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Experimental investigations of Synchronization in two optically coupled chaotic systems utilizing optical feedback and optical injection

Salam K. Mousa* **Qassim M.J.Abdulaziz **** **Kais.A. Al Naimee*****

* University of Anbar - College of education for pure sciences.
** University of Anbar - College of Applied Sciences-Heet
*** Baghdad University-College Of Science

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A B S T R A C T

An experimentally observations of chaos synchronization have been investigated between two optically coupled laser diodes. Two schemes of optical injection, bidirectional and unidirectional optical injections have been used. One of the two lasers MLD exhibits optical chaos due to external optical feedback by fiber mirror and the other laser diode SLD exhibits optical chaos by optical injection from the first one. The chaotic dynamics of both lasers were a function of laser diodes drive current. Synchronization and Anti-synchronization between two coupled laser diodes have been observed, and ensured by different measurements like time series matching ,correlation diagram(phase form)of amplitudes of coupled chaotic signals ,spectrum components coinciding of coupled chaotic signals, and coherence have been used for both injection schemes. .

1-Introduction:

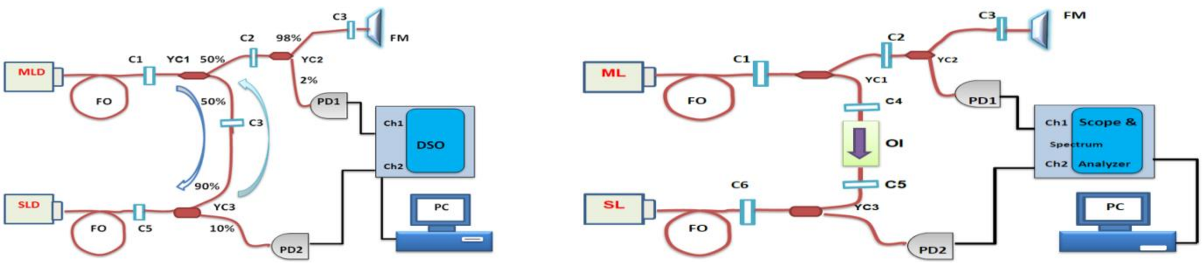
Since the seminal paper published by L.M Pecora and T.L.Carroll[1],chaotic synchronization have been taken wide interesting from researchers in different disciplines[2][3].Synchronization of chaos refers to a process wherein two (or many) chaotic systems (either equivalent or nonequivalent) adjust a given property of their motion to a common behavior due to a coupling or to a forcing(periodical or noisy)[4].Chaos synchronization has been intensively investigated in various nonlinear dynamical systems for its potential applications in chaotic communications [4]-[9].Synchronized chaotic mode hopping in two wavelength-tunable lasers have been demonstrated[10].Fast chaotic oscillation(several GHz) synchronization have been reported[11]. Synchronization of irregular spiking oscillators likewise of neuron and cardiac stimuli signals, based on Homoclinic model, have been demonstrated both experimentally and modeling[6][7][12][13].

* Corresponding author at: University of Anbar - College of education for pure sciences.
.E-mail address: salam_physics@yahoo.com

