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Chaotic communications using synchronized semiconductor lasers with optoelectronic feedback

Jia-Ming Liu *, Shuo Tang

Electrical Engineering Department, University of California Los Angeles, Los Angeles, CA 90095-159410, USA

Presented by Guy Laval

Abstract

The concepts and progress made in the research on chaotic communications using semiconductor lasers with optoelectronic feedback are reviewed. Recent experimental results are presented to demonstrate the feasibility and performance of this chaotic communication system at a high bit rate of 2.5 Gb/s with a message encoding scheme of additive chaos modulation. The message is completely blended into the chaotic fluctuations in the time domain and is spread over the broad chaotic spectrum in the frequency domain. This system has the ability to maintain identical synchronization for high performance at a high message bit rate and at a large message strength. ***To cite this article: J.-M. Liu, S. Tang, C. R. Physique 5 (2004).***

Résumé

Transmissions de signaux chaotiques impliquant des lasers semiconducteurs synchronisés et soumis à une contre réaction optoélectronique. Les concepts et les avancées réalisées dans la recherche sur les communications chaotiques impliquant des lasers semiconducteurs soumis à une contre-réaction optoélectronique sont passés en révue. Des résultats récents sont présentés ; ceux-ci démontrent la faisabilité et les performances de ce type de communication chaotique jusqu'à des débits de 2.5 Gbits/s, pour lequel un message est temporellement complètement masqué dans les fluctuations chaotiques, et spectralement étalé sur toute la bande de fréquence du chaos. Ce système est capable de maintenir un régime de « synchronisation similaire », nécessaire pour assurer de bonnes performances avec des messages à haut débit, et à forte amplitude. ***Pour citer cet article : J.-M. Liu, S. Tang, C. R. Physique 5 (2004).***

Keywords: Chaotic communication; Chaos modulation; Chaos masking; Chaos shift keying

Mots-clés : Communication par chaos ; Modulation chaotique ; Masquage chaotique ; Codage par commutation de chaos

1. Introduction

Communications with messages encoded in chaotic optical waveforms and decoded through chaos synchronization have been investigated and demonstrated using semiconductor lasers [1–6] and fiber ring lasers [7–10]. Semiconductor lasers are of particular interest in this application for many reasons: they are the established light sources for optical communication systems. They have broad bandwidths able to support high-bit-rate messages. They are able to generate chaotic waveforms of rich complexity under proper perturbations because of their intrinsic nonlinearity. In addition, semiconductor lasers are compact

* Corresponding author.
E-mail address: liu@ee.ucla.edu (J.-M. Liu).

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and electrically pumped by current injection. Thus, semiconductor lasers are chosen in the majority of research activities in this area.

A single-mode semiconductor laser does not naturally have chaotic dynamics because it is a so-called class B laser that has only two dynamical dimensions. Two approaches to generate chaotic waveforms using a semiconductor laser have been considered in the research of chaotic communications. One is to directly induce chaotic dynamics in a semiconductor laser by increasing the dynamical dimension of the laser through a proper external perturbation, such as feedback or injection [1–6]. The other is to use a semiconductor laser merely as a light source while generating the chaotic optical waveform through an external nonlinear optical system [11–13]. In this paper, we consider only single-mode semiconductor lasers with optoelectronic feedback, which belong to the first category.

With optoelectronic feedback, a single-mode semiconductor laser can have chaotic dynamics in certain operating conditions. In a chaotic communication system using semiconductor lasers with optoelectronic feedback, a message is encoded in the chaotic waveform generated by such a laser serving as the transmitter. The message can be decoded at the receiving end by synchronizing the dynamics of a matching laser serving as the receiver to the chaotic dynamics of the transmitter. Various message encoding and decoding schemes have been considered and demonstrated for chaotic communications [14–17]. The performance of the most common schemes have been studied and compared for different chaotic optical communication systems using semiconductor lasers [14]. In particular, detailed experimental studies on the performances of these message encoding and decoding schemes have been carried out for chaotic optical communications using semiconductor lasers with optoelectronic feedback [18].

In this article, we first review the concepts and progresses made in the research on chaotic communications using semiconductor lasers with optoelectronic feedback. Numerical and experimental results are provided to illustrate the concepts and to give a general picture of the current status of this research. In addition, some most recent experimental results are presented.

2. Dynamics and synchronization

For delayed optoelectronic feedback, the optical output of a semiconductor laser is converted by a high-speed photodetector to an electrical current, which, after being amplified, is fed back to the laser by adding it to the bias current of the laser. Either positive [19] or negative [20] optoelectronic feedback can be applied to a solitary single-mode semiconductor laser to generate chaotic dynamics. The feedback signal current is directly added to the bias current in the case of positive feedback, but it is inverted in the case of negative feedback. In both cases, the laser follows a quasiperiodicity route to chaotic pulsing. Frequency-locked pulsing states are also found for negative feedback but not for positive feedback [20].

In a synchronized chaotic optical communication system using semiconductor lasers, the message being transmitted is encoded in the chaotic waveform generated by a transmitter laser and is decoded through the use of a receiver laser that is synchronized to the transmitter laser. Unidirectional coupling from the transmitter laser to the receiver laser is considered for this purpose. In this section, we consider the major characteristics of chaos synchronization for this system in the absence of a message. Synchronization in the presence of an encoded message, as well as the processes of encoding and decoding the message, is discussed in the next section.

Fig. 1 shows the schematic configuration of a unidirectionally coupled system using a semiconductor laser with optoelectronic feedback as the transmitter laser, TLD. The receiver laser, RLD, can have its own feedback loop, but it receives the signal from the transmitter as the coupling for synchronization. The factor c, which has a value in the range of $0 \leqslant c \leqslant 1$, determines the relative strength between the feedback signal and the coupling signal for the receiver laser. When $c = 1$, the receiver has an open loop without feedback from its own output but has the strongest coupling from the transmitter. When $c = 0$, the receiver is decoupled from the transmitter and has its own dynamics driven solely by its own feedback.

