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Novel photonic applications of nonlinear semiconductor laser dynamics

Sze-Chun Chan · Rosemary Diaz · Jia-Ming Liu

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Abstract With a proper perturbation, even a single-mode semiconductor laser can exhibit highly complex dynamical characteristics ranging from stable, narrow-linewidth oscillation to broadband chaos. In recent years, three approaches to invoke complex nonlinear dynamical states in a single-mode semiconductor laser have been thoroughly studied: optical injection, optical feedback, and optoelectronic feedback. In each case, the nonlinear dynamics of the semiconductor laser depends on five intrinsic laser parameters and three operational parameters. The dynamical state of a given laser can be precisely controlled by properly adjusting the three operational parameters. This ability to control the dynamical behavior of a laser, combined with the understanding of its characteristics, opens up the opportunity for a wide range of novel applications. This paper illustrates the utilization of the rich nonlinear dynamics of single-mode semiconductor lasers by focusing on the period-one oscillation for its applications in tunable photonic microwave generation, AM-to-FM conversion, and dual-frequency precision Doppler lidar.

Keywords Semiconductor lasers · Optical injection · Nonlinear dynamics · Microwave photonics · Lidar

1 Introduction

Semiconductor lasers are inherently nonlinear devices. While a solitary single-mode semiconductor laser normally only emits continuous-wave radiation, its rich nonlinear dynamics can be excited with proper perturbations. It is possible to obtain many highly complex dynamical states such as stable locking, periodic oscillation, regular pulsation, quasi–periodic pulsation, frequency-locking, and chaos. The resultant dynamical characteristics can be controlled by the external operational parameters and thus be utilized for many interesting photonics applications. Various perturbation methods, most notably optical injection, optical feedback, and

S.-C. Chan (✉) · R. Diaz · J.-M. Liu
Department of Electrical Engineering, University of California, Los Angeles, CA 90095-1594, USA
e-mail: scchan@ucla.edu

optoelectronic feedback, have been investigated for this purpose. In this paper, the optical injection system is presented as an example to illustrate the diverse application opportunities of nonlinear semiconductor laser dynamics.

The dynamics of semiconductor lasers have been investigated since the very early development of laser research (Basov 1968; Broom et al. 1970). However, it was not until the early 1980s that the nonlinear laser dynamics of optically injected lasers were systematically studied (Lang and Kobayashi 1980; Kobayashi and Kimura 1981; Lang 1982). A number of research groups soon participated in the endeavor to understand these dynamics and to develop them into useful applications (Arecchi et al. 1984; Tredicce et al. 1985; Mogensen et al. 1985; Petitbon et al. 1988; Spano et al. 1989; Ramos et al. 1994; DeJagher et al. 1996; Gavrielides et al. 1997a,b, 2002; van der Graaf et al. 1997c; Braun et al. 1997; Krauskopf et al. 1998; Wieczorek et al. 1999; Yabre et al. 2000; Wieczorek et al. 2002; Eriksson 2002; Chlouverakis and Adams 2004; Murakami and Shore 2006). A more comprehensive overview of the development of semiconductor laser dynamics can be found in Krauskopf and Lenstra (2000) and the references therein. Using an optical injection setup, it is possible to control and vary the dynamical behavior of a laser by adjusting its operating conditions. The primary dynamical states of an optically injected semiconductor laser are stable locking, periodic oscillations, and chaos. The simplest state of stable locking has been intensively studied recently. It exhibits desirable high-frequency modulation characteristics, such as bandwidth enhancement, chirp reduction, and noise reduction for optical communications applications (Liu et al. 2006; Simpson and Liu 1997; Okajima et al. 2003; Hwang et al. 2004). The most complex state of chaotic oscillation has also attracted much attention in the past 10 years. The complex nature of the chaotic state has been applied in the areas of chaos synchronization for secure communications (Liu et al. 2001, 2002; Chen and Liu 2005a) and broadband waveform generation for chaotic radar and lidar applications (Lin and Liu 2004a,b,c). The remaining periodic oscillation states are useful as well. These states have been employed in novel microwave photonics applications such as all-optical microwave frequency conversion (Chan and Liu 2005b) and single-sideband frequency modulation (Chan and Liu 2006).

