Research on nonlinear dynamics of distributed feedback semiconductor laser under self-delayed feedback*

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Abstract

In this paper, various nonlinear dynamic behaviors of distributed feedback semiconductor laser (DFB-SL) subjected to self-delayed optical and electrical feedback are studied numerically. The results show that the DFB-SL output presents a variety of nonlinear dynamic states such as single-period, quasi-period, and multi-period under different optical feedback intensities. When the external light feedback reaches a certain intensity, the laser output enters a chaotic regime. When the optical feedback intensity is small, a variety of nonlinear dynamic states will appear in the DFB-SL output under different electrical feedback intensities. When the optical feedback intensity is large, the single-period dynamic state cannot be obtained by changing the electrical feedback intensity. The optical feedback and electrical feedback delay time also have a significant influence on the nonlinearity of DFB-SL. When their time delays match, the relaxation oscillation of the laser is enhanced and exhibits a single-period state. And time mismatch may lead to chaos or instability. The bias current also affects the dynamic state, however, the direction of evolution of the dynamic states is not unidirectional as the current changes unidirectionally. When the DFB-SL is in a single-period state, changing the bias current will result in the change of the single-cycle oscillation frequency. These findings provide an important theoretical basis for applying the self-delayed feedback DFB-SL to microwave photonic signal processing and secure optical communication, as well as experimental means for conducting various nonlinear scientific researches.

Keywords: distributed feedback semiconductor laser, self-delayed feedback, nonlinear dynamics

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1. Introduction

Semiconductor lasers have been widely used after decades of rapid development since they came out in the 1960s. The development of integrated optoelectronic technology enables the laser to be integrated with other optoelectronic components on the same chip, which improves the overall performance and reliability of the system. Compared with other laser sources, semiconductor lasers have smaller size, lower cost, more compact structure and more stable performance. In the science and application research based on semiconductor lasers, the linear and nonlinear dynamics of distributed feedback semiconductor lasers (DFB-SL) are developing rapidly, and the linear dynamics is mainly focused on mode coupling and coherent spectral characteristics; Nonlinear dynamics studies focus on the optimization of chaotic behavior, gain saturation and multimode characteristics of lasers, which also promote the application of lasers in complex information processing. In addition, with the development of optical communication, laser sensing, biomedicine and other fields, the nonlinear dynamic characteristics of DFB-SL laser have attracted more attention of scientists.

The external signal injection will interfere with the DFB-SL and make it produce rich nonlinear dynamic States. The main structures for DFB-SL to generate nonlinear dynamical States are: optical feedback, electrical feedback, external optical injection, noise guiding, etc. In the optical feedback structure, the output of the laser can be delayed and fed back to itself to interfere with the output of the laser, resulting in a variety of nonlinear dynamic States such as steady state, multistable state and chaos. When the feedback light reaches a certain intensity, the modes of the laser interact violently, resulting in coherence collapse, and the spectrum and spectrum of the laser evolve into a continuous spectrum[1–3]. Lang and Kobayashi[4] mentioned that DFB-SL can generate complex, high-dimensional and broadband chaotic output when additional degrees of freedom are introduced, such as external optical feedback, external optical injection or external optoelectronic feedback, etc. Based on the output characteristics of SL in external cavity structure, a differential rate equation theoretical model was proposed. The simulation of the rate equation model can reproduce the main features of the experimental observations, which lays a firm theoretical foundation for the later study of the dynamic characteristics of lasers with additional degrees of freedom. Soriano et al.[5] used semiconductor lasers with external optical feedback to achieve chaotic signal output by introducing additional degrees of freedom, which is widely used because of its relatively simple structure and less components. Saboureau et al.[6] proposed a method combining optoelectronic feedback and optical injection to control the stability of dynamic output of a semiconductor laser (SL). The results show that the optical injection locking region can be significantly expanded by appropriate optical feedback, and the optoelectronic positive feedback can amplify and stabilize the picosecond pulse train generated by optical injection. The pulse repetition rate can be effectively controlled by adjusting the bias current and frequency detuning of the SL. Tang and Liu studied theoretically and experimentally the dynamic characteristics of semiconductor lasers with optoelectronic positive feedback[7]. The results show that the dynamic behavior of the laser output is closely related to the feedback delay, and the interaction between the carrier relaxation oscillation and the optoelectronic feedback is the main reason for the different output States. In addition, the output of the laser can change from quasi-periodic oscillation to chaos under different optoelectronic feedback conditions. Optical feedback and electrical feedback play an important role in the generation of nonlinear dynamic States in lasers, but their working mechanisms are different. At present, optical feedback and electrical feedback are mostly studied separately, and the influence of the competition between them on the output results of DFB-SL is often ignored. Hizanidis et al.[8] tried to use a laser system composed of all-optical feedback and optoelectronic feedback to achieve the purpose of hiding the delay structure and ensure the safety of the system. Chen et al.[9] used the form of optoelectronic hybrid feedback to experimentally study the generation of single-frequency microwave photonic signals from DFB lasers with optoelectronic hybrid feedback. At present, most of the studies on DFB lasers with optoelectronic feedback rely on experimental data, and most of the studies focus on the application of generating a specific dynamic state, lacking the corresponding theoretical framework to explain these phenomena. This poses a challenge in understanding how optical and electrical feedback work together on the nonlinear dynamics of DFB-SL. The lack of theoretical models not only limits our ability to predict laser behavior, but also leaves us without the necessary guidance in laser design and optimization.

In this paper, various nonlinear dynamic behaviors of semiconductor lasers with external optical feedback and electrical feedback are numerically simulated. The nonlinear dynamic characteristics under different feedback intensities are systematically observed and analyzed through spectrum and frequency spectrum, and the dynamic state distribution of output characteristics with the change of feedback intensity is obtained. The internal nonlinear effect of DFB-SL is mainly reflected in the working state of the laser and the characteristics of the output signal. When the operating point of the laser is close to its threshold, the relationship between the output power and the input current of the laser will show complex nonlinear characteristics. The change of feedback strength and delay time has a significant impact on the output characteristics of the laser, especially under the action of the key factors such as electrical feedback strength, electrical feedback delay time and bias current, the output state and performance of the laser will change significantly. The study of these nonlinear phenomena can not only help us to understand the physical mechanism of lasers more profoundly, but also provide a theoretical basis for their optimization and improvement in practical applications.

