Synchronization of Chaotic Semiconductor Lasers with Optoelectronic Feedback and its Applications to Encoded Communications

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Abstract:

The theoretical study of synchronization of two coupled single – mode semiconductor lasers is achieved. The transmitter is laser subject to optoelectronic feedback that operates in a chaotic regime. The receiver can also operate in a chaotic regime similar to the transmitter. The effects of parameter mismatch on the synchronization of two lasers with optoelectronic feedback are determined, with mismatch in delay time, with mismatch in feedback strength, and with coupling strength between two systems. The synchronization is sensitive to mismatch in the delay time for the transmitter and receiver feedback loops. An open – loop receiver configuration does not have the problem of delay time mismatch and shows the highest synchronization. The synchronization phenomena that appear in the two-coupled semiconductor lasers can be used in communications systems. Finally, an encoding and decoding of message on the chaotic carrier is demonstrated.

التـــزامن بين ليـــزرات أشـــباه الموصلات التخبطيـــــة
ذات التـــغذية المرتـــدة بالالكترونيات الضوئية وتطبيقاتها في الاتصالات المشفرة

فاضـــل رحمـــة طـــاهر
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الخلاصـــــة:

تم أنجاز الدراسة النظرية للتزامن (Synchronization) بين ليزرات أشباه الموصلات المتقارنه ذات الطور الأحادي. المُرسلة (Transmitter) عبارة عن ليزر يعمل في النظـــام التخبطـــي (Chaotic Regime) نتيجـــة التغذية المرتدة ألالكترونية الضوئية (Optoelectronic Feedback). المُستقبلة (Receiver) أيضا ليزر يمكن أن يعمل في النظام التخبطي. تم تحديد تأثير عدم الموائمة بين البـــارامترات (Parameters Mismatch) للمُرســـلة و المُستقبلة على التزامن، عدم الموائمة في التأخير الزمني (Delay Time)، عدم الموائمة في شدة التغذيـــة المرتـــد (Feedback Strength) ، و شدة التقارن بين النظامين. وجد أن التزامن حساس لعدم الموائمة في التأخير الزمنـــي لحلقة التغذية المرتدة في المُرسلة و المُستقبلة مقارنة بعدم الموائمة في شدة التغذية المرتدة. التزامن يكون عالٍ في شكل المُستقبلة بدون التغذية المرتدة (Open – loop) وذلك بسبب عدم وجود مشكلة عدم الموائمة في التـــأخير الزمنـــي. التزامن لليزرين متقارنين يمكن أن يُستخدم في أنظمة الاتصالات. أخيرا، تم أظهار التشفير وإعادة فك الشفرة لرســـالة المحملة على حامل تخبطي (Chaotic Carrier).

I-Introduction:

The data encryption in chaotic communications systems has been studied intensively during recent years. The potential benefits of chaotic communications can be summarized as follows [1-5]; (i) ultra bandwidth of communication channel, (ii) high power efficiency, (iii) reduced number of components in a system, and (iv) security of communication by chaotic encryption.

Synchronization of chaotic semiconductor lasers has been given attention due to its potential in various applications especially in secure communications [6]. The basic concept of such work is synchronizing two chaotic lasers to enable efficient transmission and reception messages. The regime of complete chaos synchronization is achieved using similar components for both lasers with closed matching with respect to parameter, and operating conditions.

In previous work [7], the chaotic dynamics (oscillations) in a vertical cavity surface emitting lasers (VCSELs) diode with optoelectronic feedback is presented. This work extends the previous work and presents, numerically, the synchronization of chaotic semiconductor lasers and applications of data transmission. This paper is presented by five sections, begining by this introduction. System modeling is given in Section II. Section III covers the synchronization. Sections IV discuss the chaos communications. A brief conclusion is given in Section V.

II- System Configuration and Modeling:

For the optoelectronic system in Fig.(1), the chaotic dynamics of the transmitter is generated and controlled by optoelectronic feedback of the laser output that is converted to an electrical signal through photodetector (PD1). The dynamical state of the system is a function of the feedback strength and the delay time of the feedback loop.

The fraction of the transmitter's chaotic output intensity that is sent to the receiver is detected, amplified and coupled into driving current of the receiver. The receiver itself is a delayed optoelectronic feedback laser. The factor c (0 ¡Üc ¡Ü1) indicates the percentage of the total feedback signal in the receiver which is from the transmitter while $(1-c)$ corresponds to the fraction of the feedback signal from the receiver.

