Synchronization and bidirectional communication without delay line using strong mutually coupled semiconductor lasers*

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This paper numerically demonstrates synchronization and bidirectional communication without delay line by using two semiconductor lasers with strong mutual injection in a face-to-face configuration. These results show that both of the two lasers' outputs synchronize with their input chaotic carriers. In addition, simulations demonstrate that this kind of synchronization can be used to realize bidirectional communications without delay line. Further studies indicate that within a small deviation in message amplitudes of two sides (±6%), the message can be extracted with signal-noise-ratio more than 10 dB; and the signal-noise-ratio is extremely sensitive to the message rates mismatch of two sides, which may be used as a key of bidirectional communication.

Keywords: synchronization, bidirectional communication, without delay line, semiconductor laser
PACC: 0545, 4265T, 4230Q

1. Introduction

In recent decades, optical chaos communications based on synchronous chaotic lasers have attracted extensive attention for their potential security relying on physical encryption.[1−9] Chaotic synchronization[10−13] or communication [14−16] based on unidirectional coupling is widely studied. It is reported that unidirectional communication has been successfully demonstrated by a field experiment in a metropolitan area network,[17] and can be further improved by enhancing bandwidth of chaotic carrier[18−20] and reducing bit-error-ratio (BER),[21] e.g., by subcarrier modulation.[22] In unidirectional systems, a receiver laser is synchronous with a transmitter laser allowing unidirectional information flow. The advantage of a mutually synchronized system is its increasing the efficiency of the apparatus by allowing a bilateral conversation.

The foundation and precondition of bidirectional communication is synchronization between mutually coupled lasers. The leader-laggard-type synchronization first found in a pair of mutual-injection lasers with weak or moderate coupling strength, is not suitable for bidirectional transmission because only the laggard laser acts as a chaos-pass filtering.[23] Recently, an extremely unsymmetrical mutual injection was numerically demonstrated to achieve synchronization and bidirectional communication.[24] However, in this system, only the strong injected laser's input and output are synchronous, which means that message recovery at the strong injecting laser side will need the transmission-induced delay line. More importantly, the delay line is as twice as the transmission distance. Recent researches indicate that isochronous synchronization[25,26] can be obtained by adding individual feedback to each laser[25] or inserting a relay laser[26] or mirror[27] between them. Isochronous synchronization means that the two lasers' outputs synchronize with no time delay. Thus, when one laser's output reaches the counterpart, it will not synchronize with the counterpart's output, unless the output of the counterpart delays as long as the transmission distance. Hence, the delay line being as long as the transmission distance is indispensable at each side for message extraction. From the above analysis, we can see that applying an extremely unsymmetrical mutual injection system or isochronous synchronization system to practical communication needs delay line which is twofold transmission distance. Apparently, it is unwieldy for practical communication.

Hence, it is extremely urgent to explore another kind of synchronization which has no use for transmission-induced delay line to realize bidirectional

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information flow. This novel kind synchronization must have three terms: each laser's input and output being synchronous to remove the transmission-induced delay line; high synchronization quality to insure the decoding message quality; stability of synchronization to assure long time communication. We make a first step toward realization of such kind synchronization. In unidirectional communication system, it is known to all that the output of the receiver can synchronize with its input under locking-injection strength, which gets rid of the transmission-induced delay line in message decoding at the receiver's side. So we put forward a novel protocol such that synchronization for no delay line can be carried out based on mutual injection-locking.

In this paper, we numerically investigate the case that two semiconductor lasers are mutually coupled with strong optical injection. The simulation results show that the output of each laser can synchronize with its input carrier under strong injection, and imply that both lasers can recover the message without delay line. And our system can extract the message with signal-noise-ratio (SNR) no less than 10 dB within a small difference in amplitudes, and SNR is more sensitive to asymmetry between the message rates.

