Optical Chaos Generation and Synchronization by Optical Ring Resonator

Ayser AbdulHussain Hemed
Department of Physics, College of Education, University of Al-Mustansiriya
ayserah@live.com,

Abstract:

In this experimental study, a semiconductor laser is used to construct a new proposed scheme for fiber optics chaos generation and synchronization. This laser is subjected to a nonlinear optical feedback. The input electric pumping power and optical feedback strength, re-injected to the laser itself, are controlling the laser instability. The optical chaos, as a nonlinear effect, is successfully generated. This is due to the interaction between the nonlinearity generated by the feedback power, within the fiber loop mirror (outside the laser) and the active medium for the laser device. The laser in such a situation could be interpreted as a mutual Self Electro-Optic Effect Device (SEED). Another identical laser is successfully setup such that it operated under chaos in similar operating conditions as in the first laser. These two identical lasers are connected together as a closed - loop couple. Identical chaotic synchronization was obtained and examined. A frequency message was modulated in the transmitter laser (master laser) and successfully impeded within the generated chaos signal. The same message was successfully received securely in the receiver laser (slave laser). This is to the application of secure optical communication systems.

توليد وتزامن الفوضى الضوئية باستخدام المرنان الضوئي الحلقي

ايسر عبد الحسين حمد

قسم الفيزياء، كلية التربية، الجامعة المستنصرية

الخلاصة: في هذا البحث العملي، تم اقتراح نظام جديد لتوليد وتزامن الفوضى المسيطر عليها في ليزر شبه الموصل. هذا الليزر اخضع لتغذية عكسية ضوئية لاخطية. لااستقرارية الانبعاث الليزري في هذا النظام تم التحكم بها بوساطة كل من مستوى القدرة الكهربائية الداخلة لليزر ومستوى القدرة الضوئية المعاد حقنها للجهاز نفسه. تم وبنجاح توليد ظاهرة الفوضوية الضوئية اللاخطية عملياً. وذلك بتأثير

الظواهر اللاخطية الناتجة في القدرة الضوئية المعادة (في الليف الضوئي) مع الوسط الفعال لجهاز الليزر. ان الليزر تحت هذا الوضع يسلك كجهاز "SEED".

تم تنصيب ليزر اخر مطابق لمواصفات الليزر الاول لينتج الفوضى وبنفس شروط التشغيل. تم ربط الليزرين ببعضهما لتشكيل زوج دائرة . مغلقة، وتم الحصول على تزامن متطابق بعد اختباره. تم كذلك تضمين رسالة ترددية في الليزر المرسل (الليزر القائد) بحيث كانت هذه الرسالة مخفية ضمن موجه الفوضى. نفس الرسالة تم استلامها من قبل الليزر المستلم (الليزر التابع). هذا البحث تم تصميمه للتطبيق في مجال الاتصالات الضوئية الأمنة.

Key Words: Semiconductor Laser, Optical Chaos, Optical Loop Mirror, Nonlinear Optical feedback, and Optical fiber.

1. Introduction

The single-mode fiber was first time used in 1983 as the nonlinear medium inside a ring cavity (RC), while fiber couplers nonlinearity effects have been studied in 1982. Since then, the study of nonlinear phenomena in fiber resonator (FR) has remained a topic of considerable interest [1]. FRs have many practical applications, among them is the use in fiber laser [2], all optical signal processing [3], and fiber-based optical parametric amplifiers [4], etc. The optical fiber ring resonator (OFRR) is one of key optical devices, in which, chaotic feature has been found first by Ikeda *et. al.* [5].

Chaotic laser has aroused considerable interest owing to its wide applications in optical chaos communications [5] chaotic sensor [6], chaotic lidar, optical time domain reflectometer, fast random bit generator, and photonic ultra-wideband signal generator. Laser Diodes (LDs) have been widely used for the study of optical chaotic dynamics. Such lasers may be rendered chaotic through electronics, optoelectronic (OEFB), and optical feedback (OFB) [7]. OEFB is performed using electronic components such as amplifiers and or attenuators [8]. On the other hand, OFB in LD is performed by re-injecting some portion of the laser emission output by external-cavity (via free space) or ring-cavity (via optical fiber) geometries [8].

OFB chaos has been proposed and significant experimental and theoretical research as an alternative technique for optical communication systems due to the importance for both fundamental physics and practical applications [9].

The advantages provided by the OFB have been found to increase the side mode suppression ratio, narrowing the linewidth, and provide enhanced tunability and frequency stability; relative to that of the solitary LD. Due to these advantages, optical systems provide a simple ways of generating very high dimensional chaotic carriers that offer a substantial security level, and also the possibility of very high transmission rates [10].

