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ADVANCE AND DEVELOPMENT OF CHAOTIC OPTICAL COMMUNICATIONS: A REVIEW

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ABSTRACT

The chaotic optical communication system is a new communication system that uses optical chaotic waveform to transition the data at a high bit rate. Its probable applications include secure communications and wideband communications. The semiconductor lasers are well suited for chaotic optical communications systems because the internal laser oscillation is easy to interfere with a field of optical injection or optical feedback. Chaotic optical communication is a hopeful technique for improving the privacy and security of communications networks. It uses synchronized chaotic emitters and receiver lasers for encoding and decoding the data at the hardware level. High-speed communication has made extensive use of optical communications reliant on semiconductor lasers, which are known for their wide spectrum, low power consumption, and no constraints of electromagnetic spectrum. With the chaotic optical communication's present development phase. In this paper, we review the basic technology of chaotic optical communication and research progress. We will first look at several component-based nonlinear strategies for creating chaos. Next, we focus on enhancing security, developing chaotic optical communication transmission capacity, optical chaotic synchronization, and broadband chaotic communication. We conclude by discussing the obstacles and opportunities of chaotic optical communications.

KEYWORDS

Broadband chaos, Chaotic optical, Synchronization, Security, TDS concealment.

1. INTRODUCTION

The efficiency of the laser is emphasized in the show of important advances. A method of product of efficiencies is developed and applied to define laser performance. In the very early phases of laser development, erratic pulses and Dynamic instability started to appear from the laser. It was stated that the amplitudes of the pulses produced by a ruby solid-state laser were reported to contain pulses whose amplitudes "vary randomly". The estimation of threshold and slope efficiency is then done using efficiency factors, making it simple to assess performance (Blom and Widengren, 2017). In 1960, Maiman1 performed the first laser demonstration. A sapphire crystal that had been slightly doped with trivalent chromium ions known as a "pink" ruby was the active gain element (Krupke and Zweiback, 2020). The architecture and functionality of a ruby laser pumped by a laser diode are described. A 0.05% doped ruby crystal measuring 5 mm in length is housed inside a hemispherical laser resonator to form the laser. Up to 320 mW of pump power was supplied by a single mode gallium nitride laser diode that operated at 405 nm. When Lorenz3 discovered sensitivity to beginning conditions in the 1963 proposed the idea of chaos it marked a dramatic shift in the field and became known as the "butterfly effect." (Blom and Widengren, 2017). However, ever since, lasers and chaos have been developed separately for a very long period. Haken was the first to identify the link between chaos and lasers up until 1975 (Hutt and Haken, 2020). The semiconductor laser displays a broad range of dynamic characteristics, such as chaotic states, multimode states, period states, linewidth narrowing states, and so on, when subjected to external disturbances like optical injection and feedback. The chaotic condition makes chaotic lasers helpful for information and measurement applications due to its randomness and wide spectrum (Li, X., et al., 2021). Steady, accurate synchronization of the information transmitter and receiver (or set of receivers) is a prerequisite for the steady operation of chaotic systems. First proposed in 1990, controlling and synchronizing chaos expanded the uses of chaos, including safe key distribution, random number generation, and chaotic optical communications (Kurskoy, Yu., et al., 2021). Furthermore, during the past 30 years, nonlinear delay dynamics has been a particularly prominent study topic in the field of photonic systems. Several laser model hypotheses were proposed to explain the experimental results, and various experiments were carried out to examine the dynamics of chaotic lasers (Malica, T., 2022). It is easy to collect information about a time delay signature (TDS) thanks to bandwidth of the chaotic laser produced by semiconductor laser with optical feedback, which is restricted to relaxation oscillation frequency and autocorrelation curve. In addition, a system is huge and made up of a divided semiconductor laser, disordered components, and other functioning parts. It is needed to have a chaos laser with a broad spectrum, suppressed TDS, and integrated system (Chen, J. et al., 2018;Mu et al., 2019). Based on the various optical components' nonlinear dynamics, it is possible to categorize the methods used to create chaos. These techniques include electro-optic feedback depends on the non-linear dynamics of Mach-Zehnder modulators, opto-electronic feedback depends on nonlinear dynamics of the semiconductor laser, and all-optical feedback. Because electro-optic components have a broad bandwidth, the electro-optic feedback is more likely to be employed in high-speed chaotic optical communication (Chengui et al., 2020;Datta et al., 2021). High-precision distributed measurement technology is far-reaching and primarily consists of the chaotic Brillouin optical correlation domain analysis (chaotic BOCDA) and chaotic optical time domain reflectometer (chaotic OTDR), which is a noteworthy application for the chaotic laser (Hu et al., 2019;Zhang et al., 2021). Since then, studies have concentrated on raising the security level, synchronization quality, and transmission speed of chaotic optical communications. On the other hand, a different method of enhancing security involves making chaotic systems more complex. For practical applications, improving the chaotic optical communications' transmission capacity and range becomes increasingly crucial after security challenges are resolved (Liu et al., 2022;Gao, Wu et al., 2022). This paper's contents are arranged as follows: After introducing many techniques for creating chaos and classifying them according to the nonlinear dynamics of various optical components, we offer a summary of the important technologies that may be used to increase security. Next, we provide various techniques for creating broadband chaos. Finally, we go over the limitations and points of view of chaotic optical communications before offering a conclusion.

2. OVERVIEW OF CHAOTIC OPTICAL COMMUNICATION DEVELOPMENT

A laser wireless communication channel model is using the benefit of laser communication in space and a complete analysis of impact of the complex environment on signal transmission. A space laser communication-based optical chaotic secure algorithm has been developed (Guo and Song, 2019). Depending on this, the hybrid self-synchronization chaotic system model is proposed. It can drastically cut down on the amount of data that needs to be transmitted and only requires small amount of error correction signals to be sent over the channel to synchronize the receiving and transmitting systems. This considerably mitigates the disadvantage of the conventional technique. The erbium doped fiber laser is utilized for information transmission based on chaotic synchronization. To accomplish optical chaotic secure communication with the permitted error margin, many encryption algorithms are applied. The suggested algorithm can realize secure communication for various signals, according to the findings of numerical simulation. It also has strong security and robustness.

Wideband chaos synchronization is achieved in the digital world by learning the intricate non-linear model of a chaotic transmitter utilizing a deep learning-based method, where the neural network technology is based on deep learning to the chaotic communication system for first time in 2019 (Ke et al., 2019). As a result, it is possible to greatly simplify the chaotic receiver while maintaining security. Over a 20 km fiber link, successful 32 Gb/s message transmission concealed in the wideband chaotic optical carrier was experimentally demonstrated. High speed chaotic optical communication systems and networks can now go in a new direction thanks to the suggested deep learning based chaos synchronization approach.

A minimum shift key (MSK) space-based chaotic optical communications system can benefit from the addition of DOE by having less of a need for transmission power or receiving diameter. Therefore, it must be studied the influence of (DOE) on (BER) performance in MSK space uplink chaotic optical communication (Li, M. et al., 2020). At a transmitting terminal (Tx), two diffractive optical elements (DOEs) are included to reduce bit error rate (BER) of space-based chaotic optical communications systems. This is because the center portion of the transmission beam is blocked by the typically employed reflective optical antenna at Tx, which results in significant power consumption. They further analyze the impact of the (DOEs) using the model by comparing the BER relationship to fundamental system parameters using the BER model. This will enable a higher bit rate and wider zenith angle range while still maintaining a good BER performance.

