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GENERATION AND CONTROL OF CHAOTIC BEHAVIOUR OF PHOTONS AND PHONONS IN BIOLOGICAL MEDIA

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Abstract. It was reported the results on the numerical investigations of the dynamical behavior of photons and phonons emitted by a biological medium under the influence of millimeter or terahertz radiation. In particular it was investigated the influence of external modulation pump parameters on photons and phonons dynamics. It was found that the system displays, under certain conditions, continues waves, periodic and chaotic behaviors. A quasiperiodic route to chaos is found. The influence of some parameters on the system behavior is investigated. Finally, very good conditions for large chaotic behavior are identified.

Keywords: *Millimeter waves, generated photons and phonons, pumping control, optical feedback, periodic oscillations, quasi-periodic route to chaos.*

Rezumat. Au fost raportate rezultatele investigațiilor numerice ale comportamentului dinamic pentru fotonii și fononii emiși de un mediu biologic sub influența radiației milimetrice sau terahertzi. În special, a fost investigată influența parametrului de pompaj asupra dinamicii fotonilor și fononilor. S-a constatat ca în anumite conditii, sistemul descrie un scenariu de unde continui, unde periodice și haotice. A fost determinată modalitatea de control a sistemului din starea cvasiperiodică către cea haotică. A fost studiată influența unor parametri asupra dinamicii sistemului de fotoni și fononi la care, au fost identificate condiții de evoluție a sistemului către un regim haotic complex.

Cuvinte cheie: *Unde milimetrice, fotoni și fononi emiși, pompaj controlat, feedback optic, ocilații periodice, regim cvasi-periodic haotic.*

1. Introduction

The influence of electromagnetic fields on the living matter has become an attractive goal for modern biomedicine [1,2]. The human body is exposed daily to the radiation of various types of electromagnetic waves via the modern technologies, which are extremely widespread in everyday life. The effects produced by these radiations can destroy the body's defense and functional systems [3]. However, some classes of electromagnetic waves, e.g., millimeter (MM) and terahertz (THZ) waves can produce constructive therapeutic effects [4-6]. Thus, a multitude of companies around the world that produce medical devices are trying to replace, well known classical methods (tissue damage during surgery) with non-invasive one based on MM and THZ wave therapy [7-9]. Recently, it was demonstrated experimentally, that these waves at low intensities resonate with the electromagnetic waves generated by biological cells. These interactions correspond to 42.7 GHz, 53.5 GHz and 60.7 GHz wave frequencies and play an important role in the functional state of the cells, tissue, or even the whole organism [10].

Recent technology allows the coherent detection of THZ pulses and can be successfully applied to the spectroscopy, biomedical imaging and diagnostics [11-13]. MM and THZ waves have low photon energy between 1 and 5 meV. These energies correspond to the energy levels related to rotational and vibrational molecule modes and intermolecular vibrations, such as hydrogen bonds. Such type of low-energy allows the visualization of biomolecules, characterizing their spectral features in THz region [14,15]. Due to the low photon energy, it is not enough to cause molecular ionization. From this reason, MM and THZ waves are suitable and attractive for noninvasive biomedical imaging and possible human health effects. They could be applied in the real studies without causing biological ionizing damage opposite to damages than can be caused by X or gamma-rays.

While the practical results are quite visible and impressive, the complete understanding of physical mechanism of the interaction process of MM or THZ waves with living tissue to our knowledge still does not exist. The first theory that is focused on the generation of MM waves by the living cells was proposed by Fröhlich [16]. According to his idea, at the cellular or protein level, the appearance of certain coherent longitudinal electric modes can happen, that are stabilized by deformations arising from nonlinear effects. At low power, the MM waves can stimulate the excitation of the coherent electric vibrations provided by the biological system when it is in an active metabolic state. These coherent states could regulate the biological cell activities. The coherent waves emitted by living cells represent a complex process involving the cell membranes, protein channels, and cellular transport pumps [17,18]. However, the cell membranes are considered the basic trigger for that interaction, as they are sensible to coherent excitations regime. The cell membrane is the most considered interest in biological physics, as it acts as a gateway of the cell, where the control of many essential electrophysiological functions are important.

