doi:10.3788/gzxb20184705.0514004

单片集成半导体激光器的阵发混沌特性

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摘　要:实验研究了一种由一个分布反馈半导体激光器、一个相位控制部分和一个半导体光放大器组成的三段式单片集成半导体激光器的动力学特性. 采用常规的动力学分析方法,对不同相位控制电流下激光器输出的光谱、时间序列、相图及功率谱进行了分析,考察了其进入混沌的路径及阵发混沌的特性。研究结果表明,在适当的运行参数下,单片集成半导体激光器可呈现混沌态与稳定态随机交替出现的阵发混沌状态输出.在固定分布反馈半导体激光器电流和半导体光放大器电流不变的情况下,连续地增大相位区的电流 I_P,单片集成半导体激光器将先后经历稳定态、单周期态、阵发混沌态,最后再回到稳定态的过程.在确定了激光器处于阵发混沌态时相位区电流 I_P 的取值范围之后,进一步的分析结果表明,随着相位区电流 I_P 的增加,平均层流时间先减小,达到一个极小值后再迅速增大.

关键词:非线性光学;激光物理;实验研究;单片集成半导体激光器;阵发混沌;动力学态;平均层流时间
中图分类号:TN365; O415.5　　**文献标识码**:A　　**文章编号**:1004-4213(2018)05-0514004-7

Characteristics of Intermittent Chaos in a Monolithically Integrated Semiconductor Laser

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Abstract: Dynamical characteristics of a monolithically integrated semiconductor laser have been experimentally studied. The laser consists of a distributed feedback semiconductor laser section, a phase controlling section and a semiconductor optical amplifier section. Using a general analysis method of dynamics, we have experimentally investigated the bifurcation route to chaos and the dynamical characteristics of intermittent chaos through the optical spectra, time series, phase portraits and power spectra of the laser. The results show that, under suitable operating parameters, the monolithically integrated semiconductor laser can be driven into intermittent chaos oscillation characterized by the chaotic state stochastically interrupted by the stable state. For fixing the currents of distributed feedback semiconductor laser section and semiconductor optical amplifier section and gradually increasing the current of the phase controlling section I_P, the monolithically integrated semiconductor laser successively undergoes stable state, period one, intermittent chaos, and returns to stable state. The range of I_P required for achieving intermittent chaos oscillation is determined. Moreover, the evolution of the average laminar time with the increase of I_P has been analyzed, and the result shows that, with the increase of

Foundation item: The National Natural Science Foundation of China (Nos.61475127, 61575163, 61775184)
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Received: Dec.12, 2017; **Accepted**: Feb.27, 2018

I_P, the average laminar time decreases firstly, after reaches a minimum, and then rapidly rises.
Key words: Nonlinear optics; Laser physics; Experimental investigation; Monolithically integrated semiconductor laser; Intermittent chaos; Dynamical state; Average laminar time
OCIS Codes: 140.5960; 140.1540; 130.3120; 190.4390

0 Introduction

In nonlinear systems, there exists various routes to chaos via folding and stretching variables in the projection process. Period-doubling bifurcation and quasi-periodic bifurcation are two typical routes to chaos and have been widely investigated [1-3]. In addition, intermittency is also a well-known route to chaos and commonly observed in fluid flows, circuit oscillators and chemical reactions [4-7]. For semiconductor lasers, Low-frequency Fluctuation (LFF), explained as saddle node instability, is initially termed intermittency phenomenon and has been studied for a long time [8-10].

Nowadays, with the fast development of Photonic Integrated Circuits (PICs), Monolithically Integrated Semiconductor Lasers (MISLs) can already generate chaotic output without additional discrete components to provide perturbations, meanwhile the nonlinear dynamics of MISLs have been reported consecutively [11-16]. USHAKOV O *et al*. reported two kinds of Hopf bifurcations associated with regular self-pulsations of different frequencies [11]. YOUSEFI M *et al*. experimentally demonstrated a period-doubling transition into chaos in MISLs and proposed that the dynamics of MISLs are more stable over the lifetime of the system compared with their stand-alone counterparts [12]. We reported broadband chaos generation in a three-section MISL and investigated the dynamics and the chaotic bandwidth enhancement with optically injected MISL [13-15]. In above studies, the dynamical routes to chaos are typical period-doubling bifurcation or quasi-periodic bifurcation.

