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NUMERICAL SIMULATIONS OF DYNAMICS OF QUANTUM DOTS LASERS UNDER THE INFLUENCE OF T-TYPE EXTERNAL OPTICAL FEEDBACK. APPLICATIONS TO CHAOS BASED COMMUNICATION

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Abstract. We report the results of numerical simulations on the dynamical behavior of quantum dots laser subject to T-type optical feedback. We find that under certain conditions, due to the influence of the external feedback, the system displays strong chaotic behaviour appropriate for chaos-based communications. We demonstrate the influence of the relevant device parameters, such as feedback phases and strengths on the laser dynamics. The synchronization features of two quantum dots lasers coupled unidirectionally are studied numerically. Finally, we find the appropriate conditions for high bit rate message encoding by chaos modulation technique using compact quantum dots lasers under the influence of T-type feedback loops.

Key words: semiconductor lasers; multiple feedback; bifurcations; chaos based communications.

1. INTRODUCTION

In the last decade the phenomena of destabilization and chaos of laser emission by external cavities have been the subject of considerable attention, with the studies mainly motivated by the prospect of the applications to chaos based communication (CBC) systems. The influence of external optical feedback from a distant mirror on the dynamics of semiconductor lasers have been investigated extensively for the past two decades and many dynamical behaviors have been reported, including periodic pulsations, low frequency fluctuations, coherent collapse, optical turbulence, and chaos (for more details, see [1]). It is well known that the chaotic waveform is suitable for CBC. Thus, in the chaotic communications an improve of privacy and security in date transmission is expected, especially after recent demonstration of it in [2]. In optical CBC, the chaotic signal is generated by using semiconductor lasers with either optical or electro-optical feedback [2]-[9]. Setups using Fabry-Perot resonators under the influence of external optical feedback, have also been considered [10]-[12]. Different setups for chaotic data transmission have been proposed in the literature [13]-[18]. The input message is included into the transmitted signal as a modulation in the amplitude of the chaotic carrier (chaos modulation) [2], [10],

[11]. Under the process of synchronization [19] the message can be decoded at the receiver by comparing the input with its output. The main aim of recent technological progress is the production of structures with stable properties and the possibility of their application in different areas. The lasers with active medium quantum dots and external feedback from multi-sections might be a key element for devices used in the system of CBC. The advantages of quantum dot lasers were predicted some twenty years ago and include low threshold current, weak temperature dependence, increased material and differential gain, high modulation frequency, low jitter under pulsed operation [20]-[28]. During recent years a relevant progress is being made on the reliable fabrication of QD structures. Although quantum dot lasers are now generally better than QW lasers, the characteristics of QD lasers still deviate from the ideal case due to a number of unforeseen phenomena, including the thermal population of excited dot and barrier states, the loss of carriers to non-radiative centers and the presence of inhomogeneous broadening due to non-uniformities. As mentioned above, such compact devices with quantum dots could be the main element in the CBC systems. Thus, the communication method based on chaos would bring great benefits to secure data transmitted in communication networks. In this paper, we investigate numerically the dynamics of an integrated compact device composed of a quantum dots laser subject to the feedback from T-type cavities with the final aim of generating a chaotic waveform suitable for applications in CBC systems. The obtained results show that under appropriate conditions the laser with T-type external feedbacks show chaotic behavior appropriate for chaos based communications. The paper is structured as follows. We start in Section 2 by describing the laser setup and introduce an appropriate model to describe the system dynamics. Section 3 presents a study of the dynamics of a laser under the influence of T-type cavity feedback. The suitable conditions for the chaotic evolution of the output power system due to the influence of feedback were obtained. The synchronization properties of two such devices and the chaos modulation encryption method are also demonstrated. Finally, conclusions are given in Section 4.