Chaos laser are widely used in the fields of optical sensing, random number generation, and secure communication. They are regarded as unique signal sources (Zhang and Wang, 2020). Generated chaotic light using erbium doped fiber ring laser (EDFRL) with the wavelength of 1.53 micrometers. Binary messages are embedded in a chaotically behaving laser wave which is transmitted through a fiber-optic cable and are decoded at the receiver using a second laser synchronized with the emitter laser. Thus, veiled information at high bandwidths can be sent via chaotic optical waves. The optical carrier wave produced by chaotic laser was used for encoding the message and its transmission of more than (120) km of optical fiber in the Athens, Greece, metropolitan area network. The message is decoded by using a suitable second laser, which synchronizes with chaotic carrier to allow the carrier and the message to be separated.

As a technique to increase the security of chaotic communication, for first time, the secret key for secure chaotic communications that does not depend solely on hardware singularity is assumed to exist in the feedback phase of the chaotic system made up of the semiconductor laser subject to delayed optical feedback (Jiang, N. et al., 2020). This characteristic allows users to separately and privately construct a real random seed key through symmetric post-processing. By using bit-error-rate calculations, it is possible to statistically quantify an eavesdropper's capacity to intercept an intensity-modulated message when the transmitter is subjected to pseudo-random variation for the feedback phase. An analysis shows that even if the eavesdropper possesses the same chaotic device, he cannot synchronize and, consequently, extract the message when it is unaware of the phase changes. Finally, a key provides an evaluation of the system's security in of terms the theory of computation complexity, enabling simple comparison with traditional encryption algorithms.

Secure communication, random number creation, and optical sensing have all placed a high value on the chaotic laser produced by semiconductor lasers. It used an approach to generate a wideband chaotic signal using incoherent delayed self interference for the chaotic light from semiconductor laser coupled together with optical feedback, and it produced the smoother power spectrum and the wider effective bandwidth of chaos (Wei, X. et al., 2022). The findings demonstrate that the delayed self interference can flatten and broaden the power spectrum by removing the dominance of laser relaxation oscillation that exists in chaotic laser light. Furthermore, increases a probability distribution's symmetry via multiple magnitudes and reduces the time delay signature caused by external cavity modes.

The blind polarisation tracking chaotic decryption system was proposed (Jiang et al., 2021). Where a 112 Gbit/s message is encrypted using CMS to transmit over 1040 km single mode fiber using optical chaotic carrier generated by the optoelectronic oscillator. Blind decryption and coherent detection methods that can effectively discern between a message and a chaotic carrier with bit error rate (BER) less than the threshold of forward error correction (FEC) are combined to correctly decrypt the message. According to experimental findings, coherent detection paired with digital signal processing methods may one day help to advance chaotic optical communication in the future.

By using super orthogonal optical chaos signals (Chen et al., 2022). The two-dimensional super orthogonal electro-optic and time-delayed chaotic system as a basis for analog spread spectrum secure communication system is implemented. Two signals are coupled in a channel one at a time, depending on the binary symbol that will transmitted. The technique exhibits remarkable antinoise performance, supported by numerical simulations, via taking use of broad-spectrum and the superorthogonal properties for two chaotic optical signals. By adding modification signal time delay feedback, the system's security can be increased. A system can fend off return map attacks and time-delay signature extraction, which are built-in weaknesses of chaotic shift keying and time-delayed chaotic systems.

Chaotic dynamics in optomechanical systems are the focus of a study on cavity optomechanical chaos (Zhu et al., 2023). As a result of radiation pressure coupling between its optical and mechanical modes, cavity optomechanics offers a strong platform for studying numerous fascinating classical and quantum nonlinear interesting. Opto-mechanical nonlinearity has drawn a lot of attention because of its importance in fundamental physics as well as potential applications ranging from optical communications to secret information processing. Both fundamentals of chaos and the basic theory of broad nonlinear dynamics are introduced. Optomechanical systems are used to illustrate several nonlinear dynamical processes. Additionally, the manipulation of opto-mechanical chaotic motions by recent outstanding theoretical and practical attempts is reviewed.

Developed a novel plan in chaotic optical communication by introducing a wavelength hopping technology that depends on tunable lasers to increase the security of conventional chaos laser communication systems (Li, M. et al., 2023). In the novel approach, it's challenging for an eavesdropper to intercept information and forecast which wavelength a hopping terminal would hop to due to jumping of the wavelength and pseudo randomness of a wavelength hopping sequence. According to the outcomes of the numerical simulation, eavesdropping has an average bit error rate that is roughly 5 times higher than when worked properly. It implies implementing wavelength-hopping technology can improve system secrecy and raise the complexity of message decoding. A high level of secrecy may be realized in the design of chaotic laser communication system by using this scheme.

Detailed bifurcation analysis and chaotic behavior analysis of the nonlinear fiber the concatenated model, as well as the building of soliton and periodic solutions, are methods to improve the security of chaotic communication (Han, T. et al., 2024). Using a periodically disturbed system, time series analysis, Poincaré sections, and bifurcation diagrams are used to analyze the chaotic behavior of the system. where the level curves of the Hamiltonian system are integrated to create kink wave, periodic, and solitary wave solutions. Further understanding into the dynamics of the model are obtained by deriving Jacobian elliptic functions and singular periodic solutions. Our knowledge of the behavior of optical solitons in various fiber types can also be expanded by applying this model to birefringent or high dispersion fibers.

3. ENHANCEMENT OF CHAOTIC OPTICAL COMMUNICATION

Since the initial chaotic optical communications field demonstration in 2005, research has been focused on increasing the speed of transmission and the quality of chaotic synchronization. Chaotic security is becoming increasingly important as individuals have realized that chaotic optical communications are not as safe as they formerly thought. Increasing chaotic optical communications' transmission capacity and range becomes increasingly crucial for practical applications once the security issue has been resolved. Presented numerical analysis of a modified electrooptical system that enhanced the potential for chaotic encryption via merging the all-optical and electro-optical chaos generators, producing optical chaos in both phase and intensity (Hu H. et al., 2017). It is demonstrated that the synchronization is highly sensitive to the delay mismatch and that the sender's feedback delay time can be effectively masked, making it impossible for an eavesdropper to replicate the system.

The impact of hybrid optical/electrooptic feedback methods using conventional, phase-conjugate, or grating mirrors is assessed in a secure communications system using chaotic nanolaser (Elsonbaty, A., et al., 2018). Using two or more semiconductor laser (SL) sources or two independent polarization components of a single vertical cavity surface-emitting laser (VCSEL), the suggested hybrid optical/electrooptic feedback scheme can simultaneously suppress the TD signature in both intensity and phase of the chaotic emission at specific operation regions as in Eq.1.

$$C(\Delta t) = \frac{[\rho(t+\Delta t) - \langle \rho(t+\Delta t)\rangle][\rho(t) - \langle \rho(t)\rangle]}{\langle [\rho(t+\Delta t) - \langle \rho(t+\Delta t)\rangle]^2 \rangle^{\frac{1}{2}} \langle [\rho(t) - \langle \rho(t)\rangle]^2 \rangle^{\frac{1}{2}}} \quad (1)$$

where $\rho(t)$ is either the intensity I (t) or the phase $\varphi(t)$, $\langle\rangle$denotes the average of time series, and Δt is the time lag which is taken at 25 ps steps in numerical simulations. As shown in Fig.1. Additionally, it is discovered that the hybrid feedback maintains the unpredictability and randomness in the optical chaos emission as well as the complexity of the chaotic nanolaser's dynamical behavior.

