Controlling a chaotic anti-synchronized oscillator by a phase interplayed optical injected seed with an FBG sensor

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Abstract. In this simulation study, a fiber Bragg grating (FBG) sensor is used to partially separate a signal emitted from a laser diode (LD1), which is originally modulated with a noise source. Separation done into two parts; reflected, in which a phase is interplayed (similarly to Michelson interferometry) in order to make it differ than that passed without reflection. The two separated signals, remixed again with themselves and additionally add to a third signal came from second laser diode (LD2), which is also modulated with a noise source furthermore to a frequency message. Output signal resulted from this interferometry, originally based on two self electro optic effect devices (seed) undergoes external optical injection. Thus these two oscillators follows anti-synchronization within their emission. Observation and analyses was based on determination for their final output spectra from periodic to chaotic. FBG sensor used in this experiment is play a role of temperature (T) and/or Stress (S) controlling to the incident signal for LD1. Results shows that LD1 signal cannot modify output final signal, unless several parameters are carefully tuned. These parameters are; LD1 seed, LD2 seed, LD1 phase (filtering with FBG). These results approves novel application for operating sensors in parallel to optical communications in order to satisfy the application of high level security with two antisynchronized lasers within one chaotic transmitter.

Keywords. Chaotic Dynamics, Coupled Mode Theory, Fiber Bragg Grating, Interference, Optical Injection, Self Electro Optic Effect Device, Anti-Synchronization.

1. Introduction
The statistical and topological properties of complex connectivity structures have been studied extensively, ranging from random and scale-free networks to small-world structures and even simplicial complexes, which are topological structures used to model several body interactions [1]. Both unidirectional and bi-directional (mutual) optical injection (OI) in laser diodes has subjects of interest for many years ago. For continuous wave (CW) single-mode laser diodes it induces a broad variety of
nonlinear dynamical systems, such as; periodic and chaotic behaviours, four-wave mixing, and injection locking [2]. Injection locking, for example, occurs when the power is above the injection locking threshold and the incident wavelength (self-reinjected) is within the locking range of a longitudinal mode [3]. To overcome limitations associated with the use of external modulators, a link existed between our field and optical injection-locked lasers, which have been suggested and found attractive for generating signals with phase modulation more simply by changing the optical injection locking parameters. Detuning frequency between the injector and free-running receiver laser(s) is an important parameter, and the optical injection ratio between both injector and receiver lasers [4].

Optical fibers and fiber sensors are novel sensors that have advanced rapidly in recent decade. Because of their durability, wide bandwidth, multiplexing capabilities, ability to carry large amounts of data, small size, and electromagnetic immunity, they have been widely used in variety of applications. Wide bandwidth with low-loss single mode fiber is receiving a lot of attention in the field of optical communication. This is because it is suitable for long haul transmission waveguides operating with high-data capacity [5]. Beside, observation for transmission and reflection spectra gives an accurate tool for modern sensing application [6].

Theoretically, when run below their threshold, Fabry–Perot semiconductor optical amplifiers are similar to Fabry–Perot LDs. Accordingly, lasing occurs when the gain inside the cavity increases. The device becomes active in this state, and the injection locking mechanism selects the emitted wavelength; now, if the input wavelength is near enough to that of the laser, the laser is locked onto that wavelength. Other wavelengths will actually not be exchanged if this is not done [7]. There exist a one hundredth from optical wavelength sensitivity associated with phase shifting interferometry. Which enables noncontact mapping of surface shape, where correctly amount of phase shift is required. In reality, unwanted phase-shift errors are resulted by non-linearity of a piezoelectric transfer mirror. Furthermore, in air optics transmission, air turbulence and mechanical vibration are likely environmental disturbances that make it more sensitive [8]. Fine selection of the optical injection parameters is one of the critical key for the success in chaotic communication system. In these systems external optical injection plays an important role to establish the synchronization between transmitter and receiver furthermore chaotic generation [9].

Another option is the selective feedback, inside the laser cavity, technique which is based on making the lasers oscillate at the Bragg wavelength, using a single quarter-wavelength-shifted distributed feedback. Depending on the phase shift location, main mode is constructs. Using the transfer matrix method approach, may represent a more attractive option in the above-threshold regime compared to the previous option in laser diode [10]. FBGs have also been broadly exploited in microwave phase shifters [11]. Sensors application, in which Bragg wavelength adapts reflected wavelength, depends on applied longitudinal strain/vibration, temperature of the fiber and pressure/vibration all sensed by optical fiber grating [12].

