Volume 17, Number 1, 2024. pp. 97-105

Jordan Journal of Physics

ARTICLE

Performance Evaluation of Chaotic Semiconductor Laser

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Doi: **https://doi.org/10.47011/17.1.9**

Received on: 08/06/2022; Accepted on: 22/09/2022

Abstract: Chaotic semiconductor lasers are produced for applications in long-distance communication and for concealing modulated messages. In the present work, the dynamics of chaotic behavior in semiconductor lasers utilizing optoelectronic feedback have been investigated using the Optisystem software. Different parameters are controlled to get the optimum chaotic laser. An external perturbation is applied to the semiconductor laser output that has two control parameters, which are frequency and amplitude. Modulation is achieved by the variation in perturbation bias injunction currents while the modulation peak current is fixed. The study employs a delayed optoelectronic feedback diode laser to assess the ability to achieve chaotic output from directly frequency-modulated semiconductor lasers. This is done under various GHz modulation conditions while maintaining a fixed bias current.

Keywords: Chaos, Semiconductor laser, Optoelectronic feedback, Optical communication.

1. Introduction

Lasers, light sources renowned for their very special properties, find diverse applications. Many studies have been conducted to improve laser work and benefit from it [1]. In the 20th century, chaos emerged as a highly important subject in science. Chaos dynamics might be considered as irregular events in the time of evolution of nonlinear dynamic systems, distinct from random processes [2, 3, and 4]. Semiconductor lasers (SLs) have proven valuable in studying dynamic systems [5]. Generating chaos in semiconductor lasers requires the consideration of nonlinearity and 3-fold dimensionality as crucial conditions. Nonlinear dynamics can be described as an interdisciplinary branch of science that deals with studying systems that are described by mathematical formulas [6, 7]. In instances where the nonlinearity of the laser does not have the necessary strength, an external nonlinear element is presented for the same aim. Additionally, delaying feedback loops can increase the system's dimensionality when it is not as high as necessary [6, 8]. Changing the laser diode intensity can lead to the generation of a chaotic optical carrier. Many approaches, such as optoelectronic feedback (OEFB), optical injections, and optical feedback (OFB), can be utilized to achieve the laser's dynamic operating state [9]. Al Naeimee *et al.* have conducted both experimental and theoretical research on chaos generation using a variety of approaches, including optoelectronic [10, 11] and optical feedback with diverse control parameters [12]. An optical fiber coupler is used as feedback to help achieve chaotic behavior in semiconductor lasers [13].

Different media of transmission, possibly including optical amplifiers, may also be tested. The data should be transferred with extremely low distortion and high speed. In traditional communication systems, effectiveness is limited by channel properties, whereas in chaos communication, the bound is based on the

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characteristics of the present dynamical system [14]. Chaotic Modulation (CM) has been defined as an approach to sending messages using chaos induced by OEFB in a system used for coding and decoding the messages [15]. In CM, both the message and chaotic carrier follow new chaotic oscillations in nonlinear systems. In a non-linear oscillator, a message is mixed with the chaotic carrier and the two signals correspond to a new chaotic state, which is dissimilar from the original state. The amplitude of the message has to be small enough compared to the carrier wave in a case where an ordinary message decoding process is utilized [16]. The secure optical communication system has been researched utilizing Optisystem [17].

This work deals with chaos generation through semiconductor lasers. Factors affecting the degree and enhancement of chaos are studied and simulated by the Optisystem software. This study examines the effects of small modulations on the non-linear dynamic behavior of semiconductor lasers. The corresponding simulation model has been established in terms of dynamic time series, phase portraits, and the frequency spectrum. The impact of the modulation peak current, bias current, and frequency of the current source on the nonlinear behavior of the considered system have been studied thoroughly.

2. Theoretical Model

The entire dynamics of this system are controlled by 2 coupled variables (population inversion and photon intensity), which evolve two highly dissimilar characteristic time scales. Introducing an AC-feedback optoelectronic loop adds a 3rd freedom degree as well as a 3rd considerably slower time scale. The system comprises a closed-loop optical system that is equipped with a semiconductor laser with AC and non-linear optoelectronic feedback. The laser light produced by the system is sent to a photodetector which converts the optical signal to an electrical signal using an optical fiber. This process results in the generation of an electrical signal that is amplified by a variable gain amplifier and added to the bias current of a semiconductor laser, as shown in Fig.1.

The dynamics of carrier density N and field density S are represented by single-mode semiconductor laser rate equations (Al Naimee model) [11, 18]. These equations are properly modified to accommodate the AC-coupled optoelectronic feedback [18].

$$S^{\cdot} = [g\,(N - Nt) - \gamma_0]\,S,$$

$$N^{\cdot} = (I_0 + f_F\,(I)\,/\,eV) - \gamma_c N - g\,(N - N_t)\,S \qquad (1)$$

$$I^{\cdot} = -\gamma_f\, I + k\, S^{\cdot}$$

I represents high-pass filtered feedback current (prior to a nonlinear amplifier), $f_F\,(I) \equiv AI/(1{+}S^{\cdot}I)$ represents the function of the feedback amplifier, e represents the charge of the electron, I_0 represents bias current, g represents differential gain, and V represents the volume of the active layer, while γ_0 and γ_c represent the damping of the photon and rate of the population relaxation, respectively. N_t represents carrier density at the transparency, γ_f represents the cut-off frequency of a high-pass filter, and k represents a coefficient that is proportionate to the responsivity of a photodetector.