Another study reports that at the interaction of MM waves with biological membrane, a mechanism of nonhomogeneous dissipation of wave energy happens [19]. For collective coherent processes, a clustered bound state is created, which is localized in space and has remarkable stability properties. This may contribute to the emergence of particular regions in the membrane that are polarized and are coupled to an elastic deformation. On the other hands, the spatial localization of the polarized state proposed for molecular chains, leads to soliton formation as well as Bose condensation [20]. Base on this idea, a control mechanism with the dynamics of a biological medium that is irradiated with an external MM wave source was studied [21]. It is demonstrated that for some parameters of the model, the system dynamics displays continue periodic and chaotic behaviors.

In this paper, we report results how to control the dynamics of the Fröhlich photon and phonon systems using modulated pumping of the MM and THZ wave source. The dynamics of condensed dipole-active Bose phonons and internal Fröhlich photons can exhibit regimes of continuous waves (CW), periodic oscillations, period doublings, chaotic regimes for certain values of the system parameters as well as the modulation of external signal. The paper is organized as follows. The setup structure and mathematical model are described in Section 2. Results of the numerical simulations are given in Section 3. We discuss the influence of main parameters of output power evolution. Finally, conclusions are given in Section 4.

2. Theoretical model

It is well known, that the modulation pumping is influencing the laser dynamics, as well as the features of emitted light [22]. In case of a fiber ring laser, excited by a sinusoidally modulated pump power, several resonance peaks were observed, showing bistable behaviors. It is demonstrated that these regions depend on the powers and population distributions along the laser active medium. The influence of modulated current shape on the dynamics of a semiconductor laser with optical feedback was studied recently [23], and compared with the intensity spiking dynamics of a FHN neuron, that is modulated with the same input signal that modulated laser current. Thus, the modulation index of a sinusoidal pump can contribute to the appearance of various optical bistabilities and influence the coherent resonance control in a system of neuronal networks [24].

The theoretical model of the evolution of photons and phonons generated by the biological media was discussed in our previous papers [20,21]. Figure 1 shows the scheme of irradiation of the biological environment by MM wave source, whose profile is described by a function with sinusoidal modulated pump power: $P = P_0\left(1 + m\left(\cos 2\pi ft\right)\right)$, where m is the modulated parameter. P_0 and f represent the pump amplitude and frequency, respectively. The photons emitted by the biological medium are delayed from an external mirror, similar to the model of semiconductor lasers with external feedback [25]. Typically, the external feedback influences the dynamics of the system and can contribute to the appearance of periodic and quasi-periodic pulsations, low frequency fluctuations, as well as chaotic regimes. Here, we investigate the influence of modulation index m and external feedback parameters Γ and φ on the photons and phonons dynamics generated by the biological environment.

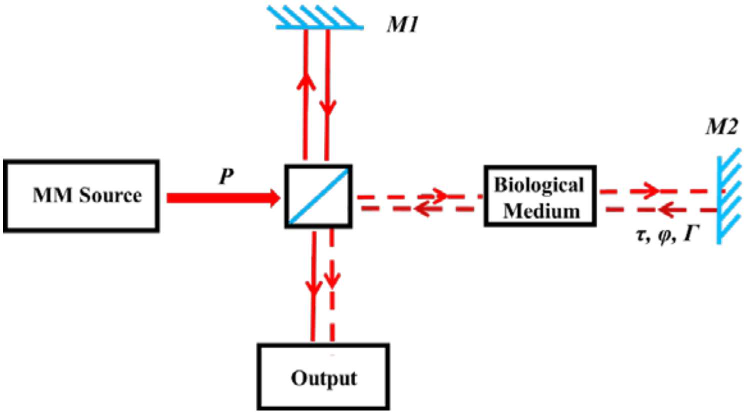

Figure 1. Schematic representation of the setup consisting of biological medium under the influence of external modulation pump.

The external optical feedback phase and amplitude are notated by φ and Γ. The incident MM wave is separated in two waves one of which is considered as reference wave and is reflected from the mirror M1. The second wave interacts with biological medium and is reflected from the mirror M2. M1 that is located at a given distance from the medium generates an external optical feedback. The output power represents the superposition on the final two wave signal.

