Optimization for chaotic synchronization in a laser diode network by hybrid feedback and unidirectional injection

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In this experimental study, several control parameters that affect laser network synchronization are investigated, namely, laser bias currents, coupling strength, optical injection (OI) strength, optoelectronic feedback (OEFB) ratio, and optical feedback (OFB) ratio. Higher nonlinearities were observed when operating lasers far away from their thresholds. The system is operated by twin laser sources in both transmitting and receiving units. Novelty is regarded by making each one of these two lasers subject to OFB and also OEFB in addition to unidirectional OI. The effect of feedback and the unidirectional OI technique is to avoid information leakage from the slave laser (SL). This is also supported by the change in time delay associated with each OFB and OEFB laser. Such a technique is called hybrid feedback and injection (HFBI). Even though a more complicated system is proposed, identical chaotic synchronization is optimized by reducing mismatching and controlling coupling strength sufficiently. Identical chaotic synchronization is achieved with different calculated cross-correlation values, which are increased from 24% to 78%. The maximum value for hidden information within chaotic modulation that was achieved and archived experimentally is 500 MHz. Synchronization diagrams provide evidence for zero-leg synchronization with no anticipated shift for resulted dynamics. Such a result occurred with the arrangement of the receiver signal time delay to compensate for the delay that comes from the signal sent from the transmitter until it reaches the receiver.

(Received September 23, 2023; accepted April 8, 2024)

Keywords: Chaotic Synchronization, Laser Network, Cross Correlation

1. Introduction

Studying chaotic dynamics in laser diodes meets increasing application areas. Neural networks, including the electrochemical communication system in the biological body, and their dynamics have been shown to be consistent with the definition of chaotic oscillation. Such a system shows some similarity to Rossler's single-band chaos with enhanced dynamical noise [1].

Besides human systems, a variety of systems, from physical to chemical, are interested in studying chaotic synchronization [2]. On the other side, laser oscillator synchronization with a radio frequency, (RF), reference signal is extremely important for a modern light source based on the accelerator. A mode-locked laser oscillator with femtosecond root mean square relative jitter is synchronized to an RF reference signal [3]. Last ref. reported the implies the interaction between two signals. One of them is considered the laser source (mode locked) while the other is an oscillator. This has found use in the digital phase detector, which was used for phase measurement. Different classifications for synchronization have been considered within the case of two coupled actual chaotic frameworks, e.g., generalized, complete, slack, phase synchronization, and so on. When the stage difference between two chaotic frameworks becomes bounded and moves chaotically within a small extent, phase synchronization occurs, whereas their amplitudes would otherwise be disorderly and uncorrelated [4].

There are also two available techniques resulting from the direction of optical power flow from the first to the second laser. The first one is called unidirectional, and the second is called mutual feedback. In the first coupling mechanism type, the resulting chaos synchronization is based mainly on the symmetric operation mechanism between the two coupled lasers. In the second type, two types of synchronization, referred to as isochronal chaos and leader-laggard chaos synchronization, are achievable [5]. In addition to these two types, there are two types of synchronization in unidirectional coupling external cavity laser diode (ECLD) systems. Complete and generalized chaotic synchronization mechanisms for these two types of chaos synchronization are based on the symmetric operation and the injection-locking effect, respectively [6]. Synchronization itself is classified into two types. The slave may be intrinsically chaotic (being stable alone), or it may simply copy, because of injection, the master's optical chaos. The first case is referred to as a "closed loop," while the second case is referred to as an "open loop" [7].

Electronic circuits' chaotic generation is an old technique. The maximum frequency for the chaotic carriers is a few tens of kHz, and the dimensionality of the generated chaos is low, allowing for easy interception and recovery of the transmitted message. Thus, on the one hand, transition to optical feedback (OFB) and optical injection (OI) was the main goal that attracted authors. On the other hand, a hyper-chaotic [8] carrier, i.e., a high dimensional chaotic attractor, is suggested by [9] as a mix technique between OEFB, with external modulation, and OFB via air optics. This is essential to ensuring privacy in optical communications. The higher the complexity of the chaotic carrier, the more difficult it is for any eavesdropper to decode the message.

The external cavity technique has recently enabled encryption up to 12 GHz with chaos carriers, as reported by Ref. [10]. This type of modulation, Frequency Modulation, (FM), for a LD subjected to feedback is available by applying a modulation of a periodic signal to the phase of the field of electromagnetics. This is to be accomplished either directly by the bias through current modulation or indirectly by an external phase modulating element [11]. For generic, laser mode is locked with an FM modulator.

Including the solution of the master equation for mode locking by using the moment method, the evolution of five pulse parameters is given as the time-varying equations. These are parallel to the well-known rate equations used for CW LDs. They are referred to as the FM mode-locking rate equations, which are all given in Ref. [12].

According to this model, all the following parameters affecting the laser emission-the round-trip time, the round-trip cavity length, small-signal gain, modulation depth-all affect the time varying pulse energy, temporal shift, frequency shift, chirp, and width.

Excitation of broad band nonlinearities, especially chaotic carriers, was studied by employing several techniques, such as attenuated OEFB [13, 14, 15], filtered OFB [16], as well as chaotic modulation [17, 18], and OI [19].

The Lang-Kobayashi equations are known to be a good model of coupled LDs with external cavity and weak optical feedback [20, 21]. While in case of subjected to optoelectronic feedback, rate equations model for LDs is given as reported in Ref. [11]. According to that model, the time rate change of internal cavity photon density and the density of carriers are affected by; "optical gain coefficient and dimensionless feedback factor". This corresponds to the following parameters: strength of the OFB and OEFB, feedback delay time and laser bias current density, device cavity photon decay rate, the spontaneous carrier decay rate. the laser waveguide confinement parameter, the electronic charge constant, the thickness of active layer, the free-running condition gain coefficient, the differential gain parameter, and the nonlinear gain parameter. Finally, dynamics for LDs under optical injection are reported by [22]. There is no clear theoretical model for the case of subjecting to three previous perturbation sources together with modulation affecting the laser network.

Till the present, most of the studies on external cavity laser diodes based on chaotic synchronization and communication have been concentrated on both mutual and unidirectional coupling chaos systems. These systems are composed of such a laser under conventional pure optical feedback. Pure means the feedback light is a linear copy of the output light but with a time delay that is determined by the length of feedback loop or the optical attenuator that controls the time delay indirectly.

The synchronization quality between two lasers is evaluated by following correlation coefficient $C(\Delta t)$ abbreviated as CC [23]:

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

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 CC is ranged as $-1 C(\Delta t) 1$, where a larger value of $|C(\Delta t)|$ means larger synchronization quality.

Experimentally complex system theory is applied to the synchronization of numerous chaotic semiconductor lasers. It specifically took into account dynamical networks made up of interconnected nodes made of semiconductor lasers, where the interaction in the network is defined by coupling the initial state of each node. Theoretical model is reported in detail by Ref. [24].

Noise improves the synchronization of system behaviors against weak input signals in the stochastic resonance phenomenon, which is caused by stochastic additive noise. Deterministic chaos produces stochastic noise as well as chaotic resonance, a phenomenon similar to stochastic resonance. Symmetrical operations and injection-locking effects, can be achieved in unidirectional coupling systems, with two types of chaos synchronization, namely complete and generalized chaotic synchronization. Complementary to what research group was investigated in earlier experiments that can be found in references that had been listed previously in the paragraph on techniques for excitation of broad-band nonlinearities, including chaos. In the following section, we will preview the experimental set-up for the present work that supports a unidirectional OI with one-stage chaotic to different chaotic emissions within a synchronized network.

Recently, a remarkable technique known as "asymmetry-induced synchronization" has been put out and thoroughly investigated. According to this scheme, the dynamical system must be asymmetric in order to maintain its stable symmetric state. This implies that, rather than creating new dynamics, the introduction of heterogeneity can be used to consistently improve the stability of synchronization in a symmetric network (or identical network) [25]. When two adjacent numbered nodes achieve successive lag synchronization, (S-LS), there is a temporal delay before they reach the same state. To be more precise, the singular network defines the S-LS, which can be thought of as a generalized version of the generalized type of LS, which is described in coupled networks [26].

Network architecture, and these symmetries dissociate the stability of cluster synchronization into separate groups. OEFB loop synchronization of intricate LDs networks with any topology have been proposed recently. Various control mechanisms, are suggested to regulate the stability of cluster synchronization in mutual networks. With a cluster synchronizes, members will synchronize to uniform dynamics, while other clusters will evolve along distinct trajectories [27].

