) should have an eigenvalue χ, and thus an eigenvalue equation is obtained as

$$\begin{vmatrix}B_{11}-\chi & A_{12} & 0 & A_{14}\\A_{21} & B_{22}-\chi & 0 & A_{24}\\0 & 0 & A_{33}-\chi & A_{34}\\A_{41} & 0 & A_{43} & A_{44}-\chi\end{vmatrix}=0 \tag{5}$$

or

$$\chi^4 + \chi^3 b_{s1} + \chi^2 b_{s2} + \chi b_{s3} + b_{s4} = 0, \tag{6}$$

where

$$\begin{aligned}
b_{s1} &= -(B_{11} + B_{22} + A_{33} + A_{44}),\\
b_{s2} &= (B_{11}A_{44} - A_{12}A_{21} - A_{34}A_{43} + B_{22}A_{33} + A_{33}A_{44} + B_{11}B_{22} + B_{22}A_{44}\\
&\quad + B_{11}A_{33} - A_{41}A_{14}),\\
b_{s3} &= (A_{21}A_{12}A_{33} + A_{21}A_{12}A_{44} - B_{11}B_{22}A_{44} - B_{11}A_{33}A_{44} + B_{11}A_{34}A_{43} - B_{22}A_{33}A_{44}\\
&\quad + B_{22}A_{34}A_{43} + A_{41}A_{14}A_{33} - A_{41}A_{12}A_{41} + A_{41}B_{22}A_{14} - B_{11}B_{22}A_{33}),\\
b_{s4} &= (B_{11}B_{22}A_{33}A_{44} - B_{11}B_{22}A_{34}A_{43} - A_{21}A_{12}A_{33}A_{44} + A_{21}A_{12}A_{34}A_{43}\\
&\quad - A_{41}A_{12}A_{24}A_{33} - A_{41}B_{22}A_{14}A_{33}).
\end{aligned}$$

If the real parts of all eigenvalues of Eq.(5) or Eq.(6) are negative, zero points of Eq.(3) will be stable, which implies that the transmitter synchronizes with the receiver. Using the parameters listed in Table 1 and $0.1 < f < 2$ in numerical calculation, the real parts of all eigenvalues of Eq.(5) are found to be negative. We conclude that synchronization between the transmitter and the receiver may be achieved by optical coupling-feedback.

Table 1. Laser parameters.

symbol	value	units	symbol	value	units
L	1200	μm	A_{nr}	2.5×10^{8}	s^{-1}
w	1.5	μm	B	1.0×10^{-10}	cm^3/s
d	0.028	μm	C	5.0×10^{-29}	cm^6/s
Γ	0.045		β_c	3	
n_g	3.6		I	50	mA
α_m	11.5	cm^{-1}	η_i	0.8	
α_{int}	20	cm^{-1}	P_s	2.2×10^{7}	
g_0	2700	cm^{-1}	γ_{BQ}	2.5×10^{10}	s^{-1}
n_s	1×10^{17}	cm^{-3}	γ_{QB}	5.0×10^{9}	s^{-1}
n_{th}	2.1×10^{18}	cm^{-3}	$\Delta\omega_m$	2×10^{9}	Rad/s
k	0.185		f	0.925	

2.3. CM characterization

It is an important issue to theoretically investigate features of the chaos masking and demodulation of a message signal. Owing to small signal modulation in CM, we can suppose that the signal is much smaller than the chaotic carrier for better security. Owing to the message signal, synchronization can be lost to a certain extent. In order to evaluate the level of synchronization loss, the error between the transmitter and the receiver can be introduced and written as $E_t - E_r \approx \delta E_t - \delta E_r = \delta(E_t - E_r) = \delta e(t)$. An error equation to the first order approximation is written as

$$\begin{aligned}
&\frac{d^4}{dt^4}\delta e + b_{1s}\frac{d^3}{dt^3}\delta e + b_{2s}\frac{d^2}{dt^2}\delta e + b_{3s}\frac{d}{dt}\delta e + b_{4s}\delta e\\
&= A_0 S(t) + A_1\frac{d}{dt}S(t) + A_2\frac{d^2}{dt^2}S(t),
\end{aligned} \tag{7}$$

where

$$\begin{aligned}
A_0 &= B_{22}(A_{34}A_{43} - A_{44}A_{33}),\\
A_1 &= (A_{33}B_{22} + A_{44}B_{22} + A_{34}A_{43} - A_{33}A_{44}),\\
A_2 &= (B_{11} - B_{22} - A_{33} - 1).
\end{aligned}$$