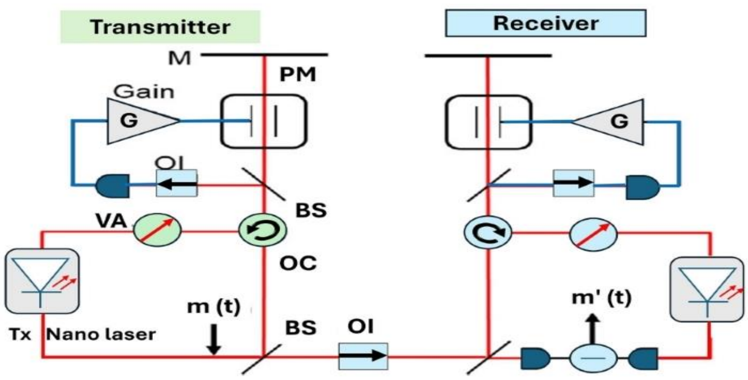

Fig. 1. Additive chaotic modulation-based communication system schematic (Elsonbaty et al., 2018)

A chaotic system has relied upon the nonlinear coupling of two late overlapping branches shown in Fig. 2. The system's feedback loop contains two delay branches and a Mach-Zehnder modulator (Wang et al., 2018). To lessen temporal correlations, chaotic voltages produced by two branches are nonlinearly transformed. The permutation entropy and the bifurcation diagram, respectively, are used to assess a complexity and dynamic properties of a created chaotic signal. Additionally, the simulation findings demonstrate that time delay signature may be efficiently hidden with the smaller feedback gain, the dynamical features can be described by the integral-differential delay equation as shown in Eq.2.

$$x(t)+\tau.\frac{dx(t)}{dt}+\frac{1}{\theta}\int_{t_0}^{t}x(s)ds=\beta\cos^2\left[x(t-T)-x(t-T-\delta T)+\phi_0\right] \quad (2)$$

while the key space is significantly expanded due to the nonlinear coupling of more adjustable factors, resulting in a significant increase in security.

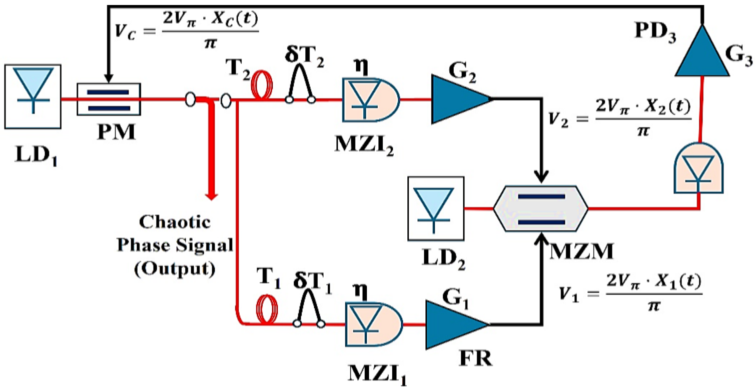

Fig. 2. The chaotic system for the feedback phase of security-enhanced EO (Wang et al., 2018)

Using atmospheric data for wind velocity, the impact of wavelength transmission was statistically examined with regard to optical communications in free space (Olukanni, E., et al., 2019). by analyzing the signal-to-noise ratio, log irradiance variance, and Rytov variance. Additionally, scintillation attenuation was computed for wavelengths of 780 nm, 850 nm, 1250 nm, and 1550 nm using the Rytov approximation. The Ilorin environment's scintillation depends on both wavelength and distance. It is noteworthy that the wavelength of 1550 nm does not present any danger to the human eye and is less susceptible to atmospheric disturbance. Therefore, the wavelength of 1550 nm needs to be employed in order to increase the efficiency of FSO transmission.

Provides a secrecy-enhanced system of chaotic optical communication with changeable RF amplifier strength, as shown in Fig. 3 (Li, M. et al., 2019). A more complicated key with the variable RF amplifier gains to strengthen the confidentiality of a chaotic optical communication system to address the security issue with information transfer. The system has a changeable RF amplifier gain. BER is typically used to evaluate the confidentiality of communication networks. Consequently, the system's BER can be expressed as in Eq.3.

$$BER(G,G') = \frac{1}{2} erfc\left(\frac{u(G,G')}{2\sqrt{2}} \right) = \frac{1}{2} erfc\left(\frac{K\alpha}{2\sqrt{2\langle (n^2(G,G')\rangle}} \right) \tag{3}$$

where α represents the masking efficiency, u(G, G') signal-to-noise ratio, n^2(G, G') root-mean-square amplitude of mismatched noise affected by G and G′ , K the current amplitudes. The numerical findings show that the authorized receiver's bit error rate is substantially lower than the eavesdropper's bit error rate. Additionally, the BER cannot be reduced by the eavesdropper by reducing the electro-optic oscillator gain's mismatch of other parameters. Future communications with a high level of privacy could be realized with such a system.

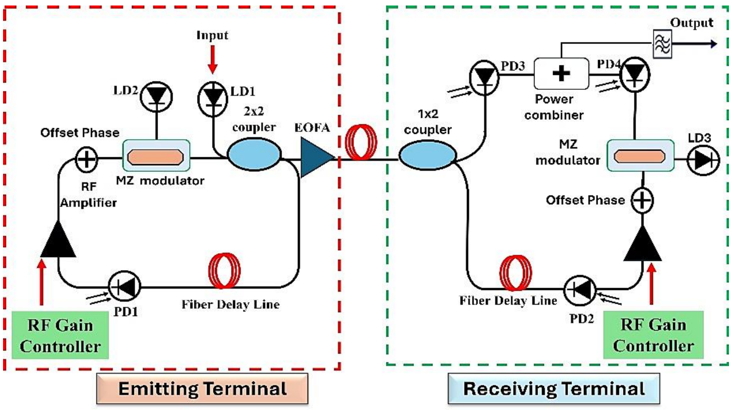

Fig. 3. The chaotic optical communication system with a variable gain RF amplifier (Li, M. et al., 2019)

Time-delay signature hiding was developed in a secure, chaotic communication system that integrates optical density with phase feedback (Wu et al., 2020). As shown in Fig. 4. To enable bidirectional communication, optical density chaos, and electro-optic phase chaos are combined. This method creates a phase chaotic signal by injecting an intensity chaotic signal into the electro-optic oscillator rather than the more conventional continuous wave (CW). Eq.4 represents the dynamic equation of the electro-optic phase-chaos generator.

$$x_n + \sigma_n \frac{dx_n}{dt} + \frac{1}{\theta_n} \int_{t_0}^{t} x_n(\xi)d\xi = \beta_n \left\{ \frac{\bar{p}_n + \bar{p}_n'}{2} + \sqrt{\bar{p}_n \bar{p}_n'} \cos[2\Delta(x_n)_{Tn} + 2\Delta(x_{n+1})_{Tn} + \phi_n] \right\} \tag{4}$$

where $\bar{p}_n$, $\bar{p}_n'$, x_n are additional phase shifts, σ_n is high cut-off time, θ is low cut-off time , ϕ_n the static offset phase of PM, β_n the feedback gain $\Delta(x_i)_{T_j} = x_i(t - T_j) - x_i(t - T_j - \delta T_i)$ (i=1,2,3,4, j=1,2,3), T_j is the delay time of the fiber delayed line, δT_i is the imbalance delay.

They showed that the design could effectively hide all time delay signatures (TDS), which corresponding to the feedback delays of both the laser and the electro-optic oscillator, using delay time identification techniques. Delay dynamics are produced on both sides by causing two output signals from the oscillators to phase-modulate one another. The interchange of data presented at both ends of the link depend on synchronization between transmitter and receiver. This plan offers a potential approach to achieving secure chaotic bidirectional confidentiality.

