Multistability in a semiconductor laser with optoelectronic feedback

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Abstract: The multistability in a single-mode distributed feedback semiconductor laser with delayed optoelectronic feedback is observed experimentally. For a given delay time, the observed dynamical state of the laser output is critically dependent on the process of varying the delay time and is limited by the range of variation. Various routes of delay time variation results in multistabilities characterized by states of different time series and power spectra.

OCIS codes: (140.5960) semiconductor laser; (230.4320) nonlinear optical devices; (999.9999) multistability;

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1. Introduction

Nonlinear dynamics of semiconductor lasers (SLs) [1-18] have been widely investigated due to their useful applications in nonlinear optics, laser spectrometry, optical communications, and optical chaos communications especially. As an important aspect of the nonlinear dynamics, multistability in a SL with feedback or optical injection has been investigated experimentally and theoretically [8-13]. In this paper, we report a new multistability observed through the continuous variation of the delay time in a SL with delayed optoelectronic feedback (OEF). In recent years, the SLs with the OEF have received considerable attention due to their application in optical chaos communication [7, 9, 14-18]. For a SL with delayed feedback, the influence of the delay time on the nonlinear dynamics of the laser has previously been investigated [7, 8, 13, 14, 16]. To our knowledge, previous results, obtained by either numerical simulations or experiments, are based on resetting the initial values when the delay time is changed. Theoretically, delay-feedback rate equations are used to model the dynamics of a SL with OEF. In numerical simulating, the output dynamics of a SL with a fixed feedback delay time τ is usually calculated by fixing the delay time at τ without considering the history of how the delay time was varied to reach the value τ . Correspondingly, the experimental result of the fixed delay time is recorded after the feedback light is blocked momentarily to erase the history of the system. Because the connection between the output dynamics at different τ is erased, these results represent the SL dynamics that starts from independently turning on feedback at different τ . In this paper, we investigate the influence of the continuous variation of the delay time on the dynamics of the SL with OEF; multistabilities are observed experimentally for the first time by continuously varying the delay time along different routes.

2. Experiment

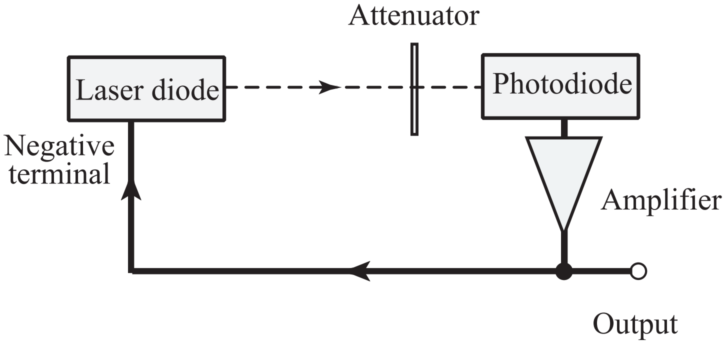

Fig. 1. Schematic diagram of the experimental setup. Dashed line: optical path; Solid line: microwave path.

The schematic diagram of the experimental setup is shown in Fig. 1. A 1.3 μm single-mode distributed feedback (DFB) InGaAsP/InP laser, whose threshold is 29 mA, is used. Throughout the experiment, the laser is biased at 1.45 times its threshold and is temperature stabilized at 21.00 °C. The optical power is detected, after a variable attenuator, by a

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photodiode (Albis PDCS65T) of 12 GHz bandwidth. The electrical output is fed back to the laser through an amplifier (Avantek SSF86-1592). The feedback is negative in the sense that a current proportional to the detected optical power is subtracted from the laser bias. It is implemented by connecting the feedback to the negative terminal of the laser. The feedback strength is denoted as a normalized quantity ξ defined in Ref. 11, which is fixed at $\xi = 0.31$ throughout this experiment. The dynamical state of the laser is monitored by simultaneously recording its time series and power spectrum using a 3-GHz digital real-time oscilloscope (Tektronix TDS 694C) and a power spectrum analyzer (HP E4407B).