2. Theoretical model

The scheme of this paper is shown in Fig. 1, which mainly includes two parts: all-optical structure and optoelectronic feedback loop. DFB-SL is the core device for generating nonlinear dynamical States; Cir is used to construct self-feedback loop and electrical feedback loop; Single-mode fiber (SMF) is used to change the loop length; Optical couplers (OC) are used to build optical and electrical feedback loops; The variable optical attenuator (ATT) is used to fine-tune the optical power and change the coupling coefficient; A polarization controller (PC) is used to adjust the polarization of the light field; A polarizing beam splitter (PBS) for splitting an incident beam into two beams of light of orthogonal polarization States; A polarization beam combiner (PBC) is used to couple two beams of light with orthogonal polarization States into one beam of light; Erbium-doped fiber amplifier (EDFA) is used to compensate for signal attenuation and signal amplification; Photodetector (PD) for photoelectric conversion; An electro-absorption modulator (EA) is used to provide electrical feedback gain.

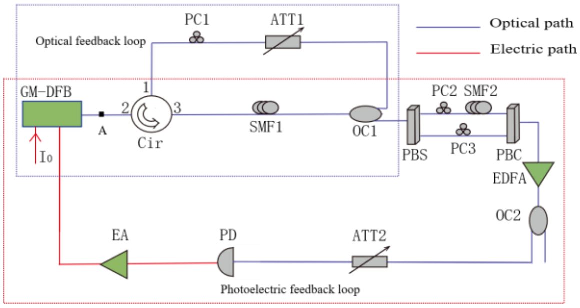

Figure 1. Diagram of the DFB-SL self-delay photoelectric feedback structure.

Under the condition of optoelectronic feedback, the dynamic behavior of the semiconductor laser can be described by the following system of equations for the photon number $S(t)$, the carrier number $N(t)$, and the phase of the feedback light $\Phi(t)$ with time:

$$\frac{dS(t)}{dt} = \{\Gamma \frac{G_N[N(t)-N_0]}{1+\varepsilon S(t)} - \frac{1}{\tau_p}\} S(t) + \frac{\Gamma \beta N(t)}{\tau_e} + 2\frac{\kappa}{\tau_{in}}\sqrt{S(t)S(t-\tau)}\cos[\theta(t)], \tag{1}$$

$$\frac{dN(t)}{dt} = \frac{I}{e}[1+\frac{\zeta S(t-\tau_{oe})}{S_0}] - \frac{N(t)}{\tau_e} - \frac{G_N[N(t)-N_0]}{1+\varepsilon S(t)} S(t), \tag{2}$$

$$\frac{d\Phi(t)}{dt} = \frac{1}{2}\alpha\{\Gamma \frac{G_N[N(t)-N_0]}{1+\varepsilon S(t)} - \frac{1}{\tau_p}\} - \frac{\kappa}{\tau_{in}}\sqrt{\frac{S(t-\tau)}{S(t)}}\sin[\theta(t)], \tag{3}$$

$$\theta(t) = \omega_0 \tau + \Phi(t) - \Phi(t-\tau), \tag{4}$$

In the formula, κ is the optical feedback intensity, which represents the decibel ratio of the feedback light intensity at the *A* point in the Fig. 1 to the laser emergent light intensity; ζ is the electrical feedback strength, which is the result of the interaction of multiple elements, and can be expressed as: $\zeta=\mu\vartheta\chi\delta$, where $\mu,\vartheta,\chi,\delta$ are the fiber loss, the optical gain of EDFA, the photoelectric conversion efficiency of PD, and the electrical gain of EA, respectively; τ and τ_{oe} are optical and electrical feedback time respectively, which are determined by the length of the optical fiber; *I* is the laser bias current; The values of saturation gain factor, confinement factor, spontaneous emission factor, center frequency and linewidth enhancement factor are mainly from references [2,6,7], which cover the range of typical commercial devices required in practical applications; The values of differential gain, transparent carrier number, threshold photon number and laser intracavity feedback time are obtained from the specifications of the commercial DFB laser used in our laboratory; The physical constants used in the model equation are the general values in the textbook; The parameter names and their corresponding values are listed in Tab. 1.

Table 1. Parameter symbols and their values.

Parameter	Symbol	Take value	Unit
Photon number	$S(t)$	—	—
Carrier number	$N(t)$	—	—
Optical power	$P(t)$	—	—
Derivative gain	G_N	$(3—4) \times 10^4$	s^{-1}
Transparent carrier number	N_0	1.36×10^8	—
Threshold photon number	S_0	4.04×10^4	—
Laser intracavity feedback time	τ_{in}	9	ps
Photon lifetime	τ_p	2	ps
Carrier lifetime	τ_e	2	ns
Electron charge	e	1.6×10^{-19}	C
Limiting factor	Γ	0.5	—
Spontaneous emission factor	β	1×10^{-5}	—
Saturation gain factor	ε	$(7—8) \times 10^{-8}$	—
Center frequency of laser	ω_0	1.938×10^{14} Hz	—
Linewidth enhancement factor	a	4.5	—