Chaotic Optically injected semiconductor lasers are promising candidates for many emerging applications including, for example, secure optical communications, high speed random number generators, chaotic radar , as well as the photonic generation of microwave signals, by properly selecting injection strength and frequency detuning, rich nonlinear dynamics, such as stable locking, period oscillation and chaos can be observed in an optically injected semiconductor lasers[8][14]. External cavity semiconductor lasers (ECSLs) have been a subject of extensive research ,because of the importance of optical feedback phenomena in technical applications like optical data storage and optical fiber communications. In most of these cases, the effects of optical feedback are to be avoided , Synchronization of low frequency fluctuation(LFF), which can be observed, in dynamics of coupled laser diodes subjected to moderate optical feedback, have been reported[15][16][17].One of the control methods of laser diode dynamics(e.g. wavelength tuning ,relaxation oscillation , regions of chaos dynamics and chaotic oscillation bandwidth)is by adjusting its injection current [18][19] .Recently synchronization phenomena generalized to comprises systems of chaotic network(more than two delayed-coupled chaotic oscillators) with different schemes of network configurations [12][13][20][21].There are different methods to measure quality of synchronization such as synchronization error, comparing spectrums of the coupled chaotic oscillators[20],[22]-[26]. The sudden transition to synchronization condition could be described by computing the mean of coherence value for all oscillators for the synchronized and non-synchronized conditions[27].Coherence has values of one when there is perfect linear interdependence the processes x and y, while it has values of zero in the case of absence of any interaction at frequency ω. At a certain frequency, when the coherence is equal one then two signals are considered to correspond to each other ideally at that value of frequency. Conversely, a coherence is equal zero. This implies that the signals are totally independent at that value of frequency.

2-Experimental setup:

In this work two schemes of optical injection have been used ,the first one is shown in the Fig(1)(a)which present the schematic diagram of the optical injection system of two optical chaotic oscillators .Both of the laser diodes(MLD and SLD) are affecting each to other at the same time forming Bidirectional coupling .The upper chaotic oscillator system consists as appear in Fig(1a)from laser diode MLD(pigtailed Anritsu GB5A016 laser diode of I_{th}=8.9mA)connected to 50:50 splitting ratio Y-coupler (YC1),which in turn one of its terms connected to external fiber mirror FM via fiber connectors C2 . The external cavity(EC) constructed from lasers pigtail plus coupler **YC1**(of 50:50splitting ratio) and fiber coupler**YC2**(98:2slitting ratio) ,the other term of **YC2**connected to fast response (NewFocus 1811 of <1ns rise time) photodetector **PD1** which connected to channel1 of DSO to detecting the upper laser(**MLD)** signal ,while the other term of the coupler **YC1** is connected to lower optical chaotic system(which consists from laser diode SLD and Y-coupler **YC3**of90:10slitting ratio) via fiber coupler **YC3**terminal .And hence the optical injection occurs by launching the optical power from each of both of the lasers to the other via the fiber connector **C3**.The laser diode **SLD**(Thorlab's bench top pigtailed Fabry Perot laser diode of I_{th}=10mA) is perturbed to chaotic state by optical injection from MLD .The signal of SLD is detected by fast response photodetector (NewFocus 1811)**PD2** .The detected signals from PD2 is connected to channel of digital sampling oscilloscope(DSOLeCrewLT342 with 25GS/sec) which also carryout other functions e.g. FFT analyzer of time domain signals, the digital oscilloscope is connected to the PC computer via the LAN network in order to extract the data from the oscilloscope. The external cavity of upper laser diode(MLD)has a 7meters of fiber length which gives τ_{ext} =2nL/c=70ns round trip time of the external cavity ,where n is the fiber core(Silica glass) refractive index ,C light velocity in the vacuum.



(a) Bi-directional optical injection **(b)** Unidirectional optical injection.**ML** :master laser diode **;** **SL**: slave laser diode **;** **C1-C6** : fiber optic connecters **;YC1-YC3 :** 1:2 **Y**-couplers **;** **PD1,PD2** : hi speed photodetectors**; FM** : fiber mirror **FO :** fiber optic ; **DSO**: Digital sampling oscilloscope; **OI**: Optical Isolator.

Figure(1) Experimental setup of (a)Bi-directional optical injection,(b)Unidirectional optical injection.