Since the laser system has an infinite number of degrees of freedom due to the delay period involved, feedback-related physics, investigated by Lang and Kobayashi, can generally be quite complex. When the physics of the effect of OI on LD is examined, this "delay-time" property is gone. First technique was demonstrated that an LD exposed to external OFB can exhibit "hysteresis" and "multistability", similar to a non-linear Fabry-Perot resonator. While, second technique with the use of fiber Bragg grating or distributed Bragg reflectors, OI devices act as a simultaneous filter and amplifier, which is very useful in optical fiber networks. Employment for theory of both techniques can give attractive phenomena especially when a third type of feedback is applied, OEFB. The overall technique will be named HFBI in this study.

2. Experimental

As shown in Fig. 1, the chaotic transmitter circuit consists of the first laser diode, LD1, which is subject to measured optical power of 40% before its detection and doing the OEFB. The remaining optical power, 60%, is directed optically toward a fiber ring cavity supplies its signal with a specific delay time. The delayed signal is directed toward optically injecting LD2 into the same transmitter unit. As a result, optical power that came from LD1 arrives at LD2 with a perturbed (chaotic) signal. LD1 is monitored and controlled during the OEFB by a photo diode, PD_1. This power portion is initially controlled by a fiber Variable Optical Attenuator, (VOA), with a Beam Isolator (BI) to guarantee unidirectional OI of optical power from LD1 to LD2 and not the reverse flow. Which is recommended for utterly eradicate the chance of second laser information exposure that increase when bidirectional injection permitted [28].

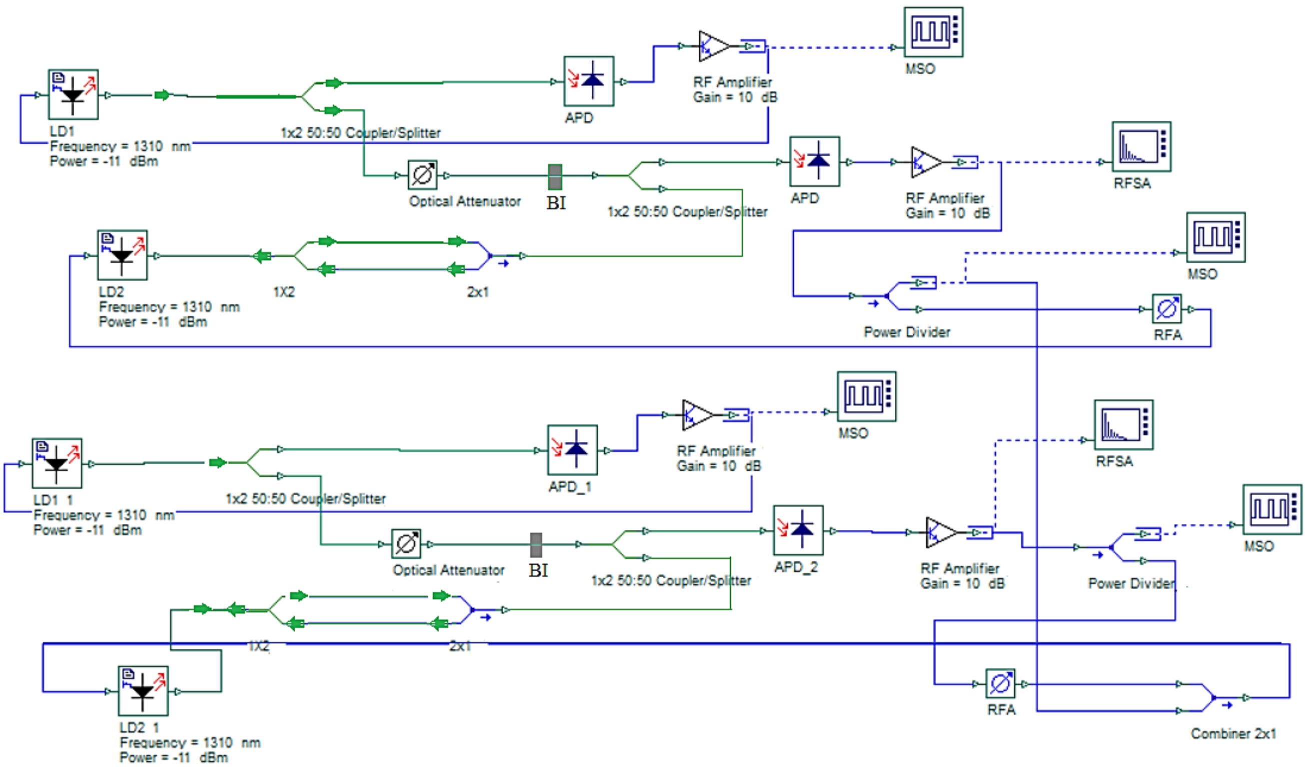

Fig. 1. Experimental set-up for closed-loop chaotic synchronization based on HFBI technique, abbreviations are reported during the text (color online)

Both of these two lasers are connected to two laser Peltier cell coolers with sensor and Ardonic type control to screen and keep their temperatures. Temperature fluctuation with such cell is around 0.5 ^{o}C. Matching operating temperature adapt minimum detuning during OI. Additionally, LD2 is also subjected to OEFB adjustable by RF, attenuator (1-10 dB scale). According to this setup, LD1 is considered the injector (master), and LD2 is the follower. The output signal is monitored and modified by the photo detector, PD_2. Which is sent to the receiver as an RF signal. According to this set-up, there is a main master laser and three SLs. During the text, they will mention slave to indicate the observed signal from the receiving circuit.

The observed data were analyzed as frequency spectra using the RF spectrum analyzer, RFSA, (MS2665C) and as a time domain using a mixed signal oscilloscope, MSO, and as attractors derived from time series. Further analysis is based on time series fast Fourier transformation. Direct frequency modulation has been implemented using (HP 8620C) sweep oscillator. The receiver unit, which is identical to the transmitter unit, is constructed as a twin circuit to that of the transmitter. This unit receives the coming signal from PD_2 as a modulated signal that injects the second SL, LD2, into the receiver unit. The latter receives dynamics from two sources, second master laser diode, LD1, and PD_2 both via a mixer.

3. Results and discussions

In addition to classification that has been mentioned in the introduction; there's another type of synchronization classification. Anti-phase synchronization, APS, in coupled chaotic frameworks has been detailed for numerous characteristic tests and hypothetical scope. In APS, the parameters of two collaborations, chaotic oscillators have the same intensity but vary in their signs. It is found that in a synchronization regime, total laser intensity breakdowns occur, commonly referred to as a Low Frequency Fluctuations, (LFF), chaotic regime. These dynamics are determined by a sharp decrease in the laser intensity (as if the laser were off), followed by slowly recovering. The time durations between two consecutive decreases are chaotic [29]. This emission in laser diode system occurs from a rapid transition of chaotic region among destabilized limit-cycle attractors that match to the external cavity modes of the OFB toward a self-pulsating dynamic of higher frequency and increasing output power [30].

With synchronization, intensity breakdowns of both lasers are observed experimentally, and the system tentatively desynchronizes, comparable to what has been reported in [31]. In order to avoid these irregularities, we calculate the CC for each observed signals matching in emission, in order to make a selection for the highest value. Calculated CC When the LD1 (master laser) is in the transmitter unit, the current is set below 21.3 mA, which is very low, equal to 23%, indicating very low correlated signals due to the decreased operation current level.

Fig. 2 gives the attractors for (A) master (M) laser in the transmitter unit and (B) slave (S) laser in the receiver unit and (C) master – slave time series. As shown in these two attractors, lasing modes follow an infinite number of emission modes and trajectories, indicating chaotic behavior for both lasers. The achieved data primarily depicts the presence of an experimental attractor with clear construction, which is necessary for a needful process. These dynamics are recorded when the two laser parameters were as the following:

The transmitter unit: LD1, master laser, current: 21.3 mA and voltage: 1.7V, LD2: current: 90 mA and voltage: 4.6V, LD2 OEFB attenuation: 2dB. Receiver unit: LD1 current: 46.5 mA and voltage: 4.8V, LD2 current: 90 mA and voltage: 4.6V, LD2 OEFB attenuation: 5dB, for both lasers temperature is equal to 21 ^{o}C. Measured OI rate is 23.29%, noting that all reported parameters are also given in the same figure.

Authors seek a better chaotic signal with less mismatching between the two units' signals. Thus, the initial conditions (including currents, OFB and OEFB) investigated in the study were primarily considered random and then arranged in a logical manner.

