Synchronization of Chaotic Injected-Laser Systems and Its Application to Optical Cryptography

Valerio Annovazzi-Lodi, *Member, IEEE*, Silvano Donati, *Member, IEEE*, and Alessandro Scirè

***Abstract*— We demonstrate that two chaotic systems, each made by two coupled semiconductor lasers, can be synchronized using direct-optical feedback. The robustness of the proposed synchronization scheme against mismatch of source parameters and difference in starting conditions is tested by numerical simulations. Applications to secure data transmission are proposed, namely chaotic masking and chaotic shift keying (CSK).**

I. Introduction

SYNCHRONIZATION of chaotic systems has been investigated by many authors in the last years [1]–[8], and different application schemes have been proposed to exploit chaotic phenomena in the field of telecommunications [3]–[8]. Chaos has been employed as a carrier on which data can be transmitted, for instance, by encoding each symbol on a different attractor or exploiting the large peak-amplitude variations produced on the chaotic waveform by a small modulating signal.

An attractive application of chaos synchronization is cryptographic communication. In this area, one exploits the peculiar feature of chaotic signals of being deterministic but, at the same time, of showing a strong dependence on small variations of the oscillator parameters and starting conditions [7], [8].

To date, different authors have proposed electrical implementations [3]–[7] suitable for synchronization of chaos; however, these schemes suffer from the limited bandwidth and substantial attenuation of standard electrical channels, which makes it difficult to hold synchronization on long hauls. On the other side, an optical approach would be required to exploit the very large bandwidth and low attenuation of a fiber channel, allowing more reliable chaotic communication.

An electrooptical approach has been proposed by using an integrated-optics Mach–Zehnder modulator [8]. In this setup, light passing through the modulator is detected by a photodiode and the output signal is fed back to the modulator control electrodes; for a suitable choice of parameters, the optical output intensity is found to be chaotic. A synchronization scheme has been studied following the Pecora and Carrol architecture. Cryptographic transmission has been proposed based on the decomposition-duplication method. However, though this approach is suitable for optical transmission, its speed is limited, since the feedback loop around the Mach–Zehnder is electrical.

Manuscript received July 26, 1995; revised January 22, 1996. This work was supported by a MURST-40% Contract.

The authors are with the Dipartimento di Elettronica, Università di Pavia, Pavia, Italy.

Publisher Item Identifier S 0018-9197(96)04132-2.

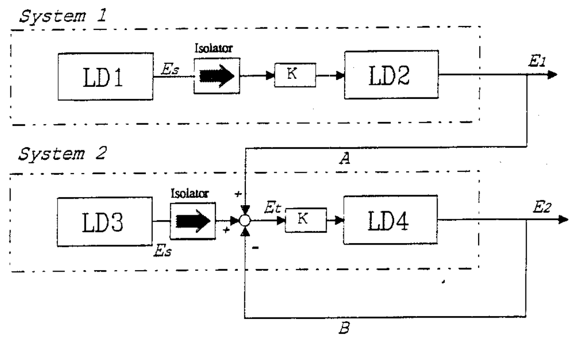


Fig. 1. Proposed all-optical scheme for the synchronization of two semiconductor lasers (LD2, LD4) driven to chaos by external injection.

In this paper, we present what, to our knowledge, is the first full optical scheme for secure transmission based on chaos synchronization. Since it does not include electrical feedback, our scheme is suitable for high-speed optical transmission. Besides other advantages, working with a larger bandwidth makes it difficult for the eavesdropper to store the encripted signal for off-line processing and decoding. Our proposal is based on injection coupling between monomode semiconductor lasers.

II. Synchronization

In a previous paper [9], we investigated the behavior of a monomode semiconductor laser subjected to increasing levels of external injection (system 1 in Fig. 1). We found that after the well-known nonlinear modulation regime followed by phase locking, the injected laser unlocks and then follows a bifurcation route leading to a chaotic regime, before it definitively locks to the injecting source. The chaotic region is found for a wide range of parameters, and it usually spans over about one order of magnitude of the injection parameter; moreover, the system routes to chaos even for moderate values of injection.

