Characteristics of the Frequency-Locked States Generated by a Semiconductor Laser under Periodical Optical Injection and Their Applications in Frequency Conversion

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ABSTRACT
Characteristics of the frequency-locked states generated by nonlinear dynamical behaviors of semiconductor lasers under periodical optical injection are investigated experimentally. The periodic optical waveforms used for injection, including repetitive pulses and sine oscillations, are generated from a laser (master laser) through self optoelectronic feedback and direct current modulation, respectively. Under proper operational conditions, namely the repetition frequency and injection strength of the injected light, microwave frequency combs are observed at the output of the injected laser (slave laser). In generating the microwave frequency combs, the pulse injection scheme shows the best performance compared to the sine modulation and cw optical injection schemes. The potential applications of these microwave frequency combs in frequency division and multiplexing are demonstrated.

Keywords: semiconductor lasers, nonlinear dynamics, frequency-locking, optical injection

1. INTRODUCTION
Nonlinear dynamical behaviors of semiconductor lasers under proper optical or electrical perturbations have been investigated extensively in recent years. Different dynamical states found have gained considerable theoretical and practical attention because of their fundamental physics and potential applications such as chaotic radar, chaotic lidar, and chaotic communications. By applying either optical periodic waveform injection or negative optoelectronic feedback to a semiconductor laser, frequency-locked states can be generated. The frequency-locked states, where the main oscillation (or pulsation frequency) of the injected laser locks to the repetition frequency of the injection waveform (or the delay loop frequency of the optoelectronic feedback systems), are of particular interest due to their potential application in frequency comb generation. Optical generations of frequency combs have been widely investigated recently. The frequency combs have found wide-spread use in high data rate optical communication systems, coherent optical waveform synthesis, optical frequency metrology, and optical clock generation. Techniques of frequency comb generation have been demonstrated using mode-locked lasers. Mode-lock lasers are very attractive optical comb sources owing to their nature of high stability, less phase and amplitude noise, and high repetition rate. However, the drawbacks of generating frequency combs utilizing mode-locked laser schemes are the system complexity and high cost. One approach to generate microwave frequency comb is demonstrated using a semiconductor laser under both negative optoelectronic feedback and modulation. The microwave comb is produced from the frequency-locked states, where the linewidth of the frequency components can be narrowed by modulating the laser at one of the comb components. Despite the advantage of lower cost and easier setup, large variation in the amplitudes of the frequency combs and the non-harmonic spikes appeared in the background noise caused by the beating of the loop frequency and pulsating frequency limit its performance in potential applications. In this study, the characteristics of the frequency-locked states generated by a semiconductor laser under periodic optical injection are investigated. Microwave frequency combs with good amplitude flatness and less spurious noise are obtained by injecting a semiconductor laser optically with periodic pulses. The performance of the microwave frequency comb generated is examined.

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2. EXPERIMENT SETUP

The schematic experimental setup of a semiconductor laser under periodical optical injection is shown in Fig. 1. Two 1300 nm single-mode distributed feedback (DFB) semiconductor lasers are used as the master (ML) and the slave (SL) lasers. Both lasers emit optical power of about 8.5 mW and have a relaxation oscillation frequency of about 7 GHz. In order to generate the periodic optical pulse train with different repetition frequencies, the optoelectronic feedback (OEF) system shown in the lower part of the setup is adopted. 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. The repetition frequencies of these pulses can be varied by tuning the delay time and the feedback strength. This pulsed laser is then served as the optical injection source in our experiment. The ML output is divided into two parts utilizing a (50:50) beamsplitter, where one is used in the feedback loop and the other is used to inject the SL. The photodetector PD1 (Albis PDCS65T) and the amplifier A1 (JCA JCA003-201) used in our experiment have bandwidths of 10 GHz and 3 GHz, respectively. An optical isolator is placed in front of the master laser to prevent the unwanted feedback in the OEF scheme. To implement a sine modulated injection scheme for comparison, direct current modulation on the ML is used while the feedback loop is blocked. A signal generator (Anritsu MG3692B) is used as the current modulation source, which is also used as a frequency synthesizer in the latter part of the experiment to stabilized the frequency components of the microwave frequency combs. The system will become the conventional cw injection scheme if the feedback loop is blocked and the current modulation is disconnected. Through the combination of a polarizing beamsplitter, a Faraday rotator, and a half-
Figure 2. Power spectra of the semiconductor laser subjected to (a) conventional CW injection (period-1 state) with resolution bandwidth of 100 kHz, (b) optoelectronic feedback (regular pulsation state) with resolution bandwidth of 100 Hz, (c) both optoelectronic feedback and direct current modulation (regular pulsation state) under modulation power of 0.0 (black), -2.5 (red), and -5.0 (blue) dBm with resolution bandwidth of 1 kHz, and (d) pure current modulation with $m = -5.0$ dBm (red) and both optoelectronic feedback and current modulation with $m = 0.0$ dBm (black), with resolution bandwidth of 1 Hz.