The dynamical characteristics of a single-mode semiconductor laser with optoelectronic feedback are determined by five intrinsic laser parameters, three operational parameters, and the response function of the photodetector-amplifier combination in the optoelectronic feedback loop. The five intrinsic laser parameters, which are the photon decay rate γ_c, the spontaneous carrier relaxation rate γ_s, the differential carrier relaxation rate γ_n, the nonlinear carrier relaxation rate γ_p, and the linewidth enhancement factor b, are specific laser properties that cannot be varied at will in operation though γ_n and γ_p vary linearly with the laser power [21]. The response function, $f(t)$, of a photodetector-amplifier combination can be chosen properly through the choice of the photodetector and the amplifier, but it is not easily varied in operation once the choice is made. In contrast, the three operational parameters, which are the laser injection current density J, the feedback delay time τ, and the normalized dimensionless feedback strength ξ, are externally controllable parameters that can be varied at will in operation to make the laser function in a desired dynamical state. The dynamical states of a single-mode semiconductor laser with optoelectronic feedback as a function of these intrinsic and operational parameters have been studied and mapped [19,20]. The route to chaotic pulsing for such a laser can be followed by varying one operational parameter, say, τ or ξ, while keeping the others fixed.

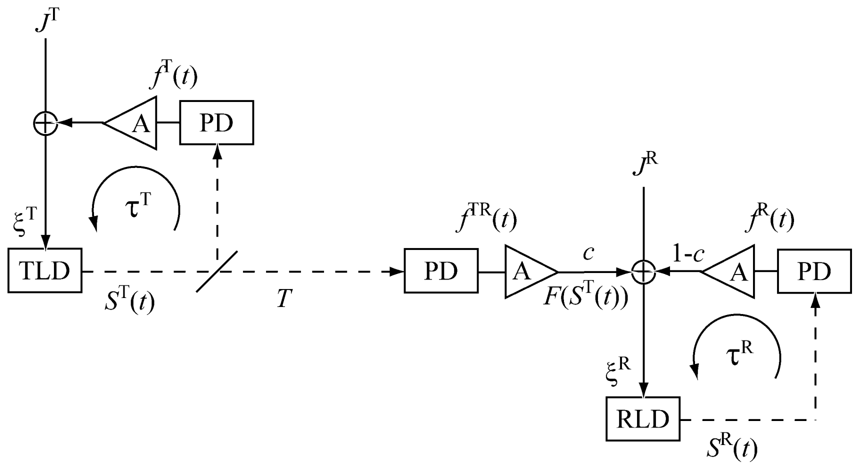

Fig. 1. Schematic configuration of a unidirectionally coupled system using semiconductor lasers with delayed optoelectronic feedback. TLD: Transmitter laser diode; RLD: Receiver laser diode; PD: Photodetector; A: Amplifier; J: Bias current; τ: Feedback delay time; ξ: Feedback strength; f: Response function; c: Coupling coefficient; T: Transmission time.

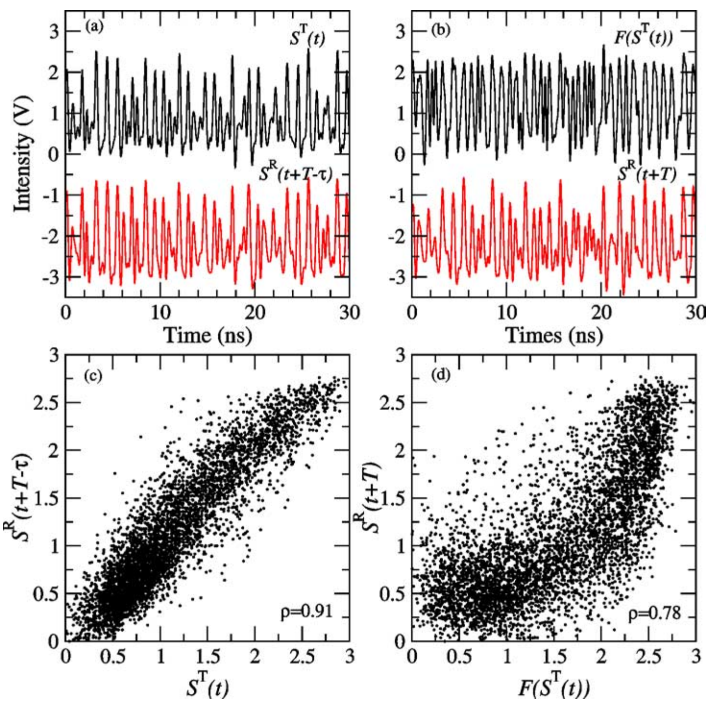

Fig. 2. Comparison of the chaotic waveforms and the correlation plots. (a) Chaotic waveforms from the outputs of the transmitter (upper trace) and the receiver (lower trace). (b) Chaotic waveforms of the driving signal (upper trace) and the output of the receiver (lower trace). (c) Correlation plot between the two traces in (a). (d) Correlation plot between the two traces in (b).

Identical synchronization with high stability and low synchronization error is desired for synchronized chaotic communication. For identical synchronization, the mathematical description of the receiver dynamics has to be identical to that of the transmitter dynamics [22]. In a realistic experimental setting, the fulfillment of this mathematical identity requires that all parameters of the receiver be matched as closely as possible to the corresponding parameters of the transmitter. Specifically for the unidirectionally coupled lasers with optoelectronic feedback depicted in Fig. 1, it requires that: (i) the transmitter laser, TLD, and the receiver laser, RLD, be chosen carefully to have closely matched intrinsic parameters; (ii) the three photodetector-amplifier combinations be selected to have matched response functions, $f^{\mathrm{R}}(t) = f^{\mathrm{TR}}(t) = f^{\mathrm{T}}(t)$; and (iii) the operational