To model the laser, we use as in [9] the modified Lang and Kobayashi equations [10], [11]

$$\frac{dE_1}{dt} = \frac{1}{2}\left\{G_n(N-N_0)\left(1-\varepsilon\Gamma E_1^2\right) - \frac{1}{\tau_p}\right\}E_1 + \frac{K}{\tau_{\text{in}}}E_s\cos\psi(t) \tag{1a}$$

$$\frac{d\psi}{dt} = \frac{1}{2}a^*\left\{G_n(N-N_0)\left(1-\varepsilon\Gamma E_1^2\right) - \frac{1}{\tau_p}\right\} - \Delta\omega_s - \frac{K}{\tau_{\text{in}}}\frac{E_s}{E_1(t)}\sin\psi(t) \tag{1b}$$

$$\frac{dN}{dt} = R_p - \frac{N}{\tau_r}G_n(N-N_0)\left(1-\varepsilon\Gamma E_1^2\right)E_1^2 \tag{1c}$$

TABLE I
PARAMETERS OF SEMICONDUCTOR LASERS USED FOR THE NUMERICAL SIMULATIONS

G_n= 8.1 10^{-13} m^3/s;	N_0= 1.1 10^{24} m^{-3};
ω= 2.5133 10^{15} rad s^{-1};	τ_p= 2 10^{-12} s;
τ_r= 2 10^{-9} s;	τ_{in}= 8 10^{-12} s;
εΓ= 9 10^{-24} m^{-3};	a*=6;
R_p= 9.075 10^{32} m^{-3} s^{-1};	E_s= 1.02 10^{10} $m^{-3/2}$ [≈E_0 (K=0)]
$\Delta\omega_s$= 2π 36 10^6 r/s.	

where we have assumed the commonly accepted notation [9], [10], which is listed below for the sake of clarity.

1) $E_s e^j \omega_s t$ is the injected field.
2) $E(t) = E_1(t)e^j(\omega t + \phi(t))$ is the laser field.
3) N is the carrier concentration and N_0 is its value at the lasing threshold.
4) G_n is the modal gain.
5) $\psi(t) = \phi(t) - \Delta\omega_s t$ is the phase difference between the internal and the injected fields.
6) $\Delta\omega_s = \omega_s - \omega_0$ is the frequency difference between the external signal and the unperturbed laser oscillation.
7) τ_p is the photon lifetime in the cavity.
8) τ_r is the electron/hole recombination time.
9) $\tau_{\rm in} = 2L/c$ is the time of flight in the laser cavity of length L.
10) $\varepsilon\Gamma$ is the product of compression and of confinement factors.
11) $R_p = J\eta/ed$ is the pump parameter which depends on supply-current density J, efficiency η, and active region thickness d.
12) $a^* = -2\omega_0/(n * G_n)\partial n/\partial N$.
13) $n^* = n + \omega_0 \partial n/\partial\omega$ is an effective refractive index.
14) K is the injection parameter, defined as the field attenuation experienced by the external signal E_s up to the superposition on E_0.

The electric fields have been normalized, as usual, i.e.,

$$E_{\rm true} = E\left[G_n \frac{h}{2\pi}\omega\frac{Z_0}{\sigma_n}\right]^{1/2}$$

where σ is the laser stimulated emission cross section, n is the refractive index, and Z_0 is the impedance of vacuum.

For a laser with output power P_0 =1 mW and with other parameter values as reported in Table I [9], the system was found to route to chaos in the range $K = 5.5 \cdot 10^{-3} - 4\ 10^{-2}$. The Lang and Kobayashi equations represent a simple and generally accepted model in the literature to describe monomode semiconductor lasers; they correctly predict all phenomena observed in the weak-to-moderate injection regimes, both from an external reflector and from another source, including chaos. Since the aim of the present work is to gain physical insight by fast numerical integration, we have not tried to develop a more accurate model including, e.g., noise sources and the laser sensitivity to ambient parameters or describing to some extent the laser-building technology.

However, for a closer simulation of a practical setup, at the end of the present section we have considered the effect of parameter deviation from nominal values.

Let us now consider two nominally identical injection systems (system 1 and system 2 as in Fig. 1) which are both driven to chaos by the injection parameter K. We want to analyze whether the output field E_2 of system 2 can be forced, by a suitable scheme, to synchronize to the output E_1 of system 1, which means, consistently with theory, that $|E_1 - E_2| \to 0$ for $t \to \infty$.

The synchronization scheme we propose is reported in Fig. 1 and is based on full optical direct feedback in a master-slave configuration. Both the output field E_1 of system 1 (the master oscillator) and the output field E_2 of system 2 (the slave oscillator) are applied, through a beam combiner, to the input of the injected laser of the slave system (LD4), with opposite sign, i.e., with a π phase shift. This arrangement can be experimentally implemented, e.g., by cascading two beam splitters and using a suitable active control of the pathlength.

A similar master-slave approach has been proposed by Chen and Dong at electrical frequencies [12]. This architecture is readily implemented with injected lasers, while the well-known scheme proposed by Pecora and Carrol [2] would require the decomposition of the chaotic system into two conditionally stable subsystems, not easily recognizeable in our case. We would like to point out that our scheme relies on field superposition, and while the same topology with simple intensity combination would not work, a practical implementation requires the same level of accuracy usually met in coherent detection or interferometry.

