Erratum to ICTON 2014 paper Tu.C2.4: Transmission of Chaotically Encrypted Signals over an Optical Channel

B.I. Lembrikov*, Y. Ben-Ezra, and Yu. Yurchenko

Department of Electrical Engineering, Holon Institute of Technology,
P.O. Box 305, 58102, 52 Golomb str., Holon, Israel
Tel: (9723) 502 6684, Fax: (9723) 502 6685, e-mail: borisle@hit.ac.il

ABSTRACT

We proposed a novel system of the coupled lasers synchronization based on the master, slave and additional feedback lasers at the transmitter and at the receiver. We investigated theoretically the influence of optical fiber dispersion and nonlinearity on the chaotically encoded signal transmission efficiency. The numerical simulations show that the efficient transmission of the chaotically modulated waveform over the optical channel of a 100 km distance and the following decoding are possible.

Keywords: chaotic encryption, semiconductor laser, optical communication.

1. INTRODUCTION

The important problems of the contemporary information transmission systems are privacy and security. Traditional cryptosystems are based on software techniques where a short secret parameter defined as the key is used, or the message is encoded directly. A novel approach to encryption is based on a hardware communication system where the encryption is directly applied to the physical layer of the communication system [1]. Chaos communication is a direct encoding and decoding scheme of a message system in a communication system. Complex chaotic carriers provide a certain degree of privacy in the hardware layer of communication protocol [1]. The advantages of the chaotic communications are following: efficient use of the bandwidth of the communication channel; utilization of the intrinsic nonlinearities in communication devices such as semiconductor diode lasers; large-signal modulation for efficient use of carrier-power; reduced number of components in a communication system; security of communication based on chaotic encryption [1]. Optical communication with chaotic laser system attracted a wide interest since the chaos communication is compatible with optical-fiber components and transmitter/receiver devices [1]. Optical-fiber communication systems using chaotic semiconductor lasers have been investigated both theoretically and experimentally [1]-[6]. Chaos-based encryption in an optical communication system uses a chaotic master laser (ML) at the transmitter in order to hide the information to be transmitted and a slave laser (SL) at the receiver, for the information recovery [5]. Typically, generation of chaotic signals can be achieved by introduction of the delayed all-optical feedback with open or closed loop, optoelectronic feedback or electro-optical feedback into diode lasers [1]. The chaos masking, chaos modulation, and chaos shift keying (CSK) techniques are mainly used in chaos communications for the "chaos + message" signal encoding and decoding [1]. In the case of the chaos masking technique, an information-bearing signal is added to a chaotic carrier outside the transmitter, and then at the receiver, the information is subtracted; in the case of the chaos modulation, the message is mixed nonlinearly with the chaotic carrier; in the case of the CSK, the transmitter laser parameters are modulated by a digital message [1]. The high-speed long-distance communication based on chaos synchronization over a commercial fiber-optic channel with a length of 120 km has been demonstrated [2].

Recently, we proposed a novel all-optical method for a chaotic encryption based on two coupled subsystems of two master single-mode vertical cavity surface emitting lasers (VCSELs) and two slaved VCSELs synchronized by ML unidirectional radiation and connected in a back-to-back scheme [7]. The proposed technique is characterized by a higher level of security in an optical channel due to its more complicated chaotic behavior [7].

In this paper, we propose a novel system of the coupled lasers synchronization both at the transmitter and at the receiver taking into account the optical channel parameters. We carried out the numerical simulations of the optical communication channel containing such a transmitter and a receiver. We investigated theoretically the influence of optical fiber dispersion and nonlinearity on the chaotically encoded signal transmission efficiency. The numerical simulations show that the efficient transmission of the chaotically modulated waveform over the optical channel of a 100 km distance and the following decoding are possible.