This paper focuses on some select novel applications of the periodic states. In Sect. 2, the experimental setup is presented. The same basic setup is shared for all the applications described in the paper. The photonic microwave applications are presented in Sect. 3. The technique compares advantageously to the common methods in photonic microwave generation. The dual-frequency precision Doppler lidar applications are presented in Sect. 4. It is followed by a conclusion in Sect. 5.

2 Experimental setup

The general dynamics of a single-mode semiconductor laser is independent of the exact design and wavelength of the laser. As long as it is a single-mode laser, a Fabry-Perot, distributed-Bragg-reflector (DBR), or distributed-feedback (DFB) laser exhibits similar dynamics under a given perturbation though quantitative operating conditions might vary. In our experiments, a 1.3 μm DFB laser is considered for optical injection. A simplified schematic diagram of the setup is shown in Fig. 1. Light is injected from the master laser through an optical isolator, a mirror, and a beam splitter into the slave laser. The injection is unidirectional such that the output of the slave laser does not affect the master laser. The output of the slave laser can be subsequently transmitted and detected. The dynamics of the slave laser are governed by five intrinsic parameters and three operational parameters (Simpson et al. 1997). The five intrinsic parameters are the cavity decay rate, the spontaneous carrier

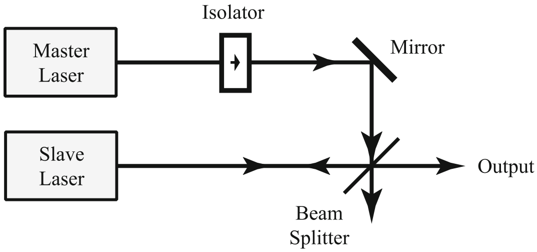

Fig. 1 Schematic of an optical injection system

relaxation rate, the differential carrier relaxation rate, the nonlinear carrier relaxation rate, and the linewidth enhancement factor (Liu and Simpson 1994; Simpson and Liu 1993). The four rates are typically in the range of 10^9–10^{11} s^{-1} and the linewidth enhancement factor is typically in between 1 and 10 (Hwang and Liu 2000). These parameters can be determined using a four-wave mixing technique (Liu and Simpson 1994; Simpson and Liu 1993) and their experimental values have been reported previously (Chan and Liu 2006). The three operational parameters are the bias current of the slave laser, the optical injection power from the master laser, and the injection detuning frequency between the master and slave lasers (Hwang and Liu 2000). The slave laser can begin from the stable locking state, where its frequency is locked by the master laser. Careful adjustments of the operational parameters can then invoke the nonlinear dynamical state of the slave laser. The slave laser can exhibit simple periodic oscillation in the period-one state by undamping the relaxation resonance at a Hopf bifurcation point. This periodic oscillation can subsequently double and then quadruple its period through nonlinear dynamical period-doubling bifurcations. Cascaded period-doubling bifurcations exist and the laser can finally enter a chaotic state through the period-doubling route. It has been demonstrated that all of the above dynamics are useful in different practical applications. In the following discussions, we focus on the applications of the period-one state.

3 Photonic microwave applications

The dynamical behavior of a typical semiconductor laser evolves at a sub-nanosecond time scale because of the fast dynamical rate parameters. Figure 2 shows the optical spectrum of the optially injected slave laser as it enters period-one oscillation from the stable locking state. In the left column, the injection power is varied while the injection detuning frequency is kept constant at zero. Starting from a low injection power of 0.50 mW, the laser is simply locked to the master laser so that there is only one optical line in the spectrum of Fig. 2(a). However, as the injection power is increased to 0.96 mW, the slave laser experiences a Hopf bifurcation and enters the period-one oscillation state. The relaxation resonance of the laser is undamped and it generates sidebands separated by 10.96 GHz in Fig. 2(b), which is close to its intrinsic relaxation resonance frequency. The generated microwave frequency increases as the injection power is further increased. This effect is shown in Fig. 2(c), (d) for injection strengths of 3.5 and 7.3 mW, respectively. The spectra in the right column show a similar variation as the injection detuning frequency is increased while the injection power is kept constant. The detuning is defined as the difference between the optical frequency of the master laser and the free-running optical frequency of the slave laser. It is negative when the master laser has a lower frequency. In Fig. 2(e), the detuning is set at −4.31 GHz, and the slave laser is stably locked to the injection frequency. The slave laser undergoes Hopf bifurcation into the period-one state when the detuning frequency is varied to −2.64 GHz as shown in