The photons and phonons emitted by the biological medium are described by the system of delayed differential equations [21]:

$$\begin{aligned}\frac{dE_1}{dT} &= -\sigma E_1 - \left(\tilde{\delta} - \tilde{\omega}_0\right)E_2 + 2\alpha\tilde{\gamma}A_1 + \alpha\left\{2\tilde{\gamma}\left[\delta - \left(A_1^2 + A_2^2\right)\right] - 1\right\}A_2 + P + \\ &+\Gamma\left[\cos(\varphi)E_1(t-\tau) + \sin(\varphi)E_2(t-\tau)\right]\end{aligned}, \qquad (1)$$

$$\begin{aligned}\frac{dE_2}{dT} &= \left(\tilde{\delta} - \widetilde{\omega_0}\right)E_1 - \sigma E_2 + 2\alpha\tilde{\gamma}A_2 - \alpha\left\{2\tilde{\gamma}\left[\delta - \left(A_1^2 + A_2^2\right)\right] - 1\right\}A_1 + \\ &+\Gamma\left[\cos(\varphi)E_2(t-\tau) - \sin(\varphi)E_1(t-\tau)\right]\end{aligned}, \qquad (2)$$

$$\frac{dA_1}{dT} = -\alpha E_2 - A_1 - \left[\delta - \nu\left(A_1^2 + A_2^2\right)\right]A_2, \qquad (3)$$

$$\frac{dA_2}{dT} = -\alpha E_1 + \left[\delta - \nu\left(A_1^2 + A_2^2\right)\right]A_1 - A_2. \qquad (4)$$

In the equations (1) - (4) we use the following addimensional parameters

$$\delta = \frac{\Delta}{\gamma},\ \tilde{\delta} = \frac{\omega^2 - c^2k^2}{2\omega\gamma},\ \alpha = \sqrt{\frac{\omega\Omega_0}{2\gamma^2}},\ \Omega_0 = \frac{4\pi d^2}{V_0\hbar},\ \tilde{\omega}_0 = \frac{\Omega_0}{\gamma},\ \tilde{\gamma} = \frac{\gamma}{\omega},\ \sigma = \frac{\gamma_f}{\gamma},\ T = \gamma t.$$

Here, ω and Ω represent the photons and phonons frequencies, while $\Delta = \omega - \Omega$ is the detuning of frequencies. The phonons and photons attenuation constants are notated by γ, and γ_f respectively. The parameter σ represents the quality factor Q of the cavity where the biological medium is located. *d* is the dipolar electric momentum, *k* is the wave vector, *c* is speed of light in vacuum, and V_0 is sample volume, and ν = ±1. Here we consider α as a parameter characterizing phonon rate losses. *Γ* and *φ* characterize the strength and phase of external feedback, respectively.

In our previous works [20,21], we demonstrated that with an external pump and varying certain system parameters, the dynamics of the output power can be controlled, in which the chaotic and periodic evolutions can be transformed into the CW regime. However, it is interesting to study the influence of modulated pump on the considered system and the possibility to control with modulation index parameter.

The system of equations (1)-(4) represent the basis for the following investigations. The output power of emitted photons and the concentration of phonons generated by the biological environment are defined respectively by $P = E_1^2 + E_2^2$, and $n = A_1^2 + A_2^2$. For the numerical calculations in the all following figures we use the following values of dimensionless parameters $\tilde{\omega}_0 = 0.1,\ \nu = 1,\ \tilde{\gamma} = 1.1,\ \tilde{\delta} = 0.1,\ \tau = 0.15,\ \delta = 3,\ \sigma = 3,\ P_0 = 85,$ $f = 2$.

3. Results of numerical simulations

Figure 2 describes the dynamics of emitted photons. In Figure 2a the output power evolution in time and the phase portraits for certain values of the system parameters is shown. One can observe that, for the modulation index *m* = 0, the evolution of the system tends to a stable stationary state, and the phase trajectories describe a stable focus. For *m* = 0.1, as shown in Figure 2b, the system describes a periodic oscillations, and the phase portrait of trajectories show the limit cycle. An increase of modulation parameter to *m* = 0.5 quasi-periodic pulsations appears in the system and the phase portrait is a deformed ellipse (see Figure 2c). Finally, an increase of *m* to *m* = 0.9, leads to the appearance of the strong chaotic regime. Thus, with the pump parameter, it is possible to control the dynamics of the system by keeping all the other parameters fixed. This is an indication that it may be possible to control the dynamics from CW to chaos only changing a single parameter.