2. LASER MODEL AND EQUATIONS

Figure 1 shows the structure of device, which consists of a quantum dots laser under the influence of optical feedback from external cavities that we have called T-type, from their form. The feedback strengths of two external cavities Γ_1 and Γ_2 are governed by the reflectivitys R_1 and R_2 with phases φ and ψ, τ_1 and τ_2 being the delays time. In this paper we study the dynamics of QDs laser, especially chaotic properties of the device, which can be tailored by appropriately designing the external cavities. We also analyze how such two devices can be synchronized and the

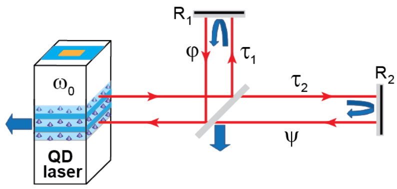

Fig. 1 – (Color online) A sketch of setup for chaos synchronization and message encoding, using semiconductor lasers under the influence of double (T - type) cavity feedback. φ and ψ are the phases in first and second branch, respectively.

chaos modulation technique applied using the rate equations model [29] with Lang Kobayashi [30] type feedback

$$\begin{aligned}\frac{dE}{d\tau} &= \frac{1}{2}(1+i\alpha)\left[-\gamma_{np}+g(2\rho-1)\right]E+ \\ &+\Gamma_1 e^{-i\varphi}E(\tau-\tau_1)+\Gamma_2 e^{-i\psi}E(\tau-\tau_2),\end{aligned} \tag{1}$$

$$\frac{d\rho}{d\tau} = -\gamma_{ns}\rho-(2\rho-1)|E|^2+(CN^2+BN)(1-\rho), \tag{2}$$

$$\frac{dN}{d\tau} = J-N-2\left[(CN^2+BN)(1-\rho)\right], \tag{3}$$

where E is the complex amplitude of the electric field, N is carrier density in the quantum well, and ρ the occupation probability in the quantum dot. We consider the approximation of a single loop and neglect the multi-reflections within cavities. Other parameters are: the Henry factor $\alpha = 2$, and $\tau_1 = 0.3$, $\tau_2 = 0.5$ are external cavity round trip times. $g = 1200$ is the differential gain, and $J = 20$ is pumping parameter. The constants $B = 0.01$ and $C = 40$ describe the transport of charge carriers through carrier-phonon interaction, $\gamma_{ns} = 1.0$, and $\gamma_{np} = 500$. These parameter values are used for the calculated results that are shown in all figures of the paper.

3. RESULTS AND DISCUSSIONS

In what follows we use equations (1) – (3) to study the dynamics of the quantum dots laser under the influence of T-type external feedback shown in Fig. 1. It is well known that the lasers under the influence of external feedback perform a chaotic behavior, applicable to chaos based communication, when the feedback strength is high enough. Otherwise, the laser generates continue waves (CW) or pulsations operations.

Figure 2 shows numerical calculations of the time evolution of the output power, the phase portrait, as well as power spectrum of QDs laser under the in-

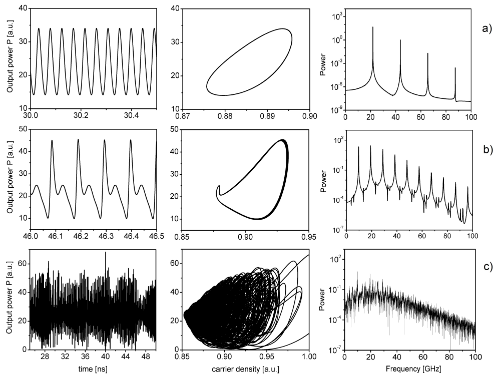

Fig. 2 – Pulse trace of output power (left), phase portrait in the plane output power carrier density (center), and power spectrum (right) of semiconductor laser under the influence of optical feedback from T - type external cavity for: a) Γ_1 = 15, Γ_2 = 16,2 (periodic behaviour); b) Γ_1 = 15, Γ_2 = 20 (period doubling); c) Γ_1 = 20, Γ_2 = 30 (chaotic behaviour). The phases are $\varphi = \pi/2$, $\psi = 3\pi/2$.