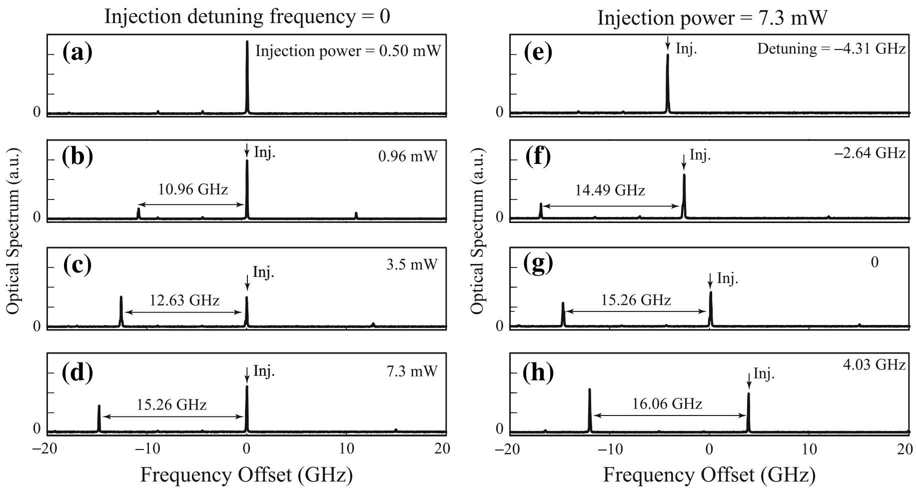

Fig. 2 Optical spectrum of the slave laser subjected to optical injection. The frequency axes are offset to the free-running frequency of the slave laser. (**a**–**d**) Injection power varies while the detuning is kept at zero. (**e**–**h**) Injection detuning varies while the injection power is kept constant at 7.3 mW. The arrows indicate the injected optical frequency component

Fig. 2(f). The generated microwave frequency increases as the detuning is further varied in the positive direction, as shown in Fig. 2(g), (h) for detuning frequencies of 0 and 4.03 GHz, respectively. These results show that continuously tunable photonic microwave frequencies on an optical carrier can be generated by varying either the optical injection power or the detuning frequency in an optical injection laser system.

Such a microwave generation technique has several advantages. First of all, the microwave frequency is widely and continuously tunable. In the example demonstrated above, the slave laser originally has a relaxation resonance frequency of about 10 GHz, which is roughly its bandwidth limit if it is used for direct current modulation. Photonic microwave generation by the period-one dynamics is not limited by the same effect. Generation of microwave frequencies beyond this intrinsic limit is clearly seen in Fig. 2. Frequencies of up to 100 GHz have been obtained using this system (Chan and Liu 2006). One significant difference of this approach versus direct modulation is that the resultant modulation is not restricted to small signals. Indeed, as shown in Fig. 2(c), (h), it is possible to obtain a strong optical sideband equal in amplitude to the carrier by properly controlling the injection parameters. The injection system is also numerically simulated using the model outlined in Chan et al. (2007a). The optical power ratio of the generated sideband to the carrier is recorded in Fig. 3. The generated microwave frequency is tuned by varying the injection strength while the injection detuning is kept constant at 10 GHz (circles), 20 GHz (squares), and 30 GHz (triangles), respectively. The results show that the period-one dynamics can generate strong modulation on the optical spectrum. The power ratio can be greater than one, which means that the sideband power can be even stronger than the carrier.

Furthermore, the microwave frequency can be easily stabilized. Because the generation is attributed to the nonlinearity of the slave laser, all the optical components co-exist inside the slave laser cavity. This facilitates different microwave locking techniques that stabilizes the intrinsic fluctuations of the generated microwave frequency. Various methods such as external injection locking, self-injection locking, subharmonic locking, and phase locking have been

