

GENERAL AND COMPLETE SYNCHRONIZATION OF MUTUAL COUPLING SYSTEM OF QUANTUM DOT SEMICONDUCTOR LASERS WITH OPTICAL FEEDBACK

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The study examines an extensive and complete synchronization of optimal feedback with quantum dot semiconductor laser mutual coupling system. This has been achieved by resolving the transmitter and receiver equations of the quantum dot lasers. Numerous crisis areas have been observed at the time of investigating the relationship between photon density and time. The authors have selected an optimal time delay for the optical feedback so as to render an appropriate situation for intermittent dynamics. The study analyses the impact created by a long external cavity of QDSL upon the synchronization process in this mutual coupling system, in the presence of the enhancement factor of ($\alpha=3$).

Keywords: *Crisis route, linewidth enhancement factor, nonlinear dynamics, optical feedback, quantum dot, semiconductor laser.*

1. INTRODUCTION

In a private communication domain, in order to keep the chaos among varying types of dynamical systems under control, the researchers have started to give preference to a chaotic synchronization process in recent years [1]. Thus, the most investigated research topic is synchronization phenomena under Quantum Dot (QD) laser chaotic. This is attributed to the sensitive nature of the phenomenon against external perturbation as an optimal feedback. Such materials execute discrete transition of the energy in addition to the predicted symmetric emission lines. These materials possess a low linewidth enhancement factor. Such a concept has been extensively investigated due to its multi-faceted applications, especially the removal of laser [2].

One of the vibrant phenomena that is discussed in different domains of physical sciences is crisis-induced intermittency. It is characterised by the unannounced creation of inappropriate bursts, out of regular evolution, under a varying number of control parameters. Such a dynamic system is managed by changing two dynamics that correspond to intermittent evolutions on two distant sub-attractors (attractor expansion) or two co-existing attractors (attractor merging) [3].

The size of QDs is in the range of a few nanometres (2–10 nm), and these minuscule-level semiconductor particles contain both electron and the holes across the spatial dimensions [4]. On the other hand, such minimal-sized QDs possess excellent optical and electronic characteristics that are unique compared to that of the large-sized particles. Pecora and Carroll proposed the concept of chaos synchronization between two nonlinear sys-

tems. These researchers utilised Lorenz system and three variables to demonstrate the proposed model [5]. The Quantum Dot Semiconductor Laser (QDSL) possesses three primary characteristics such as low threshold current density, small linewidth enhancement factor (LEF) and high characteristic temperature [6]. This synchronization setup is called complete chaos synchronization that is distinct compared to the generalization synchronization of chaotic oscillations [7]. In telecommunication applications, the QD nanostructures are generally utilised thanks to confinement of the carrier within three dimensions [8], [9]. In general, the carrier dynamics is believed to create a crucial and a negative impact on the outcomes of QD laser under optimal feedback [10] and optical injection [11].

In comparison with the rest of the SLs, the QDSLs show high sensitivity to any sort of changes in the time delay, when used with optoelectronic feedback circuits [12]. Complete and generalized chaos synchronization are two different origins of the chaos synchronization process in nonlinear delay differential systems. In the generalized chaos synchronization, soon after the transmitter signal is received, a synchronized wave form is produced by the receiver. Thus, there is a time lag between the outputs. In case of complete chaos synchronization, at the receiver, the asynchronous chaotic signal is produced before receiving the transmitter signal. For comparison, the time lag in complete chaos synchronization is lesser than that of the signal transmission that occurs between the transmitter and receiver systems [13].