In the above equations, (1) describes the rate of change of photon number $S(t)$ with time, and the first term $\Gamma \frac{G_N[N(t)-N_0]}{1+\varepsilon S(t)} S(t)$ includes the change caused by carrier gain and photon feedback. When the carrier concentration is higher than the threshold, it will increase the number of photons, while when the number of photons is too large, it will reduce the gain because of saturation effect; The second term, $-S(t)/\tau_p$, represents the consumption of photons; The third term, $\Gamma\beta N(t)/\tau_{\mathrm{e}}$, represents the conversion of carriers into photons; The fourth $2\frac{\kappa}{\tau_{\mathrm{in}}}\sqrt{S(t)S(t-\tau)}\cos\,[\theta(t)]$ is the coupling between the delayed injection light and the photons in the cavity at this time. (2) describes the rate of change of carrier number $N(t)$ with time, and the first term I/e represents the increase of carrier number caused by the injection of bias current; The second term $\frac{I}{\mathrm{e}}\frac{\zeta S(t-\tau_{\mathrm{oe}})}{S_0}$ indicates that the rate of change of the number of carriers with time is affected by the photoelectric delay. When the intensity of the DFB-SL output light is large, the delayed feedback light enhances the feedback current after photoelectric conversion, that is, the number of injected carriers is increased; The third term $-N(t)/\tau_{\mathrm{e}}$ represents the attenuation caused by the carrier lifetime; The fourth term, $-\frac{G_{\mathrm{N}}[N(t)-N_0]}{1+\varepsilon S(t)}S(t)$, represents the reduction of carriers due to stimulated emission. (3) describes the rate of change of phase, which is related to the gain and loss of photons. The change of phase will affect the interference effect of the laser and the fluctuation characteristics of the output light. When the number of photons increases (that is, the gain is greater than the loss), the phase changes faster; Conversely, when the number of photons decreases, the rate of phase change slows down.

In order to analyze the various dynamical States of DFB-SL with optoelectronic feedback, the fourth-order Runge-Kutta algorithm is used to solve the set of differential equations.

3. Results and Discussion

First, the case of only optical feedback is discussed, in which only optical feedback is affected. By observing the time series, the relationship between the number of photons and the number of carriers and the corresponding power spectrum, the internal mechanism of the laser is discussed; Then discuss the case of only photoelectric feedback (the loop on OC1 in the figure is disconnected), and explore the impact of electrical injection on the laser; Finally, the competition mechanism between optical feedback and optoelectronic feedback is discussed when optical feedback and electrical feedback coexist.

3.1 Dynamical state of a laser with only optical feedback

The lower loop of OC1 in Fig. 1 is disconnected, and there is only the loop of optical feedback at this time, as shown in the Fig. 2. At this time (2), the intensity of photoelectric feedback in the formula ζ=0.

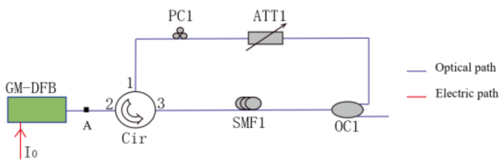

Figure 2. Diagram of the DFB-SL self-delay optical feedback structure.

3.1.1 Effect of optical feedback strength on dynamical state

Fix the following parameter values: $\tau = 1 \times 10^{-9}$, $\tau_{oe} = 4 \times 10^{-9}$, $I = 17\text{mA}$. When the κ of the optical feedback intensity is changed to 0.018, 0.044 and 0.059, respectively, the S-N diagram of the photon number in the laser cavity and the carrier number, the timing diagram and the spectrum diagram of the laser output are shown in the Fig. 3. It can be seen from the Fig. 3(a) that there is only one circular trajectory in the S-N diagram, and the corresponding timing diagram is a sinusoidal wave with a fixed distance between each peak. Combined with the power spectrum of the laser, the peak frequency is $f_1 = 3.35$ GHz, and the other peaks are high-order spectra with much lower power, indicating that the laser is in a single-cycle state. The S-N diagram of Fig. 3(b) has five closed circular trajectories, the timing diagram has an obvious envelope, and the five peaks are a whole period. For the same order, the power spectrum contains $f_2 = 4f_1/5, f_3 = 3f_1/5, f_4 = 4f_1/5, f_5 = f_1/5$ frequency components in addition to f_1 and frequency components, indicating that the laser is in a period-doubling state. It can be seen from Fig. 3(c) that the S-N diagram has no obvious loop, the timing diagram is chaotic and non-periodic, the power spectrum is almost continuous, and there is no obvious spectral component, indicating that the laser has entered a chaotic state.

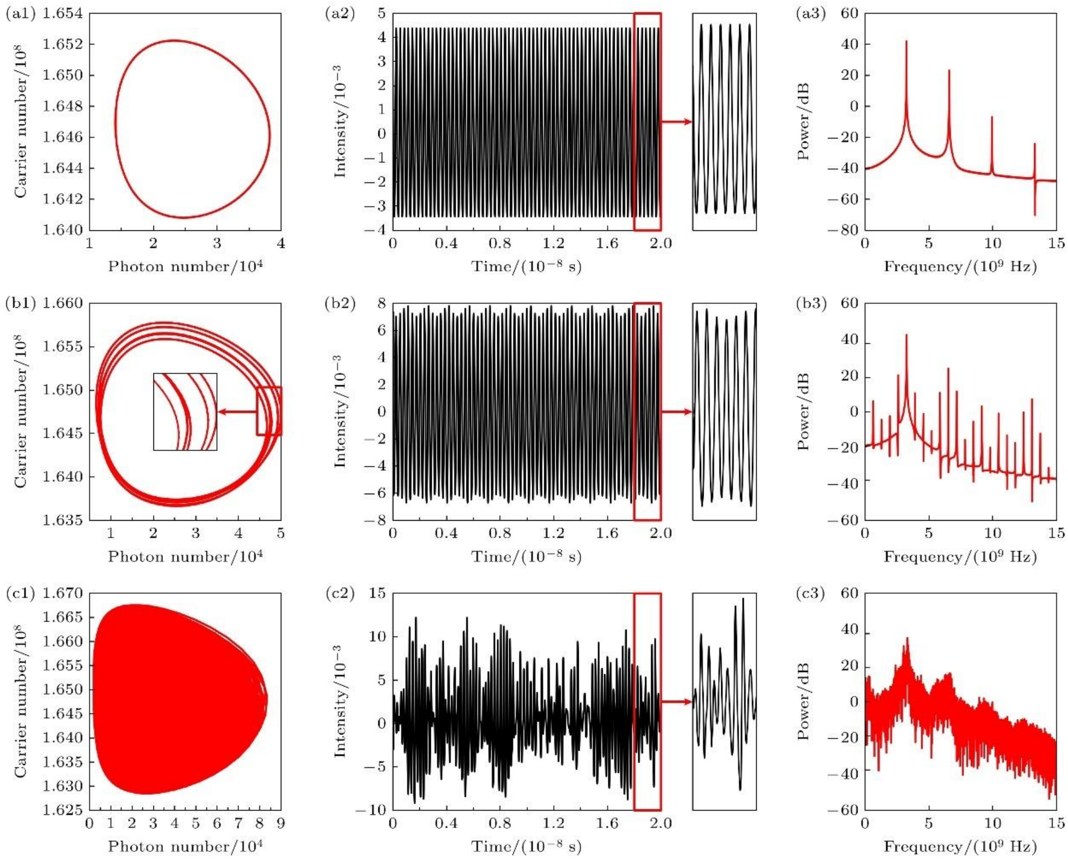

Figure 3. Under different optical feedback intensities, S-N plots of DFB lasers and their output timing plots and spectrograms: (a1)–(a3) $\kappa = 0.018$; (b1)–(b3) $\kappa = 0.044$; (c1)–(c3) $\kappa = 0.059$.

