Kuwait J.Sci., Vol.50, No.(3B),July.2023,pp(1-14)

Enhancement of optical chaos generator using double delayed feedback

Raghad I. Ibrahim

Dept. of Physics, College of Education, Mustansiriyah University,
Baghdad-Iraq.

**Corresponding author: raghedismail@yahoo.com*

Abstract

Chaotic lasers are widely used in secure communication, optical detection and other applications due to their noise-like randomness, excellent anti-jamming and other advantages. This research looks into the chaotic laser's performance at a low cost. The performance related to a semiconductor laser with double delayed feedback is observed and its characteristics are determined in experimental research utilizing OptiSystem simulator. The chaotic laser output is fed back to the Mach-Zehnder modulator (MZM) to make the original system. The gain coefficient changes dynamically, and a second time delay is introduced into the system. The feedback time and feedback strength of the improved chaotic system are studied under varying input bias current, frequency and modulation beak current. Bifurcation diagram results show that the chaotic laser output by the optoelectronic oscillator (OEO) is more complex and has lower delay characteristics. This method does not increase too much Under the premise of system cost, more complex chaotic signals can be generated, and the signal delay characteristics can be reduced, which is conducive to improving the security of the communication system.

Keywords: Chaos generation; double delayed; Mach-Zehnder modulator (MZM); optisystem simulator; optoelectronic feedback.

1. Introduction

Lasers are sources of light with very special properties, for that reason, there is a great variety of laser applications (Kokaj *et al.*,2018; Noroozi *et al.,*2017). Many studies have been conducted to improve laser work and benefit from it in applications (Cheng *et al.*,2018). Chaotic laser secure communication has received widespread attention because of its high speed, hardware encryption, and compatibility with existing optical fiber communication systems. (Ekhande & Deshmukh, 2014; Oppenheim & Cuomo, 1999; Alvarez & Li, 2006). With possible applications in signal processing and communications, chaotic systems offer a significant approach for signal design and generation. Because of its sensitivity to the initial conditions, chaotic signals are often noise-like, broadband, and complicated to predict. The two states, which are initially extremely similar, become radically distinct following a given amount of time has passed. This makes it impossible to predict the system's form with great precision at random. (Pecora & Carroll, 1990).

The generation of laser chaos mainly includes light injection, optical feedback, optoelectronic feedback and non-linear device-based optoelectronic delay feedback (Chembo, *et al.*,2019).. Among them, the optoelectronic delay feedback method based on non-linear devices has a higher spectral bandwidth and a more flexible adjustment method. (Kovanis *et al.*,1995; Suárez-Vargas *et al.*,2012; Guangjian *et al.* ,2017).

An optoelectronic oscillator (OEO) based on a Mach-Zehnder modulator (MZM) is a common way to generate chaotic lasers (Al Khafaji & Al Naimee, 2017). This kind of OEO has the advantages of simple structure, flat frequency spectrum and wide bandwidth, so there are many related researches. Callan *et al.*,2010 pointed out that the broadband chaotic signal generated by OEO can be used in distributed sensor networks and chaos-based ranging equipment (Callan *et al.*,2010). With the continuous deepening of related research and the rapid development of computer technology, the complexity of this basic chaotic laser based on OEO is no longer sufficient to counter certain cracking methods for the system. For example, an eavesdropper can extract the chaotic time-delay characteristics through time series analysis, reconstruct the OEO system (Udaltsov *et al.*,2003; Udaltsov *et al.*,2005), So threaten the security of chaotic laser secure communication. Therefore, for the basic OEO chaotic generation system, many improvements have been proposed to increase the complexity of chaotic lasers, thereby improving the security of chaotic laser secure communication. For example, if two OEOs are cascaded together, the chaotic laser generated by the first-level OEO is injected into the MZM of the second-level OEO instead of the original constant-power laser, so that the chaotic laser parameters generated by the second-level OEO will dynamically change(Zhiliang & Lingfeng, 2013). Many works are based on performance analysis and security implementation of optical communication system based on advance modulation formats (Qamar *et al.*,2017).

This work deals with the chaos generation through semiconductor lasers with double delay feedback by using Optisystem software (Optisystem16 ,2019). The erbium-doped fiber amplifier (EDFA) is utilized for reinjecting the output laser into the MZM to generate a chaotic laser signal with dynamically changing parameters. The dynamic change of the OEO parameters is realized without adding too many devices, and an additional time delay is introduced. The system can achieve higher chaotic complexity, which conceals the time delay characteristics of chaotic signals to a certain extent and improves the practicability of the system. Different parameters are considered and simulated to see the impact of chaotic behavior produced through semiconductor lasers.

2. Theoretical Model

The chaotic system with double feedback scheme is shown in Figure 1. In figure1: LD is continuous light Laser; PD is a photodetector with a certain amplification effect; Frequency (RF) driver is used to drive the MZM modulator; OC1 and OC2 are couplers, the output of MZM is divided into two by OC2 Light, all the way through the PD and RF driver to the MZM optotoelectronic reflection Feedback. All the way through the EDFA to the MZM optical feedback, so that MZM produces chaotic laser output, and the output power is P_{out}.