The transmitter and receiver systems can be modeled by means of rate equations for the photon numbers $P_{T,R}$, and the carrier numbers $N_{T,R}$ with each semiconductor laser [8]. The subscript T, R denotes to the transmitter and the receiver system, respectively. The coupled rate equations can be written as:

$$\frac{dP_T}{dt} = [G(N_T) - \gamma]P_T + R_{sp}(N_T) \quad ...(1)$$

$$\frac{dN_T}{dt} = \frac{I_T}{q} - \gamma_e(N_T)N_T - G(N_T)P_T \quad ...(2)$$

and

$$\frac{dP_R}{dt} = [G(N_R) - \gamma]P_R + R_{sp}(N_R) \quad ...(3)$$

$$\frac{dN_R}{dt} = \frac{I_R}{q} - \gamma_e(N_R)N_R - G(N_R)P_R$$

...(4)

The parameters appeared in equations are defined as follows:

The rate of stimulated emission in the active region can be expressed as:

$$G(N)=\Gamma v_g a_o (\frac{N}{V} - n_o) \quad ...(5)$$

, where Γ is the optical confinement factor and can be written as :

$$\Gamma=\frac{d}{L} \quad ...(6)$$

with d and L as the thickness of active region and the length of the cavity, respectively, v_g is the group velocity of the light, a_o is constant linear gain coefficient, n_o is the carrier density at transparency, and V is the volume of the active region which can be written as :

$$V=\frac{\pi}{4}D^2 d \quad ...(7)$$

where D is the diameter of active region.

The photon decay rate can be expressed as:

$$\gamma=v_g[\Gamma \alpha_{ac}+(1-\Gamma)\alpha_{ex}+\alpha_m] \quad ...(8)$$

where α_{ac} and α_{ex} are the scattering loss in the active and external regions respectively. The mirror loss α_m is calculated by:

$$\alpha_m=\frac{1}{2L}Ln\frac{1}{\sqrt{R_f R_r}} \quad ...(9)$$

where R_f and R_r are the power reflectivity of front and rear facets, respectively.

The term $R_{sp}(N)$ is the spontaneous emission rate and can be written as:

$$R_{sp}(N)=\frac{\Gamma\lambda^4 BN^2}{4\pi^2 \mu\mu_g \Delta\lambda_{sp} V^2} \quad ...(10)$$

where λ is the light wavelength, $\Delta\lambda_{sp}$ is the spectral width of the spontaneous emission, B is radiative recombination coefficient, μ_g and μ are the group refractive and refractive indexes of the active region, respectively.

The carrier recombination rate $\gamma_e(N)$ is given by:

$$\gamma_e=A_n+B(\frac{N}{V})+C(\frac{N}{V})^2 \quad ...(11)$$

where A_n and C are surface recombination rate and nonradiative recombination coefficient, respectively.

The net current injected into transmitter and receiver laser are:

$$I_T=I_o+I_{FT}(t-\tau_T) \quad ...(12)$$

and

$$I_R=I_o+[1-c]\,I_{FR}(t-\tau_R)+cI_p \quad ...(13)$$

where

$$I_F=\xi\frac{\eta q}{h\upsilon}P_o \quad ...(14)$$

$$I_p = \xi \frac{\eta q}{h\upsilon} P_{oT} \quad ...(15)$$

where ξ is the parameter of feedback strength, η is the quantum efficiency of the high speed photodetector, $h\upsilon$ is the lasing photon energy, and P_o is the output power emitted from each facet and can be calculated from:

$$P_o = \frac{1}{2} h\upsilon v_g \alpha_m P \quad ...(16)$$

Also I_O, $I_F(t-\tau)$, τ, q are the dc bias current, delayed feedback current, parameter of delay time, and the electron charge, respectively. The values of parameters set in numerical simulation are given in table I.

III-Synchronization:

The schematic for synchronization of two semiconductor lasers is shown in Fig.(1). The time - dependent synchronization error is introduced to quantify the synchronization and can be written by:

$$\varepsilon(t) = P_{oT}(t) - P_{oR}(t) \quad ...(17)$$

The parameters characterizing the semiconductor lasers or the optoelectronic feedback loops can never be identical in a real system. To achieve synchronization, the laser parameters are matched by carefully choosing a pair of lasers from the same batch with the closest characteristic and then fine - tuning their operating conditions [9].

The effect of the various parameter mismatches between the transmitter and receiver on the quality of synchronization is evaluated.

Figure (2) display the synchronization error and correlation plot, synchronization plot, for mismatch in feedback delay time τ (set to $\tau_T - \tau_R = 1\,ns.$) for different values of coupling strength c. It is clear that as c increase the synchronization error, Fig.(2a), due to mismatch becomes small. The correlation plot in Fig.(2b) is obtained by plotting the transmitter output power versus the receiver output power. The data is distributed along the 45^o line, indicating identical synchronization as for c= 0.9 and c= 0.99.