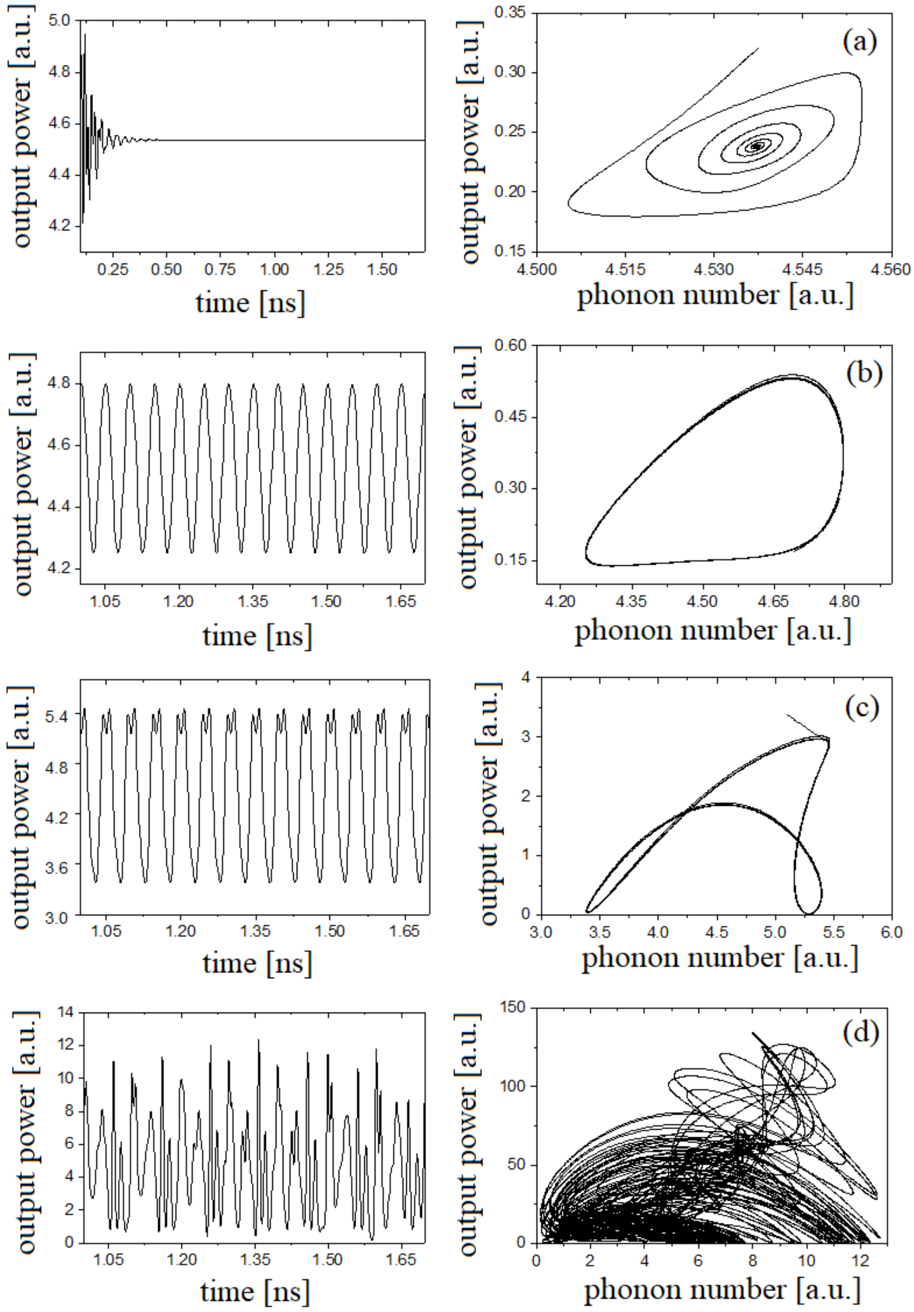

Figure 2. Time traces of the output photons power (left), and phase portrait (right) for $\alpha = 8$, $\Gamma = 2.5$, $\varphi = 3\pi/2$ and various values of modulation index: a) m = 0, b) m = 0.1, c) m = 0.5, d) m = 0.9.