In coherent optical communications high spectral purity is desired, an absolute frequency stability or a precise wavelength, optical feedback, besides optical injection, are two options to achieve such a property. Basing into above, wide applications are associated with LDs, thus lasers properties tuning techniques are required by the use of last options. Such applications are; upon detection signal to-noise ratio in communication systems, sensor technology, atomic physics and spectroscopy, length and frequency metrology [13]. One technology that can improve device operation by providing better protection against
dispersion and/or nonlinear weakness is advanced modulation formats. The use of these formats also results in a higher spectral density of information. Phase Shift Keying (PSK) is one of these formats, in which the information is plotted on the phase of the sent optical signal [14]. Good electro-optic and opto-electric interconnects in optical data communication via fiber optics is needs. The so-called self-electro-optic effect tool (seed) has been certified to meet each of these requirements. Furthermore, such devices have achieved optical bi-stability, allowing photonics to be regulated by photonics. The quantum confined Stark effect, which can be seen in quantum well materials, is the basis for these seed devices [15] [16]. These devices can run at high speeds while using very little energy [16], with simplest hardware that that required with the case of optical feedback [17] and optoelectronic schemes [18].

For the seed, that is in our study biased virtually with both lasers, one benefit is that, we can electrically adjust the diode's optical output by applying a continuous wave optical signal to the diode's input. [19] [20] [21], i.e. forcing the laser to operate in a bistability. Ref. [22] gave a model of rate equations for a single seed bistability with respect to light power, and for serially connected seeds with feedback.

2. Dynamics with Optical Injection
As mentioned above, chaotic instability of output laser can generate from one laser to another through unidirectional or mutual optical coupling. It is important to mention that the intensity of laser has two components of dominant frequency. First is the optical-carrier frequency fc measured from the speed of light c and optical wavelength λ as,

$$f_c = \frac{c}{\lambda}$$

The optical-carrier frequency ranges for SLs are on the order of many hundreds of THz (1014 Hz) (e.g., fc 200 THz for =1.5 m, C = 2.998×108 m/s, and the relaxation oscillation frequency (ROF) at kHz–GHz (103–109 Hz). Detuning can occur due to a nonlinear interaction between the ROF and the optical-carrier frequency. Chaotic fluctuation may occur when the optical carrier frequencies between an injected and injection laser are detuned to the order of the ROF. The dominance of the optical-carrier frequency of the detuning, as well as the strength coupling, are most likely to occur in this phase for chaos generation [23];

$$\frac{dA}{dt} = -\frac{\gamma_e}{2} A + i(w_0 - w_c)A + \frac{r}{2} (1 - ib)gA + F_{sp} + \eta A_i \exp(-i\Omega t)$$

$$\frac{dN}{dt} = \frac{f}{ed} - \gamma_N - \frac{2\epsilon_0 n^2}{\hbar\omega_0} g|A|^2$$

where $A_i$ is the amplitude of the field injection at an optical frequency $\omega_i$, $\eta$ is the injection coupling rate and $\Omega = \omega_i - \omega_0$ is the detuning frequency of the optical injection. The equation of complex field given has to be use because of the phase difference $\phi$, between the injection field $A_i$ and the intracavity oscillating field which is nonlinearly coupled to the magnitude of oscillating field and is not arbitrary. It is possible to reformulate this equation in the form of two coupled real rate equations in terms of $\phi$ and $|A|$ [24].

3. Dynamics with modulation
Consider the LD interferometer, it is an unstable MI with a path difference due to path difference $\Delta$. If function generator supplies a signal which modulates initially the injection current of the first laser diode. During each disturbance of the signal, then the injection current is modulated linearly. Under the assumption that both of optical power and the optical frequency vary linearly with the injection current, we can write [25]:

$$\frac{dA}{dt} = -\frac{\gamma_e}{2} A + i(w_0 - w_c)A + \frac{r}{2} (1 - ib)gA + F_{sp} + \eta A_i \exp(-i\Omega t)$$

$$\frac{dN}{dt} = \frac{f}{ed} - \gamma_N - \frac{2\epsilon_0 n^2}{\hbar\omega_0} g|A|^2$$
\[ i(t) = i_o + a_i t \quad (4) \]
\[ p(t) = p_o + a_p t \quad (5) \]
\[ v(t) = v_o + a_v t \quad (6) \]

where \( i(t) \), \( p(t) \) and \( v(t) \) are injection current, optical power and optical frequency, respectively, \( a_i, a_p, a_v \) and \( i_o, p_o, v_o \) are constant parameters depending on the set up parameters.