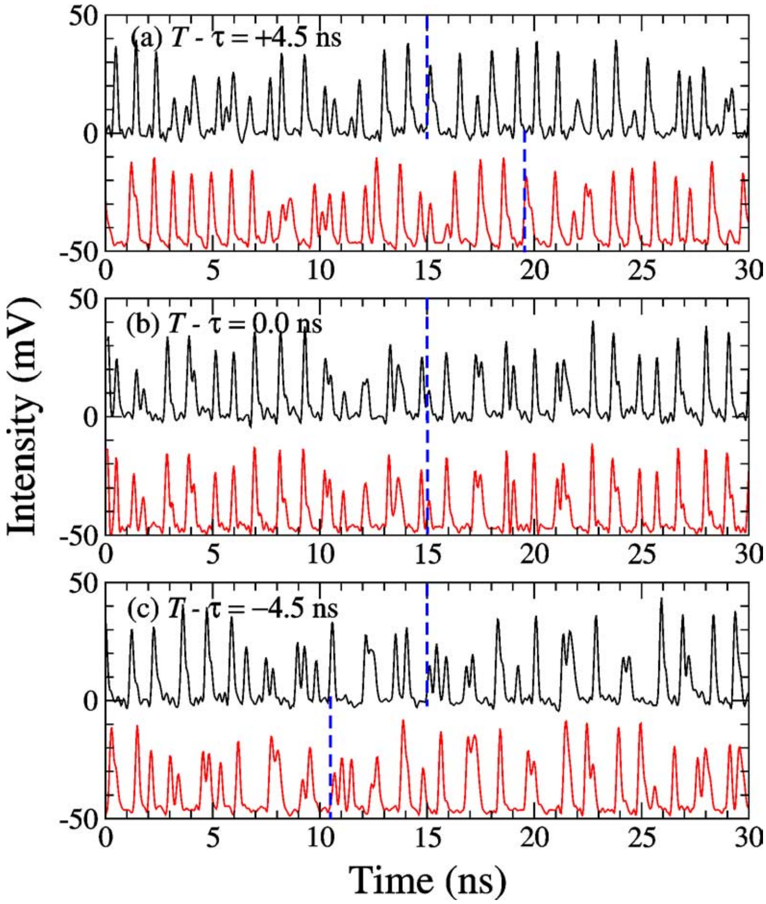

Fig. 3. Time series of the synchronized chaotic outputs from the transmitter laser (upper trace) and the receiver laser (lower trace) at $c = 1.0$. (a) Retarded synchronization with $T - \tau = +4.5$ ns. (b) Instant synchronization with $T - \tau = 0.0$ ns. (c) Anticipated synchronization with $T - \tau = -4.5$ ns.

parameters be matched, $\tau^R = \tau^T$, $J^R = J^T$, and $\xi^R = \xi^T$. When these conditions are satisfied, identical synchronization is possible. Fig. 2 shows experimentally measured chaos synchronization results obtained using closely matched InGaAsP lasers at 1.3 μm wavelength [23] as TLD and RLD with an open-loop configuration of $c = 1$ and $\xi^R = \xi^T$. The transmission time T from TLD to RLD and the feedback delay time τ for the transmitter have to be taken into consideration in the comparison between the output waveforms of RLD and TLD shown in Fig. 2(a) and in the correlation plot shown in Fig. 2(c). Shown in Fig. 2 (b) and (d) are, respectively, the comparison and correlation between the output waveform, $S^R(t + T)$, of RLD with a proper time shift of T and the coupling signal, $F(S^T(t))$, received by RLD after detection and amplification. In reality, there is always a bandwidth limitation by the photodetector-amplifier combination due to its limited response speed. There are also large signal distortion and saturation due to its limited linear response range. Therefore, because of such distorted transformation by the photodetector-amplifier combination, the signal $F(S^T(t))$ received by RLD is the same as the signal that is fed back to TLD but is not identical to the output waveform $S^T(t)$ of TLD. It can be clearly seen from the data presented in Fig. 2 that the chaotic output waveform of RLD is not copying the received signal but is synchronized to that of TLD.

Recently, through theoretical analysis and numerical simulation, a new regime of anticipated synchronization is discovered in nonlinear dynamical systems with delayed feedback [24–26]. In this regime, a driven receiver system synchronizes with the future state of a driving transmitter system. Thus the receiver can anticipate the chaotic dynamics of the transmitter in real time. Meanwhile, there have been a lot of experimental efforts trying to demonstrate the anticipated synchronization [27,28]. However, in [27] the observed anticipation time is in disagreement with the theoretical expectation [24–26], and in [28] the receiver laser is in fact synchronized to the transmitter laser in a retarded synchronization regime.

Using our unidirectionally coupled semiconductor lasers with optoelectronic feedback, we can experimentally demonstrate anticipated, instant, and retarded synchronization simultaneously. In fact, a hallmark of identical synchronization for a unidirectionally coupled, delayed feedback system is a time shift of $T - \tau$ between the synchronized chaotic output waveforms of the receiver and the transmitter, as is accounted for in the plots shown in Fig. 2 (a) and (c). This characteristic leads to retarded synchronization for the receiver output to lag behind the transmitter output in time when $T - \tau > 0$, instant synchronization for the receiver output to time exactly with the transmitter output when $T - \tau = 0$, and anticipated synchronization for the receiver output to lead the transmitter output in time when $T - \tau < 0$ [29]. Fig. 3 shows the experimentally observed characteristics of these three scenarios, proving that identical synchronization has been accomplished in this system. It is noted that these phenomena are observed for the open-loop configuration with $c = 1$ as well as for the closed-loop configuration with $c \neq 1$ so long as the conditions for synchronization mentioned above are satisfied [29]. We have experimentally demonstrated that anticipated, instant, and retarded synchronization are unified phenomena under the general concept of chaos synchronization with time shift in nonlinear dynamical systems with delayed feedback.