In what follows the dynamics of the system (1)-(4) is presented for an increase of parameter α to $\alpha = 15$, i.e. increase of phonon rate losses. As was expected an increase of α from 5 to 15 lead to a more complex dynamics even for m = 0 (see Figure 3). As one can see, for m = 0, the time evolution of the emitted photons describes a regime of periodic waves with the phase portrait as a complicated limit cycle.

For an increase of modulation index parameter to m = 0.9 in the system new harmonics appears and the phase portrait becomes more complex. Thus, with the help of parameter α one can transform periodic regime to quasi-chaotic.

One can conclude that the dynamic of system is strongly dependent on both parameters α and m.

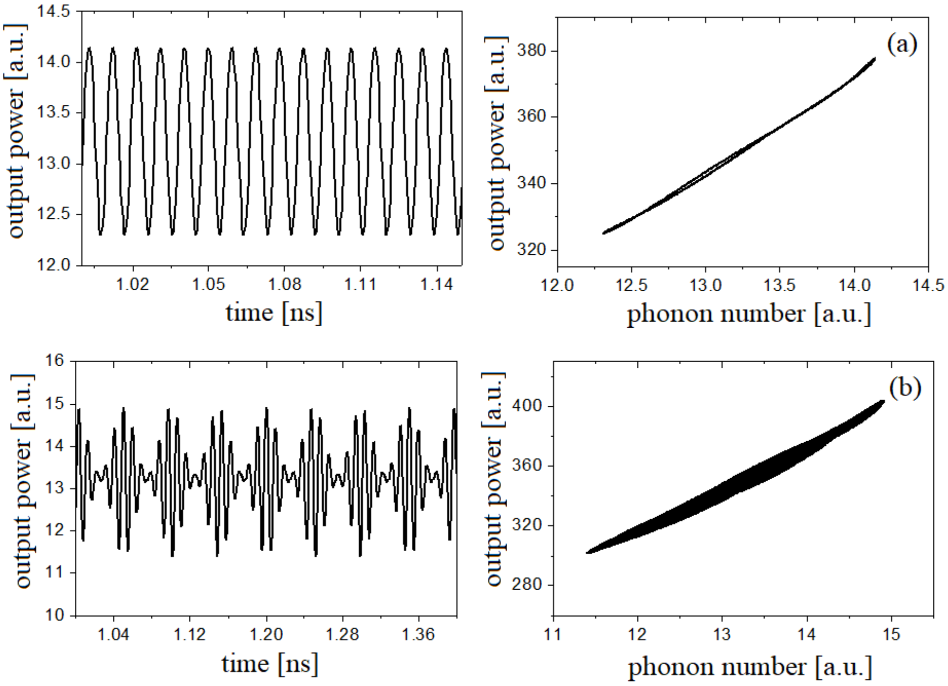

Figure 3. Time traces of the output photons power (left), and phase portrait (right) for $\alpha = 15, \Gamma = 2.5, \varphi = 3\pi/2$ and two values of modulation index: a) *m* = 0, b) *m* = 0.9.

The external phase can influence the evolution of output power. Thus, we change the phase from $\varphi = 3\pi/2$ to $\varphi = \pi$ and vary the modulation pump from 0 to 0.9 for parameters as in Figure 2. As shown in Figure 4 for *m* = 0, periodic oscillations can be observed in the dynamics of the system, and with its increase of it to *m* = 0.9 strong chaotic oscillations appear. The phase trajectories describe a strange attractor for chaotic behavior is shown in Figure 4b.