For analytical and numerical purposes, re-writing Eq. (1) in a dimensionless form would make sense. By introducing the new variables $x = g/\gamma_c\, S$, $y = g\gamma_0\,(N - Nt)$, $w = (g/\,k\gamma_{c)}\, I - x$ and the time scale $t^{\cdot} = \gamma_0 t$, the photon density $x^{\cdot}$ and carrier density $y^{\cdot}$ dynamics can be described by typical equations of single-mode semiconductor laser rate, which has been modified suitably to include AC coupled feedback loop. For analytical and numerical purposes, it would be best to write the rate equations in a dimensionless form [18, 19]. In this case, the rate equations can be expressed as:

$$x^{\cdot} = x(y - 1) \qquad (2)$$

$$y^{\cdot} = \gamma\,(\delta_0 - y + f(w + x) - x.y) \qquad (3)$$

$$w^{\cdot} = -\,(w + x) \qquad (4)$$

where $f(w + x) \equiv \alpha(w{+}x)/(1{+}s(w{+}x))$, $\delta_0 = (I_0 - I_t)/(I_{th} - I_t)$,$(I_{th} = eV\,\gamma_c((\gamma_{0/}\, g) + N_t)$ is the solitary laser threshold current, $\gamma = \gamma_c/\gamma_0$, $\varepsilon = \omega_0/\gamma_0$, $\alpha = Ak/(eV\,\gamma_0)$ and $s = \gamma_c\, s^{\cdot}k/g$.

The output light is directed to a photodetector, which produces a current proportional to optical intensity. The corresponding signal is fed into an amplifier with variable gain, characterized by a non-linear transfer function denoted as $f\,(w + x) \equiv \alpha\,(w + x)/(1 + s(w + x))$. After that, the signal is used as feedback to the LD injection current. The strength of feedback has been specified by a gain of the amplifier in the Al Naimee model [18].

Following the rate equation modification, this model predicts unstable behaviors. The transitions between the periodic and chaotic states have also been researched. The effect of periodically modulating injection current on the chaotic attractors, utilizing an identical theoretical model by adding the perturbation term, has been analyzed. The system output becomes chaotic. There are several possibilities for accomplishing these conditions [20].

The injection modulated current in the pumping term (H) in Eq. (4) must be substituted by the periodically modulated current. Input current equation will be expressed as:

$$w^{\cdot} = -(w + x) - (1 + H) * x \qquad (5)$$

Here, H represents the periodically modulated current, which can be calculated as:

$$H = A \text{ x } \sin(2\text{x } \Pi \text{ x } f\text{x } t) \qquad (6)$$

Here, A and f represent perturbation amplitude and frequency, respectively.

3. Results and Discussion

The simulation setup of the proposed optoelectronic feedback system has been illustrated in Fig. 1. This simulation was performed using Optisystem software.

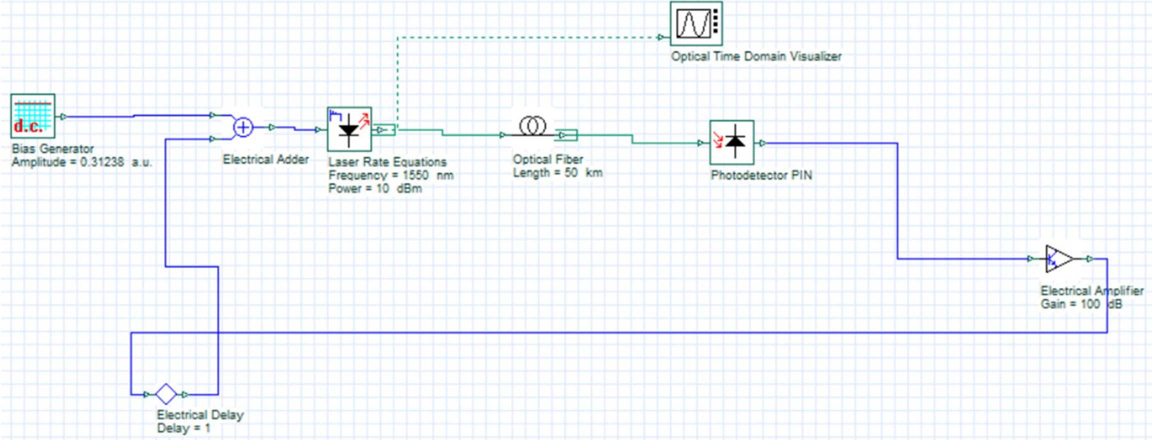

FIG. 1. Chaotic laser simulation using Opisystem.