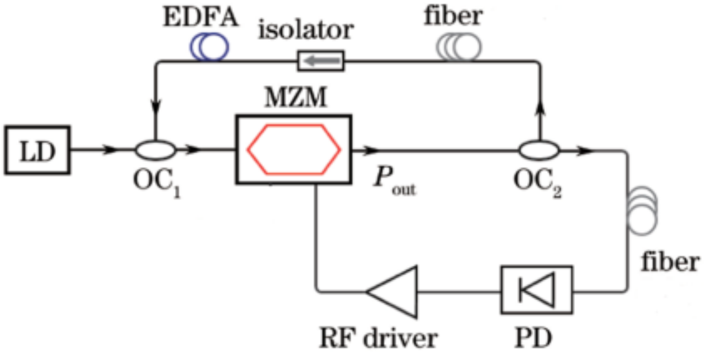


Fig. 1. Schematic diagram of the OEO chaotic system with double delay feedback

The output characteristic of the non-linear device MZM of the OEO chaotic system with double delay feedback is represented in equation (1):

$$P_{\text{out}} = P_{\text{in}} \cos^2\left[\frac{\pi V(t)}{2V_{\pi RF}} + \frac{\pi V_{\text{B}}}{2V_{\pi DC}}\right], \tag{1}$$

Where: P_{in} represents the input optical power; V (t) represents the load on MZM Modulation voltage; V_B is the bias voltage; $V_{\pi RF}$ represents the RF half-wave voltage; $V_{\pi DC}$ represents the bias half-wave voltage.

The original OEO system equation is:

$$\left(1+\frac{f_{\text{L}}}{f_{\text{H}}}\right)V(t) + \frac{1}{2\pi f_{\text{H}}}\frac{\text{d}}{\text{d}t}V(t) + 2\pi f_{\text{L}}\int_{t_0}^{t} V(t)\text{d}t = PgGA\frac{\pi}{2\text{V}_{\pi\text{RF}}}\cos^2\left[\frac{\pi V(t-T_1)}{2V_{\pi\text{RF}}} + \frac{\pi V_{\text{B}}}{2V_{\pi\text{DC}}}\right], \tag{2}$$

The formula: T_1 is the optoelectronic feedback delay time of the system itself; f_H and f_L are the high and low cut off frequencies of the band pass filter; A is the light of the entire system; g is the gain of the photodetector; G is the gain of the RF driver; P is the static power of the continuous light laser.

The chaotic time series output by OEO is $x(t) = \frac{\pi V(t)}{2V_{\pi RF}}$, Cut-off time $t_{\text{H}} = \frac{1}{2\pi f_{\text{H}}}$,When low pass is off time $t_{\text{L}} = \frac{1}{2\pi f_{\text{L}}}$, MZM phase $\phi = \frac{\pi V_{\text{B}}}{2V_{\pi\text{DC}}}$, Enter 2 Line normalization and ignoring the smaller terms, we can get the Ikeda equation (Kouomou,2005):

$$x(t)+t_{\mathrm{H}}\frac{\mathrm{d}}{\mathrm{d}t}x(t)+\frac{1}{t_{\mathrm{L}}}\int_{t_0}^{t}x(t)\mathrm{d}t=\beta_1\cos^2[x(t-T_1)+\phi] \tag{3}$$

Where the strength of the optoelectronic feedback gain $\beta_1=PgGA\frac{\pi}{2V_{\pi\mathrm{RF}}}$.Because of the delay time, The chaotic behavior generated by the system based on this equation has extremely high Attractor dimension, whose Lyapunov dimension can be reached under certain conditions 1,000 or more(Nguimdo, 2011).From equation (3), we can see that the chaotic output of OEO is

$$C_1(t)=P\cos^2[x(t)+\phi]$$

The chaotic light output at the output of the original optoelectronic oscillator is 3dB.The coupler is equally divided into two beams of light, one of which is amplified by EDFA. Then, it is coupled with the static fixed power laser emitted by the continuous laser, and then Enter the MZM for a second time to perform non-linear modulation and generate chaotic lasers. The delay time of the light path feedback is T_2, and the EDFA magnification is A_1,The improved system equation is

$$\begin{aligned}\left(1+\frac{f_{\mathrm{L}}}{f_{\mathrm{H}}}\right)V(t)+\frac{1}{2\pi f_{\mathrm{H}}}\frac{\mathrm{d}}{\mathrm{d}t}V(t)+2\pi f_{\mathrm{L}}\int_{t_0}^{t}V(t)\mathrm{d}t=&\\ [P+A_1C_1(t-T_2)]gGA\frac{\pi}{2V_{\pi RF}}\times&\\ \cos^2\left[\frac{\pi V(t-T_1)}{2V_{\pi\mathrm{RF}}}+\frac{\pi V_{\mathrm{B}}}{2V_{\pi\mathrm{DC}}}\right]&\end{aligned} \tag{5}$$