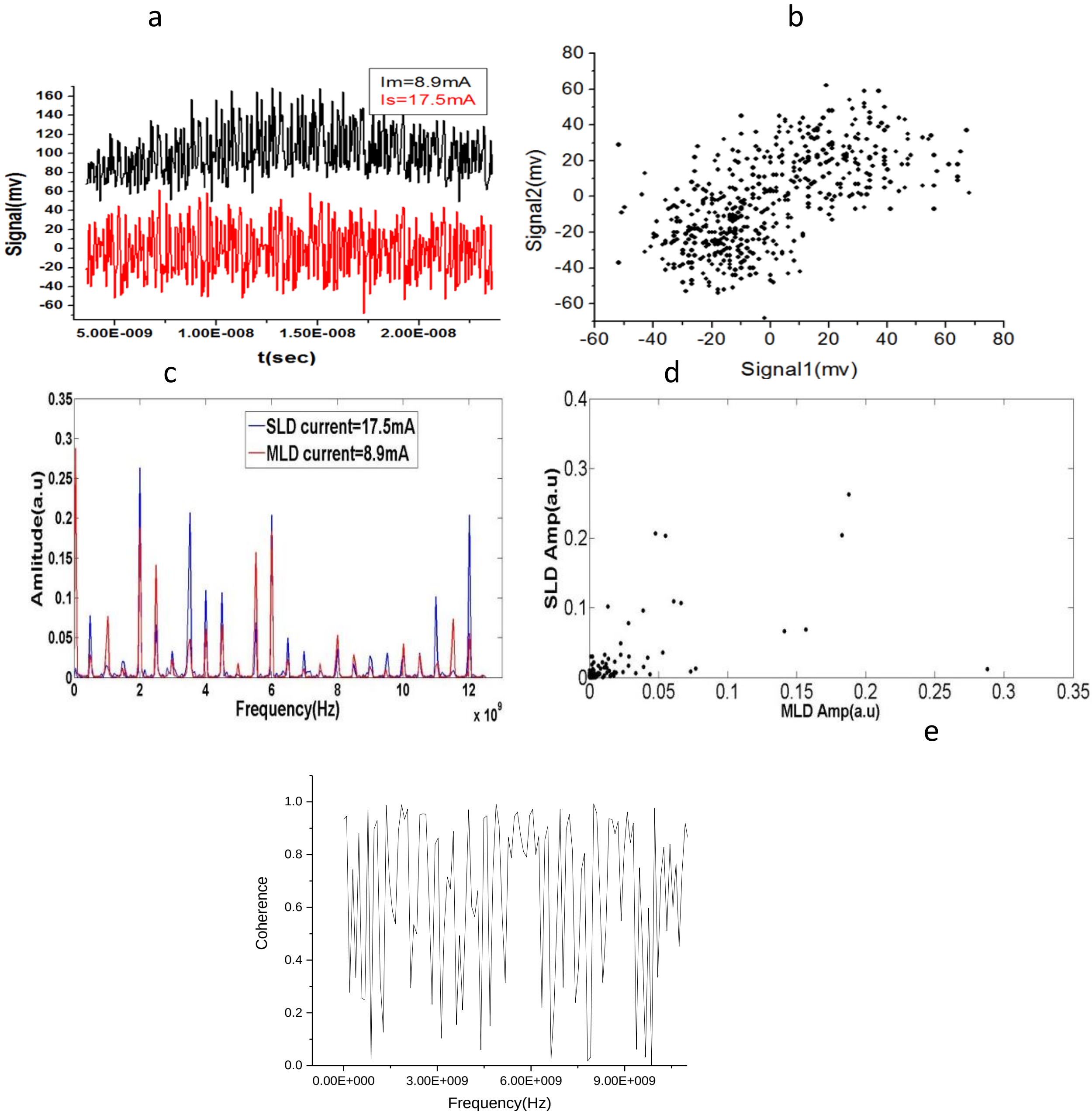
Fig.(1b), shows Unidirectional injection scheme that is by inserting optical isolator(OI) in optical injection path(between YC1 and YC3) to prevent optical light to launching from SLD to MLD ,in this case **MLD** is called **Master laser diode** and **SLD** is **Slave laser diode** ,therefore dynamical response will determined by master laser diodes behavior

3-Results and Discussions:

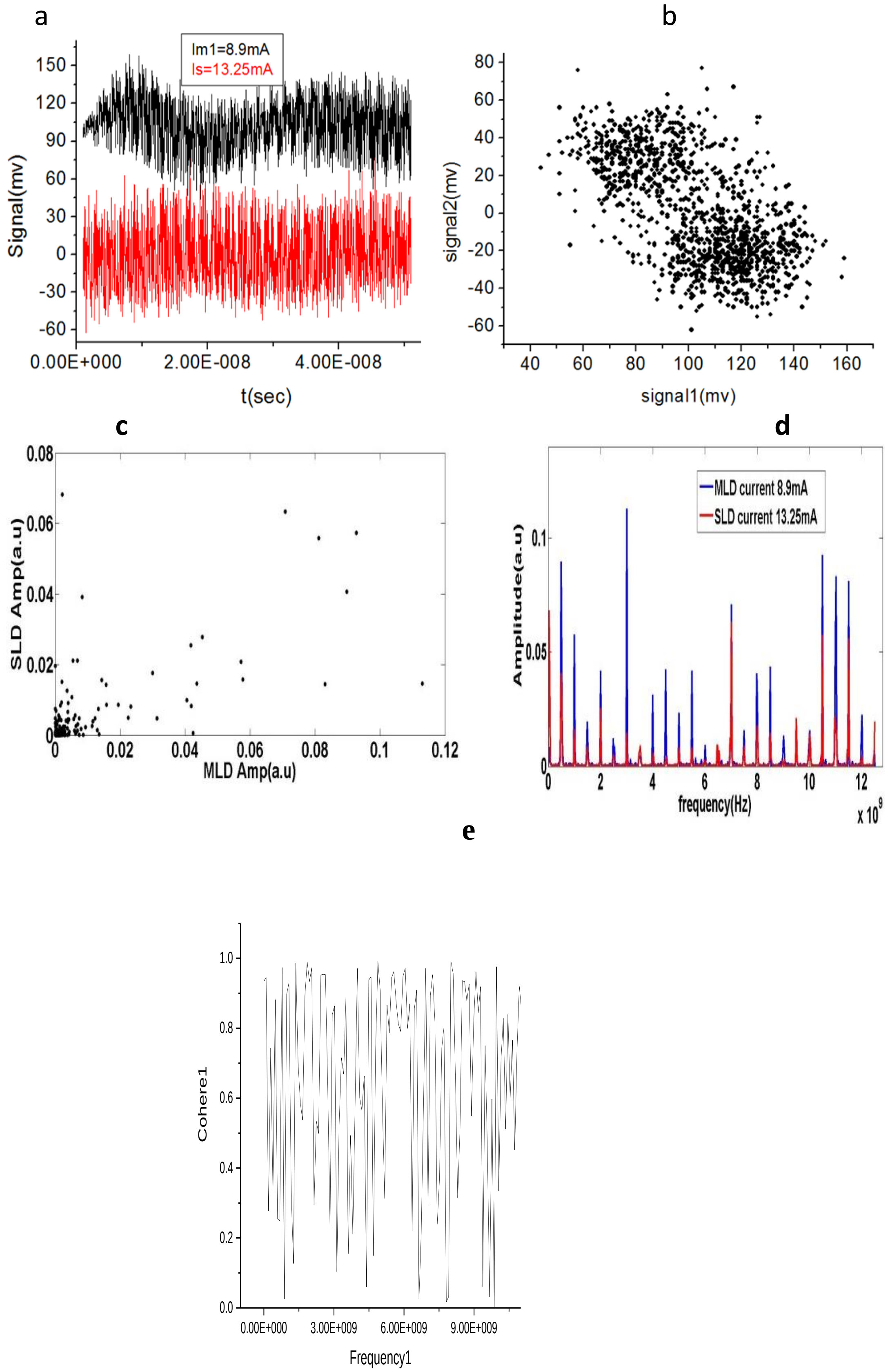
I-Bidirectional coupling: In this case each laser operate as drive and as response at the same time because each one of the two lasers injects a portion of its power on to other laser, Fig(2-a)oscilloscope traces of MLD signal(black trace) and SLD signal(red trace),Fig(2-b) oscilloscope trace(Phase mode)shows correlation between MLD signal and SLD signal. Fig(2-c)spectrums of the MLD signal(blue trace) and