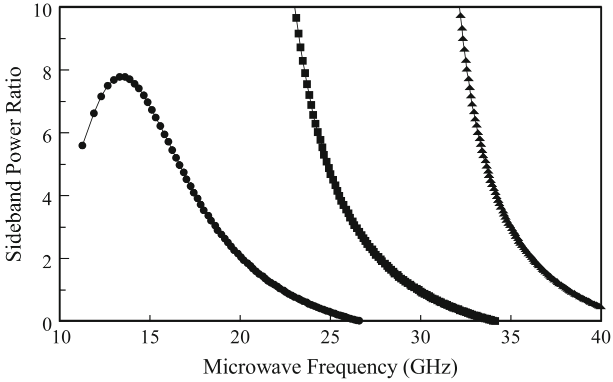

Fig. 3 Optical power ratio of the generated sideband to the carrier. The injection strength is varied to tune the microwave frequency while the injection detuning is kept at 10 GHz (•), 20 GHz (■), and 30 GHz (▲), respectively

investigated (Simpson and Doft 1999; Simpson 1999; Chan and Liu 2004; Chan et al. 2007b). The generation of a 40 GHz photonic microwave signal with less than 1 Hz fluctuation has been demonstrated using the subharmonic locking technique (Chan et al. 2007b). The goal of these microwave locking techniques is to reduce the microwave (not optical) linewidth. By applying a microwave current modulations on the slave laser, microwave frequency of the period-one state is locked and it gives a narrowed microwave linewidth. The locked state is useful for precise lidar applications that will be described in Sect. 4.

Another significant characteristic of the period-one state is that the optical spectrum is asymmetric with the low-frequency sideband dominating the high-frequency sideband, which can be clearly seen in Fig. 2. This asymmetry is caused by the antiguidance factor of the semiconductor laser, which tends to red-shift the cavity resonance when an optical injection is applied. As seen in Fig. 2, a nearly single-sideband spectrum can be obtained by properly tuning the operational parameters. Most interesting is the spectrum in Fig. 2(h), which has a single-sideband of the same amplitude as the carrier. This is a desirable property that can be utilized for radio-over-fiber transmission to avoid the chromatic dispersion power penalty (Chan et al. 2007a).

These period-one photonic microwave characteristics of the optically injected semiconductor laser are compared in Table 1 to those of other common photonic microwave generation methods based on semiconductor lasers such as direct modulation, self-pulsation, mode locking, heterodyning, optical phase-lock loop, and dual-mode cavity. Direct modulation is the most straightforward method, but it is limited to small-signal modulation and its bandwidth is limited by the intrinsic resonance frequency of the laser (Hwang et al. 2004). The optical spectrum of a directly modulated laser is also inherently double-sideband. Specially designed lasers such as self-pulsating and mode-locked lasers can be operated at much higher frequencies (Landais et al. 2006; Novak et al. 1995). However, these methods rely on the resonances of the cavity and thus have a limited tuning range. The bandwidth limitation can be avoided by employing heterodyne on two independent lasers. Although the method is simple, the resultant beat signal has poor stability because the two lasers have independent fluctuations in amplitude, frequency, and phase. The signal purity can be significantly improved by constructing an optical phase-lock loop (Johansson and Seeds 2003). Unfortunately, such a method often requires high-speed and very precise electronics to

Table 1 Comparison of photonic microwave sources based on semiconductor lasers

Method	Tunability	Stability	Electronics	Single-sideband
Direct modulation	Limited	Good	Simple	No
Self-pulsation	Limited	Good	Simple	No
Mode-locking	Limited	Good	Simple	No
Heterodyne	Good	Poor	Simple	Yes
Optical phase-lock loop	Good	Good	Complicated	Yes
Dual-mode	Good	Moderate	Complicated	Yes
Period-one state	Good	Good	Simple	Yes

rapidly correct the signal fluctuations. Dual-mode lasers have a similar problem in stability (Pajarola et al. 1999) because the two modes, though of the same laser, are generally independent. These problems pose significant challenges to the design of lasers for photonic microwave applications. Another common technique uses external optical modulators such as electro-optic and electro-absorption modulators. These are promising techniques that support very high-frequency operation (Bortnik et al. 2007), but high-speed modulators require an external laser source and the materials for such modulators are usually quite lossy. These external modulations are often incorporated in the optoelectronic oscillator (OEO) architecture (Yao and Maleki 1996, 1997; Yao et al. 2000). While an OEO is capable of generating narrow-linewidth microwave signals, it requires a long length of fiber to realize a high-quality cavity and a strong external laser to act as a pump source. In any case, the period-one dynamics of an optically injected semiconductor laser appears to be a useful alternative source for photonic microwave generation. It has favorable properties in terms of tunability, stability, and simplicity. The practicality can be improved if the master and slave lasers are integrated or packaged together in a single, compact unit.