From (4) and (5), we can get

$$\begin{aligned}\left(1+\frac{f_{\mathrm{L}}}{f_{\mathrm{H}}}\right)V(t)+\frac{1}{2\pi f_{\mathrm{H}}}\frac{\mathrm{d}}{\mathrm{d}t}V(t)+2\pi f_{\mathrm{L}}\int_{t_0}^{t}V(t)\mathrm{d}t=&\\ PgGA\frac{\pi}{2V_{\pi\mathrm{RF}}}\cos^2\left[\frac{\pi V(t-T_1)}{2V_{\pi\mathrm{RF}}}+\frac{\pi V_{\mathrm{B}}}{2V_{\pi\mathrm{DC}}}\right]+&\\ \mathrm{PgGA}\frac{\pi}{2V_{\pi\mathrm{RF}}}\cos^2\left[\frac{\pi V(t-T_2)}{2V_{\pi\mathrm{RF}}}+\frac{\pi V_{\mathrm{B}}}{2V_{\pi\mathrm{DC}}}\right]\times&\\ gGAA_1\frac{\pi}{2V_{\pi\mathrm{RF}}}\cos^2\left[\frac{\pi V(t-T_1)}{2V_{\pi\mathrm{RF}}}+\frac{\pi V_{\mathrm{B}}}{2V_{\pi\mathrm{DC}}}\right]。&\end{aligned} \tag{6}$$

$\beta_2=gGAA_1\frac{\pi}{2V_{\pi\mathrm{RF}}}$ is the gain intensity of the optical path feedback. The hysteresis differential equation of the double-delay system is Derived(Juan *et al.*,2016):

$$\begin{aligned}x(t)+t_{\mathrm{H}}\frac{\mathrm{d}}{\mathrm{d}t}x(t)+\frac{1}{t_{\mathrm{L}}}\int_{t_0}^{t}x(t)\mathrm{d}t=&\\ \beta_1\cos^2[x(t-T_1)+\phi]\times&\\ \{1+\beta_2\cos^2[x(t-T_2)+\phi]\}_0&\end{aligned} \tag{7}$$

To facilitate numerical simulation, let $y(t) = \int x(s)\mathrm{d}s$. The output OEO characteristic is Improved by differential equation (8):

$$\begin{cases} \frac{\mathrm{d}x(t)}{\mathrm{d}t} = -\frac{1}{t_{\mathrm{H}}}\left\{x(t) + \frac{1}{t_{\mathrm{L}}}y(t) - \beta_1 \cos^2[x(t-T_1)+\phi]\{1+\beta_2\cos^2[x(t-T_2)+\phi]\}\right\} \\ \frac{\mathrm{d}y(t)}{\mathrm{d}t} = x(t) \end{cases} \tag{8}$$

This equation discuss the chaotic behavior caused by the two delay times and gain coefficients in the system. The influence of signal dynamics for communication systems, unpredictable, therefore, it is necessary to enhance the chaotic carrier signal.

3. Experimental Model

OptiSystem 16 software is used for developing and simulating an optical chaos generating circuit with double delay feedback. In addition, OptiSystem can be defined as a software package for optical communication devices that allows users to create, test, and simulate optical links in advanced optical networks' transmission layer. The suggested approach's simulated circuit design, where built-in components have been utilized with suitable specifications, is shown in Figure 2. It is made up of an SL, MZM, amplifier and photo-detector (PD). The MZM can be defined as a device which is utilized for the determination of the relative phase shifting between two collimated beams from coherent source of the light either through changing the length of one of the arms or through placing a sample in one of beams' paths. MZM includes two input and two output ports. A fundamental MZM is constructed with the use of two couplers, one of them at input, which plays the role of a splitter and the other one is at output, acting like combiner.

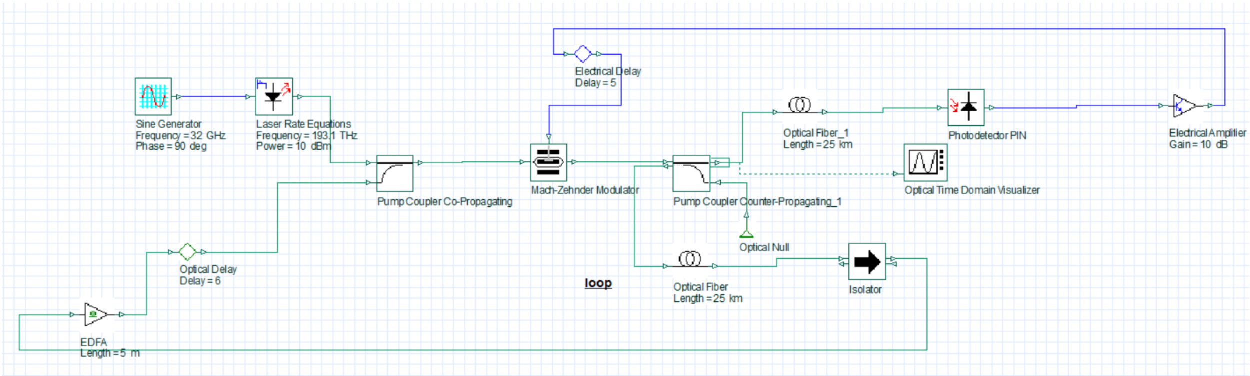


Fig. 2. Block diagram of the OEO chaotic system with double feedback by using OptiSystem.

In Figure 2, Light is split in two interferometer arms by input coupler and re-combined at output-by-output coupler. The coupler is equally divided into two beams of light, one of which is amplified by EDFA. Then, it is coupled with the static fixed power laser emitted by the continuous laser, and then Enter the MZM for a second time to perform non-linear modulation and generate chaotic lasers. The other one is from MZM then into the PD for the purpose of converting optical signal into electrical signal, the photodetector is coupled to the amplifier then to the feedback arm (MZM). The length of the optical path of two arms is not equal, which makes phase shift that corresponds to the delay be a wave-length function of input signal. OEFB's chaotic behavior has been researched under impacts of MZM bias voltage.