After recombination between the two arms, the output of the interferometer, for each point \((x, y)\), the optical intensity is given by:

\[ I(x \leftrightarrow y) = B(x, y) \times [1 + V(x,y)\cos\theta(x,y,t)] \quad (7) \]

where \( \theta(x,y,t) \) is the difference in phase between the two interacting beams. Since it is unaffected by shifts in optical strength, the fringe visibility \( V(x,y) \) is independent of time. \( B(x,y) \) is the background intensity, which is linearly proportional to the optical power. It is possible to formulate: \( B(x,y,t) = B_0(x,y) + a_0(x,y)t \), where \( B_0(x,y) \) and \( a_0(x,y) \) are also constant coefficients. The interferometer phase is related to the path difference \( \Delta \) and to the optical frequency through the relation:

\[ \phi(x,y,t) = \phi_0 + a_0(x,y)t \quad (8) \]

where again, \( a_0(x,y) \) is a constant coefficient while \( \phi_0 \) is a phase offset. Finally, the corrected phase-shifted intensity \( I(x, y, t) \) is given in Ref. [25]. Ref. [26] suggested another intensity equation for identical laser diode interferometer, but with a dynamical phase change. According to it, a special algorithm is suggested, the resulted intensity \( I'(x, y, t) \) is now function to laser bias intensity, modulation intensity, and the phase variation in dynamic case.

4. Simulation setup

In additional to chaos carrier bandwidth increase [27] complexity for this carrier is required. As shown in Fig. (1), a laser diode (LD1) is worked as a self electro-optic effect device (seed) with selected values (100, 200, 300). The resulted signal is sent to a 1×2 10:90 directional coupler (fork), one output port is delivering the power into detection (Osiroscope (Osi) and Radio Frequency spectrum analyser (RFSA)), this is after introducing a 10dB RF amplifier. The second fork port represents the interferometry one, in which the signal is passing via an optical fiber isolator (OI) his function is preventing the LD1 from backreflected power to make the seed working in isolator manner. LD1 optical power is then incident into a uniform fiber Bragg grating (UFBG) (with Bragg wavelength \( \lambda_B = 1550 \) nm), his function is splitting the power into two portions in order to generate the final dynamics. The portion that succeed in passing through it (with \( \lambda_n \neq 1550 \) nm) representing the transmitted portion, while the one that satisfies \( \lambda_B \) will reflected back and then extracted virtually (identical to fiber optical circulator). Accordingly, their exists two portions from the original one signal, these two portions virtually experimented for interchanging two parameters; phase \((0, 60, 90)\) deg, then these two portion is recombined using a 10:90 pumb-prob combiner-1 (or 50:50 ordinary optical combiner) according to experiment circumstance. This interchange expected to introduce new dynamics differs than that with the solitary laser (LD1). The UFBG itself is
also employed to control the generated dynamics instantly, many parameters virtually controlled; stress \( (250,500,1000) \) pa, (stress \( zz \) gives no results) and temperature \((20,40,60)\) °C.

The second laser diode (LD2) has the same operating wavelength, and the same seed source of noise is receiving the previous signal via 10:90 pump-prob combinar-2 (or ordinary optical combiner) in order to mix these two new signals. LD2 itself is used to carry a frequency modulated signal generated by FM direct (internal) modulator, with constant frequency values (100 MHz). For all possible terminal from these fibers a detection is connected in order to follow the signal development from the LD1 to LD2. Seed itself is also virtually experimented such that its value is varied between LD1 and LD2 for three different values (100,200,300).

![Figure 1. Simulation setup for unidirectional optical injection from LD1 into LD2 using a one region UFBG sensor.](image)

5. Results and discussion

As shown in figure 1, there are mainly four visualizing outputs, LD1 with its own seed (OV_1), LD1 for light passing through FBG sensor (OV_3), LD1 for light reflected by FBG sensor (OV_2), and finally, phase shifted LD1 light after mixing with seed LD2 light (OV_2). All these observations were made for follow the light dynamics step by step in order to interprets the final result which is OV_4. Part of these were analyses out of this discussion, while the other were analyzed with aid of Origin, i.e. date drawn from Optisystem into origin in order to test and draw their phase and frequency (fast Fourier transformation FFT), to ensure their periodicity dynamics.