As an example to illustrate the usefulness of the period-one state in communications, we utilize the fact that the frequency generated is dependent on the injection power (Chan et al. 2006). Suppose that the optical beam that is injected to the slave laser carries a signal that is modulated with data in the amplitude modulation (AM) format. Then the generated microwave frequency of the period-one oscillation in the slave laser is modulated accordingly. However, as is illustrated in Fig. 2(a)–(d), a variation in the optical injection power due to the AM signal causes a variation in the frequency of the sideband. The data format is thus transformed into frequency modulation (FM) at the output of the slave laser. Simultaneously, the data is upconverted from the baseband into the microwave domain. Such AM-to-FM upconversion is applicable at the interface of conventional AM optical networks to FM radio-over-fiber systems. The concept is demonstrated in Fig. 4. A 622 Mbps data stream is modulated on the amplitude of the master laser. The AM data spectrum and eye diagram are shown in Fig. 4(a). The amplitude-modulated laser light is then injected into the slave laser. The operational parameters are adjusted such that the slave laser exhibits period-one oscillation. Because the injection strength is modulated, the period-one microwave frequency is modulated accordingly. The central frequency of the period-one oscillation is 16 GHz, but the frequency is modulated with a maximum deviation of 600 MHz. Thus, the AM injection data stream is transformed into FM on the period-one oscillation. When the output of the slave laser is detected by a photodetector and the FM signal is demodulated by a microwave frequency discriminator, the final result is shown in Fig. 4(b). By comparing the data spectra

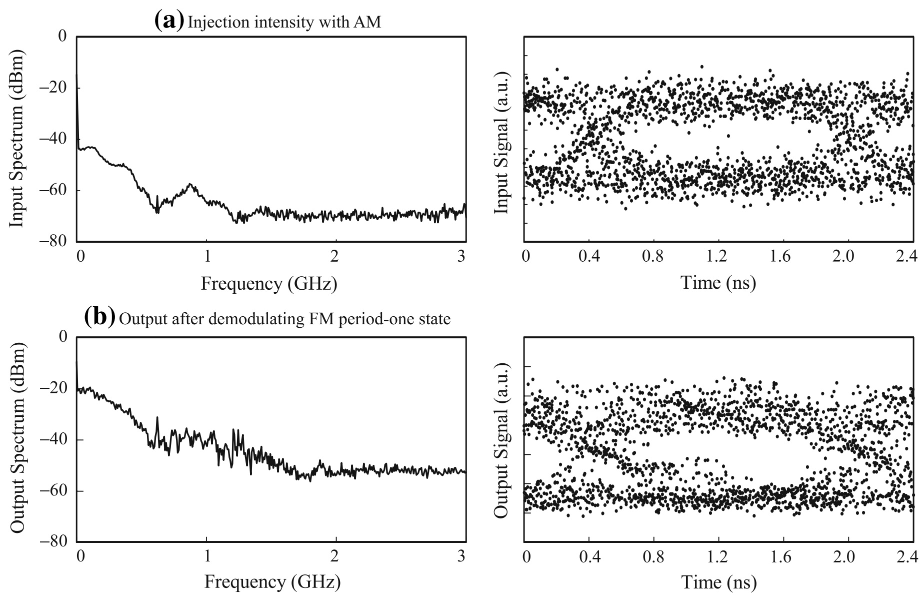

Fig. 4 AM-to-FM conversion: (**a**) AM injection input data and (**b**) demodulated FM output data

in Fig. 4, it is observed that the signal is slightly deteriorated by the AM-to-FM transformation. Nevertheless, the eye diagrams show acceptable results with a measured bit-error rate of less than 10^{-9}. The above results merely show one example to illustrate that the periodic nonlinear laser dynamics have useful applications for optical communications. The usefulness of these periodic dynamics is not limited to the communications areas. The following section illustrates an application in lidar detection.