The output of the optoelectronic oscillator is feedback to the MZM through a delayed optical path, So that the gain coefficient of the original OEO is dynamically changed, and an additional time delay is introduced to the system to make the system output a more complex chaotic laser signal. The above characteristics are conducive to building a chaotic secure communication system with higher security.

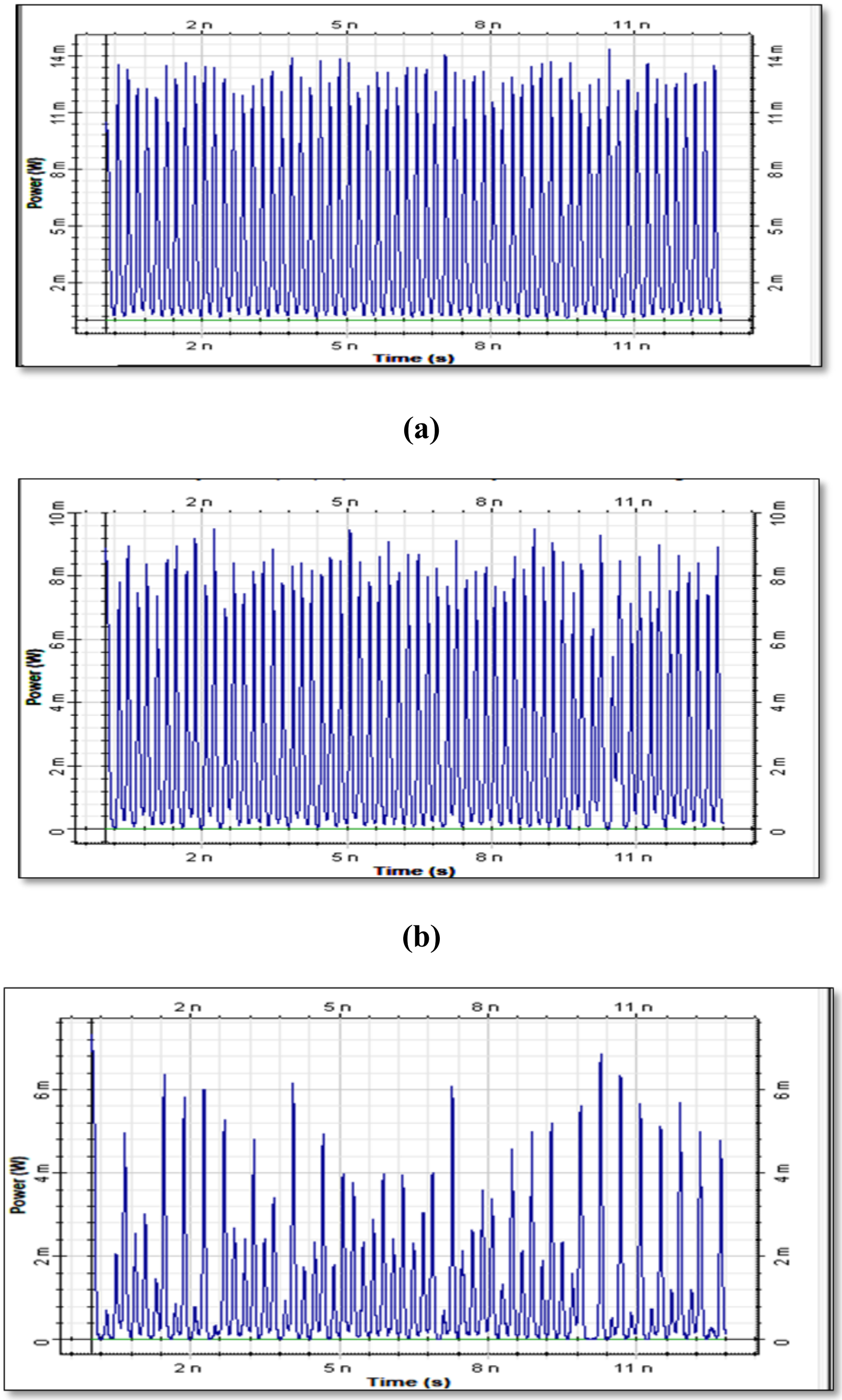
Different parameters are considered to see the impact of chaotic behavior produced through semiconductor lasers. Chaotic laser has been controlled under varying input bias current, frequency and modulation beak current as follow.

3.1 Changing Bias Current (Route of Quasi-Periodic & Chaos)

Parameters of semiconductor lasers to generate chaos are given in Table 1. Quasi periodic behavior of chaotic pulses can be observed when the Modulation peak current is fixed at 40 mA. Bias current is varied from 70 mA to 36 mA, route from quasi-periodic to chaos can be observed in Figure. 3(a,b,c). The span of each bunch is approximately equal to 1 ns. After 1 ns, new bunch of chaotic pulses starts. With the rise in bias current, the frequency of Bunches increase, which overlapped with each other giving rise to chaotic route.