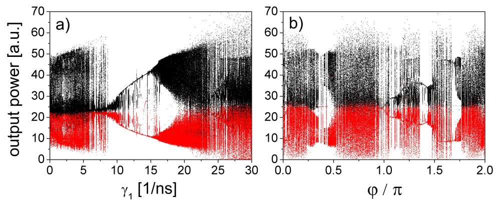

Fig. 3 – (Color online) Numerically calculated bifurcation diagrams for Γ_2 = 25 and $\psi = 3\pi/2$. a) Γ_1 being a bifurcation parameter and phase fixed to $\varphi = \pi/2$, b) φ bifurcation parameter and Γ_1 = 20.

fluence of optical feedback from T-type external cavities. We consider the feedback strengths Γ_1 and Γ_2 the main parameters to vary, and as mentioned above, are governed by the cavity reflectivities R_1 and R_2, respectively. Figure 2(a) shows the dependence of the output power on time under periodic oscillations for Γ_1 = 15, Γ_2 = 16,2. As one can see the phase portrait is a stable limit cycle, and one dominant mode is obtained in the power spectrum. Figure 2(b) shows the period doubling for Γ_1 = 15, Γ_2 = 20. The phase portrait is deformed limit cycle, and in power spectrum a new harmonic is present. Figure 2(c) illustrates the strange attractor for the following values of the feedback strengths Γ_1 = 20, Γ_2 = 30 where the output power performs chaotic behaviour and the power spectrum is wide.

The bifurcation diagram is an important tool when analyzing the QDs laser dynamics. The feedback strength Γ_1 is considered to be the main parameter of bifurcation in Fig. 3(a) for fixed phases $\varphi = \pi/2$ and $\psi = 3\pi/2$. In this bifurcation diagram is observed predominant chaotic strong oscillations even at low values of feedback strength. These oscillations are resulting from the existence of feedback strength Γ_2

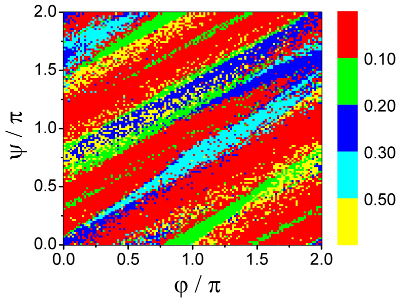

Fig. 4 – (Color online) Autocorrelation time in the plane of two phases (ψ - φ) and for the feedback strengths Γ_1 = 20 and Γ_2 = 25. The step of phase variation is 0.05 radians.

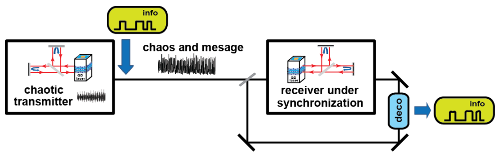

Fig. 5 – (Color online) Schematic representation of the chaos modulation technique.

in the second branch. The periodic oscillations are observed for values of the feedback strength Γ_1 from 10 to 15. For large values of Γ_1 chaotic behavior persists. Thus, for low and large values of the feedback strength Γ_1, the system displays a chaotic behavior. On the other hand, in Fig. 3(b) the main bifurcation parameter is considered the phase φ. One can see from this bifurcation diagram the wide chaotic regimes, which ensure appropriate conditions for optical communications based on chaos. Thus, due to the interest in achieving of high secured chaos-based communications the regions with chaotic behavior of the laser will be identified. It is well known, that the laser dynamics have more pronounced chaotic behavior when his auto-correlation time is smaller. To establish these regions, we calculate the auto-correlation time of the studied quantum dots semiconductor laser under the influence of optical feedback from T-type cavity. The results of this calculations are presented in Fig. 4 in the plane of phases (ψ - φ). Here the red regions correspond to the strong chaos regime of the semiconductor laser with auto-correlation time less than 0.1 ns. It is seen that rather wide regions of phases with small auto-correlation time exists and conditions for CBC can be easily achieved.