2. CHAOTIC COMMUNICATION SYSTEM STRUCTURE

The block diagram of proposed chaotic communication system shown in Fig. 1 consists of four identical synchronized semiconductor lasers ML, feedback ML (FML), SL and FSL belonging to the transmitter and receiver, respectively. CSK encoding scheme is used. The transmitter and receiver systems are isolated from one another by means of the optical insulator (OI). Instead of optical mirror feedback, or electro-optic feedback, in our case the synchronization feedback is provided with FML and FSL. The optical channel includes single mode fiber (SMF) with a length of 100 km, Erbium doped fiber amplifier (EDFA) for the fiber loss compensation and a dispersion compensation fiber (DCF). ML, FML, SL and MSL are assumed to be identical. Unlike the four-chaotic-semiconductor-laser scheme [6], in the proposed scheme FML and MSL play a role of the active controlled feedback, and the same channel is used for the synchronization and the message transmission.

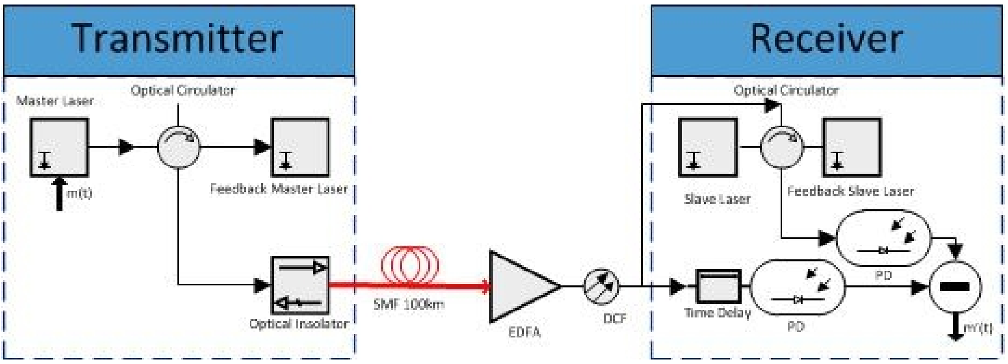

Figure 1. The chaotic optical communication system consisting of the synchronized transmitter lasers (ML, FML), receiver lasers (SL, FSL), optical SMF channel, OI, EDFA, and DCF.

3. THEORETICAL MODEL

Synchronized semiconductor lasers exposed to optical feedback manifest chaotic dynamics [1]. The theoretical analysis of the chaos in synchronized semiconductor lasers is based on the Lang-Kobayashi (LK) equations [1], [8]. It has been shown that the mirrors can be replaced with the master VCSELs providing the efficient tunable feedback which realizes a more complicated chaos and increases the communication system security [7]. In such a case, the LK equations for ML, FML, SL, and FSL have the form [1], [7], [8].

$$\frac{dE_1}{dt} = k_1(1+ia_1)(G_1-1)E_1(t)+\gamma_{21}E_2(t-\tau_1)\exp(-i\omega_2\tau_1) \tag{1}$$

$$\frac{dE_2}{dt} = k_2(1+ia_2)(G_2-1)E_2(t)+\gamma_{12}E_1(t-\tau_1)\exp(-i\omega_1\tau_1) \tag{2}$$

$$\frac{dE_3}{dt} = k_3(1+ia_3)(G_3-1)E_3(t)+\gamma_{13}\eta E_1(t-\tau_{\Sigma 1})\exp(-i\omega_1\tau_{\Sigma 1}) \tag{3}$$

$$\frac{dE_4}{dt} = k_4(1+ia_4)(G_4-1)E_4(t)+\gamma_{34}E_3(t-\tau_5)\exp(-i\omega_3\tau_5) \tag{4}$$

$$\frac{dN_i}{dt} = \frac{J_i - N_i - G_i\left|E_i\right|^2}{\tau_{ei}}, \quad i = 1,2,3,4 \tag{5}$$