With the increase of the feedback intensity, the competition between the feedback light and the cavity mode becomes more intense, resulting in drastic changes in the optical field and carrier concentration inside the laser. At low feedback intensity, the DFB-SL behaves as a steady state, similar to a free output, and the output optical power is stable and has no obvious fluctuation. When the feedback strength increases to a certain level, the laser begins to enter the single cycle state. In this state, the output signal shows regular fluctuations, and there is a main peak in the spectrum, which corresponds to the frequency of the laser oscillation. The reason is that the introduction of feedback light breaks the original stability, and the mode seeded by relaxation oscillation is enhanced, resulting in periodic changes in its output. Further increasing the feedback strength, the laser may experience a period-doubling bifurcation. This phenomenon is manifested by the presence of multiple harmonic components in the spectrum of the output signal, for example, a component with a frequency of $f_1/5$ outside the fundamental frequency (f_1). The formation of this period-doubling state originates from the interaction between the intracavity mode and the feedback light, which leads to the appearance of new and more complex oscillation modes in the laser. When the feedback strength reaches a critical value, the laser output will undergo coherence collapse and eventually evolve into a broadband chaotic state. In this state, the spectrum shows an almost continuous state without obvious periodic features. The reason for the emergence of chaos is that the intensity of the feedback light has made the competitive advantage between different modes in the laser difficult to determine, and the output of the laser has become extremely complex and chaotic, showing chaotic behavior. It should be noted that the chaotic behavior is sensitive to the initial conditions, and the chaotic state of the laser can be synchronized, which is different from the randomness exhibited by the noise[10].

3.1.2 Effect of optical feedback time on dynamical state

Fix the following parameter values: $\kappa = 0.02$, $\tau_{\mathrm{oe}} = 4 \times 10^{-9}\mathrm{s}$, $I = 17\mathrm{mA}$. The optical feedback time τ are set to 2.18 and 2.21 ns, respectively. At this time, the S-N diagram in the laser cavity, the timing diagram and the spectrum diagram of the laser output are shown in the Fig. 4. It can be seen from the Fig. 4(a) that the S-N diagram has only one circular trajectory, the corresponding timing diagram is a sinusoidal wave without obvious envelope, and the laser power spectrum only shows a single peak of frequency f_1=3.0873 GHz in the same order of frequency, indicating that the laser is in a single period state. The S-N diagram of Fig. 4(b) can not distinguish the internal structure in a certain range, or can be regarded as a thick ring trajectory. The timing diagram has a clear envelope. In the same order of frequency in the power spectrum, besides the f_1 frequency component, there are also complex frequency components, indicating that the laser is in a multi-cycle state and has multiple modes.

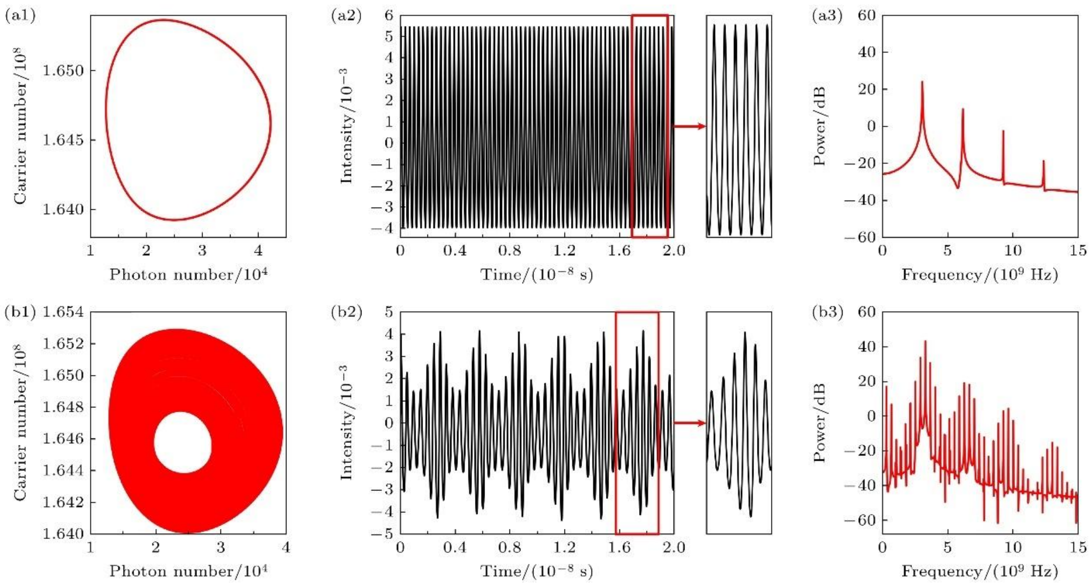

Figure 4. Under different optical feedback time, S-N plots of DFB lasers and their output timing plots and spectrograms: (a1)–(a3) τ=2.18 ns; (b1)–(b3) τ=2.21 ns.

As the optical feedback time continues to increase, the state of the laser alternates between single cycle and multiple cycles, similar to Fig. 4(a)(b). In a laser, there is competition between different modes. Different optical feedback time means different length of optical fiber access loop. With the change of optical fiber length, the time delay of feedback signal causes phase change, which will significantly change the competition relationship between different modes. The length of the optical fiber directly affects the propagation time and phase relationship of the optical signal in the feedback loop[11–13]. The feedback time delay affects the phase matching between the feedback light and the intracavity mode of the laser. When the phase of the feedback light is synchronized with the phase of the intracavity mode, the single cycle state of the laser output signal will be enhanced and become more stable. Of course, the change of the fiber length changes the oscillation mode of the loop[14,15].

