Dynamics of Quantum Dots Lasers under the Influence of Double Cavity External Optical Feedback

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***Abstract*—We report the results of numerical investigations of the dynamical behavior of an integrated device composed of a semiconductor laser with quantum dots active medium and a double cavity that provides optical feedback. Due to the influence of the feedback, under the appropriate conditions, the system displays chaotic behavior appropriate for chaos-based communications. The optimal conditions for chaos generation are identified. It is found that the double cavity feedback requires lower feedback strengths for developing high complexity chaos when compared with a single cavity.**

***Index Terms*—quantum dots, optical feedback, pulse traces, bifurcations**

I. INTRODUCTION

During the last years the synchronization of chaotic oscillators has been the subject of significant studies due to its fundamental and applied interests [1]. From the application point of view, chaos-based communications have become an option to improve privacy and security in date transmission, especially after the recent field demonstration of the metropolitan fiber networks of Athens [2]. In optical chaos-based communications, the chaotic waveform is generated by using semiconductor lasers with either all-optical or electrooptical feedback loops. [3,4]. In particular, semiconductor lasers subject to the influence of optical feedback from a distant mirror have been investigated extensively for the past two decades and different dynamical behaviors have been characterized, including periodic and quasi-periodic pulsations, low frequency fluctuations and coherent collapse (for more details, see [5]). Due to the continuing technological progress, multi-section lasers with active medium quantum dots have reach stable operation. Arakawa [6] predicted that semiconductor lasers with active medium quantum dots have small temperature dependence performance than the existing semiconductor lasers, and that they will not degrade at the high temperature. In recent years, their dynamics has become the object of study and theoretical researches are necessary for the development and extension of the theory of nonlinear dynamics in semiconductor lasers with quantum dots active medium. Here we consider a configuration which includes feedback from an integrated double cavity.

II. MODEL AND EQUATIONS

We investigate the phenomenon of dynamical chaos of semiconductor lasers with quantum dots active medium shown in Figure 1. The setup consists of a semiconductor laser operating under the influence of an external optical feedback from double external cavity. The first mirror is located at distance *l* from the laser facet. The distance between first and second mirrors is *L*. The phase φ in the air gap can be changed by a piezo-element. On the other hand, the optical feedback phase ψ in the second cavity (resonator) can be controlled by a small injecting current into the passive section.

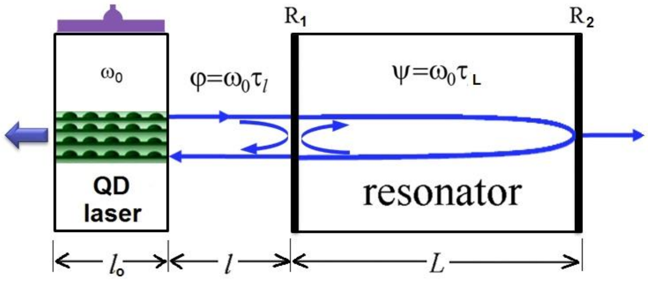

Fig. 1. Laser setup.

For modeling of the dynamics of quantum dots laser under the influence of double feedback we use the following equations [7,8]

$$\frac{dE}{d\tau} = \frac{1}{2}\left(1+i\alpha\right)\left[-\gamma_{np} + g(2\rho-1)\right]E + \Gamma_1 e^{-i\varphi}E(\tau-\tau_l) + \Gamma_2 e^{-i(\varphi+\psi)}E(\tau-(\tau_l+\tau_L)) \quad , \qquad (1)$$

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

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

where E is the complex amplitude of the electric field, N is the carrier density in the in quantum well, and ρ is the occupation probability in the quantum dot. τ_l and τ_L are external cavity round trip times. N_d is the 2D density of dots, and J is pumping parameter. Γ_1 and Γ_2 represent the feedback levels. The parameters Γ and τ describe the feedback connection and the delay time, respectively. The constants B and C describe the transport of charge carriers through carrier-phonon interaction. α is the linewidth enhancement factor. φ is the feedback phase of air gap and ψ the phase of passive section.

III. NUMERICAL RESULTS

We have examined the dynamics of semiconductor lasers with quantum dots active medium using equations (1)–(3) and the following main parameters τ_1=0.2, τ_2=0.5, α=2.0, γ_{np}=500.0, J=20.

A. Pulse traces

Fig. 2 shows numerical calculations of pulse traces of output power a), carrier density b), and occupation probability in quantum dot c) for the self-pulsation laser operation. The self-pulsation is almost stable during 50 ns integration time duration. The frequency of the pulsation shown in Fig. 2 is approximately 23 GHz. Fig. 2 (d) shows the phase portrait in the plane of two parameters (P-N) and the phase trajectory becomes a limit cycle.

