Chaos synchronization and communications of bidirectionally versus unidirectionally coupled bandwidth-enhanced semiconductor lasers

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Both bidirectional and unidirectional synchronizations of feedback-induced chaos between bandwidth-enhanced semiconductor lasers by strongly injection-locked technique are analyzed and compared theoretically, and the related communication performances of both systems are also preliminarily examined. With extra external optical injection, the modulation bandwidth of chaos synchronization system can be greatly enhanced about three times under given parameters. The two systems both possess good robustness to parameters mismatching, where the bidirectional system shows higher quality synchronization than the unidirectional one within a broad range of mismatched parameters. Both systems can efficiently transmit high-speed signal.

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1. Introduction

Since the first prediction of chaos synchronization by Pecora and Carroll in 1990 [1], synchronization of chaotic oscillations in semiconductor lasers (SLs) has been widely studied because of its potential application in secure communications [2-8]. Generally, a SL subjected to optical feedback, optical injection or optoelectronic feedback can behave rich nonlinear dynamic states including chaotic intensity fluctuations [9-11], where a SL with optical feedback can be served as one of good candidate source generators of chaos secure communications because it can generate high-dimensional broadband chaos and then ensure a high level of security [11-13]. In recent years, many schemes of secure communications based on feedback-induced chaos in SLs have been proposed, and the systematical performances of synchronization and data communications have been investigated theoretically and experimentally [14-19]. It is well known that signal transmission rate of direct-modulation optical communication system based on SLs is limited by their modulation bandwidths, which is determined by the laser's relaxation oscillation frequency and is usually of the order of several gigahertzes. During the past two decades, many efforts have been done in order to enlarge the modulation bandwidth of laser, where the strongly optical injection locking from another laser has been proven to be one of the valid approaches [20-26]. Similarly, in order to increase the signal transmission rate of SLs based chaos communication system, the bandwidth-enhanced unidirectional chaos synchronization between SLs was proposed through using strongly injection-locking technique [26], where both transmitter laser and receiver laser are respectively subjected to external optical injection from different lasers. In this paper, we extend the systematical frame of [26] to the case of bidirectional communications. Bidirectional coupled system has received considerable attention [27-32] during past few years due to its some unique merits in secret communications such as good robustness to parameter mismatches [27] and great potential in transmission through a public channel [28], where nonlinear dynamics of such mutually coupled SL system have been studied and the influences of the transmission path and feedback/coupling strength on synchronization are also addressed [29-31]. In this work, the bidirectional and unidirectional synchronizations of feedback-induced chaos between bandwidth-enhanced semiconductor lasers by strongly injection-locked technique have been examined and compared. For the purpose of comparison, based on the experimental system configuration in Ref. [27], the closed-loop configuration of bidirectional system is used for assuring stable isochronal synchronization [32], while unidirectional system adopts an open-loop configuration. Simulated results show that the modulation bandwidth can be enhanced about three times under given parameters, and both systems can achieve a good synchronization and possess a good robustness to parameters mismatching. Furthermore, 6Gb/s high speed chaotic data transmission based on bidirectional or unidirectional system is preliminarily demonstrated.

2. Systematical configuration and theory

Fig. 1 displays the systematical configuration. The output of SL1 is divided into two beams, where one is fed back to SL1 itself with a feedback strength σ_t by the external mirror M1 and the other is injected into the SL2 with an injection strength ρ_{tr}. During bidirectional communications, the SL2 output undergoes a similar process with a feedback strength σ_r and an injection strength ρ_{rt}. The unidirectional operation can also be realized just by inserting an isolator (IS3) between the BS1 and BS3 and removing the reflector M2. Under special operation conditions, the bidirectional or unidirectional chaos synchronization between the SL1 and the SL2 can be realized. For the purpose of the modulation bandwidth enhancement, both the SL1 and the SL2 are respectively injected by external semiconductor lasers with similar device parameters, i.e. ISL1 and ISL2. Without feedback, both the SL1 and the SL2 will oscillate at stable injection-locked states. In this setup, τ_t and τ_r are delayed feedback time of the SL1 and the SL2, respectively, τ_{tr} and τ_{rt} are the delayed injection times between the SL1 and the SL2, $\eta_{inj,t}$ is the external injection strength from ISL1 to SL1 and $\eta_{inj,r}$ is the external injection strength from ISL2 to SL2. In Figure 1, for bidirectional communications, message m_1(t) is encoded into SL1 by directly current modulation and transmitted towards SL2, and another different message m_2(t) is sent from SL2 to SL1. Once this system synchronizes, outputs of SL1 and SL2 are dropped from BS1 and BS2 (or BS3 and BS4) and converted into electronic signals by PD1 and PD2 (or PD3 and PD4), thus one can obtain the message difference m_2(t)-m_1(t) (or m_1(t)-m_2(t)). Finally, according to the message difference and m_1(t) (or m_2(t)) , m_2(t) sent from SL2 (or m_1(t) sent from SL1) can be decoded in SL1 port (or SL2 port).