3.2 Dynamical state of a laser with only electric feedback

The loop on OC1 in Fig. 1 is disconnected, and there is only the loop of photoelectric feedback, as shown in the Fig. 5. At this time, the optical feedback intensity in (1) and (3) κ=0.

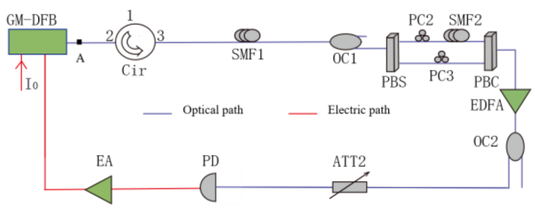

Figure 5. Diagram of the DFB-SL self-delay electricity feedback structure.

Fix the following parameter values: $\tau = 1 \times 10^{-9}$s, $\tau_{oe} = 4 \times 10^{-9}$s, $I = 17$mA. The ζ of the optoelectronic feedback intensity are set to 0.045, 0.0555, 0.0973 and 0.19, respectively. The S-N diagram in the laser cavity, the timing diagram and the frequency spectrum diagram of the laser output are shown in the Fig. 6. From the Fig. 6(a) —(c), it can be seen that the laser output gradually transits from single-cycle oscillation to multi-cycle oscillation, and then evolves into chaotic state with the increase of optoelectronic feedback strength. The S-N diagram of Fig. 6(d) looks like a circular trajectory, but it is different from the S-N diagram of P1. At this time, when the carrier number changes dramatically, the photon number does not change significantly, and then reaches a steady state, the pulse width of the timing diagram will be significantly reduced, while the pulse interval remains stable. This phenomenon shows that the laser can release a large number of photons in a very short time to form a high-frequency pulse output, the power spectrum has multiple frequency peaks, and the bandwidth is significantly increased, indicating that the laser is in a mode-locked state, at this time, the different oscillation modes in the laser have a definite phase relationship, and a short pulse laser output is generated[16].

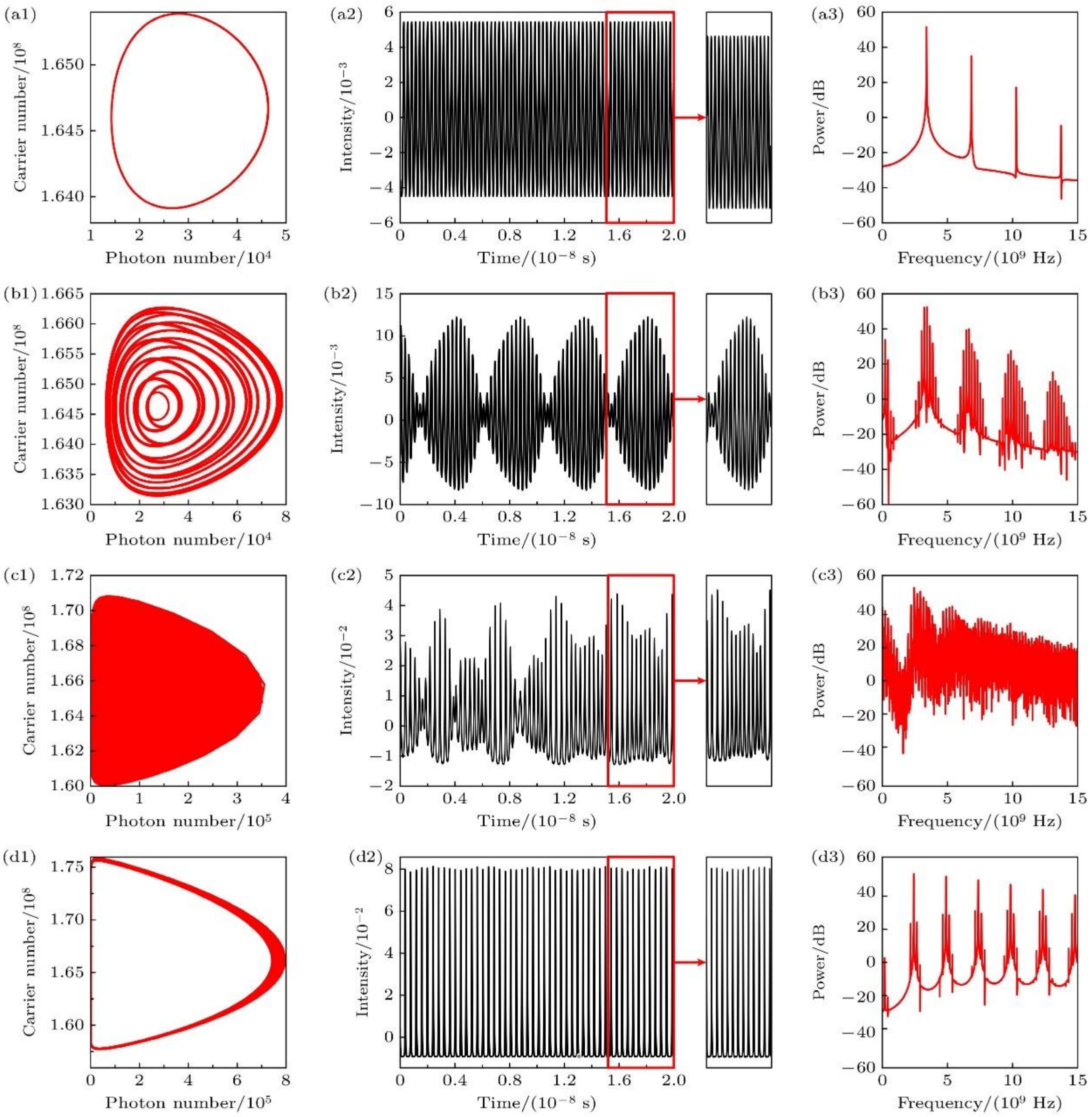

Figure 6. Under different feedback intensity, S-N plots of DFB lasers and their output timing plots and spectrograms: (a1)–(a3) ζ=0.045; (b1)–(b3) ζ=0.0555; (c1)–(c3) ζ=0.0973; (d1)–(d3) ζ=0.19.