Yupapin *et. al.* have reported a very promising technique of signal transmission security using chaotic behaviors of light propagating in a nonlinear OFRR. Transmittivity of the OFRR (separately from laser internal cavity) is given by the well-known Airy formula [11];

$$T_R = \frac{P_t}{P_i} = \left|\frac{A(L)}{A(0)}\right|^2 \quad . \quad . \quad . \quad (1)$$

where: P_i and P_t is the input and transmitted powers, $A(L)$, $A(0)$ are the transmitted and input fields, such that $A(L)$ represents the adding for contributions of an infinite number of round-trips, in any distance L inside the fiber cavity L_R. The origin of the nonlinear effects in fiber resonators is evident from Airy equation, which is due to the round-trip phase shift, which gives rise to the self-phase modulation (SPM) effect [1] and also XPM etc.

In the case of optical chaotic communication the particular requirement is to provide appropriate optical coupling between the transmitter and the receivers to enable synchronization and hence message secure transmission. Early experiments demonstrated successful communication systems in both all-optical (free space) and optoelectronics (mixed systems) feedback. High bit rates have been achieved in these two techniques, but nonlinear optical loop mirror (NLOLM) experiments in communication have been still not fully understood so far [12].

A single ring resonator coupled with one coupler is shown in fig. 2. The material of the ring could be either a silica fiber or a silicon plane waveguide.

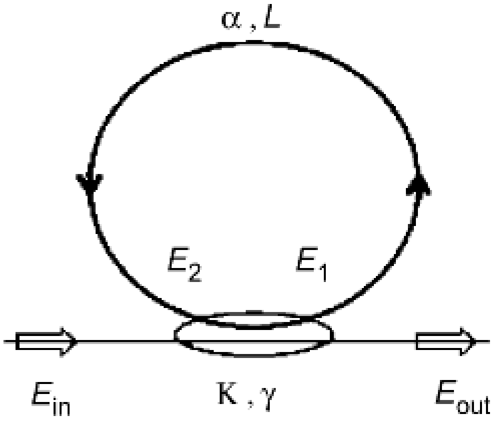


Figure 1: Schematic of a fiber ring resonator with a single directional coupler

When an input signal light with the amplitude of the electric field, E_{in}, is passed though the coupler, and than launched into the ring, the amplitude of the electric field in the ring becomes E_1, which travels along the ring for a round trip and then reenters the coupler at which point, the light electric field is E_2. Finally the light passes though the coupler again and the output field is E_{out}. Here, the input light is assumed to be a single-mode with an amplitude E_o and an initial phase f_o. Hence, the input light field can be expressed as:

$$E_{in}(t) = E_o(t)e^{-i\emptyset_o(t)} \quad . . . \quad (2)$$

The relation between the electric field $E_1(t),\ E_2(t)\ and\ E_{in}(t)$ and the output field $E_{out}(t)$ can be expressed by the following equations:

$$E_1(t) = \sqrt{(1-\gamma)(1-k)}E_2(t) + i\sqrt{(1-\gamma)(1-k)}E_{in}(t) \quad . . . \quad (3)$$

$$E_{out}(t) = \sqrt{(1-\gamma)(1-k)}E_{in}(t) + i\sqrt{(1-\gamma)(1-k)}E_2(t) \quad . . . \quad (4)$$

$$E_2 = E^{i\emptyset-\alpha L/2}E_1 \quad . . . \quad (5)$$

After one round-trip, the electric field $\mathrm{E_1(t)}$ causes a change in the refractive index of the fiber due to Kerr effect:

$$n = n_o + \Delta n = n_o + \left(\frac{n_2}{A_{eff}}\right)|E_1(t)|^2 \quad . . . \quad (6)$$

Therefore the $\mathrm{E_2(t)}$ has a *Self Phase Modulation*-induced phase shift including linear and nonlinear parts:

$$\emptyset = \emptyset_o + \frac{\pi}{2} + \Delta\emptyset_{NL} \quad . . . \quad (7)$$

Because $\Delta\emptyset_{\mathrm{NL}} = 2\pi/\lambda\Delta \mathrm{nL}$. Thus, previous equation can be written as:

$$\emptyset(t) = \emptyset_o + \frac{\pi}{2} + \frac{2\pi n_2 L}{\lambda A_{eff}}\ |E_1(t)|^2 \quad . . . \quad (8)$$

Where λ is the wavelength of light in vacuum, L is the length of fiber ring resonator, $\mathrm{n_2}$ the nonlinear refractive index coefficient of the fiber and A_{eff} the effective cross-section of the fiber core. We assume that the coupler can be characterized by the intensity coupling coefficient k and the insertion loss g [13].