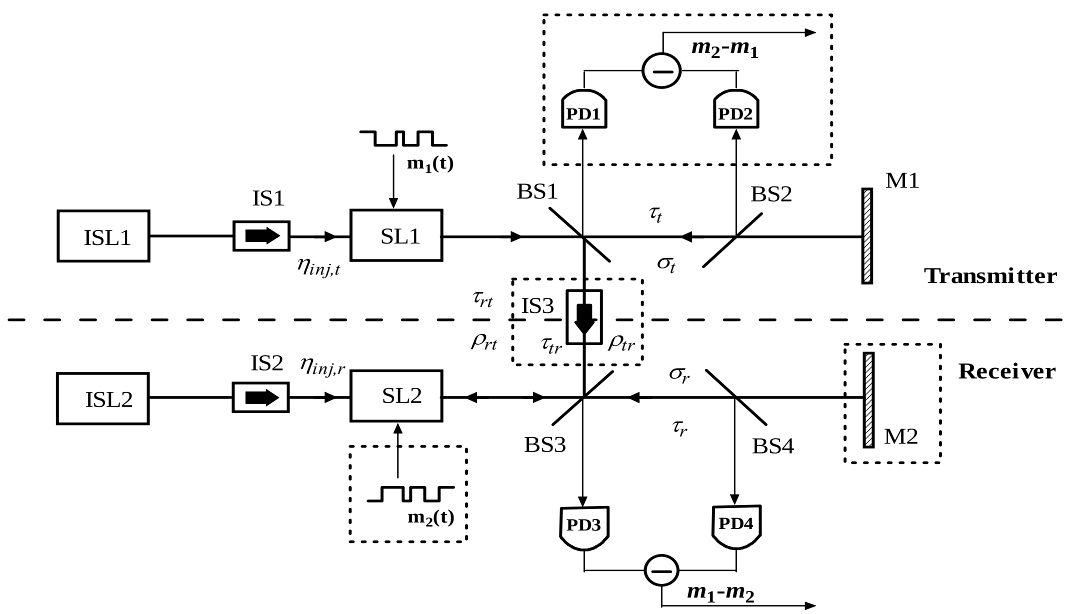

Fig. 1. Schematic configuration of the bidirectional and unidirectional synchronization system of feedback-induced chaos between strongly injection-locked semiconductor lasers. SL1, SL2, transmitter and receiver lasers; ISL1, ISL2, external lasers; IS1-IS3, optical isolators; BS1-BS4, beam splitter; PD1-PD4, photodetector; M1 and M2, mirrors.

In such a scheme, this system can be theoretically described by a set of following modified rate equations [26] including the laser fields $E_{t,r}$, the phases $\varphi_{t,r}$, and the carrier number $N_{t,r}$ in active region. For the SL1

$$\frac{dE_t(t)}{dt}=\frac{1}{2}\left[G_{N,t}(N_t-N_0)-\frac{1}{\tau_p}\right]E_t(t)+\frac{\eta_{inj,t}}{\tau_{in}}E_{ext}(t)\cos\theta_t+\frac{\sigma_t}{\tau_{in}}E_t(t-\tau_t)\cos\xi_t+\frac{\rho_{rt}}{\tau_{in}}E_r(t-\tau_{rt})\cos\beta_{rt}+F_{et}(t) \tag{1}$$

$$\frac{d\phi_t(t)}{dt}=\frac{1}{2}\alpha\left[G_{N,t}(N_t-N_0)-\frac{1}{\tau_p}\right]-\frac{\eta_{inj,t}}{\tau_{in}}\frac{E_{ext}(t)}{E_t(t)}\sin\theta_t-\frac{\sigma_t}{\tau_{in}}\frac{E_t(t-\tau_t)}{E_t(t)}\sin\xi_t-\frac{\rho_{rt}}{\tau_{in}}\frac{E_r(t-\tau_{rt})}{E_t(t)}\sin\beta_{rt} \tag{2}$$

$$\frac{dN_t(t)}{dt}=\frac{J_t}{ed}-\frac{N_t(t)}{\tau_s}-G_{N,t}(N_t-N_0)E_t^2(t)+F_N(t) \tag{3}$$

with

$\theta_t = \phi_t(t) - \Delta\omega_t t$, $\xi_t = \phi_t(t) - \phi_t(t-\tau_t) + \omega_t\tau_t$, $\beta_{rt} = \phi_t - \omega_t\tau_{rt} - \Delta\omega_{rt} t$.