Table 1. Semiconductor Laser Parameters (with different bias current)

Parameter Name	Value	Parameter Name Value Unit
Wavelength	1550	nm
Power	10	dBm
Bias current	36-70	mA
Threshold power	0.0154	mW
Power (at bias current)	0	dBm
Modulation peak current	40	mA
Threshold current	33.46	mA



(a)

(b)

(c)

Fig. 3. Semiconductor laser output at bias current (a)- 60 mA, (b)-50 mA, (c)- 40mA.

With the decrease in value of bias current, clear variation in amplitude of pulses can be observed in Figure. 3(a,b,c) in which many low amplitude pulses are followed by high amplitude pulses. that is mean, chaotic behavior increased.

The bifurcation diagram, shown in Figure 4, summarizes the scenario that leads to chaotic behavior. The bifurcation diagram shows the intensity related to laser output (peak-to-peak) with the modification of control parameter (bias current of laser source). Within the steady increase (2mA) in the control parameter (bias current), the bifurcation diagram is established.

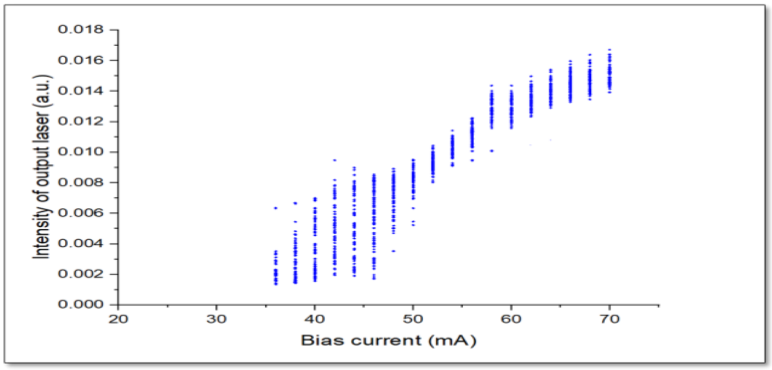


Fig. 4. Bifurcation diagram for the variation of bias current.

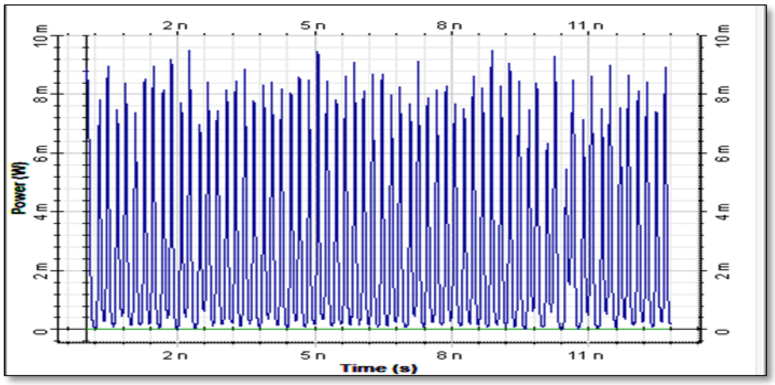
The bifurcation diagram is explained the region from (35-70) mA, as follows: At the beginning, the first region from (35-50) mA, will demonstrates the chaotic oscillation. Gradually increasing the bias current, the quasi- periodic behavior begins to appear. there is the presence of some points in the diagram which indicated to a stable equilibrium, therefore the dynamics of SL is in the form of quasi- periodic motion at (52-70) mA. This mean that, the variation in the bias current led the system to change from chaos at (35-50) mA to quasi periodic at (52-70) mA.

3.2 Changing Modulation Peak Current (High Amplitude Pulses)

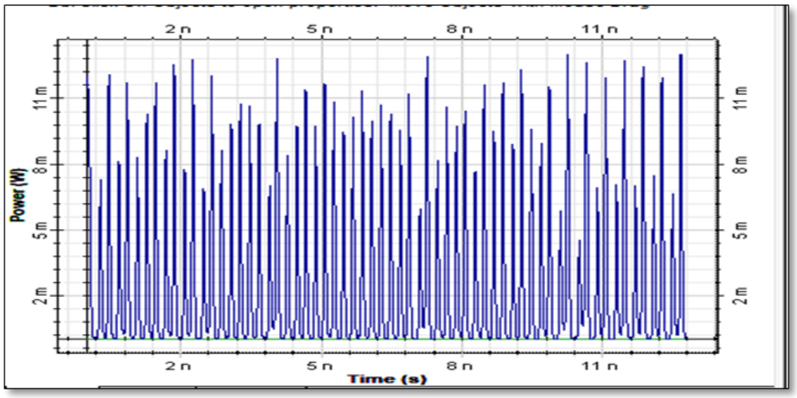
Table 2 shows the parameters to generate chaotic behavior through semiconductor lasers with variations in Modulation peak current. Keeping the bias current 50mA, Modulation peak current is changed from 30 mA to 105 mA. At low Modulation peak current, amplitude of generated pulses is extremely low which not only deviate these pulses from chaotic behavior but also of no use for any suitable fiber length. With the increase in value of Modulation peak current, clear variation in amplitude of pulses can be observed in Figure.5(a,b,c) in which many low amplitude pulses are followed by high amplitude pulses.