2. Model

The scheme is depicted in Fig. 1. Two semiconductor lasers (SL_1 and SL_2) mutually couple in a face-to-face configuration. The coupling coefficient from SL_1 (SL_2) to SL_2 (SL_1) is represented with $\kappa_{\rm inj12}$ ($\kappa_{\rm inj21}$), and the coupling time is denoted as $\tau_{\rm c}$. The PD_1, PD_2, PD_3, and PD_4 are the photodetectors used to detect the input signal and output signal of each laser.

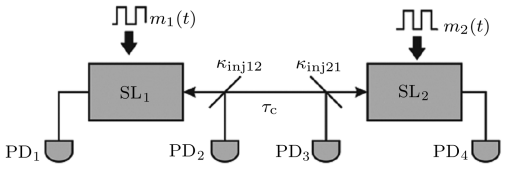


Fig. 1. Scheme of two semiconductor lasers strong mutually coupled in a face-to-face configuration.

The dynamics of SL_1 can be governed by a set of equations as follows:

$$\frac{{\rm d}N_1(t)}{{\rm d}t} = \frac{I}{qV} - \frac{N_1(t)}{\tau_{\rm n}} - g(N_1(t)-N_0)\frac{S_1(t)}{1+\varepsilon S_1(t)}\ , \tag{1}$$

$$\frac{{\rm d}S_1(t)}{{\rm d}t} = \Gamma g(N_1(t)-N_0)\frac{S_1(t)}{1+\varepsilon S_1(t)} - \frac{S_1(t)}{\tau_{\rm p}} + \frac{\Gamma\beta N_1(t)}{\tau_{\rm n}} + 2\frac{\kappa_{\rm inj21}}{\tau_{\rm in}}\sqrt{S_2(t-\tau_{\rm c})S_1(t)}\cos\varepsilon_{2,1}(t), \tag{2}$$

$$\frac{{\rm d}\phi_1(t)}{{\rm d}t} = \frac{1}{2}\alpha\left[\frac{\Gamma g(N_1(t)-N_0)}{1+\varepsilon S_1(t)} - \frac{1}{\tau_{\rm p}}\right] - \frac{\kappa_{\rm inj21}}{\tau_{\rm in}}\sqrt{\frac{S_2(t-\tau_{\rm c})}{S_1(t)}}\sin\varepsilon_{2,1}(t), \tag{3}$$

where subscripts 1 and 2 denote SL_1 and SL_2, respectively, N_1, S_1 and ϕ_1 are carrier density, photon density and phase, respectively, $\varepsilon_{2,1}$ represents the coupling phase of SL_1, defined as follows:

$$\varepsilon_{2,1}(t) = \omega_2\tau_{\rm c} + \phi_1(t) - \phi_2(t-\tau_{\rm c}) + (\omega_2-\omega_1)t, \tag{4}$$

where ω_1, ω_2 are the anglular frequencies of free-running SL_1 and SL_2, respectively.

The frequency detuning between the two lasers is defined as

$$\Delta\nu = (\omega_1-\omega_2)/2\pi. \tag{5}$$

Here we consider the situation that the injection strength is symmetric, i.e. $\kappa_{\rm inj21} = \kappa_{\rm inj12} = \kappa_{\rm inj}$:

$$\kappa_{\rm inj} = (1-R)\sqrt{\frac{r_{\rm inj}}{R}}, \tag{6}$$

where R is the intensity reflectivity of the laser cavity (the same reflectivity for both the front and rear facets of the laser is assumed), $r_{\rm inj}$ represents the percentage of the one laser's output amplitude injected into the counterpart. Note that a similar modeling stands for SL_2 when subscripts 1 and 2 are exchanged.