In our work, we have utilized the concept of external modulation, where the pumping power is supplied to the laser cavity through the external current source. We are able to create a chaotic signal using laser rate equation mode and a DC generator drive. The DC bias generator is opened up, and the mode is changed from normal to sweep mode. This fundamentally causes the bias generator to create random values, which in turn randomly vary the laser's center frequency. The operating wavelength of the laser is kept at 1550 nm, although it can be set to any other wavelength. For convenience, the semiconductor laser generates chaos with a threshold current set to approximately 33.46 mA and a threshold power of 0.0154 mW. To investigate the impact of various parameters on the chaotic behavior of the laser, we vary the 'Bias current' and 'Modulation Peak Current' of the semiconductor laser at a power level of ten dBm. Additionally, we vary the frequency of the current source to observe its effect on chaotic pulses, as shown in Fig. 2.

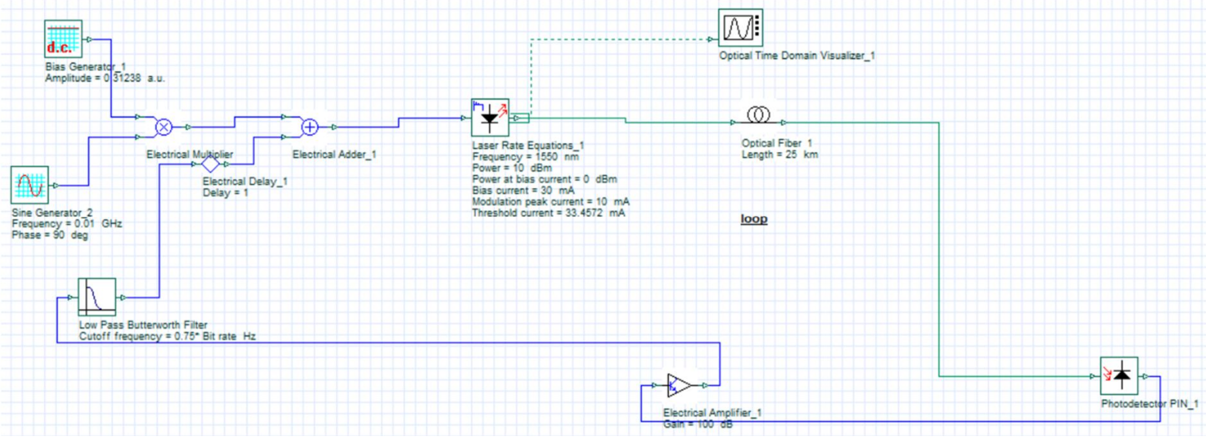

FIG. 2. Chaotic laser modulation using Opisystem.

In this circuit (Fig. 2), we combine the DC bias generator's output with the sine generator's output to observe the effects of adding a DC component. Additionally, we modify the properties of the generators to observe the effects of changing every one of the properties. The bias generator is a block acting as a DC source. By double-clicking on the block, the general properties of the bias generator can be seen. Under the main window, the amplitude can be changed.

3.1 Changing Bias Current (Route from Quasi-Periodic to Chaos)

In the presented configuration (Fig. 1), the strength of the feedback has been constant, whereas the control parameter with the laser injection bias current has been variable. A variety of optical intensity oscillation dynamics have been found, including limit cycles, quasiperiodic, and chaos oscillations.

Parameters of semiconductor lasers used to generate chaos are given in Table 1. At the beginning, when the bias current is low, i.e., 1 mA, the quasi-chaotic behavior of pulses can be observed where bunching of chaotic pulses can be seen. The span of each bunch is approximately 1 ns. After 1 ns, a new bunch of chaotic pulses begins. As the bias current increases, the frequency of these bunches increases, causing them to overlap with each other. This overlapping gives rise to a chaotic route, as shown in Figs. 3 and 4.

Figs. 3 and 4 depict the transition from quasi-chaotic to chaotic behavior, as the bias current increases from 1 mA to 27 mA.

TABLE 1. Semiconductor laser parameters (with different bias currents).

Parameter Name	Value	Unit
Wavelength	1550	nm
Power	10	dBm
Bias current	1- 27	mA
Threshold power	0.0154	mW
Power (at bias current)	0	dBm
Modulation peak current	10	mA
Threshold current	33.46	mA