3. Results

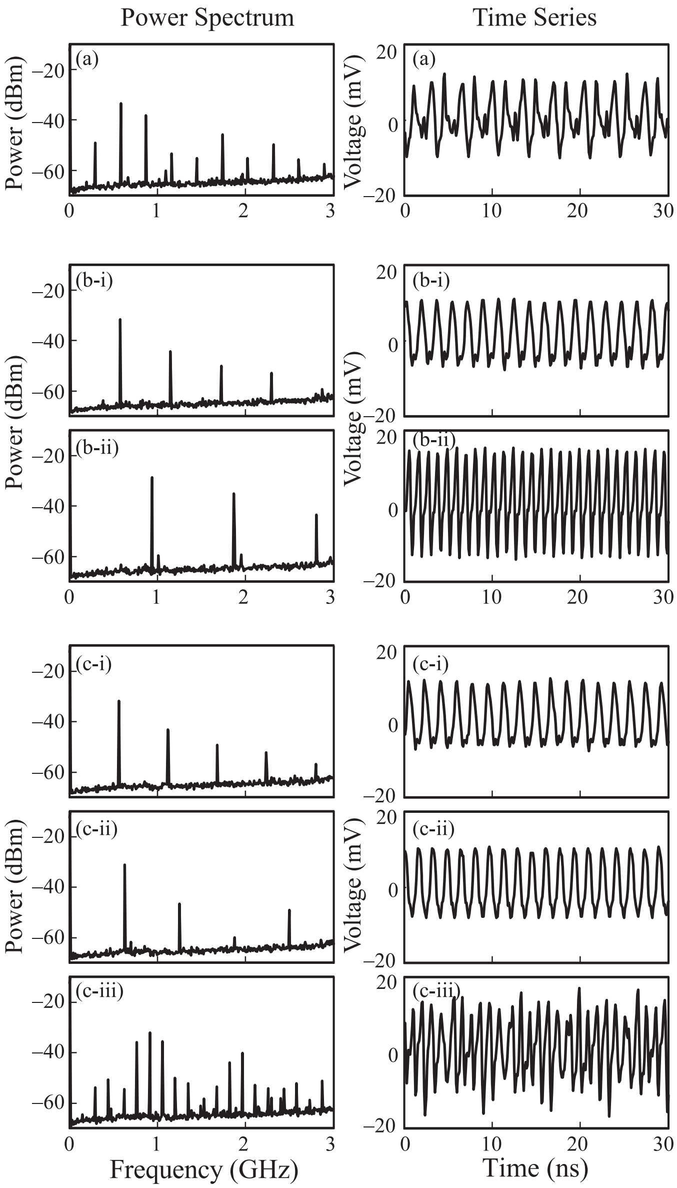

Fig. 2. Power spectra and time series experimentally observed. The delay time: (a) 13.13 ns, (b) 13.27 ns, and (c) 13.67 ns.

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Limited by the experimental condition, the delay time varies within a range of 13.07 to 14.34 ns in this work. During the experiment, we observe that if the delay time is varied along different routes, the output dynamics of the SL at a fixed delay time may be different, i. e., multiple stable states exist for a given delay time. Figure 2 shows the time series and the power spectra of the possible states for different delay times, where the delay time is: (a) 13.13 ns, (b) 13.27 ns, and (c) 13.67 ns. For τ =13.13 ns, the time series and power spectrum of SL are shown in Fig. 2(a). The output state is unique and is 4:8 frequency locked (FL) [16]. But for τ =13.27 ns and 13.67 ns, multiple states exist. For τ =13.27 ns, we find two states, shown in Fig. 2(b), that can be reached through different routes. Although both of them are regular pulsing (RP), they clearly have different power spectra and different time series. The peak frequencies of the two states are 0.578 and 0.937 GHz, respectively. For τ =13.67 ns, three possible states, shown in Fig. 2(c), that can be observed through different routes. The three states include two RP (see (c-i) and (c-ii)) and one quasi-periodic pulsing (QP) (see (c-iii)) states. Their peak frequencies of power spectrum are 0.563, 0.630, and 0.915 GHz, respectively. From Fig. 2, it can be deduced that the output dynamics of a SL with OEF is very complicated, and multiple states can exist for a given set of operating parameters.