The synchronization error for mismatches a in feedback strength ξ (set to $\xi_T - \xi_R = 0.15$) are shown in Fig.(3) for different values of coupling strength c. From this, the feedback strength mismatch does not significantly affect the synchronization quality, while the influence of the delay time mismatch is very significant. The quality of synchronization increase rapidly for $(c > 0.6)$ and is the largest for open - loop receiver configuration (c = 1).

IV-Communications:

Different schemes of secure message transmission based on chaotic synchronization have been proposed up to now: chaos masking (CMA), chaos modulation (CMO), chaos shift keying (CSK), and ON/OFF shift keying (OOSK) [10].

In this paper, a model for chaos modulation is considered. Figure (4) shows a schematic of message encoding and decoding in the proposed chaos synchronization system, where the open - loop configuration (c=1) is used. The information transmitted using chaotic dynamics properties based on chaos modulation can be obtained with a message, m(t), added directly to the transmitter injected current

$$I_T = I_o[1+m(t)] + I_{FT}(t-\tau_T) \quad ...(18$$

Figure (5) depicts the simulation results of encoding and decoding the message. The message was a 2^7-1 pseudo – random PN sequence, of 5% from chaotic carrier, at 250 Mbits/s (third trace). The top trace is the transmitter output power with message. The second trace is the receiver output power, which is due to the synchronization equal to the transmitter output before the addition of message. The message is decoded by subtracting the receiver output power (second trace) from the received signal as shown in fourth trace. The quality of the message can be improved with the suppression of the fast oscillation in decoded signal by the application of a fifth – order Butterworth low pass filter (bottom trace).Fig.(6) Shows the recovered message for 0.5 Gbits/s (a) and 1.0 Gbits/s (b).

V-Conclusion:

The optoelectronic feedback lasers exhibit high frequency chaotic oscillators. The chaos synchronization of two such systems is achieved. Synchronization between the transmitter and receiver lasers has been achieved by a unidirectional coupling of part of light output from the transmitter laser to the receiver laser. A small mismatch in delay time of the feedback loop strongly degrades the synchronization quality. The quality of synchronization shows an increase with increase of the c factor. The target of this paper is introducing the use of time – delayed systems for optical communication using VCSELs at 1.3 μm wavelength. It shown by numerical simulations that message encoding can be performed in the present chaos synchronization system by directly modulating the transmitter laser output. A pseudo-random PN sequence with bit rate up to 1Gbits/s (250 Mbits/s, 500 Mbits/s, and 1 Gbits/s) is successfully recovered when chaos synchronization is achieved.

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Table I: Parameter values used in the numerical simulations.

NO.	PARAMETER	VALUE
1	R_r	0.95
2	R_f	0.95
3	α_{ex}	$10\ cm^{-1}$
4	$\xi_T = \xi_R$	0.65
5	$\tau_T = \tau_R$	7.1 nsec.
6	α_{ac}	$10\ cm^{-1}$
7	v_g	$7.5 * 10^9\ cm.sec^{-1}$
8	n_o	$10^{18}\ cm^{-3}$
9	μ_g	3.2
10	μ	3.2
11	$\Delta\lambda_{sp}$	60 nm
12	A_n	$10^8\ sec^{-1}$
13	B	$10^{-10}\ cm^3.sec^{-1}$
14	λ	1.3 μm
15	a_o	$2.5*10^{-16}\ cm^2$
16	η	0.7
17	q	$1.6*10^{-19}$ C.
18	$h\upsilon$	$1.52*10^{-19}$ J.
19	I_o	8.1 mA.
20	c	variable
21	C	$3*10^{-29}\ cm^6.sec^{-1}$
22	D	5 μm
23	d	3 μm
24	L	8 μm