In an experimental setting, the ability to synchronize does not guarantee the stability and quality of synchronization. The stability, or robustness, of chaos synchronization is determined by the susceptibility of the synchronization to perturbations, from intrinsic and extrinsic noise sources as well as from the message encoding process, that can desynchronize the system. The quality of synchronization is determined by the fidelity of synchronization between the receiver and transmitter output waveforms. High synchronization quality requires stable synchronization because desynchronization clearly results in a large synchronization error. However, stable synchronization does not necessarily guarantee high synchronization quality because synchronization error can be contributed by synchronization deviations in the absence of desynchronization bursts [14]. The robustness of synchronization can be measured by the transverse Lyapunov exponent between the receiver and the transmitter of the system [30]. Desynchronization can happen if any perturbation acting on a synchronized trace at a point where a local transverse Lyapunov exponent is positive. A necessary condition for robust synchronization is that the largest average transverse Lyapunov exponent, λ_T, for the synchronized system be negative. A larger value of λ_T makes the system more resilient to a perturbation of a given strength. The synchronization quality can be measured by the synchronization error, ζ, or the correlation coefficient, ρ, between the output waveforms of the receiver and the transmitter [14,31]. For the optoelectronic feedback system shown in Fig. 1, the synchronization error is defined as

$$\zeta = \frac{\langle |S^T(t) - S^R(t)| \rangle}{\langle |S^T(t)| \rangle}, \tag{1}$$

and the correlation coefficient is defined as

$$\rho = \frac{\langle [S^T(t) - \langle S^T(t) \rangle][S^R(t) - \langle S^R(t) \rangle] \rangle}{\langle |S^T(t) - \langle S^T(t) \rangle|^2 \rangle^{1/2} \langle |S^R(t) - \langle S^R(t) \rangle|^2 \rangle^{1/2}}. \tag{2}$$

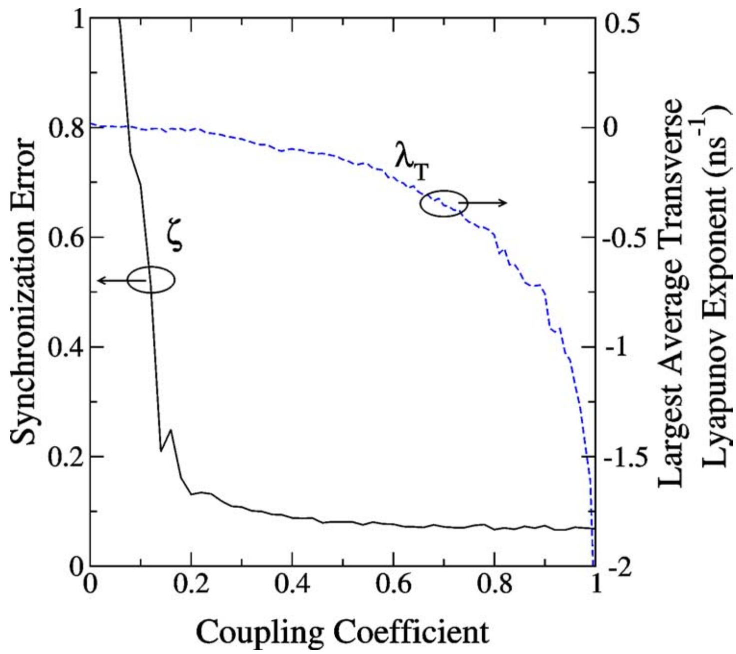

Fig. 4. Numerically calculated synchronization error and theoretically calculated largest average transverse Lyapunov exponent versus coupling coefficient.

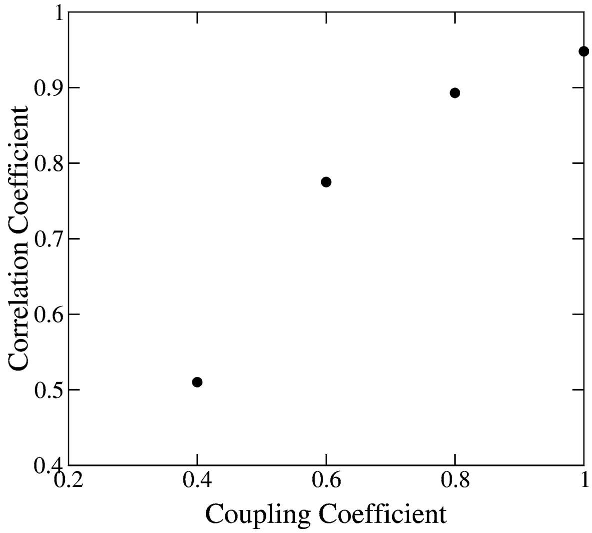

Fig. 5. Experimentally measured correlation coefficient versus coupling coefficient.

The robustness and quality of synchronization depend on many factors, including the system configuration, the parameters of the system, the mismatch in parameters and in operating conditions between the transmitter and the receiver, and the coupling between the transmitter and the receiver. The effects of such factors for synchronization robustness and quality of this optoelectronic feedback system have been thoroughly studied [23,32,33]. Here we consider only the effect of the coupling coefficient c indicated in Fig. 1. The theoretically calculated values for the largest average transverse Lyapunov exponent, λ_T, and the numerically calculated synchronization error, ζ, are both plotted in Fig. 4 as a function of the value of c. From these results, it is seen that: (i) the system can be stably synchronized with a small error only when the coupling coefficient is sufficiently large; and (ii) the open-loop configuration with $c = 1$ has the most stable synchronization with least error. These observations are confirmed by the experimentally measured correlation coefficient shown in Fig. 5 as a function of the coupling coefficient. We conclude from these theoretical, numerical, and experimental results that stable synchronization with a passable quality for this system is experimentally feasible only for $c > 0.4$ and that the open-loop configuration with $c = 1$ is the most desirable configuration for high-quality synchronization of this system.