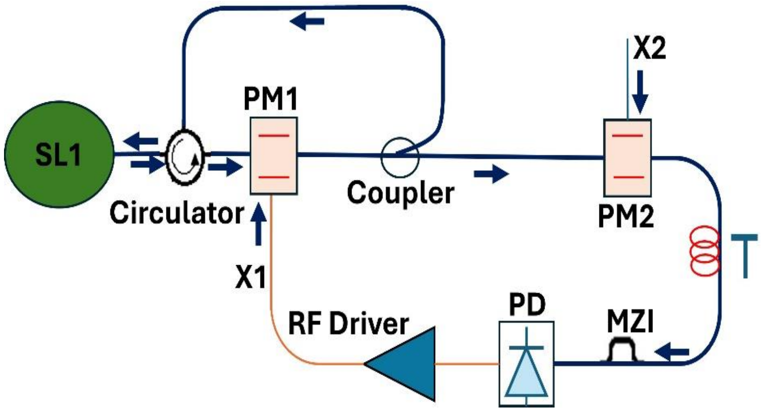

Fig. 4. The cascade schematic diagram (Wu et al., 2020)

To solve one of the important problems, which is the time delay signature (TDS), secure communication system enhanced by electro-optical chaos and immune to time delay signature extraction was created (Huang et al., 2021). The system's mathematical model, taking into account the temporal delay caused by the entire feedback loop, is expressed by Eq.5.

$$\begin{cases} \dfrac{dx_1}{dt} = -x_1 - a\displaystyle\int_o^t x_1(s)ds + \beta_1 \cos^2(x_2 + \varphi_1) \\ \dfrac{dx_2}{dt} = -x_2 - a\displaystyle\int_o^t x_2(s)ds + \beta_2 \cos^2(x_1 - x_3 + \varphi_2) + \beta_3 \cos^2(x_1 + x_3 + \varphi_3) \\ \dfrac{dx_3}{dt} = -x_3 - a\displaystyle\int_o^t x_3(s)ds + \beta_4 \cos^2(x_2(t-\tau) + \varphi_1) \end{cases} \quad (5)$$

where $x_i(t)$ is the state variable, β_i is the feedback strength, a is the response time of the feedback loop, $x_i(t-\tau)$ is the time delay feedback variable, τ is the intrinsic time delay, and φ_i is the offset phase, i = 1, 2, 3, 4. As shown in Fig. 5. They suggested a technique whereby one could simultaneously decrease the dimensionality of transmitted signals and raise a nonlinear dimensions of chaotic system at the transmitter, resulting in a "deficiency of data dimensionality". Only one-dimensional signal is broadcast for communication, using 3D chaotic system as a transmitter. Additionally, a hybrid receiver is created. The architecture not only makes it impossible to extract TDS but also keeps all the data needed for chaos synchronization with a simple implementation.

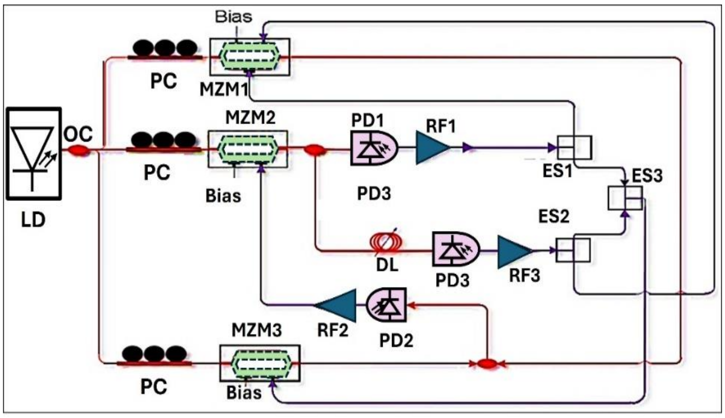

Fig. 5. Schematic diagram of a system (Huang et al., 2021)

A novel method using a two-component system of optical scattering components and the electrooptic self-feedback phase modulation loop to hide TDS and simultaneously enhance security against malicious attack (Gao, Z. et al., 2022). As shown in Fig.6. A secret chaotic modulated signal is temporarily jumbled in the time domain. The final modulated signal ED2(t) in the time domain can be expressed as in Eq.6.

$$E_{D2}(t) = F^{-1}\left[F(E_{pm}(t)).H_{D2}(w)\right] \quad (6)$$

Where F( ) stands for Fourier transform, F −1( ) stands for Fourier inverse transform, Epm the output signal, and HD2 (ω) the transfer function of the dispersion component (D2). An error-free, security-enhanced the chaotic optical communication system has successfully undergone proof-of-concept testing. The proposed technique might offer a promising path for physically secure chaotic optical communication systems depending on pure hardware.

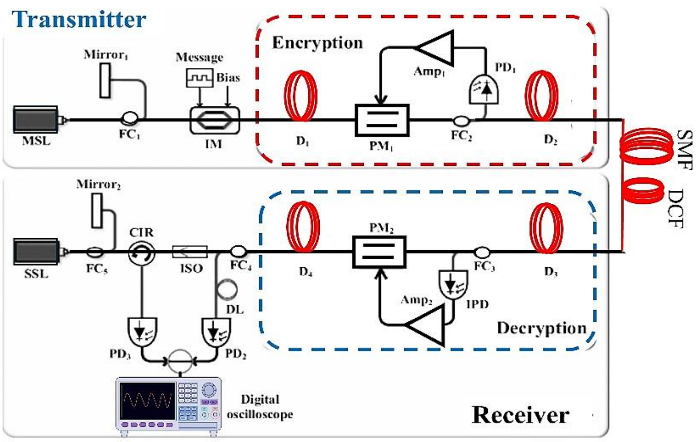

Fig. 6. Scheme of proposed security enhanced chaotic optical system (Gao, Z. et al., 2022)

Gained attention of optical feedback in semiconductor lasers to suppress the time-delay signature and create high-quality chaotic has attracted attention. By properly integrating the dispersion module into feedback loop, which is the creation process of the time-delay signature (TDS), It solves the time delay concealing issue without appreciably adding to the original architecture's complexity (Li M., et al., 2024). All-optical feedback and optical injection work together to create the complex chaotic signal, and the dual filter structure and well-adjusted parameters of each device conceal the TDSs. Where connects fiber Bragg gratings (FBGs) with different dispersion coefficients. The core notion of this proposal extends to various opt-electrical chaotic dynamics, which contain a feedback cavity, and overcome the feedback chaotic systems security issue without requiring a lot of additional work during implementation.

4. OPTICAL CHAOS SYNCHRONIZATION

An approach has been built to wideband chaos creation and synchronization in semiconductor lasers under stable amplitude self phase modulated optical injection (Zhao et al., 2020). As shown in Fig.7. Where an electro-optical phase modulator modulates the output of a continuous wave laser using output of an external cavity semiconductors laser (ECSL), which is then used to inject stable amplitude self-phase modulated light once again in (ECSL). A created chaos's effective bandwidth is extended from a few GHz to over 20 GHz. Furthermore, high quality synchronization between two broadband chaotic signals with the effective bandwidth larger than 20GHz is established through experimentation. Used cross-correlation (CC) coefficient to assess the synchronization quality, and for clearly display the synchronization performance, which is defined as in Eq.7.

$$CC = \frac{\langle (I_1(t) - \langle I_1(t)\rangle)(I_2(t) - \langle I_2(t)\rangle)\rangle}{\sqrt{\langle (I_1(t) - \langle I_1(t)\rangle)^2\rangle \langle (I_2(t) - \langle I_2(t)\rangle)^2\rangle}} \tag{7}$$

where $I_1(t)$ and $I_2(t)$ are the intensity time series, <·> represents the time averaging. That the suggested approach achieves synchronization with a large bandwidth increase when compared to chaos creation using traditional optical feedback (COF).