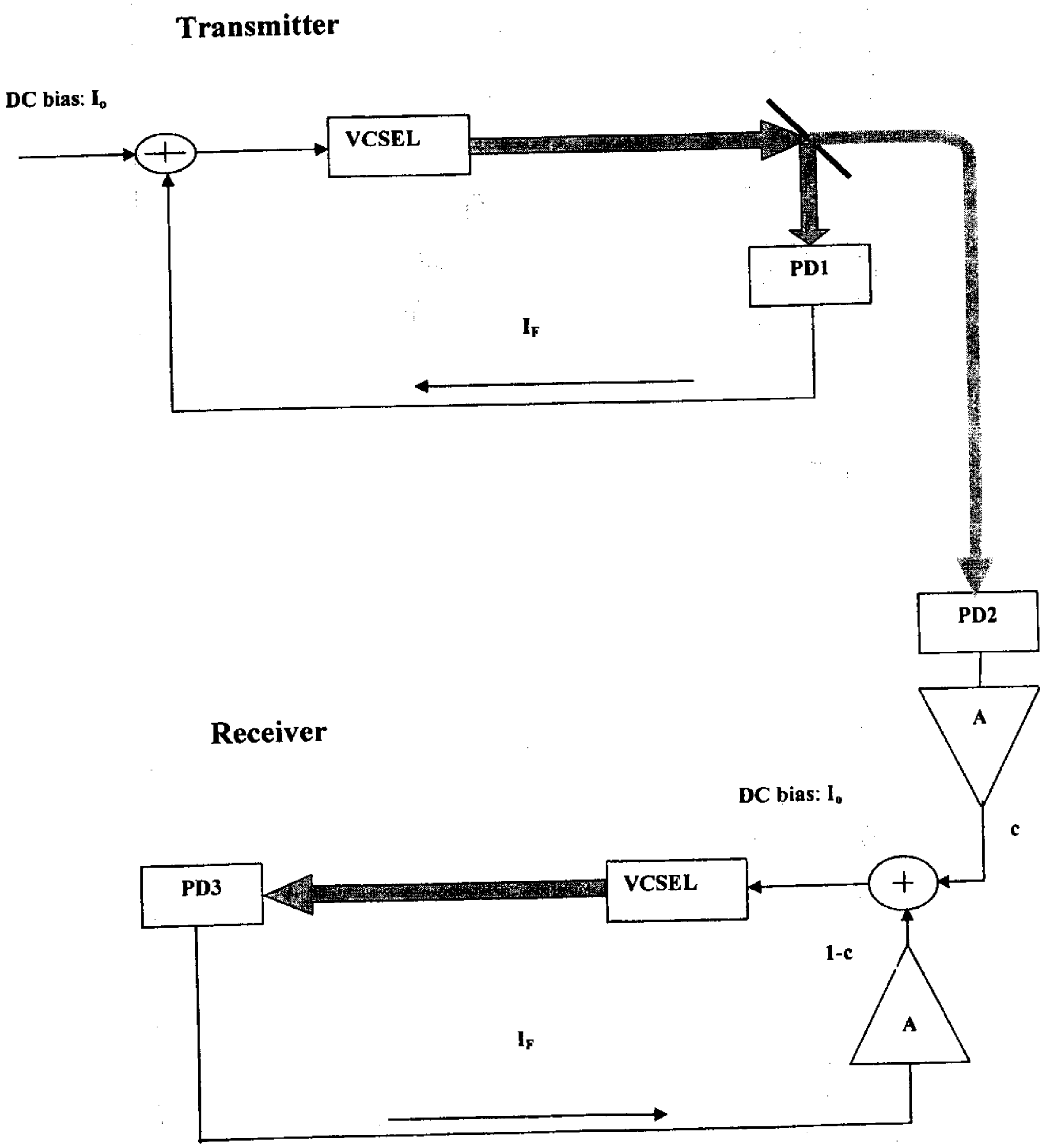

Figure (1): Schematic for synchronization of two chaotic lasers with delayed optoelectronic feedback. **VCSEL**: laser source; **PD**: photodetector; $\mathbf{I_o}$: dc bias current; $\mathbf{I_F}$: feedback current; **A**: amplifier; **c**: coupling strength.