The principle of operation can be easily explained assuming for the moment that the two systems in Fig. 1 are identical and have the same starting conditions. In this case, the systems are already synchronized, since the output signals are identical ($E_1 = E_2$). It follows that the contributions of E_1, E_2 to injection cancel each other, and system 2 is virtually isolated from system 1. However, should a small perturbation cause $E_1 \neq E_2$, an error signal $E_1 - E_2$ would arise and contribute to injection of system 2, modifying its regime until once more $E_1 = E_2$. This proposed synchronization scheme has been studied numerically for a large range of parameters.

System 1 has been described by (1); for system 2, in additon to straightforward notation changes, the equation set has been modified to describe the local feedback and the injection from system 1. Namely, the last term in (1a) describing amplitude has been substituted by

$$\frac{K}{\tau_{\rm in}} E_t \cos(\Phi_2 - \Phi_t) \tag{2a}$$

and the last term on (1b), which describes phase, has been substituted by

$$\frac{K}{\tau_{\rm in}} \frac{E_t}{E_2} \sin(\Phi_2 - \Phi_t) \tag{2b}$$

where E_t is the total injected field, i.e., $E_t \exp(j\Phi_t) = E_0 + E_1 \exp(j\Phi_1) - E_2 \exp(j\Phi_2)$.

We have begun by considering nominally identical systems with different starting conditions. In Fig. 2, we report a typical

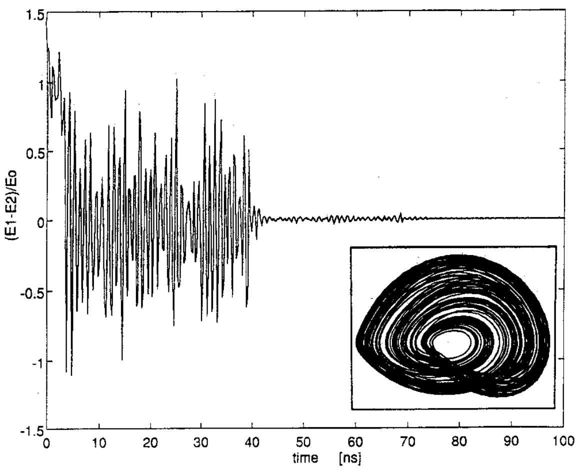


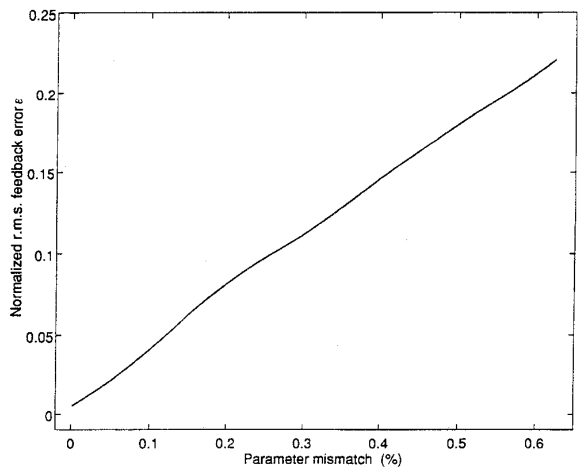
Fig. 2. Normalized feedback error $(E_1 - E_2)/E_0$ during a synchronization transient. System 1 is on the chaotic orbit shown in the insert ($K = 6\ 10^{-3}$), while system 2 has nominally identical values of parameters but starts from an arbitrary initial condition.

time evolution of the normalized feedback error $(E_1 - E_2)/E_0$ for $K = 6 \cdot 10^{-3}$: after a transient, a region is entered where the systems are permanently synchronized, and the error is steadily reduced down to a small value ($\approx 1.2 \cdot 10^{-3}$). Consistently with previous works [9], [11], in Fig. 2 and throughout this paper we report time-domain signals and spectra as would be observed after beating with a local oscillator at optical frequency ω_s.