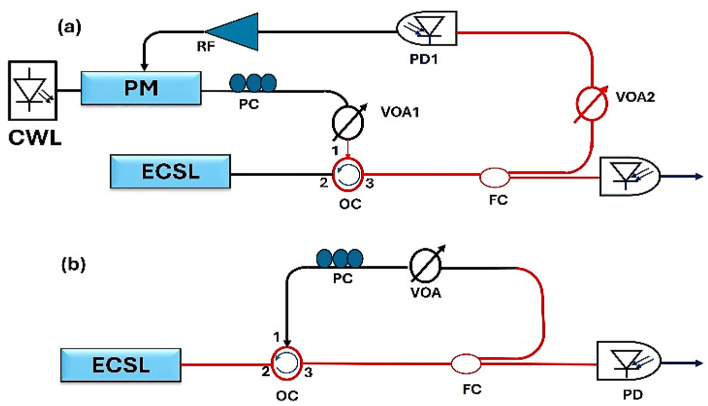

Fig. 7. The experimental configurations for (a) chaos generation system, and (b) ECSL with traditional optical feedback (COF) (Zhao et al., 2020)

Bidirectional and unidirectional optical feedback injection systems have both been applied (Al Bayati et al., 2020). By linking a portion of the output power of transmitter to the driving current of receiver, the chaos is brought into synchronization. The bidirectional synchronization produced complete chaos synchronization when the bias current was 1.8 mA. When bias current was 120 nA, the unidirectional synchronization produced good results. The residual chaos and the cross-correlation coefficient are two metrics used to assess the quality of synchronization. Eq.8 and 9 provide definitions for the residue of chaos synchronization and cross-correlation R_{xy}, respectively.

$$R_{chaos} = \left| \frac{x_T - x_R}{x_T} \right| \tag{8}$$

where x_T and x_R are the intensities of the transmitter T and receiver R oscillator systems, respectively.

$$R_{xy} = \frac{\langle (x(t) - \langle x(t) \rangle)(y(t+\Delta t) - \langle y(t) \rangle) \rangle}{\left(\langle (x(t) - \langle x(t) \rangle)^2 \rangle \langle (y(t+\Delta t) - \langle y(t) \rangle)^2 \rangle \right)^{1/2}} \tag{9}$$

where x(t) is the input of the master laser, y(t) is the output of slave laser, ⟨ ⟩ is the temporal average, and Δt is the time shift between two laser outputs. White noise signals with different amplitudes and frequencies were applied with external disturbances as different methods of chaos synchronization, also variable frequencies with fixed amplitudes. White noise signals can produce very good chaotic synchronization results. To explore chaos synchronization of the (closed loop system) unidirectional arrangement, white noise signal, and frequency modulation were employed as control parameters in an experimental setting for the first time.

The performance of the bidirectional long-distance chaos communication was simulated by a fiber-optic chaos synchronization system (Li N., et al., 2021). As shown in Fig. 8, same the driven chaos signal injection from located remotely driving laser (DL) across the long distance fiber is used in this system to synchronize the chaos between two response lasers (RLs). and describe semiconductor lasers' dynamic behavior, which is represented by the following Eq.10.

$$\frac{dN_{D,RL1,RL2}}{dt} = \frac{I}{q} + \frac{N_{D,RL1,RL2}(t)}{\tau_n} - G_{D,RL1,RL2} \left| E_{D,RL1,RL2}(t) \right|^2 \tag{10}$$

where the subscripts D, RL1 and RL2 stand for driving laser, response laser 1 and response laser 2, respectively. q is the electronic charge, I is the bias current, G denotes the linear gain, and E represents the slowly varying amplitude of the optical field. The simulated findings demonstrate that under ideal operating circumstances, good quality chaos synchronization between the two RLs may be accomplished, notwithstanding the poor synchronization quality between any RLs and DL, which helps enhance the system's security. This system's security, communication performance, and effects of the long-distance fiber channel have all been investigated using a novel message encryption and decryption technique together with two synchronized chaos output signals of RLs acting as two chaotic carriers. After adopting an optimized system configuration, it is possible to successfully decode two 10 Gb/s messages that are traveling adversely over a 100 kilometer fiber connection.

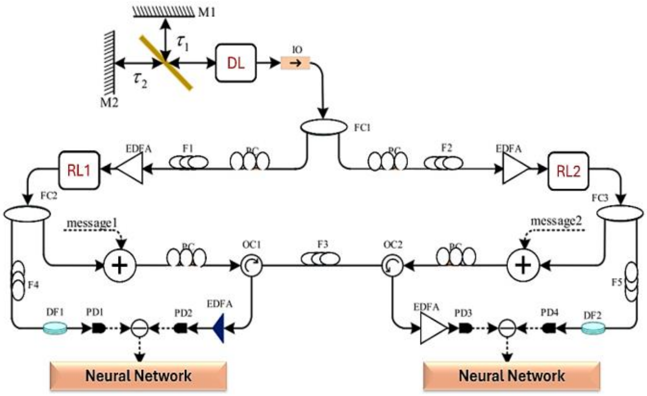

Fig. 8. Bidirectional long-distance chaotic secure communication system schematic diagram with machine learning capabilities. **(Li N., et al., 2021)**

An electro-optic coupling mutual injection method for optical chaotic production and synchronization in secure communications (Gong et al., 2022). Shown in Fig. 9. Suggests a traditional model-based Electro-optic linked mutual injection chaotic system. The system's mathematical model in the linked mutual injection system is represented by Eq.11.

$$\begin{cases} x_1(t)+\tau_1\dfrac{dx(t)}{dt}+\dfrac{1}{\theta_1}\displaystyle\int_{t_0}^{t}x_1(\xi)d\xi=\beta_1\cos^2\left[x_3(t-T_1)-x_2(t-T_1)+\Phi_1\right] \\ x_2(t)+\tau_2\dfrac{dx(t)}{dt}+\dfrac{1}{\theta_2}\displaystyle\int_{t_0}^{t}x_2(\xi)d\xi=\beta_2\cos^2\left[x_3(t-T_2)-x_1(t-T_2)+\Phi_2\right] \\ x_3(t)+\tau_3\dfrac{dx(t)}{dt}+\dfrac{1}{\theta_3}\displaystyle\int_{t_0}^{t}x_3(\xi)d\xi=\beta_3\cos^2\left[x_1(t-T_3)-x_2(t-T_3)+\Phi_3\right] \end{cases} \tag{11}$$

where x_i is the state parameter, $\tau_i=\dfrac{1}{f_l}$, $\theta_i=\dfrac{1}{f_h}$, where f_h, f_l are respectively the highest and lowest frequency of the equivalent filter of each branch , β_i is system's feedback gain, and Φ is the offset phase of the system. The chaotic signal produced by system exhibits high level of randomness, a spectrum with a uniform power distribution, complexity in the chaotic signal's output, and a waveform that challenging to anticipate and understand. An effective chaotic synchronization between the transmitters and the receivers is accomplished via tuning system parameters properly. A communication system that depends on this structure also retains high-sensitivity to important factors while having low-sensitivity to mismatch of common characteristics, resulting in enhanced secrecy and synchronization effects. In conclusion, the plan implements highly confidential, chaotic communication.

