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Coherence Resonance in Optical Feedback Chaos: Hiding Frequency in Chaos Communication

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Abstract

In this chapter, an experimentally and numerically conducted investigation of the existence of high chaotic spiking in the dynamics of semiconductor lasers with AC-coupled optical feedback, the bifurcation diagram by feedback strength attenuation and the bias current as a control parameter was done. A semiconductor laser subjected to an external optical feedback can present a big change of dynamic behaviors, such as periodic and quasi-periodic oscillations, chaos, coherence collapse, and low-frequency fluctuations (LFF's) that degrade the laser characteristics. The chaotic instability is experimentally investigated on feedback strength as a control parameter, and the resulted dynamic is monostability. Finally, we indicated that the observed chaotic dynamic is a good candidate to hide information in order to investigate the resonance phenomena, which is important for chaos to encrypt data in optical communication, where data disappear when modulated in a chaos carrier. The aim of this chapter is to investigate the encryption area in the chaotic system when the applied frequency is 1–500 MHz, for satisfying the secure communication.

Keywords: chaos communication, chaotic instability, chaos modulation, hidden frequency, resonance phenomena

1. Introduction

In communication, one requests the data to be transferred efficiently. In another expression, the data must be transferred fast and with very low deformation. In classical communication sketches, the maximum limits for high efficiency is enjoined with the properties of the channel, while in chaos communication, this maximum limit is dependent on the characteristic of the dynamical system being utilized [1]. Chaos mathematically and physically was studied to describe an attitude of dynamical systems that are extremely sensitive to the initial state of the system, that is, a tiny disturbance in the initial condition produces significantly varying

attitude, known as the butterfly effect [2]. It indicates that the long-term prognosis is hopeless even if the system is deterministic, which is defined as a deterministic chaos [2]. The state of a dynamical system develops with time that may exhibit dynamics [2]. Several systems dynamic display the chaotic behavior everywhere; however, in most states, the chaos exists only in a subset space, for a group of initial conditions may lead to the same chaotic area, for example, the chaotic attitude may take place on the attractor [3]. Methods for steadying changeful cases in a nonlinear dynamical system employing a tiny perturbation fall into two general groups: feedback and non-feedback sketches. A concept of chaos and instabilities can be controlled efficiently utilizing feedback (closed-loop) system to steady changeful cases, which was proposed by Ott et al. [4] in 1990 [5].

In this chapter, the chaos optical communication was generated. Then the chaos control with feedback attenuation as a control parameter was investigated experimentally. The bias current as a control parameter was investigated numerically, and also the chaotic instability of the semiconductor laser was demonstrated experimentally. Finally, we find the encryption range in the chaotic carrier by applying frequency of 1–500 MHz, and then we observed the low-frequency fluctuations (LFF) phenomena with high frequency.

2. Chaotic spiking generation

The dynamical chaos is an irregular oscillation for time evolutions in nonlinear dynamical systems, appearing clearly in their outputs as a deterministic manner and it is different from random processes [6]. Nonlinearity of a system is one of the important factors to observe chaos [7]. Semiconductor lasers have been shown to be relevant devices in the research of dynamical systems [8]. The intensity of the light emitted by a semiconductor laser is stable when there is no external perturbation, while the semiconductor lasers are easily destabilized by external perturbation, since they are the introduction of an extra degree of freedom to lasers. When the light of the laser is reflected and part of it re-enters into the laser, the laser intensity can become unstable, displaying a broad range of dynamical behaviors [9]. The semiconductor laser-based oscillators' operation in the chaotic regime can be achieved by applying optical feedback [10], optoelectronic feedback [11], or optical injection [12], and their chaotic behavior appears either in the amplitude or in the wavelength regime. A semiconductor laser subjected to external optical feedback can present a large variety of dynamic behaviors, such as periodic and quasi-periodic oscillations, chaos, coherence collapse, and LFF that degrade the laser characteristics [13]. One special unsteady attitude is known as LFF [14, 15], that occurring repeatedly when the laser operates near to the threshold and also submitted to moderate optical feedback from the external cavity in which the round-trip time that is much longer than the period of the solitary laser's relaxation oscillation frequency [5].

Theoretically, the LFF was demonstrated as an impact between the local chaotic attractor and the antimode [16] as a chaotic route by the drift [16] or as a contest between steady and unsteady external cavity modes. While it was experimentally explained that LFF is strongly

dependent on the injection current. Initially, the LFF was known in the low-injection current close to the threshold, whereas lately it was also noticed in a high-current injection [16]. Therefore, LFF is a general event in semiconductor lasers by an optical feedback [16]. Several people studied in chaotic generation and control, theoretically and experimentally, and therefore, we show part of it. Al-Naimee et al. published several papers in semiconductor lasers with optoelectronic feedback, optical feedback, and optical injection. In 2009, they demonstrated experimentally and numerically the presence of slow chaotic spiking sequences in semiconductor laser dynamics with optoelectronic feedback, where the timescale of these dynamics was wholly determined by the high-pass filter which included in the feedback loop [17]. Then, they were presented in 2010; the experiment studied the analysis of chaos generation showing the generation of a mixed spectrum in the time series and the attractor is presented. They stated that the control of chaotic behavior can be achieved by applying a low level of perturbation signals [18]. They are also studied; the quantum dot light emitting diode (QD-LED) model was examined first under bias current without any external perturbation where it exhibits chaotic phenomena since the model has multi-degrees of freedom [19]. The nonlinear dynamics of a semiconductor quantum-dot (QD) laser subject to external optical feedback was examined by using a dimensionless model in [19, 20]. It is perturbed by both small signal and direct current modulations (DCM). Then, this system exhibits mixed-mode oscillations (MMOs) under DCM [19]. Quantum dot light emitting diode dimensionless model displays homoclinic chaos; it is also able to reproduce mixed mode oscillations and chaotic spiking regimes [21]. Then, in 2015, they presented an experiment of the existence of chaotic spiking in the dynamics of a semiconductor laser output with an optical feedback using nonlinear optical fiber loop mirror [22]. Also, they presented in 2016, experimentally, the efficient bandwidth of chaotic signals which has been measured and can be increased by injecting current which is an important parameter in chaos communication [23].

3. Chaos in optical communication

3.1. Generation of optical chaotic carrier

The excellent model for nonlinear optical system is the semiconductor laser with feedback for chaotic dynamics [24]. Semiconductor lasers are different from other lasers in the low reflectivity of the internal mirrors in the laser cavity. That domain usually is from 10 to 300% of an intensity in the Fabry-Perot semiconductor lasers. Therefore, the feedback effects are important in the semiconductor lasers. A large absolute value of a line width enhancement factor α is another difference, which is α = –2 to −6, convened in semiconductor lasers, while the value of line width in another laser is roughly 0. This information drives to interesting and an assortment of dynamics of several other lasers. The optical feedback reflectivity is from weak to moderate, the output power of the laser shows interesting dynamical attitudes like a steady state, periodic and quasi-periodic oscillations, and chaos for the variety of system variables. The external reflectivity scopes are not just

interesting but also really significant in current implementations of semiconductor lasers like an optical information storage arrangement. A semiconductor laser dynamical behavior with optical feedback is mainly influenced by three parameters in the system, which include the reflectivity and the length of the external mirror and the bias injection current. The dynamic behaviors of a semiconductor laser with optical feedback are not simple and strongly dependent on the feedback reflectivity. According to the behaviors of the laser output, by an increase of the feedback, reflectivity can be characterized by the dynamics of the output power into five regions (I–V) [25, 26]; depending on the phase of the returned light into the laser cavity, the laser line width is increased or decreased for the very tiny feedback regime I. The laser shows mode hopping among several external cavity modes (regime II) by an increase of the feedback scale. At moderate levels of the feedback amplitude reflectivity around 1%, chaos can be observed, that corresponds to the regimes III and IV. The coherence collapse occurs in the laser output power, with further increase of the feedback level, in which the line width is drastically broadened and the coherence length of the laser is much reduced. These regions are very important in actual optical data storage systems. A very high-feedback level (regime V) corresponds to a stable laser operation. They are much interested in the regimes III and IV, which show chaotic dynamics [24]. These regions are shown in **Figure 1** [27].

Here we present the experimental configuration for a semiconductor laser with optical feedback in order to investigate the existence of fast, chaotic spiking in the dynamics of a laser; this is schematically shown in the **Figure 2**. A closed-loop optical system consists of a semiconductor laser (1310 NM) (NOYSE FIBER SYSTEM). The output laser is connected to the 2 by 2 direction coupler (DC); the two output DCs are connected together to a variable optical attenuator (VOA), while another branch of the DC is connected to a photodetector (NEW FOCUSE; Model 1811–125 MHz an InGaAs/PIN). The output signal from photodetector is observed with a four-channels digital storage oscilloscope (DSO) (TEKTRONIX-TDS2024B), used to analyze the time series with the possibility of direct fast Fourier transformation. Then the results are analyzed by a personal computer with origin program. The round-trip time of external cavity of the laser used is 50 ns, which is given by this formula:

$$\tau_{ext} = 2nL/c \qquad (1)$$

where L is the length of the fiber which is equal 5 m, n is a refractive index of the fiber core (silica glass), and c is the speed of light in vacuum.