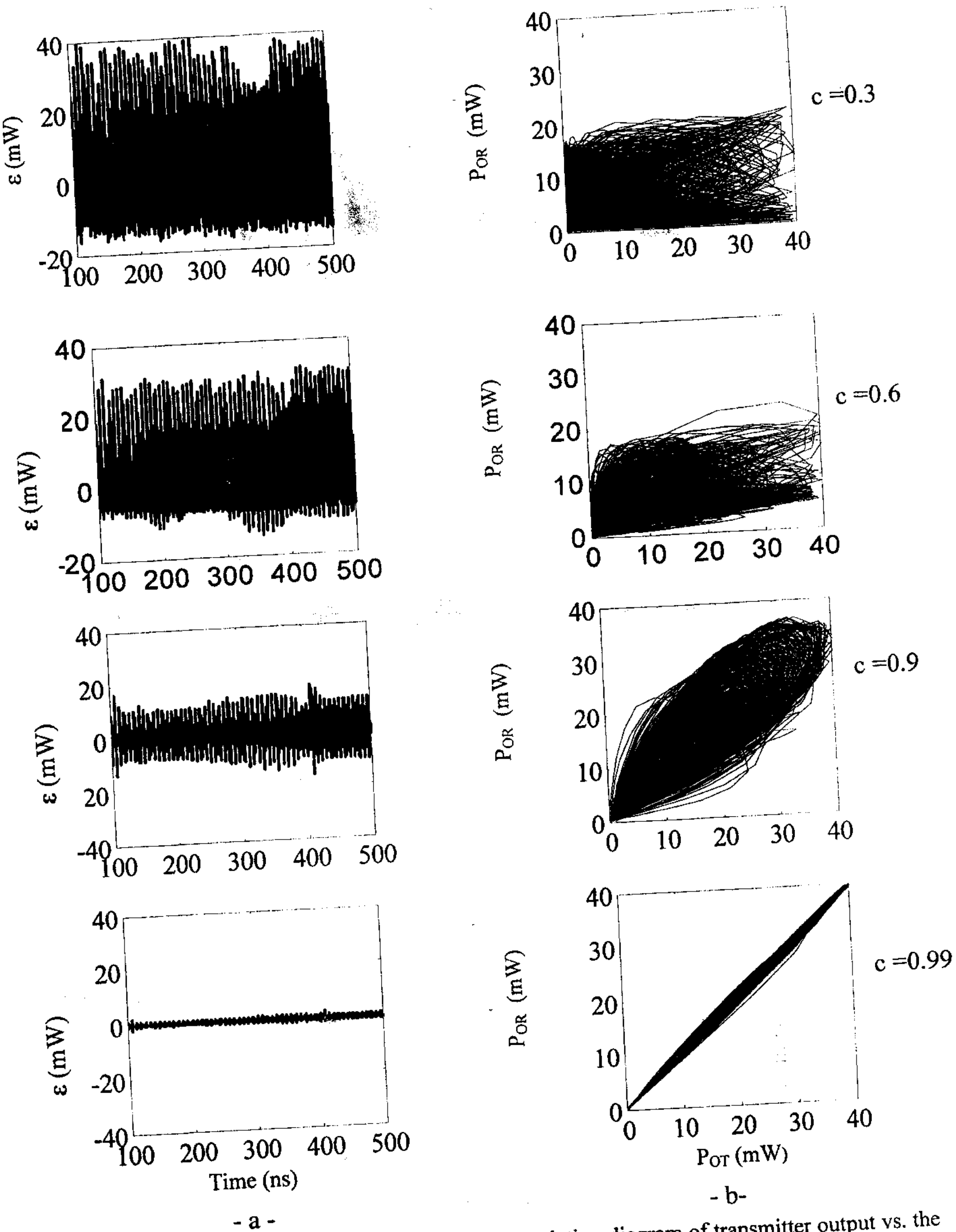

Figure (2): (a) Synchronization error ε and (b) Correlation diagram of transmitter output vs. the receiver output from mismatch in feedback delay time τ at different values of coupling strength c.