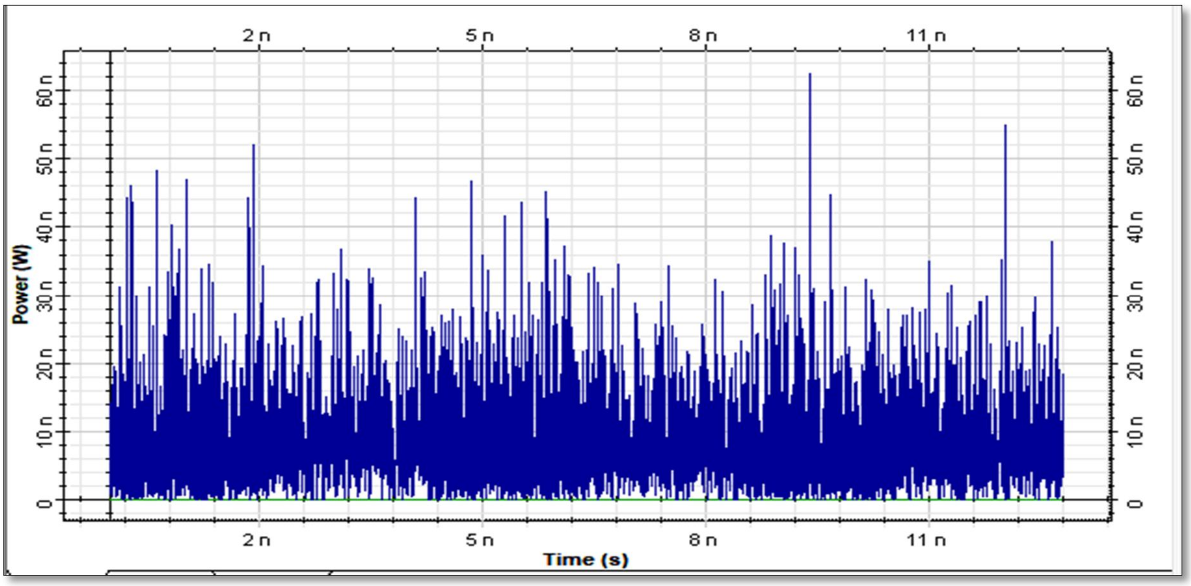

FIG. 3. Semiconductor laser output at bias current = 1mA.

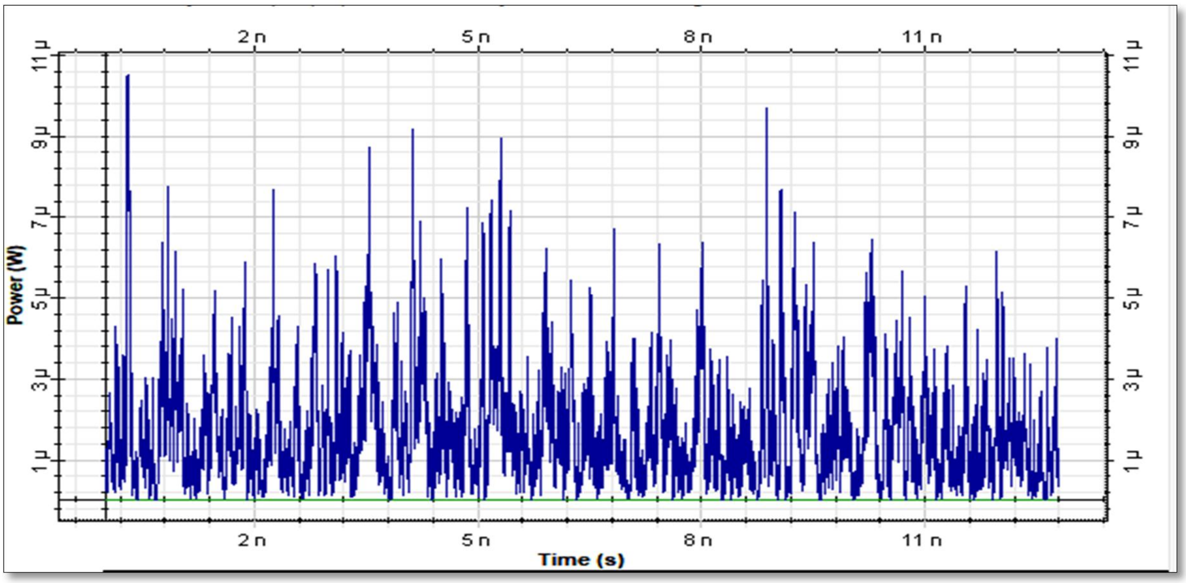

FIG. 4. Semiconductor laser output at bias current = 27mA.

It is seen from Figs. 4 and 5 that changes in the time series of the generated chaotic signals due to the increase in injection bias current in the DC generator result in an increase in the number amplitude of the spiking rate.

The bifurcation diagram, depicted in Fig. 5, summarizes the scenario that leads to chaos. This diagram illustrates the intensity related to the laser output (i.e. the peak-to-peak) with the modification of the control parameter (i.e. bias current of laser source). The bifurcation diagram is constructed based on the steady increase (1mA) in the control parameter (i.e. the bias current).

