COMMUNICATION WITH CHAOS USING SEMICONDUCTOR LASERS WITH AN AIR GAP

T. Oloinic[1], S. S. Rusu[1], and V. Z. Tronciu[1,2]

[1]Department of Physics, Technical University of Moldova, Chisinau, Republic of Moldova
[2]Ferdinand-Braun-Institut Leibniz-Institut für Höchstfrequenztechnik
Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany

(Received September 01, 2015)

This paper reports the numerical results of the dynamical behavior of an integrated semiconductor laser subject to multiple optical feedback loops. The laser setup consists of a distributed feedback active section coupled to multi section cavities. It has been found that, due to the multiple feedback loops and under certain operating conditions, the laser displays chaotic behaviors appropriate for chaos-based communications. The optimal conditions and suitable parameters for chaos generation have been identified. The synchronization of two unidirectional-coupled (master–slave) systems has been studied. Finally, examples of high bit rate message encoding and decoding have been described and discussed.

1. Introduction

During the last years, the dynamics of semiconductor lasers has become the subject of various investigations due to the interest in the prediction of the evolution of laser setups. Distributed feedback (DFB) lasers with multi sections are the key element for various devices used in the optical communication system. It is well known that, in semiconductor laser applications, the presence of an optical feedback is inevitable. The external mirrors of the laser setup or the connection to other optical components of the system can create this feedback. A small amount of the optical feedback created by a plane mirror can cause the system destabilization and the appearance of instabilities. Thus, optical feedback can have a significant effect on the dynamic behavior of the semiconductor laser (for details see [1]). Even simple reflections from the exterior mirrors might cause different phenomena, such as coherent collapse, frequency fluctuations, self-pulsations, chaos, etc. The presence of periodical or chaotic oscillations is a well-known fact in semiconductor lasers with optical feedback. The chaotic behavior can be both useful, for example, in the case of chaos-based communication systems and undesired, and should rather be avoided or fixed in other applications.

In this paper, we analyze the way for the laser to be destabilized by external cavities. Using the chaotic oscillations produced by multi-sections laser setup in a chaos-based communicational system is the main aim of present paper. Chaos-based communication becomes more attractive because it allows a further security improvement of the optical data transmission. Interest in this domain has considerably increased after the practical prove of the optical communication based on chaos in the network of optical fibers in Athens [2]. Different optical feedbacks are usually used in chaos-based communication optical systems: complete optical [3, 4] or electro-optical [5, 6]. Typically, to generate chaos, delay time must be longer than a few hundred picoseconds. The purpose of this paper is to present results related to chaos-based communication using semiconductor lasers with optical feedback from multi cavities, one being air. Appropriate conditions for the chaotic evolution of the system due to the influence of this feedback have been obtained. We have studied the phenomenon of synchronization of two such systems and determined the regions of synchronization for two identical lasers. Finally, examples of message encoding and decoding have been presented in the chaotic modulation method.

2. Laser Model and Equations

We consider a device shown in Fig. 1; it consists of a semiconductor laser operating under the influence of a multiple optical feedback from an external cavity similar to that described in [7]. For modeling the scheme shown in Fig. 1, we use a single mode model of a laser operating in a continuous wave mode. Phases φ and ϕ can be easily controlled by a low injected current applied to the phase sections.

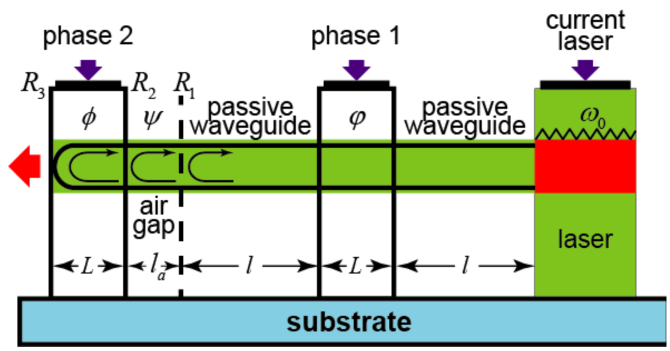

Fig. 1. Scheme of a semiconductor laser with optical feedback from multi section cavities.