SLD signal(red trace) and Fig(2-d) shows correlation diagram of the amplitudes of coupled signals FFT[13],that is when currents of the two lasers are (I_{MLD} =8.9mA and I_{SLD}=17.5mA)

For the case of **I_{MLD}=8.9mA and I_{SLD}=13.25mA**,Fig(3-a) shows the signals of MLD and SLD of colors black and red respectively. Fig(3-b2)shows the correlation diagram(out phase correlation)clearly they appear as negative slope and called Anti synchronization[3], while fig(3-c) shows the spectrums of MLD signal(blue trace) and SLD signal (red trace) and there are a high coinciding between frequency components of the two coupled signals ,fig(3-d) shows correlation diagram of the amplitudes of coupled signals FFT amplitudes, and fig.(3-e) shows the coherence. In Fig(4-a) an oscilloscope traces shows occurring synchronization between MLD signal and SLD signal as a train of packed chaotic spikes in case of **I_{MLD}=12mA and I_{SLD}=24.3mA**, fig(4-b) shows an oscilloscope trace of two coupled signal in correlation diagram(phase form) ,fig(4-c) shows spectrums of the two coupled signals and it is appear a high degree of matching of spectrum components ,and fig(4-d)shows correlation diagram of the amplitudes of coupled signals FFT and fig.(4-e) shows the coherence ..



Figure(2) Synchronization of bidirectionally coupled two chaotic oscillators ,a:time series ,**b:**correlation diagram(in phase),c:FFT of MLD(blue trace) and SLD(red trace) signals ,d: FFT, and e:the coherence. amplitudes correlation of MLD and SLD signals in case of I_{MLD} =8.9mA and I_{SLD}=17.5mA



Figure(3) Anti-synchronization (out phase synchronization) of bidirectionally coupled two chaotic oscillators **I_{MLD}=8.9mA and I_{SLD}=13.25mA.**(a:time series ,b**:**correlation diagram(in phase),c:FFT of MLD(blue trace) and SLD(red trace) signals ,d: FFT, and e:the coherence).