More recently, Intermittent Chaos (IC) has been reported in PICs. BOSCO A K D et al. experimentally and theoretical investigated crisis-induced intermittency in a PIC consisting of a DFB laser, two Semiconductor Optical Amplifiers (SOAs), and a passive waveguide coated by high reflection film[16], and focused on the analysis of the influence of the SOA current on the IC. We designed another novel style PIC characterized as a three-section MISL, which is composed of a Distributed Feedback Semiconductor Laser (DFB-SL) section, a phase (P) section and a SOA section [17], and analyzed the influence of the SOA current on the performance of IC [18].

Physically, the PICs used in Refs.[16-18] can be attributed to a DFB-SL with time-delayed optical feedback from a short external cavity, and the feedback strength is determined by I_{SOA}. Therefore, these relevant investigations can be regarded as the influence of feedback strength on the performance of IC. For the MISL fabricated by ourselves [17], except that the feedback strength can be adjusted, the feedback phase can also be adjusted by controlling the current of the phase section (I_P). In this paper, we emphasize the influence of feedback phase on the characteristics of IC, which is implemented by adjusting I_P. After recording the time series, power spectra, and phase portraits of the output signal from MISL, the characteristics of the intermittent chaos oscillations is investigated. Furthermore, the evolution of the Average Laminar Time (ALT) of intermittent chaos versus I_P has been analyzed.

1 Experimental setup

Fig. 1 is the schematic diagrams of experimental setup and MISL. As shown in Fig. 1(b), the MISL is composed of a DFB-SL section, a P section and a SOA section with lengths of 220 μm, 50 μm and 240 μm, respectively. The temperature and current of each section are controlled by high-accuracy laser diode controller (ILX-Lightwave, LDC-3724B), and the currents for DFB-SL section, P section and SOA section are labeled as I_{DFB}, I_P, and I_{SOA}, respectively. The device material of the MISL is grown on an S-doped n-type InP substrate by the Metal-organic Chemical Vapor Deposition (MOCVD), and the chip is cleaved with a reflectivity of 0.32 for both facets. Complex-coupled grating is formed in the DFB-SL section to guarantee stable single-mode emission. The P section is a passive waveguide fabricated with quantum well materials whose wavelength of band gap is 1 440 nm. When the I_P is varied, the feedback phase is changed due to the change in effective refractive index of the waveguide. The SOA section is used to control the feedback strength via adjusting I_{SOA}[19]. So the MISL can be regarded as a DFB-SL with an ultrashort optical feedback, which is supplied by an ultra-short active feedback cavity.