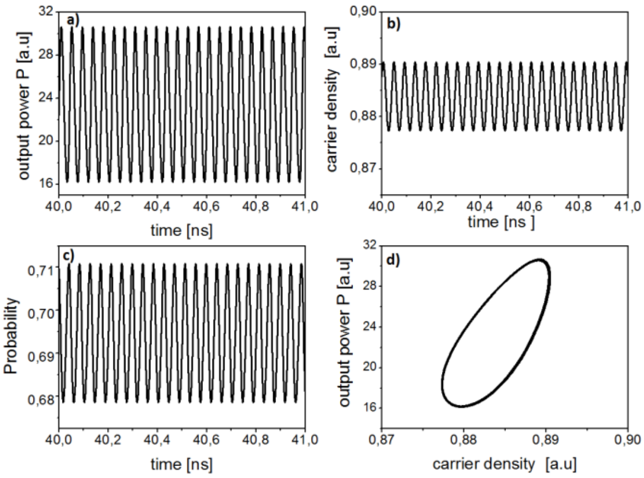

Fig. 2. Self-pulsations: Time evolution of a) output power P, b) density of carriers N and c) of the occupation probability in quantum dots ρ. d) Phase portrait in the plane output power P - the density of carriers N. Other parametrs: B=0.01, C=40.0, g=1200.0, Γ_1=11.0, Γ_2=20.0, $\varphi=\pi/2$, $\psi=\pi$.

Figure 3 illustrates time traces and phase portrait of a semiconductor laser under the influence of double feedback for quasi-periodic behavior for the parameters similar to those of Figure 2 except the phase φ which is φ=-π/2. One can observe the new harmonics which appears in the system. As the phase ψ is changed to zero (see Figure 4) the oscillations of output power become more complicated and the phase portrait is more complex. As the feedback strength is changed to Γ_1=5.0, the strange attractor becomes more complicated (see Figure 5). Finally an increase of γ_{ns}=3.0, leads to optical turbulence in the system (see Figure 6).

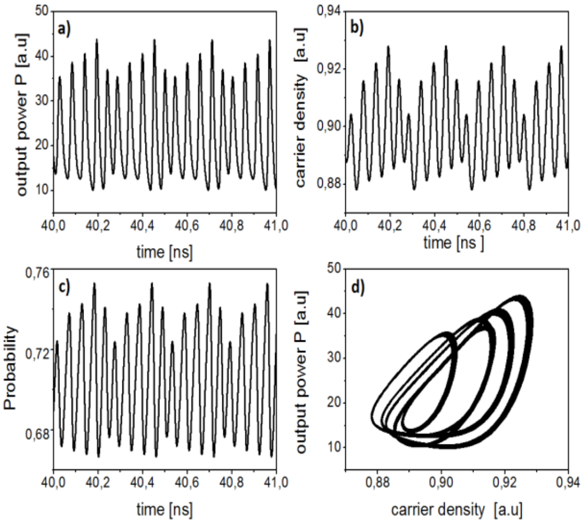

Fig. 3. Quasi-periodic behavior: Time evolution of a) output power P, b) density of carriers N and c) of the occupation probability in quantum dots ρ. d) Phase portrait in the plane output power P - the density of carriers N. Other parameters: B=0.01, C=40.0, g=1200.0, Γ_1=11.0, Γ_2=20.0, φ=-π/2, $\psi=\pi$.

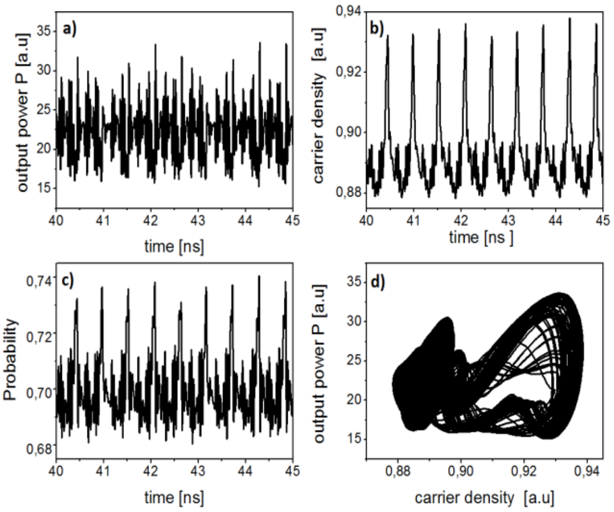

Fig. 4. Moderate chaos: Time evolution of a) output power P, b) density of carriers N and c) of the occupation probability in quantum dots ρ. d) Phase portrait in the plane output power P - the density of carriers N. Other parameters: B=0.01, C=40.0, g=1200.0, Γ_1=11.0, Γ_2=20.0, φ=3.14/2.0, ψ=0.