An analogue message signal may always be a complex function of $s = A_m[\exp(-j\omega t)]$ with the modulation depth A_m and the modulation frequency $f_m = \omega/2\pi$. We assume that the error must be similar to the modulation signal in form and taken as $\delta e(t) = a[\exp(-j\omega t)]$ because of the error resulting from the perturbation of the message signal. One obtains a formula of chaotic synchronization error as follows:

$$a(\omega) = \frac{-\omega^2 A_2 - j\omega A_1 + A_0}{\omega^4 - j\omega^3 b_{1s} - \omega^2 b_{2s} - j\omega b_{3s} + b_{4s}}\rho_k A_m \tag{8}$$

or

$$|a| = A_{\rm m}\rho_{\rm k}\frac{\sqrt{[(A_0-\omega^2)x-\omega A_1 y]^2+(A_0-\omega^2 A_2)y]^2}}{x^2+y^2} = \gamma A_{\rm m}, \quad (9)$$

where $x=\omega^4-\omega^2 b_{2\rm s}+b_{4\rm s}$, $y=-\omega^2(\omega b_{1\rm s}+b_{2\rm s})$, and

$$\gamma=\rho_{\rm k}\frac{\sqrt{[(A_0-\omega^2)x-\omega A_1 y]^2+(A_0-\omega^2 A_2)y]^2}}{x^2+y^2}$$

and the phase is

$$\vartheta={\rm tg}^{-1}\left[\frac{\omega A_1 x+(A_0-\omega^2 A_2)y}{\omega A_1 y-(A_0-\omega^2 A_2)x}\right]. \quad (10)$$

Obviously, the error increases with increasing the message signal. The demodulated signal $s_{\rm d}(t)$ is deduced as follows:

$$\begin{aligned} s_{\rm d}(t) &= E_{\rm t}(t)+s(t)-E_{\rm r}(t) \\ &\approx \delta e(t)+s(t) \\ &= a\exp[-{\rm j}(\omega t+\vartheta)]+A_{\rm m}\exp(-{\rm j}\omega t) \\ &= [\gamma\exp(-{\rm j}\vartheta)+1]A_m\exp(-{\rm j}\omega t). \end{aligned} \quad (11)$$

So the demodulation may be achieved from Eq.(11), where the demodulated signal quality is also related to the coefficient and phase of the error.

3. Numerical results

Figure 2 illustrates a process of synchronization between the transmitter and the receiver with the parameters in Table 1, where the insert shows the chaotic attractor of the transmitter S-LD. It can be found that

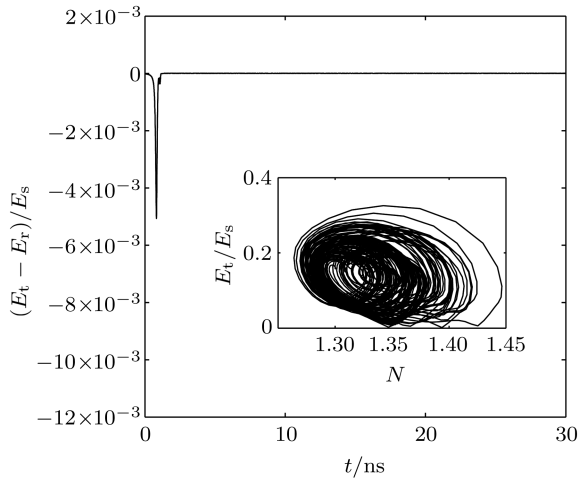


Fig.2. Synchronization. The insert shows the chaotic attractor.

the transmitter S-LD is synchronized with the receiver S-LD after a few oscillations. The receiver and transmitter of the system based on Fig.1 have the same configuration, so the receiver can be used as a transmitter for realizing dual-directional communication.

3.1. CM encoding

In CM encoding method, chaotic wave is used to mask a message signal for performing secure communication. In order to analyse the performance characteristic of the system, we define an absolute synchronous error and an instantaneous synchronous error, respectively, as

$$\Delta = <|E_{\rm t}(t)-E_{\rm r}(t)|/E_{\rm s}>, \quad (12)$$

$$\varepsilon(t)=[E_{\rm t}(t)-E_{\rm r}(t)]/E_{\rm s}, \quad (13)$$

where the bracket denotes average of time.