The effect of the attenuation feedback strength is a control parameter for generating chaotic behavior in the semiconductor. In our experiment, a VOA is used to control the attenuation feedback strength (0–15) dB. **Figures 3–7a** represent the time series of the nonlinear dynamic, which are important to show the time evolution of photon density. **Figures 3–7b** shows the phase space (attractor) of the oscillator by using an embedded technique with appropriate delays; the trajectories are different in diameters and dense and its looks very strange (strange attractor). While the **Figures 3–7c** represent the power spectra of the chaotic signal, the FFT figures are exponentially decayed to distinguish chaotic signal from other signals like noise; this agrees with [28]. The spiking rate and amplitude of the chaotic signal decrease with increasing the attenuation feedback strength as shown in **Figure 8** which
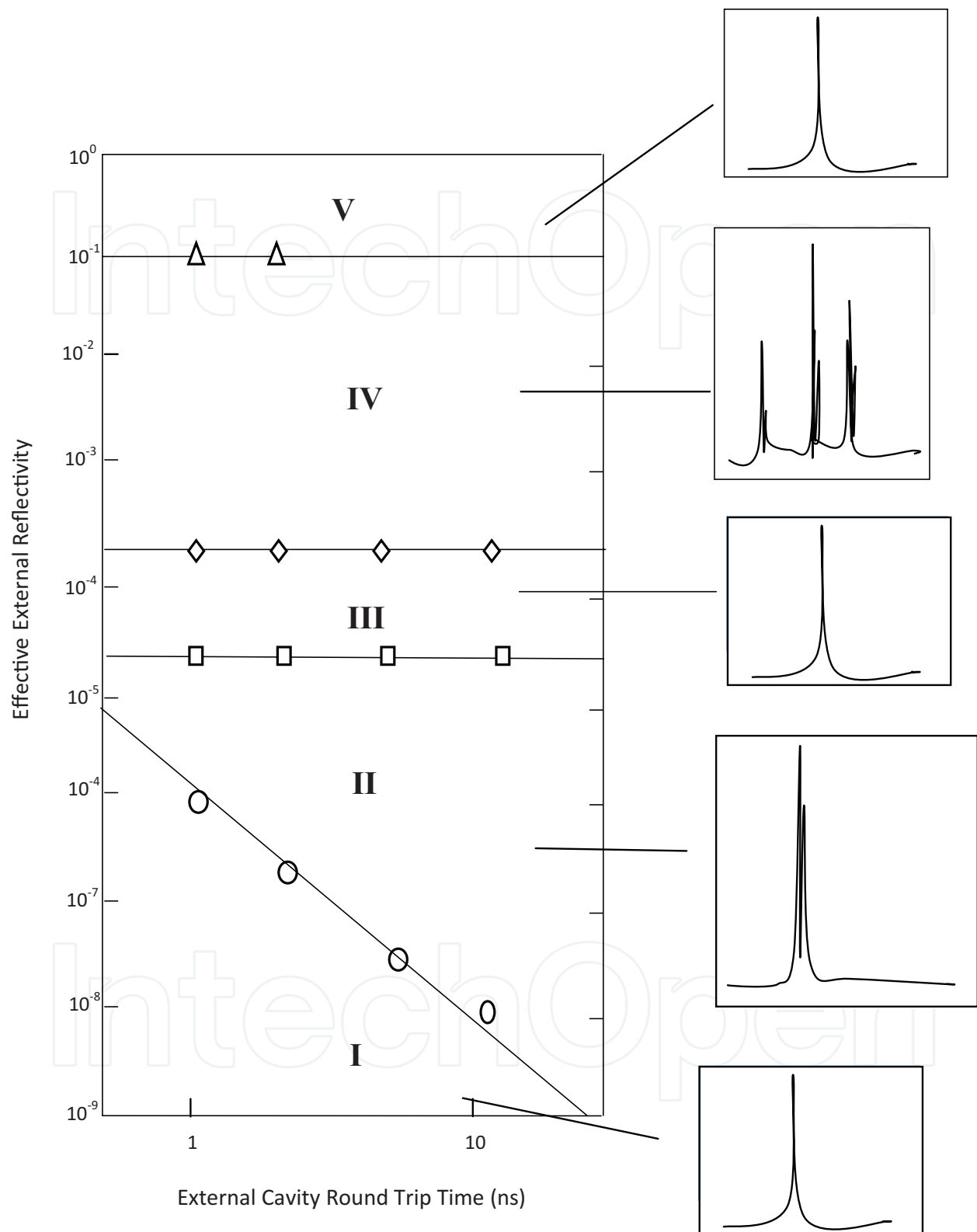
Figure 1. Regimes of optical feedback effects occurring for different values of the external reflectivity and the external cavity length [27].

is representing the bifurcation diagram. The bifurcation diagram represents the peak-to-peak laser output intensity versus the attenuation in feedback strength as a control parameter. In this plot the spiking rate and amplitude of the chaotic signal can be observed as
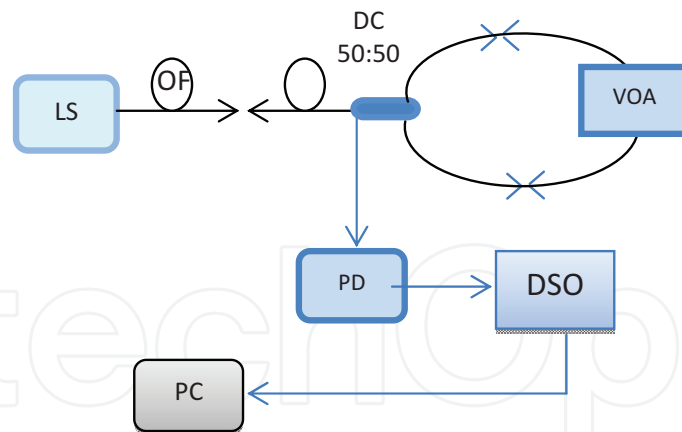
Figure 2. Experimental setup of semiconductor lasers with optical feedback systems. LS: semiconductor laser 1310 nm, OF: optical fiber, DC 50:50: directional coupler 2 by 2 single mode, VOA: variable optical attenuator, PD: photodetector, DSO: digital storage oscilloscope, and PC: personal computer.

decreasing gradually with increasing feedback strength; this result agrees with reference [22]; this type of feedback is called negative feedback. The bifurcation diagram for optical attenuation from 0 to 8.5 dB means high-feedback strength, the dynamics of the oscillator is chaotic with high intensity. When the optical attenuation increases from 9 to 12 Db, the dynamics of the oscillator becomes less because of the low ratio of the feedback strength and from 12.5 to 15 Db, the dynamics of the oscillator becomes constant because the chaos goes into saturation.