Portion (50%) of the amplified optical power that had been leaving the ring resonator will back to the laser itself, the other portion (50%) is going to the output, after mixing with the optical power coming from laser. Supposing ℓ to be the distance from the laser front facet to the external mirror (which is here the ring resonator) and $\mathrm{n_{r2}}$ to be the refractive index of the external cavity, and c as the speed of light in vacuum, the feedback light has a time delay of:

$$\tau = \frac{2n_{r2}\ell}{c} \qquad . \quad . \quad . \quad (9)$$

The electric component of the optical fields in the laser cavity, i.e. in the solitary laser, and the external cavity along the z direction are assumed as:

$$E_{lc} = [A_1(z,t) + B_1(z,t)]e^{jwt} + C.C., for \quad 0 \leq z \leq L_{lc} \ . \ . \ . \ (10)$$

$$E_{ec} = [A_2(z,t) + B_2(z,t)]e^{jwt} + C.C., for \quad L_{lc} \leq z \leq L_{lc} + \ell \ \ldots \ (11)$$

Where A_1 and A_2 are the forward travelling components of the fields, while B_1 and B_2 are the backward traveling components, respectively. L_{lc} is the length of the laser cavity. In the present model, the OFB is counted as the time delay of the laser light at the front facet due to round trips in the external cavity. That is, the boundary conditions at the back facet $(z = 0)$ and front facet $(z = L_{lc})$ become:

$$A_1(0,t) = r_b B_1(0,t) \qquad . \quad . \quad . \quad (12)$$

$$B_1(L_{lc},t) = r_1 T A_1(L_{lc},t) \qquad . \quad . \quad . \quad (13)$$

$$A_2(L_{lc},t) = t_{12} X A_1(L_{lc},t) \qquad . \quad . \quad . \quad (14)$$

where the function determines the amount of the feedback due to time delay in the external cavity and is determined by:

$$T = 1 + \frac{t_{12}t_{21}}{r_1}\sum_{m=1}^{\infty} r_{cx}^{m} r_2^{m-1} e^{-jmw\tau} \frac{\mathrm{A}_1(L_{lc}, t - m\tau)}{\mathrm{A}_1(L_{lc}, t)}$$
$$\equiv |T|e^{-j\emptyset} \qquad . \quad . \quad . \quad (15)$$

and the transmission function

$$\mathrm{X} = 1 + \sum_{m=1}^{\infty} r_2^{m} r_{ex}^{m-1} e^{-jmw\tau} \frac{\mathrm{A}_1(L_{lc}, t - m\tau)}{\mathrm{A}_1(L_{lc}, t)} \qquad . \quad . \quad . \quad (16)$$

Here, the index m counts the round trips in the external cavity, t_{21} and t_{12} are the transmission coefficients at the front facet from the laser cavity to the external cavity, and from the external cavity to the laser cavity, respectively, r_b is the reflection coefficient at the back facet, r_1 and r_2 are the reflection coefficients at the front facet from the sides of the laser cavity and the external cavity, respectively, and r_{ex} is the reflection coefficient at the external mirror [14].

In previous works, paper [15] and thesis [16], chaos generation and synchronization was demonstrated experimentally using OEFB and OFB (via free space), separately. The last one is carried out by constructing the so called free space external cavity technique. In this paper, we propose a LD system with feedback formed by a nonlinear ring resonator (RR) from the LD optical output signal that re-injected back to the internal laser cavity. This particular form of feedback is sensitive to the optical phase of the laser output.

2. Experimental part

The LD used in this study, was one part of transceiver, having two single-mode fiber connectors for each part from it. Its model is: HP Agilent “HFCT-5205”. The laser (transmitter) part is a Fabry-Perot (FP) laser resonator, operating at 1300nm. Maximum power coupled to fiber is 0.2 mW, and the output spectral root mean square width is $\Delta\lambda = 7.7\ nm$. It is module for serial optical data communications applications. Its active material (InGaAs) uses a multiple quantum well laser as its optical source. The package of this laser is designed to allow repeatable coupling into single mode fiber.

As shown in fig. 2, the LD output is going directly toward one port of 2×2 symmetric fiber coupler/splitter (with FC connector terminals), 50:50 coupling/splitting ratio. The second port of this coupler is giving the overall laser output, while the remaining two ports connected with each other's, and it capable to insert a variable optical fiber attenuator (VOFA). In this argument, the two connected splitter ports construct the so called nonlinear optical loop mirror or FRR.