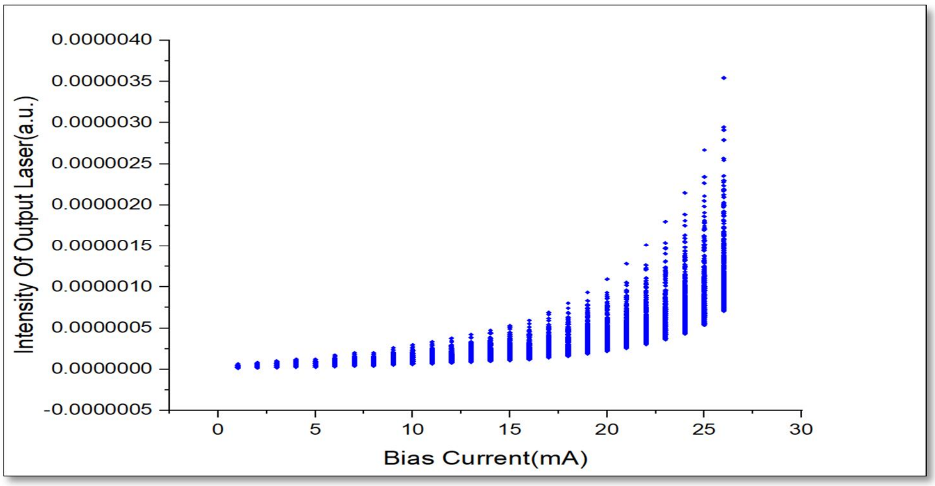

FIG. 5. Bifurcation diagram for the variation of bias current.

The bifurcation diagram provides insight into the behavior of the system across the range of bias currents from 1 to 27 mA. The quasi-chaotic behavior appears within the range from 1 to 15 mA. As the bias current gradually increases from 15 to 27 mA, chaotic behavior appears. This means that the variation in the bias current led the dynamic system of SL to change from quasi-chaotic to chaotic.

3.2 Changing Modulation Peak Current (High Amplitude Pulses)

Table 2 shows the parameters used to generate chaos in semiconductor lasers by varying the modulation peak current. While keeping the bias current unchanged, the modulation peak current is changed from 1 to 26 mA. At low modulation peak current values, the amplitude of generated pulses is extremely low, deviating from chaotic behavior and rendering them unsuitable for practical applications requiring a specific fiber length. With the increase in value of the modulation peak current, a clear variation in the amplitude of pulses can be observed in Figs. 6 and 7. Higher amplitude pulses follow the occurrence of many low amplitude pulses.

TABLE 2. Semiconductor laser parameters (with different modulation peak current).

Parameter Name	Value	Unit
Wavelength	1550	nm
Power	10	dBm
Bias current	30	mA
Threshold power	0.123	mW
Power (at bias current)	0	dBm
Modulation peak current	1-26	mA
Threshold current	33.46	mA

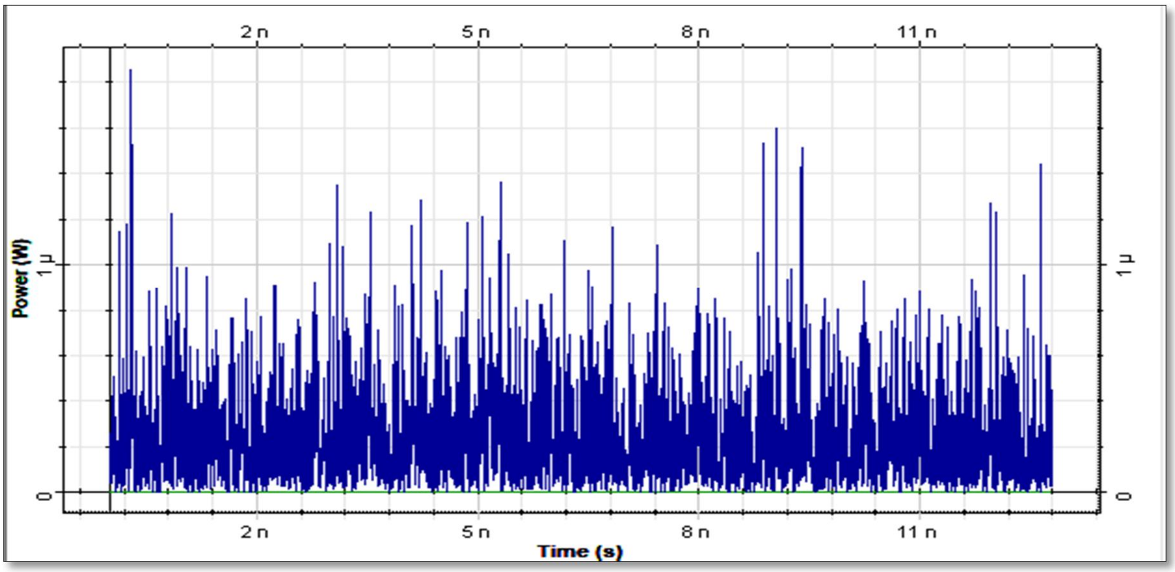

FIG. 6. Semiconductor laser output at modulation peak current = 1 mA.