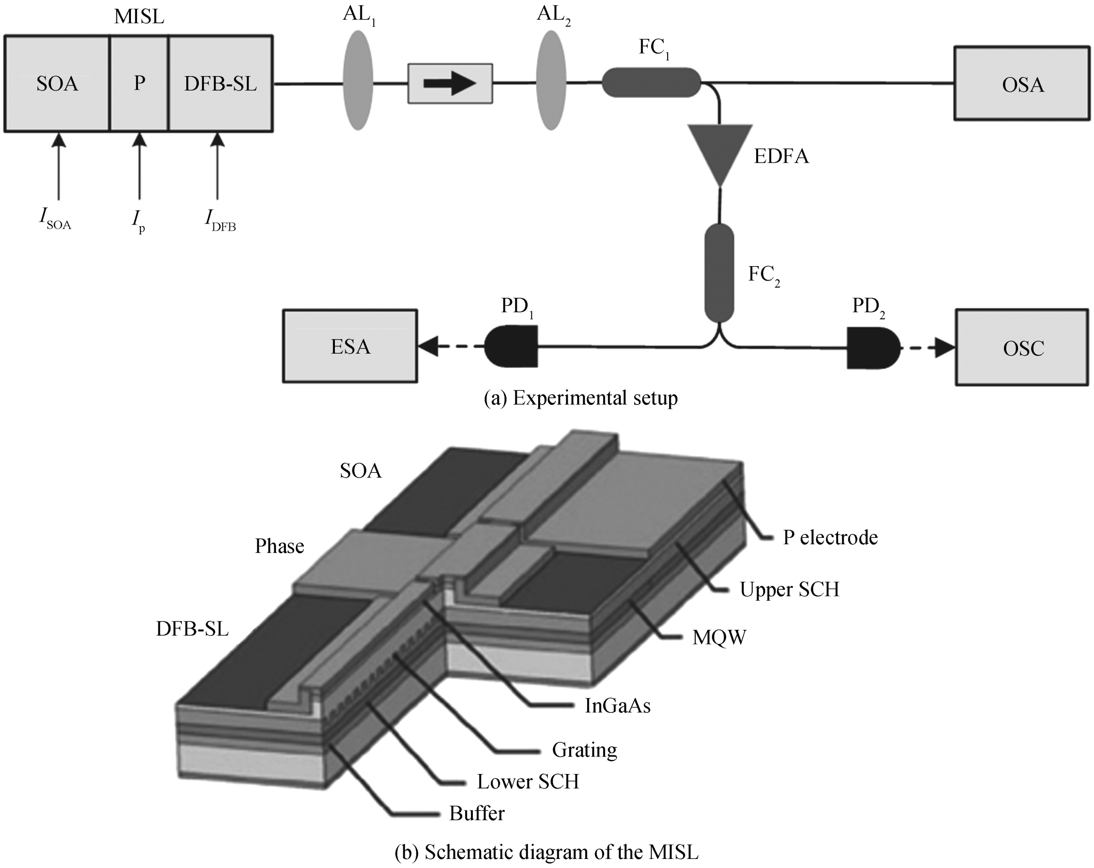
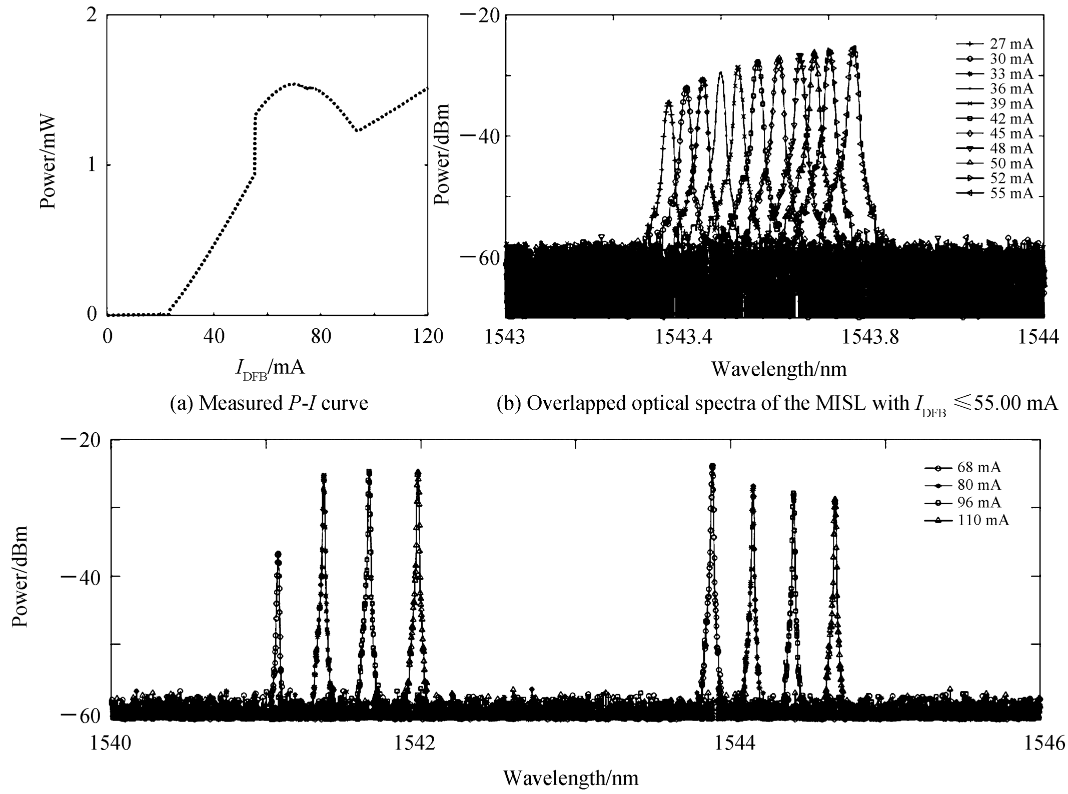


