Dynamical characteristics of a semiconductor laser injected by optical pulses with high repetition rate

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ABSTRACT
The nonlinear dynamics of a semiconductor laser (slave laser) injected by optical pulses with high repetition rate are investigated experimentally. The pulses for injection are generated from a laser (master laser) subjected to either an optoelectronic feedback or an optical feedback. The repetition rates of the pulses are controlled by varying the delay time and the feedback strength of the feedback loop. By injecting the repetitive optical pulses of different intensities and repetition frequencies into another laser (slave laser), rich dynamical states including regular pulsations, frequency beatings, and chaotic pulsations are observed. Moreover, frequency-locked states with different winding number, the ratio of the main pulsation frequency of the slave laser and the repetition frequency of the injected pulses, are also found. Compared to a laser subject to a sine modulated optical injection, the linewidths of the high-order microwave components in the output spectrum of the slave laser are substantially narrower for the laser under repetitive optical pulse injection.

Keywords: semiconductor lasers, nonlinear dynamics, frequency-locking, chaos

1. INTRODUCTION
Nonlinear dynamics of semiconductor lasers subjected to optical injection has been widely investigated in the past two decades. Various dynamical states found have gained considerable theoretical and practical attention due to their fundamental physics and potential applications such as chaotic radar, chaotic lidar, and chaotic communications. By controlling the injection strength and the detuning frequency between the master and the slave lasers, induced periodic oscillations and chaotic oscillations have been observed. Furthermore, and break-up of two tori routes to chaos have been reported. In a master-slave configuration, the slave laser can be optically injected by the master laser with a light of constant or a time-dependent intensity. The dynamical characteristics of non-constant optical injection in semiconductor lasers have been studied widely in recent years.

However, few works have been reported on the nonlinear dynamics of semiconductor lasers injected by repetitive optical pulses. In this paper, we study the nonlinear dynamics of semiconductor lasers under repetitive optical pulse injection experimentally. Instead of locking the slave laser by injecting a light with constant intensity, a repetitive pulse train generated from a master laser under optoelectronic feedback or optical feedback is injected. The frequency-locked states have been found for repetition frequency of the injected pulses varying from around 600 MHz to 2 GHz. While the frequency-locking phenomenon generally occurs in nonlinear systems when a driving frequency is an integer multiple or submultiple of an intrinsic frequency of the system, to the best of our knowledge, most studies of frequency-locking phenomenon in semiconductor lasers involve electronic modulations through the bias current. The frequency-locking phenomenon of semiconductor lasers subject to optical pulse injection is investigated the first time. Instead of locking a laser by sending a modulation frequency through the bias current electronically, frequency locking intrinsically driven by the injected optical pulses is observed that it can be utilized in optical communication applications such as frequency conversion and OTDM. Furthermore, we also study the complex dynamics of a semiconductor laser induced by optical pulses. The comparison of the slave laser under optical pulse injection and sine modulated optical injection has been investigated as well.

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Figure 1. Experimental setup of a semiconductor laser under repetitive optical pulse injection. The pulses are generated by a laser subjected to either an optoelectronic feedback or an optical feedback. The dashed lines indicate the electronic path and the solid lines indicate the optical path. LD: laser diode, PD: photodetector, OI: optical isolator, BS: beamsplitter, PBS: polarizing beamsplitter, HW: half-wave plate, VA: variable attenuator, FR: Faraday rotator, ESA: electrical power spectrum analyzer, OSA: optical power spectrum analyzer, and OSC: real-time oscilloscope.

2. EXPERIMENT SETUP

Figure 1 shows the schematic of experimental setup of the optical pulse injected semiconductor laser. Two 1300 nm single-mode distributed feedback (DFB) semiconductor lasers are used as the master (LD1) and the slave (LD2) lasers. Both lasers emit optical power of about 7.5 mW and have a relaxation oscillation frequency of about 10 GHz. The output beam of the master laser is divided into two parts utilizing a (50:50) beamsplitter, where one of them is used for the feedback loop and the other is used to inject the slave laser. For the feedback loop, the output of the master laser is fed back to itself either optically from a movable mirror or optoelectronically via a photodetector. The photodetectors (Albis PDCS65T) and the amplifier (MITEQ AFS6-00102000-30-10P-6) used in our experiment have bandwidths of 10 GHz and 20GHz, respectively. Different dynamical states such as regular pulsation (RP), quasiperiodic pulsation (QP), and chaotic pulsation (CP) can be obtained by controlling the delay time and the feedback strength with the movable mirror and the variable attenuator. An optical isolator is placed in front of the master laser to prevent the unwanted feedback in the optoelectronic feedback (OEF) scheme. Under proper operation conditions, the master laser can be stabled in the RP states that the laser produces output with repetitive optical pulse trains. The repetition frequencies of these pulses can be varied by tuning the delay time and the feedback strength. This pulsed laser is then...
Figure 2. Time series and power spectra of pulsation states with $(ξ_i, f_{rep}) = (a) \text{P1P (0.25, 2.6), (b) P2P (0.24, 1.475), (c) P3P (0.25, 1.275), and (d) P4P (0.24, 1.025).}$ (i) power spectra of the injected pulses, (ii) power spectra of the slave laser, and (iii) time series of the laser output and the injected pulses. The time series of the injected pulses in (iii) are scaled for clarity.