4 Dual-frequency precision lidar applications

Lidar applications in velocity measurement, imaging, and range finding are widely studied. Considerable progress in lidar detection has been made as advances in laser technology enable various lidar system designs. Lidar systems are usually designed to accomplish one specific task. A novel chaotic lidar (CLIDAR) system utilizing the chaotic state of a semiconductor laser has recently been demonstrated to have a 3 cm range resolution using noncoherent microwave correlation and a 5.5 mm range resolution using coherent optical correlation (Lin and Liu 2004b). In this section, we illustrate the application of the period-one dynamics for precision lidar applications. Unlike the CLIDAR, this is a dual-frequency Doppler lidar that can precisely measure the velocity of a remote target. It can also measure the range to a target, using a different principle from that of the CLIDAR.

The period-one dynamics of the optically injected semiconductor laser enables both velocity and range measurements in lidar detection. Because of the single-sideband nature of the optical spectrum seen in Fig. 2, this is a dual-frequency Doppler lidar (DFDL). Due to intrinsic laser noise, the detected microwave beat frequency typically results in a microwave linewidth of about 10 MHz. However, as mentioned in Sect. 3, the microwave stability can be significantly improved by applying the external microwave locking technique. In doing so, the detected beat frequency fluctuation can be reduced by several orders of magnitude. The stability of the locked period-one state allows accurate velocity measurement. The DFDL capability of the system has been used to measure velocities as low as 26 μm/s (Diaz et al. 2006).

The dual-frequency lidar system is based on the schematic of the experimental setup shown in Fig. 1 as the source. The dual-frequency beam emitted by the slave laser is divided into two parts with a beam splitter. The transmitted part of the beam is directly detected by a photodiode where the beat frequency f_{RF} serves as a reference signal. The reflected part of the beam is directed to a remote target moving at a constant velocity v. The backscattered light from the target is detected by a second photodiode. The microwave envelope of the target arm experiences a Doppler shift. This Doppler shift frequency is extracted by mixing the signals of the two photodiodes with a microwave mixer. The output of the mixer is sent to a data acquisition system and is recorded on a computer. A 5.5 km length of fiber (approximately 8 km optical path) is inserted in the target arm to demonstrate the long range capability of the system.

A complete analysis of the Doppler lidar system is described in Diaz et al. (2006). Here, we list only the signal at the output of the mixer

$$P_{mix} = 2A\cos(2\pi f_{RF}^{D} t + 4\pi d f_{RF}/c - \Phi), \tag{1}$$

where $f_{RF}^{D} = 2v f_{RF}/c$ is the Doppler shift frequency, c is the speed of light, d is the initial distance between the target and the detector, Φ is the random phase noise difference between the reference and target arms, and A is a proportionality constant (Diaz et al. 2006). The Doppler shift is obtained by taking the power spectral density (PSD) of P_{mix} provided that the random phase Φ is negligibly small. Thus, the magnitude of the velocity is measured. The direction of motion can be easily determined by implementing an in-phase and quadrature detection as demonstrated by Morvan et al. (2002).

As shown in Eq. 1, the microwave Doppler shift is measured rather than the optical Doppler shift. Accurate velocity measurement thus depends on the microwave stability rather than the optical frequency stability. The optical linewidth does not affect the performance of the system. This is a significant distinction over traditional single-frequency Doppler lidars that are limited in their long-range capabilities by the optical coherence length. Our system is only limited by the microwave frequency fluctuation and the corresponding microwave coherence length. By applying a microwave modulation to lock the period-one state, microwave frequency fluctuation of less than 1 kHz can be easily obtained. The corresponding microwave coherence length is estimated to be greater than 24 km. In contrast, when the locking is not applied, the microwave coherence length is estimated to be only about 2.4 m since the microwave linewidth is approximately 10 MHz.

Experiments are carried out to demonstrate the performance of the DFDL. The data obtained from an experiment with $f_{RF} = 17$ GHz is shown below. The acquisition time is 1000 s in order to achieve millihertz resolution. Figure 5(a), (b) shows, respectively, the mixer output in the time and frequency domains when microwave locking is applied. Figure 5(c), (d) shows the mixer output when the microwave locking is not applied. In the locked case, the random phase Φ in Eq. 1 is negligible. The mixer output produces a clear sinusoid in Fig. 5(a), and a clear peak at 3 mHz in the frequency domain in Fig. 5(b). This yields a velocity of 26 μm/s, which is in excellent agreement with an independent measurement of the target velocity. In contrast, when the microwave locking is not applied, the random phase Φ in Eq. 1 obscures the Doppler information in Fig. 5(c), making determination of the Doppler shift impossible in Fig. 5(d). The DFDL method can be used to accurately measure a wide range of velocities over various distances. The detailed results are reported in Diaz et al. (2006).