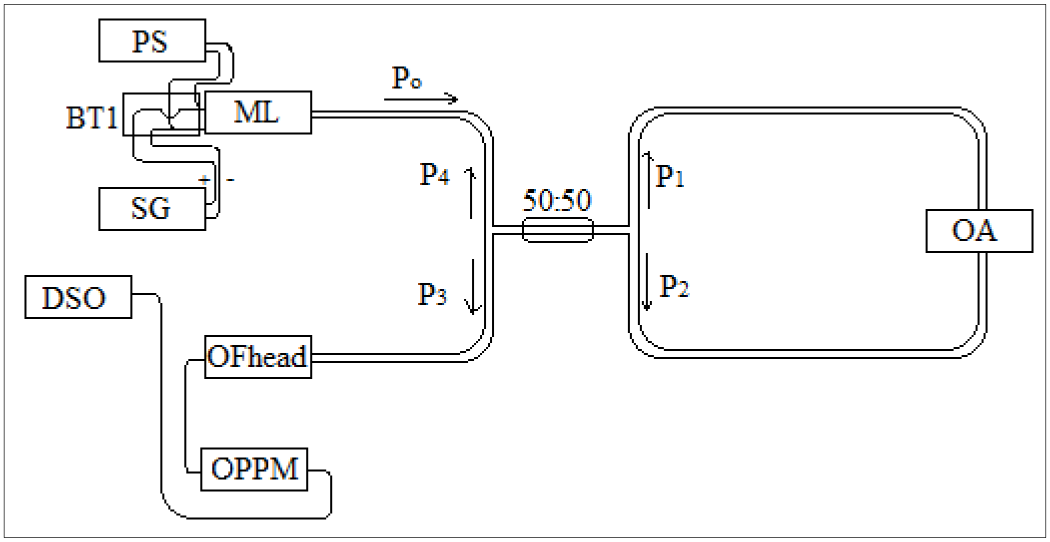


Figure 2: Fabry-Perot LD subjected to nonlinear optical feedback to generate chaotic emission. PS: power supply, LD: laser diode, OFHead: optical fiber head for optical pulse power meter (OPPM), DSO; four channels digital

storage oscilloscope, OA: variable fiber optic attenuator, SG: signal generator, and 50:50 optical fiber beam splitter/coupler.

LD experimental measured threshold current is 14 mA, It is driven by DC current near above that level and the laser running at room temperature. In this setup, the LD subjected to coherent optical feedback from the OFRR. In fact, this coupler/splitter will split the coming optical field (P_o) from the LD into to equal and coherent fields (P_1 and P_2). This coupler/splitter will introduce a phase shift of $(\pi/2)$ between these two ports, which make it an important for working as an interferometer. In case of adjusting the VOFA at 0 dB scale, the two light beams will undergo opposite paths inside the OFRR with full power, which means maximum feedback strength. Any higher attenuation scale gives lower feedback strength. Where according to the coupled-mode theory, which is used commonly for directional couplers, portion of the two neighbor optical fields transmitted in the coupler/splitter arms will transfer between them when they been closer to each other's (fused coupler region with $z\ cm$ long, fig. 3, where the fundamental mode in each core propagates partially in the cladding, which is now associate and overlapping for the two cores, then in special conditions the optical power will transfer between them. This may give rise to the feedback strength returned to the LD (P_4) and to that going to the circuit overall output (P_3). In the other hand, the same fact could give rise to the signal (preferable) noise and LD chaotic level.

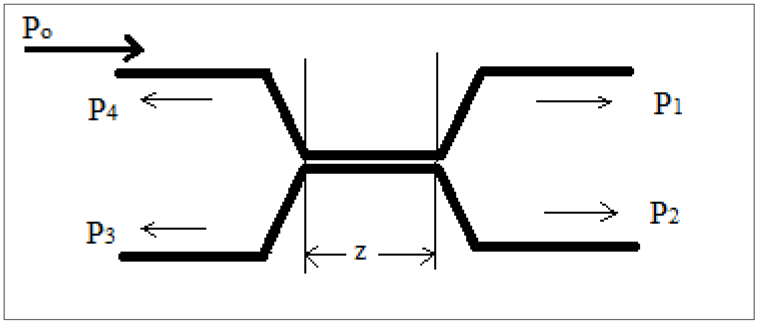


Figure 3: Optical powers directions in the 2×2 directional coupler/splitter

Losses in this coupler/splitter are: excess loss, insertion loss and isolation loss (Crosstalk). In this setup, the losses will be small, where all input and output optical power is contained either in the overall output signal or in the feedback signal.

Only limited portion from the laser emitted power will return to laser cavity as a feedback. The incoming optical field (returned from the OFRR to the LD cavity), may interfere linearly with those outgoing from the LD. The remaining part (port 3) is detected and converted optical signal into an electrical signal with a fast amplified telecom photodiode, this electrical signal forwarded in oscilloscope. The controllable parameters of this NOLM feedback system are the frequency modulation, pumping power, and the feedback strength. By adjusting of these parameters, the system operated in different chaotic states.

One of the most important applications of optical chaos generation is the chaotic synchronization (coupling between chaotic transmitter and chaotic receiver). Fig. 4 shows the chaos synchronization setup, the emitter and receiver are uni-directionally connected and the receiver is operating under identical conditions as the emitter. Fig. 5 its photograph picture.