The internal parameters of the two lasers are assumed to be identical except for optical frequency: the linewidth enhancement factor $\alpha = 5.5$, the differential gain $g = 2.125\times10^{-15}$ m^3/s, the active region volume

$V = 1.5 \times 10^{-16}$ m^3, the carriers lifetime $\tau_{\rm n} = 2$ ns, the photon lifetime $\tau_{\rm p} = 2$ ps, the transparency carrier density $N_0 = 3\times10^{23}$ m^{-3}, the laser cavity round time $\tau_{\rm in} = 9$ ps, the threshold current 12 mA, the spontaneous rate $\beta = 1.0 \times 10^{-5}$, the gain saturation coefficient $\varepsilon = 3.0 \times 10^{-23}$, the optical confine factor $\Gamma = 0.4$, and the coupling delay time $\tau_{\rm c} = 3$ ns.

3. Numerical results

3.1. Synchronization

Synchronization quality is mainly influenced by coupling strength, frequency detuning and bias current. The correlation coefficient (CC) is an important parameter describing synchronization quality, which can be defined as:[28]

$$\mathrm{CC}(\Delta t) = \frac{< [X(t) - < X(t) >][Y(t+\Delta t) - < Y(t+\Delta t) >] >}{< |X(t) - < X(t) > |^2 >^{1/2} < |Y(t+\Delta t) - < Y(t+\Delta t) > |^2 >^{1/2}}, \tag{7}$$

where $< \cdot >$ means time average, $X(t)$ and $Y(t)$ are the time dependent intensities of signals to be estimated, respectively.

We concentrate on the synchronization performance between the output $P_1(t)$ of SL_1 and its input $P_2(t-\tau_{\rm c})$ (PD_1 and PD_2); also the synchronization performance between the output $P_2(t)$ and input $P_1(t-\tau_{\rm c})$ of SL_2 is focused on (PD_3 and PD_4), simultaneously.

Figure 2 shows an example of synchronization between the output and input of SL_1. The waveforms are almost similar, as exhibited in Figs. 2(a) and 2(b), indicating synchronization between them. A standard tool for detecting synchronization, the cross-correlation function $\mathrm{CC}(\Delta t)$ defined in Eq. (7), is plotted in Fig. 2(c). A high peak nearly to 1.0, locating at zero time shift, also means that the output and input of SL_1 are synchronous with no time delay. The synchronization quality is investigated by plotting the output intensity versus input intensity, as displayed in Fig. 2(d). A cloud of points nearly arranged around 45° straight line can be obtained. Similar results for the synchronization between the output of SL_2 and its input are shown in Fig. 3. The calculated CCs are 0.9722 and 0.9544, respectively.

All the above results indicate that the output and input of each laser are synchronous under mutual injection-locking coupling.

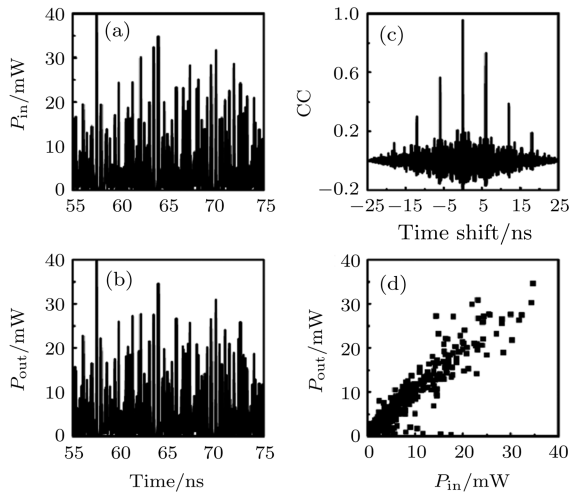


Fig. 2. (a), (b) Time series of the output and input of SL_1, respectively; (c) cross-function of the output and input of SL_1; (d) correlation plots of the output and input of SL_1, for these four cases, the coupling efficient $\kappa_{\rm inj} = 0.70$, bias current $I = 1.5I_{\rm th}$ and $\Delta\nu = 2.0$ GHz.