We apply the approximation of a single loop and neglect the multi-reflections within cavities. Note that, this approximation is used just for simplifying our numerical calculations. Thus, the system dynamics is analyzed in the framework of the extended Lang-Kobayashi model [8] for the complex amplitude of electric field E and carrier density N

$$\frac{dE_{t,r}}{dt} = (1+i\alpha)\left[\frac{g\left(N_{t,r}-N_0\right)}{1+\varepsilon\left|E_{t,r}\right|^2} - \frac{1}{\tau_{ph}}\right]\frac{E_{t,r}}{2} + \gamma_{t1,r1}e^{-i\varphi}E_{t,r}(t-\tau_1)$$
$$+\gamma_{t2,r2}e^{-i(\varphi+\psi)}E_{t,r}(t-\tau_2) + \gamma_{t3,r3}e^{-i(\varphi+\psi+\phi)}E_{t,r}(t-\tau_3) + k_r E_t, \tag{1}$$

$$\frac{dN_{t,r}}{dt} = \frac{I_{t,r}}{e} - \frac{1}{\tau_e}N_{t,r} - \frac{g\left(N_{t,r}-N_0\right)}{1+\varepsilon\left|E_{t,r}\right|^2}\left|E_{t,r}\right|^2. \tag{2}$$

Subscripts t and r refer to transmitting and receiving lasers, respectively. The last term in (1) is present only in the receiving laser and describes the unidirectional coupling between the transmitter and the receiver. Parameter k_r is the laser field intensity injected into the secondary laser. τ_1, τ_2, and τ_3 are the delays of the external cavities. $\gamma_{t1,r1}$, $\gamma_{t2,r2}$ and $\gamma_{t3,r3}$ are the feedback strengths governed by reflectivity R_1, R_2 and R_3, respectively. Other parameters have values: Henry factor $\alpha = 5$, differential gain coefficient $g = 1,5\cdot10^{-8}\,\mathrm{ps}^{-1}$, and saturation of the gain coefficient is $\varepsilon = 5\cdot10^{-7}$. The lifetimes of photons and charge carriers are $\tau_{ph} = 3\ \mathrm{ps}$ and $\tau_e = 2\ \mathrm{ns}$. The parameter values are used for the calculated results that are shown in all figures of the paper.

3. Numerical Results

For a relatively low optical feedback signal intensity, the laser emits in a continuous wave mode or a periodic oscillation mode. Figure 2 shows the pulse traces for (a) output power and (b) carrier density for the periodic behavior. The phase portrait shown in Fig. 2c represents a limit

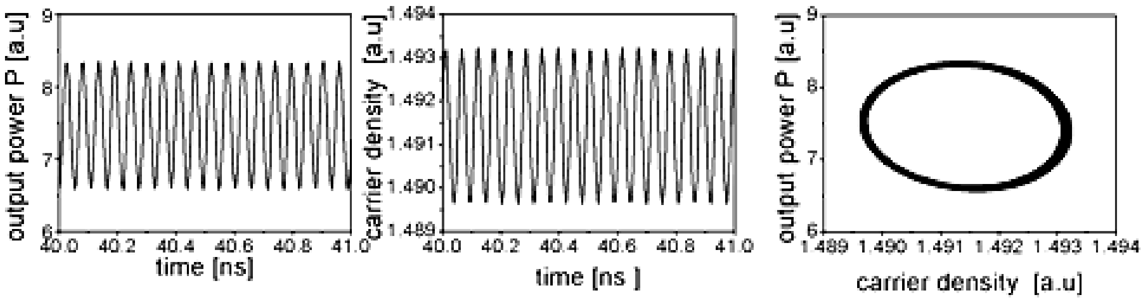

Fig. 2. Periodic behavior. Pulse trace of (a) output power and (b) carrier density. The phase portrait of semiconductor laser under the influence of multiple cavity optical feedback in the plane of two parameters (P – N). The other parameters are $\alpha = 5$, $\gamma_1 = 5$, $\gamma_2 = 5$, $\gamma_3 = 5$, $\varphi = \pi/2$, $\psi = 0$.

cycle. The chaotic regime appears only when the returned signal intensity is high enough. Figure 3 shows the time evolution of (a) output power and (b) carrier density of a semiconductor laser under the influence of optical feedback from multi cavity in the chaotic regime. Figure 3c shows

