Secure communication scheme using chaotic laser diodes subject to incoherent optical feedback and incoherent optical injection

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We propose a secure communication scheme based on anticipating synchronization of two chaotic laser diodes, one subject to incoherent optical feedback and the other to incoherent optical injection. This scheme does not require fine tuning of the optical frequencies of both lasers as is the case for other schemes based on chaotic laser diodes subject to coherent optical feedback and injection. Our secure communication scheme is therefore attractive for experimental investigation.

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Synchronization of chaotic oscillators and its application to secure communications have attracted considerable interest during the past decade.[1–4] In particular, laser diodes subject to delayed, coherent optical feedback have revealed themselves to be good candidates for secure communications.[5,6] However, in such schemes in which single-mode laser diodes subject to coherent optical feedback are implemented, synchronization performance depends on the detuning between the free-running frequencies of the transmitter and the receiver lasers. In particular, negative detuning by a few hundred megahertz of the receiver frequency relative to the transmitter frequency leads to a large degradation of the synchronization.[7] From a practical point of view, it is therefore interesting to investigate alternative cryptographic schemes that would not require fine tuning of the optical frequencies. A possible solution involves laser diodes subject to incoherent optical feedback and injection. Indeed, incoherent optical feedback has been proved to induce a large variety of dynamic instabilities[8,9] such as chaos. Moreover, the phases of the feedback and injection fields do not intervene in the dynamics of the laser diodes.

In this Letter we propose a novel secure communication scheme based on anticipating synchronization[10] of two chaotic laser diodes in which the transmitter laser is subject to incoherent optical feedback and the receiver laser is coupled to the transmitter laser by incoherent optical injection. The message is encrypted by chaos shift keying.[11] In this scheme the feedback and the injected fields act on the population inversion in the laser's active layers but do not interact coherently with the intracavity lasing fields. For this reason, the secure communication scheme that we propose does not require fine tuning of the optical frequencies of both lasers and is therefore attractive for experimental realization.

In the scheme that we propose (Fig. 1), the linearly polarized output field of the transmitter laser first undergoes a 90° polarization rotation through an external cavity formed by a Faraday rotator (FR) and a mirror. It is then split into two parts by a nonpolarizing beam splitter (BS): One part is fed back into the transmitter laser, and the other part is injected into the receiver laser. The polarization directions of the feedback and injection fields are orthogonal to those of transmitter and receiver output fields, respectively. In other words, the transmitter laser is subject to incoherent feedback, whereas the receiver laser is subject to incoherent injection. An optical isolator (ISO) shields the transmitter from parasitic reflections from the receiver. If necessary, one can place a linear polarizer (LP) between the Faraday rotator and the mirror to prevent coherent feedback induced by a second round trip in the external cavity. To encode a

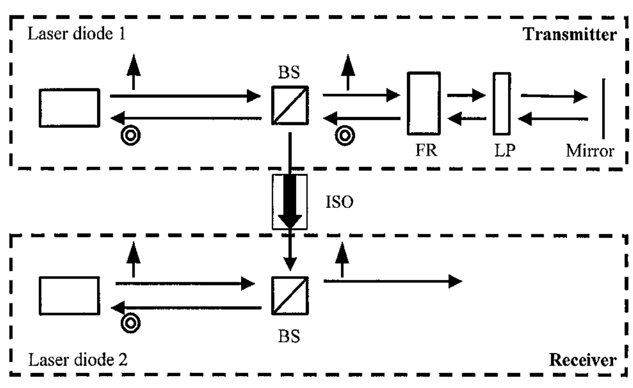

Fig. 1. Schematic representation of the secure communication scheme. See text for definitions.

message, one switches the current of the transmitter laser between two discrete values corresponding to bits 0 and 1.