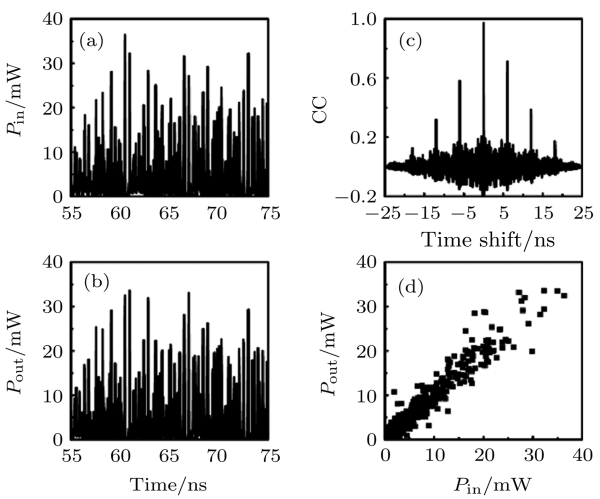


Fig. 3. (a), (b) Time series of the output and input of SL_2, respectively; (c) cross-function of the output and input of SL_2; (d) correlation plots of the output and input of SL_2, all parameters for these four cases are the same as those of Fig. 2.

3.2. Demonstration of bidirectional communication without delay line

Next the bidirectional message transmission is verified by using the proposed scheme. We add 1.0 Gbit/s message by current modulation to each laser, and the procedure to decipher the message at each side is exhibited in Fig. 4.

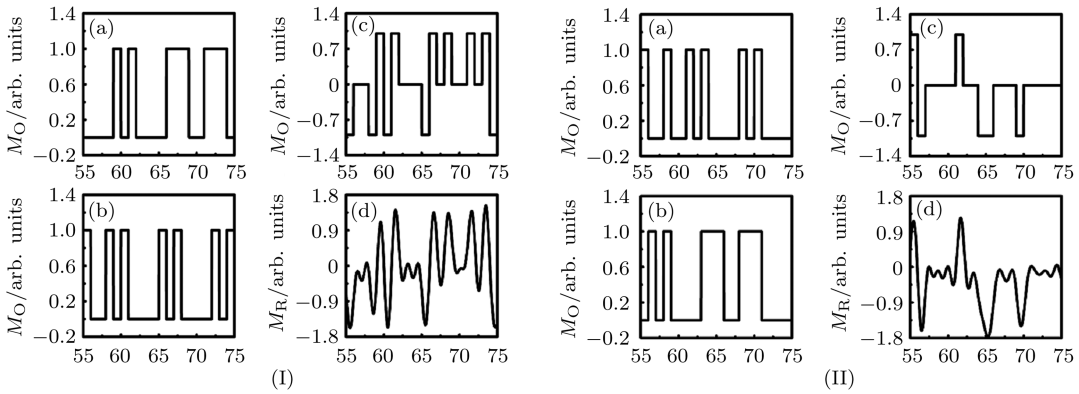


Fig. 4. Illustration of message decoding processes. Figure (I) represents message extraction at SL_1 side: (a) the message waveform of SL_2 received by SL_1 at time t; (b) the message waveform of SL_1 at time t; (c) the difference of message $(m_2(t-\tau_c)-m_1(t))$, which is reconstructed by optical power difference $(P_2(t-\tau_c)-P_1(t))$; (d) the difference of input optical power and output optical power filtered by a low pass filter with a cutoff frequency of 0.7 GHz, Figure (II) denotes message extraction at SL_2 side, (a), (b), (c) (d) have the same meanings as those of figure (I).

For example, the procedure to decipher the message m_2 at SL_1 side is displayed in Fig. 4(I) as follows: (a) denotes the message of SL_2 received by SL_1, message transmission from SL_2 to SL_1 needs time, so when the message sent by SL_2 arrives at SL_1 side, it will become $m_2(t-\tau_c)$; (b) represents the message $m_1(t)$ encrypted on SL_1 at time t; (c) represents the difference of the message; (d) denotes the difference between the input optical power $P_2(t-\tau_c)$ and output optical power $P_1(t)$. Figure 4 reveals that the difference between optical power allows SL_1 to reproduce the difference of messages with no lag compensation $[m_2(t-\tau_c)-m_1(t)]$. After digitalizing the difference, only the sender of m_1 can decrypt the content of m_2 by adding m_1 to the digitalized difference. And the procedure to decipher the message m_1 at SL_2 side is analogous to that at SL_1 side. More importantly, our system has no use for the transmission-induced delay line to decoding message at each side.