The analogue CM numerical result is illustrated in Fig.3 where we suppose that a white noise should exist in channel, whose mean is zero and the square root is $1.3\times10^{-6}\,E_{\rm s}$. This white noise is supposed to be present in all the following numerical simulations. The parameters of the message signal are $f_{\rm m}=1\,$GHz and $A_{\rm m}=0.65\times10^{-3}\,E_{\rm s}$. From Fig.3(a), we can find that the chaotic wave successfully masks the message signal. Figure 3(b) shows the result of the synchronous demodulation of the message based on $[E_{\rm t}(t)+s(t)-E_{\rm r}(t)]=s(t)+\delta e(t)$, where $\varepsilon(t)$ varies between -0.5×10^{-4} and 0.5×10^{-4}, $\Delta\approx0.4\times10^{-4}$, and $(A_{\rm m}/E_{\rm s})/\Delta\approx16$ where $(A_{\rm m}/E_{\rm s})/\Delta$ is the ratio of the signal to the absolute synchronous error when 2000 mean values are taken in numerical calculation, which also implies that the demodulated message signal is dominant. Owing to the message signal and noise effects, the demodulated message signal is distorted. However, Fig.3(c) shows the well filtering result. Figure 4 illustrates the numerical results of another high rate of digital CM, where the message signal has a rate of 5Gbit/s and an amplitude of $1.3\times10^{-3}E_{\rm s}$. $\varepsilon(t)$ varies between -0.45×10^{-4} and 0.45×10^{-4}, $\Delta\approx0.44\times10^{-4}$ and $(A_{\rm m}/E_{\rm s})/\Delta\approx17$, which also implies that the demodulation of the message signal can be achieved. Table 2 gives the relationship between absolute synchronous errors and bit rates, and the absolute synchronous error at high modulation rates is smaller than that at low modulation rates.

Table 2. Absolute synchronous errors versus bit rates.

Rate/(Gbit/s)	8.0	4.0	2.0	1.0	0.8	0.4	0.2
$\Delta/10^{-5}$	3.5	6.7	9.1	10.2	7.8	6.7	5.2

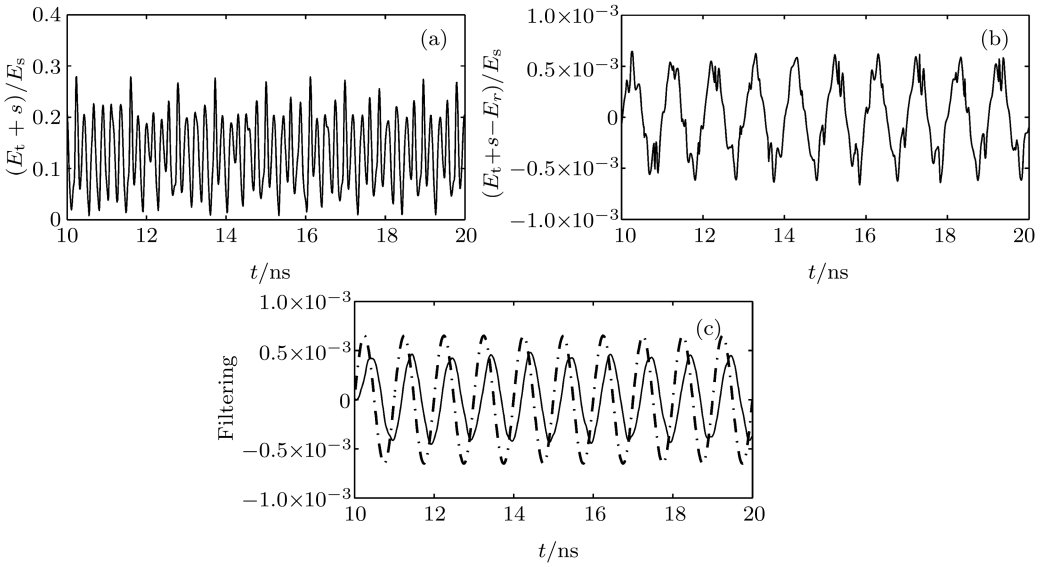


Fig.3. Analogue CM encoding: (a) chaotic wave masking the message signal, (b) synchronous demodulation, (c) filtering where dashed line is the message signal.