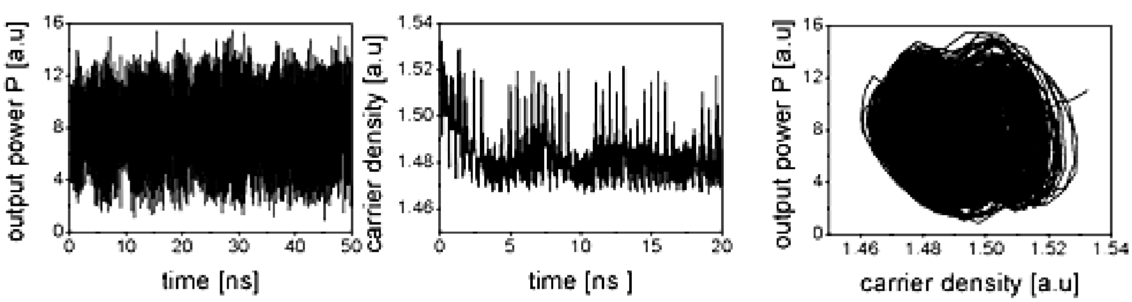

Fig. 3. Chaotic behavior. Pulse trace of (a) output power and (b) carrier density. The phase portrait of semiconductor laser under the influence of multiple cavity optical feedback in the plane of two parameters (P – N). The other parameters are $\alpha = 5$, $\gamma_1 = 5$, $\gamma_2 = 10$, $\gamma_3 = 15$, $\varphi = \pi/2$, $\psi = 0.11$

the appearance of a strange attractor in the plane of two parameters. Thus, due to the influence of the multiple feedbacks, the laser behavior has been found to be chaotic for a large range of parameters and laser bias currents. Even both experiments and theoretical calculations for these lasers demonstrate the presence of chaotic behaviors in the laser dynamics [7]. By acting on the bias of the phase sections, the chaos amplitude and bandwidth could also be tuned.

Figure 4 displays typical bifurcation diagrams of a semiconductor laser under the influence of multi section optical feedback, where feedback strengths γ_1 and γ_2 act as bifurcation parameters. For each value of the feedback strength, the figure displays the values of the maxima (black) and minima (red) of the time traces of the emitted power. Figure 4 shows that

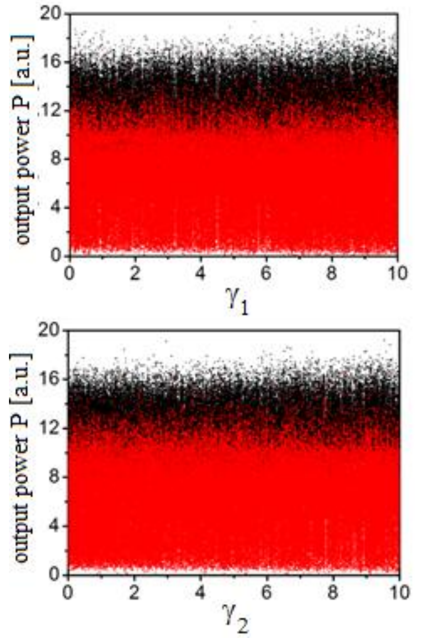

Fig. 4. Bifurcation diagram for γ_1 (top) and γ_2 (bottom) as bifurcation parameters. Other parameters are: $\varphi = \pi/2$, $\psi = 0$, $\phi = 3\pi/2$.

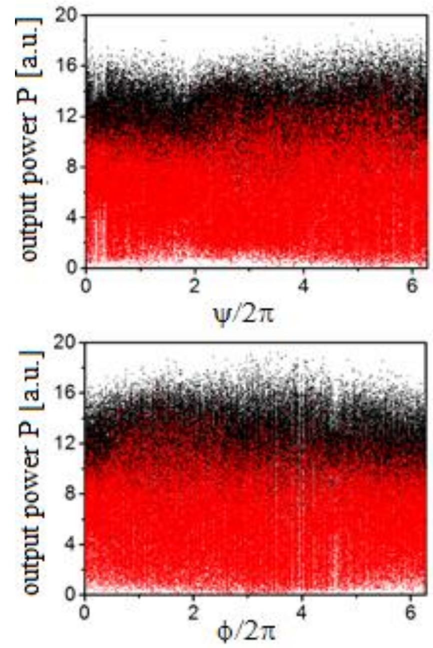

Fig. 5. Bifurcation diagram for $\psi/2\pi$ (top) and $\phi/2\pi$ (bottom) as bifurcation parameters. Other parameters are: $\varphi = \pi/2$.

even for low values of feedback strength γ_1, the dynamics of the laser is already chaotic due to the influence of the feedback of other sections. It is evident from the figure that the amplitude of the chaotic oscillations slightly increases with increasing feedback strengths γ_1 and γ_2. When both feedback strengths are fixed to $\gamma_1 = 20$ ns^{-1} and $\gamma_2 = 15$ ns^{-1}, as shown in Fig. 5, fully developed chaotic dynamics is found for any value of phases ψ and ϕ.