3.2. Chaotic instability of the semiconductor laser

By the chaotic evolution, the self-mixing outputs of the semiconductor lasers observed the bistability and multistability. In a periodic case, the output laser shows hysteresis in addition to simply periodic oscillation [25]. Based on these phenomena, proposed a novel application, for example, by counting the fringes obtained from bistable self-mixing inter-ference between the internal field and an optical feedback light in the laser cavity, the dis-placement measured is performed. From asymmetric waveforms showing hysteresis, a direction of displacement is simultaneously determined [25]. In many different systems, by using intrinsic or hybrid optical circuits, the optical bistability was observed. If a sys-tem has two output states for the same value of input over some range of input values, the system is considered optically bistable. Under some operating conditions, the two optical cases originate from the stable-state and transient characteristics of the nonlinear optical system. That input and output relation is described by a multivalued function and has many stable and transient states in a nonlinear system which known as multista-bility [29]. In our experiment of chaotic instability, by using the configuration setup in **Figure 2**, the result appears that the chaotic instability of optical feedback by optical feedback attenuation as a control parameter is monostability, as shown in **Figure 9**. This figure is obtained by using a bifurcation diagram from 0 to 15 dBm and again plots the bifurcation diagram from 15 to 0 dBm in the same time to conserve the initial conditions of the chaotic system.
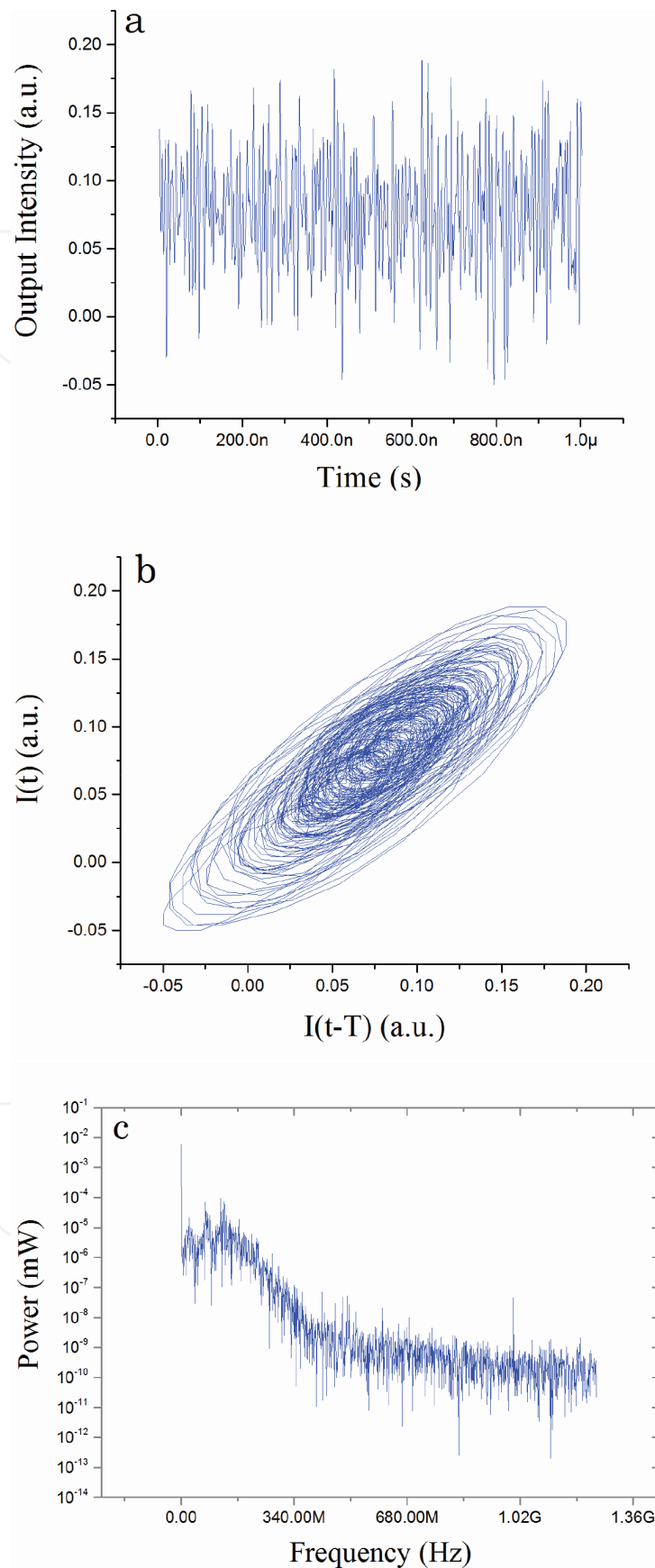
Figure 3. The effect of attenuation feedback strength of 0 dB (a) time series (b) attractor (c) FFT.
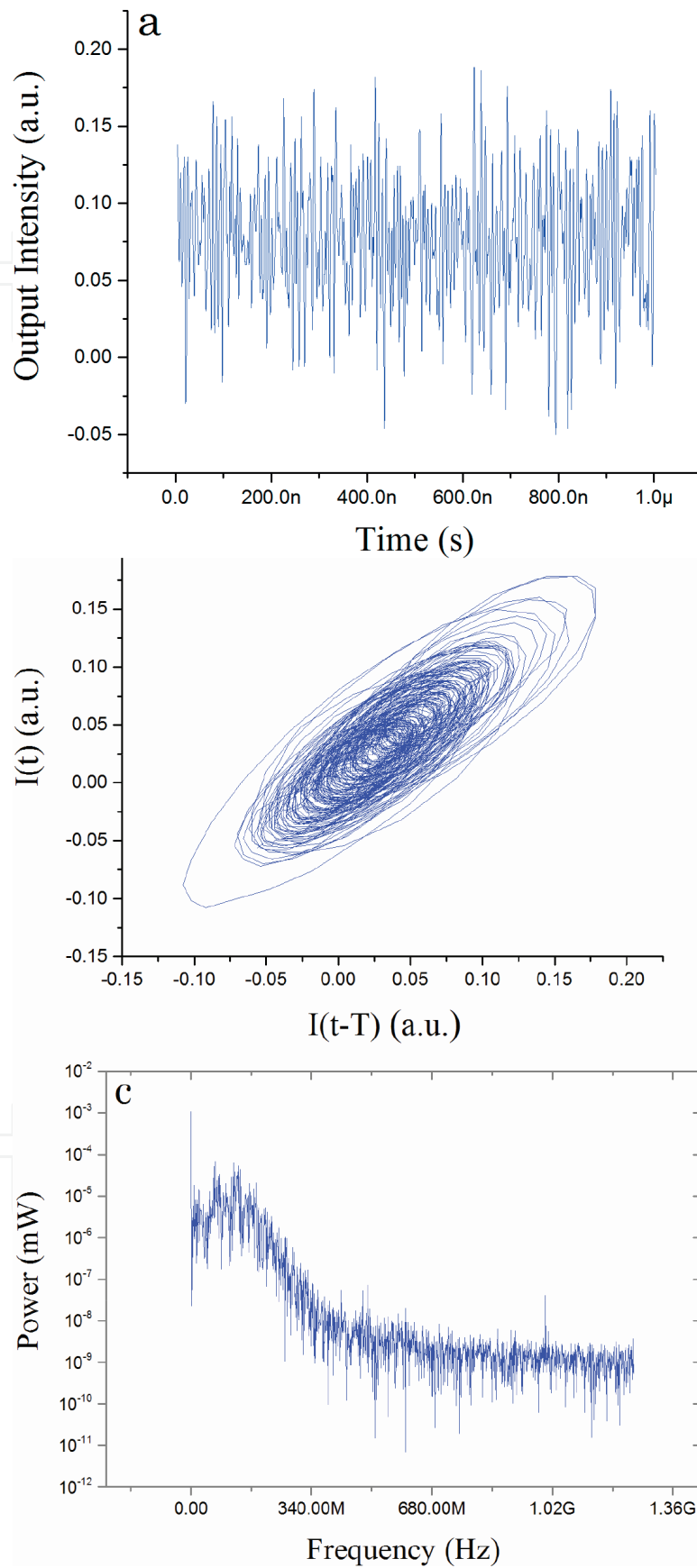
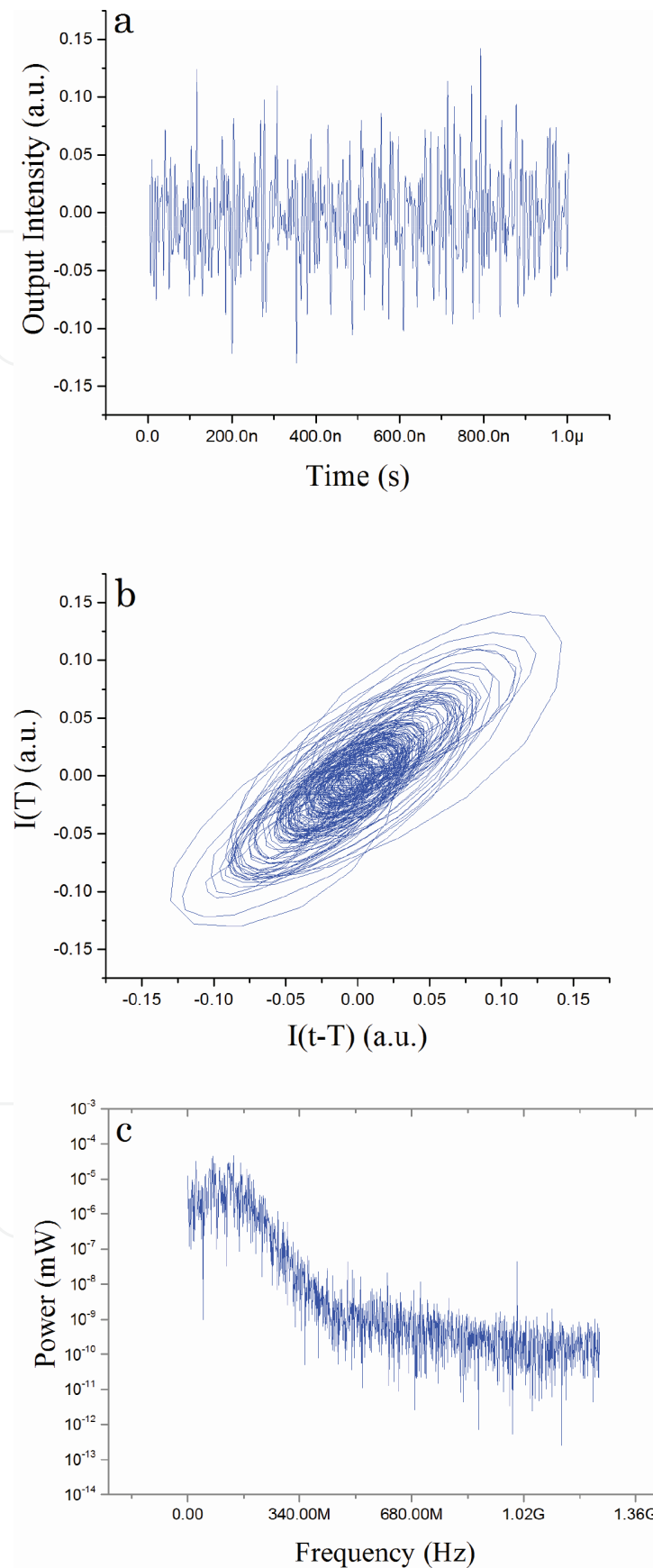**Figure 4.** The effect of attenuation feedback strength of 2.5 dB (a) time series (b) attractor (c) FFT.