To describe our system dynamics, we have extended the model that was presented in Ref. 8 and which is valid for lasers subject to incoherent optical feedback:

$$\frac{\mathrm{d}P_1}{\mathrm{d}t} = \left(G_1 - \frac{1}{\tau_{p1}}\right)P_1(t) + \beta_1 N_1(t) + F_1(t)\,, \quad (1)$$

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = \frac{I_1(t)}{e} - \frac{N_1(t)}{\tau_{s1}} - G_1[P_1(t) + \kappa P_1(t-\tau)]\,, \quad (2)$$

$$\frac{\mathrm{d}P_2}{\mathrm{d}t} = \left(G_2 - \frac{1}{\tau_{p2}}\right)P_2(t) + \beta_2 N_2(t) + F_2(t)\,, \quad (3)$$

$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = \frac{I_2}{e} - \frac{N_2(t)}{\tau_{s2}} - G_2[P_2(t) + \sigma P_1(t-\tau_c)]\,, \quad (4)$$

where $G_j = G_{Nj}(1 - \epsilon_j P_j)(N_j - N_{0j})$, with $j = 1$ for the transmitter and $j = 2$ for the receiver. In Eqs. (1)–(4), P_j and N_j are the photon number and the electron–hole pair number, respectively, in the active region of laser j. N_{0j} is the value of N_j at transparency. τ_{pj}, τ_{sj}, I_j, G_{Nj}, and ϵ_j are, respectively, the photon lifetime, the carrier lifetime, the injection current, the gain coefficient, and the gain saturation coefficient of laser j. e is the electronic charge. F_j is a Langevin noise force that accounts for stochastic fluctuations arising from spontaneous-emission processes. The Langevin forces satisfy the relations $\langle F_j(t)F_j(t')\rangle = 2N_jP_j\beta_j\delta(t-t')$, where β_j is the spontaneous-emission rate. The operating parameters κ, τ, and σ are the strength and the delay of the feedback at the transmitter and the coupling strength at the receiver, respectively. The time taken by the light emitted by the transmitter to reach the receiver is τ_c. We use typical values for the internal parameters of the transmitter laser: $\tau_{p1} = 2$ ps, $\tau_{s1} = 2$ ns, $G_{N1} = 1 \times 10^4\ \mathrm{s}^{-1}$, $N_{01} = 1.1 \times 10^8$, $\beta_1 = 5 \times 10^3\ \mathrm{s}^{-1}$, and $\epsilon_1 = 7.5 \times 10^{-8}$. In a first step, the parameters at the receiver are chosen to be identical to those of the transmitter. After that, we consider slight differences between the corresponding parameters.

In the absence of stochastic terms F_j, and for identical internal and operating parameters, the exact synchronous solution,

$$P_2(t) = P_1(t - \Delta t), \qquad N_2(t) = N_1(t - \Delta t)\,, \quad (5)$$

where $\Delta\tau = \tau_c - \tau$ is the synchronization lag, exists only if the injection strength at the receiver exactly matches the feedback strength at the transmitter, i.e., $\sigma = \kappa$. It should be noted that this condition is not sufficient for observation of synchronization between the two lasers, since solution (5) can be stable or unstable. Solution (5) means that the receiver at time t can anticipate the signal that will be injected at time $t + \tau$. The anticipation time is τ, the feedback delay at the transmitter. Anticipating synchronization was demonstrated recently to result from the interaction between delayed feedback and dissipation and to be a universal phenomenon in nonlinear dynamic systems with unidirectional coupling.[7,10,12,13]

The synchronization between the two lasers is robust with respect to stochastic fluctuations induced by spontaneous emission, as shown in Fig. 2. The feedback strength and delay at the transmitter are $\kappa = 0.41$ and $\tau = 9$ ns, respectively. The coupling strength exactly matches the feedback strength at the transmitter, i.e., $\sigma = \kappa$. The injection currents of the two lasers are $I_j = 1.8 \times I_{\mathrm{th}j}$, $j = 1, 2$, where $I_{\mathrm{th}j}$ is the threshold current of laser j. For these values the output of the transmitter laser is chaotic and exhibits the characteristics of sustained relaxation oscillations and of spiking [Fig. 2(a)].[8] At time t, the receiver output synchronizes almost perfectly with the transmitter output at time $t - \Delta t$ [Fig. 2(b)]. The good quality of the synchronization is shown in the synchronization diagram [Fig. 2(c)], in which the output of the receiver