In order to introduce another controlling parameter, radio frequency attenuator, RFAT, is inserted in the injection current that coming from master laser, ML, which going to the slave laser, SL.

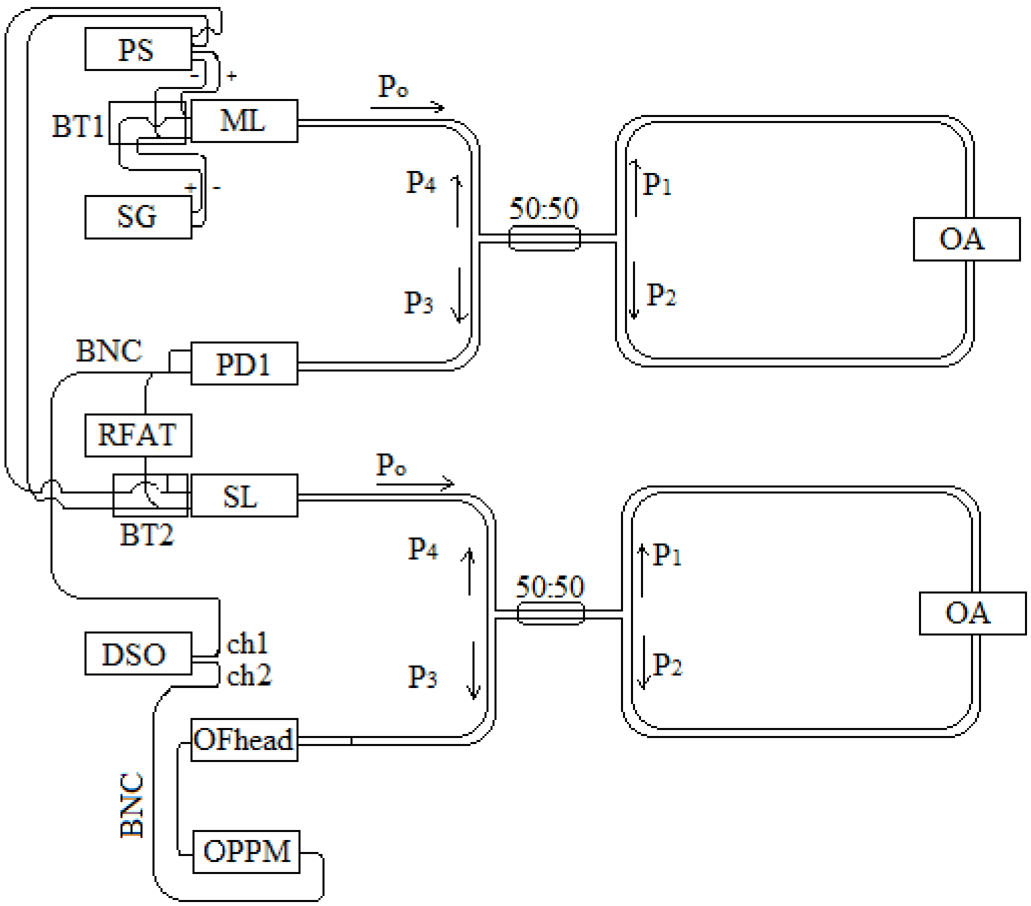


Figure 4: Chaos synchronization between transmitter and receiver subjected to nonlinear optical feedback. SL: slave LD, ML: master LD, RFAT: radio frequency attenuator, ch1 and ch2: channels of the oscilloscope, PD1: photo diode detector, BT1 and BT2: bias tees, finally, BNC: low impedance cables.

3. Results and Discussions

Laser device running under the positive, optical feedback in this setup is equivalent to second order Kerr effect SEED device but in forward bias. The first part of this study is the determination of the special chaotic properties for chaotic generation of the signal generated at the transmitter in fig. 2. When the optical feedback re-enters to the master laser, the reflective optical power provides a broadband chaotic signal at the transmitter’s output.

For small optical feedback strengths, the laser still operates under continues wave (CW) emission, while, chaotic behavior (pulsation emission) appears for large enough feedback strength limit, as given by the microsecond scale time space and its phase space in fig. 5. This observation carried out with laser bias current of 14 mA (-11.8 dBm output power), which represents just near above this device threshold level.