where $E_{1,2,3,4}(t)$ are the slowly varying envelopes (SVEs) of the ML, FML, SL, and FSL electric fields, respectively, $N_{1,2,3,4}(t)$ are the ML, FML, SL, and FSL normalized carrier densities, respectively, k_i are the cavity losses, α_i are the linewidth enhancement factors (LEFs), G_i is the optical gain, $\gamma_{ik}, i,k = 1,2,3,4$ are the coupling constants for the ML, FML, SL and FSL electric fields, $\omega_1 = \omega_4, \omega_2 = \omega_3$ are the optical frequencies, J_i are the injection currents, τ_{ei} are the carrier lifetimes, η is the coupling rate, τ_i are the light propagation times along the trajectories between lasers and circulators shown in Fig. 1, $\tau_{\Sigma 1} = \tau_1 - \tau_3 + \tau_2 + \tau_4$. In the case of the incoherent chaos synchronization, the lasers' intensities $I_i \sim \left|E_i\right|^2$ are synchronized [9]. The synchronization occurs when equations (1), (3) and (2), (4), respectively, become identical [9]. These conditions for the proposed system had been obtained earlier [7].

4. SIMULATION RESULTS

Equations (1)-(5) with the synchronization conditions [7] have been solved numerically using VPI Photonics simulation tools (www.vpiphotonics.com) and the following numerical values for the waveform and optical channel parameters. The sample carrier mode center frequency and bandwidth are 193.1×10^{12} Hz and 1280×10^{9} Hz, respectively, the sampling rate is 160×10^{9} Hz, the bit rate of CSK is 2.5×10^{9} bit/s, the time delay is 4 ns, and the direct bias current is 40 mA. We used the data for a Multiple Quantum Well (MQW) laser with a device length of 360 μm and active region width of 2.5 μm. Current efficiency is equal to unity, a nominal wavelength is 1552.5 nm, an effective group refractive index is 3.7, the internal loss index is 3000 m^{-1}, confinement factor is 0.56, the optical coupling efficiency is equal to unity, initial carrier density is $10^{24}\ \mathrm{m}^{-3}$, linear gain coefficient is $30\times10^{-21}\ \mathrm{m}^2$, LEF is $\alpha_i = 3$, the fiber length is 100 km, the fiber attenuation is $0.25\times10^{-3}\,\mathrm{dB/m}$, the fiber dispersion is $16\times10^{-6}\ \mathrm{s/m^2}$ with $0.08\times10^{3}\ \mathrm{s/m^3}$ slope, the fiber nonlinear index is $2.6\times10^{-20}\ \mathrm{m^2/W}$, $\tau_1 = 12.2\times10^{-15}\ \mathrm{s}$.

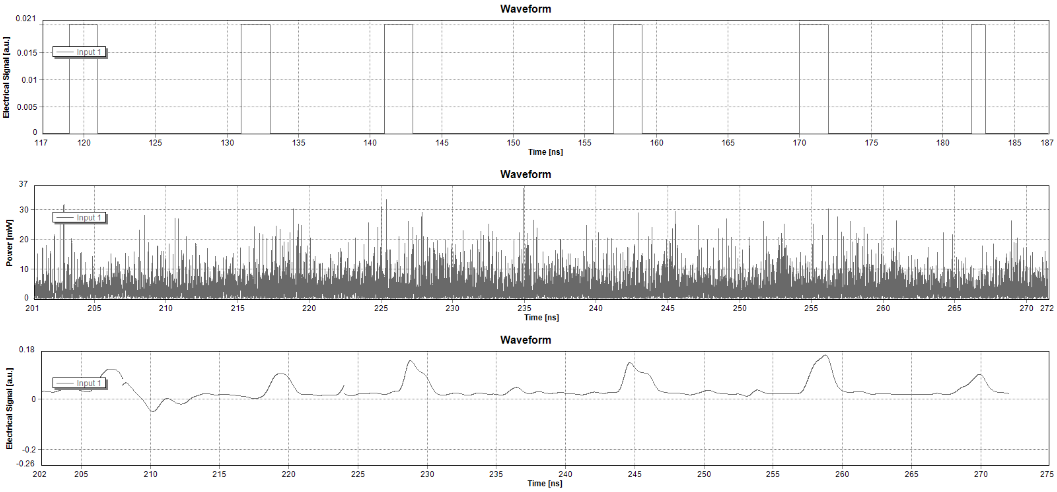

Figure 2. The encoded message (upper box), the chaotic waveform with the encoded message (middle box), and the decoded message (lower box) for the chaotic communication system with a fiber length of 100 km.