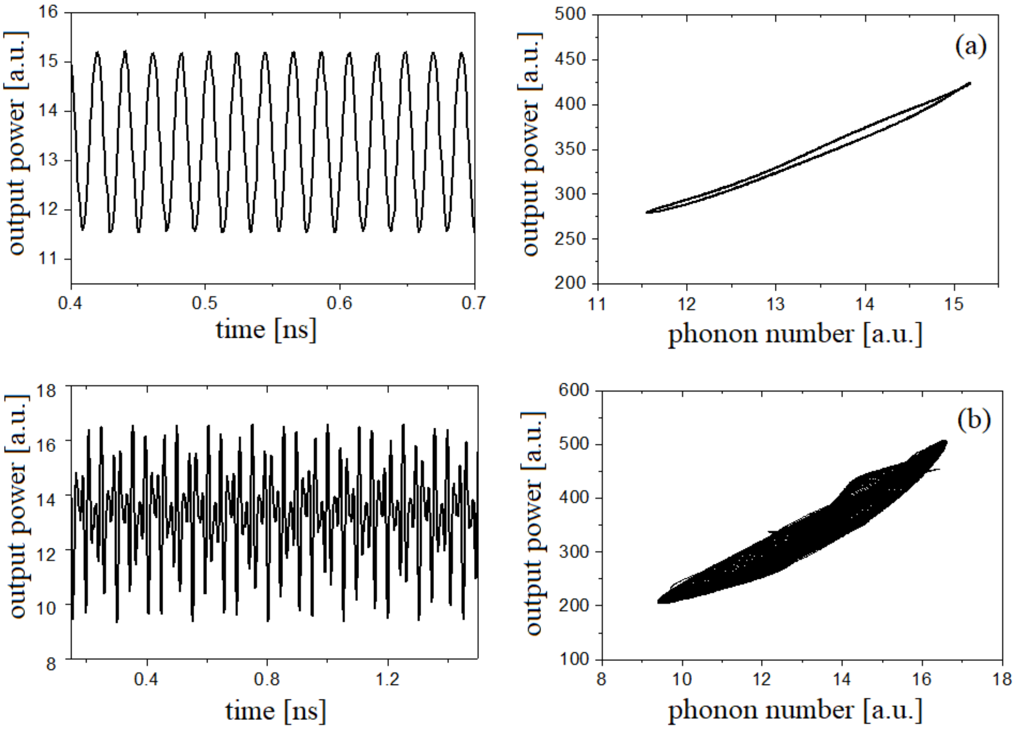

Figure 4. Time traces of the output photons power (left), and phase portrait (right) for $\alpha = 8$, $\Gamma = 10$, $\varphi = \pi$, and various values of modulation index: a) *m* = 0, b) *m* = 0.9.

Next, we describe the system dynamics in terms of bifurcation diagrams. Figure 5 shows bifurcation diagram, where feedback strength *Γ* is considered as bifurcation parameter. The diagram shows the dependence of photon number on the feedback strength for maximum (black) and minimum (red) values and for different pump parameter *m*. Each dot represents a peak of the output power for a fixed value of feedback strength.

Thus, for a given value of the feedback strength, the figure displays the values of all the local maximal (black) and minimal (red) of the time traces, calculated within 50 ns, of the emitted output power.

For *m* = 0, the systems starts from CW operation - region A in both Figures 5a and 6A, followed by periodic oscillations - region B in both Figures 5b and 6B.

The regions C and D (Figure 5a and Figures 6C and 6D) are characterized by chaotic waves. An increase of *m* to 0.1 results in a small change in the bifurcation diagram (see Figure 5b). When *m* = 0.5 the region of CW disappears (see Figure 5c) and the behavior becomes more complicated. For *m* = 0.9, in the bifurcations diagram chaotic regimes are obtained (see Figure 5d and Figures 6E and 6F).