2. RATE EQUATION OF QUANTUM DOT LASER

In a rate equations method, three coupled equations are included, such as the carrier density (N), photon density (E) and occupation probability (ρ). In case of QD semiconductor devices, the wetting layer is first injected with the carriers prior to

its inculcation into dots at a capture rate that is severely based on the population of the dots. Equations (1)–(3) correspond to the rate equations [14], [15]. Thus, the rate equations generally denote the carrier dynamics of QD materials [16]:

$$\frac{dE_{(T,R)}}{dt} = E_{(T,R)} \left(-\frac{1}{2t_s} + \frac{g_o \nu}{2} (2\rho_{(T,R)} - 1) \right) + \frac{\gamma}{2} E_{(T,R)} (t - \tau_{(T,R)}) + \frac{\gamma}{2} E_{(T,R)} (t - \tau_c) + R_{sp} \quad (1)$$

$$\frac{d\rho_{(T,R)}}{dt} = -t_n \rho_{(T,R)} - g_o (2\rho_{(T,R)} - 1) |E_{(T,R)}|^2 + CN_{(T,R)}^2 (1 - \rho_{(T,R)}) \quad (2)$$

$$\frac{dN_{(T,R)}}{dt} = J_{(T,R)} - \frac{N_{(T,R)}}{t_d} - 2n_d CN_{(T,R)}^2 (1 - \rho_{(T,R)}) \quad (3)$$

Here, $N_{(T,R)}$ denotes the carrier density in the well for both transmitter and the receiver lasers, $E_{(T,R)}$ corresponds to the complex amplitude of the electric field for both transmitter and receiver lasers, the occupation probability in a dot is denoted by $\rho_{(T,R)}$ for a transmitter laser and a receiver laser, the lifetime of the photon is denoted by t_s ; t_n and t_d correspond to the timelines of the carrier in well and dot, respectively; n_d denotes the 2D density of the dots; and finally the pump is denoted by $J_{(T,R)}$. γ and $\tau_{T,R}$ denote the feedback level and delay time correspondingly for the transmitter laser and the receiver laser. Here, $\tau = 2L/c$ corresponds to the round-trip time of light

within the external cavity (L) and c denotes the velocity of light [15]. C corresponds to Auger carrier capture rate [16].

The researchers conducted the theoretical investigation of the mutual coupling system which might possess either one type or both types of synchronization, for instance, complete and generalized for transmitter and receiver quantum dot semiconductor lasers with optical feedback. The same laser value exists for both on linewidth enhancement factor ($=3$), current density whereas it is different in case of coupling time delay between the transmitter and receiver lasers, τ_c .

3. RESULTS AND DISCUSSION

MATLAB software was used to simulate the values for photon density, occupation probability, carrier number and the attractor with the help of 4th order Runge-Kutta numerical method. Figure 1a portrays the QDSL photon density as a function of

time when $\alpha = 3$, ($\tau = 124$ ps). The density of the photon reached $32 \times 10^{20} \text{ m}^{-2}$ and also diminished to a chaotic behaviour. There was no periodic behaviour observed for the transmitter and receiver of the QDSL, whereas the attractor between the photon

density values of the receiver and transmitter lasers was clearly not periodic with non-synchronization as shown in Fig. 1b. Figure 1c, e shows the time series for the photon density values of the transmitter and receiver (of QDSL) lasers, when $\alpha=3$, ($\tau=125$ and 126 ps). Thus, there is stabil-

ity in the behaviour at a steady state period. General and complete synchronization outcomes are shown in Fig. 1d, f, while from Fig. 1a, c, e, it can be understood that the change on time delay by 1 ps is a good outcome to be applied further.