We have clarified different aspects of the dynamics of a semiconductor laser with integrated multi-section feedback for obtaining chaotic behaviors. In what follows, we are interested in the transmitter–receiver configuration (see Fig. 6) and in the evaluation of its synchronization properties. Figure 7 shows the synchronization diagram in the place of different parameters. One can see the wide region of perfect synchronization (grey region) with the cross correlation coefficient higher than 0.99.

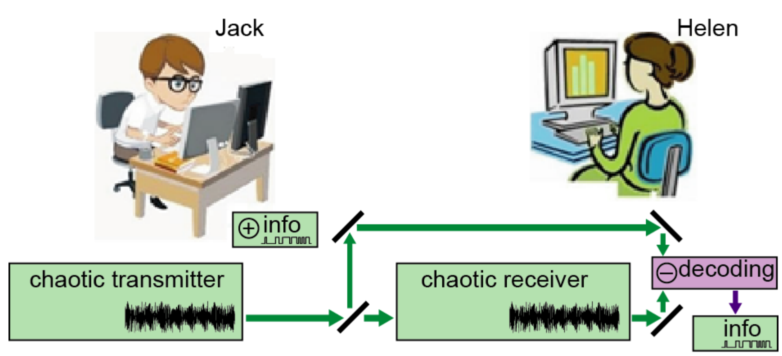

Fig. 6. Transmitter–receiver configuration.

The level of the coupling parameter is k = 100 ns^{-1}. Thus, for this set of parameters and coupling

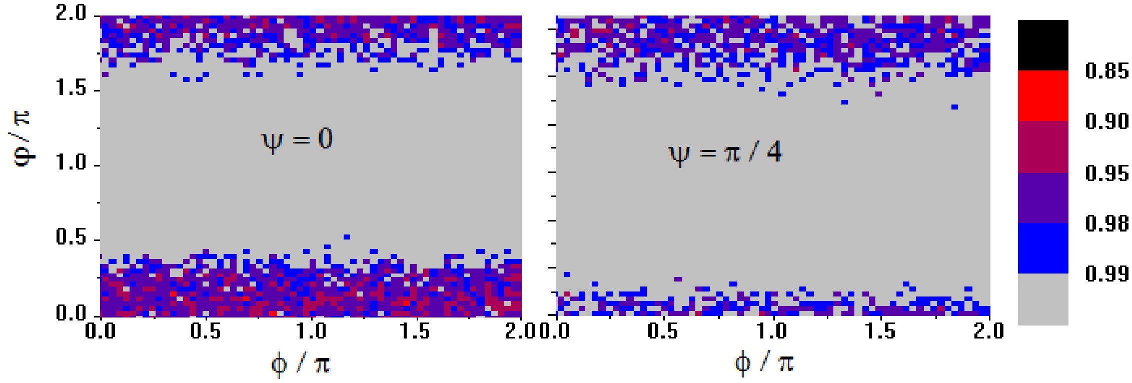

Fig. 7. Synchronization diagram in the φ–ϕ plane for the level of the coupling parameter of k = 100 ns^{-1} and different values of parameter ψ.

coefficient, the synchronization map shows a clear synchronization process.

Further on, we study the transmission–reception configuration and evaluate the synchronization properties of the two lasers. We examine the encrypting and decrypting of a digital message in the optical communication systems based on chaos. In the specialized literature, various methods of chaotic encryption have been proposed, such as modulation chaos [3], chaotic switch of the key [9], chaotic masking [10], etc. We analyze in detail only the case where the informational message is included as a chaotic modulation amplitude, i.e., the so-called chaotic modulation.