As shown in part A, from the figure, positive and negative amplitudes are shifted due to the shift in phase of the two lasers. While receiver dynamics anticipated transmitter dynamics, such a phenomenon can be understood from the delay time (leg) it undergoes for the signal to travel from the first to the last laser. The resulting effect is leg synchronization.

It is convenient that the oscillator's phase is much more sensitive to perturbations than its amplitude. For low network laser coupling strength, two units' interacting oscillators can have mismatch of their phases with the interaction hardly affecting their amplitudes.

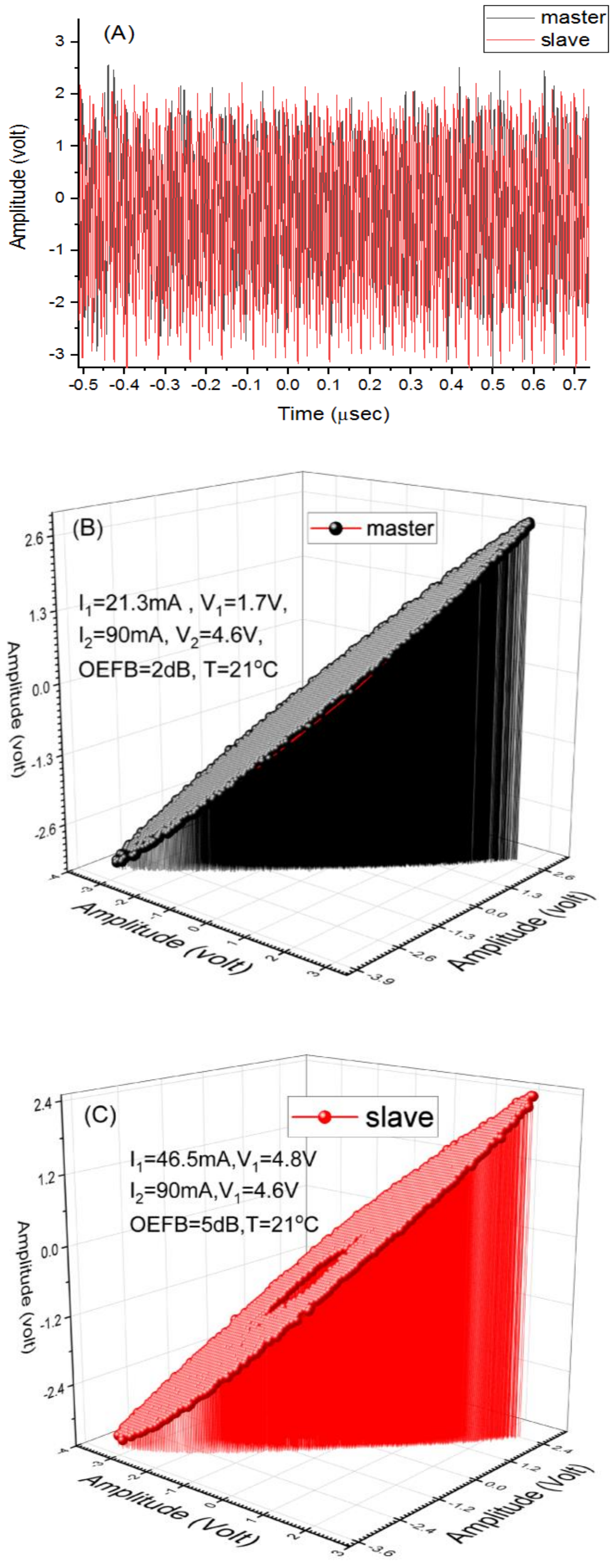

Fig. 2. Measured Master - Slave (M-S) resulted chaotic dynamics in transmittance unite. "(A)" time series, "(B)" and "(C)" their chaotic attractors (color online)

The master-slave (M-S) two signal mismatch for the injection currents is appearing in part C of the figure, which seems too large. Theoretically, intrinsic characteristics of the LDs outputs, such as the emission wavelength and oscillation frequency, are closely dependent on the injection current, while in this experiment, the network exhibits different responses.

In Fig. 3, which includes the D, E, and F subfigures and the M-S synchronization diagram, two signals synchronize and CC (calculated using the OriginPro 20 software), respectively, are all presented.

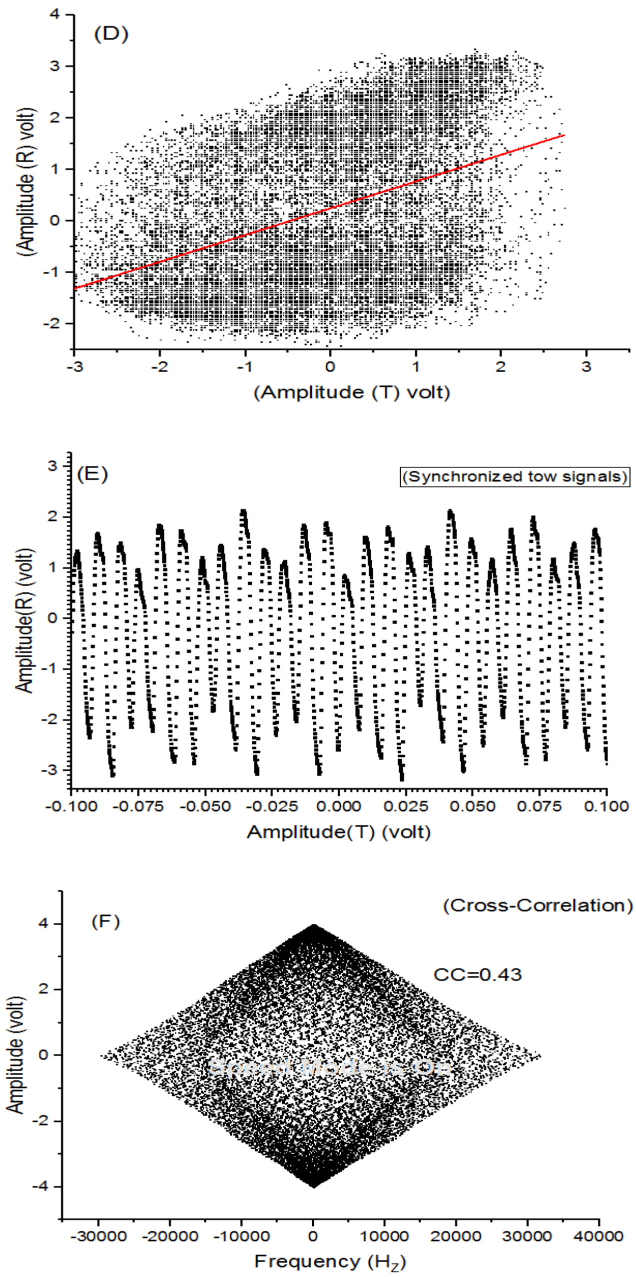

Fig. 3. Calculations and examination for M-S Cross-Correlation for data achieved from Fig. 2. "(D)" synchronization diagram "(E)" Synchronized two signals "(F)" Cross-Correlation

The two signals are not correlated, but even with this low value (CC=0.43), the synchronization diagram subjected to linear fitting and both signals are still synchronized with general type. This synchronization is due to direct RF modulation by modulation, which makes the S laser follow the M laser via its bias.

As mentioned in Ref. [32] CC meter gives the correlation for +1 and anti-correlation for -1. Observations for Fig. 4, CC, drawn from time trace, ranged from anti. (blue) to correlated (red). It shows that the achieved value tends towards red, i.e., that is, a linear amplitude relation existed between these two chaotic lasers.