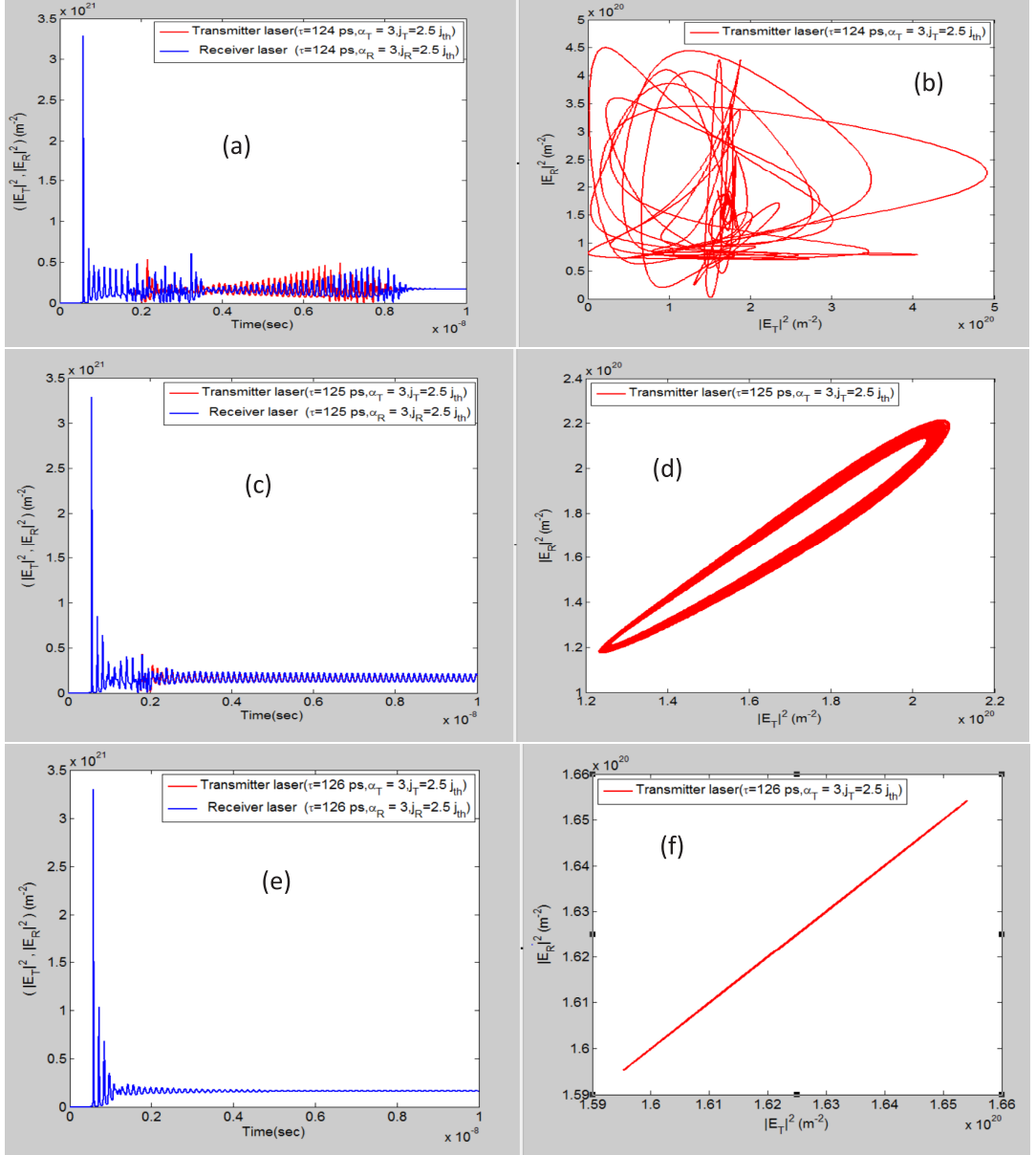


Fig. 1. Photon density of transmitter and receiver (QDSL) as a function of time at various values of time delay as in (a, c, e) chaotic attractor and stable for photon density of transmitter as a function of photon density of receiver (QDSL); (b) chaotic; (d) general synchronization; (f) complete synchronization.