3. Message encoding and decoding

Several encoding and decoding schemes have been considered and demonstrated for chaotic communications. The most important ones include chaos shift keying (CSK), chaos masking (CMS), and chaos modulation. For chaos modulation, possible encoding and decoding schemes include additive chaos modulation (ACM) and multiplicative chaos modulation (MCM). The characteristics and performances of CSK, CMS, and ACM for different chaotic communication systems based on semiconductor lasers have been investigated and compared [14,18,31]. Fig. 6 shows the schematic setup of these three encoding and decoding schemes for the chaotic optical communication system using semiconductor lasers with optoelectronic feedback. Among these three encoding schemes, only the ACM scheme preserves the mathematical symmetry between the transmitter and the receiver in the presence of a message being encoded while the message encoding process in each of the other two schemes breaks such symmetry. Thus, only the ACM scheme can maintain identical synchronization in the process of message encoding, as is demonstrated by the experimental data shown in Fig. 7. For this reason, it has been shown both numerically [14] and experimentally [18] that the ACM encoding scheme has the best performance among the three schemes for a given chaotic communication system. In addition, because the random bits of a message is fed back to the transmitter in an ACM encoding scheme, the dynamics of the transmitter is also influenced by the message bits. Therefore, the ACM scheme has the additional benefit of increasing the complexity of the transmitter dynamics for a chaotic communication system [31]. In the following, we consider only the ACM encoding scheme.

It is possible to use either a closed-loop receiver or an open-loop receiver for a chaotic optical communication system using semiconductor lasers with optoelectronic feedback. Fig. 8 shows the general schematic configuration for such a system using the ACM encoding and decoding scheme. In this diagram, as that in Fig. 1, the receiver has a closed loop when $0 < c < 1$ but an open loop when $c = 1$. In this configuration, the beam splitter, BS, that accepts the message into the system and splits the

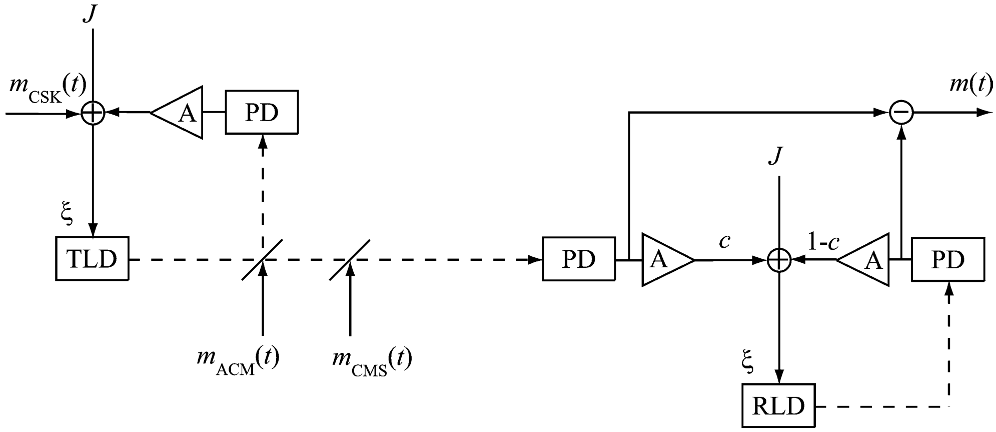

Fig. 6. Schematic setup of message encoding and decoding for the chaotic optical communication system using semiconductor lasers with optoelectronic feedback. CSK: Chaos shift keying; CMS: Chaos masking; ACM: Additive chaos modulation; $m(t)$: Message.

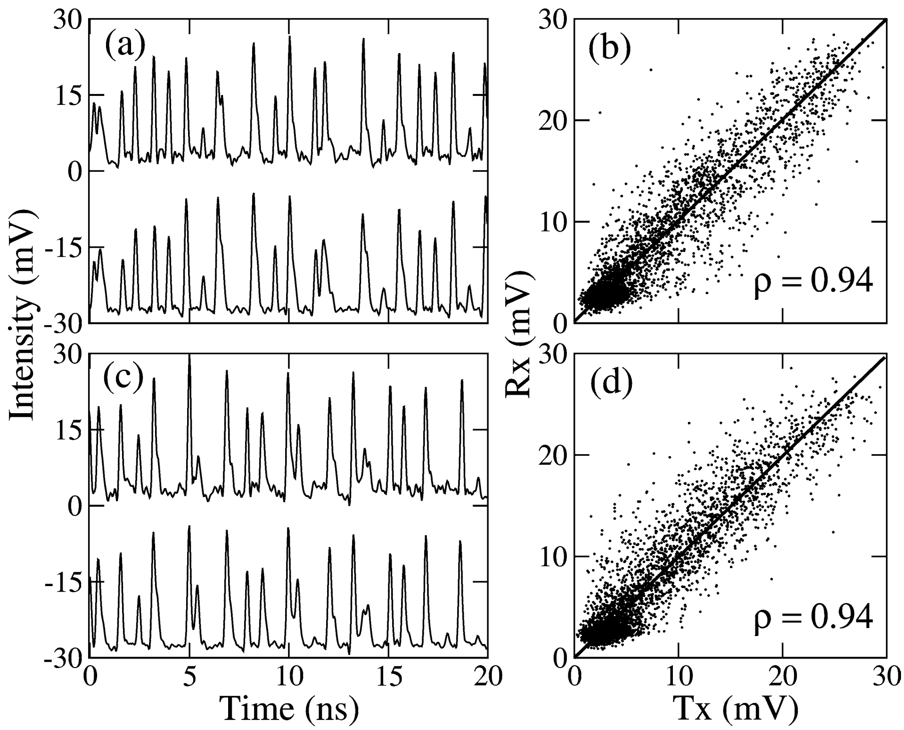

Fig. 7. Time series and correlation plots of the transmitter and the receiver outputs. (a) and (b) are obtained without an encoded message; (c) and (d) are obtained with an encoded message. Tx: output of the transmitter; Rx: output of the receiver.

transmitter output into feedback and transmitted beams has a reflectance-to-transmittance ratio of $R : T = a : (1 - a)$. In order to maintain the mathematical symmetry between the transmitter and the receiver for identical synchronization, the coefficient a that determines this ratio cannot be chosen arbitrarily but is determined by the value of the coupling coefficient c chosen for the receiver. It can be shown that this symmetry is maintained for

$$a = \frac{1}{1+c}, \quad \text{thus} \quad c = \frac{1-a}{a}. \tag{3}$$

For the open-loop configuration with $c = 1$, we find that $a = 1/2$ and a 50/50 beam splitter is used to split both the transmitter output beam and the input message equally into the two paths. For a closed-loop configuration with $c < 1$, we find that $a > 1/2$; then the transmitter output and the input message are divided unequally and differently into the two paths.