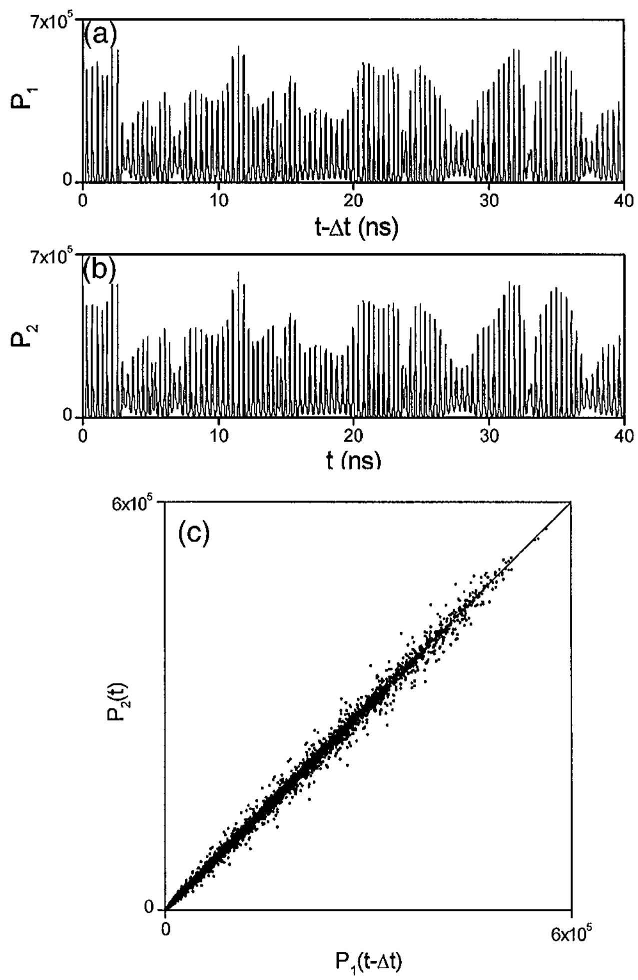

Fig. 2. (a) Output of the transmitter shifted by Δt. (b) Output of the receiver laser. (c) Synchronization diagram of the receiver output, $P_2(t)$, versus the transmitter output, $P_1(t - \Delta t)$. The laser parameters are identical, and the injection current at the transmitter is not modulated. The stochastic terms $F_{1,2}(t)$ are taken into account.

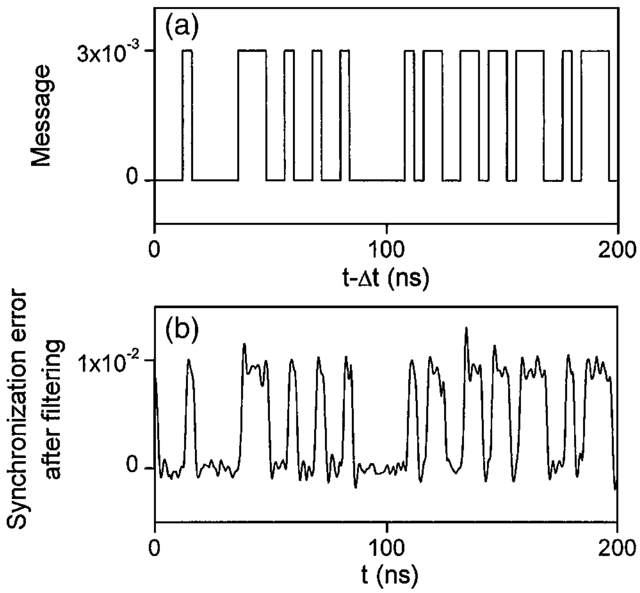

Fig. 3. (a) Encoded message at a bit rate of 250 Mbits/s. (b) Synchronization error after filtering.

at time t is plotted versus the output of the transmitter at time $t - \Delta t$. The synchronization quality can be characterized by computation of the linear correlation coefficient r. For the parameter values that we use, $r = 0.993$, indicating a good level of synchronization. The synchronization is also robust to small mismatches between corresponding parameters in the two systems. The correlation coefficient remains greater than 0.9 if discrepancies between the transmitter and the receiver parameters are within 1%. It is worthwhile to note that a 1% mismatch between the gain coefficients corresponds to a frequency detuning of several hundreds of gigahertz if the frequency dependence of the gain is taken into account.[14] The robustness of the synchronization to small parameter mismatches makes the scheme that we propose practical.