In previous paragraph we have investigated the dynamics of a single semiconductor quantum dots laser under the influence of double feedbacks of T-type configuration. In what follows, we consider two identical lasers, connected in the transmitter-receiver configuration, as shown in Fig. 5. We study the synchronization of these two devices, as well as the possibility of its use for message encoding and decoding in CBC. For this purpose, we use the chaos modulation technique

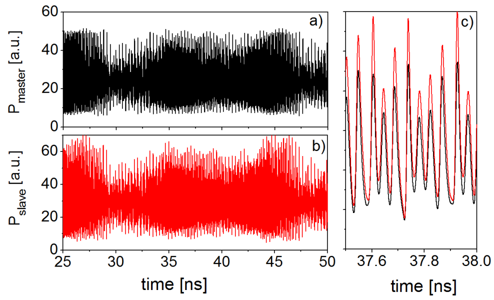

Fig. 6 – (Color online) The phenomenon of synchronization of the transmitter-receiver configuration shown in Figure 5 for coupling parameter $k = 50$. Pulse traces of master a) and slave b) lasers showing chaotic behavior. c) Insert of both synchronized pulses of master and slave lasers. Other parameters: Γ_1 = 20 and Γ_2 = 25, $\varphi = \pi/2$, $\psi = 3\pi/2$.

[31]-[33], in which the message encoding consists in a small amplitude modulation added to the master emitted laser field. After the process of perfect synchronization of master (transmitter) and slave (receiver) lasers the message at the receiver is decoded by making the difference of input on it signal and output one. Considering that the transmitter and receiver lasers are connected unidirectionally, in the follows we presents the numerical analyze of the synchronization properties of this system. The signals of master and slave lasers will be more synchronized when the cross-correlation coefficient is close to the unity. Figure 6 shows the optical power time trace of master (a) and slave (b) lasers in the synchronization process under the influence of double optical feedback of T-type configuration. Also, in Fig. 6(c) the insert of both synchronized pulses of master and slave lasers are presented and similarity of time traces is clearly seen.

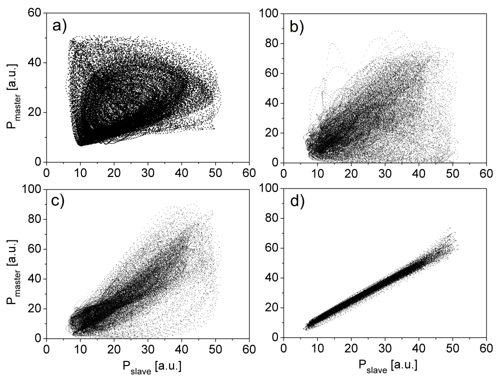

Fig. 7 – Numerically calculated synchronization diagrams in the chaotic behavior for different levels of coupling parameter: a) $k = 0$, b) $k = 30$, c) $k = 40$, d) $k = 50$. Other parameters: Γ_1 = 20, Γ_2 = 25, $\varphi = \pi/2$, $\psi = 3\pi/2$.

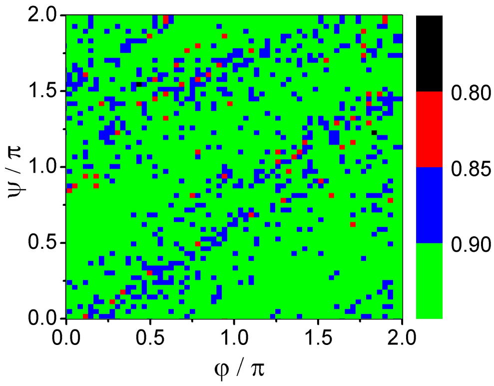

Fig. 8 – (Color online) Cross-correlation coefficient in the plane of phases (ψ - φ) for coupling coefficient $k = 50$ and feedback strengths Γ_1 = 20, Γ_2 = 25.