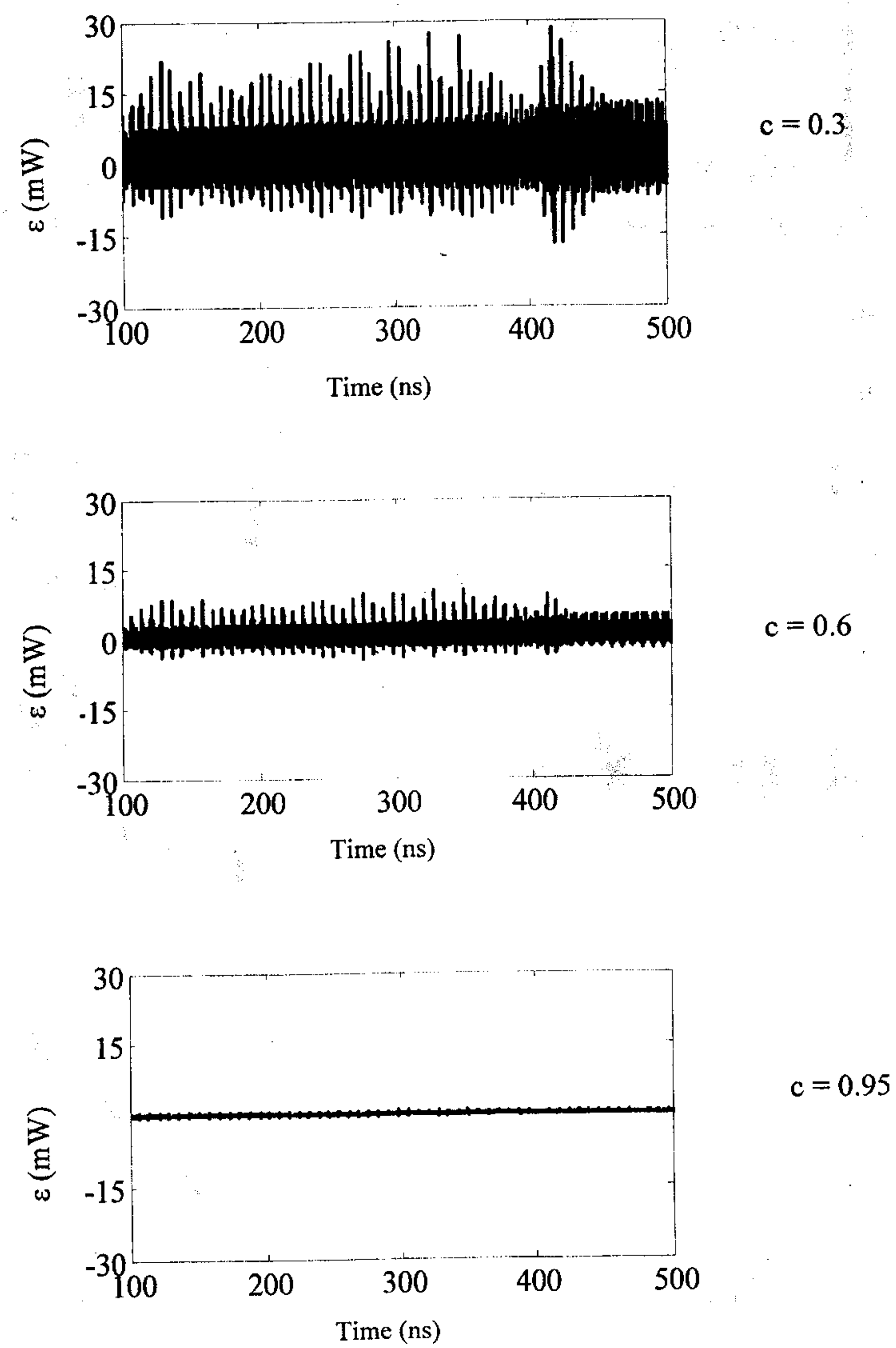

Figure (3): Synchronization error ε from mismatch in the feedback strength ξ at different values of coupling strength c.