The output power of the laser can be changed by adjusting the amplitude of the feedback current. When the feedback strength increases, the output may reach a new stable point, but if the feedback is too strong, it may also lead to output instability. Electrical feedback can adjust the bias operating point of the laser, which affects the optical output mode of the laser, resulting in possible steady-state, periodic oscillation, or chaotic behavior[17–19]. Under the action of electrical feedback, the dynamic behavior of DFB-SL may change dramatically. Proper feedback can enhance the stability of the laser, but if the feedback strength is too large, it may lead to self-oscillation, which makes the laser output show strong fluctuations. The nonlinear effect will change with the change of feedback strength, which may lead to multi-mode oscillation or chaos. The output mode of the laser may become more complex at high feedback strength. The competition between different modes will lead to changes in the intensity and frequency of the output light, and may even cause mode hopping. This modal competition may affect the overall quality and stability of the signal. For strong electrical feedback, the phase relationship between different modes can be kept consistent[20,21]. By adjusting the phase of the feedback signal, multiple modes can be ensured to overlap each other at a specific time to form a strong pulse. Strong electrical feedback can also introduce frequency modulation, which makes the output frequency of the laser change within a certain range, and the light waves of different frequencies will produce interference effects in phase, thus leading to the formation of pulses. Strong electrical feedback suppresses the phase noise and frequency noise of the laser, thereby improving the stability of the output signal. This noise suppression helps to maintain the mode-locked state.

3.3 Dynamical state of a laser with optical and electrical feedback coexisting

The structure of optoelectronic feedback is shown in Fig. 1. We will study the effects of different optoelectronic feedback strength, feedback delay time and bias current on various dynamic States.

3.3.1 The effect of the intensity of photoelectric feedback on the dynamical state

In Fig. 7, when the intensity of optical and electrical feedback is low ($\kappa \leqslant 0.06, 0.006 \leqslant \zeta \leqslant 0.05$), there will be changes between P1, period-doubling, multi-period and chaotic States; The blue area represents the free output, because when both the optical and electrical feedback intensities are small ($\kappa \leqslant 0.06, \zeta \leqslant 0.006$), the feedback light and current received by the DFB-SL are too small to cause dynamic changes in the laser; The white area is affected by the amplifier gain, fiber coupling efficiency and other experimental conditions, which is beyond the allowable range of parameters and will not be discussed in this paper. When the intensity of optical and electrical feedback is high, the output of the laser is chaotic. Optical feedback can enhance the single cycle oscillation of a laser. In fact, the feedback optical signal may interfere with the cavity mode, resulting in a phase change, which in turn affects the stability and intensity of the output light. Electrical feedback can control the output power, spectral width and wavelength by adjusting the driving current and other parameters of the laser, which can improve the frequency stability and anti-disturbance ability of the laser. Electrical feedback helps to suppress the phase noise of the laser output, thereby enhancing the signal-to-noise ratio and stability of the signal. When the optical feedback is too strong, it may cause self-oscillation or unstable output of the laser, and the electrical feedback can restore the stability of the system by adjusting the gain or suppressing the noise. When the feedback parameter is set to a certain value, the competition between optical and electrical feedback may lead to the transition of the laser from a stable mode to a chaotic state, resulting in severe fluctuations in the intensity and wavelength of the output light.

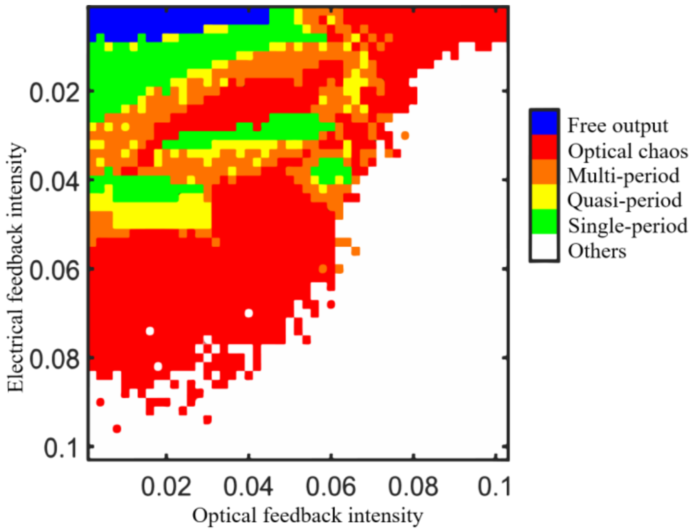

Figure 7. Effect of photo-electrical feedback intensity on laser dynamics.

3.3.2 Effect of delay time of optical and electrical feedback on dynamical state

It can be seen from the Fig. 8 that the dynamic state of the laser will change when the electrical feedback delay time is changed alone, but under certain conditions (such as τ=1.1 ns, τ = 2 ns), the dynamic state of the laser output will not change when the electrical feedback delay time is changed alone, which is P1 or multi-period state, which is related to the phase change caused by different feedback delays.

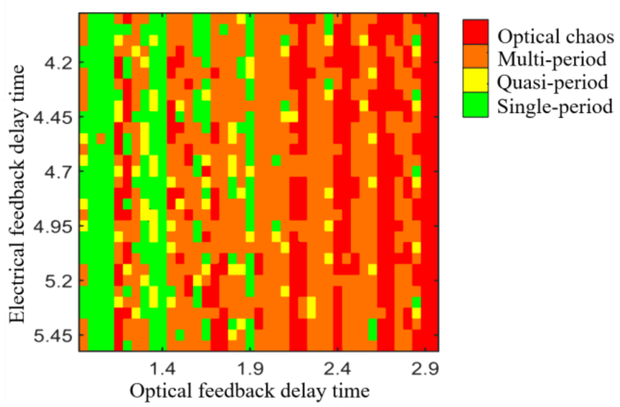

Figure 8. Effect of optical-electrical feedback delay time on laser dynamics.