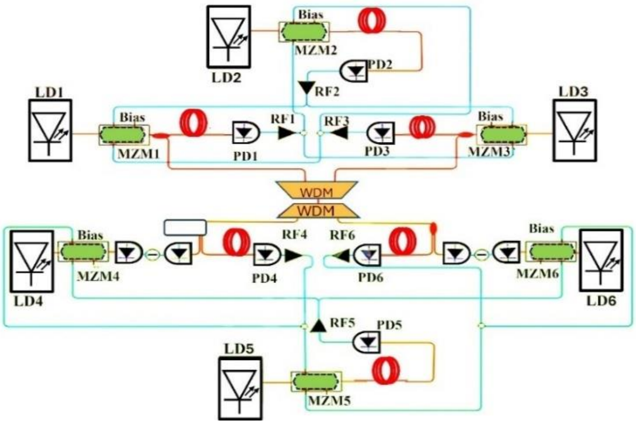

Fig. 9. Schematic of a chaotic communication system using mutual injection and electro-optic coupling (Gong et al., 2022)

A distributed fiber Raman amplifier DFRA and an erbium doped fiber amplifier (EDFA) were used in hybrid amplification to achieve long-range chaotic synchronization via fiber relay transmission (Wang L. et al., 2023). As shown in Fig. 10. Computer simulations and experiments expound that the heightened spontaneous emission noise and self-phase-modulation are reduced by low-noise DFRA, enabling hybrid amplification to extend the chaos-fidelity transmission distance. Launching power, the DFRA to EDFA gain ratio, the length of a single span fiber, and the number of fiber spans are few examples of the hybrid-relay conditions that are evaluated for optimization. Experimentally, the 1040-km chaotic synchronization with synchronization coefficient above 0.90 is attained, which forms basis for optical chaos communication and key distribution for backbone networks.

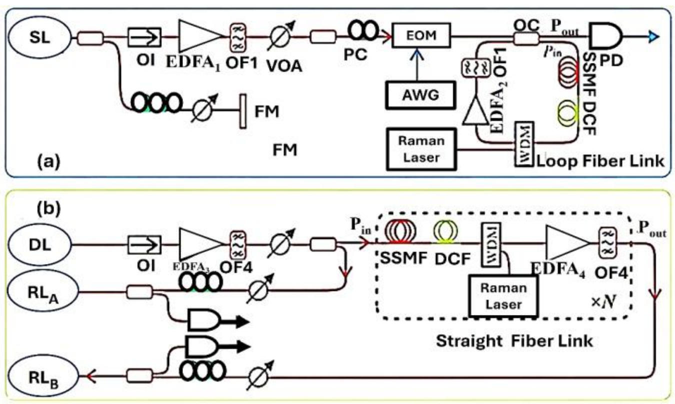

Fig. 10. (a) The fiber-loop experiment to investigate laser chaos fidelity transmission; (b) long-range chaos synchronization setup (Wang L. et al., 2023)

A novel strategy that optimizes identical chaotic synchronization by appropriately controlling coupling strength involves examining a number of control parameters that impact laser network synchronization, including laser bias currents, coupling strength, optical injection (OI) strength, optoelectronic feedback (OEFB) ratio, and optical feedback (OFB) ratio (Hemed, A., et al., 2024). The correlation coefficient C(Δt), is used to assess the synchronization quality between two lasers, as shown in Eq.12.

$$C(\Delta t) = \frac{\langle [P_1(t) - \langle P_1 \rangle][P_2(t+\Delta t) - \langle P_2 \rangle] \rangle}{\{\langle [P_1(t) - \langle P_1 \rangle]^2 \rangle \langle [P_2(t+\Delta t) - \langle P_2 \rangle]^2 \rangle\}^{1/2}} \qquad (12)$$

where P_1 and P_2 is the lasers output powers of, LD_1 and LD_2, respectively, brackets < > means the time average, Δt is the time shift. The unidirectional OI method and feedback have the effect of preventing information leakage from the slave laser (SL). The variation in time delay linked to each OFB and OEFB laser further supports this. This method is referred to as hybrid feedback and injection (HFBI). By minimizing mismatching and appropriately regulating coupling strength, identical chaotic synchronization is maximized. Zero-leg synchronization with no expected shift for the resulting dynamics is demonstrated via synchronization diagrams.

5. THE GENERATION OF BROADBAND CHAOS

Many methods to increase the bandwidth of chaos, including optical injection, mutual injection, altering optical feedback structure, and chaotic laser post-processing. The mutual-injection structure with a two-distributed feedback laser to enhance the bandwidth and flatness of chaotic signals was developed (Qiao et al., 2019). As shown in Fig.11. To create wideband flat chaos, coupling strength, and frequency detuning were studied. When coupling strength is 1.635 and frequency detuning is 33.5 GHz, a flatness of 5.6 dB is obtained, and chaotic signal covered by a spectrum is larger than 50 GHz, or around 6.42 times the optical feedback signal. A method's structure is straightforward to modify and regulate. It's advantageous for increasing the chaotic optical time domain reflectometer's resolution and rate of generating random numbers. In short, an industrial use of the chaotic laser can be further supported by the broadband chaos.

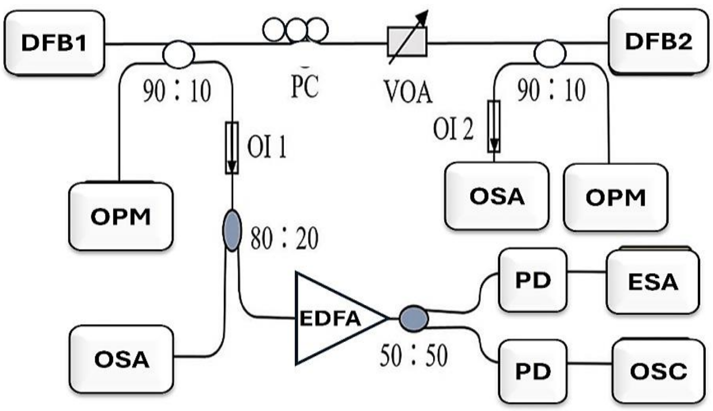

Fig. 11. Chaotic laser based on mutual injection (Qiao et al., 2019)

It is thoroughly explored how generated chaos's efficient bandwidth and time-delay signature (TDS) features, are influenced by feedback intensity, phase-modulated index, and interference delay. By a broadband complex enhanced chaos production method utilizing semiconductors laser with delayed interference self-phase feedback (Zhao et al., 2019). The experimental setup is illustrated in Fig. 12. They show that the effects of spectrum broadening induced by phase modulation and delayed interference nonlinear filtering may be combined to generate wideband chaos with the flat spectrum and exceptional TDS suppression qualities across a wide dynamic operating range. The phase transformation rate equation can be shown as in Eq.13.

$$\varphi(t) = K_{PM} N\left(\left|E(t-\Delta t)\right|^2\right)\pi \quad (13)$$

where φ(t) is the phase-shift induced, K_{PM} is the phase modulation index, $N\left(\left|E(t-\Delta t\right|^2\right)$ stands for the normalized electronic PM driving signal, E the slowly-varying complex electric field, and Δt is the delay of the driving signal. Not only can the effective bandwidth of the clutter be increased significantly but also the complexity of the chaos can be greatly increased by suppressing TDS towards characteristic level close to 0. This is compared with the applicable schemes for chaos formation under delayed interferometric optical feedback, conventional optical feedback, and single self-modulating optical feedback.