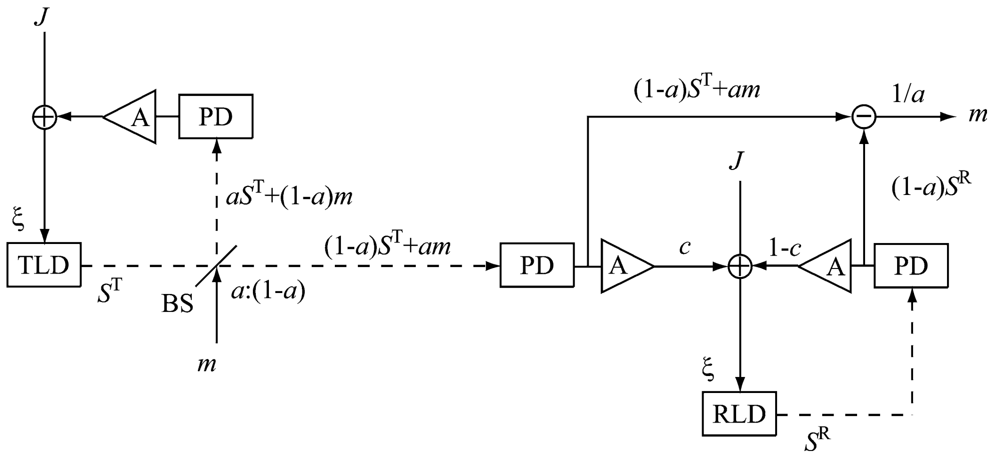

Fig. 8. General schematic configuration for the chaotic communication system using the ACM encoding and decoding scheme.

With a closed-loop receiver, the delay time of the receiver loop, τ^R, also has to be closely matched to that of the transmitter loop, τ^T. Even with a value of c as large as 0.8, the synchronization quality drops quickly for a mismatch of just a few percent between these two delay times [32]. This issue clearly does not exist when an open-loop receiver is used. Thus, to defeat an eavesdropper, the security of a chaotic communication system can be increased with a simple strategy: by choosing the reflectance of the beam splitter BS in the transmitter loop to be larger than 50% so that the coefficient a has a value $a > 1/2$, message recovery through identical synchronization is possible only when a closed-loop receiver is carefully chosen with a precisely defined value for the coupling coefficient c determined by the relations in Eq. (3) and a feedback delay time matching that of the transmitter loop. This strategy works for any closed-loop receiver. As is discussed in the preceding section, stable synchronization is experimentally feasible only for $c > 0.4$, and the synchronization stability and quality increase with an increasing value of c. Therefore, a value of a slightly larger than $1/2$ can be chosen when applying this strategy so that the corresponding value for c can be sufficiently large, but still smaller than 1, to ensure good synchronization stability and quality for low-error message recovery.

The open-loop configuration with $c = 1$ has the highest synchronization stability and quality. Therefore, when all other operating conditions remain the same and the ACM encoding scheme is employed, a chaotic communication system with an open-loop receiver has the best performance with the lowest bit-error rate (BER) as compared to one with a closed-loop receiver. Clearly, an open-loop receiver system has to be chosen over a closed-loop receiver if the added security from the strategy discussed above is not needed.

4. System performance

System performance of chaotic communication is investigated using the semiconductor laser system with optoelectronic feedback [1,18]. A message is encoded through the ACM scheme with an open-loop receiver for the best performance. With the ACM scheme, the encoding of the message does not break the symmetry between the transmitter and the receiver. Therefore, a large signal modulation is possible without deteriorating the synchronization quality. This scheme is different from the chaos masking scheme which has been used in many other chaotic optical communication systems [3,15,34]. Since the chaos masking scheme breaks the symmetry between the transmitter and the receiver, the message has to be small in order not to deteriorate the synchronization quality. Furthermore, with the ACM scheme, it is very difficult to filter the received signal in order to get the message, such as by an eavesdropper. It is not only because the system is originally in a chaotic pulsing state already but also the dynamics of the system is further nonlinearly changed by the feedback modulation of the message. It has been demonstrated that the encoding of the message in the ACM scheme can significantly increase the complexity of the chaotic carrier [18].

Representative message recovery data at 2.5 Gb/s with pseudorandom digital bits are shown in Fig. 9. From top to bottom, the time series are the received signal, the receiver output, the recovered message, and the input message, respectively. From either the received signal or the receiver output alone, the message cannot even be discerned directly because the message is completely blended into the fluctuations of the chaotic carrier. However, when the receiver output is subtracted from the received signal, the message is successfully decoded because the receiver output is reliably synchronized to the chaotic carrier generated by the transmitter. By comparing the recovered message with the input message, it is clear that the message is successfully recovered at this high bit rate. Similar performance is also observed in the frequency domain. Fig. 10 shows the