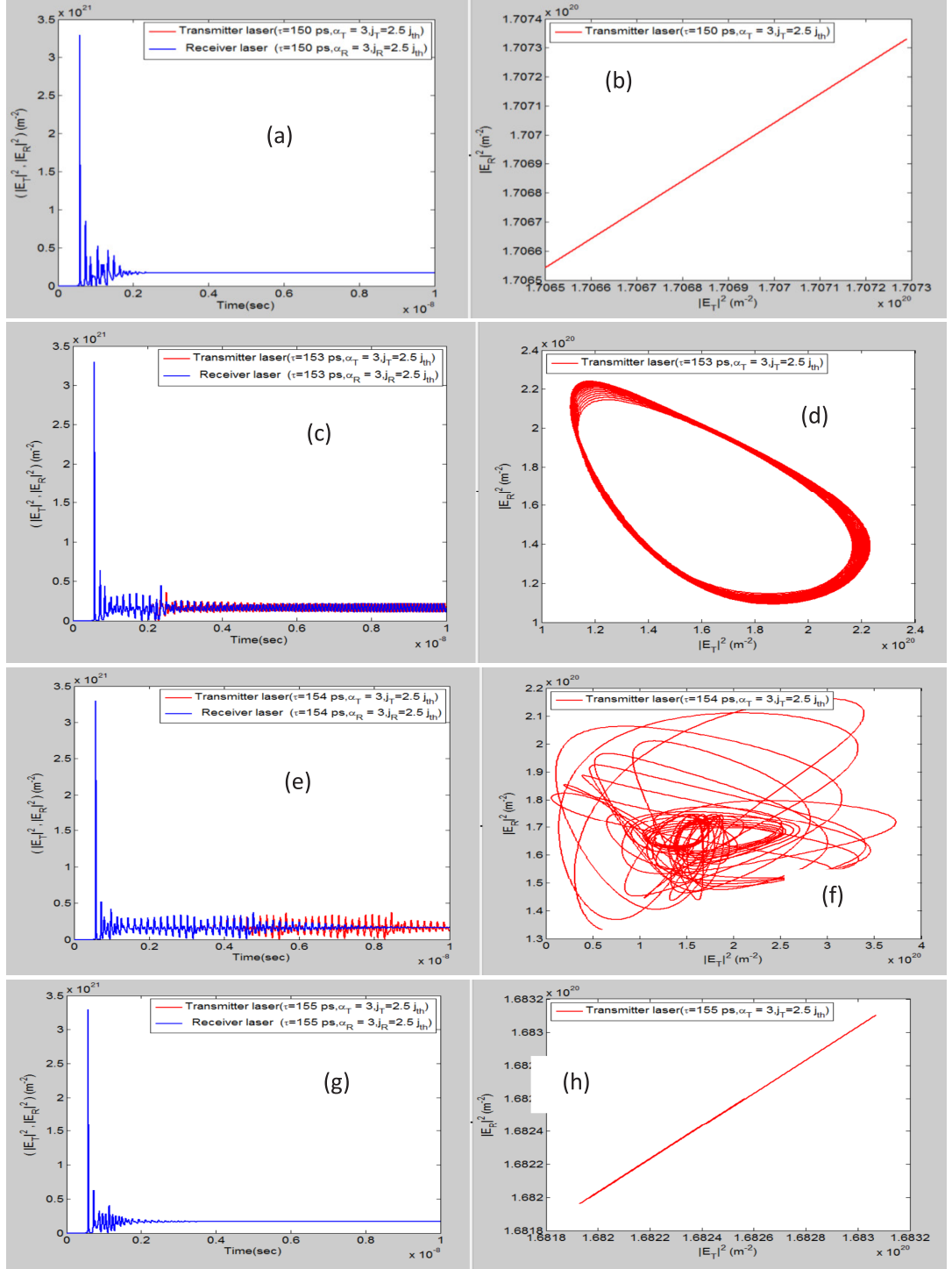
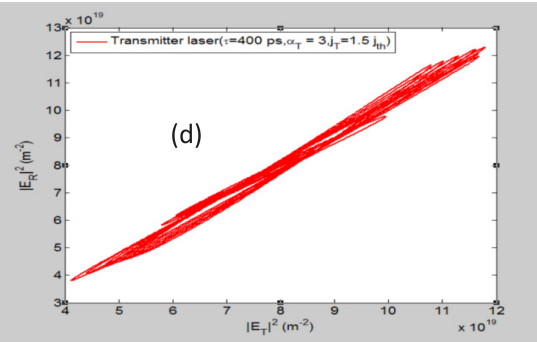
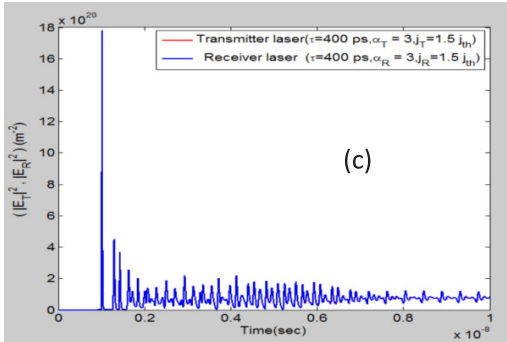
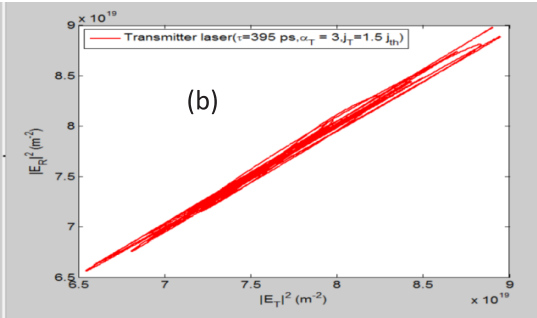
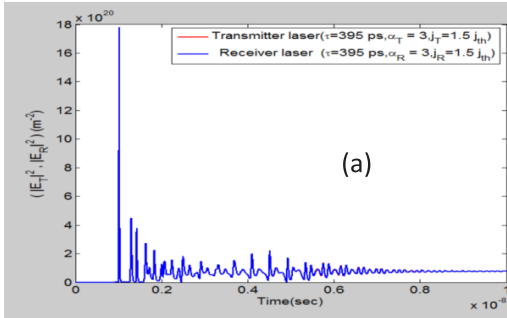