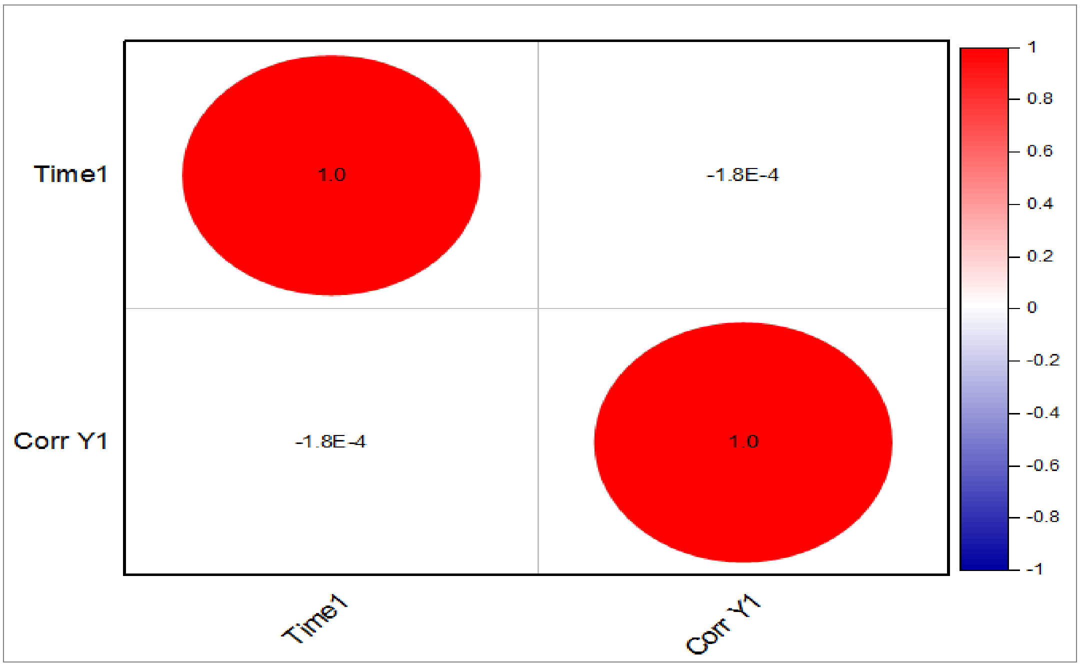

Fig. 4. Calculations and examination for M-S Cross-Correlation for data achieved from Fig. 3 (color online)

It is clear that the correlation between M-S lasers for measurement given in Fig. 3 is low because the generated dynamics only affects the feedback phases, detuning, of both lasers. This implies matching in operating conditions for these lasers. Bias voltage, operation current and ambient temperature, all affecting peak wavelength in default case. In the present experiment, all previous parameters contribute as a network, which makes it far from the default case. The generated nonlinearity of phase modulation perturbations associated with heat fluctuations are the difference between laser and temperatures. The expected chaotic term source is quite complicated, where there are three terms affecting the rate equations, portion for the OFB and its delay, OEFB and its delay and finally, OI with its own delay. All gives a complex nonlinear relationship with the output of these two lasers. As a result, the evolution of optical fields for M-S systems, including their networks, is functionally correlated to each initial condition in the set-up.

It is worth mentioning that this observation is different from that in the scenario where the output of only one LD in the transmitter unit is directly injected into an identical LD in the receiver unit. As mentioned in the previous introduction section, in order to achieve an identical chaotic pattern and then identical synchronization, a symmetric operation is needed, otherwise an injection-locking effect arises.

Going to new operation parameters in master laser, reported in Fig. 5, for the network. The transmitter unit: LD1, master laser, current: 42.1 mA and voltage: 2.3 V, LD2: current: 90 mA and voltage: 4.6 V, LD2 OEFB attenuation: 2 dB. Receiver unit: LD1 current: 46.5 mA and voltage: 4.8 V, LD2 current: 90 mA and voltage: 4.6 V, LD2 OEFB attenuation: 5 dB, for both lasers temperature is equal to 21 ^{o}C.

Results for the M-S time series are given in part A from the figure, in which amplitudes are fluctuated in both signals in a slightly different manner with less mismatching in position with periodic attractors in B and C. Shifting in positive and negative time series for the two amplitudes is lower than that in parameters observed in Fig. 2A.

Such observation agrees with research by Braiman *et. al.*, which is reported in Ref. [25], which demonstrated that introducing random spatial variation can significantly improve synchronization. Furthermore, by arbitrarily disordering the pendulum lengths, a chaotic condition of identical arrays may be transformed into a well-synchronized periodic behavior. Since variety will stifle chaos and provide a coherent pattern.

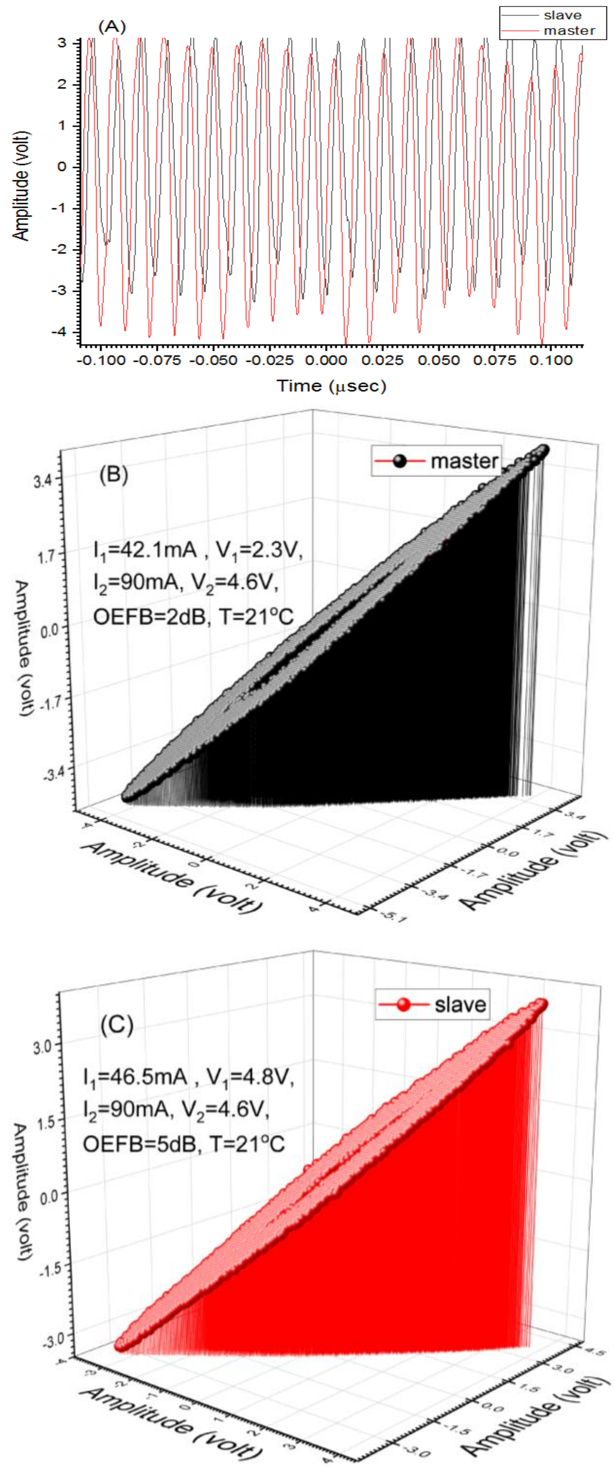

Fig. 5. Measured M-S dynamics in transmittance unite. "(A)" Time series, "(B)" and "(C)" M and S chaotic attractors, respectively (color online)

The CC is shown in Fig. 6, which is increased to 59%. This means that LD1 is forcing the laser network to operate in a similar manner.

This value for CC indicates that the injection-locking effect is despot, where the evolution of M laser is driven towards that of S laser, and consequently, the CC between them is rather high in both Figs. 5 and 6. They can even synchronize with each other as long as the injection from the first one is sufficiently strong, i.e., its operation parameters increase.

During this experiment operation, as mentioned above, currents and values are different, and OEFB is also different. Such a difference is interpreted as equivalent parameters to compensate for the expected real mismatch between the two separated units. Recalling that OFB and OI both remain constant, indicating that their effects are matched in the two units.