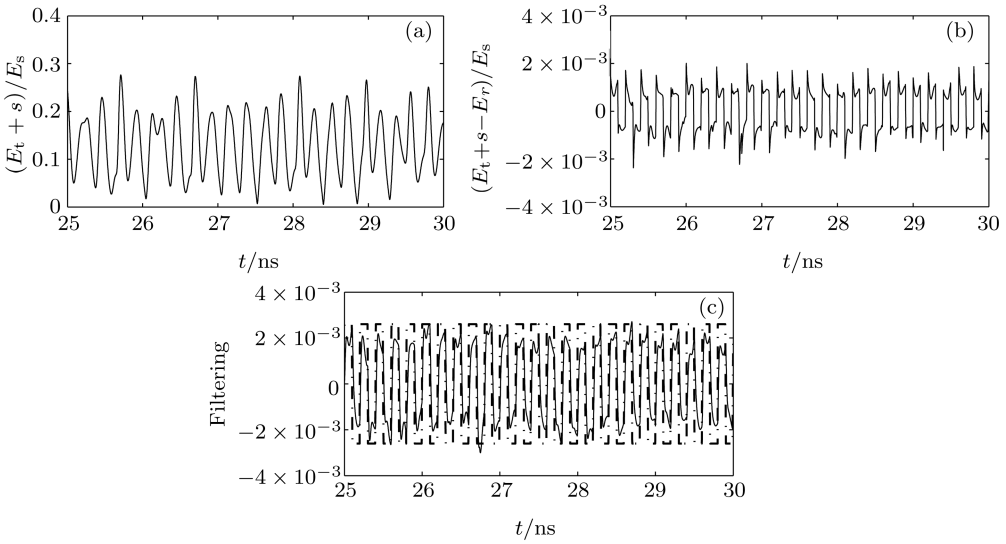


Fig.4. Digital CM encoding: (a) chaotic wave masking the message signal, (b) synchronous demodulation, (c) filtering where dashed line is the message signal.

3.2. CMA encoding

In CMA encoding method, chaotic wave may usually be used as a basic carrier to carry a message signal by modulating the transmitter. Figure 5 shows an analogue CMA result, where the current of the transmitter S-LD is modulated by a sinusoidal signal with a frequency of 0.2 GHz and an amplitude of $1\%I$. Figure 5(a) shows the chaotic carrier, Fig.5(b) shows the synchronous demodulation and Fig.5(c) shows the filtering result. Figure 6 illustrates another digital CMA result where the current of the transmitter S-LD is modulated by a digital signal with a rate of 0.2 Gbit/s and an amplitude of $1\%I$. We can find that the CMA results show the good secret and demodulation characteristics.

3.3. On/Off encoding

One parameter of chaotic transmitter is shifted to encoding chaos in CSK to realize chaotic secure communication. Here, chaotic On/Off encoding is introduced, we can shift the current of the transmitter S-LD continuously between I and $(1+10\%)\,I$. When

the key turns on I, code '0' can be supposed to be encoded while the key turns off I or on $(1+10\%)I$, code '1' is encoded. We can suppose a demodulation of code '0' if synchronization is achieved on I or a demodulation of code '1' if synchronization is lost on $(1+10\%)I$. Figure 7 shows the result of On/Off encoding, where (a) illustrates the chaotic carrier and (b) illustrates the chaotic demodulation with a modulation rate of 0.2 Gbit/s. We find that it takes about $0.4\,\text{ns} \sim 0.8\,\text{ns}$ to achieve synchronization on code bit '0', which implies that the bit rate of the MQW laser system is lower than 1 Gbit/s. This bit rate is higher than that of semiconductor laser systems[12−14] because the oscillation frequency of MQW laser is higher than that of semiconductor laser.