and for the SL2

$$\frac{dE_r(t)}{dt} = \frac{1}{2}\left[G_{N,r}(N_r - N_0) - \frac{1}{\tau_p}\right]E_r(t) + \frac{\eta_{inj,r}}{\tau_{in}}E_{ext}(t)\cos\theta_r + \frac{\sigma_r}{\tau_{in}}E_r(t-\tau_r)\cos\xi_r + \frac{\rho_{tr}}{\tau_{in}}E_t(t-\tau_{tr})\cos\beta_{tr} + F_{er}(t) \tag{4}$$

$$\frac{d\phi_r(t)}{dt} = \frac{1}{2}\alpha\left[G_{N,r}(N_r - N_0) - \frac{1}{\tau_p}\right] - \frac{\eta_{inj,r}}{\tau_{in}}\frac{E_{ext}(t)}{E_r(t)}\sin\theta_r - \frac{\sigma_r}{\tau_{in}}\frac{E_r(t-\tau_r)}{E_r(t)}\sin\xi_r - \frac{\rho_{tr}}{\tau_{in}}\frac{E_t(t-\tau_{tr})}{E_r(t)}\sin\beta_{tr} \tag{5}$$

$$\frac{dN_r(t)}{dt} = \frac{J_r}{ed} - \frac{N_r(t)}{\tau_s} - G_{N,r}(N_r - N_0)E_r^2(t) + F_{Nr}(t) \tag{6}$$

where $\theta_r = \phi_r(t) - \Delta\omega_r t$, $\xi_r = \phi_r(t) - \phi_r(t-\tau_r) + \omega_r\tau_r$, $\beta_{tr} = \phi_r - \omega_r\tau_{tr} - \Delta\omega_{tr} t$. Subscripts t and r stand for the SL1 and the SL2, $\Delta\omega_t$ is the frequency difference between SL1 and ISL1, and $\Delta\omega_r$ is the frequency difference between SL2 and ISL2. In this model, the amplitude and carrier noise ($F_{ei}=[2R_{sp}N_i]^{1/2}\zeta_{ei}$ and $F_{Ni}=[2R_{sp}N_i]^{1/2}\zeta_{ei}+[2N_i/\tau_s]^{1/2}\zeta_{Ni}$) are considered as Gaussian random variables with $<\zeta_{ei}>=<\zeta_{Ni}>=0$ and $<\zeta_{ei}^2> =<\zeta_{Ni}^2>=1$, where i is chosen to be 't' or 'r' to denote the SL1 or the SL2 respectively. The other parameters and their values used in numerical calculations are given in Table 1.

Table 1. List of simulation parameters.

Symbol	Parameter	Value
α	Linewidth enhancement factor	3
G_N	Linear gain coefficient	$8.4\times10^{-13} m^3 s^{-1}$
τ_p	Photon lifetime	1.93ps
τ_s	Carrier lifetime	2.04ns
τ_{in}	Round-trip time in the laser cavity	8ps
τ_t, τ_r	Delayed feedback time of two lasers	4ns
τ_{tr}, τ_{rt}	Delayed injection time of two lasers	4ns
N_{th}	Threshhold carrier density	$2.02\times10^{24} m^{-3}$
$\eta_{inj,t}$, $\eta_{inj,r}$	External optical injection rates	0.25
σ_t, σ_r	External optical feedback rates	0.22
ρ_{tr}, ρ_{rt}	Injection rate of mutual couple	0.22
R_{sp}	Spontaneous emission rate	1.28×10^{12}
J_t, J_r	Injected currents	$1.3\times J_{th}$
ω_t, ω_r	Angular frequency of free-running	200THz
$\Delta\omega_t$, $\Delta\omega_r$	Frequency difference between the laser and its external injection laser	-4GHz

3. Results and discussion

For simplification, we consider the isochronal synchronization case namely so-called chaos synchronization with zero time delay. Under this circumstance, τ_{tr} and τ_{rt} are assumed to be same for bidirectional system while τ_t and τ_{tr} are assumed to be same for unidirectional system, although these times can be chosen to be different in our model. With this assumption, we can directly examine the synchronization from the time series, and conveniently calculate the cross-correlation degree without shifting the output time series of SL1 and SL2 in time domain.