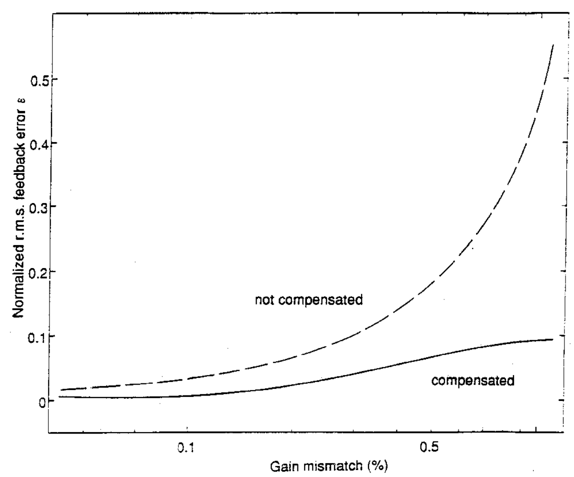
Plots similar to those of Fig. 2 have been obtained for different values of K and of the initial conditions as well as changing the dissonance $\Delta\omega_s$. In general, though the details and the duration of transient can be markedly different, synchronizaton is reached for a wide range of parameters. An attenuation both on the local feedback (path B in Fig. 1) and on the master injection field (path A in Fig. 1) should have been introduced to take into account the loss of the beam combiner, the output splitters of systems 1 and 2, and the fiber. The last contribution can be significant on path A in long-haul transmission experiments; however, since loss effect can be compensated by an adequate variation of K in the slave system, in the reported simulations we have always assumed lossless optical connections, without lack of generality.

Anyway, we have found that a moderate loss L does not prevent synchronization, as long as it is balanced on pathlengths A and B. Moreover, introducing a controlled loss (i.e., reducing the loop gain of the local feedback) can even increase performance, giving shorter transients before synchronization. With our parameters we found $L = -0.3$ as the optimum value.

Of course, in a practical case one cannot assume perfect parameter matching; for a closer simulation of an experimental setup we have introduced an uncompensated mismatch of all parameters reported in Table I. Alternatively, we have considered a mismatch of gain G_n, which has been compensated by acting on the pump in order to restore the nominal laser output value, as one would easily do in the laboratory.



(a)



(b)

Fig. 3. (a) Normalized r.m.s. feedback error ε as a function of parameter mismatch to simulate synchronization of physically different systems. All parameters of Table I are varied at the same time. (b) Normalized r.m.s. feedback error ε as a function of gain mismatch without compensation (dotted line) and after acting on the pump to restore the output power (full line).

In order to describe the effect of mismatch when the chaotic waveform is superimposed on a constant field, we introduce the relative feedback error ε, which is calculated on the varying components only. Parameter ε is defined as the ratio of the r.m.s. value of the synchronization error $\sigma_{12} = \sigma(E_1 - E_2)$ to the r.m.s. value of the chaotic waveform of the master system $\sigma_1 = \sigma(E_1)$, and reads

$$\varepsilon = \frac{\sigma_{12}}{\sigma_1} \tag{3}$$

As it can be seen from Fig. 3(a), changing together all parameter values of $\Delta = 0.2\%$ gives $\varepsilon \cong 0.07$, which means that the error is far lower than the amplitude of chaos. In practice, it can be concluded that matching between the two systems should be within 0.5%.

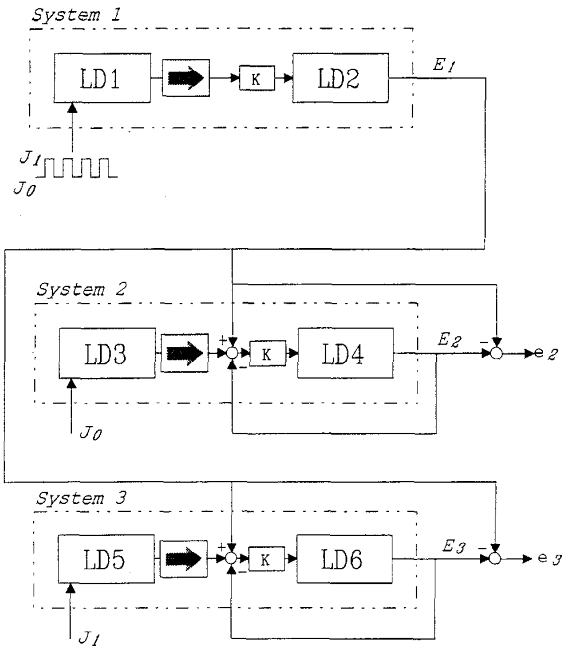


Fig. 4. Scheme of secure transmission based on chaotic shift keying (CSK). System 1 (at the transmitter end) is switched between two closely spaced orbits, which represent bit "1" and bit "0", by changing the pump value from J_1 to J_0. Systems 2 and 3 (at the receiver end) are replicas of system 1 and synchronize on bit "0" and "1," respectively.

In Fig. 3(b), ε is reported as a function of gain mismatch both with and without compensation, performed by restoring the nominal output power by means of the pump current.

Since our scheme is based on field superposition, we have also investigated the effect of a propagation delay τ in the local feedback, finding that for efficient synchronization τ must be small with respect to the inverse of the bandwidth of the chaotic waveform. This result puts a limit on the length of path B. Moreover, for the system to work properly, the relative phase between fields E_1 and E_2 must not differ sensibly from the nominal value π and the error φ due, for example, to beamsplitter nonidealities, must be small. With our choice of parameters, path B can be of the order of a few cm while φ must not exceed 5°. A similar conclusion applies to the relative phase of E_s.