Fig.1 Experimental setup and schematic diagram of the MISL

Throughout the experiment, all the temperatures of three sections in the MISL are maintained at 20.26 ℃. The optical output of the MISL firstly passes through an aspheric lens (AL_1), an optical isolator (ISO), AL_2, and then is divided into two parts by a fiber coupler (FC_1). One is sent to an optical spectrum analyzer (OSA, Ando AQ6317C) to monitor the optical spectrum, the other is firstly amplified by an Erbium Doped Fiber Amplifier (EDFA). The amplified optical signal is further divided into two parts. One is transferred into electronic signal via a photo-detector (PD_1, U2T-XPDV3120R, 70 GHz bandwidth), and then is sent to an electrical spectrum analyzer (ESA, R&S©FSW, 67 GHz bandwidth) for measuring the power spectrum, the other is transferred into electronic signal via PD_2 (New Focus 1544-B, 12 GHz bandwidth), and is sent to an oscilloscope (OSC, Agilent DSOX91604A, 16 GHz bandwidth) for monitoring the time series.

2 Experimental results and discussion

Fig. 2 shows the P-I curve and the overlapped optical spectra of the MISL under different I_{DFB} when both I_P and I_{SOA} are fixed at 0 mA. Under this condition, the threshold current (I_{th}) of the MISL is about 23.10 mA, as shown in Fig. 2(a). With the increase of I_{DFB} from I_{th} to 55.00 mA, the output power linearly increases, and meanwhile the oscillated wavelength of unique mode moves towards longer wavelengths, as shown in Fig. 2(a) and (b). However, further increasing I_{DFB}, the output power undergoes rapid increasing, decreasing, and linearly increasing, as shown in P-I curve. Further inspecting the optical spectrum, it can be found that there are two modes co-existing in the MISL (as shown in Fig. 2(c)) when $I_{DFB} > 55.00$ mA. Since the gain for two compound-cavity modes locating at the stop band are comparable[20], two modes can be lased simultaneously. Under this case, the dynamics of the MISL becomes much more complicated, which results in the nonlinear variation trend of output power with the increase of I_{DFB}. Based on our experimental observation, the intermittent chaos occurs only for the case that the MISL operates at two-mode emitting state. Considering that the emphasis of this work is about the influences of the feedback phases on the performances of IC, we fix I_{DFB} at 78.54 mA ($\approx 3.4I_{th}$) and I_{SOA} at 34.50 mA in the following discussion.



(a) Measured *P*-*I* curve　(b) Overlapped optical spectra of the MISL with $I_{DFB} \leqslant 55.00$ mA

(c) Overlapped optical spectra of the MISL with $I_{DFB} > 55.00$ mA

Fig.2 Output characteristics of the MISL under different I_{DFB}, where I_P and I_{SOA} are fixed at 0 mA