Message encoding is achieved by means of chaos shift keying.[11] The bit stream modulates the injection current at the transmitter; i.e., bits 0 and 1 correspond to two different values of the injection current. Here we choose to use $i_0 = 1.8 \times I_{\text{th},1}$ and $i_1 = 1.003 \times i_0$. At the receiver, a replica of the transmitter laser is used. The injection current at the receiver, I_2, is set to i_0. Message decoding is achieved by computation of the normalized synchronization error, $\Delta P = [P_1(t - \Delta t) = P_2(t)]/P_0$, where P_0 is the mean value of the receiver output in the absence of optical injection. The synchronization error is low-pass filtered by a fourth-order Butterworth filter with a cutoff frequency of $1.3B$, where B is the bit rate. The 0 bits are then detected when the filtered synchronization error is close to zero. By contrast, the 1 bits are detected when the synchronization error is large because of the mismatch between the injection currents. Figure 3 shows a 250-Mbit/s message transmission for lasers chosen to be identical and with stochastic terms $F_{1,2}(t)$ taken into account. We have checked that the encoded bits cannot be detected by direct observation in the time domain or after low-pass filtering of the transmitted signal. Moreover, assuming that the transmitter parameters are unknown, replication of the system by an eavesdropper would be extremely difficult for two reasons. First, parameter mismatches of only a few percent (typically 5%) lead to severe degradation of the synchronization quality, such that recovery of the message is no longer possible. Second, from one laser chip to another, critical parameters such as carrier and photon lifetimes can vary considerably (1–3 ns and 1–2 ps for the two chips[14]).

In conclusion, we have demonstrated a novel secure communication scheme based on anticipating synchronization of laser diodes subject to incoherent optical feedback and injection. This scheme is remarkable in that it requires no fine tuning of the laser optical frequencies, unlike other schemes based on laser diodes subject to coherent optical feedback. This scheme requires no fine tuning because of the absence of interaction between, on the one hand, the intracavity fields and, on the other hand, the injected and fed back fields; the latter interact only with the carrier density. Our secure communication scheme is therefore attractive for experimental and operational investigations.

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References

1. L. M. Pecora and T. L. Carrol, Phys. Rev. Lett. **64,** 821 (1990).
2. K. M. Cuomo and A. V. Oppenheim, Phys. Rev. Lett. **71,** 65 (1993).
3. J. P. Goedgebuer, L. Larger, and H. Porte, Phys. Rev. Lett. **80,** 2249 (1998).
4. G. D. Van Wiggeren and R. Roy, Science **279,** 1198 (1998).
5. C. R. Mirasso, P. Colet, and P. García-Fernández, IEEE Photon. Technol. Lett. **8,** 299 (1996).
6. V. Annovazzi-Lodi, S. Donati, and A. Scire, IEEE J. Quantum Electron. **33,** 1449 (1997).
7. Y. Liu, H. F. Chen, J. M. Liu, P. Davis, and T. Aida, Phys. Rev. A **63,** 031802(R) (2001).
8. J.-L. Chern, K. Otsuka, and F. Ishiyama, Opt. Commun. **96,** 259 (1993).
9. J. Houlihan, G. Huyet, and J. G. McInerney, in *Proceedings of LEOS 2000* (IEEE Lasers and Electro-Optics Society, Piscataway, N.J., 2000), p. 68.
10. H. U. Voss, Phys. Rev. E **61,** 5115 (2000).
11. H. Dedieu, M. P. Kennedy, and M. Hasler, IEEE Trans. Circuits Syst. II **40,** 634 (1993).
12. V. Ahlers, U. Parlitz, and W. Lauterborn, Phys. Rev. E **58,** 7208 (1998).
13. C. Masoller, Phys. Rev. Lett. **86,** 2782 (2001).
14. G. P. Agrawal and N. K. Dutta, *Long-Wavelength Semiconductor Lasers* (Van Nostrand Reinhold, New York, 1986).