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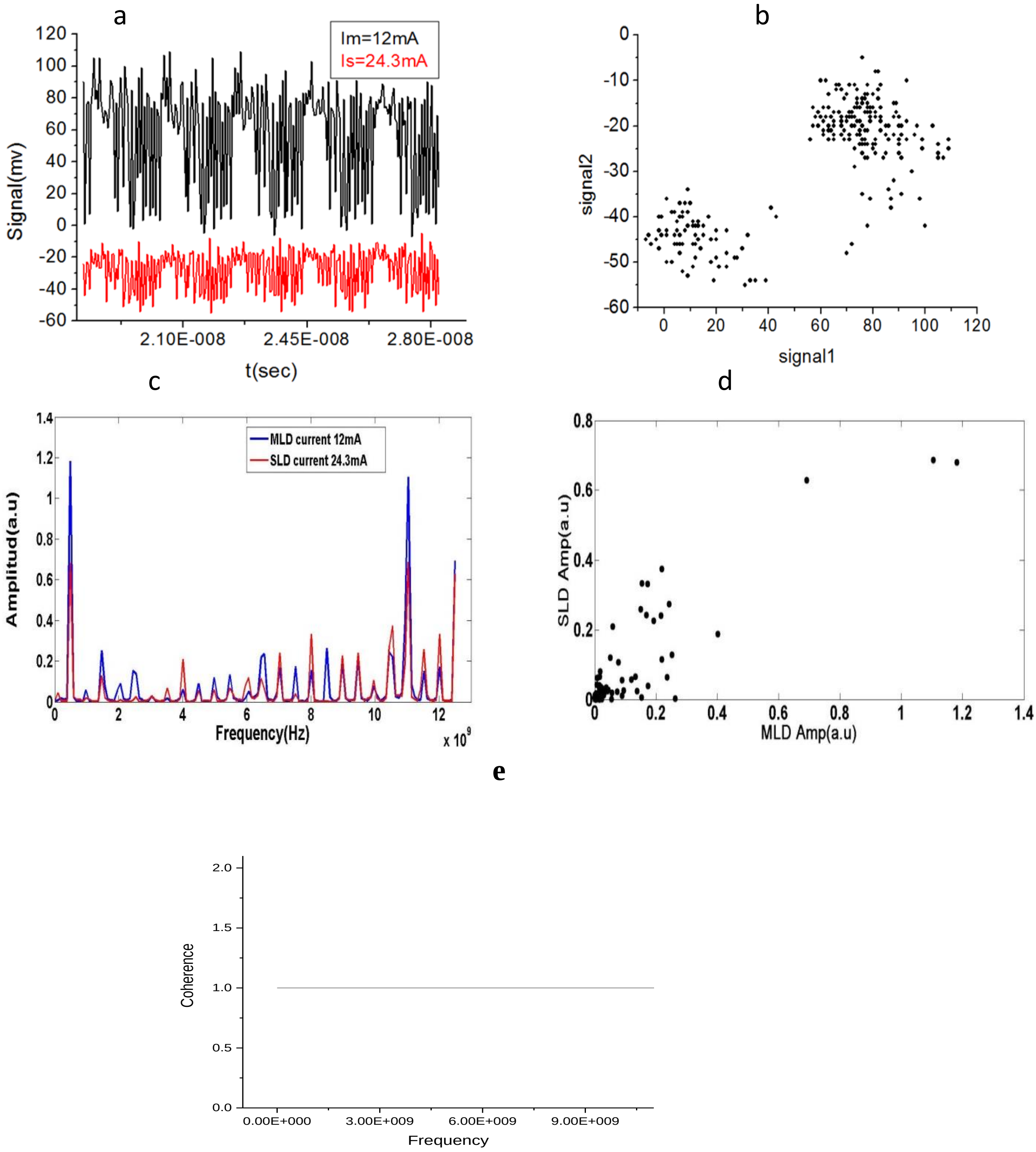
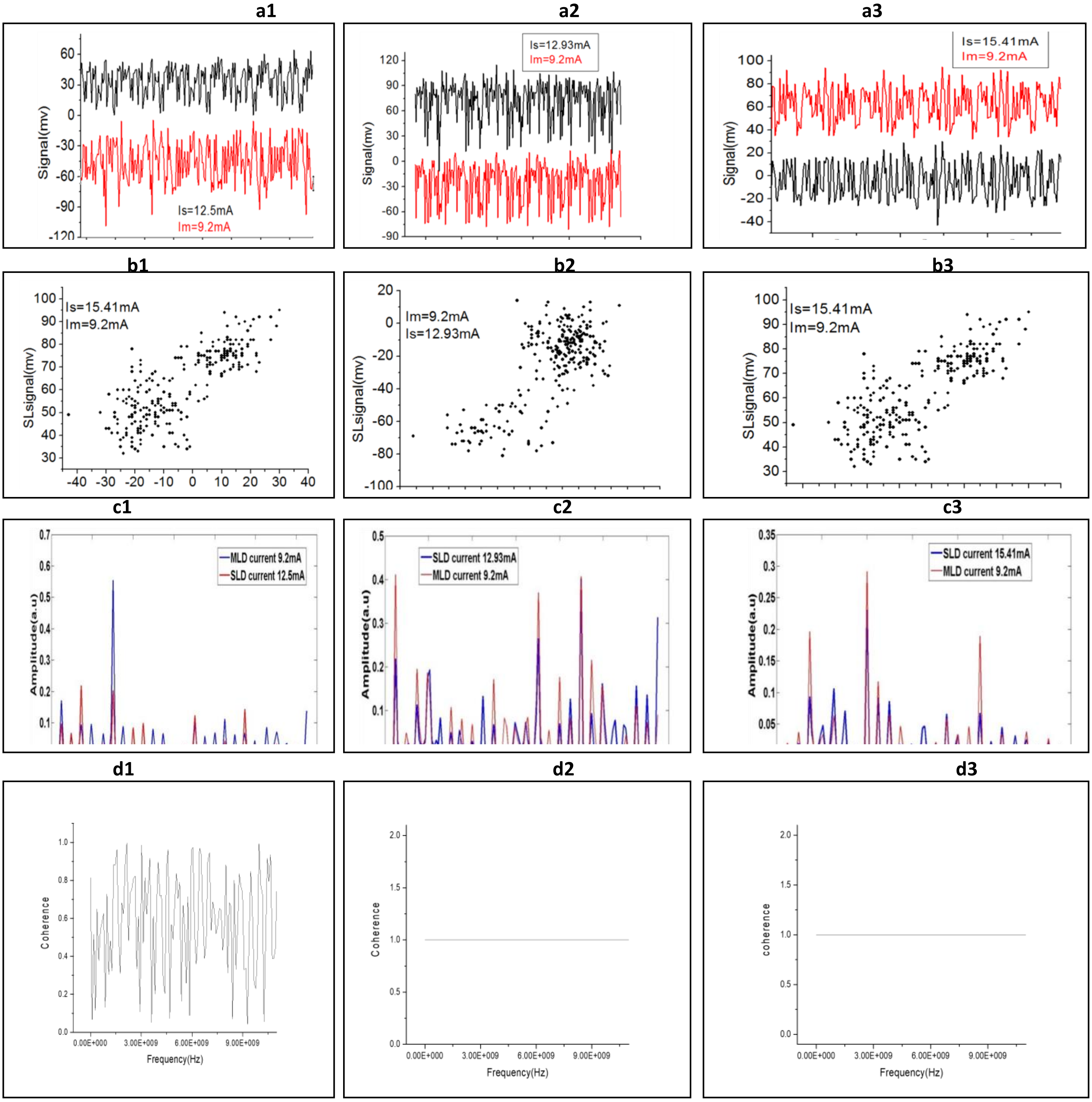