Table 2. Semiconductor Laser Parameters (with different modulation peak current)

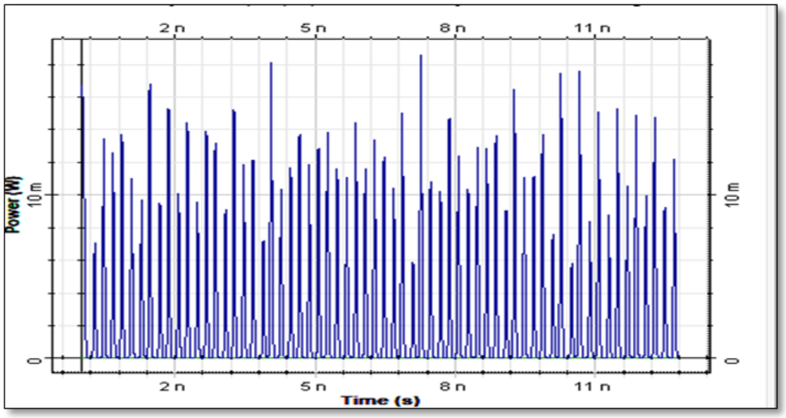
Parameter Name	Value	Parameter Name Value Unit
Wavelength	1550	nm
Power	10	dBm
Bias current	50	mA
Threshold power	0.123	mW
Power (at bias current)	0	dBm
Modulation peak current	30-105	mA
Threshold current	33.46	mA



(a)



(b)



(c)

Fig. 5. Semiconductor laser output at modulation peak current (a) 40 mA,(b) 70 mA,(c) 80 mA.

With the increase in value of modulation peak current, clear variation in amplitude of pulses can be observed in Figure. 5(a,b,c) in which many low amplitude pulses are followed by high amplitude pulses, that is mean, chaotic behavior increased.

The ideal amount of increment and frequency of amplitude are connected to the regularity of a non-linear dynamic system, the shift from a quasi-periodic to a chaotic state is depicted. In addition, the bifurcation diagram is used for checking the chaotic routes as well as evolutions of output in non-linear systems as a function of control parameter variations. The bifurcation diagram, Another important characteristic of chaos is the transition among different dynamical states (steady state, periodic, and chaotic sequences), referred to as "bifurcation". A definition of bifurcation mathematically is the qualitative change in a phase portrait under the variation of parameters. A chaos idea and how it occurs in a system can be imagined by the diagram of bifurcation. Figure 6 shows a bifurcation diagram for various modulation peak currents.

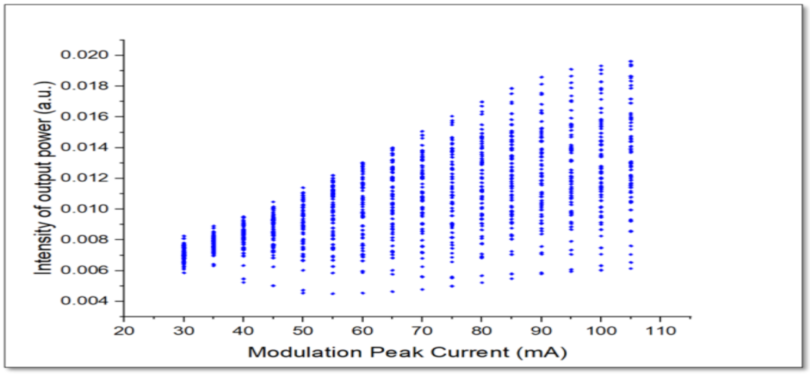


Fig. 6. Bifurcation diagram with various modulation peak current.

This figure shows these values of modulation peak current led the system to change from Quasi-Periodic at (30-64) mA and to chaos at (65-105) mA. The results show that the modulation peak current might be considered a parameter at an ideal frequency (5 GHz) that controls the system's collective dynamics, and that the varied amplitudes were used to regulate the chaotic system from quasi periodic to chaos, and after that to periodic. bifurcation diagram