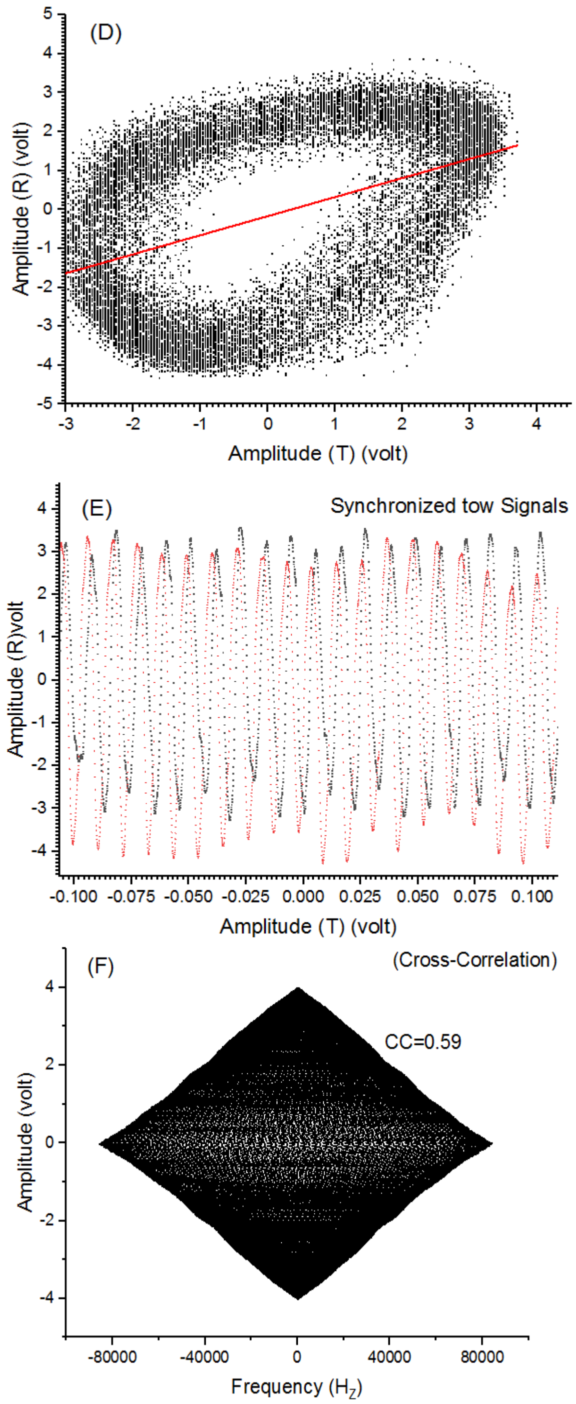

Fig. 6. Calculations and examination for M-S Cross-Correlation for data achieved from Fig. 5. "(D)" synchronization diagram, "(E)" Synchronized two signals, and "(F)" Cross-Correlation (color online)

It is also observed that when the ratio of the CC was less than 50%, the dynamics of one of the two lasers would be dominant over the other, while when the ratio of the cross correlation was increased more than 50%, we would notice the appearance of both lasers matching together looks like a one signal.

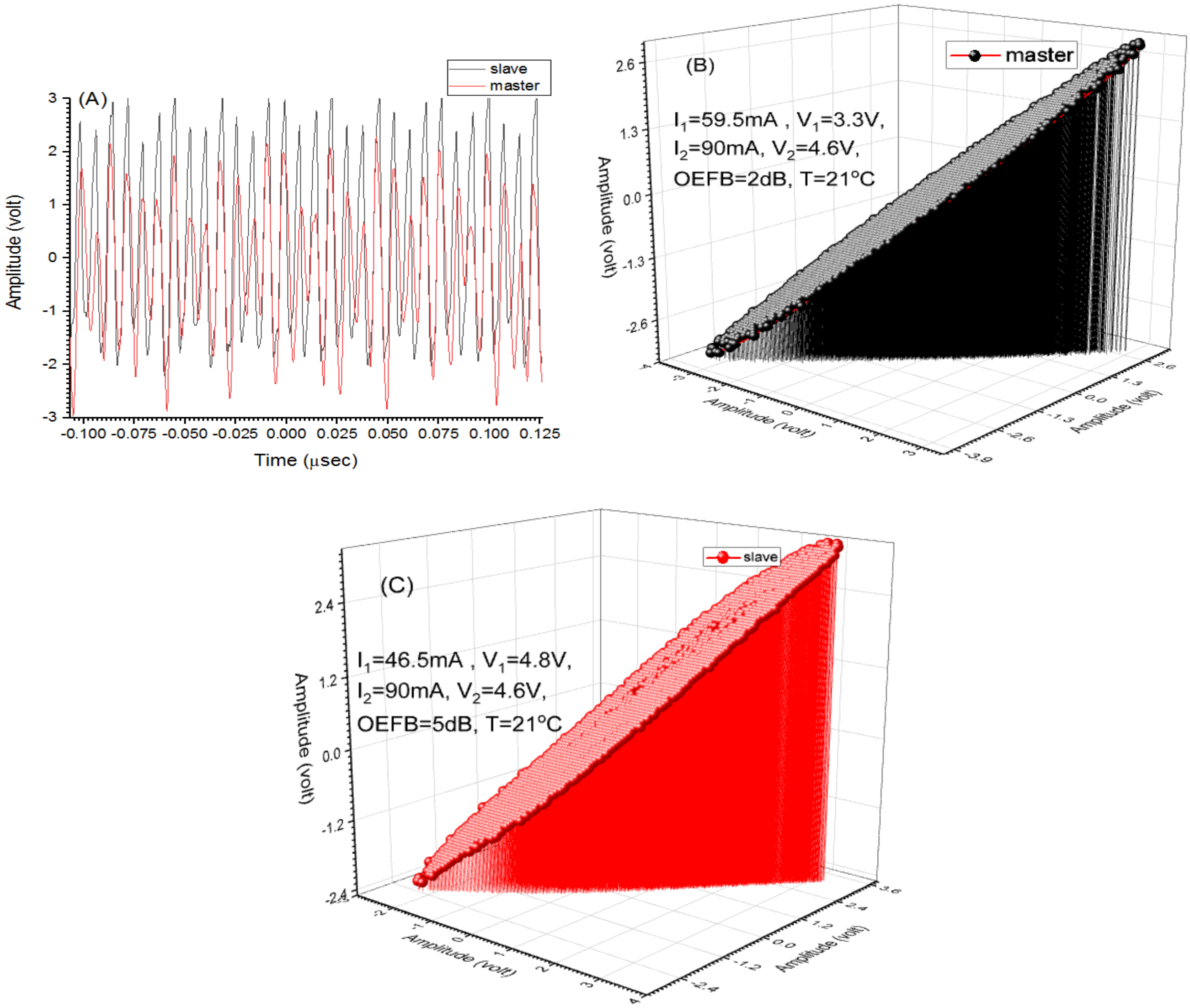

Fig. 7. M-S dynamics in transmittance unite. "(A)" time series,"(B)" and "(C)" their chaotic attractors (color online)

As reported by Ref. [33], the measurement of the anticipation time between the transmitter and receiver lasers can be confirmed by studying the quality of synchronization between them outputs. The last is related with cross correlation and synchronized two signals' figures. The peak amplitude relation for both lasers is given in Fig. 6D, with a circular shape M vs. S relation, with y-shifted linear fitting.

Fig. 7 depicts a new variation in master laser initial condition as the following parameters.

The transmitter unit: LD1 current: 59.5 mA and voltage: 3.3 V, LD2: current: 90 mA and voltage: 4.6 V, LD2 OEFB attenuation: 2dB. Receiver unit: LD1 current: 46.5 mA and voltage: 4.8 V, LD2 current: 90 mA and voltage: 4.6 V, LD2 OEFB attenuation: 5dB, for both lasers temperature is equal to 21 ^{o}C.

The time trace observed in Part A of Fig. 7 indicates a matching between the two laser signals. Such a matching is interpreted as a zero-leg or elimination for the time delay covered by the transmitter signal. Anticipated time is, in fact, compensated by adding additional delay to the receiver signal to overcome the delay.

As evidence for chaotic emission, time traces present the variable amplitude level for all peaks within the observation range. Furthermore, the time intervals for each identical peak are also variable. Both of the last observations give the property of chaos. More confirmation for these dynamics comes from the attractors and parts (B and C) in the last figure; they give another evidence as they are strange with an infinite number of lasing modes for the expected time evolution of the system.