The simulation results for the encoded message, the chaotic waveform with the encoded message, and the decoded message for the fiber length of 100 km are presented in the upper, middle, and lower boxes of Fig. 2. It is seen that the chaotic behavior is strongly manifested and decoding is efficient.

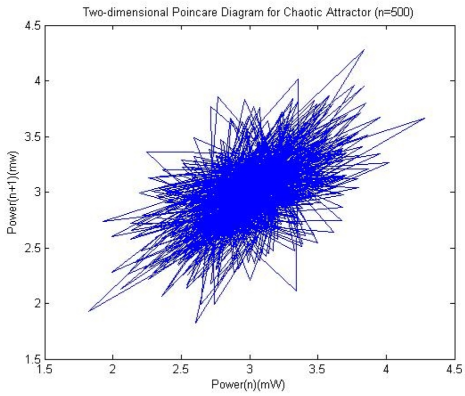

Figure 3. The attractor of the encoded waveform for the chaotic communication system with four synchronized lasers.

The attractor of the encoded chaotic waveform is shown in Fig. 3. Comparison of the simulation results with the theoretical and experimental results [2]-[6] shows that the proposed system with the feedback between MLs and SLs instead of an external cavity with an optical mirror can be more efficient than a standard system.

4. CONCLUSIONS

We have shown theoretically the possibility of the chaotic communication system based on the four synchronized semiconductor laser two of which provide the feedback instead of the cavity with mirrors. The system demonstrates an efficient encoding, transmission over the distance of 100 km and decoding of the waveform with CSK.

REFERENCES

[1] A. Uchida: *Optical Communication with Chaotic Lasers*, Wiley-VCH, Weinheim, Germany, 2012.

[2] A. Argyris, D. Syvridis, L. Larger, V. Annovazzi-Lodi, P. Colet, I, Fischer, J. Garcia-Ojalvo, C.R. Mirasso, L. Pesquera, and K.A. Shore:"Chaos-based communications at high bit rates using commercial fibre-optic links, *Nature*, vol. 438/17, pp. 343-346, Nov. 2005.

[3] Ning Jiang, Wei Pan, Bin Luo, Shuing Xiang, and Lei Yang: Bidirectional dual-channel communication based on polarization-division-multiplexed chaos synchronization in mutually coupled VCSELs, *IEEE Photonics Technology Letters*, vol. 24, no. 13, pp. 1094-1096, Jul. 2012.
[4] V. Annovazzi-Lodi, G. Aromataris, and M. Benedetti: Multi-user private transmission with chaotic lasers, *IEEE Journal of Quantum Electronics*, vol. 48, no. 8, pp. 1095-1101, Aug. 2012.
[5] V. Annovazzi-Lodi, M. Benedetti, S. Merlo, T. Perez, P. Colet, and C.R. Mirasso: Message encryption by phase modulation of a chaotic optical carrier, *IEEE Photonics Technology Letters*, vol. 19, no. 2, pp. 76-78, Jan. 2007.
[6] Nianqiang Li, Wei Pan, Bin Luo, Lianshan Yan, Xihua Zou, Ning Jiang, and Shuing Xiang: High bit rate transmission using a four-chaotic-semiconductor-laser scheme*, IEEE Photonics Technology Letters*, vol. 24, no. 12, pp. 1072-1074, Jun. 2012.
[7] Y. Ben-Ezra, B.I. Lembrikov, and Yu. Yurchenko: A novel all-optical system of the chaotic encryption for optical networks, in *Proc. 12th Int'l. Conf. on Transparent Optical Networks (ICTON 2010*), Munich, Germany, 27 Jun.-1 Jul. 2010, paperWe.A4.1..
[8] R. Lang and K. Kobayashi: External optical feedback effects on semiconductor injection laser properties, *IEEE Journal of Quantum Electronics*, vol. 16, no. 3, pp. 347-355, Mar. 1980.
[9] E.M. Shahverdiev and K.A. Shore: Duality of existence for synchronization of unidirectionally coupled chaotic external cavity semiconductor lasers, *Physic Letters A* 295, pp. 217-219, 25 Mar. 2002.