In practice, the message amplitudes and bit rates of one side are likely deviation from that of the other side. Wherefore, it is absolutely necessary to study the effects of different message amplitudes and bit rates on the SNR of recovered message. Figure 5 displays the effect of message amplitudes difference on the extracted message SNR. Within small amplitudes difference (±6%), the two sides can decode the message with SNR more than 10 dB, nevertheless SNR declines quickly when the message amplitudes difference exceeds 6%. On the other hand, a small message rates difference ($\geq \pm 1.6\%$) can prevent a proper message bidirectional transmission, as exhibited in Fig. 6. The rigorous qualification enhances message security.

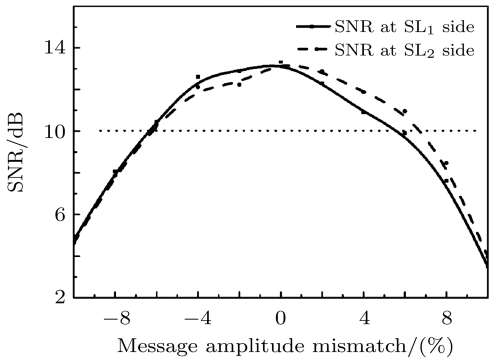


Fig. 5. Influence of message amplitudes mismatch on SNR.

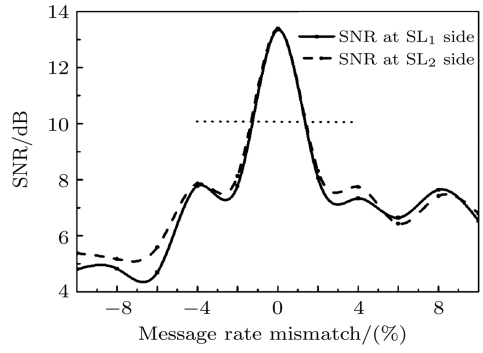


Fig. 6. Status of SNR with different message bit rates.

3.3. Analysis of security

Now it is worth analysing the security aspects of our scheme. The outputs of the two lasers are accessible from the same communication channel. As a result, an eavesdropper can easily obtain the difference $P_1 - P_2$ of optical power which may reproduce the difference between the messages, as discussed above. Thus, the message difference '1' means that the bit sent by SL_1 is a '1' while the one associated with SL_2 is a '0'. A similar conclusion holds when the message difference is '–1'. However, when the eavesdropper obtains message difference '0', she has no clue as to which bits are being sent. By calculation with statistical probability methods, the BER of the eavesdropper is 0.5, which means that the eavesdropper fails to recover the message. However, the eavesdropper can use another laser SL_3 with another message m_3 mutually coupled with SL_1 to eavesdrop the message m_1. But she is insensible of the message rates and amplitudes, so she can hardly recover the message m_1 correctly.

4. Conclusion and discussion

In conclusion, two mutually injected lasers present synchronization between each laser's output and input under strong coupling strength. This kind of synchronization attributes to injection-locking. As is known, a laser subjected to optical injection will tote the information of injection signal. When the injected signal reaches a high value (strong injection), the injected laser will export the same signal as the injected signal, which is called 'injection locking'. It is based on mutual injection locking that we carried out synchronization between the output of each mutually injected laser and its input carrier. This kind of synchronization is beneficial to implement bidirectional communication without transmission-induced delay line. The scheme needs to negotiate a key such as code length. We believe that our scheme is of great benefit for the realization of practical bidirectional communication.

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