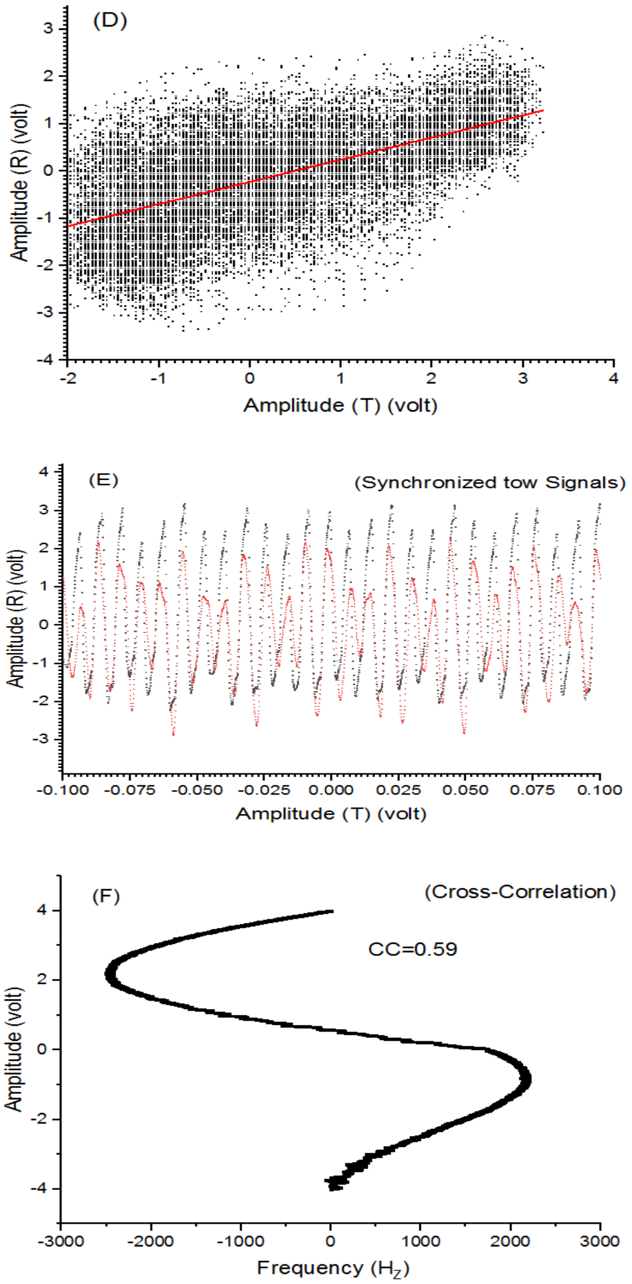

Fig. 8. Calculations and examination for M-S Cross-Correlation for data achieved from Fig. 7. "(D)" synchronization diagram, "(E)" Synchronized two signals, and "(F)" Cross-Correlation (color online)

In case of changing only voltage for M laser, and keeping all remaining parameters as it, results are given in Fig. 9. It indicates a large change in M-S laser outputs than those observed with last run.

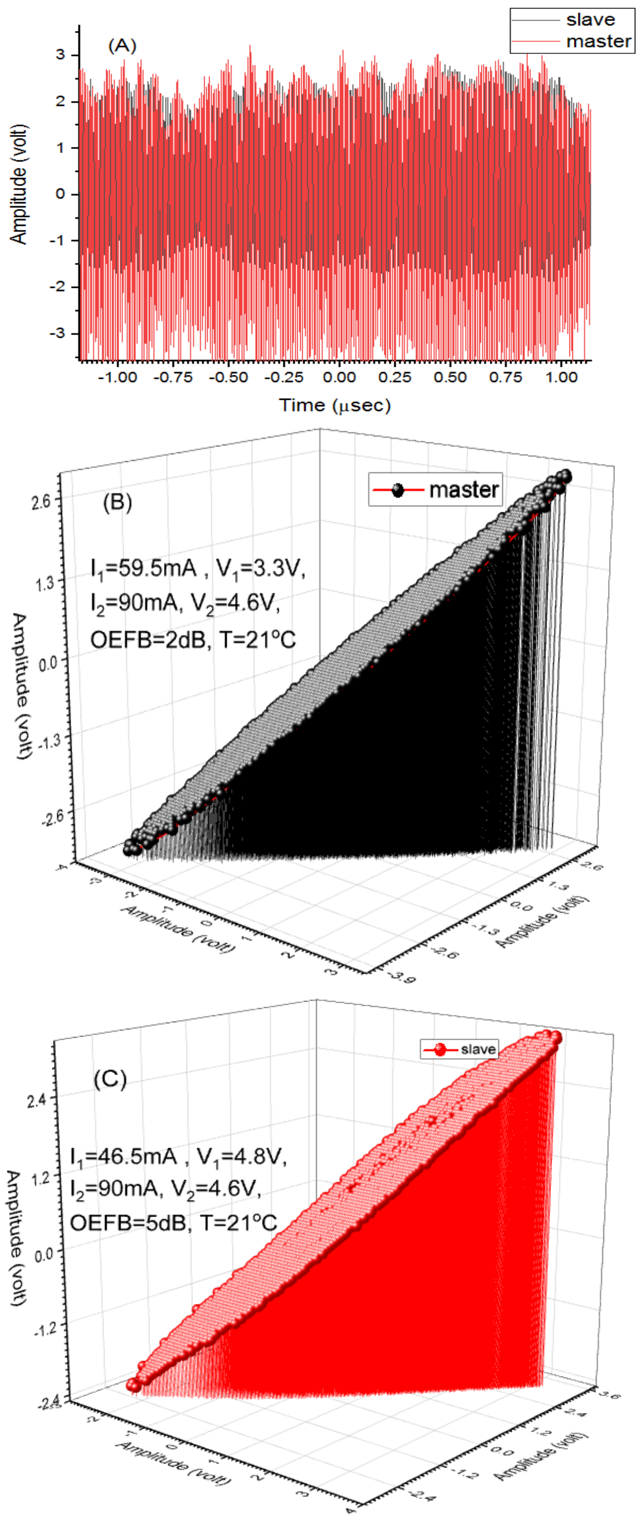

Fig. 9. Measured Master - Slave (M-S) dynamics in transmittance unite. "(A)" time series, "(B)" and "(C)" their chaotic attractors (color online)

Time trace in this figure shows chaotic signals with mismatching. Emission during the operation of system is unstable with no periodic behavior.

Measurements and analysis for CC with signals given in Fig. 9, is given in Fig. 10. Matching should be qualified by setting feedback parameters then comparison with respect to the theoretical model, which is not available for three feedback (OFB, OEFB and OI) techniques. Feedback strength affects the OFB and also OEFB, while detuning is affecting the OI. Thus, the results quality can be calibrated by comparing them with statistical rules in such a situation. Good matching, as reported by Ref. [33], for M-S emitted signals should obey both linear fitting for the synchronization diagram and a slope equal to (1).

Likewise, Fig. 10D shows the M-S synchronization diagram with less slope means less synchronization quality. The ratio of the existing remaining mismatches is related to the effect of signal first order dispersion and attenuation during transmission via optical fiber, attenuator, connectors, and couplers.

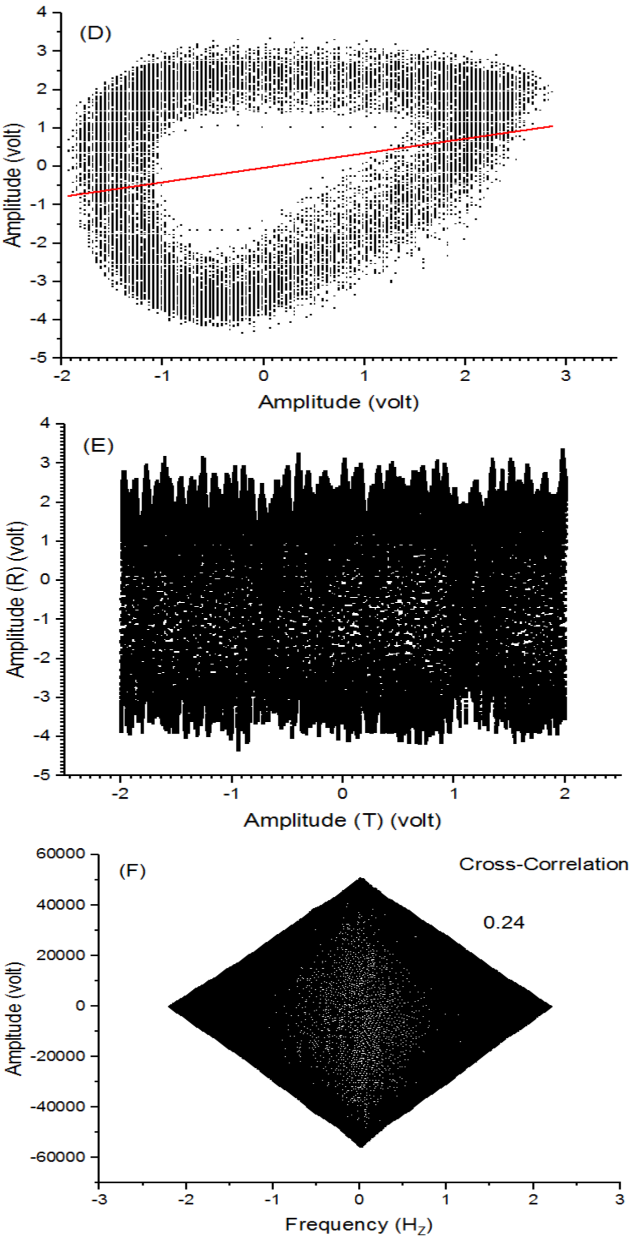

Fig. 10. Calculations and examination for M-S correlation for data achieved from Fig. 9 "(D)" synchronization diagram, "(E)" Synchronized two signals, and "(F)" Cross-Correlation

Ref. [34] reported that different laser modes in solitary laser running, class-B lasers, are subject to relaxation oscillations (ROs) that induce positively correlated dynamics. This observation is also valid in the presence of optical feedback and injection in our experiment. Therefore, it is assumed that the shifted frequency components which correspond to the correlated dynamics of polarization modes are related to the ROs.