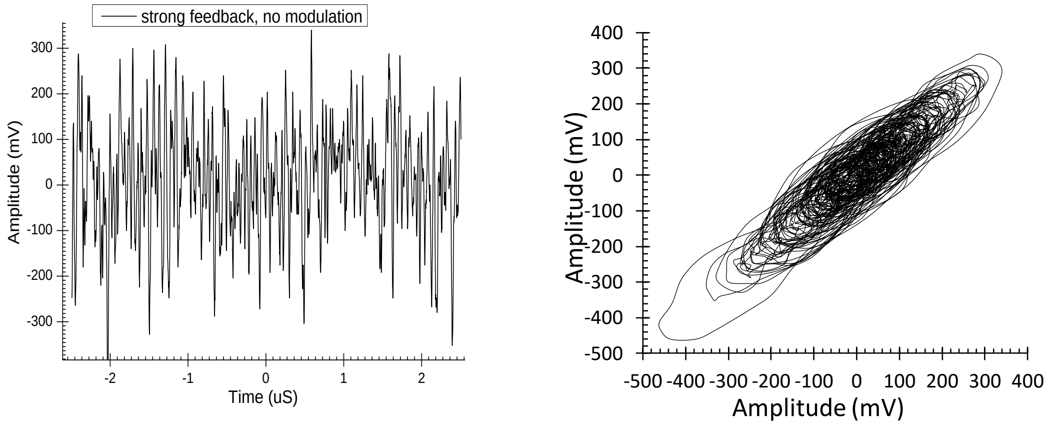


Figure 5. Chaotic dynamics for LD by OFRR.
Left (a): time space and right (b): phase space.

It observed that any slight change in feedback strength, by controlling the fiber optic attenuator, transition occurs in laser emission from periodic to robust chaotic behavior. Modulating laser with small signal (2.88 MHz) with (-12.51 dBm) output optical power, laser returned to emit periodically, fig. 6.

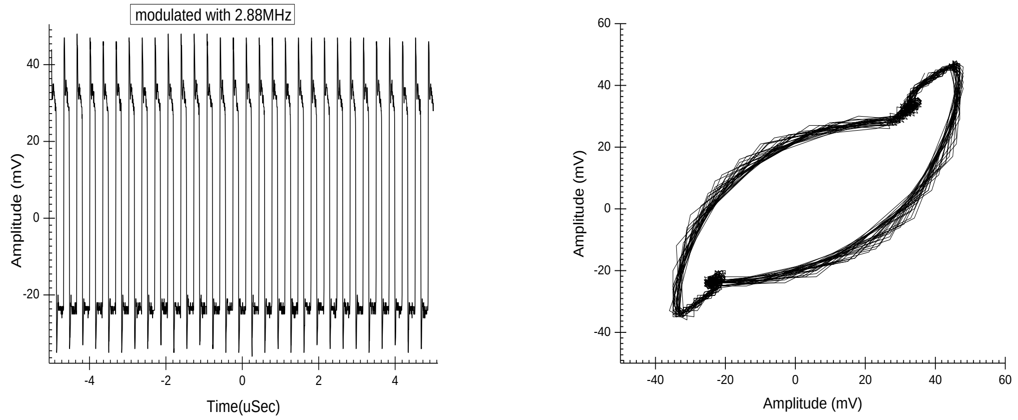


Figure 6. Laser periodic running with the strong feedback of OFRR and low frequency modulation Left: time space and right: phase space.

The frequency modulation enhanced the fluctuation of chaos states in the master LD subjected to strong feedback. Increasing the modulation to 13.76 MHz with the same feedback strength, the master LD returned to operate chaotically, as shown in figure 7.

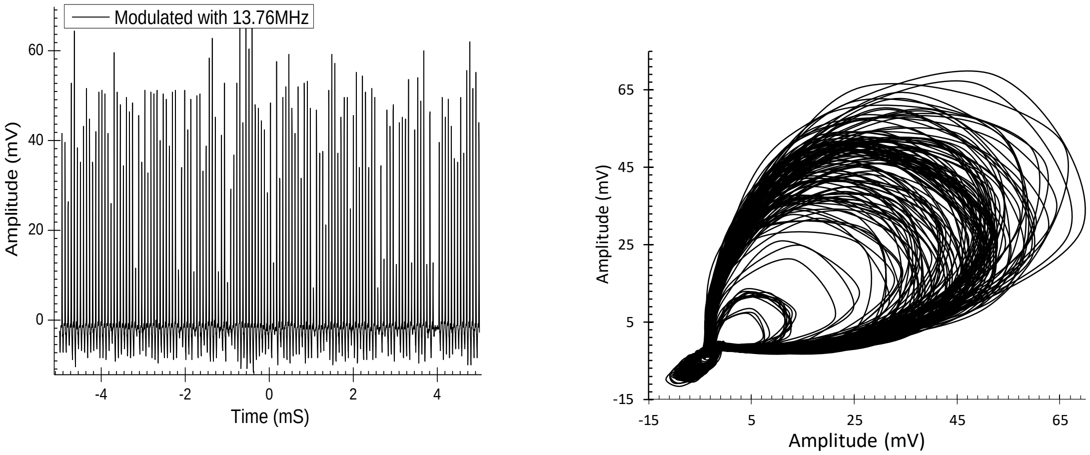


Figure 7. Laser chaotic running with the strong feedback of OFRR and moderate frequency modulation. Left: time space and right: phase space.