The rate equations can be numerically solved by the fourth-order Runge-Kutta method. Calculations show that the chaotic carrier frequency of SL1 is greatly enhanced under strong external optical injection, and the relaxation oscillation frequency is increased from about 2.7GHz to about 8GHz. The origin of this phenomenon may be attributed to the interference between the optical frequency of the original laser oscillation and the shifted frequency of external strong optical injection [21]. Therefore, the strong optical injection technique can greatly improve the chaotic carrier frequency and will be helpful in constructing a high-speed chaos communication system.

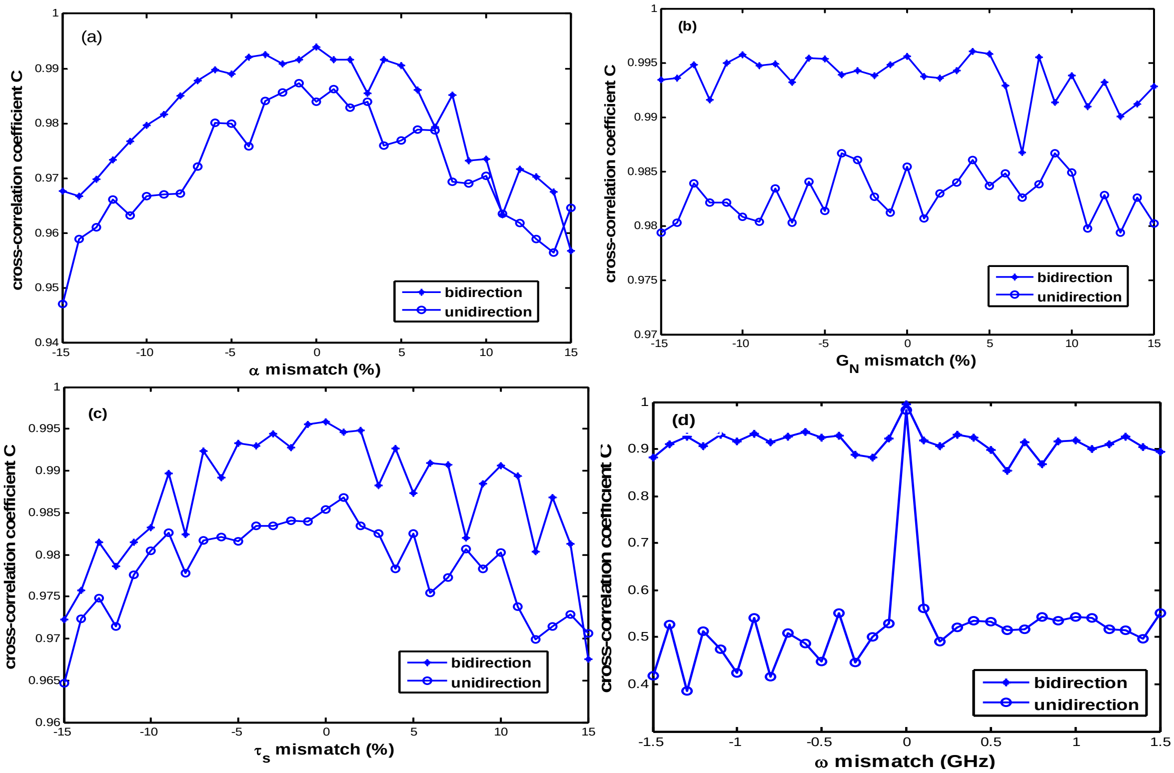

Fig. 2. Variation of correlation coefficient C with different mismatched parameters, where (a), (b), (c) and (d) corresponds to mismatched α, G_N, τ_s and ω, respectively.

In the following, we will compare the parameters mismatching robustness between unidirectional and bidirectional optical coupling systems. Here, we consider the effects of four typical parameters' mismatch, namely the linewidth enhancement factor α, the linear gain coefficient G_N, the carrier lifetime τ_s and the free-running angular frequency ω, on the synchronization quality. To evaluate the synchronization quality, we define the cross-correlation coefficient C as follows

$$C = \frac{\left\langle \left(P_t(t) - \left\langle P_t(t)\right\rangle\right)\left(P_r(t) - \left\langle P_r(t)\right\rangle\right)\right\rangle}{\sqrt{\left\langle \left(P_t(t) - \left\langle Pt(t)\right\rangle\right)^2\right\rangle \left\langle \left(P_r(t) - \left\langle P_r(t)\right\rangle\right)^2\right\rangle}} \tag{7}$$

where the output power is calculated by $P=[hc\omega\alpha_m/(4\pi\mu_g)]|E|^2$ (h is the Plank constant, c is the speed of light in vacuum, α_m=45cm^{-1} is the facet loss and μ_g= 4 is the group refractive index).