Fig. 2. Photon density of transmitter and receiver (QDSL) as a function of time for various values of time delay as in (c, e) chaotic attractor; (a, g) stable; (b, h) complete attractor synchronization; (d) general attractor synchronization; (f) chaotic behaviour for photon density of transmitter as a function of photon density of receiver (QDSL).

Figure 2a portrays the photon density values of the QDSL as a function of time, when $\alpha = 3$, ($\tau = 150ps$). According to the figure, the photon density values attained $32 \times 10^{20} \text{ m}^{-2}$, whereas the stable behaviour of the QDSL transmitter and receiver along with complete synchronization is shown in Fig. 2b. The researchers found a clear chaotic behaviour of the photon density of both receiver and transmitter lasers in case of general synchronization between the photon density of the receiver and transmitter lasers as in Fig. 2c, d, when ($\tau = 153ps$). Further, Figs. 2e and 2f show an excellent chaotic behaviour for transmitter and receiver lasers of the QDSL and attractor with non-synchronization between the photon density of the receiver laser and the respective transmitter laser, when ($\tau = 154ps$). Due to the complete synchronization at ($\tau = 155ps$), the outcomes were good to be used on applications with a stable behaviour as shown in Fig. 2g, h.

The photon density of QDSL, as a function of time, when $\alpha = 3$, is ($\tau = 395, 400, 410, 415, 420ps$) respectively (see Fig. 3a, c, e, g, i). The chaotic behaviour is demonstrated in case of the whole existing values and the photon density of $18 \times 10^{20} \text{ m}^{-2}$. Figures 3f and 3j show a stable behaviour of the transmitter and receiver lasers of the QDSL with complete synchronization. The intermediate chaotic behaviours of the photon density of receiver and transmitter lasers between the complete and general synchronization are illustrated in Fig. 3b, d and h. The chaos synchronization between the photon density of the receiver and transmitter lasers is shown, when ($\tau = 395, 400, 415ps$). Figures 3f and 3j portray an excellent chaotic behaviour for transmitter and receiver of the QDSL and attractor with synchronization between the photon density of the receiver laser and the transmitter laser. These outcomes are crucial in the development of communication applications.