III. Criptography

In the following, we propose two schemes for secure transmission based on the chaotic synchronization architecture described in the previous section. The first implements the concept of chaos shift keying (CSK) or chaotic switching [4], and the second is simply the chaotic masking of the transmitted signal [5].

A. Chaotic Shift Keying

In Fig. 4, the transmitter (system 1) is switched between two different chaotic orbits by modulating the supply current of the injecting laser by the bit stream to be transmitted; bits

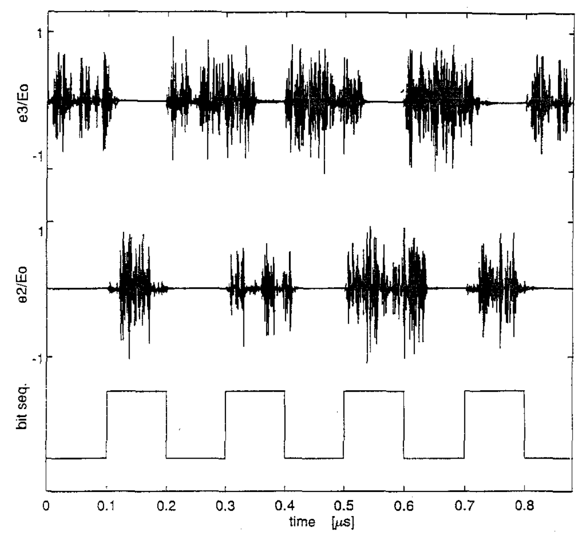


Fig. 5. Normalized output signals e_2, e_3 showing demodulation of bit "0" and bit "1." Synchronization is reached after a transient.

"1" and "0" correspond to different pump currents J_1 and J_0. For a secure transmission, we must select two closely spaced chaotic orbits so that the transmitted bits cannot be detected by direct observation of the chaotic signal E_1 in the time domain or in the phase plane. Switching between orbits belonging to different attractors would offer better-defined symbol encoding and can be used for standard (noncryptographic) transmission, as already proposed at electrical frequencies [4].

Decoding at the receiver end is performed by using two replicas of system 1, the first (system 2 in Fig. 4) is pumped at current J_0 and the second (system 3 in Fig. 4) at J_1. The received signal is sent to both decoders; however, only the one having the pump current corresponding to the transmitted bit will synchronize. Signals e_2 and e_3 are then obtained as the difference between the output, E_2 or E_3, of each decoder and the chaotic received signal. Finally, the transmitted bits can be conveniently recovered, detecting which of e_2 and e_3 is zero.

The selection of the system parameters is critical since it must guarantee secure transmission as well as efficient decoding. Working on too closely spaced orbits would require a very precise matching between transmitter and receiver; in addition, synchronization transients would be long, and detection error rate would increase.

On the other side, selecting too distant orbits would allow the eavesdropper to make a working copy of the receiver even without an accurate knowledge of the parameters; moreover, symbols could even be detected by observation of the shape of the waveform.

In Figs. 5–7, we show the results of numerical simulations based on the set of parameters of Table I and further assuming $J_0 = 65$ mA, $J_1 = 66.3$ mA, which corresponds to encoding bit "0" on the orbit $K_0 = 6 \cdot 10^{-3}$ and bit "1" on the orbit $K_1 = 7.2 \cdot 10^{-3}$, respectively

In Fig. 5 the outputs e_2, e_3 of the decoders for bit "0" and "1" are compared to the transmitted digital signal (at the

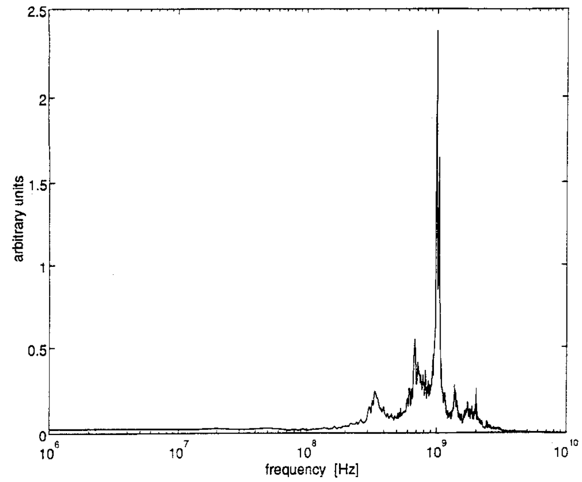


Fig. 6. Typical spectra of transmitted signal E_1 for a random sequence of bit "1" and bit "0" (CSK). Information cannot be extracted by observation in the frequency domain.