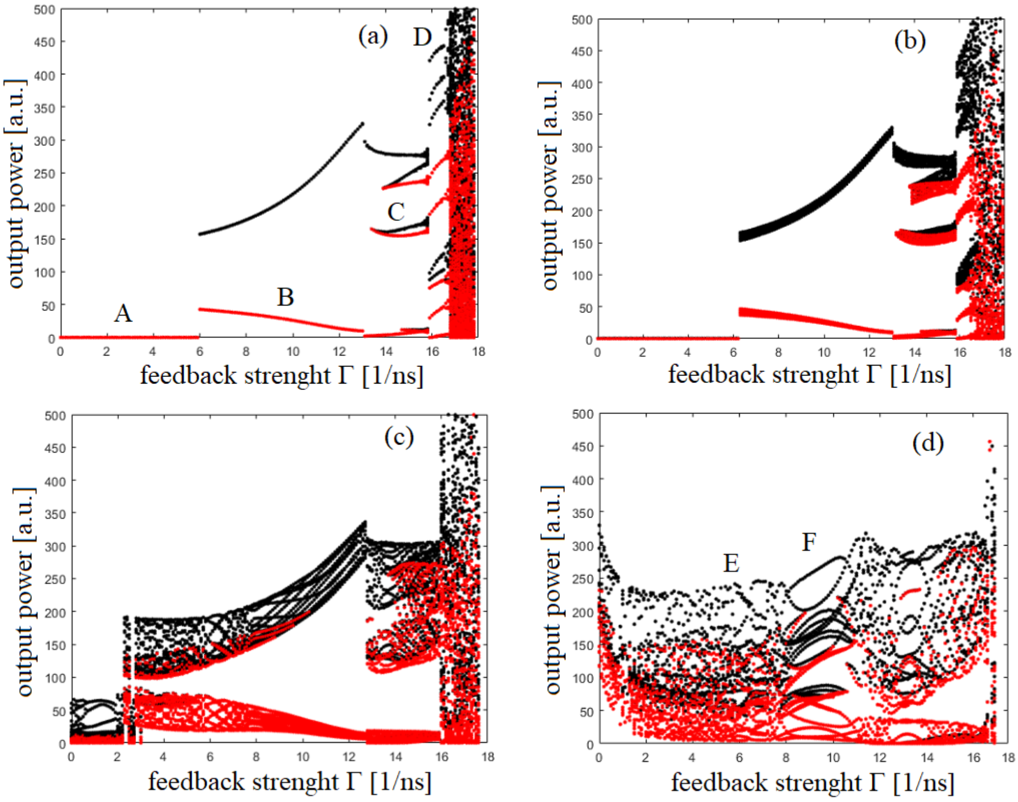

Figure 5. Numerical bifurcation diagram of the output power for amplitude of the optical feedback as bifurcation parameter, where: $\alpha = 8$, $\varphi = 3\pi/2$, a) *m* = 0, b) *m* = 0.1, c) *m* = 0.5, d) *m* = 0.9.

Thus, a scenario compatible with that of quasiperiodic route to chaos is observed. Thus, the influence of external optical feedback on the dynamics of emitted Fröhlich photons and phonons is very sensitive to external feedback parameters and can influence the system stability.

We can control the dynamics of the system via two main parameters the feedback strength of external feedback and modulation pump index.