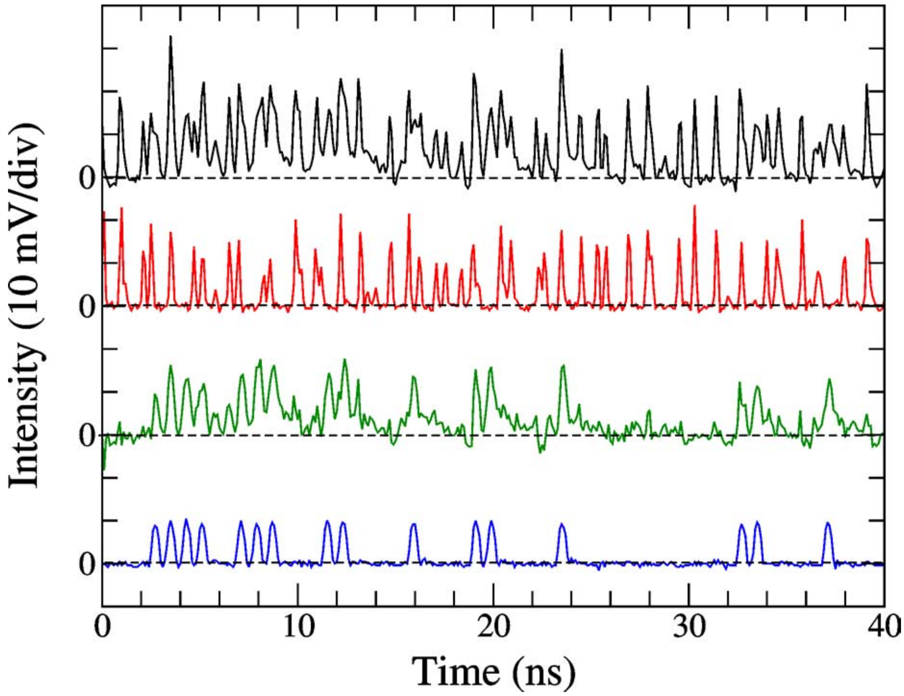

Fig. 9. Transmission of a pseudorandom digital bit sequence at 2.5 Gb/s bit rate. From top to bottom, the time series are the received signal, the receiver output, the recovered message, and the input message. Each dashed line indicates the baseline position at 0 mV of the corresponding trace.

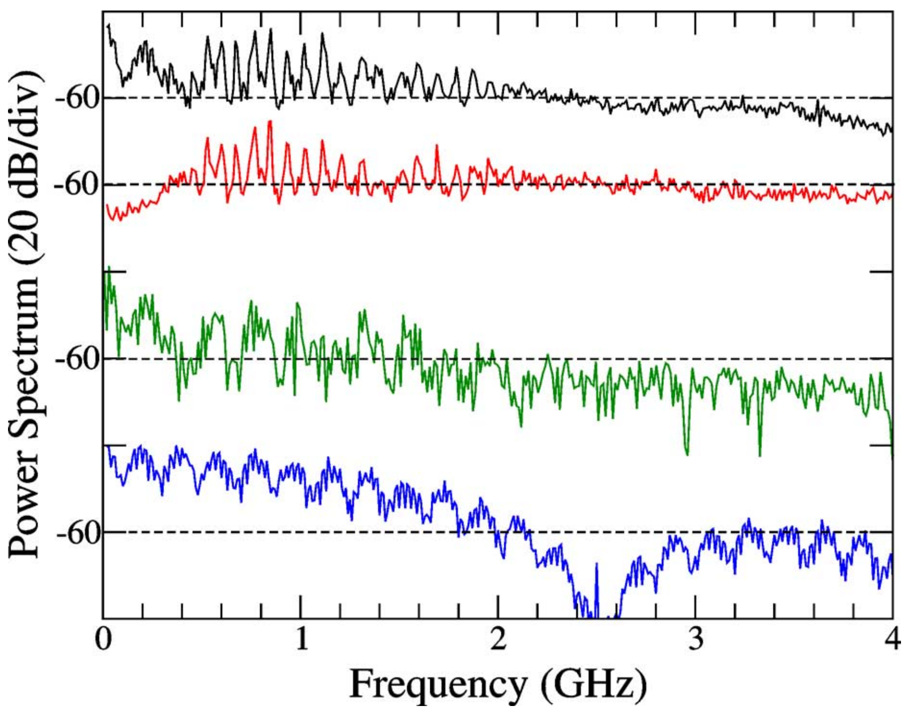

Fig. 10. Corresponding power spectra of the time series shown in Fig. 9. Each dashed line indicates the reference level at −60 dBm of the corresponding trace.

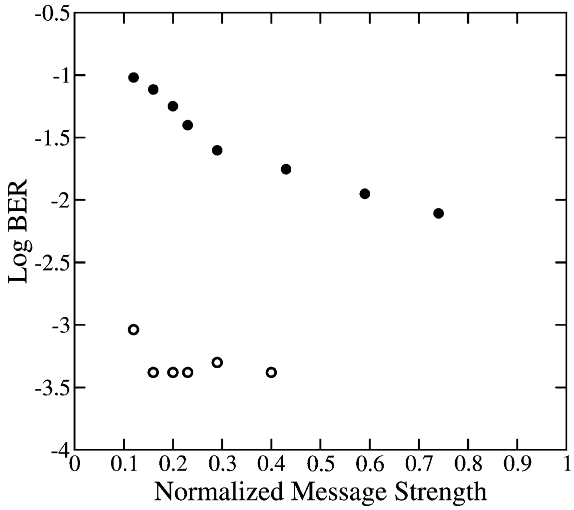

Fig. 11. System BER versus message strength. Solid circles are for the chaotic communication system with the ACM scheme. Open circles are for the system with the lasers operated in a CW stable state without chaotic dynamics.

experimentally measured power spectra for the corresponding time series in Fig. 9. From either of the top two power spectra of the received signal and the receiver output, respectively, it is not possible to even tell if a message is encoded, let alone decoding it. Therefore, the security of chaotic communication is achieved by blending the message into the temporal fluctuations of the chaotic waveform, thus spreading it over the broadband spectrum of the chaotic carrier. By demonstrating the transmission of a pseudorandom digital message at 2.5 Gb/s bit rate, it is also shown that chaotic communication can be implemented with commercial standards such as that for digital OC-48 systems.