In general, the synchronization quality is mainly affected by dispersion value and modulation index. The synchronization is more stable in addition to these parameters, in addition to other parameters related to efficiency of feedback techniques and the variation that the signal should satisfy during this setup before reaching the receiver. The observed signal to noise (SNR) for the chaos signal in the electric domain is slightly degraded. Again, the output of the slave unit is highly similar to that of the master with CC > 0.59. Even though small noise is recorded by RF spectrum analyzer, shown in Fig. 11, the existence of such a noise level does not affect the CC, while stronger noise (OSNR < 20 dB) will definitely ruin the consistence of waveforms in the receiver. The Fourier space in the last two figures confirms the fluctuated pulsation for the two M-S lasers with shifted amplitude frequencies and generation of new side mode in S spectrum. Frequencies in M laser signal has less broadening that that observed in S laser spectrum.

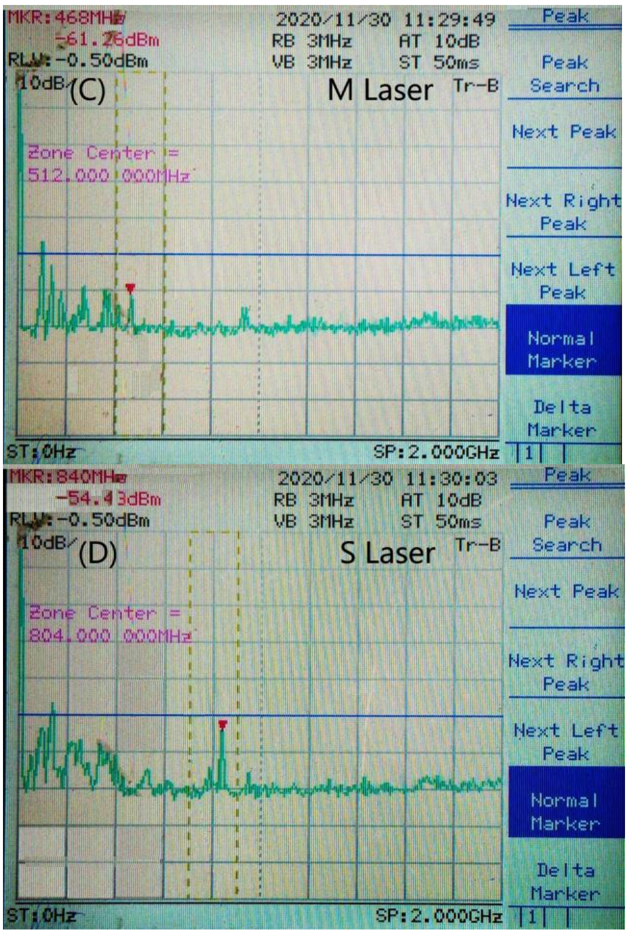

Fig. 11. Fourier (RF) spectra for M and S lasers signal from observations given in Fig. 9, "(C)" M laser, "(D)" S laser (color online)

The system also has the probability of being further developed based on the proposed hybrid design principle to achieve more complexity. This system's performance could be influenced by different implemented techniques in analogue and also digital transmission. For example, an additional nonlinear transform in the analogue part may increase the dynamical complexity. This is the cost of degradation of the synchronization performance.

As shown in Fig. 10, stronger interaction between the subsystems of a laser network leads to a more stable synchronization manifold, but synchronization is only stable in that range for which coupling strengths meet special types of parameters for the dynamical system, such as that achieved in Fig. 8 in which $CC \geq 0.50$, or more matching with greater CC value. This result gave desynchronization thresholds mentioned in pioneer Refs. [35] and [36] which are the size limits for an identical synchronization for an array (network) of linearly coupled systems

Going to other operating parameters for LD1 M laser, which is shown in Fig. 12, as the following; LD1 current: 80.9 mA, voltage: 4.4 V, LD2 current: 90 mA, voltage: 4.6 V, OEFB attenuation: 2 dB. Receiving unit: LD1 current: 46.5 mA, voltage: 4.8 V, FM=500 MHz. LD2 current: 90 mA, voltage: 4.6 V, OEFB attenuation: 5 dB.

Semiconductor laser response to direct modulation by including a current term inside rate equations. Such a term is proportional to the uploaded frequency value and, consequently, signal phase. Interactions then occur between modulation frequency and external cavity modes, resulting in new forms of chaotic signals.

According to last parameters for M laser, the CC is enriched but the chaotic behavior, observed in in parts B and C from the figure, for the two signals is lost. It was observed during the experiment that chaotic transmitter unite affects uni-directionally and chaotic receivers, but still the latter is able to enrich the oscillations of the first one with advanced peaks than transmitter.

As reported by Ref. [33] anticipated and zero-lag synchronization, as an elusive phenomenon, are both relates the time delay expected to make leg in receiver dynamics. It observable when drawing synchronize two signals or even drawing the two signals in time series together. Receiver will advance transmitter amplitudes. Such effect is observed in our results (Figs. 4 and 5). While remaining plots gives no delay due to adding delay intentionally to the receiver signal.

Any small-time delay present in path from transmitter to receiver may also cause phase reduction and phase lock, as reported in Ref. [37]. In additional, anticipation time does not depend on the external-cavity length in the pure OFB regime.

This result agrees with what has been mentioned in Ref. [38]. For the case of modulation, frequency spectra for each given measurement from the above are taken simultaneously as the following; Statistics for M-S lasers signals that given in Fig. 12 is calculated and shown in Fig. 13. In part D, synchronization quality is increased, in part E matching is decreased, while the CC diagram is reinforced. The calculated CC in these operating parameters reaches its maximum value (78%) in the overall investigated parameters. This large value is the result of the application of external modulation that reinforced the master laser signal to interact in different conditions with SLs signals, resulting in higher synchronized signals.