Figure 5. The effect of attenuation feedback strength of 6 dB (a) time series (b) attractor (c) FFT.
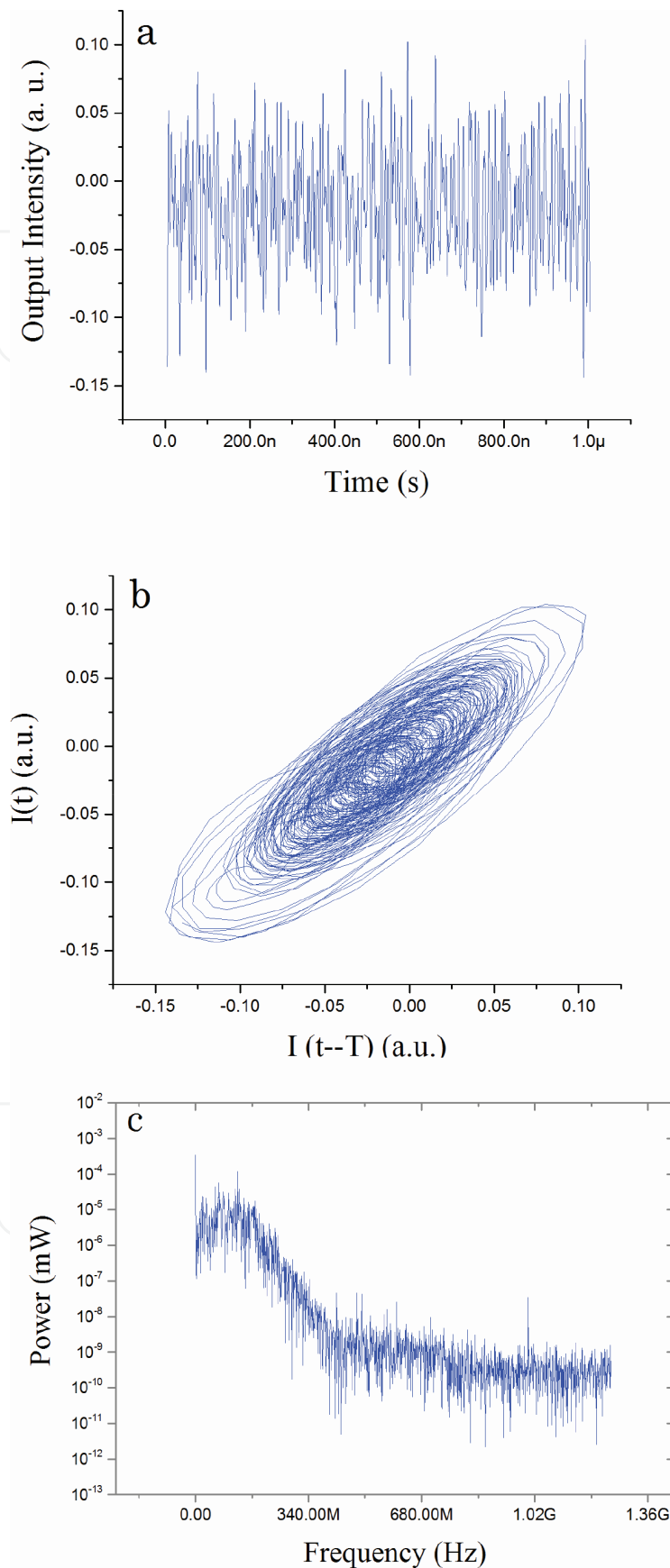
Figure 6. The effect of attenuation feedback strength of 10 dB (a) time series (b) attractor (c) FFT.
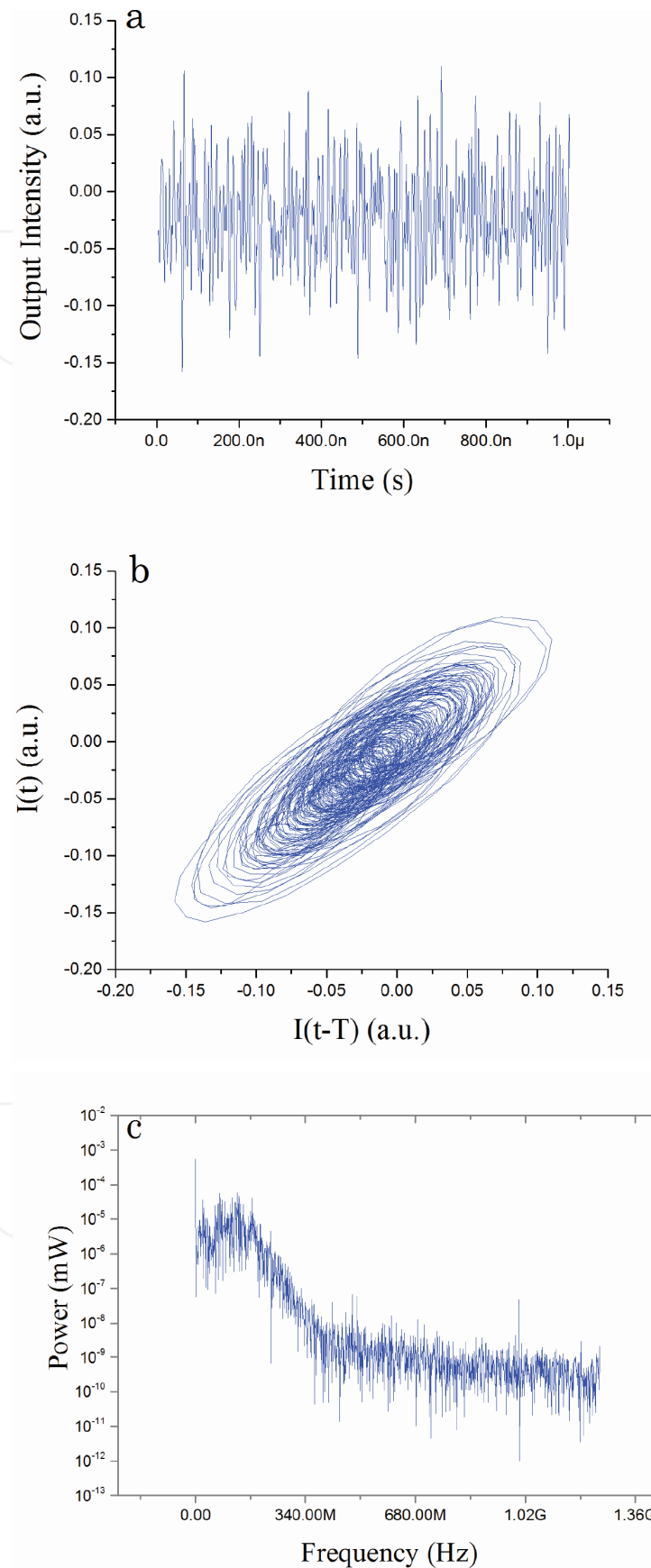
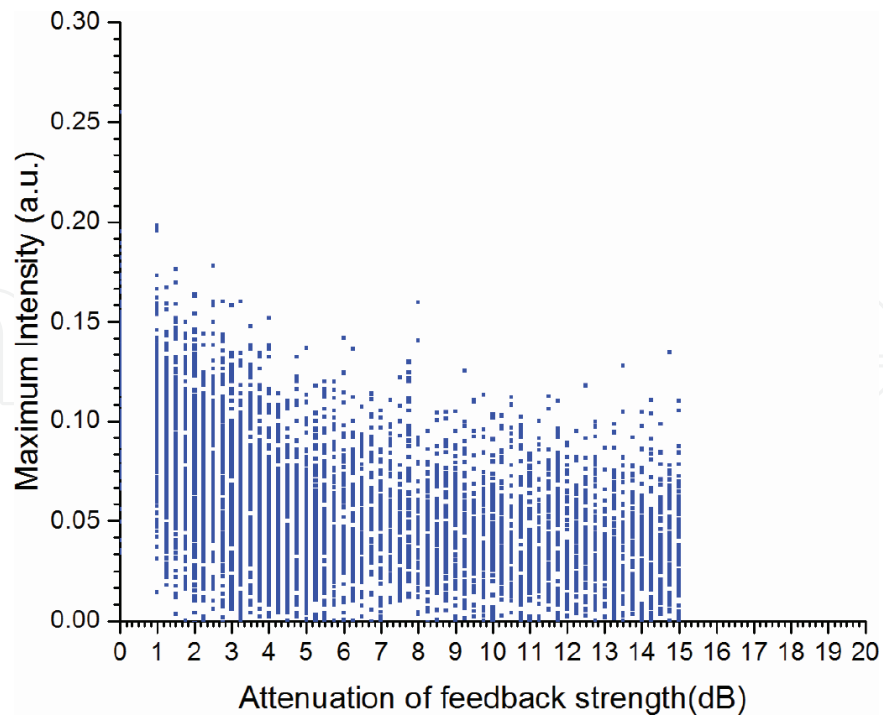**Figure 7.** The effect of attenuation feedback strength of 15 dB (a) time series (b) attractor (c) FFT.

Figure 8. Bifurcation diagram of chaotic laser intensity as a function of the attenuation feedback strength (dB).
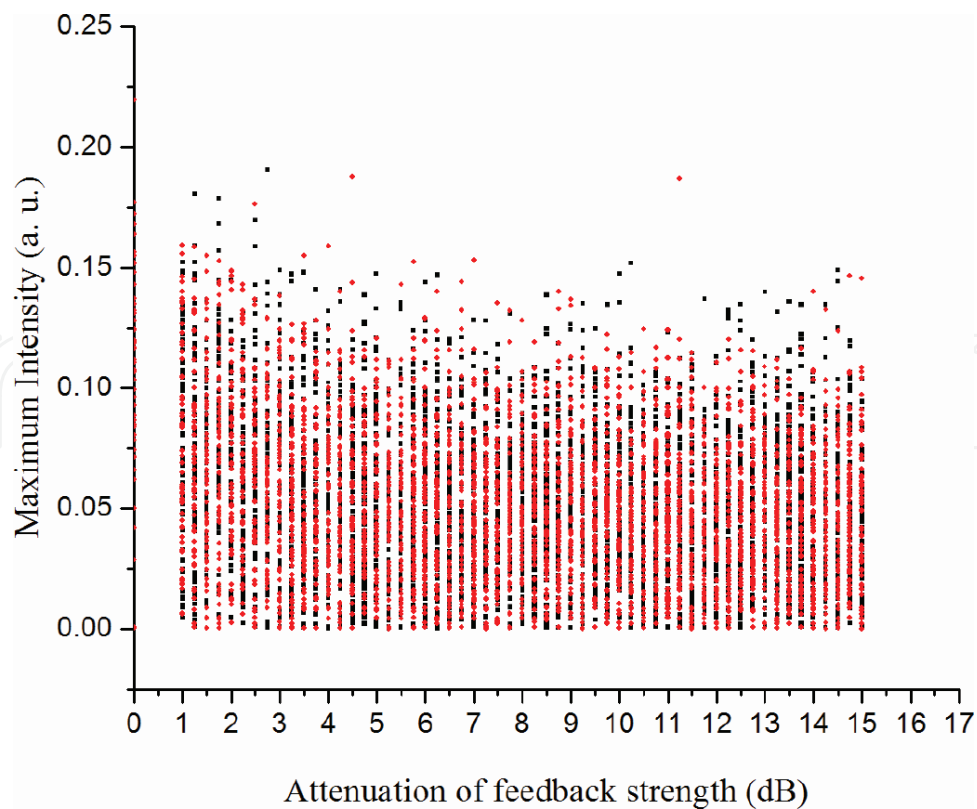