It is well known that in order to achieve high-quality chaos synchronization, it is important to match the parameters of these two lasers. However, one cannot to find two identical SLs in practice. Moreover, the inner parameters of SLs usually degrade during operation due to the temperature, aging etc. [33, 34].

Therefore, it is necessary to investigate the effects of parameter mismatches between the lasers on the quality of synchronization. Fig. 2 shows how the cross-correlation coefficient C of bidirectional and unidirectional system vary with the parameter mismatches within a mismatched range from -15% to 15%. From these diagrams, one can observe that the cross-correlation coefficient C varies from about 0.95 to 0.99 except for mismatched ω with a mismatched range from -1.5GHz to 1.5GHz as shown in Fig. 2 (d). From Fig. 2 (d), mismatched angular frequency between the SL1 and SL2 has greater effect on the system synchronization than other mismatched parameters. The unidirectional system is more sensitive to mismatched angular frequency than the bidirectional one, which is in accord with previous related reports [27], [35], [36]. The best chaos synchronization is achieved at zero mismatch of ω, and the cross-correlation coefficients of both systems rapidly decrease with the increase of the detuning value. As for other three mismatched parameters, one can see that the cross-correlation coefficients remain a high level and vary smoothly. Obviously, the robustness of bidirectional system to mismatched parameter is better than that of unidirectional one. The reason maybe lie on that the bidirectional system has a better symmetric feature than the unidirectional system.

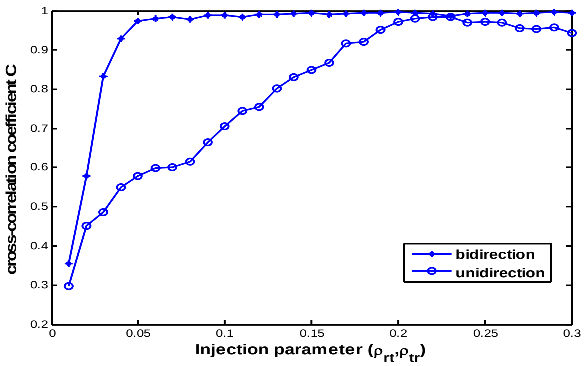

Fig. 3. Correlation coefficient C versus the injection parameter for unidirectional and bidirectional systems.

In Fig. 3, we show the effect of injection parameter ρ on C. For the convenience of comparison, we consider the symmetrically configured system, and ρ_{tr} is the injection parameter for the unidirectional system while ρ_{tr} and ρ_{rt} (ρ_{tr}=ρ_{rt}) are the injection parameters for the bidirectional one. From this diagram, it can be seen that the correlation coefficient increases with increased ρ. The bidirectional system reaches a good synchronization faster and has a larger range of good synchronization than the unidirectional system.