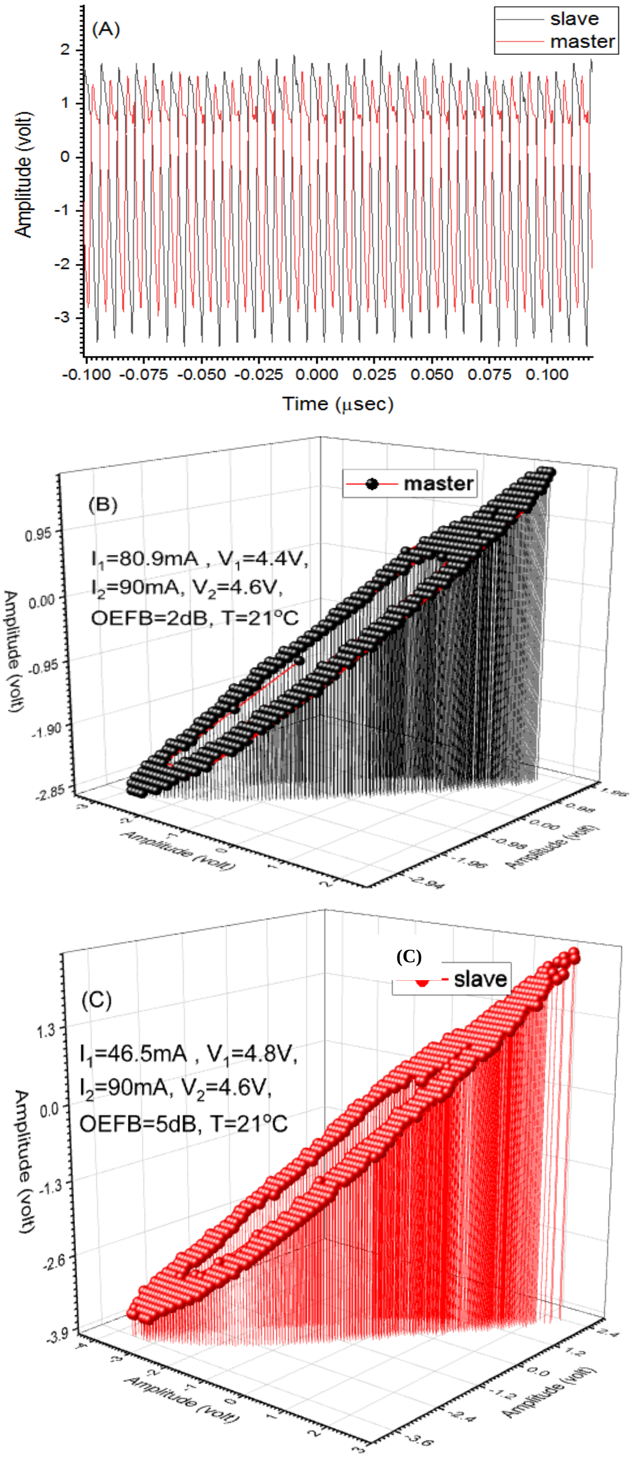

Fig. 12. Results for M-S dynamics in transmittance unite. "(A)" time series, "(B)", and "(C)" are two signals periodic attractors for M and S, respectively (color online)

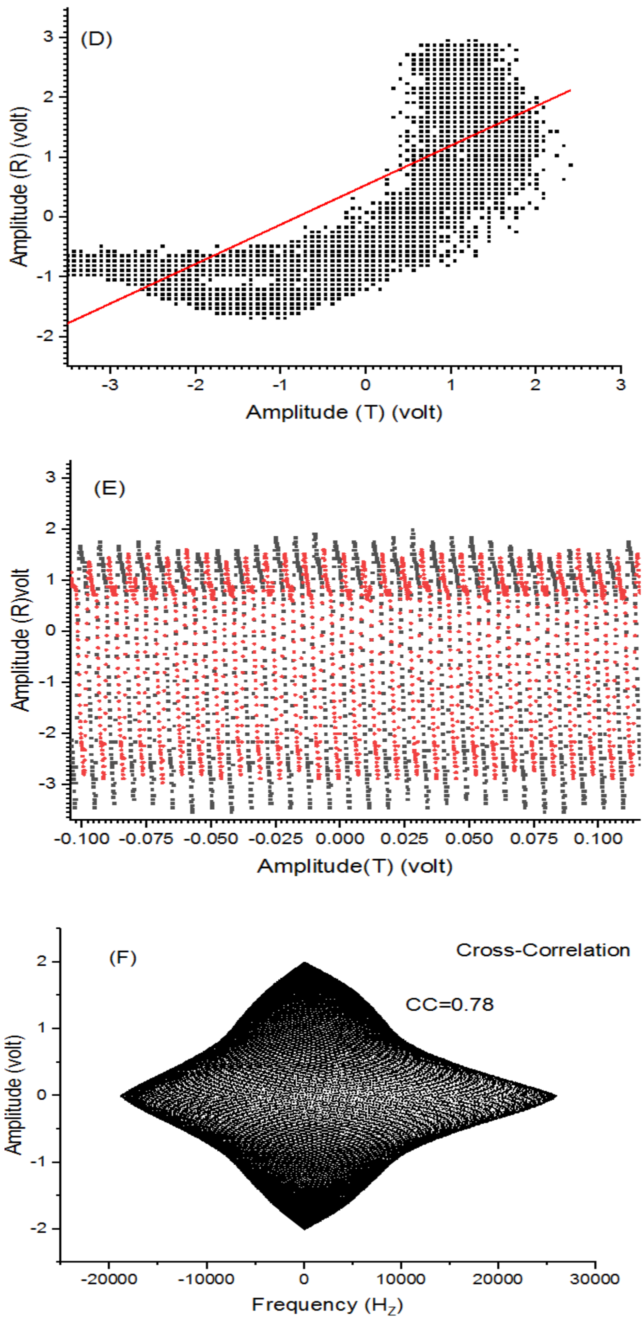

Fig. 13. Calculations and examination for M-S data achieved from Fig. 12. "(D)" synchronization diagram, "(E)" Synchronized two signals, and "(F)" Cross-Correlation (color online)

The Fourier space in Fig. 14, also confirms the fluctuated pulsation and spikes for the two M-S lasers with shifted peak frequencies and the observed new side mode in S spectrum is disappeared. M laser signal in this spectrum (part C) is broadened and in S laser spectrum (part D) has less broadening.

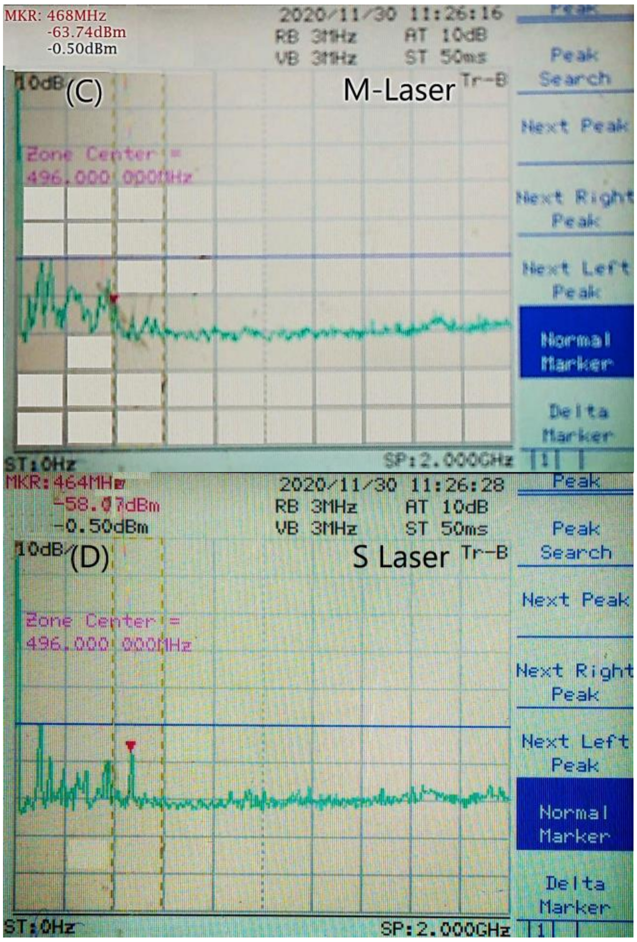

Fig. 14. Fourier (RF) spectra for M and S lasers signal from observations given in Fig. 12, "(C)" M laser, "(D)" S laser (color online)

Results indicate a fast variation in CC from maximum value to very low value. This satisfies a chaotic system's behavior. In which emissions do not have long-term prediction. This observation agrees well with what Ref. [1] mentioned.

For those results that have a high enough CC, one observes that synchronization between two units occurs in such a manner that dynamics are released from an interaction between several external resonating modes. In synchronous states, the second resonator is function to the first, and the dominant resonator behaves like the one in a single oscillator. Two types of synchronous states resulted, depending on which resonator was the dominant one. Fluctuation in the CC is associated with and affected by fluctuations in chaotic behavior in both lasers. While M-S lasers are, in this case, a system of lasers, they are in fact a network of disturbed lasers. This observation is also reported in Ref. [39].

4. Conclusions

A variety of delays to zero-leg synchronization with unidirectional RF chaotic modulation were observed in this study. The HFBI technique is applied to both transmitting and receiving units. With proper selection of the hybrid parameters, broadband-pulsation optical chaotic signals with high dynamical complexity are obtained. The resulting noise-like signal is a broad-band continuous waveform with different shapes. Its generation was conditional on the strength of chaotic RF modulation.

System destabilization during the synchronization is observed. Such a phenomenon is controlled by making feedback parameters match and then mismatch. This is to apply the concept of the varying topology in the cluster network. This approach connects changes in the synchronization levels for varying mismatches, making the master slave desynchronized and then synchronized with irregular and chaotic pulsation.

For chaotic communication and synchronization, identical M-S laser signals in a closed-loop are realized. M lasers forced all lasers in the network, resulting in synchronization degrees dependent on individual parameters for each laser in the network.

Acknowledgments

The authors would like to thank Mustansiriyah University (www.uomustansiriyah.edu.iq) in Baghdad, Iraq, for its support in the present work. Also, the authors would like to thank Professor Thorsten Ackemann, SUPA and Department of Physics, University of Strathclyde, Strathclyde, UK, for his important discussions.

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