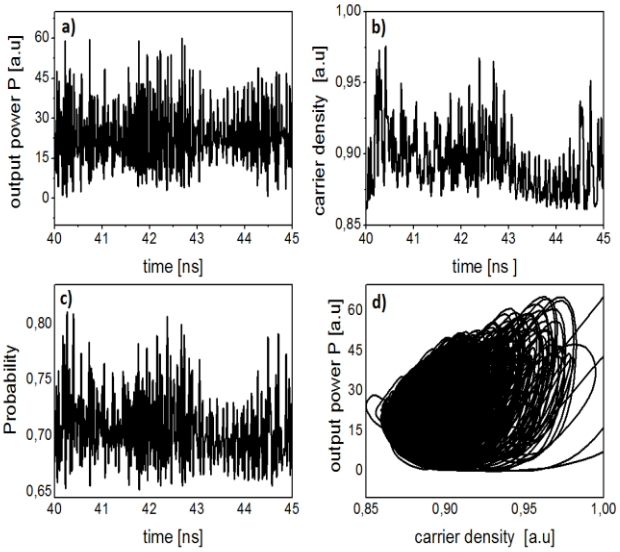

Fig. 5. Strong chaos: Time evolution of a) output power P, b) density of carriers N and c) of the occupation probability in quantum dots ρ. d) Phase portrait in the plane output power P - the density of carriers N. Other parametrs: B=0.01, C=40.0, g=1200.0, Γ_1=5.0, Γ_2=20.0, φ=3.14/2.0, ψ=3.14.

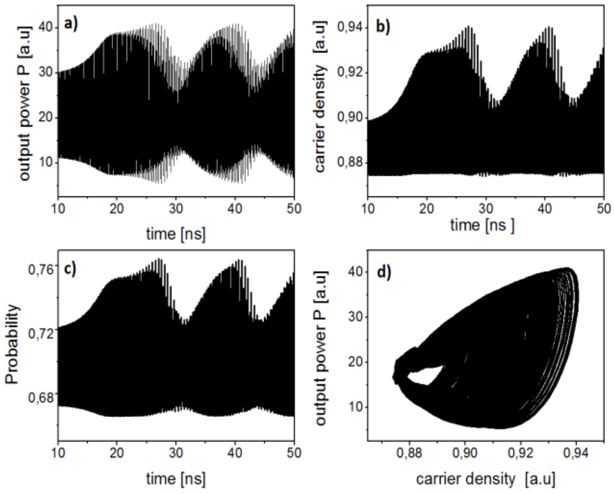

Fig. 6. Strange attractor: Time evolution of a) output power P, b) density of carriers N and c) of the occupation probability in quantum dots ρ. d) Phase portrait in the plane output power P - the density of carriers N. Other parametrs: B=0.01, C=40.0, g=1200.0, Γ_1=11.0, Γ_2=20.0, γ_{ns}=3.0, φ=3.14/2.0, ψ=3.14.

B. Bifurcations diagrams

Next we examine the laser dynamics in terms of bifurcation diagrams. A typical calculation of bifurcation is shown in Figure 7, where the feedback strengths γ_1 (top) and γ_2 (bottom) are the bifurcation parameter. This figure shows the dependence of the maximum and minimum of the photon number on the feedback strength. When we increase the injected current, the continue wave (CW) operation is observed (see Fig.7). Then the laser begins to produce pulsations (P) through a Hopf bifurcation (H) marked by a circle in Fig. 7. One can observe that the case of γ_1 being bifurcation parameter the system behaviour is slightly different; the Hopf bifurcation is shifted to a lower feedback level involving the appearance of low amplitude chaotic behaviour for low feedback strengths followed by the CW operation and a scenario compatible with the quasiperiodic route to chaos.