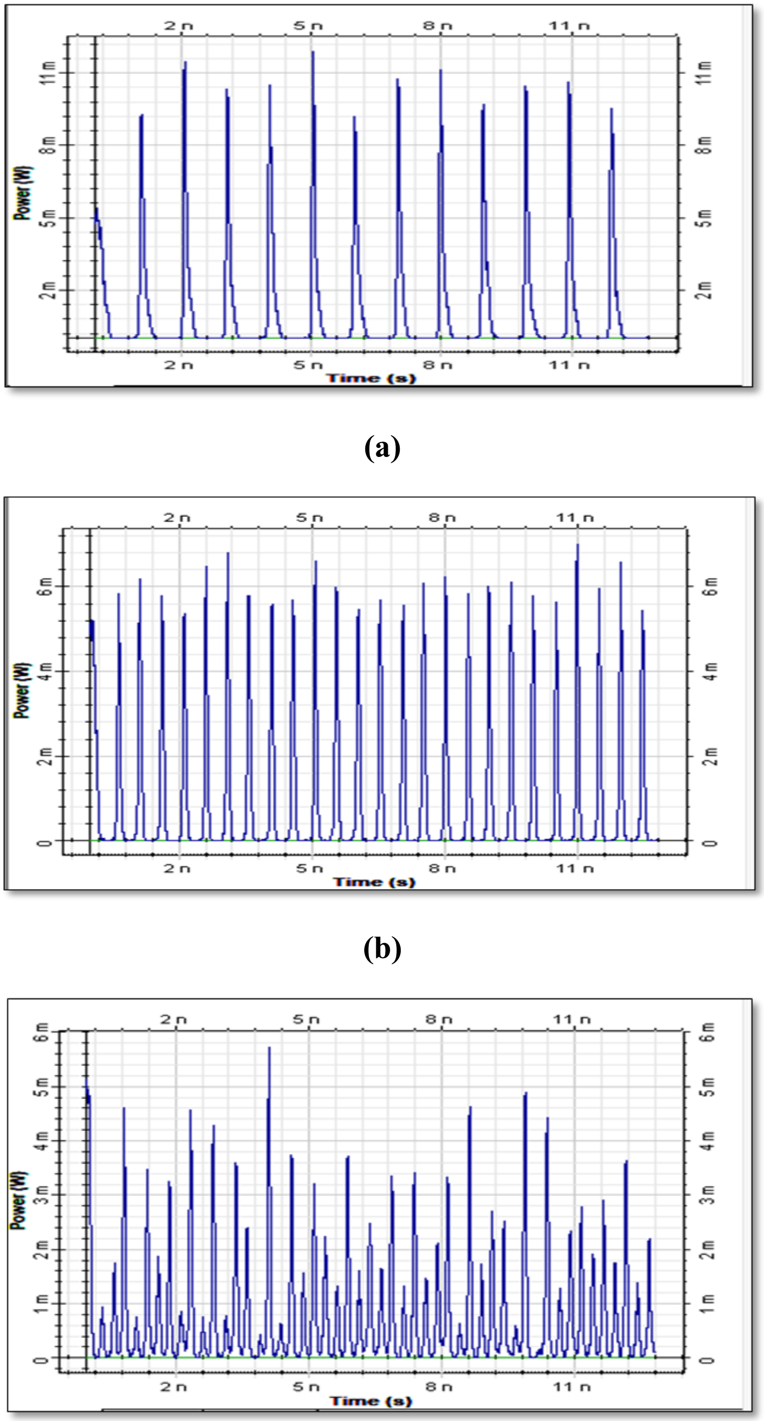
3. 3 Changing Frequency of Current Source (Random Amplitude Pulses)

Suitable pumping power or current is required to achieve the chaotic nature of pulses. At low frequency of current source when the strength of electric field is not very high, pulses of same amplitude are observed. Increasing the frequency results in the variation of amplitude of pulses due to increase in field strength. The modulation peak current and bias current have been fixed at 28mA and 38mA sequentially. Table 3 shows the parameters of current source applied for external modulation by setting the frequencies from 0.75 to 8 GHz.

Table 3. Current Source Parameters (with different frequencies)

Parameter	Name Value	Unit
Frequency	0.75-8	GHz
Amplitude	1	a.u.
Phase	90	Deg
Bias	0	a.u.

Figure.7(a,b,c) are the outputs of semiconductor lasers in response to change the frequency of the current source. These values of frequencies led the system to change from Quasi-Periodic to chaos.



(a)

(b)

(c)

Fig. 7. Semiconductor laser output at frequency of current source (a) 2 GHz,(b) 3GHz,(c) 4 GHz.

In the Figure .7(c), 'Gain Quenching' which is one of the properties of chaotic pulses can be observed in which few pulses of high amplitude are immediately followed by pulses of very low amplitude. The pulses produced in this way are Gaussian in nature and can be checked by applying Gaussian Fit. External frequency modulation is an important method to control chaos. The bifurcation is shown in Figure 8, summarizes the frequency modulation utilized to the source through a function generator.

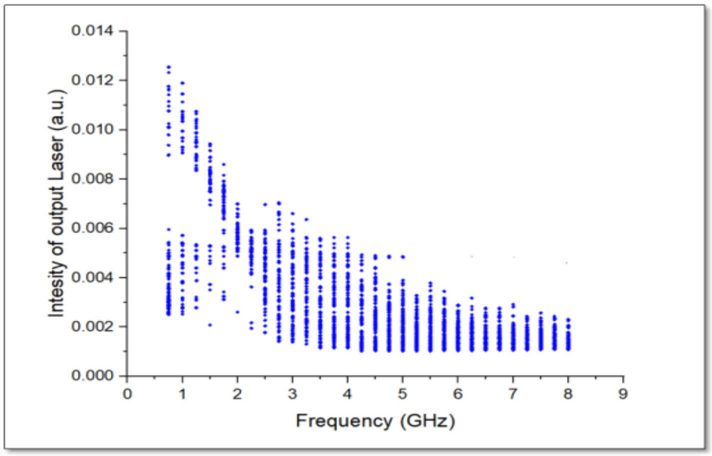


Fig. 8. Bifurcation diagram with different frequency modulation.

The findings suggest that frequency modulation can be used as a control parameter for the system's collective dynamics. The chaotic system has been controlled at several frequencies, ranging from quasi periodic at (0.5-2.5) GHz to chaos at (2.75-4.75) GHz, and ultimately periodic at (5-8) GHz. As a result, highly intriguing outcomes were found when frequency is added to chaotic systems.