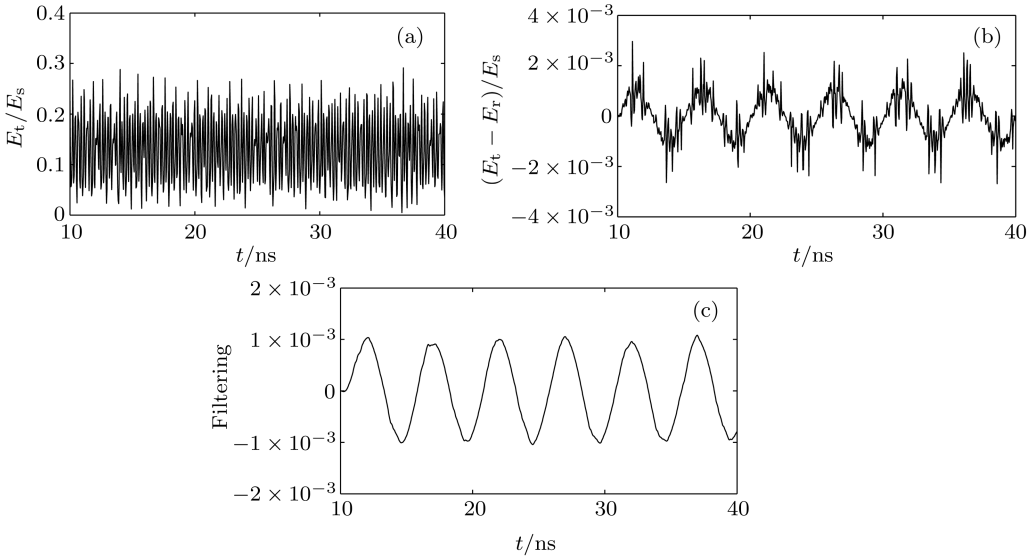


Fig.5. Analogue CMA encoding: (a) chaotic carrier, (b) synchronous demodulation, (c) filtering.

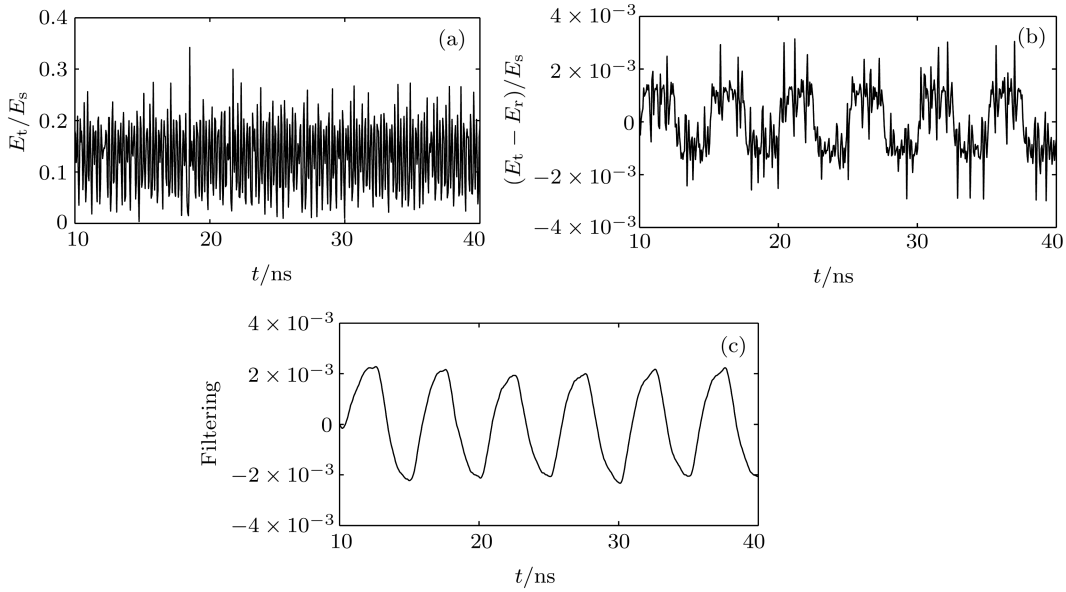


Fig.6. Digital CMA encoding: (a) chaotic carrier, (b) synchronous demodulation, (c) filtering.

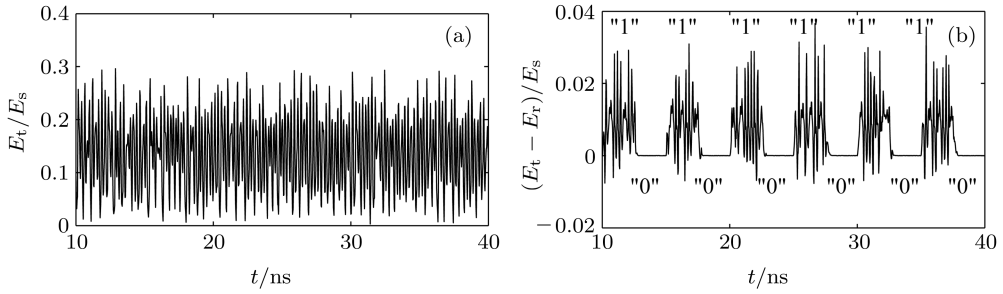


Fig.7. On/Off encoding: (a) chaotic carrier, (b) decoding.

4. Conclusion

The chaotic synchronization based on MQW laser system using optical coupling-feedback is studied for dual-directional secure communications. The synchronization and performance characteristics of the system are analysed both theoretically and numerically. This system will be of high bit rate and secrecy and can be applied in high rate and large bandwidth dual-directional secure communications.

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