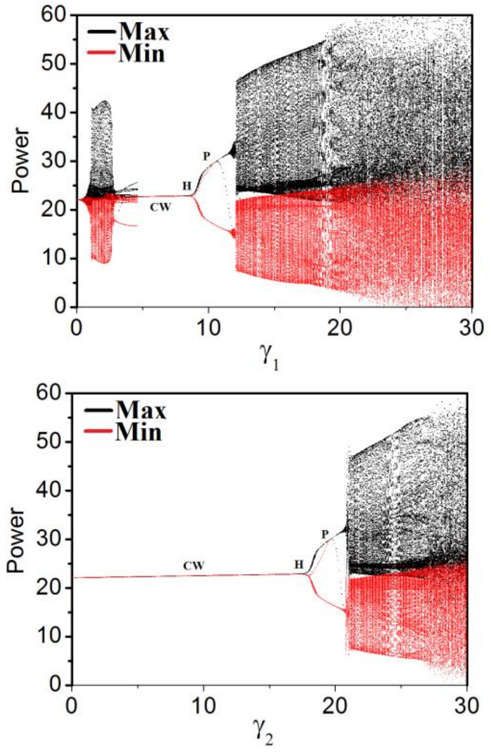

Fig. 7. Bifurcation diagrams for feedback strength γ_1 (top) and γ_2 (bottom) being a bifurcation parameter. The H denote Hopf-bifurcations and P periodic solution. The parameters are $B = 0.01$, $C = 40$, $J = 20$, $g = 1200$, $\gamma_{ns} = 1.0$, $\gamma_{np} = 500.0$, $\alpha = 2.0$.

Figure 8 display the bifurcation diagrams of a semiconductor laser with active medium quantum dots subject to optical feedback for the feedback phases acting as bifurcation parameters. Let us, e.g., consider the case of feedback phase ψ fixed to π while the feedback phase φ is increased. As shown in Fig. 8a, for values of phase $0.6\pi<\varphi<1.5\pi$ the dynamics of the laser is chaotic due to the influence of the feedback. It can be noticed from the figure that the amplitude of the chaotic oscillations is big and appropriate for chaos based communications [11-13]. When feedback phase φ is fixed to $\pi/2$ and the phase ψ is varied, as shown in Figure 8b), fully developed chaotic dynamics is found for the following intervals of phase ψ - $0<\psi<0.25\pi$ and $1.6\pi<\psi<2\pi$. Thus, the proposed setup can generate the fully chaotic pulse traces suitable for chaos based communications.

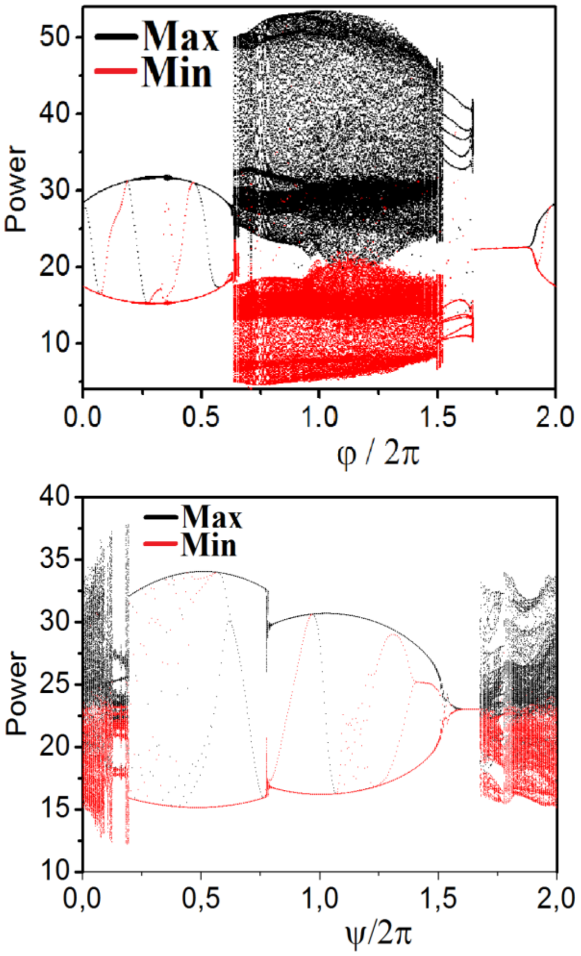

Fig. 8. Bifurcation diagrams for phase φ (top) and ψ (bottom) being a bifurcation parameter. The parameters are $B = 0.01$, $C = 40$, $J = 20$, $g = 1200$, $\gamma_{ns} = 1.0$, $\gamma_{np} = 500.0$, $\alpha = 2.0$.

IV. CONCLUSIONS

In this paper we have studied the dynamics of a device composed by a semiconductor laser with active medium quantum dots subject to a double cavity optical feedback. Main advantages of proposed scheme include the existence of two feedback strengths, two feedback phases and two delay times that can be controlled separately. The results show the following features: under appropriate conditions the setup shown in Fig. 1 is capable of generating a robust chaotic waveform within some regions. Such devices are promising candidates for fast communications based on chaos.

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