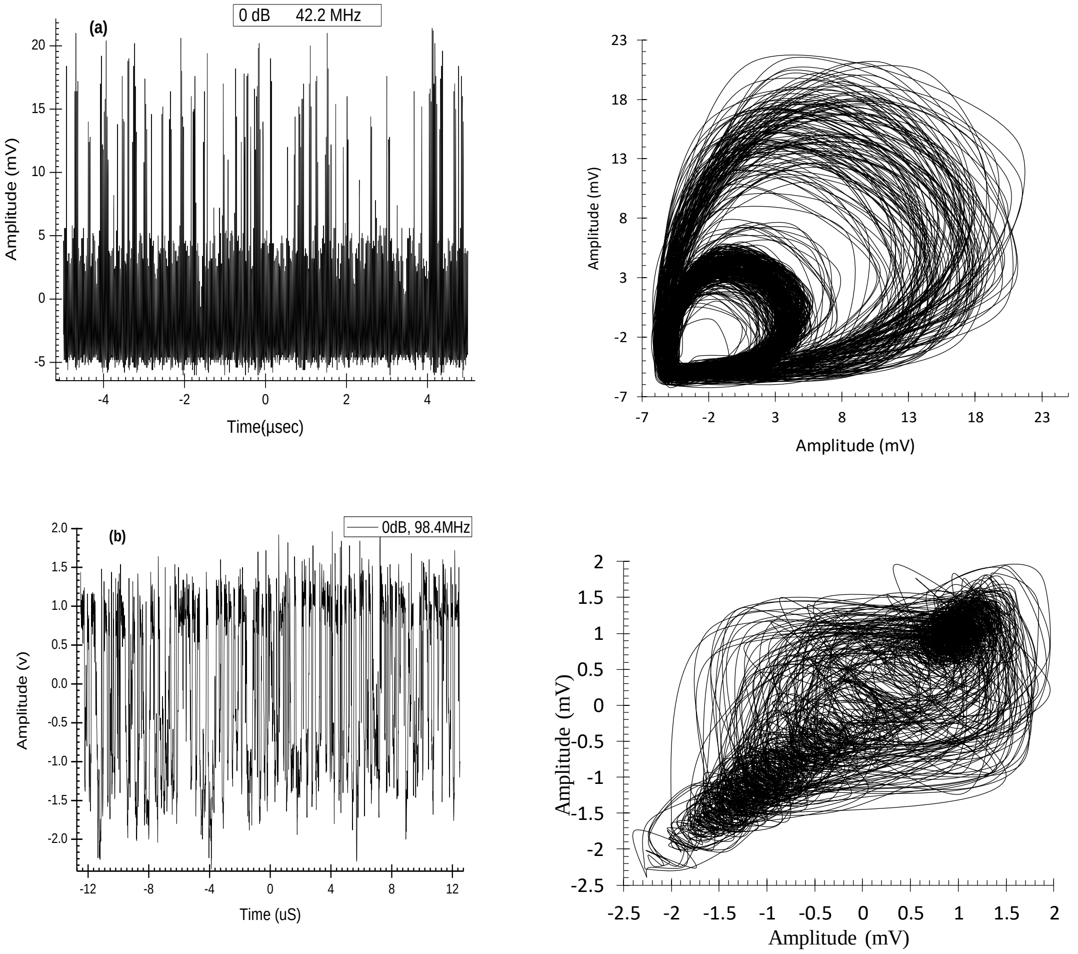
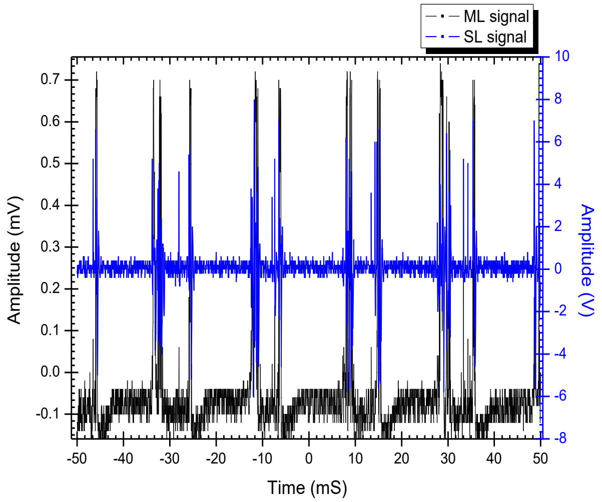
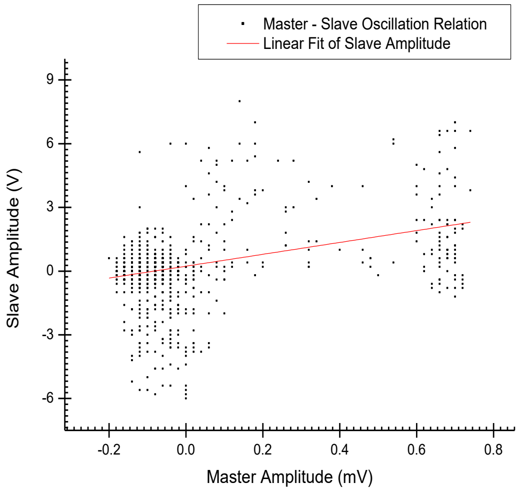