wave plate (HW2), a free space optical circulator is formed and output of the ML can inject into the SL optically. In the experiment, the detuning frequency $\Omega$ between the master and the slave lasers is fixed at 11.7 GHz by fine-tuning the temperature of each laser, the normalized injection strength $\xi$ from the ML to the SL is 0.31 adjusted through rotating the other half-wave plate (HW1), and the repetition frequency $f_{rep}$ of the injected periodic waveform is set at 1.0 GHz. The electrical power spectra of the ML and SL outputs are displayed and recorded using a power spectrum analyzer PSA (Agilent E4407B) with a bandwidth of 26.5 GHz, where the photodetectors PD2 and PD3 (DSC30S) and the amplifiers A2 and A3 (MITEQ AFS6-00102000-30-10P-6) used to measure the respective ML and SL output have 3-dB bandwidths of 20 GHz.

3. RESULTS

To investigate the characteristics of the semiconductor laser under different optical periodic injections, detail spectra of the frequency components of various injection waveforms are examined first. Repetitive pulses generated by the OEF system and sine modulated signal generated through direct current modulation on the ML are investigated and compared with the cw injection case. Figures 2(a) and (b) show the power spectra of the period-one oscillation (P1) and the regular pulsation (RP) states generated by the semiconductor laser subjected
Figure 3. Power spectra of (a) ML and (b) SL output when the laser is under direct sine modulation with a fixed modulation frequency of 1 GHz and modulation power of -5.0 dBm.

Figure 4. Power spectra of (a) ML and (b) SL output, for an injected regular pulsing state with pulsing frequency of 1 GHz. Within ± 5-dB amplitude variation, the microwave frequency comb with 20 GHz bandwidth is obtained.

to conventional cw injection and optoelectronic feedback with resolution bandwidths of 100 kHz and 100 Hz, respectively. The 3-dB spectral linewidths of about 2 MHz and 900 Hz are estimated which quantify the stability of the P1 state under the cw injection and the RP state under the optoelectronic feedback. As can be seen, broader linewidth of the cw injection case is observed as shown in Fig. 2(a) due to the intrinsic spontaneous noise of the laser system. For the RP state as shown in Fig. 2(b), the spectral linewidth of the frequency component is much narrower caused by the locking from the delayed feedback loop.

To further reduce the spectral linewidth of the RP state, a stable external microwave at a modulation frequency $f_m = f_{rep} = 1.0$ GHz is then applied. When increasing the modulation power $m$ from -5.0 (blue), -2.5 (red), to 0.0 dBm (black), the modulation frequency locks to the frequency component directly and the linewidth is reduced as shown in Fig. 2(c) with a resolution bandwidth of 1 kHz. To verify the characteristics of the RP state generated under both electrical feedback and modulation ($m = 0$ dBm, black curve in Fig. 2(c)), the spectrum zoomed to a smaller span is investigated and compared to the direct current modulation ($m = -5.0$ dBm) case as shown in Fig. 2(d). As can be seen, in Fig. 2(d), the spectral linewidths of the RP state under both OEF and external microwave modulation (black) and solitary current modulation (red) cases are both about 1 Hz, which are limited by the resolution bandwidth. Compared to the linewidth of the RP state under OEF only, a linewidth reduction of 900 times is achieved by applying the external microwave modulation. In our experiment, the RP state with external modulation and the sine modulation waveforms generated in ML...
are utilized as the injection sources.