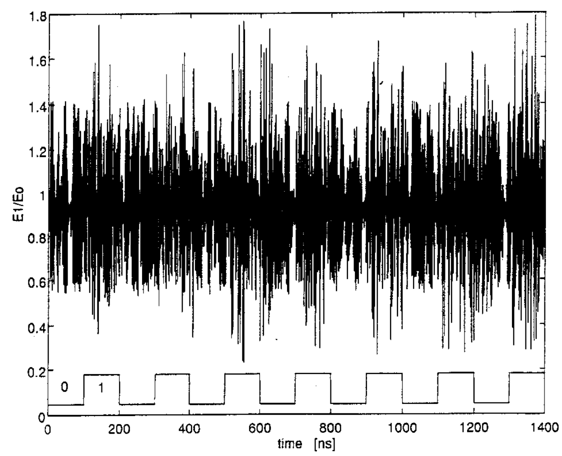


Fig. 7. Typical sample of signal E_1 when a bit sequence is transmitted (CSK). Information cannot be extracted by observation of time-domain waveform.

bottom). After a transient, signal e_2 falls to zero when system 2 synchronizes (bit "0" transmitted), while it is chaotic when it does not (bit "1" transmitted). Signal e_3 from the other decoder has a complementary trend.

In Fig. 6, a spectrum of signal E_1 is shown that corresponds to the transmission of a random sequence of bits at 5 MHz repetition frequency. From direct observation in the frequency domain it seems not possible to extract information, not even the bit frequency. The same conclusion would be taken from observation of the phase-plane plots, because the two orbits have been selected to be very close. Simulations have been performed for modulating signals in the range 1 MHz–200 MHz since the chaotic spectrum (as detected after beating with a local oscillator at frequency ω_s) is around the relaxation frequency of the laser (1 GHz) [8]. Higher data rates could be obtained with a different source. We have also tested different values of K spanning the whole chaotic range.

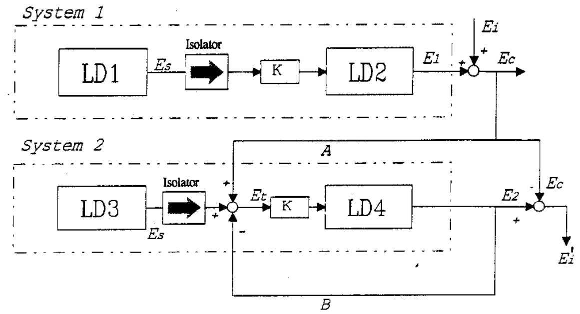


Fig. 8. Scheme of chaotic masking. Chaotic field E_1 generated by system 1 (at the transmitter end) is added to the signal E_i to be transmitted. System 2 (at the receiver end) synchronizes to E_1 in spite of the added signal, which can be recovered by difference.

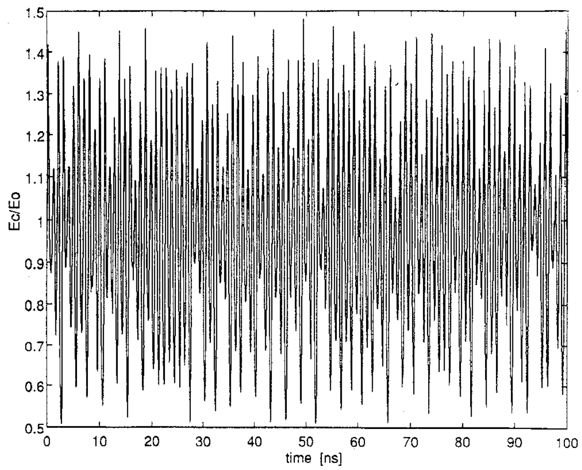
Finally, in Fig. 7 we report a sample of the transmitted signal E_1 together with the trasmitted bit string to show that neither the single bits nor switching between bits can be detected by observation in the time domain. We would like to point out that the proposed scheme does not rely on accurate coding of bits "1" and "0" on two given orbits corresponding to nominal values of K. Rather, it is based on synchronization between chaotic lasers; the two orbits are arbitrary, provided they are different and yet close enough for efficient operation. It follows that the system performance is not strongly sensitive to small parameter deviation from nominal values, provided that the transmitter and the receiver are tuned to each other. Trimming can be performed from time to time by transmitting a given digital word. Since just small adjustments should be required, it would be unpractical for the eavesdropper to get enough information to replicate the system.