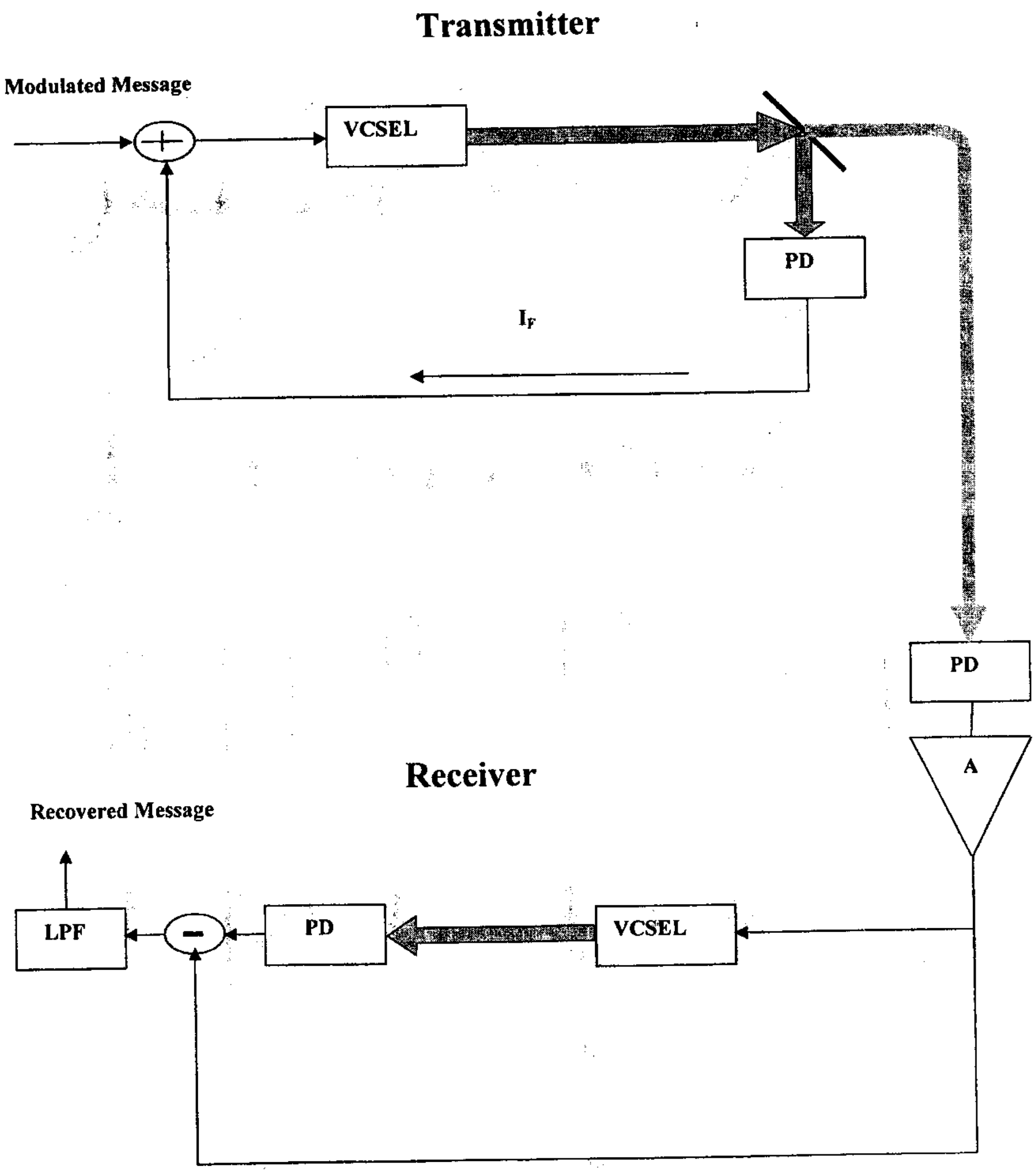

Figure (4): Schematic for synchronized optical communication system using chaotic semiconductor laser. **VCSEL**: laser source; **PD**: photodetector;; **A**: amplifier; **I_F**: feedback current, **LPF** : low pass filter.

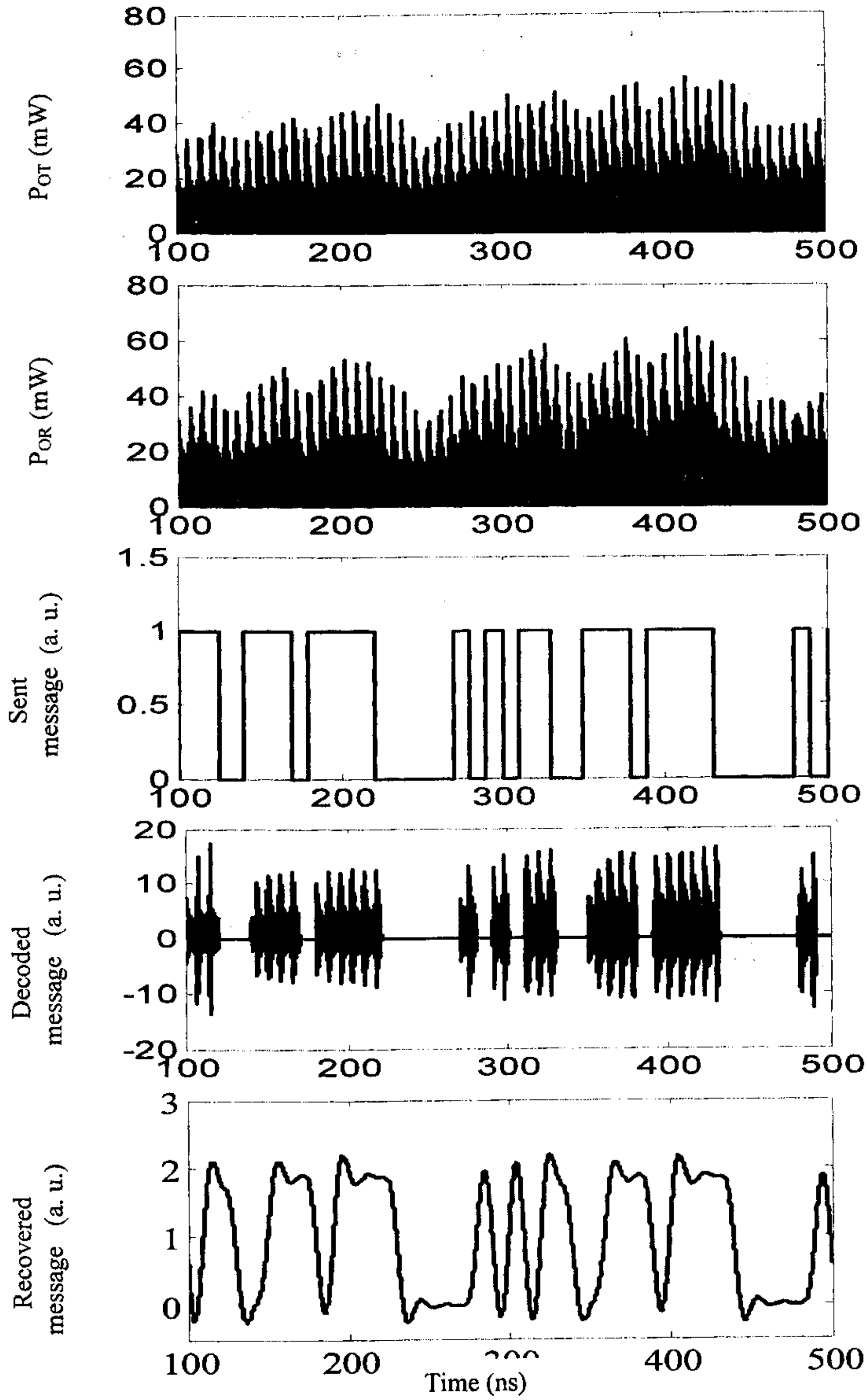

Figure (5): Encoding and decoding ot message at 250 Mbits/s. Top to bottom: time series of transmitted signal, receiver laser output, original message, decoded message, and recovered message after filtering.