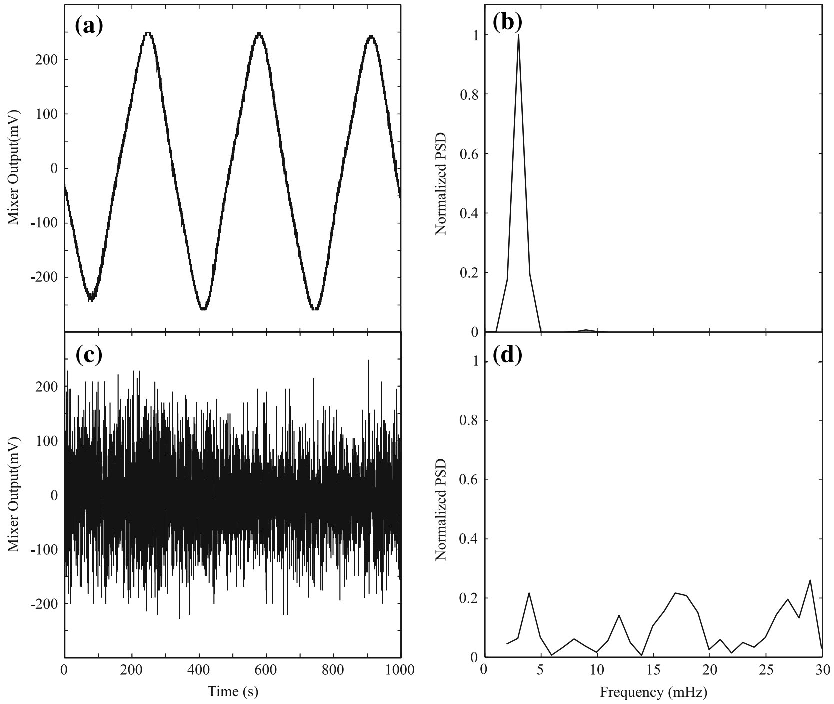

Fig. 5 Mixer output for $f_{\mathrm{RF}} = 17\,\mathrm{GHz}$. The target moves away from the detector at $26\,\mu\mathrm{m/s}$. The Doppler shift frequency is 3 mHz: (**a**) Doppler measurement with locked period-one state, (**b**) the corresponding normalized power spectrum (PSD), (**c**) Doppler measurement with unlocked period-one state, and (**d**) the corresponding normalized PSD

The period-one dynamical state can also be used to measure the range to a target. The technique is very similar to some phase noise measurement methods (Rubiola et al. 2005). In our current configuration, the period-one oscillation can be viewed as a stable photonic microwave oscillator source. Splitting the output beam into a reference and a target arm and recombining the signals with an RF mixer essentially multiplies a delayed version of the signal with itself. Provided that the delay fulfills the quadrature condition, the transfer function of this type of layout is proportional to $\sin^2(\pi f \tau)$, where τ is the delay time difference between the two arms (Rubiola et al. 2005). The power spectrum contains a series of zeroes at multiples of $1/\tau$, so the distance information can be extracted. The same experimental setup used for the velocity measurement is used for the ranging demonstration except that the target is kept stationary. Figure 6 shows the data obtained with the method described. The black lower trace shows the power spectrum of the mixer output when the period-one state is locked by a microwave modulation, but with residual phase noise. Because the period-one frequency is stable, the quadrature condition can be met by fine-tuning the delay. Thus the curve shows the periodic drops predicted by the transfer function. The gray upper trace shows the power spectrum of the mixer output in the absence of external modulation. The large contribution of the frequency fluctuation prevents the quadrature condition from being constantly fulfilled. Comparing this curve to the black curve, it is evident that the periodic structure clearly seen in the black curve disappears.