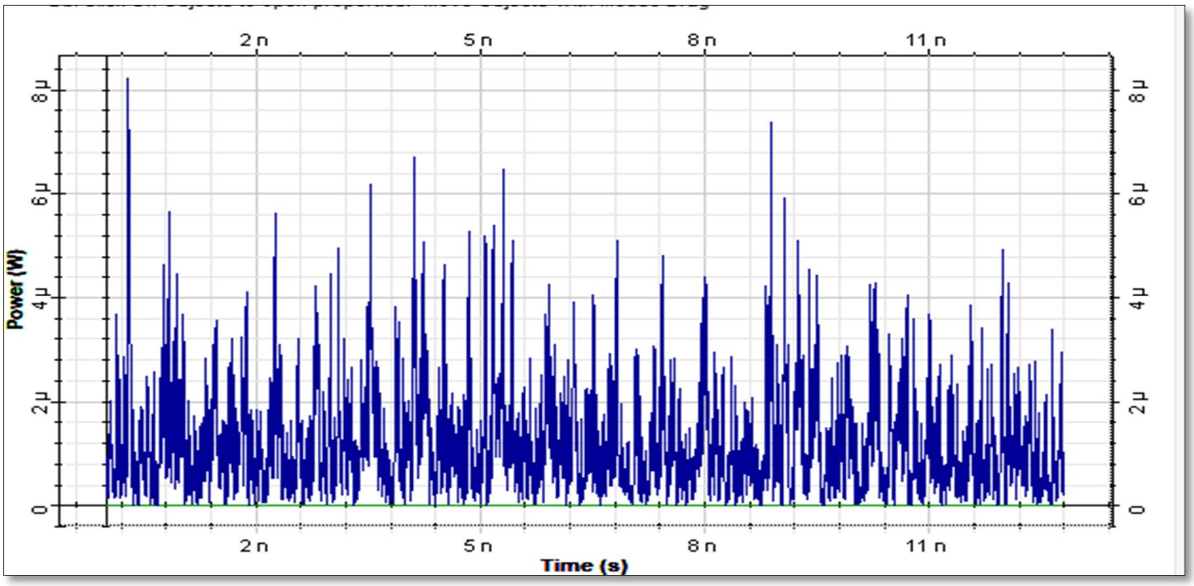

FIG. 7. Semiconductor laser output at modulation peak current = 18 mA.

The bifurcation diagram was used for checking chaotic routes and the evolution of output in the nonlinear systems as the control parameters vary. Figure 8 shows a bifurcation diagram for various modulation peak currents.

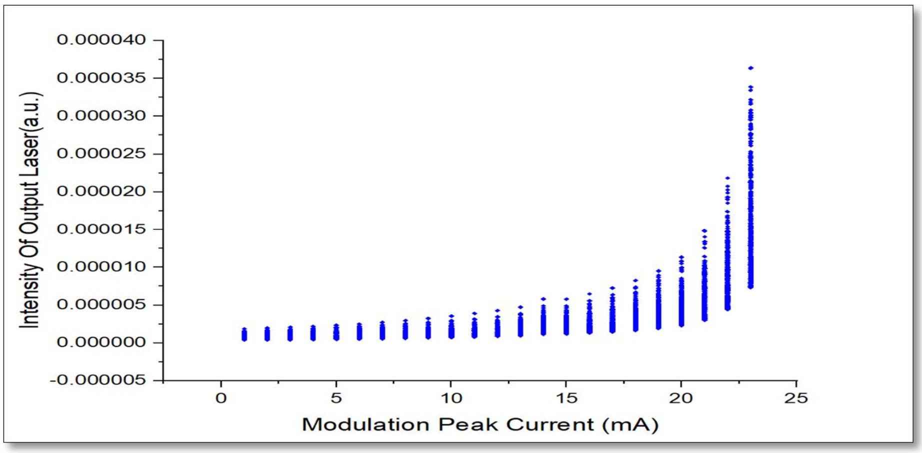

FIG.8. Bifurcation diagram with various modulation peak currents.

Fig. 8 shows that the values of modulation peak current led the system to change from quasi-chaotic behavior at 1-10 mA to chaotic behavior at 10-24 mA.

The results show that the modulation peak current might be considered a parameter that controls the system's collective dynamics, with varying amplitudes regulating the system's transition from quasiperiodic to chaotic, and eventually to periodic behavior.

3.3 Changing Frequency of Current Source (Random Amplitude Pulses)

The frequency of a sine generator plays a fundamental role in the number of retrieved spikes per period of modulation. Those findings are greatly important for the chaotic operation of chaotic lasers in applications like optical communication systems.

Suitable pumping power or current is required to achieve the chaotic nature of pulses. At a low frequency of the current source, when the strength of the electric field is not very high, pulses of the same amplitude are observed. Increasing the frequency results in the amplitude variation of pulses due to an increase in field strength. Table 3 shows the parameters of the frequency generator that are applied for external modulation by setting the frequencies ranging from 0.2 to 3 GHz.

Figs. 9 and 10 are the outputs of semiconductor lasers in response to the change in frequency.

TABLE 3. Current source parameters (with different frequencies).