B. Chaotic Masking

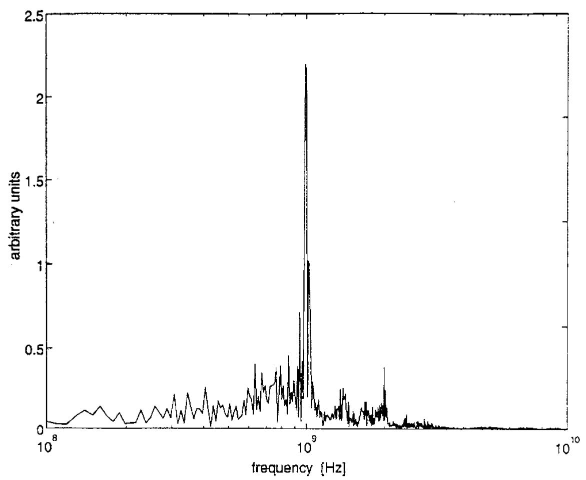
CSK allows a high level of security which relies upon a rather complicated implementation requiring three matched injection systems. On the other side, we have considered another cryptographic scheme, namely, chaotic masking, where the signal is not encoded on, but just summed up to chaos so that it cannot be detected by observation of the time and frequency domain. This approach is less efficient because only a part of the transmitted power carries information, most being used to mask information. However, it is simple to implement as it requires only two injection systems.

The scheme, which is shown in Fig. 8, is similar to the basic synchronization setup of Fig. 1, but now an optical carrier E_i modulated by the bit sequence is summed to E_1 and the composite signal E_c is transmitted. Decoding is performed by system 2 provided that it synchronizes only on the chaotic component of the received signal, which is therefore available on output E_2. The reconstructed bit stream E_i' is then obtained by making the difference between E_c (taken from path A using a beamsplitter) and E_2.

In Fig. 9(a), we show a sample of the chaotic waveform E_1. It is evident that the amplitude of signal E_i must not exceed



(a)



(b)

Fig. 9. (a) Sample of chaotic waveform E_1 and (b) spectrum of the transmitted composite signal E_c.

10–20% of the chaotic waveform and that its fundamental frequency must be close to that of chaos (i.e., to the relaxation frequency of the laser $f_r \approx 1$ GHz), otherwise information could be extracted directly from the waveform (or from the spectrum). Low signal amplitude is also mandatory for effective synchronization of system 2, since the added signal obviously disturbs the feedback loop of the slave system. With these assumptions, efficient masking has been obtained [Fig. 9(b)] and in Fig. 10 we show the reconstructed bit sequence E_i' after synchronization and subtraction of chaos.

Notice that since in chaotic masking chaos is simply used to hide the signal, coherent superposition of fields E_1 and E_i is not required; in a practical implementation, however, using a fraction of the output of laser LD1 as the signal carrier would offer a simple way of getting an accurate superposition of the optical spectra.

Finally, we wish to point out that chaotic masking is far more secure than masking with white noise. In the latter case,

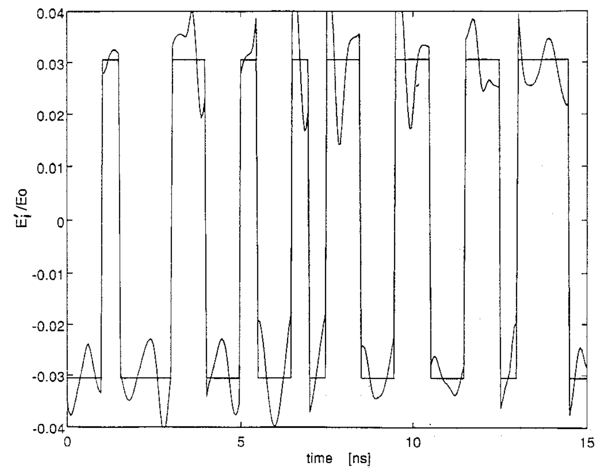


Fig. 10. Reconstruction of the bit sequence by synchronization and subtraction of chaos.

data bits can be extracted by a using a correlator; in the former case, as we have found by simulations, this is not possible, since the correlation time of the bits and of the chaos are almost identical.

IV. Conclusion

We have shown how two chaotic laser-injection systems can be synchronized by optical feedback. We have proposed two approaches for secure transmission which rely on the proposed scheme and allow the exploitation of the large bandwidth available on optical networks. CSK is more efficient and secure, since the signal is encoded on the chaotic waveform. On the other side, chaotic masking is more simple to implement since only two injection-laser systems are used, and parameter matching and stability requirements are relaxed.

References

[1] T. Kapitaniak, "Synchronization of chaos using continuous control," *Phys. Rev. E*, vol. 50, no. 2, pp. 1642–1644, Aug. 1994.

[2] L. M. Pecora and T. L. Carrol, "Synchronization in chaotic systems," *Phys. Rev. Lett.*, vol. 64, no. 8, pp. 821–824, Feb. 1990.