served as as the convenient optical injection source in our experiment. Through the combination of a polarizing beamsplitter, a Faraday rotator, and a half-wave plate (HW2), a free space optical circulator is formed so that the output from the master laser can inject into the slave laser while the slave laser output can be examined simultaneously. In the experiment, the detuning frequency between the master and the slave lasers are fixed at 6.76 GHz and the injection strength from the master laser to the slave laser is adjusted through rotating the other half-wave plate (HW1). By injecting the slave laser with pulses of different injection strengths and
The nonlinear dynamics of the optical pulse injection system is strongly influenced by the normalized injection strength \( \xi \) and the repetition frequency \( f_{\text{rep}} \) of the injected pulses, where \( \xi \) is defined as the square root of the ratio of the injected power and the power of the slave laser output. Figure 2 shows the power spectra and the time series of the frequency-locked states for a semiconductor laser under repetitive pulse injection. The bias currents of the master and the slave lasers are set at 23 mA and 25 mA, respectively. For a normalized injection strength \( \xi \) and a repetitive frequency \( f_{\text{rep}} \) (in GHz) of \((\xi_i, f_{\text{rep}}) = (0.25, 2.6)\), a period-1 pulsation (P1P) state shown in Fig. 2(a) is found. Figures 2(a-i) and (a-ii) show the power spectra of the injected pulses and the slave laser output, respectively. Figure 2(a-iii) shows the time series of the slave laser output and the injected pulse, respectively. Obviously, the laser is locked to the injected pulses with \( \rho = 1/1 \), where the winding number \( \rho \) is defined as \( \rho = f_o/f_{\text{rep}} \), which is the ratio of the main oscillation frequency of the slave laser \( (f_o) \) and the repetition frequency of the injected pulses \( (f_{\text{rep}}) \). When \( \xi_i \) and \( f_{\text{rep}} \) are tuned to \((\xi_i, f_{\text{rep}}) = (0.24, 1.475)\), a period-2 pulsation (P2P) state is obtained and shown in Fig. 2(b). As can be seen in Fig. 2(b-iii), each of the injected pulses induce two cycles of oscillations in the slave laser output. Further tuning \( \xi_i \) and \( f_{\text{rep}} \) to \((0.24, 1.275) \) and \((0.25, 1.05)\), a period-3 pulsation (P3P) and a period-4 pulsation (P4P) states as shown in Figs. 2(c) and (d) are obtained respectively. As can be seen, when \( f_{\text{rep}} \) decreases from 2.6 GHz to 1.025 GHz, \( \rho \) changes from 1/1 to 4/1 accordingly. Frequency-locked states with \( \rho = 5 \) and 7 are also observed experimentally. These frequency-locked states with various winding numbers can be utilized in many applications, such as frequency-conversion in optical communications. As we increase the bias current of the slave lasers to above 30 mA, or equivalently lower the normalized injection strength \( \xi_i \), only frequency-locked states with \( \rho = 1/1 \) can be found.

To generate pulses with higher repetition frequencies, the optical feedback (OF) scheme is instead adopted. By disconnecting the electronic feedback loop and remove the optical isolator as seen in Fig. 3, the master laser can be modified into an OF scheme. Under proper optical feedback, the master laser produces repetitive pulses with repetition frequency up to 11.5 GHz in our experiment. By injecting these pulses to the slave laser, the nonlinear dynamics of the slave laser under high-repetition frequency pulse injection are examined. Figure 3 shows the power spectra of the slave laser subjected to optical pulse injection with pulses generated from the master laser with optical feedback. The repetition frequency \( f_{\text{rep}} \) of the pulses is fixed at 7.15 GHz while the injection strength \( \xi_i \) varies. As can be seen in Figs. 3(a) and (b), when \( \xi_i \) gradually decreases from \( \xi_i = 0.31 \) to 0.27, frequency-beating phenomena are observed. The beat frequencies change from 4.8 GHz (shown in Fig. 3(a)) to 2.45 GHz (shown in Fig. 3(b)) as \( \xi_i \) decreases. Besides those frequencies induced, the frequency component of 7.15 GHz from the injected pulses remains clear and unaltered. When \( \xi_i \) decreases to 0.11, the slave laser is driven into instability where a spectrum with broad bandwidth is seen in Fig. 3(c). A dip near the 7.15 GHz
Figure 4. Power spectra of (i) the sine modulated signals, (ii) the slave laser with modulation index $\xi_m = -5.0$ dBm, and (iii) the slave laser with $\xi_m = -1.2$ dBm. The modulation frequencies are $f_{mod} = (a) 1.475$, (b) 1.275, and (c) 1.025 GHz.