In a chaotic optical communication system with the ACM encoding scheme, a large message strength can be implemented without breaking the symmetry between the transmitter and the receiver. Therefore, the message strength can be increased to improve the system performance. Fig. 11 shows (in solid circles) the measured BER of the chaotic communication system under different message strengths. As is shown, the system BER is found to drop significantly when the message strength is increased. The BER of this system is mainly contributed by the synchronization errors caused by the mismatch between the transmitter and the receiver dynamical systems. Other factors that also limit the system performance include the intrinsic laser noise, the electrical noise of the photodetectors and amplifiers, and the overall bandwidth of the system. Also shown in Fig. 11 (in open circles) is the BER of the system when the lasers are operated in a CW stable state without chaotic dynamics. With the lasers operated in such a stable state, there is no need for either chaos synchronization or parameter matching between the transmitter and the receiver. From these data, it is seen that a large BER already exists in the system in the absence of chaotic dynamics because of the many performance-limiting factors that are independent of the nonlinear dynamics and synchronization of the transmitter and receiver lasers. For chaotic communication with the lasers operating in the chaotic state, the effects of these factors are further amplified through the generation of additional synchronization errors. Therefore, to improve the system performance, it is very important to reduce the noise and to increase the overall bandwidth of the system.

In the chaotic communication system using semiconductor lasers with optoelectronic feedback, both chaos synchronization and message encoding and decoding are accomplished through the coupling of the optical intensity of the outputs from the transmitter and the receiver. This system is not an optically coherent system in the sense that the optical phase does not matter but only the chaotic nature of the optical intensity is utilized. Therefore, the transmission link between the transmitter and the receiver for this system does not necessarily have to be optical but can be electrical or wireless as well. Fig. 12 shows the configurations of this system for electrical cable transmission and wireless transmission, compared with the optical transmission. The three links share the same transmitter and receiver configurations. The difference is only in the transmission channel which can be optical, electrical, or wireless. The potential of implementing chaotic communication through different transmission links increases the flexibility and practicality of chaotic communications using this system.

5. Conclusions

Chaotic communication is demonstrated using synchronized semiconductor lasers with optoelectronic feedback. Issues such as synchronization between the transmitter and the receiver dynamical systems and system performance of chaotic

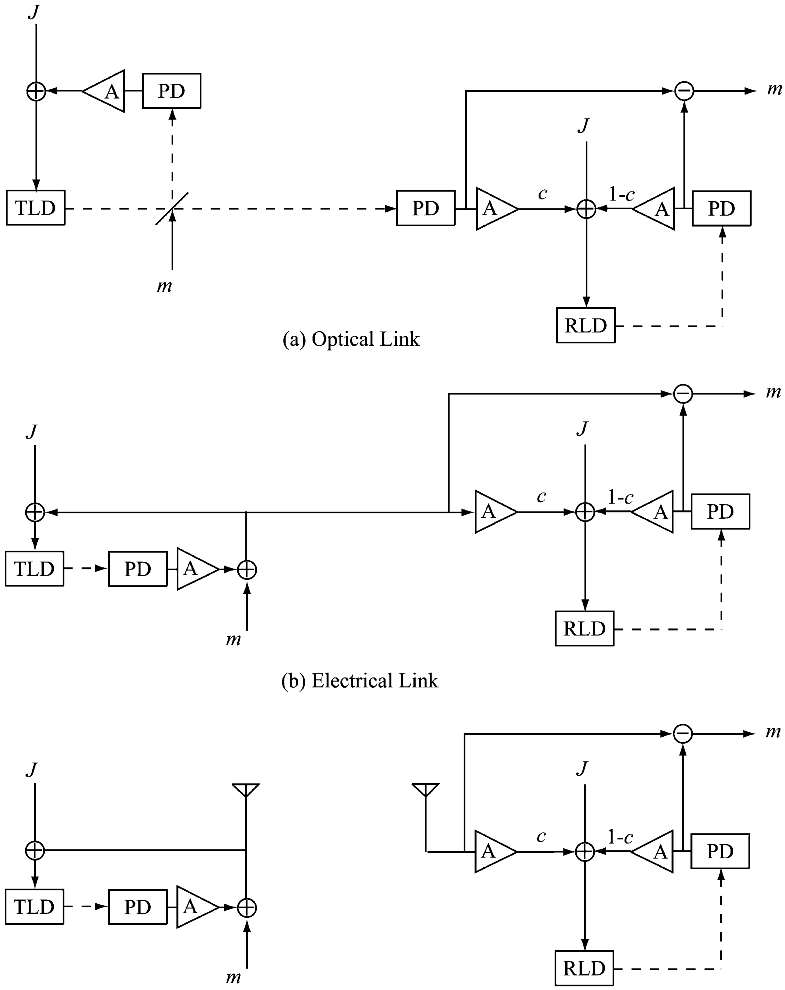

Fig. 12. Schematic configurations of chaotic communication using optical, electrical, and wireless links.

communication are discussed in detail. In synchronized chaotic communications, it is important to study the robustness of chaos synchronization not only before a message is encoded but also after the message is encoded. Different encoding and decoding schemes can have different effects for either maintaining or breaking the symmetry between the transmitter and the receiver. For high performance chaotic communications, it is necessary to choose an encoding scheme such as ACM that can maintain the symmetry in the process of message encoding.

In a chaotic communication system with delayed feedback, the receiver can be either configured with an open loop or a closed loop. An open-loop configuration can generally provide better system performance while a closed-loop configuration can potentially provide higher security. For a chaotic communication system using semiconductor lasers with optoelectronic feedback, the transmission link between the transmitter and the receiver can be optical, electrical, or wireless, depending on the system requirement. Therefore, there is much flexibility in configurating such a chaotic communication system. The demonstration of chaotic communication at 2.5 Gb/s with our system shows that chaotic communication is feasible at a high bit rate with reliable message recovery. System BER can be further improved by reducing noise and expanding the bandwidths of the components in the system and by closely matching the transmitter and the receiver to reduce the synchronization errors.

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