[3] U. Parlitz, L.O. Chua, Lj. Kocarev, K. S. Halle, and A. Shang, "Transmission of digital signals by chaotic synchronization," *Int. J. Bifurc. Chaos*, vol. 2, no. 4, pp. 973–977, Apr. 1992.

[4] H. Dedieu, M. P. Kennedy, and M. Hasler, "Chaos shift keying: Modulation and demodulation of a chaotic carrier using self-synchronizing Chua's circuits," *IEEE Trans. Circuits Syst. II*, vol. 40, no. 10, pp. 634–642, Oct. 1993.

[5] K. M. Cuomo, A. S. Oppenheim, and S. H. Strogatz, "Synchronization of Lorentz-based chaotic circuit with applications to communications," *IEEE Trans. Circuits Syst. II*, vol. 40, no. 10, pp. 626–633, 1993.

[6] S. Hayes, C. Grebogi, E. Ott, and A. Mark, "Experimental control of chaos for communication," *Phys. Rev. Lett.*, vol. 73, no. 13, pp. 1781–1784.

[7] K. M. Cuomo and A. S. Oppenheim, "Circuit implementation of synchronized chaos with applications to communications," *Phys. Rev. Lett.*, vol. 71, pp. 65–68, Jan. 1993.

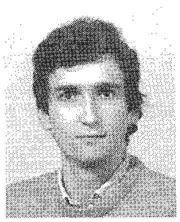
[8] P. Celka, "Chaotic synchronization and modulation of nonlinear time-delayed feedback optical systems," *IEEE Trans. Circuits Syst. I*, vol. 42, no. 8, pp. 455–463, Aug. 1995.

[9] V. Annovazzi-Lodi, S. Donati, and M. Manna, "Chaos and locking in a semiconductor laser due to external injection," *IEEE J. Quantum Electronics*, vol. 30, no. 7, pp. 1537–1541, July 1994.

[10] R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," *IEEE J. Quantum Electronics*, vol. QE-16, no. 3, pp. 347–355, Mar. 1980.

[11] J. Sacher, D. Baums, P. Panknin, W. Erlsässer, and O. Göbel, "Intensity instabilities of semiconductor lasers under current modulation, external light injection and delayed feedback," *Phys. Rev. A*, vol. 45, pp. 1893–1905, Feb. 1992.

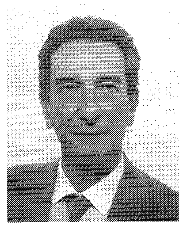
[12] G. Chen and X. Dong, "On feedback control of chaotic continuous-time systems," *IEEE Trans. Circuits Syst. I*, vol. 40, no. 9, pp. 591–601, Sept. 1993.



Valerio Annovazzi-Lodi (M'89) was born in Novara, Italy, on November 7, 1955. He received the degree in electronic engineering from the University of Pavia, Italy, in 1979.

Since 1979, he has been working at the Department of Electronics at the University of Pavia in the field of electrooptics, formerly on injection-modulation phenomena in lasers and on the fiber gyroscope, and later on birefringence effects in optical fibers, fiber sensors, and transmission via diffused infrared radiation. In 1983, he became a Staff Researcher at the Department of Electronics of the University of Pavia and in 1992 he became an Associate Professor in the same institution.

Dr. Annovazzi-Lodi is member of AEI.



Silvano Donati (M'75) received the degree in physics from the University of Milan, Italy, in 1966.

For nine years, he was with CISE, Milan working on noise in photomultipliers and avalanche photodiodes, nuclear electronics, and electrooptic instrumentation (laser telemetry, speckle pattern interferometry, gated vision in scattering media). In 1975, he joined the Department of Electronics, at the University of Pavia as Internal Lecturer and worked on feedback interferometers, fiber gyroscope, and noise in CCD's. In 1980, he became Full Professor of Optoelectronics, and since then his main research interests have been optical fiber sensors, passive fiber components for telecommunications, free-space and guided optical interconnections, and locking and chaos in lasers. He has authored or coauthored nearly one hundred papers and holds four patents.

Dr. Donati is a member of AEI, APS, OSA, and ISHM, and has actively served to organize several national and international meetings and schools in the steering and program committees or as a chairman. He also worked in the standardization activity of CEI/IEC (CT-76 laser safety and CT-86 optical fibers).

Alessandro Scirè was born in Rimini, Italy, on June 26, 1971. He received the degree in electronic engineering, *cum laude*, in 1995 from the University of Pavia, Italy.

Upon graduation, he worked for some months at the Electrooptics Laboratory of the University of Pavia. His research interests are semiconductor lasers, injection phenomena, and chaos.