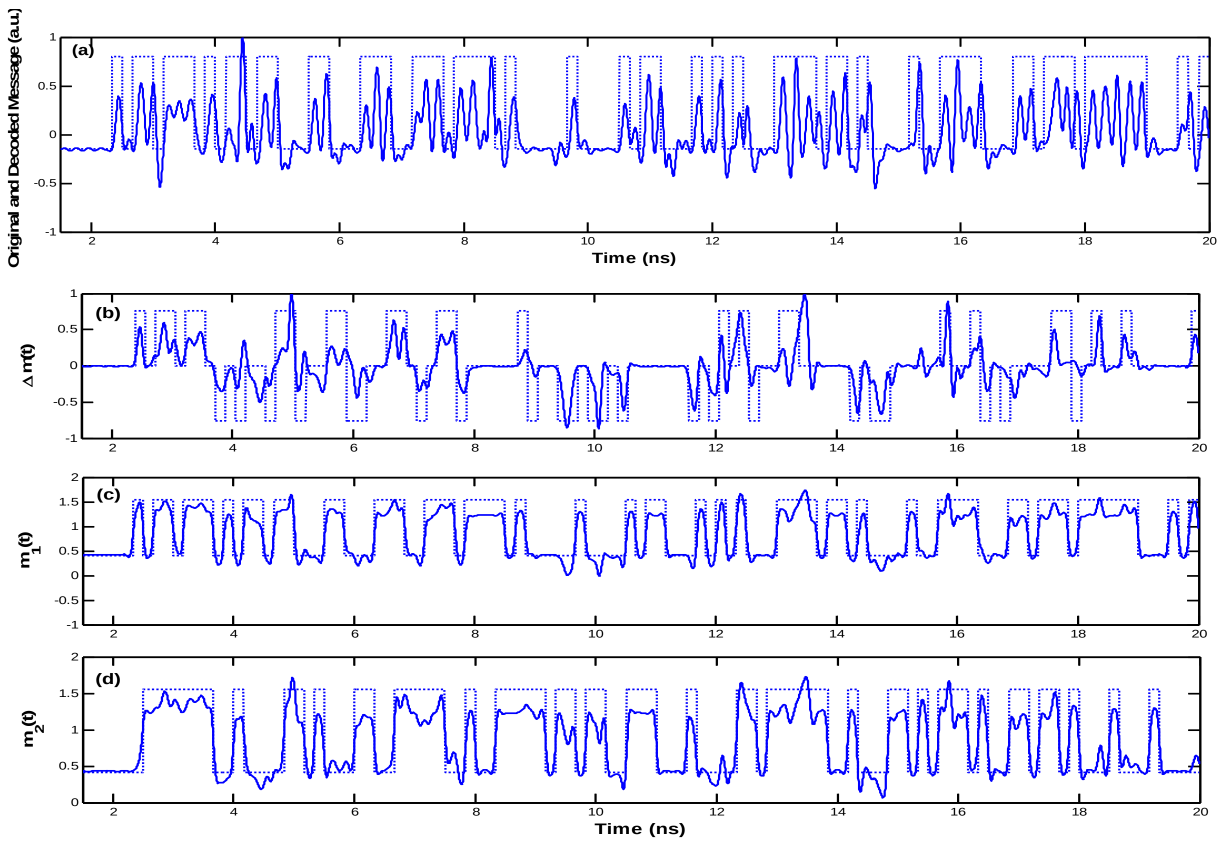

Fig. 4. Bandwidth-enhanced chaos communications with 6Gb/s signal for the injection delayed time is equal to the feedback delayed time. Fig. (a) corresponds to unidirectional chaos communications, where the dashed line is the encoded message in SL1 port and the solid line is the decoded message in SL2 port. Figs. (b)-(d) correspond to bidirectional chaos communications, where (b) the dashed line is the encoded message difference and the solid line is the decoded message difference, (c) the dashed line is the encoded message in SL1 port and the solid line is the decoded message in SL2 port, (d) the dashed line is the encoded message in SL2 port and the solid line is the decoded message in SL1 port.

Finally, we examine the communication performances of both chaos synchronization systems as shown in Fig. 4. Here, the signal encryption scheme is chosen to be chaos-shift keying (CSK). The bit rate of the random digital sequence is 6Gb/s, which is larger than the relaxation oscillation frequency of the laser at free-running. The modulation degree is m=0.05. From these figures, it can be seen that message transmission can be realized for both systems, while the bidirectional system has a relatively better performance than the unidirectional system. However, the signal decoding effect is not perfect, which maybe due to the decoding method [37, 38].