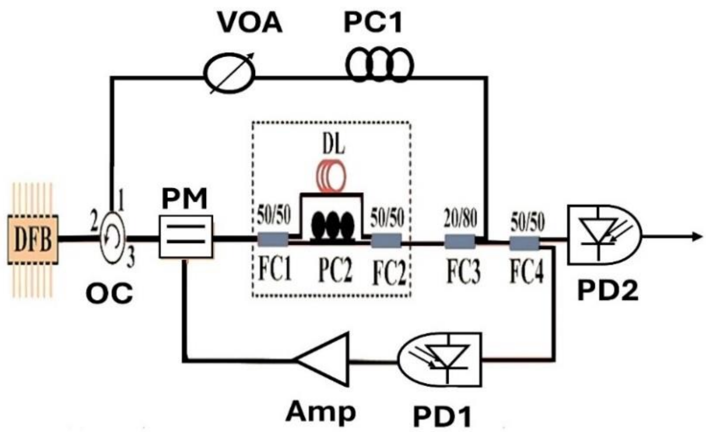

Fig. 12. The suggested scheme's experimental configuration (Zhao et al., 2019)

A chaos production in semiconductor lasers for enhanced bandwidth and suppression of TDS is susceptible to feedback of parallel coupled loop resonators (Jiang et al., 2020). As shown in Fig. 13. Where parallel coupling ring resonators (PCRR) are used as reflectors in external feedback semiconductor laser-based chaos creation method that allows for enhancement of the simultaneous bandwidth and exceptional time-delay signature (TDS) repression. The output chaos is expressed by Eq.14.

$$E(t)_{out} = E(t-\tau_f/2) * h_2(t) \quad (14)$$

where $h_2(t)$ is the convolution of the response function of the "Throughput" port and $E(t-\tau_f/2)$ the delayed laser output. Additionally, compared to conventional optical feedback configuration, chaos bandwidth can be increased, and TDS of the chaos can effectively be suppressed towards an undetectable level with non-linear feedback of PCRR. Wideband complex chaos can be produced flexibly according to the proposed technique.

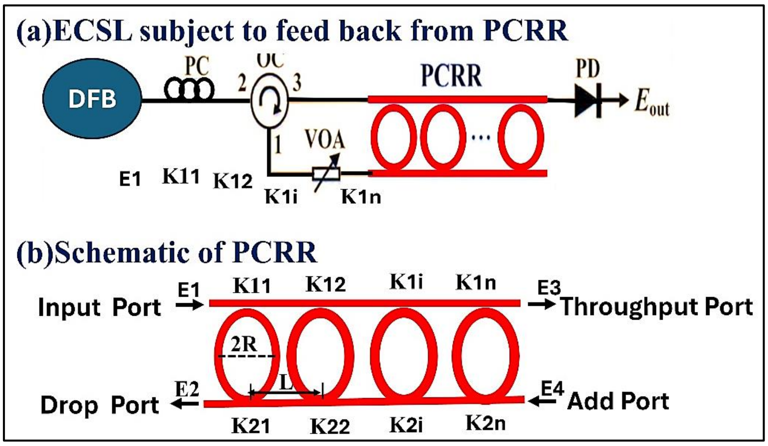

Fig. 13. (a) ECSL-based chaos generating scheme diagram subject to non-linear feedback from PCRR; (b) PCRR configuration in detail (Jiang et al., 2020)

Notion uses optical feedback with a triple-mode micro-square laser to produce chaos in the broadband flat microwave spectrum (Li et al., 2022). Experimental setup is illustrated in Fig.14. Where the bandwidth of the chaotic can be greatly improved by tuning the lasing mode intensities, frequency intervals, and optical feedback intensity. The flat bandwidth is significantly larger than the relaxation oscillation frequency due to presence of two mode-beating peaks. Experimentally, a tri-mode mode laser's chaotic output spectrum with flatness of 8.3 dB and an effective bandwidth of 35.3 GHz is achieved.

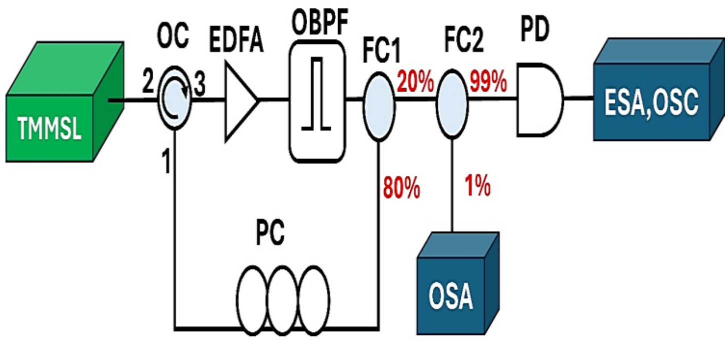

Fig. 14. Generation of wideband chaos using a TMMSL three-mode micro square laser with optical feedback (Li et al., 2022)

Implemented as an optical chaos communication method for safe transmission of the quadrature amplitude modulation (QAM) data, depending on semiconductor lasers subjected to optical injection of intensity modulation (Wang Y. et al., 2023). As shown in Fig. 15. Two chaotic sources were created at the transmitter side to serve as chaotic carriers with differing modulation parameters. These chaotic carriers were then employed to drive two receivers in two different channels. The proposed laser system can be represented by Eq.15.

$$\frac{dN_{T_{1,2},R_{1,2}}(t)}{dt}=\frac{I}{qV}-\frac{1}{\tau_n}N_{T_{1,2},R_{1,2}}(t)-G_n\left[N_{T_{1,2},R_{1,2}}(t)-N_0\right]\left|E_{T_{1,2},R_{1,2}}(t)\right|^2 \quad (15)$$

where the subscripts $T_{1,2}$, and $R_{1,2}$ stand for TL1, TL2, RL1 and RL2, respectively, q is the electronic charge, V is the volume of the active region, I = $1.8I_{th}$ is the injection current (I_{th} is the threshold current), E(t) denotes the slowly varying complex amplitude of the electric field, N(t) represents the carrier density in the laser cavity, τ_n is the carrier lifetime, G_n is the gain coefficient, and N_0 is the carrier density at transparency. In conventional single-mode fiber (SMF), a 20-Gb 16-QAM message was successfully retrieved with distance of transmission of more than 120 kilometer, while a 20-Gb 64-QAM message was limited to the fiber transmission distance of 20 km. According to numerical results, this approach enables high-quality chaos synchronization and broadband chaos creation for simultaneous encryption of a two messages for safe communication.

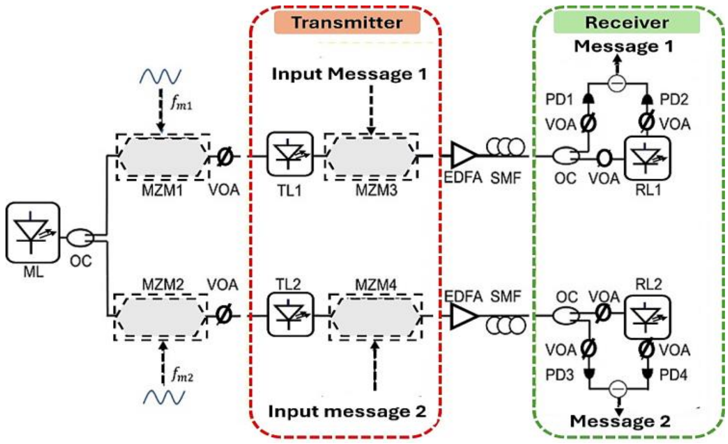

Fig. 15. Two-channels chaotic communication system undergoing optical injection for IM (Wang Y. et al., 2023)

6. COMPARATIVE STUDY

The table below shows the comparison between previous works.