peak is observed, which is due to the gain saturation. Unlike the constant injection case, the pulse injection system is more complex and the chaotic states with broad bandwidths are easily to obtain.

To investigate the difference between the nonlinear dynamics of a semiconductor laser under pulse injection and sine modulated optical injection, Fig. 4 plots the power spectra of the slave laser subject to a sine modulated optical injection. The main differences between a sine modulated light and a pulse train are in the duty-cycle in the time domain and the high-order harmonics in the frequency domain. By modulating the bias current of the master laser directly, sine modulated optical signal is obtained and injected into the slave laser. Figures 4(a) to (c) show the power spectra of the semiconductor laser under sine modulation injection with modulation frequencies of $f_{mod} = 1.475$, 1.275, and 1.05, respectively. The modulation frequencies are chosen to be exactly the same as those seen in the pulse injection case shown in Fig. 2 for comparison. Figures 4(a-i)-(c-i) show the power spectra of the sine modulated injection signals. Figures 4(a-ii)-(c-ii) and Figs. 4(a-iii)-(c-iii) show the power spectra of the slave laser with the modulation indexes of $\xi_m = -5.0$ dBm and -1.2 dBm, respectively. When $\xi_m = -5.0$ dBm, the modulation is too weak that almost no high-order harmonics of the laser is observed in the output spectra. When the modulation index increases from -5.0 dBm to -1.2 dBm, the magnitudes of the high-order harmonics become larger and the spectra look similar to those seen in the pulse injection cases shown in Fig. 2.
Figure 5. Power spectra of the laser output centered at (a) 1.275 GHz and (b) 3.825 GHz for the pulse injection and sine modulated cases seen in Fig. 2(c-ii) and Fig. 3(b-iii), respectively.

However, if we go into the details of the power spectra of the sine modulated injection and the pulse injection cases, the linewidths of the high-order components reveal their difference. The power spectra of the laser output under pulse injection and sine modulated injection for the case of $f_{\text{rep}} = f_{\text{mod}} = 1.275$ GHz, as those shown in Fig. 2(c-ii) and Fig. 4(b-iii), are compared. Figures 5(a) and (b) show the power spectra of the 1st-order (1.275 GHz) and the 3rd-order (3.825 GHz) frequency components, respectively. The red curves indicated the spectra of the slave laser subjected to the pulse injection and the black curves indicated the spectra of the slave laser subjected to the sine modulated injection. Without injection, the linewidths of the microwave frequency components generated by the nonlinear laser dynamics are generally broad due to the intrinsic noise. They are about 1 MHz for most of the harmonic components in our experiment. With injection, the linewidths of the output spectra can be locked and narrowed. The 3-dB linewidths of the 1st-order harmonic in the pulse and sine modulated injection cases are measured to be 0.15 MHz and 0.155 MHz as shown in Fig. 5(a). But for the 3rd-order harmonic at 3.825 GHz shown in Fig. 5(b), the linewidths are measured to be 0.2 MHz and 1.1 MHz for the pulse and sine modulated injection cases, respectively. This is mainly due to the high-order harmonic components inject into the slave laser in the pulse injection case, where no high-order component is presented in the sine modulated case. As the result, the linewidths of the high-order harmonics under optical sine modulated injection are broader due to the nonlinear intrinsic noise. This result is found in all cases regardless of the repetition frequencies.

4. CONCLUSIONS

The dynamical characteristics of a semiconductor laser optically injected by high-frequency repetitive pulses generated by an optoelectronic and an optical feedback laser are investigated experimentally. By varying the intensity and repetition frequency of the injected pulses, various dynamical states are found. For lower repetition frequencies, frequency-locked states with different winding numbers are observed. For higher repetition frequencies, various dynamical states such as frequency-beatings and chaotic pulsations are observed. Moreover, compared with the sine modulated optical injection, linewidths of the high-order harmonics of the slave laser output spectra are substantially narrower for the laser under repetitive optical pulse injection.

ACKNOWLEDGMENTS

This work is supported by the National Science Council of Taiwan under contract NSC 96-2112-M-007-006.
REFERENCES