Figure 9. Chaotic instability of optical feedback as a function of the attenuation feedback strength (dB).
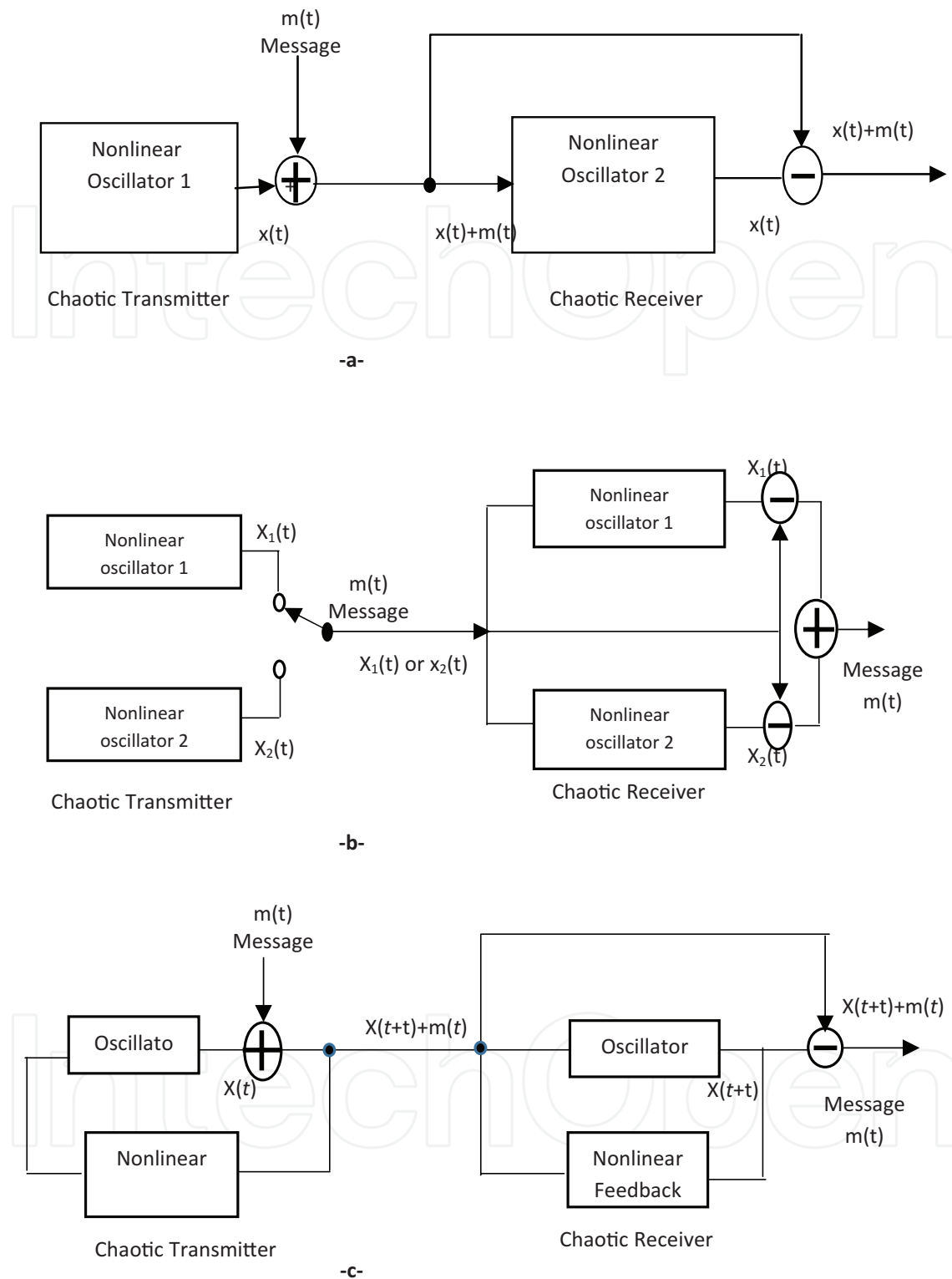
Figure 10. The schematic diagram of chaos encryption, (a) CMA, (b) CSK, and (c) CMO [31].

3.3. Encryption of message

There are three primary message encryption methods utilizing optical communications chaos [30], which will be explained in a next section.

- Chaotic masking (CMS): with a transmitter laser (TL), a chaotic carrier is generated. Then, the message is directly added to the chaotic carrier, see **Figure 10a**.

- Chaotic shift keying (CSK): the injection current of the transmitter laser is used to modulate the message directly. Therefore, the transmitter laser produces the chaotic carrier for a message concealed in it, as shown in **Figure 10b**.

- Chaotic modulation (CMO): it involves adding the output power of the transmitter laser to the message. Therefore, this mixer of the signal and message is sent back to the transmitter laser through a feedback loop as a modulation to produce a chaotic carrier as shown in **Figure 10c** [30].

There are two kinds of chaos modulation such as direct current modulation and external modulation of the semiconductor laser [32]; in our experiment, the external modulation was used. The external modulation in optical communication divides into two types. A first kind is dependent on the absorption modification of a semiconductor material when the external electric field is applied, which is known as an electro-absorption modulator, while the second kind relies on the refractive index variation observed in several crystals under an external electric field that is called an electro-optic modulator. Additionally, with the interferometry structure, like a Mach-Zehnder structure, there can be a modulation of the intensity of a light wave because a change in the refractive index itself does not allow modulation of the intensity of a light wave. A Mach-Zehnder structure enables to convert the induced phase modulation into the desired intensity modulation.

4. Electro-absorption modulation

The effective band gap Eg of a semiconductor material decreases when an external voltage is applied; hence, this fact is important in this kind of modulation. Then, if the frequency υ of an incoming light wave is chosen so that its energy $E = h\upsilon$ is smaller than the bandgap when no voltage is applied, the material will be transparent. In another word, the effective band gap will be reduced when an external voltage is applied, which means that the wave of light will be absorbed by a material when $E > Eg$, that is, a shift of a semiconductor absorption edge under the effect of the external voltage is delineated in **Figure 11**. Through duly selecting the wavelength signal so that it expertise a significant variation in the absorption when the voltage is applied, consequently it becomes possible to perfect optical modulation controlled via an electrical signal. An ideal absorption against the function of applied voltage transfer for an electro-absorption modulator is shown in **Figure 11**.

Since the refractive index of a semiconductor material and the absorption is linked by Kramers-Kronig relations of the kind

$$\Delta n(\omega) \; = \; \frac{c}{\pi} \int\limits_{0}^{+\infty} \frac{\Delta \alpha(\omega')}{\omega'^2 - \omega^2} d\,\omega' \tag{2}$$
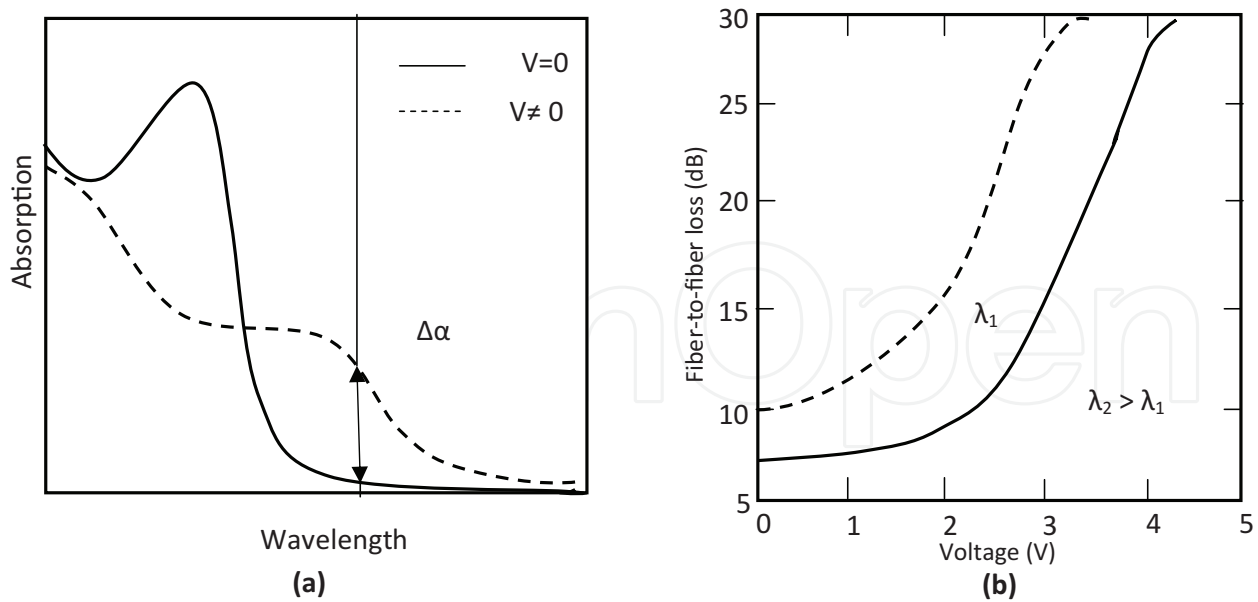
Figure 11. (a) Absorption of a semiconductor as a function of wavelength with and without an external an applied electric field. (b) Typical loss versus applied voltage curves for an electro-absorption modulator [32].

where Δn is change in the refractive index produced by a variation in the coefficient of absorption $\Delta \alpha$ and c is the speed of light in a vacuum, to achieve an optical modulation shifting by the absorption edge and also to make a change in the refractive index of the material; hence, the modulation occurred in the signal of a phase or instantaneous frequency. Hence, via an electro-absorption modulator, some amount of frequency chirping will be introduced. The produced frequency chirp will usually be lower than when a semiconductor laser direct current modulation is used, as shown **Figure 11** [32].

In this chapter, the experiment setup of semiconductor lasers and signal generators in order to satisfy chaos modulation and study the resonance phenomena is shown in **Figure 12**. This experimental setup consists of a fiber-coupled semiconductor laser source (HP/Agilent model 8150 A optical signal source) which is connected with a signal generator (Agilent N9310A
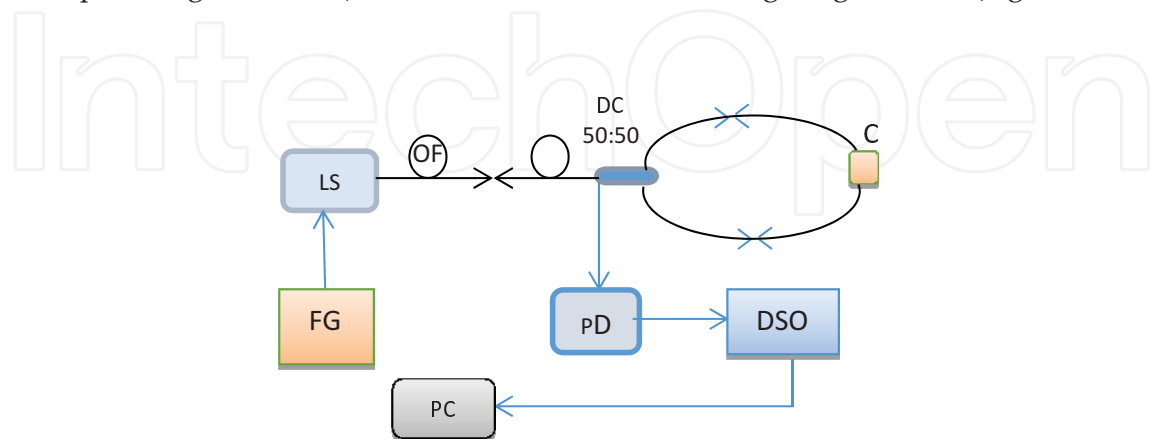