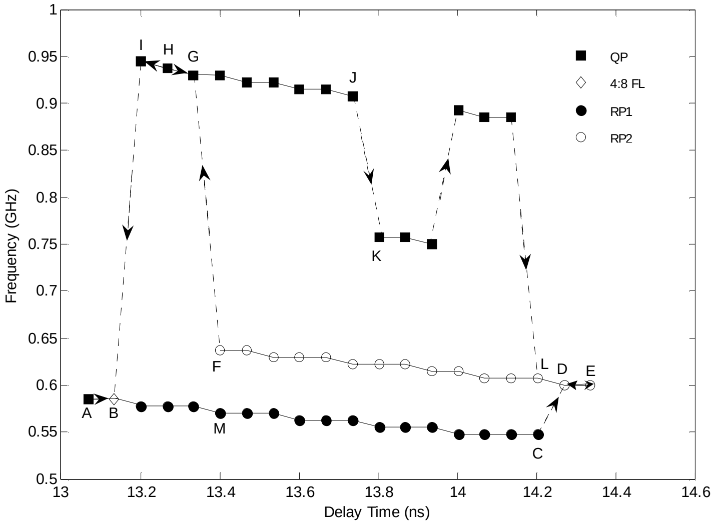

Fig. 3. Dependence of the peak frequency of power spectrum on the delay time, where the arrows mark the routes of varying the delay time, and different symbols characterize different output states of SL observed experimentally.

Figure 3 gives the dependence of the peak frequency of power spectrum on the delay time, where the arrows show the varying routes and different symbols characterize different output states of SL observed experimentally. The delay times at points A and E are the minimum and maximum values of the delay time of this experiment, respectively. Starting from point A with τ =13.07 ns, the output of the SL with OEF is QP. When the delay time is increased gradually from 13.07 ns, all the oscillation frequencies decrease, the output state becomes 4:8 FL when τ is increased to 13.13 ns (at B). With further increase of the delay time, the state of the SL enters RP1 (see the lowest branch) when the odd harmonics of half of the peak frequency disappear in the power spectrum. Beyond τ =14.2 ns (point C), the RP peak frequency suddenly jumps to a higher value (from C to D), thus entering a higher branch of RP2. The difference in peak frequency between C and D is approximately equal to the loop frequency. Continuously increasing the delay time further, the peak frequency decreases smoothly again along the branch of RP2 from D to E. After arriving at E, we begin to decrease the delayed time, it will come back to A but along another route of D-F-G-I-B-A (see the middle branch). The dynamics of the SL undergo RP2, QP and returns to 4:8 FL, forming a hysteresis loop. If one then reverses the direction after the state has entered QP (between G-I), by increasing the delay time, the peak frequency varies along another route G-J-K-L; the state of SL undergoes QP and finally enters RP2 at point L (see the uppermost branch). In the range of 13.07 -14.34 ns, there are two hysteresis loops and multistability exists.

4. Discussion

It has to be pointed out that multistability generated by different variation routes of the delay time is easy to be concealed. For example, considering an experiment limited to the variation of the delay time within a range of 13.4 to 14.34 ns (i. e. between F and E or M and E). If the initial state is on the lowest branch, the possible routes are M-C-D-E-D-F and F-D-E. The output cannot enter the uppermost branch (G-J-K-L) for it cannot jump to QP in the branch G-I. Meanwhile, it cannot return to the lowest branch once it has entered the middle branch. If the initial state is in the middle branch (D-F), through varying the delay time within 13.4-14.34 ns the state of SL cannot enter either of the other two branches, and the observed result of the SL is unique. If the initial state is in the uppermost branch (G-J-K-L), the output state can enter the middle branch but cannot enter lowest branch through varying the delay time. Therefore, either only one state or at most two states can be observed, depending on the initial state, if the delay time is limited to vary between 13.4 and 14.34 ns. It can thus be concluded that the states that can possibly be observed at a given delay time depends on the range of delay time varied throughout the experiment. Then it is also possible that the states shown in Fig. 3 are not complete because we have observed experimentally within a finite range of τ between 13.07 and 14.34 ns. Additionally, it is expected that multistable states can be traced through routes of varying other operating parameters such as the injection current to the laser or the feedback strength. It is not the purpose of this Letter to investigate such possible routes.

5. Conclusions

In conclusion, we have experimentally reported for the first time the multistability generated in a SL with OEF by the continuous variation the delay time along different routes. Even with the delay time varying within a finite range, multiple stable states are observed. The observed dynamical state of the SL with OEF is a function of the varying process of the delay time as well as the range of variation. The previous research results that did not trace the routes only revealed partially the dynamics of the SL with OEF. We believe that this work will be helpful to give a profound insight on nonlinear dynamics of the SLs with OEF and exploit some new multistable devices.

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