Table 1. The comparisons between previous works

Ref. name, year	Proposed methodology	Solved problems
Hu H. et al., 2017	Presented a novel architecture for optical chaos communications, by combine the optical and photoelectric techniques, where the modified photoelectric system achieves an optical chaos in both intensity and phase.	Concealing the feedback delay time, and synchronization.
Elsonbaty, A., et al., 2018	Using conventional, phase-conjugate, or grating mirrors in a secure communications system using chaotic nanolaser.	Complexity of the chaotic nanolaser's dynamical behavior.
Olukanni, E., et al., 2019	The three-dimensional (3D) chaotic system is dependent on electro-optical (EO) non-linear devices.	TDS concealment.

Ref. name, year	Proposed methodology	Solved problems
Li M. et al., 2019	The gain adjustment of RF amplifier is used as key in high dimensional chaotic optical communication system to improve secrecy.	The BER, space, and complexity of the key.
Wu et al., 2020	Using its identification techniques, the phase chaotic signal is produced by the intensity chaos injection condition rather than the conventional CW injection.	Concealment of TDS
Huang et al., 2021	A novel 3D chaotic EO and single-signal induced synchronization strategy with strong nonlinear inversion capability of deep learning and hybrid receiver is designed.	TDS concealment, quality of chaotic synchronization.
Gao, Su et al., 2022	Using two optical dispersion components and a photoelectric self-feedback phase modulation loop for encryption and decryption of External temporal self-feedback hardware.	TDS concealment and malicious attacks.
Li M., et al., 2024	Ntegrating the dispersion module into feedback loop, Where connects fiber Bragg gratings (FBGs) with different dispersion coefficients.	The time delay concealing without architecture's complexity
Zhao et al., 2020	Using external cavity semiconductor laser (ECSL) and photoelectronic hybrid feedback is a novel method for producing broadband chaos.	Bandwidth of the chaos, Wideband chaos synchroniztion transmission capacity
Al Bayati et al., 2020	An optical communication system was used depending on synchronization of two chaotic semiconductor lasers, through two systems of the optical feedback injection, bidirectional and unidirectional.	Chaos synchronization
Li N., et al., 2021	The driven chaos signal injection from located remotely driving laser (DL) across the long distance fiber is used in this system to synchronize the chaos between two response lasers (RLs).	Good quality chaos synchronization between the two RLs accomplished.
Gong et al., 2022	A chaotic system for photoelectric mutual injection based on the classical chaotic model of photoelectric density.	Chaotic synchronization, Bit error rate.
Wang L. et al., 2023	A fiber relay transmission combined with hybrid erbium doped fiber amplifier (EDFA) and distributed fiber Raman amplifier (DFRA) amplification is used in a Long-range chaos synchronization scheme.	Chaos synchronization, Chaos transmission distance.
Hemed, A., et al., 2024	A novel strategy that optimizes identical chaotic synchronization by appropriately controlling coupling strength examining a number of control parameters that impact laser network synchronization.	Chaos synchronization.

Ref. name, year	Proposed methodology	Solved problems
Wang et al., 2018	The chaotic system of the photoelectric feedback phase depends on the non-linear coupling of a two delayed interfering branches.	Feedback gain, complex chaotic signal, and the key space.
Qiao et al., 2019	Use the mutual-injection architecture with two semiconductor lasers with distributed feedback.	The bandwidth and the flatness of chaotic signals.
Zhao et al., 2019	The semiconductor laser subject to delayed interference self-phase-modulated optical feedback is used in a broadband complexity-enhanced chaos creation technique.	Broadband chaos with flat spectrum, suppression of TDS.
Jiang et al., 2020	Parallel coupled ring resonators (PCRR) are used as exterior reflector of the ECSL in external feedback semiconductor laser-based chaos production system.	Bandwidth of chaos and time delay signature (TDS) suppression.
Li et al., 2022	Using a three-mode micro-square laser with optical feedback to adjust laser mode intensity, optical feedback, and strength frequency periods to produce chaos in a broadband flat microwave spectrum.	Chaotic bandwidth.
Wang Y. et al., 2023	Optical chaos communication scheme depends on semiconductor laser subject to the intensity modulation IM optical injection for a secure transmission of the QAM messages.	Broadband chaos, chaos synchronization.

7. DISCUSSION

Enhancement of Chaotic Optical Communication has been the focus of study since the first chaotic optical communications field demonstration. Chaotic security is becoming increasingly important as individuals have realized that chaotic optical communications are not as safe as they formerly thought. This necessitates looking into wideband and low TDS integrated chaotic laser. Therefore, to provide a more steady chaotic performance for industrialization and practical application, an integrated chaotic laser is needed. Utilizing cutting-edge components and signal processing techniques, like a 3D chaotic system, where Potential uses for the proposed 3D chaotic oscillator include secure communication, chaos computing, and random number generation. And by properly integrating the dispersion module into feedback loop, which is the creation process of the time-delay signature (TDS), It solves the time delay concealing issue without appreciably adding to the original architecture's complexity. Also the chaotic optical communication with changeable RF amplifier strength, a more complicated key with the variable RF amplifier gains to strengthen the confidentiality of a chaotic optical communication system to address the security issue with information transfer. But There is a problem is the statistical analysis, which can be solved by decrease the dimensionality of transmitted signals and raise a nonlinear dimensions of chaotic system at the transmitter, resulting in a "deficiency of data dimensionality".

In addition to what was mentioned above, the problem of synchronization remains that must be solved by an effective chaotic synchronization between the transmitters and the receivers is accomplished via tuning system parameters properly, where a communication system also retains high-sensitivity to important factors while having low-sensitivity to mismatch of common characteristics, resulting in enhanced secrecy and synchronization effects.

Also, it is necessary to increase the bandwidth of chaos by tuning the lasing mode intensities, frequency intervals, and optical feedback intensity, where with increase the bandwidth of chaos will be times that of the chaos generated by optical feedback, and will be valuable for providing wideband chaos sources for applications in secure optical communications, high-speed random bit generation and highresolution chaotic radar. The core notion extends to various opt-electrical chaotic dynamics, which contain a feedback cavity, and overcome the feedback chaotic systems security issue without requiring a lot of additional work during implementation.

8. CONCLUSION

This paper comprehensively examines studies on the development of chaotic optical communication as well as both domestic and international development patterns. Additionally, TDS suppression, chaotic synchronization for the chaotic optical communication depending on the chaotic laser, and security enhancement are included. A preliminary analysis of the work and important technologies that may be used as references results in a specific reference and reference for study of chaotic optical communication technology. It is challenging to concurrently acquire broadband and low TDS characteristics in a chaotic source. This necessitates looking into wideband and low TDS integrated chaotic laser. Furthermore, the integrated hybrid chaotic laser continues to depend on several separate elements. Therefore, to provide a more steady chaotic performance for industrialization and practical application, an integrated chaotic laser is needed. Utilizing cutting-edge components and signal processing techniques, the transmission of bit rate can be increased, as the distance of transmission, and synchronization. However, progress has slowed down recently, which we think is because there is still a security issue with chaotic optical communications. Thus, the main goals of this study in chaotic optical communications have been to increase security by masking the time delay or, as was already noted, by making the chaos more complicated. Following the resolution of the aforementioned issues, the chaotic optical communications are prepared for use in practical applications.

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