5.1 Oscillator Dynamics with the Effect of Seed:

With referencing Fig. 1, in order to compare difference between emission of both LD1 and LD2, visualization was done for both of them by OV_1 and OV_2, respectively. Results are shown in figure 2, in which time series between each part of these results are not repeated in any other individual shape. This
is because the influence of these optoelectronic devices, when combined with quantum well self-electro-optic effect seeds, causes changes in the active medium optical absorption as a result of induced changes in an electric field that propagates perpendicularly to the quantum well material's very thin semiconductor layers. Application of continuous wave (CW) optical signal to the input of the diode one expect ability to manage its optical output electrically, which what we observe in our calculations. The difference between all observed spectra is related with the nature of this effect, non-periodicals, that is our goal based on for generating chaotic dynamics. Seed values tested for three values (100, 200, 300), which represents randomness for oscillator. Attractors for all above time series gives the map of emission variation due to the change of these seeds, A, B, C are from LD1 (OV_1), while D, E and F are from LD2 (OV_2).

Figure 2. Results for dynamics associated with LD1 (OV_1) with variable seed (100,200,300), and LD2 (OV_2) seed (100,200) where both T (20°C) and Phase (P) (0) was constant. (A) Time series (B) Phase space for (A). Details are given inside each shape.

Further analysis was carried out for results achieved by visualizers (OV_1) and (OV_2), in order to be able distinguish attractors more precisely, and compare it with FFTs, Fig. (3). three dimensional attractors were plotted using the origin program, Fig. (3). As reported by Ref. [28]; from a three-dimensional time-delay reconstructed attractor, the Poincaré section can be obtained by a clock-wise rotating slicing two-dimensional plane. Attractor were denser (rout modes paths increases) amplitudes as we increase LD1...
seed from 100 to 200. Anomalous behavior observed only in LD1 seed 300, in which the oscillator be running with unique single mode, i.e. without any randomness. Theoretically, seeds associated with Fabry-Perot etalon containing nonlinear semiconductor material, as mentioned in last paragraph, if an electric field is applied perpendicular to that material, layers are quantum well material, optical absorption can be changed. Due to this effect, device follow bi-stability and optoelectronic feedback (OEFB) if quantum confined combined with optical detection. OEFB offers a best option in order to prevent problems associated with optical feedback. Simulation based on playing with two primarily beams originally derived from the same light source. According this property, in reality operation, source power fluctuations results no effects into emitted signal. This will make applications that requires more stability such as cascadable logic and transmitting units, operates with higher efficiently.

Results given in Fig. (4) shows the same effect that had been measured for LD1, attractor behavior similarly to that observed in Fig. (3). This is due to matching between laser sources LD1 and LD2, and also seed 1 and seed 2 this makes the resulted signals virtually exactly the same, off course this is not available in reality operation. Mixing between both signals emitted from LD1 and LD2, where both devices emit at the same wavelength, bias level and the only changed parameter is the path difference which is for both paths kept as it in these two experiments.

Varieties of optical fiber sensors techniques are in usages, which can be listed as three categories: External or extrinsic parameter: In this fiber is merely transferring channel of the measured factor to a distant location. Intrinsic parameters: In which optical properties are response to strain/and/or/temperature hybrid parameters: In which the light is communicated over the optical fiber further transduced as electricity on a remote optical receiver. In this study, hybrid sensor operation is tested with association of phase difference.

5.2 Results for Dynamics with Optical Injection;
5.2.1 Phase Variated Injection with FBG sensor Temperature control. In this paragraph, phase varied intentionally for the emission of LD1 in order to generating a new dynamics regime. Difference in phase was created by constructing a virtual optical fiber Michelson interferometer etalon. This etalon constructed by the division for LD1 signal into two parts, as indicated in simulation set up, Fig. (1). The division is based on FBG sensor, which permit to portion of light (not satisfy Bragg wavelength) to pass through it. Otherwise, light that satisfy last condition will have reflected back. Instead of directed to laser itself, reflected light will follow new direction. This situation is identical to the use of optical fiber circulator.