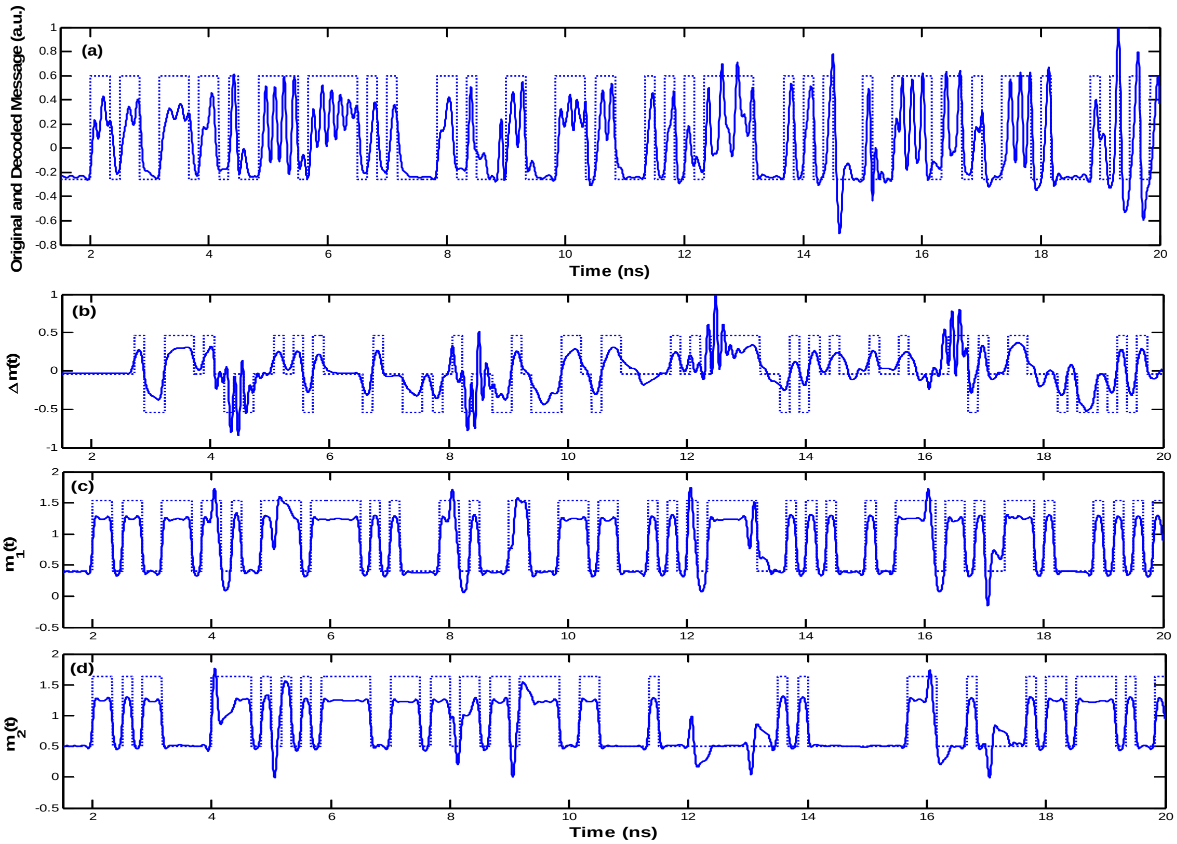

Fig. 5. Bandwidth-enhanced chaos communications with 6Gb/s signal when the injection delayed time is twice of the feedback delayed time. Figure (a) corresponds to unidirectional chaos communications, where the dashed line is the encoded message in SL1 port and the solid line is the decoded message in SL2 port. Figure (b)-(d) correspond to bidirectional chaos communications, where (b) the dashed line is the encoded message difference and the solid line is the decoded message difference, (c) the dashed line is the encoded message in SL1 port and the solid line is the decoded message in SL2 port, (d) the dashed line is the encoded message in SL2 port and the solid line is the decoded message in SL1 port.

It should be pointed out that above results are obtained based on this assumption that the delayed injection time is equal to the delayed feedback time. However, it is difficult to satisfy in practice. In the following, we will preliminarily consider this general case that the delayed injection time is longer than the delayed feedback time. Fig. 5 shows the corresponding communication performances of both chaos synchronization systems for the delayed injection time is twice of the delayed feedback time (i. e., τ_t=τ_r=4ns and τ_{tr}=τ_{rt}=8ns). From this diagram, one can observe that the system still can decode the message effectively. Further simulations show that when the delayed injection time is much longer than the delayed feedback time, the communication quality can not be guaranteed. Under this circumstance, some possible alternative approaches such as inserting a partially transparent mirror in the transmission path [29] should be used to solve this problem. However, this content is beyond this work.

4. Conclusions

In summary, we have analyzed and compared the bidirectional and the unidirectional synchronization characteristics of feedback-induced chaos in strongly injection-locked semiconductor lasers, and the related communications performances at a high bit rate (6Gb/s) of both systems also have been preliminarily examined. The results show that modulation bandwidth of such system can be greatly enhanced about three times by extra external strong optical injection, which affords a possibility to transmit a higher bit rate signal than the relaxation oscillation frequency of the laser at free-running. The robustness of the bidirectional system to mismatched parameters is better than that of the unidirectional system. The frequency detuning between the SL1 and SL2 has a strong effect on the quality of synchronization, and the best chaos synchronization is located at zero mismatch of ω. Other parameters, for example α, G_N and τ_s, have slight effects on the chaos synchronization.

Within certain mismatched parameter range, both systems possess a good robustness. Under CSK encryption, both systems can efficiently realize the signal transmission at a higher bit rate than the relaxation oscillation frequency of the laser at free-running.