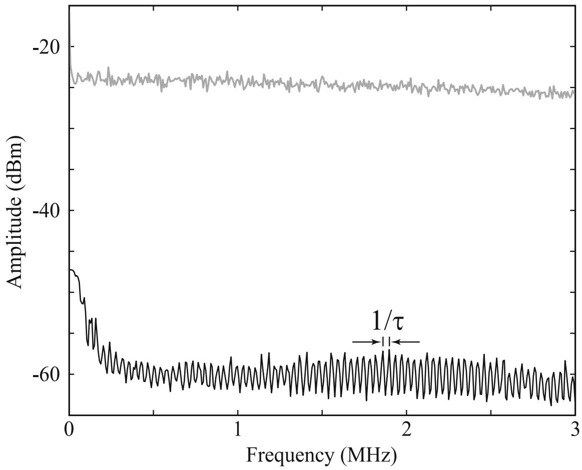

Fig. 6 The power spectrum of the mixer output is measured. The black lower trace is the power spectrum when the period-one state is locked by microwave modulation. The gray upper trace is the power spectrum when the period-one state is not locked. The resolution bandwidth of the spectrum analyzer is 3 kHz

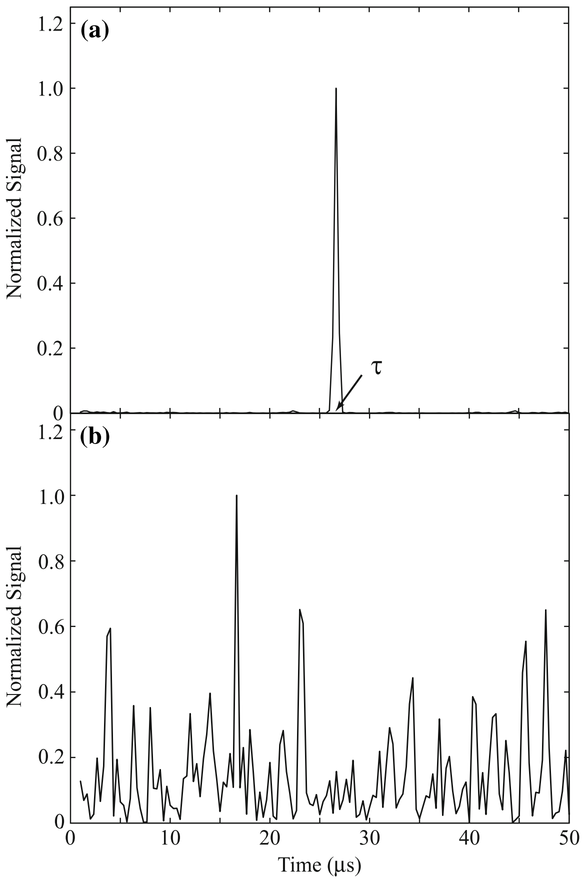

Fig. 7 The inverse Fourier transform of the measured power spectra from Fig. 6. (**a**) The transform of the black trace of Fig. 6. (**b**) The transform of the gray trace of Fig. 6

The optical path difference is measured by calculating the spacing between adjacent zeroes in the power spectrum. This is realized by taking the inverse Fourier transform of the power spectrum. Figure 7(a) is the inverse Fourier transform of the black curve shown in Fig. 6. This curve reveals a clear peak indicating the delay time difference of 26.7 μs between the reference and target arms. This corresponds to an optical path difference of 8.01 km, which is consistent with an independent measurement. Figure 7(b) shows the inverse Fourier transform corresponding to the gray curve shown in Fig. 6. This curve clearly shows the absence of delay time information. Hence, a stable microwave oscillation is key for obtaining precise measurements of velocity and range.

5 Conclusion

Semiconductor lasers exhibit rich nonlinear dynamical characteristics. By properly controlling these dynamics in a system such as the optical injection system, many interesting photonic applications can be realized. This paper focuses only on a few applications of only the period-one dynamics in the areas of microwave photonics and lidar detection. Generation of a photonic microwave is possible due to the period-one oscillation dynamics. The resultant microwave signal can be widely tuned, easily stabilized, and optically controlled. The oscillation is applied, as an example, to perform AM-to-FM data conversion for interfacing conventional optical networks and radio-over-fiber systems. Dual-frequency precision Doppler lidar applications are made possible by the stability of the microwave signal. By stabilizing the microwave beating signal, regardless of the optical coherence, long range and precise Doppler shifts of the microwave signals can be determined. These applications merely illustrate some novel applications of just one dynamical state. Clearly, there is a wealth of interesting and useful applications to be developed for each state of the nonlinear laser dynamics.

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