To investigate the difference between the nonlinear dynamics of a semiconductor laser under sine modulated optical injection and periodical pulse injection, Figs. 3 and 4 plot the power spectra of the (a) ML and the (b) SL output subject to a sine modulated and repetitive optical pulse injection, respectively. The main differences between a sine modulated light and a pulse train are in the duty-cycle in the time domain and the existence high-order harmonics in the frequency domain. For the pulse injection case, the energy in each harmonics are being redistributed through frequency beating and mixing and the energy roll off at a higher frequency. Within a $\pm 5$-dB amplitude variation, the microwave frequency comb generated as shown in Fig. 4(b) has a 20 GHz bandwidth with 1.0 GHz line spacing. It can be utilized in microwave frequency comb generation and frequency conversion in optical communications. On contrary, for the sine modulated injection case, the SL output shows almost no high-order harmonics. This is because that, for periodic pulse injection, the high-order harmonic components of the repetitive pulse waveform inject into the laser together with the fundamental frequency component ($f_{rep}$) while a pure sine modulated signal does not contain high-order harmonics other than the fundamental modulation frequency.

To examine the performance of the microwave frequency comb generated by injecting the SL with the repetitive pulses, the spectral purity and single-side band (SSB) phase noise are measured. Figure 5(a) shows the power spectra of the 1st harmonics of the output from the ML (red) and the SL (black) shown in Fig. 4, respectively. As can be seen, both curves have a 3-dB linewidth of about 1 Hz, which is the resolution bandwidth of the spectrum analyzer. Figure 5(b) shows the SSB phase noise of the ML (dotted curves) and the SL (solid curves) of the 1st (black), 6th (red), and 20th (green) harmonics at offset frequencies between 10 kHz to 500 kHz. The SSB phase noise of the frequency components of the microwave frequency comb are significantly suppressed compared to the injected RP state. For the 1st harmonic of the microwave frequency comb generated, a SSB phase noises of -60 dBc/kHz (-90 dBc/Hz estimated) at an offset frequency of 25 kHz is measured. For the 20th harmonic, a SSB phase noise suppression of more than 15 dB relative to the SL output is achieved. Compared to the frequency comb generated utilizing negative optoelectronic feedback system as shown in Ref. 27, better performance in the reduction of spurious noise and broad and flat frequency comb are obtained using optical pulse injection scheme. In sum, microwave frequency combs with high stability, high flatness, broad bandwidth, and less noise disturbance are demonstrated experimentally.

Furthermore, in order to demonstrate the application of frequency conversion or broadcasting using the microwave frequency comb generated by optical periodic pulse injection, modulation at the frequency of the desirous comb line is applied to the SL. Figure 6(a) shows the spectrum of the original frequency comb (red) with line spacing of 1.0 GHz and the broadcasting spectrum (black) with $f_m = 6.0$ GHz (6th comb line) and $m = 8.0$ dBm. Because of the nonlinear interaction among the comb lines, modulating on one of the comb lines will
result in modulation of other comb lines. Therefore, both frequency down-conversion and up-conversion can be achieved simultaneously. The conversion gain will increase when increasing the modulation power. Figure 6(b) shows the relation between the conversion gain and the modulation power, where the solid lines are the linear fits of each harmonics. When the modulation power is below than -12 dBm, the modulation is too weak to have any observable effect on the spectrum. When the modulation power is above 20 dBm, the modulation strongly influences the nonlinear dynamics of SL and the SL will be driven into unstable states. Under proper modulation power, the SL shows good performance in the frequency conversion application. For the down-conversion case, as shown in the 1\textsuperscript{st}, 2\textsuperscript{nd}, and 5\textsuperscript{th} comb lines, the linear relation between the conversion gain and modulation power is observed. The same behavior is also obtained in the up-conversion cases as shown in the 7\textsuperscript{th}, 10\textsuperscript{th}, and 20\textsuperscript{th} comb lines. The ratio of conversion gain between the main modulated (6\textsuperscript{th}) comb line and other comb lines is about 1.78.

4. CONCLUSIONS

In conclusion, we study the characteristics of semiconductor laser under periodical optical injection experimentally. Repetitive pulses and sine modulated optical injections are investigated and compared with the cw injection case. When an external microwave modulation is applied to the optoelectronic feedback loop, regular pulsing states with 1 Hz spectral linewidth are obtained. Compared with the sine modulated optical injection, a 20 GHz microwave frequency comb with a flatness within ±5-dB is demonstrated experimentally using optical pulse injection scheme. A single-side band phase noises of -60 dBc/kHz (-90 dBc/Hz estimated) at an offset frequency of 25 kHz is measured for the 1\textsuperscript{st} harmonic and a noise suppression of more than 15 dB relative to the slave laser output in the 20\textsuperscript{th} harmonic is also achieved. Moreover, for frequency conversion application, both frequency down-conversion and up-conversion are realized simultaneously. The ratio of conversion gain between the main modulated (6\textsuperscript{th}) comb line and other comb lines is about 1.78.

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