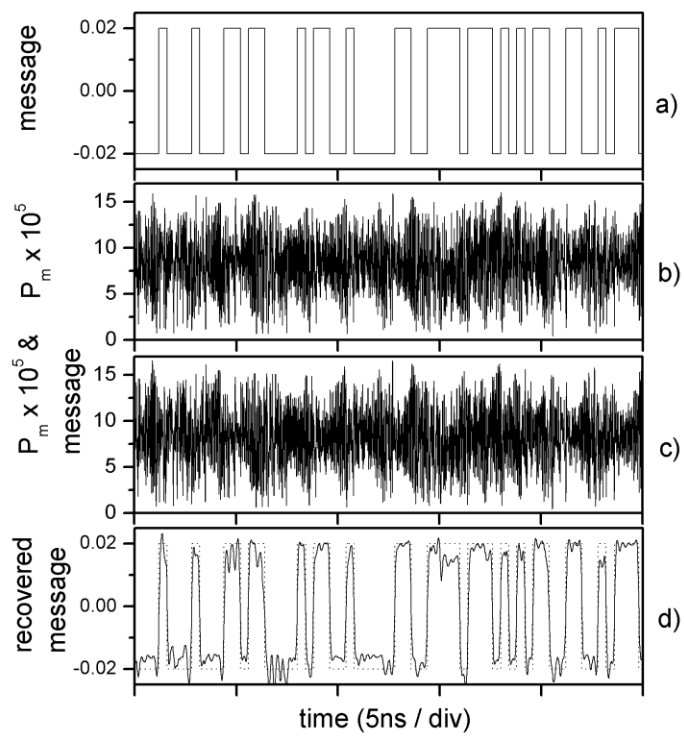

Fig. 8. Numerical results of a 5-Gbit/s digital message encryption obtained with chaotic lasers.

Figure 8 illustrates the transmission of a digital signal. Panel (a) shows the shape of an incident 5Gb/s signal, i.e., the signal that should be sent. Panels (b) and (c) show the output power of the master laser without and with a message, respectively. Panel (d) is the decoded and recovered message after filtering the information signal (solid line) and the incident signal (dotted line). This figure shows that, for an ideal case where the parameters of both lasers coincide, the message is fully recovered. Thus, we have shown theoretically that the chaotic modulation method can be easily implemented in optical communication systems based on chaos.

4. Conclusions

In the limits of Lang–Kobayashi equations, the dynamics of a single mode semiconductor laser with optical feedback that comes from multi cavities has been studied. The presence of several sections results in a complication of system oscillations. An advantage of the proposed system compared with that of conventional optical feedback is that the chaotic behavior occurs for short lengths of cavities, which makes a more compact device. On the other hand, under certain conditions, two such laser systems could be synchronized when they operate under chaotic emitter–receiver configuration. For the parameter values, the perfect synchronization has been obtained, the possibility of encryption and decryption of the message by chaotic modulation method has been demonstrated. The message can be adequately restored by the receiver even at high speed information transmission.

Acknowledgments. The authors acknowledge the support of STCU projects no. 5993, 5937, 15.817.02.22F 14.02.116F. VZT acknowledges the Alexander von Humboldt Foundation and the support from the CIM–Returning Experts Programme.

References

[1] Fundamental Issues of Nonlinear Laser Dynamics, B. Krauskopf and D. Lenstra (Eds.), AIP Conference Proceedings, pp. 548, (2000)
[2] A. Argyris, D. Syvridis, L. Larger, et al., Nature 438, 343 (2005)
[3] C. R Mirasso, P. Colet, and P. Garcia-Fernandez, IEEE Photon. Technol. Lett. 8, 299 (1996)
[4] S. Sivaprakasam and K. A. Shore, Opt. Lett. 24, 466 (1999)
[5] S.Tang and J. M. Liu, Opt. Lett. 26, 596 (2001)
[6] N. Gastaud, S. Poinsot, and L. Larger, Electron. Lett. 40, 898 (2004)
[7] V. Z. Tronciu et al., IEEE J. Quantum Electron. 46, 1840 (2010)
[8] R. Lang and K. Kobayashi, IEEE J. Quantum Electron. 16, 347 (1980)
[9] C. R. Mirasso, Int. Spring School on Fundamental Issues of Nonlinear Laser Dynamics 548, 112 (2000)
[10] T. Heil, J. Mulet, I. Fischer, et al., IEEE J. Quantum Electron. 38, 1162 (2002)