Parameter	Name Value	Unit
Frequency	0.2- 3	GHz
Amplitude	1	a.u.
Phase	90	Deg
Bias	0	a.u.

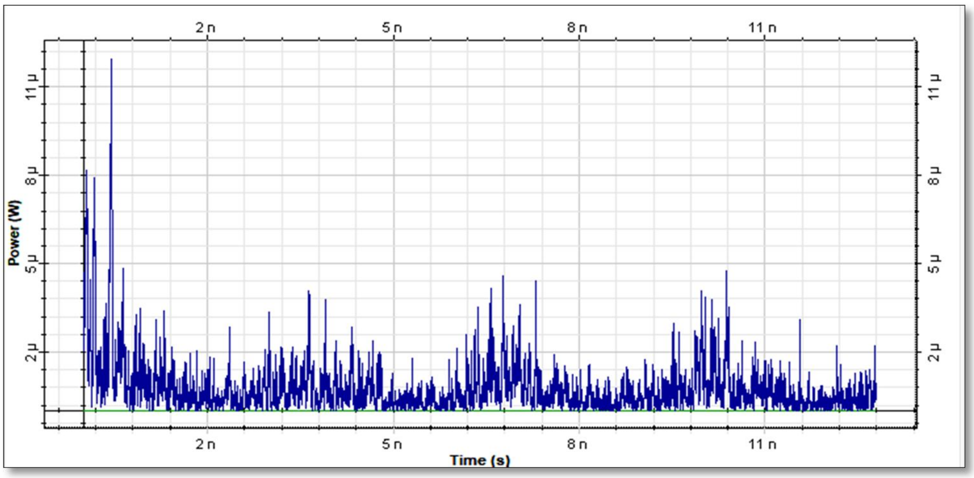

FIG. 9. Semiconductor laser output at 0.3GHz frequency of current source.

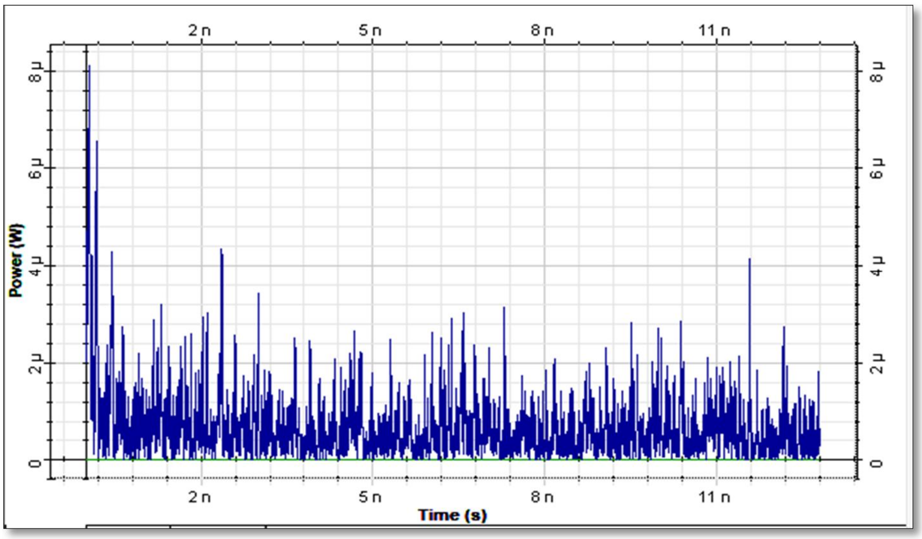

FIG. 10. Semiconductor laser output at 1 GHz frequency of current source.

The bifurcation diagram, shown in Fig. 11, summarizes the frequency modulation that has been applied to the source through a function generator.

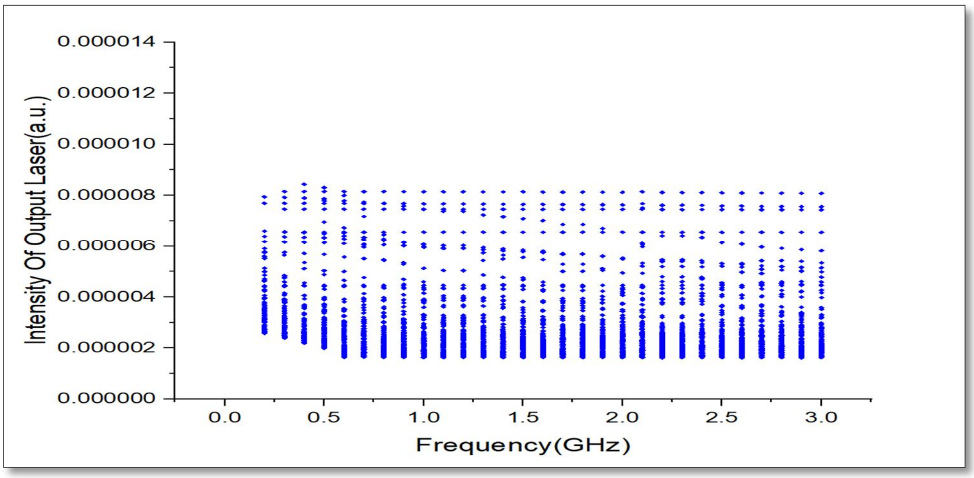

FIG. 11. Bifurcation diagram with different frequency modulation.