![Figure 4. FFTs and 3-D attractors for dynamics associated with LD2 (OV_2) seed (100, 200) where both T (20°C) and Phase (P) (0) was constant, all for time series that is given in figure 2. Details are given inside each shape.](image-url)
Figure 5. Results for the output measured time series from OV_4 for signal mixing between LD1 and LD2, with constant LD1 seed (100) and LD2 seed (200), and variable both T (20, 40, 60) °C and P (0, 60, 90) degree.

Shifting in phase changed for the following three values; (0, 60, 90) degree. During this phase variation, FBG sensor itself plays additional role. This role is making the phase variation itself unstable by changing the FBG sensor temperature into the following three values; (20, 40, 60) °C. Simulation results are given in Fig. (5), in which time series and their associated 2D attractors are given.

According to these results, time series clearly fluctuated under the effect of external inserted perturbations. These perturbations excited outside the laser device, only by making in phase variation in LD1 two parts. The FBG sensor itself plays a role of selectively partial reflector that gives the opportunity for controlling the shape of emitted spectrum from LD1, before mixing it with the LD2. The last laser is the one that responsible for optical transmitting, while the LD1 is the responsible for only generating the perturbations related to chaos. Together they are representing a chaotic transmission unit, with the ability for change of chaos carrier specification instantaneously by deriving the temperature of the FBG sensor reflector. According to results given in figure 5, the most filled attracter is; (D) (P=60, T=20 °C) and (g) (P=90, T=20°C), this indicates appropriate initial conditions with these values.

Interchanging phase property for one of these two parts leads to interference effect. With this effect, if we reinject the new signal to mix with the signal that came from LD2, a new wave with hybrid specification can be resulted in. Furthermore, LD2 itself is subjects to another modulated seed effect. With adding a frequency message (100 MHz) one can exam the resulted signal security, by observing its time, phase (attractor), and frequency spaces. According to these two observations, one can consider that the contribution of one laser in resulted dynamics is not equal i.e. each laser signal has its own association. This is due to several parameters that differs between both interacted signals, such as path covered before interacting, which may change the phase difference between these two signals. Noting that this interaction happens in isolated two oscillators, i.e. each laser is prevented from back reflected optical power, and mutual or uni-direction optical injection. Optical injection and feedback carry almost several nonlinear effects in SLs, such as; with mutual injection: mode hopping, mode locking and chaos [29], and with uni-direction injection: rout to chaos [30]. Ref. [31] reported that master LD frequency stability with optical injection transferred into high power slave LD, which has bad spectral properties in solitary running. This
indicates a frequency and then phase correlation associated with injection-locking. In this study the situation is optical injection but with seed and out of laser cavity injection. Observation for the same attractor scenario, one finds that in part (c) (seed of LD1 300 and T=20°C) from the attractors, number of mode routs drops faster, indicating returns to periodic oscillation. Seed performance in this simulation gives interaction between two bi-stable devices, where in ref. [32], two-terminal devices are mentioned. Results approves no need to requirement of precise control of bias beam powers, power supply voltages, and reflections of the output back onto the system. Where in this simulation, as we previously mentioned, no back reflected optical power considered. Besides data coding application, these devices results are preferred for optical processing application.

Figs. (6), (7) and (8) are gives FFTs and 3D attractors for the same variables that measured with Fig. (5), but the phase P is changed for them from 0 to 90 deg., respectively. With these phase, temp. and seed parameters, observation indicates a small selected phase values contribution with dynamics in resulted output signal.

**Figure 6.** Results for the measured FFT and attractors for the signals given in figure 5, OV_4. Variation of FBG sensor T (20, 40, 60) °C with constant LD1 seed (100) and LD2 seed (200), and P (0) deg.
Figure 7. Results for the measured FFT and attractors for the signals given in figure 5, OV_4. Variation of FBG sensor T (20, 40, 60) °C with constant LD1 seed (100) and LD2 seed (200), and P (60) deg.

Figure 8. Results for the measured FFT and attractors for the signals given in figure 5, OV_4. Variation of FBG sensor T (20, 40, 60) °C with constant LD1 seed (100) and LD2 seed (200), and P (90) deg.