Figure 7 shows the numerical results of synchronization process of master and slave laser for different values of coupling parameter and the following values of the feedback strength Γ_1 = 20, Γ_2 = 25, and phases $\psi = 3\pi/2$, $\varphi = \pi/2$. For the coupling parameter $k = 0$, the process of synchronization is absent and a lack of correlation between outputs can be seen in Fig. 7(a). Thus, the synchronization map shows a cloud of points. Figure 7(b) shows the synchronization map for an increase of the values of coupling parameter. Thus, when we consider $k = 30$ the synchronization map indicates a start of synchronization process but very week. A further increase of the coupling parameter to $k = 40$ leads to an improve of the synchronization process. Figure 7(d) shows the process of synchronization for the coupling parameter $k = 50$. For this increased value of the coupling coefficient the synchronization become clear and the cross correlation coefficient approaches unity. Thus, we obtained a good synchronization for coupling parameter $k = 50$. For a better understanding of the process of synchronization we will investigate its quality by calculating the cross correlation coefficient for coupling coefficient fixed to $k = 50$ (see Fig. 8). The green color denotes a high degree of synchronization and the cross correlation coefficient being higher than 0.90. From this diagram we purpose to select the values of phases which correspond to point A for the following process of encoding and decoding of digital message within the chaos modulation technique.

In what follows, we study the transmission and reception of the digital message by setup consisting of two identical lasers connected in unidirectional configuration as shown in Fig. 5. We examine the encryption and decoding of 10 Gb/s digital message in the chaos modulation technique using the values of phases of point A in Fig. 8. This procedure is illustrated in Fig. 9. Panel (a) shows the shape of incident digital signal. This message is added by chaos modulation technique to the transmitted chaotic signal. Panels (b) and (c) show the output power of the master laser without message and with it, respectively. No one can distinguish the presence of message in the panel (c), comparing with panel (b). Finally, panel (d) shows the recovered and decoded message, and filtered by an appropriate low-pass filter. As shown in this figure, for the case when the parameters of both lasers coincide the message is fully recovered.

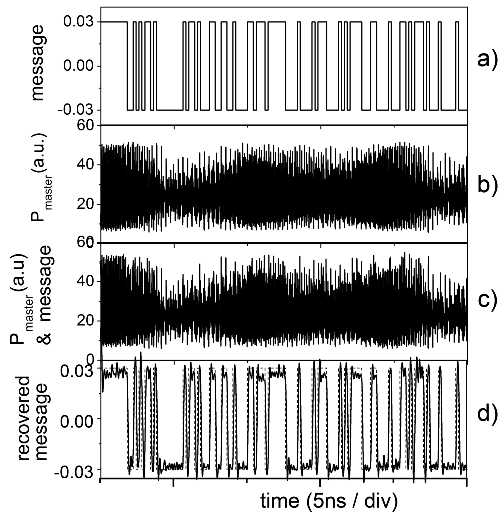

Fig. 9 – The results of numerical calculations of encoding and decoding of a 15 Gbit/s digital message using chaos modulation technique in the master and slave lasers configurations shown in Figure 5. a) Encoded digital message; b) Output of the master laser without message; c) Transmitted signal (with message); d) Decoded message and recovered message after filtering (solid line) and input message (dotted line). Other parameters: Γ_1 = 20, Γ_2 = 25, $\varphi = \pi/2$, $\psi = 3\pi/2$, and $k = 50$.

Thus, we have shown in this paper that chaos modulation technique can be implemented in the setup consisting of two identical quantum dots lasers under the influence of external T-type optical feedbacks. Finally, we believe that our work provides a good basis for future study, and, in particular, provides some pointers for more detailed experimental investigations and practical applications of chaos modulation technique using quantum dots lasers in chaos based communication systems.

4. CONCLUSIONS

The dynamics of a quantum dots semiconductor laser with optical feedback that comes from T-type cavities was investigated. The presence of two external cavities results in a more complex system oscillations keeping the devise compact. Thus, an advantage of the proposed system compared with that of conventional optical feedback is that the chaotic behavior appropriate for CBC occurs for short lengths of cavities, and can be controlled by two phases. We have shown that two of these devices with identical parameters can be synchronized when operating in the chaotic regime in a master-slave conguration. We show that, for the parameter values where synchronization with higher cross correlation coefficient is achieved, it is possible to encode a higher bit rate message in the carrier using the chaos modulation technique. Finally, the message can be appropriately recovered. We believe that our work provides a good basis for future study and, in particular, provides some pointers for more detailed investigations of compact quantum dots lasers with feedback from external cavities and their applications for chaos-based communication.

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