2.1 Route of the dynamical state

Firstly, we investigate the dynamical characteristics of the MISL for $I_{DFB} = 78.54$ mA and $I_{SOA} = 34.50$ mA under different I_P. Fig. 3 displays the times series, phase portraits, and power spectra for several typical dynamical states output from the MISL obtained under different I_P. As shown in the first row, for $I_P = 5.20$ mA, the output intensity is nearly a constant with small ripples due to the noise, the phase portrait is an extended dot, and the power spectrum is similar to the noise floor. As a result, the dynamical state of the MISL is a stable (S) state. For I_P increases to 8.30 mA (as shown in Fig.3(b)), the time series shows a regular oscillation with an undamped relaxation, whose fundamental frequency is close to the relaxation oscillation frequency and is about 9.1 GHz obtained from the power spectrum, and the phase portrait shows a dense dot. As a result, it can be determined that the dynamical state of the MISL is a period-one (P1) state. Further increasing I_P to 8.90 mA (as shown in Fig.3(c)), the laminar regions of low amplitude correspond to the stable state while the bursts of high amplitude consist of complex chaotic fluctuations. The alternation between stable state and chaotic state is a typical intermittency transition, which is different from the transition from a period-doubling dynamics to chaotic dynamics[13]. Additionally, the phase portrait includes some scattered dots (a chaotic attractor) besides a concentrated spot (a stable attractor) and the power spectrum covers a relatively wide frequency range, which reveals the intermittency between stable state and chaotic state. For $I_P = 11.00$ mA (Fig.3(d)), the dynamical state of MISL returns to stable state, and all the properties are similar to that for $I_P = 5.20$ mA. The physical mechanism for the variation of dynamical states resulted by increasing I_P can be explained as follow. During the process of gradually increasing I_P, the effective refractive index of P section is varied accordingly. As a result, the phase and the optical feedback supplying for DFB-SL are changed during increasing I_P, and then the laser can be driven into different dynamical states for different I_P[21]. By carefully adjusting I_P, the IC occurs for 8.50 mA $<I_P<$9.30 mA. Next, the detailed characteristics of the intermittent chaos will be analyzed.