5.2.2 Phase Variated Injection with FBG sensor Stress control. As reported in Ref. [33] stress induced Birefrengence in optical fiber which can be employed for spectrum observations associated with FBG sensor. The shift between two generated core axis could introduce a beat length with which the signal and the reflection and transmission spectra directlyy affected. As before, LD1 phase varied for the same values; 100, 200 and 300 for only LD1 one arm. FBG sensor temperature is kept constant on 20 °C. The sensor stress component xx is changed for specific values, 250, 500 and 1000pa. Results for these measurement is given in Fig. (9), in which time signals and their 2D phase spaces are given. Emission seems still chaotic, with unsmooth mode routs esspecially for high intensity values.

Figure 9. Results for OV_4, timeserie and its attractors with (LD1 seed =100) and LD2 seed =200), LD1 P (0, 60, 90) deg, FBG sensor T (20) OC, and stress (250, 500, 1000) Pa.
The Bragg wavelength is determined by the temperature of the fiber as well as the optical fiber grating's longitudinal strain applied and felt. Furthermore, by moving longitudinally optical light of wavelengths about Bragg wavelength into fiber and quantifying wavelength reflected by the grating, one can gain insight into the pressure/vibration applied to the optical fiber. Equations for forward and backward propagating waves, as well as their coupling conditions, are given by coupled mode theory (CMT). When the coupling is maximized, the amplitude reflect coefficient and power reflect coefficients are maximized.

**Figure 10.** Results for measured 3-D attractors, and FFTs with constant LD1 SEED (100) and LD2 (200), T (20) °C with variable; Ph (0, 60, 90) deg, and stress (250, 500, 1000) Pa.
Results shown in Fig. (10), shows that variation of stress value from 250 to 1000 Pa, gives distinguishable change in attractor density i.e. randomness density, which is observable from FFT spectra. This is in case of keeping constant both seed and temperature.

5.3 Transmitter Unite Correlations

In contrast to matching required for identical synchronization conditions [34][35]. In practice, operating communication systems under complicated conditions, faces mismatch of the parameters is high level probability. This may lead to the degradation of decryption quality. From the chaotic dynamics privacy point of view, sensitivity to initial conditions is also a great concern. For the current study, this factor is employed inversely, i.e. mismatch is required initially between master and slave lasers. This is in order to make encryption more complicate with dynamics initial conditions that achievable by the presence of FBG sensor. Seed causes shift of the exciton absorption spectrum in a multiple quantum well due to a quantum confined Stark effect or other quantum effects which was used as the mechanism of bistability. Complex multi-stable states depend on the power and/or wavelength of incident light into p-i-n semiconductors. It is not possible to oscillate two bistable devices with the same spectrum. This fact make it attractive to operate a system of oscillators at the same unite with flixeability of stantinus controlling it to achieve complexity. As mentioned by Ref. [22], Seeds can transilates LD from stable into unstable, including Hopf bifurcation, oscillation state based on input power. Results for LD1 and LD2 calculated correlation for several variations including FBG T and Stress and optical injection phase are given in Fig. (11).

These results agrees well with those results recently published by Ref. [36]. According to our results, seed makes anti-synchronization is available, this phenomenon whereby the slaved seed oscillator have the same amplitude but opposite signs with those of the master oscillator. Anti-synchronization allows for the enhancement of chaotic 3D attractors complexity which are identical in each oscillators that low correlated. Ref. [37] reported that signal transports without changing its temporal profile if nonlinear dispersion occurs which can recompense material dispersion. This effect is also can control mixing dynamics between two laser signals with high enough optical powers. From physics and neuroscience to engineering and socioeconomic structures, complex networks (such as anti-synchronized oscillators) are used to define a variety of processes in nature and technology [38].
6. Conclusions

Presence of seed in quantum well LDs enhances the laser emission perturbations. These perturbations can be employed for unidirectional, external optical injection in order to generate chaos. This injection type, can be controlled by changing specific oscillator signal parameters, which is in this simulation the phase. Additional control is added using an FBG sensor as a selectively reflector/transmitter. Two parameters for this sensor are tested, which are; T and S, for achieving additional randomness. Results achieved in this study, indicates that interaction between these two lasers with the presence of seed in both of them, generates chaotic antisynchronized emission. Several shapes of attractors are achieved, from limit cycle to strange indicating variety of signals from periodic to moderate chaotic bandwidths.

7. References

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