Figure(4) Synchronization of bidirectionally coupled two chaotic oscillators in case of **I_{MLD}=12mA and I_{SLD}=24.3mA.**(a:time series ,b**:**correlation diagram(in phase),c:FFT of MLD(blue trace) and SLD(red trace) signals ,d: FFT, and e:the coherence).

mirror(FM) see Fig(1-b) ,while SLD gets to chaotic state by optical injection from MLD[2] .We have fixed the current of master laser I_{MLD} to about 9.2mA and we were changing the current of slave laser diode I_{SLD} ,we have got a wide range of synchronization ,and Anti-synchronization (Synchronization in opposite direction of the phases of the signals or negative slope of phase form)between MLD and SLD signals ,Fig(5-a1) shows oscilloscope traces of

II- Unidirectional optical injection :
In this scheme as can be seen from the Fig(1-b) an optical isolator inserted in the path of the optical injection(between YC1 and YC3) to prevent light injection from SLD to MLD and only permits the light to pass from MLD to SLD, therefore SLD undergo to effects of MLD and hence MLD is called Master laser and SLD is Slave laser ,here MLD gets a chaos from optical feedback by fiber

capture of MLD and SLD in phase form where showing the regression line of the phase points tending to take aligning to straight line ,Fig(3-c) shows FFT analysis of chaotic signals MLD and SLD colored by red and blue respectively indicating to high degree of congruent spectrum components between the synchronized signals. In the case of I_{MLD}=9.2mA and I_{SLD} =15.41mA we get the Fig(3-a) which is an oscilloscope traces of synchronization of coupling between MLD signal and SLD signal of colors red and black respectively, Fig(3-b) shows oscilloscope trace of phase form of coupling chaotic signalsin, while Fig(3-c)shows the spectrums of coupled synchronized chaotic signals reveals extent of matching of the spectrum components of the coupled chaotic signals synchronized MLD signal(red color) with SLD signal(black color) for the case of I_{MLD}=9.2mA and I_{SLD}=12.5mA.Fig(5-b1) shows phase portrait or correlation diagram between MLD signal and SLD, showing *anti-synchronization* case where the inclination of regression line of the points is 180° or out-phase between MLD and SLD, signal. Fig(5-c) shows FFT spectrum of chaotic signals of MLD and SLD showing to coinciding frequency components between MLD and SLD signals, clearly there a high matching in the frequency components between coupled signal referring to synchronization quality of the signals[13].By raising I_{SLD} to 12.93mA while I_{MLD} remained on 9.2mA we get the Fig(3-a)which shows oscilloscope traces of SLD with MLD signals colored by black and red respectively, Fig(3-b) shows oscilloscope



Figure(5):(a1-a3) oscilloscope traces of MLD and SLD signals red and black respectively. (b1-b3)Phase form(correlation diagram),(c1-c3) FFT(d1-d3) coherence of MLD and SLD signals red and blue respectively in all cases, and I_{MLD}=9.2mAwhile for a1: I_{SLD}=12.5mA, a2: I_{SLD}=12.93mA and for a3 : I_{SLD} =15.41mA.

4-Conclusion:

In this work we present the analysis of experimental results of synchronization between two optically coupled high frequencies, chaotic oscillators, by optical injection. Two schemes of optical injection have been carried out between the two laser diodes , Bidirectional and Unidirectional injections . Different types of measurements have been used to show extent of synchronization between coupled optical chaotic oscillators. Wide ranges of synchronization and anti-synchronization cases have been attained by adjusting the biasing currents of bidirectional coupled lasers at certain values, that control the dynamical behavior of the laser diodes. By inserting optical isolator, unidirectional optical injection have been obtained and wide range, high quality synchronization and anti-synchronization have been achieved, by adjusting the biasing currents for both of MLD and SLD. Both coupling schemes offer applications for high speed, synchronized, secured optical communication .

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الفحوصات التجريبية لتزامن اثنين من نظم الشواش المترابطة بصريا باستخدام التغذية الاسترجاعية البصرية والحقن البصري.

سلام خلف موسى   قاسم محمد جميل عبدالعزيز   قيس عبدالستار النعيمي

الخلاصة:

تم التحقق تجريبيا من مشاهدات تزامن الشواش بين اثنين من ثنائيات الليزر المترابطة بصريا. وقد استخدمت اثنين من مخططات الحقن البصرية، ثنائي الاتجاه وأحادي الاتجاه. احد الليزرات MLD يستعرض شواشا بصريا بسبب التغذية الاسترجاعية البصرية الخارجية بواسطة مرآة ليفية ,والليزر الاخر SLD يستعرض شواشا بصريا عن طريق الحقن البصري من الليزر الاول. ان الديناميكيات الشواشية لكلا الليزرين كانت دالة لتيار تشغيل ثنائيات الليزر. وقد لوحظ حالات تزامن وعدم تزامن بين اثنين من ثنائيات الليزر المترابطة، وتم التاكد منها بواسطة القياسات المختلفة مثل السلاسل الزمنية ، مخطط الارتباط (شكل الطور) لسعة الإشارات الشواشية المترابطة،مكونات الطيف المتطابقة للاشارات الشواشية المترابطة، والتشاكه قد تم استخدامها في كل من مخططات الحقن.