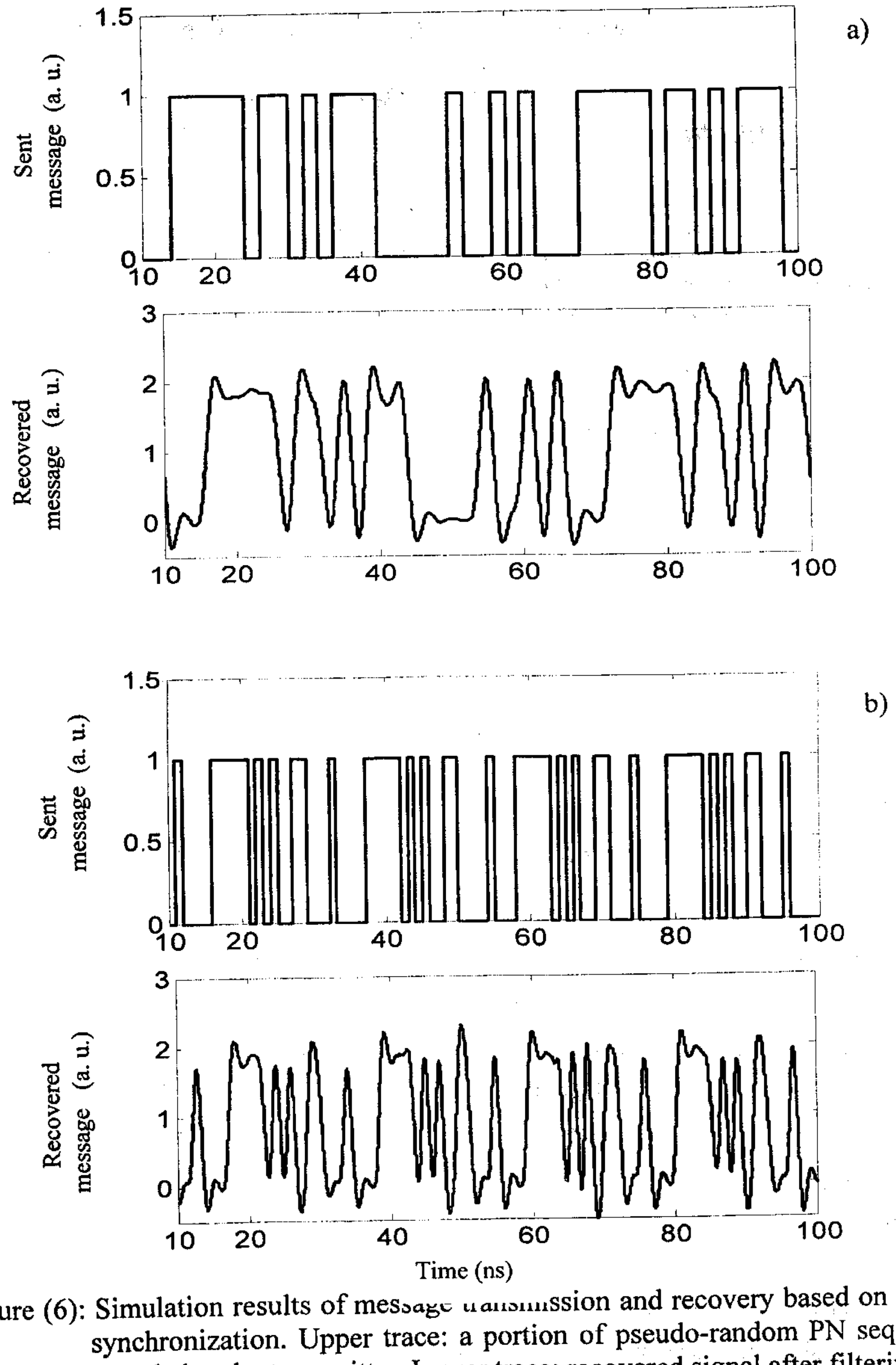

Figure (6): Simulation results of message transmission and recovery based on chaos synchronization. Upper trace: a portion of pseudo-random PN sequence encoded at the transmitter. Lower trace: recovered signal after filtering for (a) 0.5 Gbits/s and (b) 1.0 Gbits/s.