4. Conclusion

In this work, the chaotic behavior produced through semiconductor laser by using double delay feedback is studied. The output of the OEO is feedback to the MZM through a delayed optical path, so that the gain coefficient of the original OEO is dynamically changed, and an additional time delay is introduced to the system to make the system output a more complex chaotic laser signal. The above characteristics are conducive to building a chaotic secure communication system with higher security. Moreover, by adding a light path feedback delay, the parameter interval that could not produce chaos also enters chaos, the path into chaos increases, and the practicability of the system is improved. The results show that semiconductor laser and their effect on chaos are observed and controlled by varying different parameters such as bias current, modulation beak current and frequency. These parameters are adjusted and optimized to produce useful chaos to be utilized as carrier to hide high data rate message for long distance communication. However, this method additionally introduces another set of oscillator structure, which is complex and has many restrictions and is difficult to popularize and apply.

ACKNOWLEDGMENTS

The author would like to thank Mustansiriyah University(www.uomustansiriyah.edu.iq) Baghdad-Iraq for its support in the present work.

References

Al Khafaji, R.K. and Al Naimee, K.A. (2017). Chaos Modulation by Mach-Zehnder Interferometer, International Journal of Engineering Research & Science (IJOER),3(1), 15-23.

Alvarez, G. and Li, S. (2006). Some basic cryptographic requirements for chaos-based cryptosystems. International journal of bifurcation and chaos, *16*(08), 2129-2151.

Callan, K.E., Illing, L., Gao, Z., Gauthier, D.J. and Schöll, E. (2010). Broadband chaos generated by an optoelectronic oscillator. Physical review letters, 104(11), 113901.

Chembo, Y. K., Brunner, D., Jacquot, M., & Larger, L. (2019). Optoelectronic oscillators with time-delayed feedback. Reviews of Modern Physics, 91(3), 035006.

Cheng, X., Xu, F., Shang, J. and Li, C.(2018). A study on the amplification of active-mirror Yb: YAG lasers. Kuwait Journal of Science, 45(4).

Ekhande, R. and Deshmukh, S. (2014). Chaotic signal for signal masking in digital communications. International organization of Scientific Research Journal of Engineering, 4(2), 29-33.

Guangjian, Z., Baofu,Z., Chengxin,L. & Yichao,T. (2017) .Chaotic photonic compressed sampling based on optoelectronic oscillator , Chinese Journal of Lasers , 44(11):1106002.

Juan, Y., Wei, P., Nian-Qiang, L., Li-Yue, Z. and Qing-Xi, L. (2016). Two broadband chaotic signals generated simultaneously by semiconductor ring laser with parallel chaotic injection. ACTA PHYSICA SINICA, 65(20).

Kokaj, J., Shuaib, A., Makdisi, Y., Nair, R. and Mathew, J. (2018). Femtosecond laser based deposition of nanoparticles on a thin film and its characterization. Kuwait Journal of Science, 45(4).

Kouomou, Y.C., Colet, P., Larger, L. and Gastaud, N. (2005). Chaotic breathers in delayed electro-optical systems. Physical review letters, 95(20), 203903.

Kovanis, V., Gavrielides, A., Simpson, T.B. and Liu, J.M. (1995). Instabilities and chaos in optically injected semiconductor lasers. Applied physics letters, 67(19), 2780-2782.

Nguimdo, R.M. (2011). Chaos and synchronization in opto-electronic devices with delayed feedback.

Noroozi, M.J., Saedodin, S. and Ganji, D.D.,(2017). A new approximate-analytical method to solve non-Fourier heat conduction problems. Kuwait Journal of Science, 44(2).

Oppenheim, A.V. and Cuomo, K.M. (1999). "Chaotic Signals and Signal Processing" Digital Signal Processing Handbook Ed. Vijay K. Madisetti and Douglas B. Williams Boca Raton: CRC Press LLC.

Optisystem 16 [Computer software]. (2019). Retrieved from www.optiwave.com.

Pecora, L. M., & Carroll, T. L. (1990). Synchronization in chaotic systems. Physical review letters, 64(8), 821.

Qamar, F., Islam, M. K., Shah, S. Z. A., Farhan, R., & Ali, M. (2017). Secure duobinary signal transmission in optical communication networks for high performance & reliability. IEEE Access, 5, 17795-17802.

Suárez-Vargas, J.J., Márquez, B.A. and González, J.A. (2012). Highly complex optical signal generation using electro-optical systems with non-linear, non-invertible transmission functions. Applied Physics Letters, 101(7), 071115.

Udaltsov, V.S., Goedgebuer, J.P., Larger, L., Cuenot, J.B., Levy, P. and Rhodes, W.T. (2003). Cracking chaos-based encryption systems ruled by nonlinear time delay differential equations. Physics Letters A, 308(1), 54-60.

Udaltsov, V.S., Larger, L., Goedgebuer, J.P., Locquet, A. and Citrin, D.S. (2005). Time delay identification in chaotic cryptosystems ruled by delay-differential equations. Journal of optical technology, 72(5), 373-377.

Zhiliang, H.H.S.W.Y. and Lingfeng, L. (2013). Chaos Generation of Variable Parameters and Secure Communication Based on Optoelectronic Feedback Oscillation [J]. Acta Optica Sinica, 5.

Submitted: 14/11/2021
Revised: 04/01/2022
Accepted: 05/01/2022
DOI: 10.48129/kjs.17025