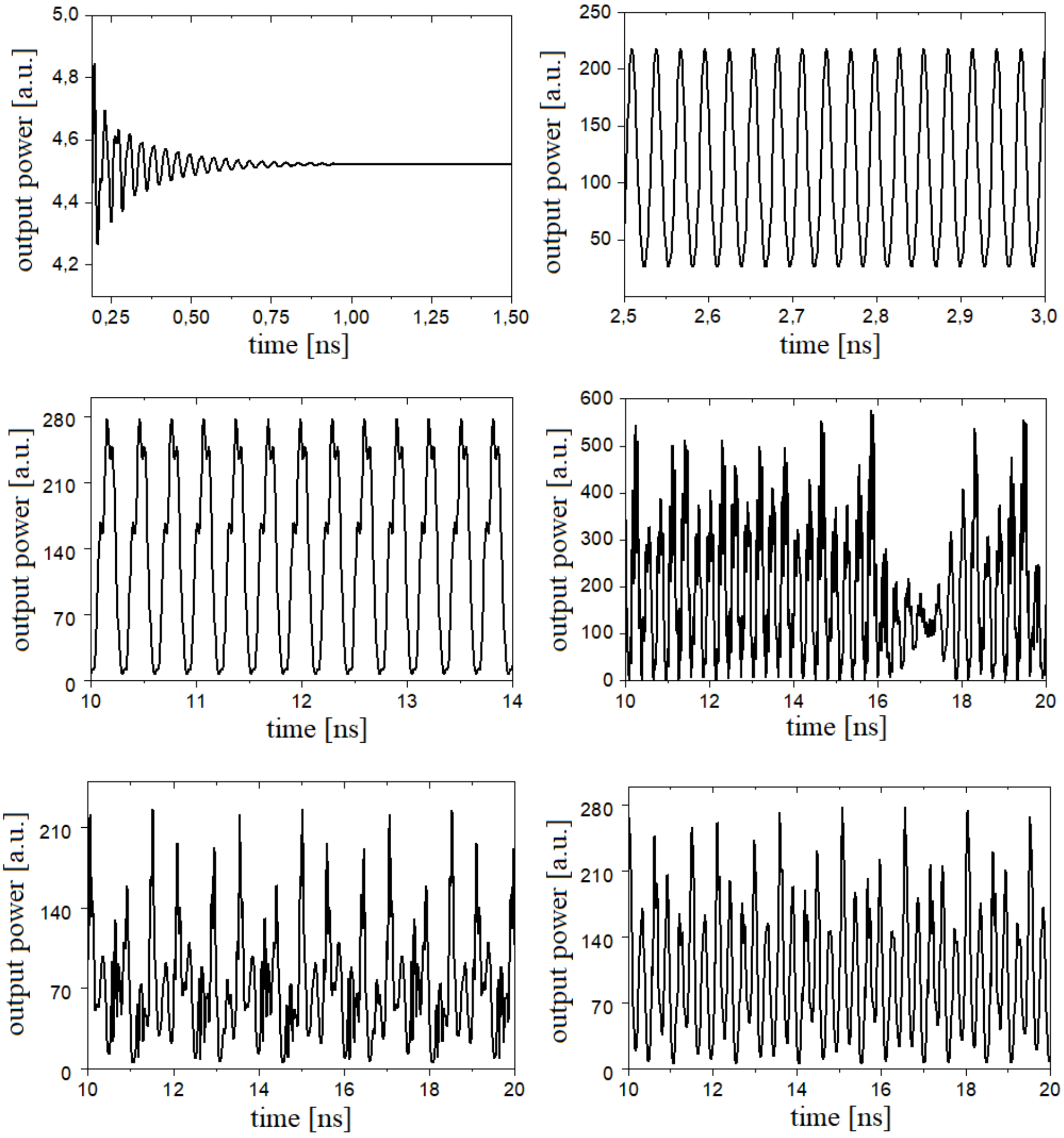

Figure 6. Time traces of the output photons power for $\alpha = 8$, $\varphi=3\pi/2$ and various values of modulation index: (A) m = 0, Γ = 4; (B) m = 0, Γ = 10; (C) m = 0, Γ = 15; (D) m = 0, Γ = 17; (E) m = 0.9, Γ = 5; (F) m = 0.9, Γ =10.

5. Conclusions

In this paper we report a model for generation and control of chaotic behavior of Fröhlich photons and phonons in a biological medium. The dynamics of condensed dipole-active Bose phonons and internal Fröhlich photons is influenced by external optical feedback. Thus, the dynamics of systems can exhibit regimes of continuous CW, periodic oscillations, period doublings, chaotic regimes for certain values of the system parameters. An important goal of this study is the influence of modulation parameter of external pumping on the dynamics of the system.

In the absence of modulation pump parameter, *m*, the evolution of the system for certain fixed parameters tends to a stable stationary state, and the phase trajectories describe a stable focus. A small increase of *m* contributes to the appearance of a periodic oscillation in the system, and the phase portrait of trajectories show a limit cycle. For moderated and large values of modulation parameter, one can observe the occurrence of quasi-periodic pulsations as well as strong chaotic regimes. Thus, the transition of the system from stable states to periodic oscillations, from periodic regime to quasi-periodic pulsations as well as from quasi-periodic pulsations to chaotic behavior is possible only via a single variable parameter.

The parameter α that characterizes the phonon rate losses also influence the dynamics of the emitted photons and phonons. For large values of m, the model shows a strong chaotic oscillations regime and the phase trajectories describe strange attractors. The same regimes, i.e., chaotic oscillations and strange attractors can be obtained under the influence of external feedback amplitude and phase.

The dynamics of the systems was also described and in terms of bifurcation diagrams, considering feedback strength Γ as bifurcation parameter. Thus, with our model we can control the dynamics of the system via two main parameters the feedback strength of external feedback and modulation pump parameter.

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