Figure 12. Experimental setup of chaos modulation [LS: semiconductor laser 850 nm, FG: function generator, DC 50:50: directional coupler 2 by 2 multi-mode optical fiber, C: adaptor FC: FC connector].
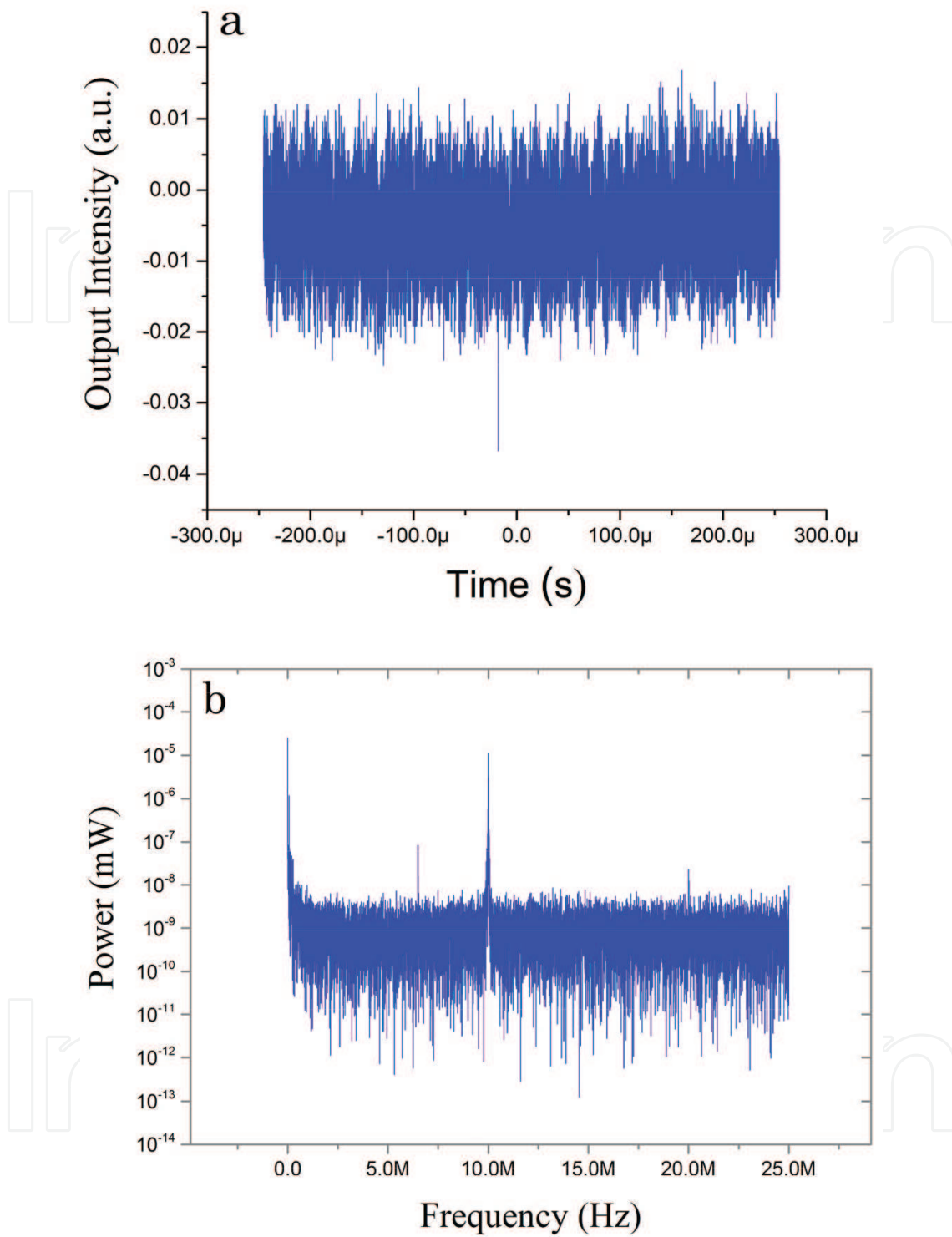
Figure 13. Experiment of chaos modulation 10 MHz (a) time series (b) FFT.

RF signal generator 9–3 GHz); the output power of the laser source is connected by a DC multimode fiber optics 2 by 2. Then, the two branch outputs are connected together by an FC adaptor to make a loop mirror, while the reflected light from coupler is split in two ways, one
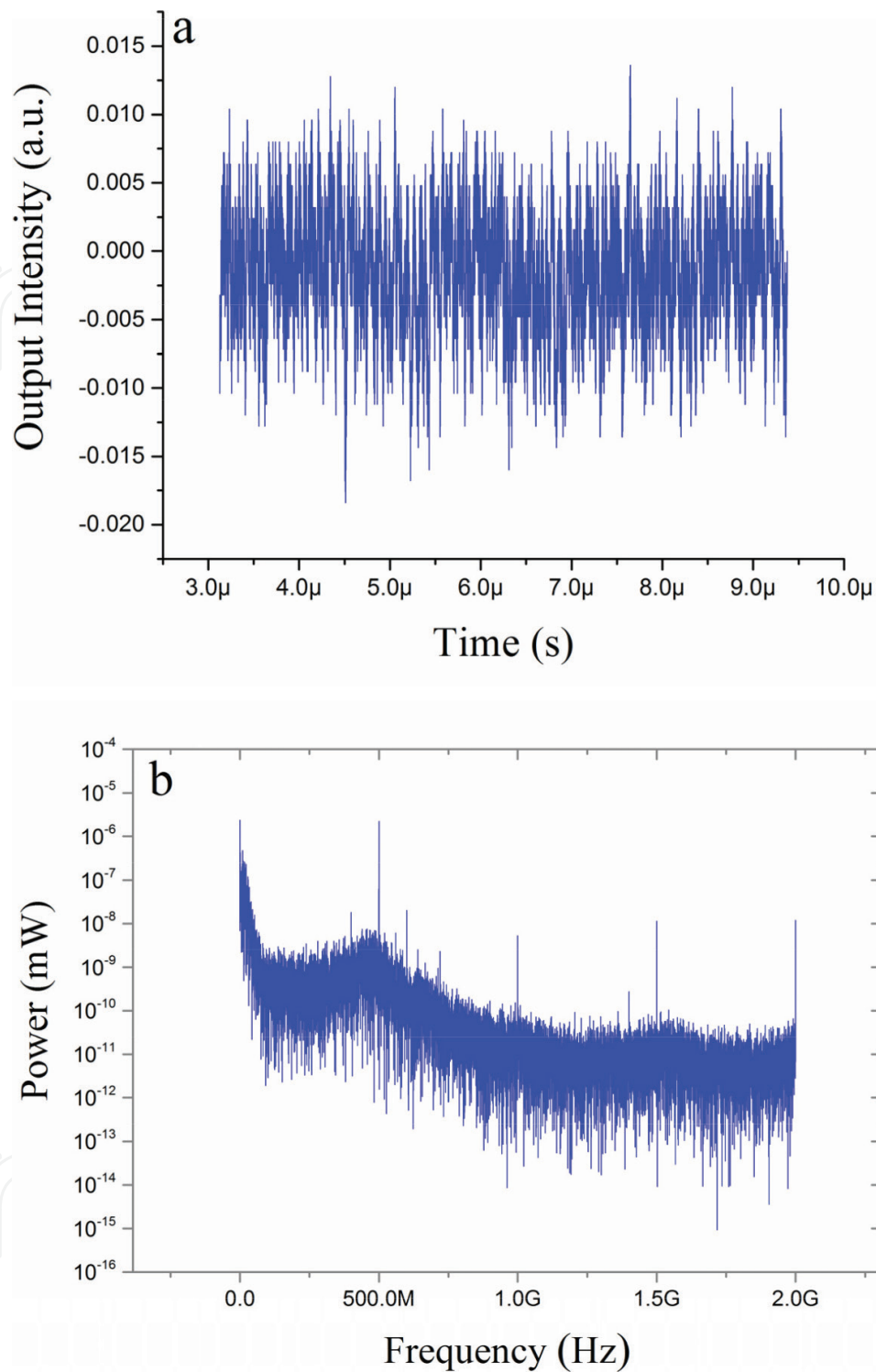
Figure 14. Experiment of chaos modulation 500 MHz (a) time series (b) FFT.

directed towards the cavity of semiconductor laser as feedback and the other detected by a fast InGaAs photodetector (rise/fall time < 1 ns, bandwidth 1.2 GHz, and the spectral response range is 800–1700 nm). Then the detected signal is amplified by an oscilloscope (GOS −652G
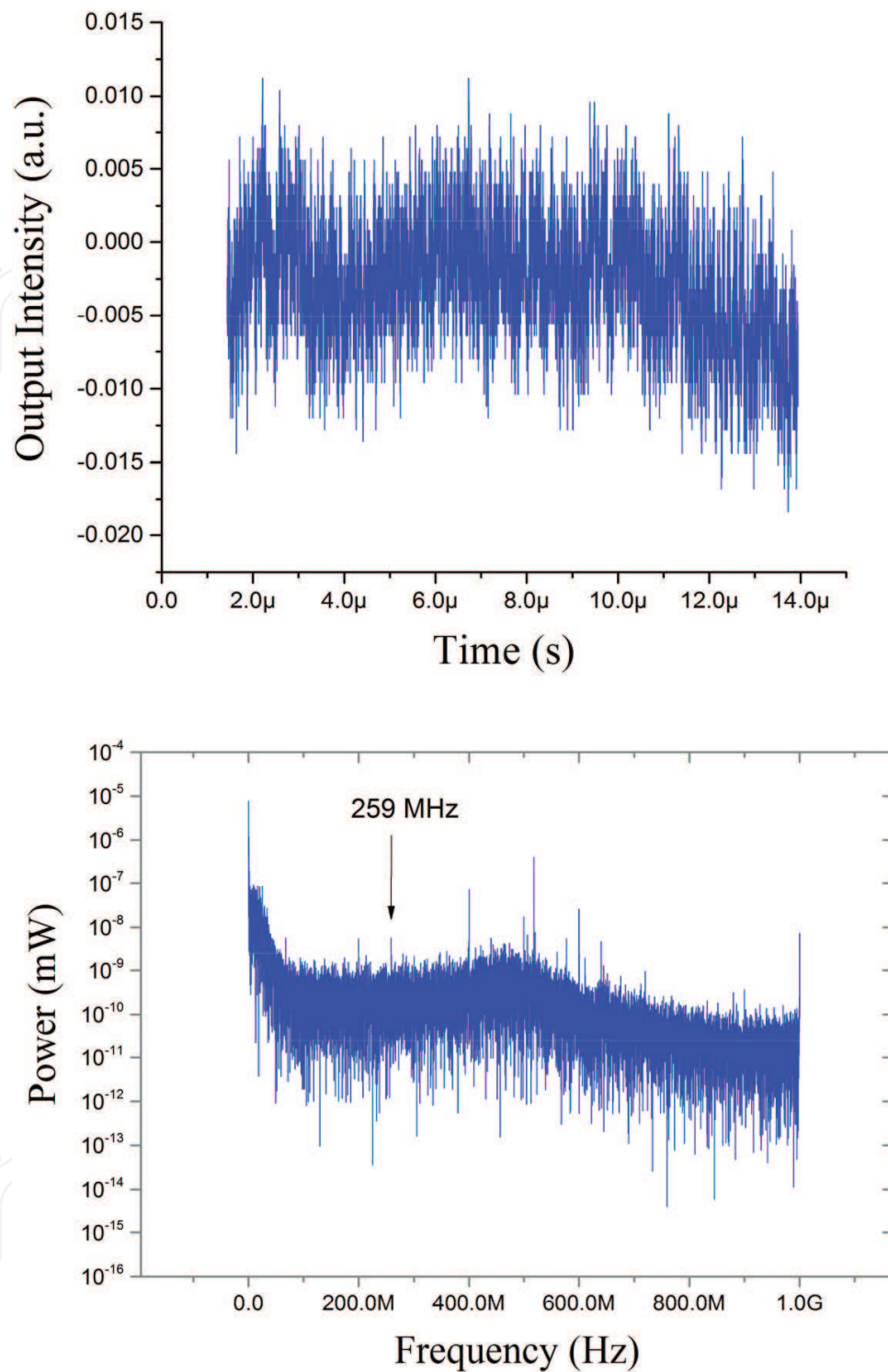
Figure 15. Experiment of chaos modulation 259 MHz (a) time series (b) FFT.