Figure 8. Laser chaotic running with a constant strong feedback of OFRR. (a) 42.2 MHz and (b) 98.4 MHz modulation frequency with lower bias current.

Increase of modulation to 42.2 MHz, for the same feedback strength and LD output power, gave chaotic emission, fig. 8a. More increase of modulation 98.4 MHz with decrease the bias current gave the observation of the so called *strange attractor* shape by the phase space, as shown in fig. 8b. Careful adjustment for feedback level for both the transmitter "master laser" and the receiver "slave laser", and make a fine selection to the injection strength from the master laser to the receiver. The receiver is synchronized to the transmitter when the phase difference is experimentally set to zero. The power spectrum of the synchronized receiver is shown in fig. 5(a), which is very similar to that of the transmitter.





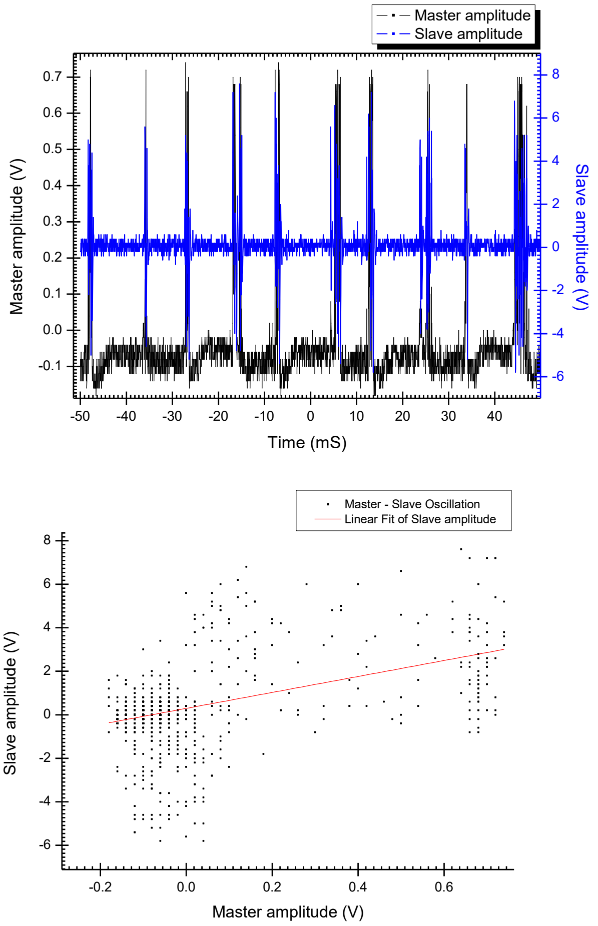


Figure 9: Time series of the synchronized chaotic lasers outputs.
Upper trace (a): transmitter laser, and lower trace (b): the receiver laser

In the experiment, the time difference is first set to be zero by adjusting the transmission path and the feedback loops. Fig. 9 shows the waveforms of the chaotic outputs of the transmitter laser (upper trace) and the receiver laser (lower trace), respectively. As can be clearly seen, the two waveforms are almost identical chaotic pulsing waveforms and the time shift between them is zero, which indicates that the receiver laser is synchronized to the transmitter laser.

The quality of the synchronization is measured by calculating the *cross-correlation* between two time series of transmitter and receiver lasers. The correlation would be unity for perfectly synchronized systems and zero for independent systems. The measured correlations here were 0.259 for fig. 9a and 0.249 for fig. 9b.

Chaos synchronization has been achieved by optical frequency matching between the corresponding modes of the transmitter and receiver lasers and by injecting the chaotic output of the transmitter into the receiver.

As indicated by [12], *SEEDs* setting ranges from very simple devices using one quantum well LD simultaneously as both photo detector and a modulator. Thus the basic concept for chaos generation in both parts from this work is the *SEEDs*.

4. Conclusions:

Optical chaos generation and synchronization based on NLOLM feedback is available and it is compact. The dynamical behavior, the emission, of the semiconductor laser that includes a NOLM is sensitive to the feedback optical power ratio. Periodic, quasi-periodic, and *chaotic* behaviors with synchronization are observed by adjusting pumping power, optical feedback strength, and modulated frequency.

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