The interaction between optical feedback and electrical feedback affects the output characteristics of the laser. When the delay time of the two is matched, the enhanced feedback can stabilize the output; When the delay time is not matched, the enhanced feedback may lead to chaos or instability. Chaotic systems are extremely sensitive to initial conditions, which leads to the unpredictability of orbits and the complexity of trajectories in phase space.

Features in the chaotic spectrum include: aperiodicity, with drastic effects on small changes in the period or initial conditions. The chaotic characteristics of lasers can be applied to information encryption and signal processing (such as chaotic communication) to improve the security of information transmission. With the high sensitivity of chaotic lasers, they can also be used in chemical sensors and environmental monitoring to detect small changes. In the single-cycle state, the laser output is a stable periodic waveform, which is easy to control and predict, and the output intensity usually repeats in a fixed time interval. The single-cycle laser signal can be used in high-precision measurement and communication clocks, gravitational wave detection, interferometry and other fields. In laser processing and cutting, providing stable laser output can enhance processing accuracy and efficiency. In optical communication systems, single-cycle lasers can be used for accurate timing and modulation of signals to ensure reliable transmission of information.

In the Fig. 7 and the Fig. 8, the number of the multi-cycle part is not the same. By comparing the Fig. 6(b) and the Fig. 4(b), it can be seen that the number of the multi-cycle is different, and the optical feedback intensity, the photoelectric feedback intensity and the electric feedback delay time are different. The number of multi-cycle can be changed by changing some parameters, but the number of multi-cycle can not be changed only by a single parameter. In a laser, the feedback light on the one hand enhances the stimulated emission and on the other hand interacts with the newly generated light in the cavity. Their phase relationship will lead to the appearance of interference phenomena, which may form an enhanced or reduced effect. This interference and superposition effect is actually the basis of the phase stability of the light wave. In the electrical feedback loop, the output light intensity of the laser is converted into an electrical signal and then injected into the laser, thus affecting the internal carriers of the laser. The interaction of these two feedback mechanisms makes the output characteristics of the laser more complex. A change in a single parameter, such as the magnitude of the bias current, often does not result in a significant change in the number of output cycles. This is because the output of the laser depends not only on the current, but also on the interaction of the light waves in the cavity. The output of the DFB laser produces the desired dynamic state by changing multiple parameters at the same time. The gain and phase of the laser can be controlled more effectively by adjusting the optical feedback and the electrical feedback at the same time, so that the multi-cycle number can be adjusted more accurately. By adjusting the delay time and optical feedback, the resonance condition of the laser can be changed, and the change of the number of multi-cycles is more obvious. In practical applications, the output characteristics of the laser can be accurately controlled by adjusting the parameters of optical feedback, electrical feedback and delay time, and then the number of multi-cycles can be changed.

3.3.3 Effect of bias current on dynamical state.

Fix the following parameter values: $\kappa = 0.08$, $\zeta = 0.01$, $\tau = 1 \times 10^{-9}$s, $\tau_{oe} = 4 \times 10^{-9}$s. Set the bias current *I* to 40, 36, and 20 mA, respectively. At this time, the S-N diagram in the laser cavity, the timing diagram and the spectrum diagram of the laser output are shown in the Fig. 9. From Fig. 9(a) to(c), it can be seen that DFB-SL can transit from chaotic state to single-period state with the increase of bias current.

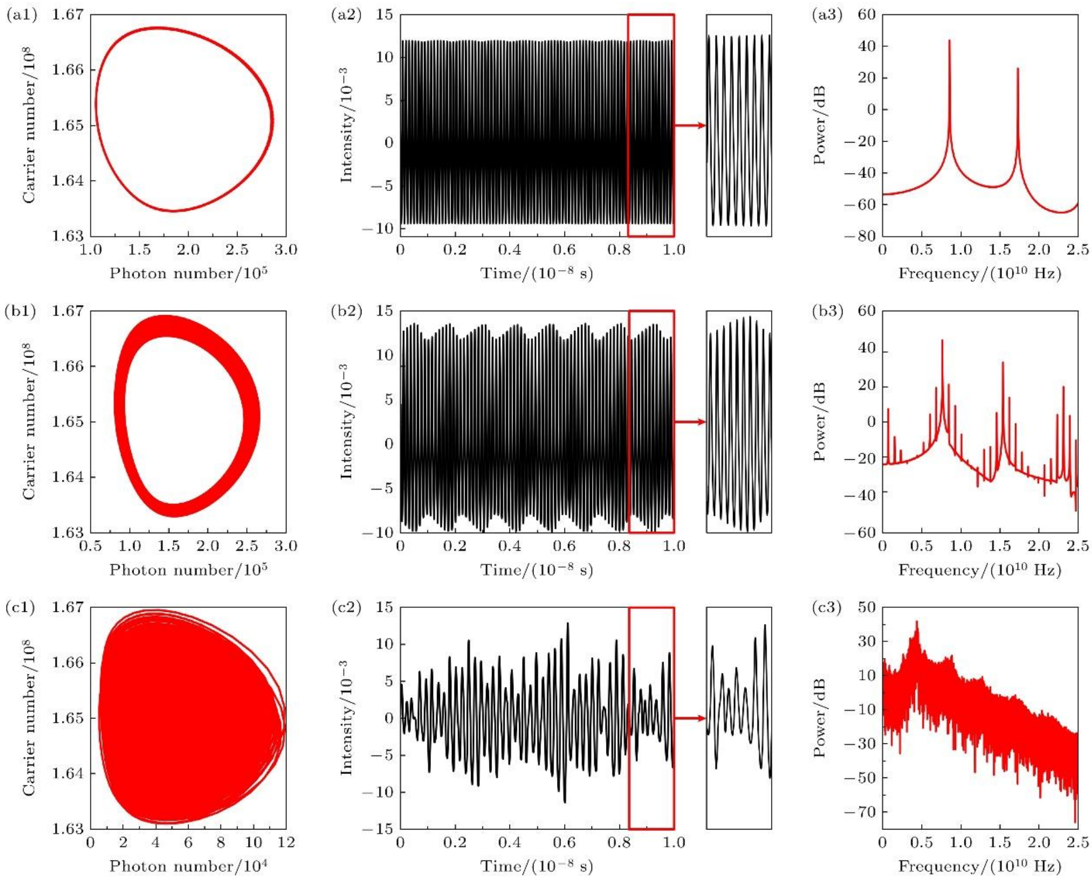

Figure 9. Under different bias current, S-N plots of DFB lasers and their output timing plots and spectrograms: (a1)–(a3) *I*=40 mA; (b1)–(b3) *I*=36 mA; (c1)–(c3) *I*=20 mA.