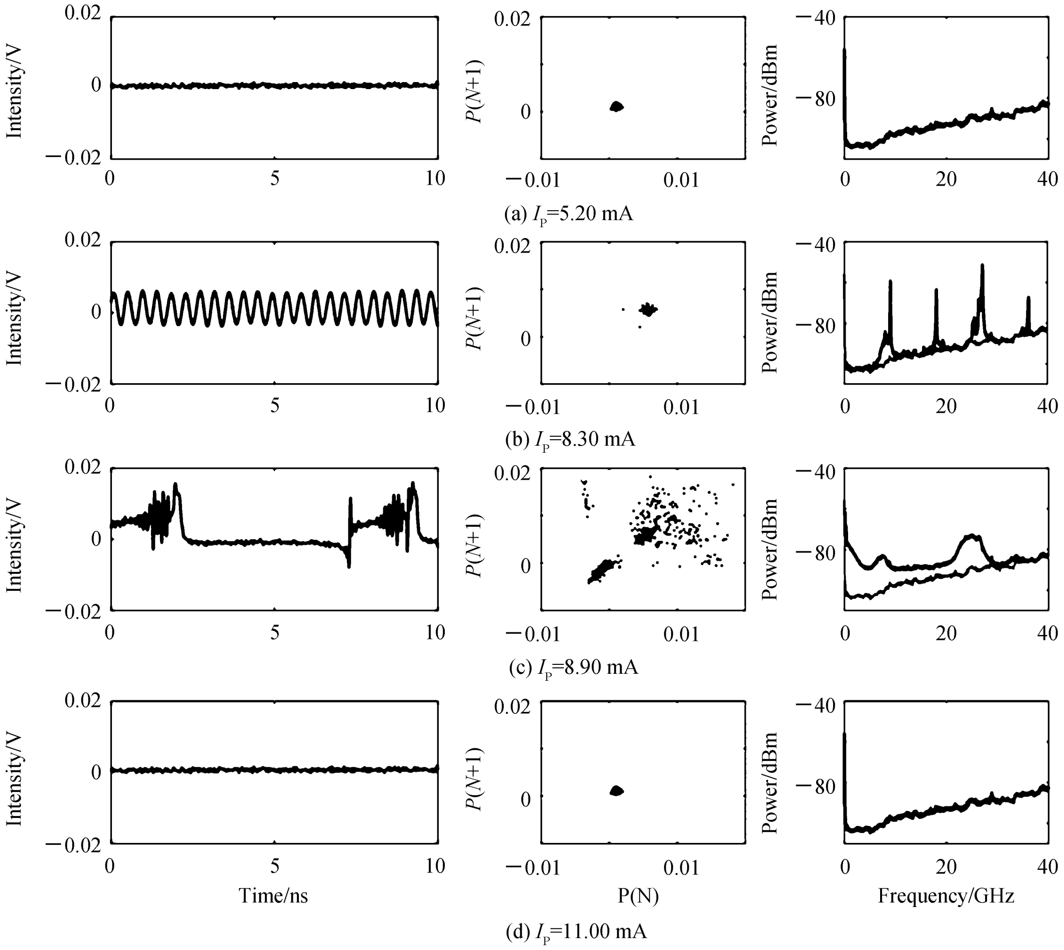


Fig.3 Time series, corresponding phase portraits and power spectra of typical dynamical states output from the MISL with I_{DFB}=78.54 mA and I_{SOA}=34.50 mA (the grey curves in power spectra are for the noise floor of measurement apparatus)

2.2 Characteristics of the intermittent chaos

Fig. 4 shows the detailed time series of IC output from the MISL under I_{DFB}=78.54 mA, I_{SOA}=34.50 mA and I_P=8.53 mA. In Fig. 4(a), the intermittent chaos time series within 1000 ns window is presented. We can find about 150 bursts with high amplitude away from the laminar regions with low amplitude. The laminar regions and bursts are stochastically alternated, which reveals the MISL enters intermittency state. To further distinguishing the details, we zoom the time series within 100 ns and 20 ns time windows, as shown in Fig. 4(b) and 4(c). Combining Fig. 4(b) and Fig. 4(c), we can see that the time durations of every burst and laminar region are stochastic. As mentioned above, the bursts corresponds chaotic oscillation and meanwhile the laminar regions correspond to stable state. Every chaotic burst begins with a sharp pulse, then lasts about 2～5 ns randomly and finally returns to the stable state.

To further explore the statistical characteristics of the intermittent chaos time series, wecollect plenty of time series under a set of given operating parameters, and then calculate the ALT. Fig. 5(a)-(c) give a part of time series under I_P=8.53 mA, 8.90 mA, and 9.20 mA, respectively. From the diagrams, it can be seen that, the duration times of laminar region are different for different value of I_P.

The ALT can be calculated based on a great deal of experimental data, and the variation of the ALT with the increase of I_P is shown in Fig. 6. Obviously, with the increase of I_P from 8.53 mA to 9.30 mA, the ALT first gradually decreases to arrive at a minimum, and then rapidly increases. The reason may be that the feedback phase is changed with the increase of $I_P$due to the change in effective refractive index of the P section. Such a result is different from the power law distribution obtained under continuously varying I_{SOA} in previous reports[16, 22].