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References

[1] L. M. Pecora, T. L. Carroll, Phys. Rev. Lett. **64**, 821 (1990).
[2] Y. Liu, H.F. Chen, J.M. Liu, P. Davis, T. Aida, Phys. Rev. E **63**, 031802 (2001).
[3] S. Tang, J. M. Liu, IEEE J. Quantum Electron. **39**, 708 (2003).
[4] X. F. Li, W. Pan, B. Luo, D. Ma, Appl. Opt. **45**, 2510 (2006).
[5] W. L. Zhang, W. Pan, B. Luo, X. F. Li, X. H. Zhou, M. Y. Wang, Appl. Opt. **46**, 7262 (2007).
[6] S. Ebisawa, S. Komatsu, Appl. Opt. **46**, 4386 (2007).
[7] A. Murakami, J. Ohtsubo, Phys. Rev. A **65**, 033826 (2002).
[8] T. Deng, G. Q. Xia, L. P. Cao, J. G. Chen, X. D. Lin, Z. M. Wu, Opt. Commun. **282,** 2243 (2009).
[9] X. Wang, G. Xia, Z. Wu, J. Opt. Soc. Am. B **26**, 160 (2009).
[10] Q. Yang, Z. Wu, J. Wu, G. Xia, Opt. Commun. **281**, 5025 (2008).
[11] J. Mørk, B. Tromborg, J. Mark, IEEE J. Quantum Electron. **28**, 93 (1992).
[12] J. Ohtsubo, IEEE J. Quantum Electron. **38**, 1141 (2002).
[13] A. Locquet, C. Masoller, C. R. Mirasso, Phys. Rev. E **65**, 056205 (2002).
[14] P. Colet, R. Roy, Opt. Lett. **19**, 2056 (1994).
[15] Y. Liu, H. F. Chen, J. M. Liu, P. Davis, T. Aida, IEEE J. Quantum Electron. **48**, 1484 (2001).
[16] S. Tang, J. M. Liu, IEEE J. Quantum Electron. **39**, 1468 (2003).
[17] A. Sánchez-Díaz, C. R.Mirasso, P. Colet, P. García-Fernández, IEEE J. Quantum Electron. **35**, 292 (1999).
[18] J. M. Liu, H. F. Chen, S. Tang, IEEE J. Quantum Electron. **48**, 1475 (2001).
[19] J. M. Liu, H. F. Chen, S. Tang, IEEE J. Quantum Electron. **38**, 1184 (2002).
[20] T. B. Simpson, J. M. Liu, IEEE Photon. Technol. Lett. **9**, 1322 (1997).
[21] A. Murakami, K. Kawashima, K. Atsuki, IEEE J. Quantum Electron. **39**, 1196 (2003).
[22] N. H. Zhu, W. Li, J. M. Wen, W. Han, W. Chen, and L. Xie, IEEE J. Quantum Electron. **44**, 528 (2008).
[23] S. F. Liu, G. Q. Xia, J. G. Wu, L. F. Li, Z. M. Wu, Acta Phys. Sin. **57,** 1502 (2008).
[24] J. Wang, M. K. Haldar, L. Li, F. V. C. Mendis, IEEE Photon. Technol. Lett. **8**, 34 (1996).
[25] X. J. Meng, T. Chau, M. C. Wu, Electron. Lett. **34**, 2031 (1998).
[26] Y. Takiguchi, K. Ohyagi, J. Ohtsubo, Opt. Lett. **28**, 319 (2003).
[27] N. Gross, W. Kinzel, I. Kanter, M. Rosenbluh, L. Khaykovich, Opt. Commun. **267**, 464 (2006).
[28] E. Klein, N. Gross, E. Kopelowitz, M. Rosenbluh, L. Khaykovich, W. Kinzel, I. Kanter, Phys. Rev. E **74,** 046201 (2006).
[29] R. Vicente, C. R. Mirasso, Opt. Lett. **32**, 403 (2007).
[30] M. C. Chiang, H. F. Chen, J. M. Liu, IEEE J. Quantum Electron. **41**, 1333 (2005).
[31] M. C. Chiang, H. F. Chen, J. M. Liu, Opt. Commu. **261,** 86 (2006).
[32] E. Klein, N. Gross, M. Rosenbluh, W. Kinzel, L. Khaykovich, I. Kanter, Phys. Rev. E **73,** 066214 (2006).
[33] H. Temkin, C. L. Zipfel, V. G. Keramidas, J. Appl. Phys. **52**, 5377 (1981).
[34] M. Fukuda, Reliability and degradation of semiconductor lasers and LEDs, Norwood, MA: Artech House, 1991.
[35] Y. Liu, P. Davis, Y. Takiguchi, T. Aida, S. Saito, J. M. Liu, IEEE J. Quantum Electron. **39,** 269 (2003).
[36] R. Vicente, T. Pérez, C. R. Mirasso, IEEE J. Quantum Electron. **38**, 1197 (2002).
[37] A. Murakami, K. A. Shore, Phys. Rev. A **72**, 053810 (2005).
[38] X. F. Li, W. Pan, B. Luo, D. Ma, IEEE J. Quantum Electron. **42**, 953 (2006).

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