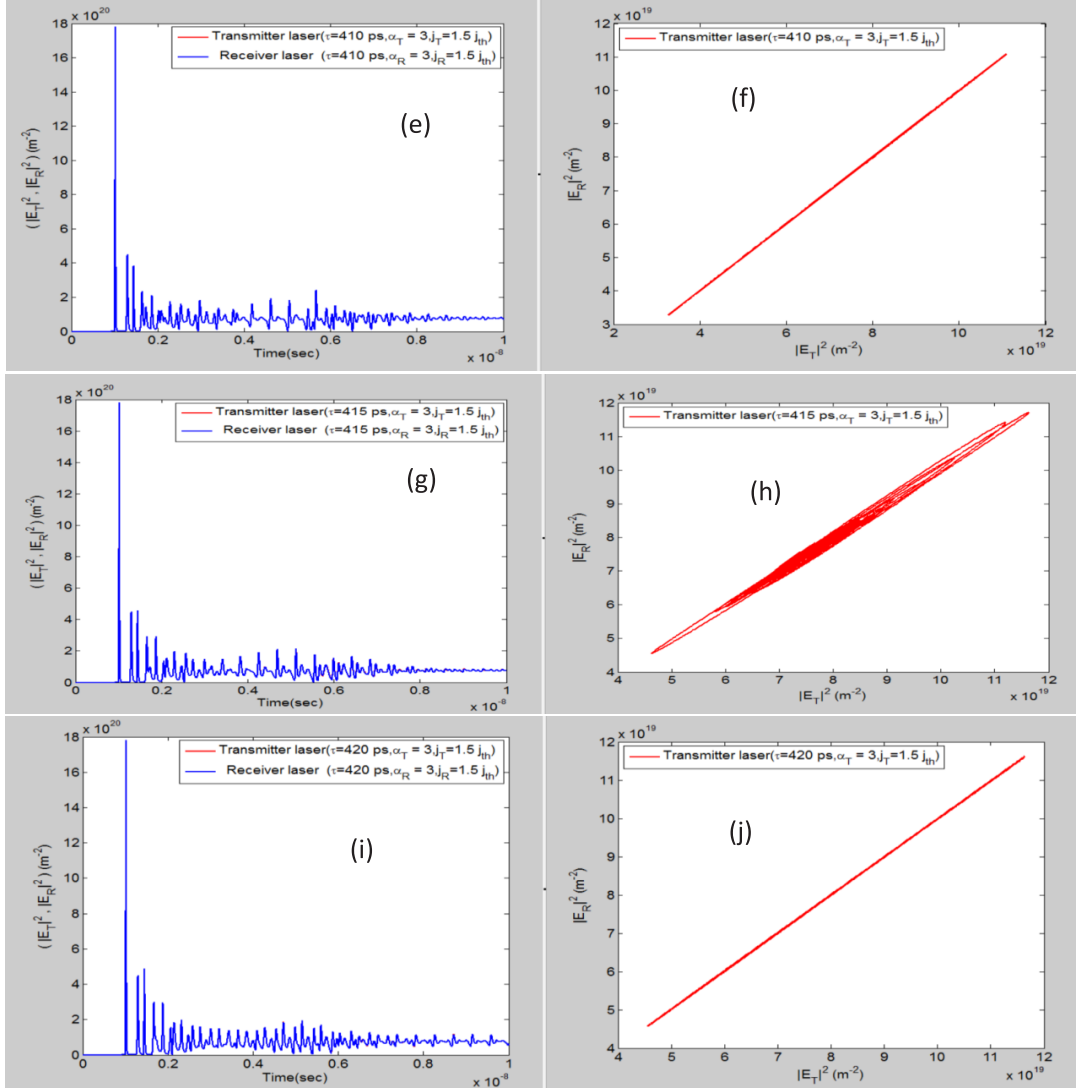


Fig. 3. Photon density of transmitter and receiver (QDSL) as a function of time for various values of time delay as in (a, c, e, g, i) chaotic; (b, d, f) like complete attractor synchronization; (h, j) complete synchronization of QDSL.

CONCLUSIONS

The authors of the current study conducted generalized and complete synchronization of the QDSL mutual coupling system along with optical feedback, on the basis of time delay. The impact of the QDSL with optical feedback dynamics, under a linewidth enhancement factor

of 3, remains an important behaviour in the chaotic synchronization process. The study reached excellent outcomes at ($\tau = 410, 420$ ps) with complete synchronization that could be applied in coding and decoding signal communication activities.

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