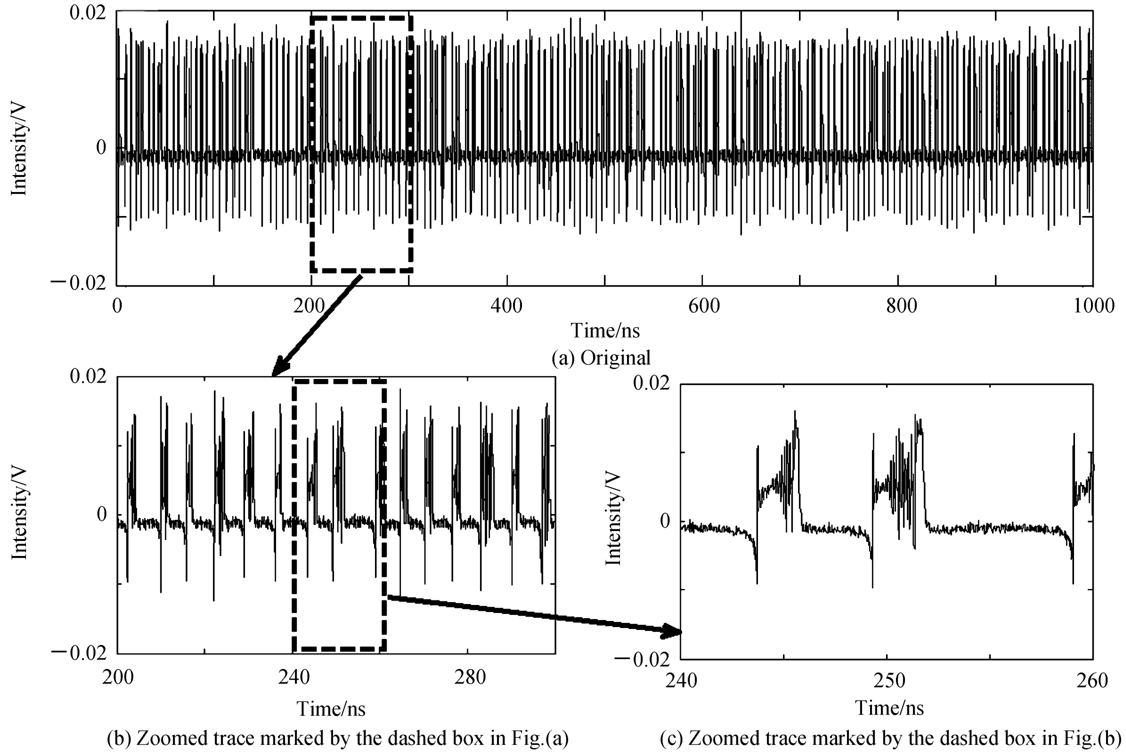


Fig.4 Time series of the intermittent chaos output from the MISL for $I_{DFB}=3.4I_{th}$, $I_{SOA}=34.50$ mA and $I_P=8.53$ mA

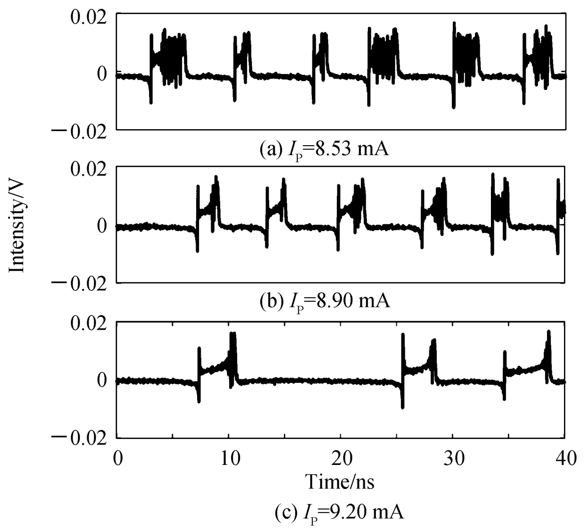


Fig.5 Time series of the MISL emission under different currents of the phase section

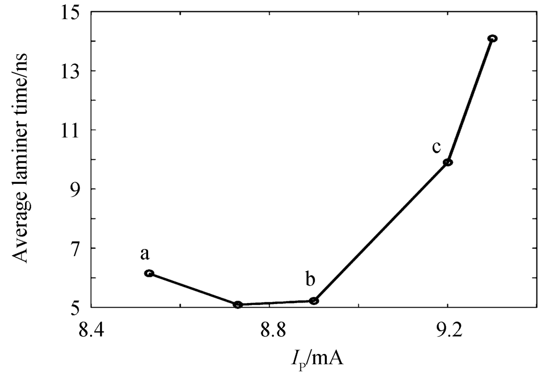


Fig.6 The average laminar time variance as function of I_P

3 Conclusion

In thiswork, the nonlinear dynamics, particularly the intermittent chaos, in a three-section MISL under different I_P is investigated experimentally. The results show that the route of the dynamical states evolution in the MISL is S-P1-IC-S, where the IC behavior is a stochastic alternation between stable state and chaotic state. Through collecting a great of time series, the evolution of the ALT with I_P is analyzed. With the increase of I_P, the ALT first gradually decreases to arrive at a minimum, and then rapidly increases, which is different from the power law distribution reported in previous researches through increasing the amplifier section current.

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