This change is mainly attributed to the significant effect of the magnitude of the bias current on the balance between the gain coefficient and the loss. When the bias current is at a low level, the gain of the laser is not enough to effectively offset the loss inside the optical cavity, and the laser cannot maintain a stable oscillation output, and the output optical signal shows highly chaotic characteristics in phase and amplitude. This instability is mainly caused by the nonlinear phase-amplitude coupling effect. When the gain is below a certain threshold, the system becomes particularly sensitive to external disturbances, which further exacerbates the uncertainty and leads to the emergence of chaos. In this state, the coherence of the light is significantly reduced, and the output light intensity of the laser becomes unstable and may switch rapidly between different modes. At this time, the state of carriers and photons in the laser is extremely unstable and vulnerable to external influences, which makes the laser produce an unpredictable competition of multiple dynamic States. With the further increase of the bias current, the gain is gradually enhanced, the carrier relaxation oscillation plays a dominant role, the dynamic state finally becomes dominant, and the laser shows a stable single-cycle state. It should be noted that the frequency of the single cycle state increases with the increase of the bias current, as shown in the Fig. 10, which may be the result of a variety of physical mechanisms. This is because increasing the bias current directly leads to a significant increase in the carrier concentration in the semiconductor laser. The increase of carrier concentration not only increases the laser gain, but also introduces the optical path difference, which leads to the blue shift of the cavity mode and the increase of the laser emission frequency.

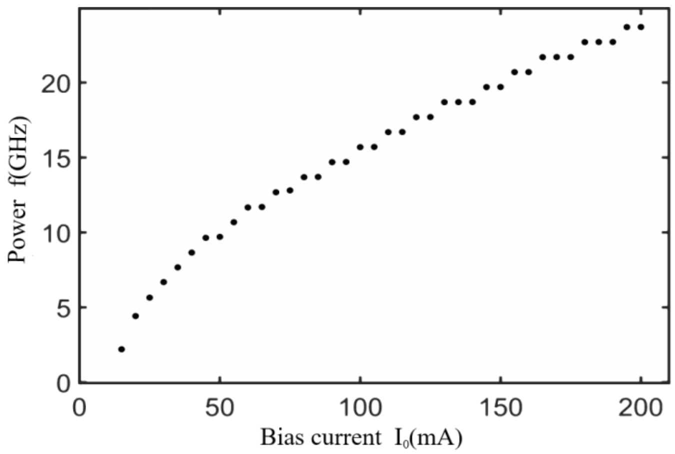

Fig. 10. Effect of the bias current on P1 signal frequency.

3.3.4 Application advantages of lasers with both optical and electrical feedback

Optical and electrical feedback DFB lasers have excellent modulation performance. They can flexibly adjust the working wavelength of the laser by adjusting multiple parameters of optical and electrical feedback. They can integrate multiple feedback mechanisms, reduce the dependence on complex external equipment, and show stronger anti-interference ability in the face of external interference.

Optical feedback DFB lasers are mainly used to achieve high stability and high precision laser output in single cycle applications. Its working principle is to introduce a periodic refractive index change in the active region of the laser to form a grating structure, so as to select light of a specific wavelength for feedback. This kind of single-cycle laser can maintain the single-mode characteristic of the output light and reduce the frequency drift under specific working conditions. It is widely used in optical communication, sensors, precision measurement and other fields[22]. In contrast, the optoelectronic feedback mechanism combines the characteristics of optical feedback and electrical feedback, which makes the laser perform better in dynamic response and stability. Photoelectric DFB lasers can maintain output stability over a wide range of operating conditions and quickly adjust their output characteristics in the face of external disturbances. In the field of quantum computing and quantum communication, multi-cycle output can generate a variety of quantum States, support the operation and transmission of quantum bits, and promote the development of quantum technology[23]. Electrical feedback DFB laser can provide a stable laser source in the generation and manipulation of quantum States through the precise control of laser output by current feedback, which is essential for the operation of quantum bits and the measurement of quantum States. However, the optical-electrical feedback semiconductor laser can maintain the high stability and efficiency of the laser under a wider range of operating conditions. This kind of laser not only improves the generation rate of quantum States, but also enhances the anti-interference ability of the system, which makes it show greater application potential in frontier technologies such as quantum communication and quantum computing. In chaotic optical communication, optical feedback semiconductor lasers usually introduce time delay tags due to their feedback mechanism[24]. This time delay tag may affect the synchronization and transmission efficiency of the signal, resulting in difficulties in decoding at the receiving end. The optoelectronic common feedback semiconductor laser can effectively eliminate this time delay tag by combining optical feedback and electrical feedback. The mechanism of optoelectronic feedback enables the laser to adjust the feedback parameters in real time when generating chaotic signals, thus achieving faster response and higher signal stability. This characteristic is particularly important in chaotic optical communication, because it not only improves the speed of data transmission, but also enhances the anti-interference ability of the system, making the transmission of information more reliable.

4. Conclusion

In this paper, the nonlinear dynamic behaviors of DFB-SL with optical and electrical feedback are studied by numerical simulation. The results show that the output characteristics of the laser are significantly affected by the different optical and electrical feedback intensities and delay times, especially the output state and performance of the laser will be significantly changed under the action of the key factors such as the optical and electrical feedback intensities, the optical and electronic feedback delay times, and the bias current. These factors not only affect the stability and output mode of the laser, but also may lead to complex dynamic behavior, such as chaotic state or periodic oscillation. The results show that the bias current is tunable to the frequency of the monocyclic signal. Through the study of these nonlinear characteristics, this paper provides an important theoretical basis for understanding the behavior of lasers under different operating conditions.

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