The chaotic system has been controlled at several frequencies, ranging from quasi-chaotic at 0.2-0.6 GHz to chaotic at 0.6-3 GHz. As a result, highly intriguing outcomes were found when the frequency was added to chaotic systems. The findings suggest that frequency modulation can be used as a control parameter for the system's collective dynamics.

4. Conclusion

This paper successfully explores various techniques for generating optical chaos using semiconductor lasers, employing the Optisystem software for the study. The chaos produced through the semiconductor laser is simulated by using direct modulation in which a current source and delay optoelectronic feedback of the semiconductor laser are directly connected to the semiconductor laser. The impact on chaos is observed by varying different parameters of the laser and current source. Control over different frequencies is achieved when the chaotic output signal is subjected to external perturbation. The results demonstrate that optoelectronic delayed feedback laser diodes can be manipulated to reach specific nonlinear states, such as quasi-chaotic and chaotic, by adjusting bias current, modulation peak current, and frequency of the current source. Laser and current source parameters are optimized to produce useful chaos suitable for concealing high data rate messages in long-distance communication. Chaotic dynamics have been considered as one of the good candidates for information hiding, which is an important aspect of data encryption in optical communications.

Acknowledgments

The author would like to express their thanks to Mustansiriyah University, Baghdad, Iraq, for the support that it has provided in this study.

References

[1] Qamar, F.Z., Jordan J. Phys., 14 (3) (2021) 201.

[2] Sciamanna, M. and Shore, K.A., Nat. Photonics, 9 (3) (2015) 151.

[3] Uchida, A., "Optical Communication with Chaotic Lasers: Applications of Nonlinear Dynamics and Synchronization", (John Wiley & Sons, 2012).

[4] Ma, C.-G., Xiao, J.-L., Xiao, Z.-X., Yang, Y.-D. and Huang, Y.-Z., Light Sci. Appl., 11 (1) (2022) 1.

[5] Fischer, I., Vicente, R., Buldú, J.M., Peil, M., Mirasso, C.R., Torrent, M.C. and García-Ojalvo, J., Phys. Rev. Lett., 97 (12) (2006) 123902.

[6] Song, S., Sun, F., Chen, Q. and Zhang, Y., IEEE Trans. Terahertz Sci. Technol., 5 (1) (2014) 131.

[7] Li, S.-S., Zou, X., Zhang, L., Jiang, L., Wang, L., Wang, A., Pan, W. and Yan, L., IEEE Photonics J., 14 (2) (2022) 1.

[8] Ikeda, K., Opt. Commun., 30 (2) (1979) 257.

[9] Rauf, K. and Yasir, M., Int. J. Comput. Commun. Eng., 2 (2) (2013) 97.

[10] Ibrahim, R.I., Al Naimee, K.A.M. and Yaseen, S.K., Baghdad Sci. J., 18 (1) (2021) 2411.

[11] Al-Naimee, K., Marino, F., Ciszak, M., Abdalah, S.F., Meucci, R. and Arecchi, F.T., Eur. Phys. J. D, 58 (2) (2010) 187.

[12] Younis, Y.T., Musa, S.K., Abdalah, S.F., Ahmed, A.K., Meucci, R. and Al Naimee, K.A., Results Phys., 6 (2016) 243.

[13] Annovazzi-Lodi, V., Benedetti, M., Merlo, S. and Norgia, M., Comptes Rendus Phys., 5 (6) (2004) 623.

[14] Baptista, M.S., Macau, E.E. and Grebogi, C., J. Nonlinear Sci., 13 (1) (2003) 145.

[15] Tronciu, V.Z., Mirasso, C.R., Colet, P., Hamacher, M., Benedetti, M., Vercesi, V. and Annovazzi-Lodi, V., IEEE J. Quantum Electron., 46 (12) (2010) 1840.

[16] Ohtsubo, J., "Semiconductor Lasers: Stability, Instability and Chaos", (Springer, 2012).

[17] Qamar, F., "Design & Analysis of Secure Optical Communication System with Advance Modulation Formats", (University of Engineering & Technology, Taxila, 2018).

[18] Al-Naimee, K., Marino, F., Ciszak, M., Meucci, R. and Arecchi, F.T., New J. Phys., 11 (7) (2009) 73022.

[19] Abdulrahman, W.S., Al Naimee, K.A. and Eisa, A.H., Int. J. Pure Appl. Sci. Technol., 31 (1) (2015) 6.

[20] Eisa, A H., Abdalah, S.F., Abdulrahman, W.S. and Naimee, K.A, Int. J. Innov. Technol. Res., 4 (46) (2016) 4842.