(20 MHz)); after that the output signal is observed by a four-channel oscilloscope DSO model GWinstek GDS-3504 (500 MHz −4GS/s) which is used to analyze the time series with the possibility of direct fast Fourier transformation. Then the results are analyzed by a personal computer with an origin program.
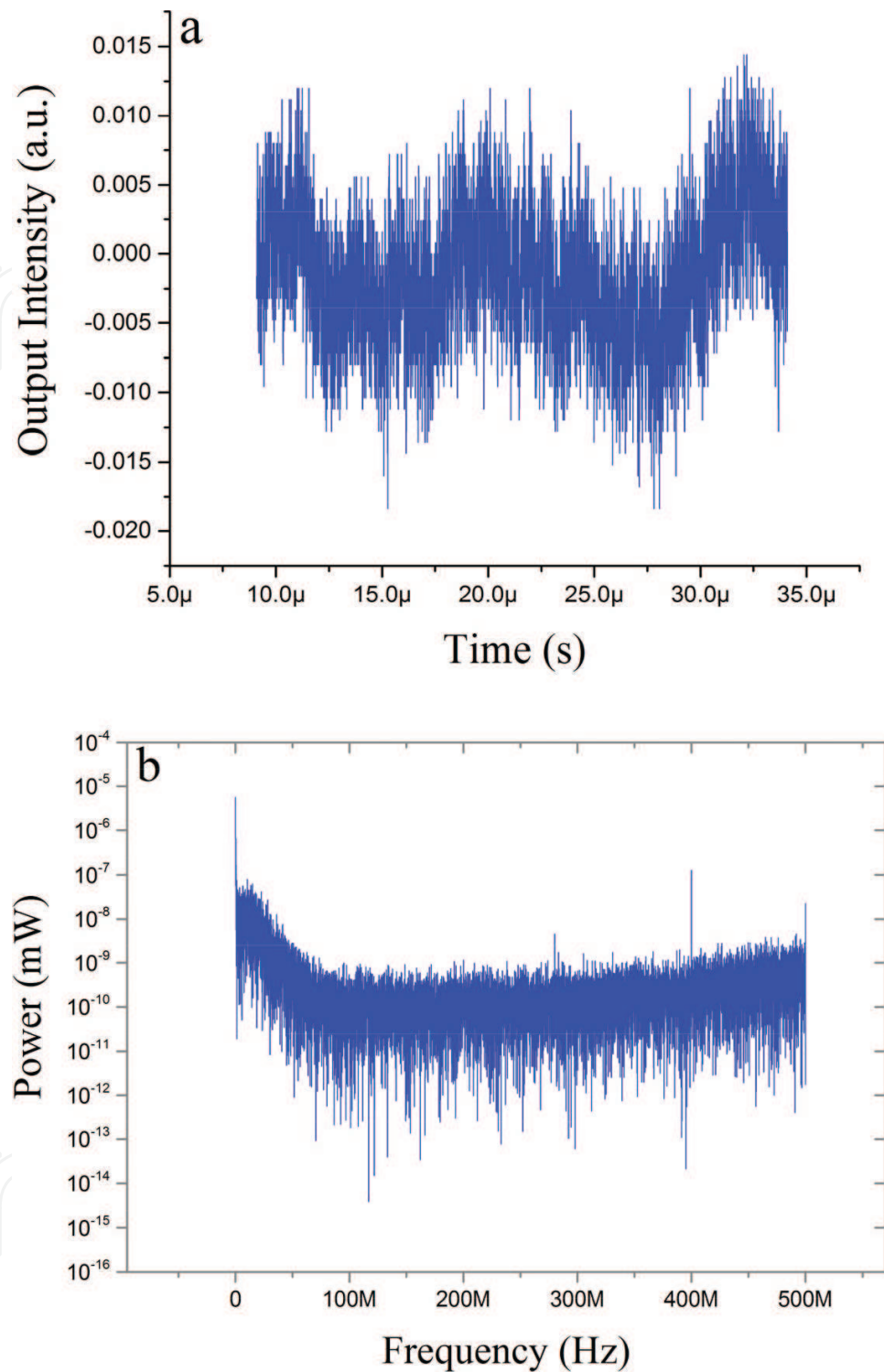
Figure 16. Experiment of chaos modulation 200 MHz (a) time series (b) FFT.

The intrinsic dynamic resonance in the photon-carrier interaction determines the modulation response of semiconductor lasers. To investigate the resonance phenomena for satisfying the encryption of secure optical communication, a frequency of 1–500 MHz is applied. We see that the external frequency in the pumping current is able to enhance the regularity of the drop-out
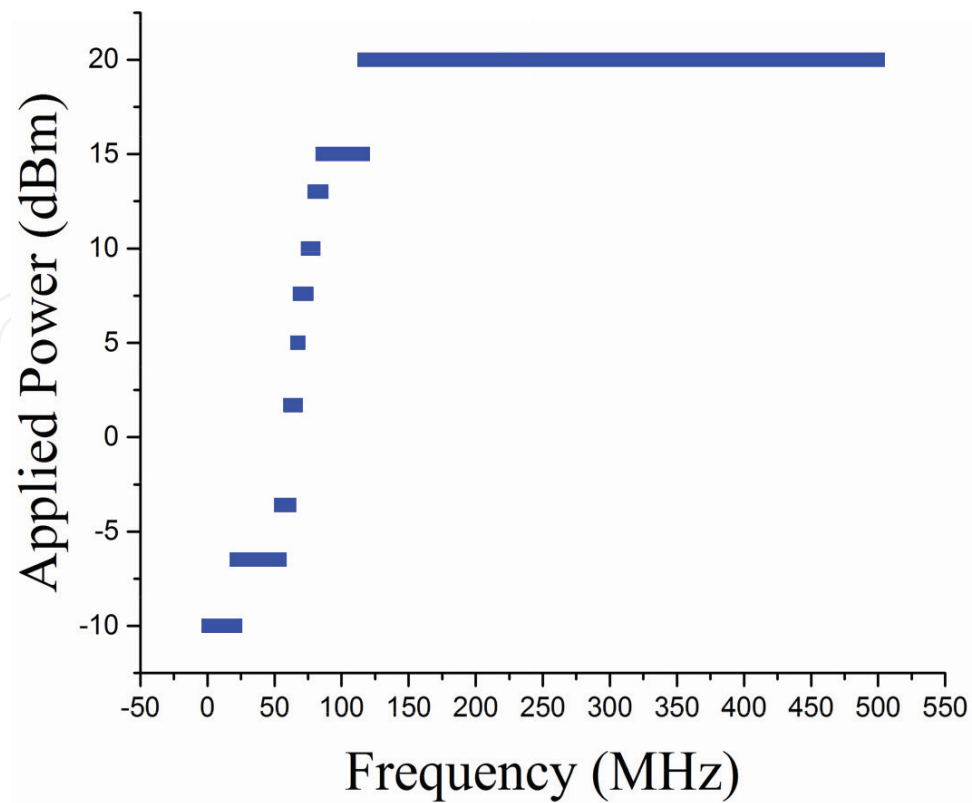
Figure 17. Distribution of change of applied power(dBm) as a function of applied frequency (MHz).
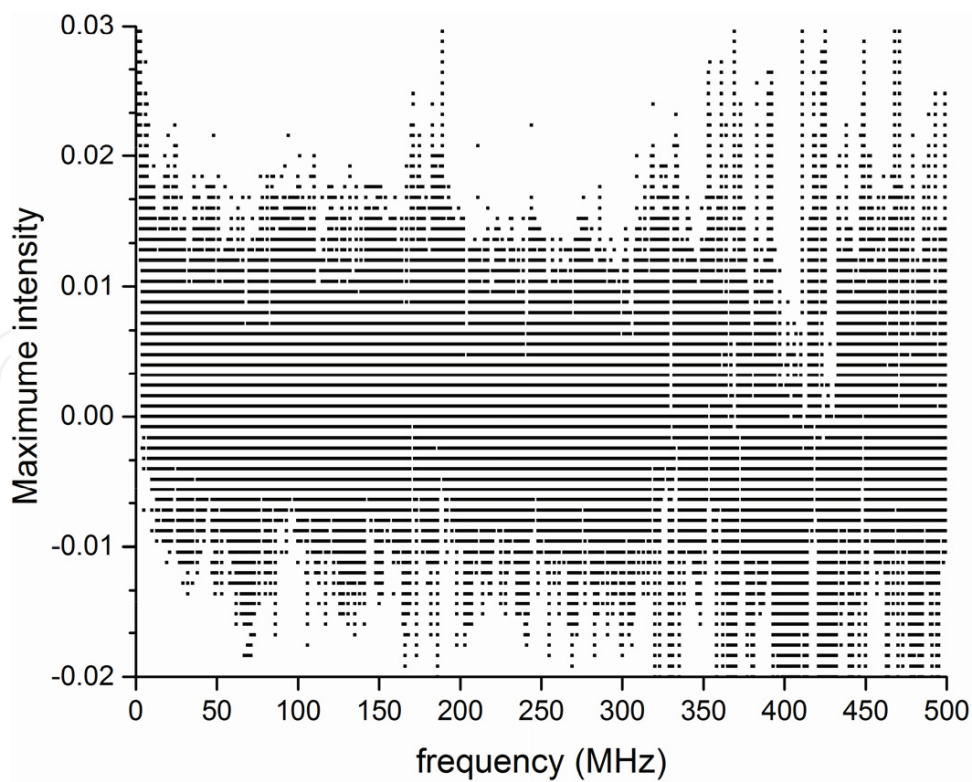

Figure 18. Bifurcation diagram of the laser intensity as a function of the external modulation frequency.
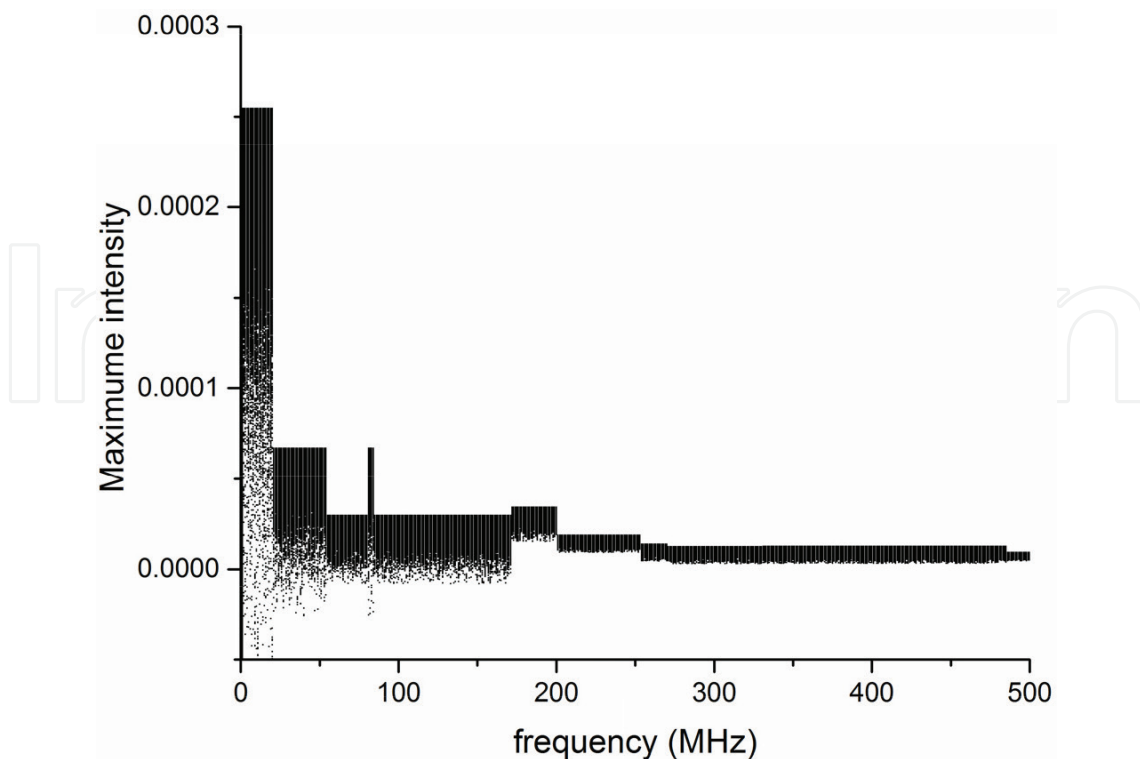
Figure 19. The distribution of the bifurcation diagram.

time series emitted by the laser. Frequency in this experimental setup can also enhance the response of the laser to an external periodic drive as shown in **Figures 13–16** which represent the chaos modulation. Coherence resonance is a manner in the chaotic dynamic, that is, regularity of the time between power dropouts for a given value of the feedback strength [33]. This phenomenon occurs by applying an external noise signal to the chaotic system [34], while the laser with optical feedback may display chaotic dynamics with fast pulses at the time scale of the time delay and much slower power drops [33]. In our experiment the coherence resonance phenomena appear when applied different frequencies. **Figures 13–16a** show the time series as a sinusoidal wave for different frequencies applied, the amplitude applied from the signal generator to modulate frequency is between −10 and 20 dBm, and the current density of the chaos signal is fixed at 595 μW/volt. The LFF was investigated for high-frequency injection-current modulation in a semiconductor laser with optical feedback. This result appears in **Figure 16a** at a frequency applied at 200 MHz; then, they observed resonant oscillation of the laser output power that was synchronized with the modulation, which is common in semiconductor lasers with optical feedback. However, LFF appeared for the detained modulation frequency from an external cavity mode. This result agrees with [16]. The power spectrum of different frequencies is analyzed, observing a sharp peak, low spiking peak, and hidden frequency peak. A sharp frequency peak in the modulation period for certain frequencies [(1–138), 140, (247–258), 260, (266–270), (272–278), 340, (344–346), 370 & 371, and (378–500 MHz)] corresponded to the amplitudes (–10,–6.5,–3.6, 1.7, 7.6, 10, 13, 15, and 20 dBm), while the low spiking frequencies appear at 144, 259, 271, 280, 300–304, 338, 339, 341–343, 347 & 348, 368 & 369, and 372 to 377 MHz corresponding to amplitude 20 dBm, as shown in **Figure 15b**. Then

the area of hidden frequencies is in 139, 141–143, 145–239, 261–265, 279, 281–299, 305–337, and 349–367 MHz, which corresponds to amplitude 20 dBm, as shown in **Figure 16b**. **Figure 17** shows the changes in applied power with increased frequency. In this figure, one notices the increase in the applied power from the signal generator (−10 to 20 dBm) with an increase in the frequency modulation. **Figure 18** shows the bifurcation diagram of the laser intensity as a function of the external modulation frequency, in accordance with [35]. In this figure, one observed that the dynamic is chaotic behavior when applied to different frequencies. **Figure 19** shows the distribution of the bifurcation diagram. **Figure 19** shows different regions—instable regions (0– MHz and from 172 to 253 MHz) and then the stable regions (85–171 MHz and 255–500 MHz). These regions are important in satisfying an encryption message in the investigations of secure communication.

5. Theory of semiconductor lasers with optical feedback

A laser is described theoretically by three variables: the electric field in the laser, the polarization of the laser medium, and the population inversion to induce the laser oscillation [25]. Theoretically, the semiconductor lasers' static characteristics with optical feedback can be investigated by the relations among the reflectivity of internal cavity and external reflector, the gain in the medium, and other static laser parameters. However, the dynamic characteristics must be described with time-dependent equations of the systems. A laser is essentially a chaotic system; however, every laser does not show chaotic oscillations. According to the scales of the decay rates in the differential equations, lasers are classified into three categories. When we need all of three rate equations to describe a laser, the laser is a chaotic system and it is called a class C laser. Actually, infrared oscillating gas lasers like NH3 and Ne-Xe lasers exhibit chaotic oscillations in their output powers [25]. The second one is a class B laser, in which the time constant of the polarization is very fast and the polarization equation is adiabatically eliminated. Then, the laser is described by the two equations of field and population inversion, and it is a stable laser if there is no external perturbation. The third one is a class A laser, whose field equation is enough to describe the system, and it is the most stable class of lasers. The polarization term is adiabatically eliminated for class B semiconductor laser; this effect is replaced by a linear relation between polarization and the field. Semiconductor lasers population inversion is replaced by density carriers N produced by a recombination of the electron hole. The absolute square of the field amplitude (which is equivalent to the photon number) and the density carriers are frequently used as the variant of an equation rate for semiconductor lasers [25]. The dynamics of intensity fluctuation in a single-mode semiconductor laser is modeled by the Lang-Kobayashi model, which are historical milestone papers for semiconductor lasers' chaotic dynamics [36], which include the effect of optical feedback time delay [37]. The Lang-Kobayashi equations for the complex amplitude electric field E (t) and the carrier number N (t) are written as follows [38]:

$$\frac{dE(t)}{dt} = \frac{1}{2}(1 + ia)[G(t) - \gamma]E(t) + KE(t - \tau_f)\exp(-\omega\tau_f) + \sqrt{2\beta N(t)X} \tag{3}$$

$$\frac{dN(t)}{dt} = \frac{i}{q} - \gamma_d N(t) - G(t) \, |E(t)|^2 \tag{4}$$

where G(t) is the optical gain defined by this formula:

$$G(t) = \frac{g[N(t) - N_o]}{1 + s \, |E(t)|^2} \tag{5}$$

ί: is the bias current and $|E(t)|^2$: the laser intensity or the number of photons inside the cavity which is calculated from the square of the electric-field amplitude, that is, $I = |E(t)|^2$. α is a line width enhancement factor, N_o is a transparency carrier number, g is a differential gain coefficient, s is again saturation coefficient, γ is a photon decay rate, γ_d is a carrier decay rate, β is a spontaneous emission rate, τ_f is a delay time, and K is the feedback strength. The spontaneous emission processes are considered by introducing independent Gaussian noise sources X with zero mean and unity variance into the rate equation. These equations represent the nonlinear dynamical system which produced chaos in the semiconductor laser with OFB.

6. Conclusions

The generated chaos in the semiconductor laser with optical feedback could be controlled by the feedback strength parameter. The chaotic instability was experimentally investigated with feedback attenuation as a control parameter and the resulting dynamics was monostability. Then, we indicated that the observed chaotic dynamic is a good candidate to hide information in order to investigate the resonance phenomena, which is an important part of chaos to encrypt data in optical communication, where data disappears when modulated in a chaos carrier. Therefore, the best regions for hiding frequency are 145–239 MHz, 281–299 MHz, 305–337 MHz, and 349–367 MHz. Finally, LFF appears with high frequency from 25 to 500 MHz.

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