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Highly Stable and Broadly Tunable Photonic Microwave Generation Using Period-One Nonlinear Dynamics of Semiconductor Lasers

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Abstract–Period-one nonlinear dynamics in a semiconductor laser subject to external injection of a highly correlated optical comb are investigated for photonic microwave generation. The optical carrier of the optical comb excites the period-one dynamics, giving rise to broadly and continuously tunable microwave generation with constant power from a few to tens or even hundreds of gigahertz. A harmonic of the optical comb phase-locks the lower oscillation sideband of the period-one dynamics, leading to stabilization of such generated microwaves, down to a 3-dB linewidth of 1 Hz. By taking advantage of frequency multiplication in yielding the optical comb, only an electronic microwave reference at a small fraction, such as one-tens, of the generated microwave frequency is required to achieve stabilization.

1. Introduction

Period-one (P1) nonlinear dynamics in a semiconductor laser subject to continuous-wave optical injection have attracted much research interest not only for fundamental understandings of nonlinear dynamics and laser physics [1-5] but also for various technological applications in photonics and microwaves [6-12]. One promising application of the P1 dynamics is to take advantage of the self-sustained microwave oscillation of the laser intensity for photonic microwave generation [13-22]. While broadband frequency tunability can be achieved by simply adjusting the power and frequency of the optical injection, optical single-sideband modulation is so feasible as to mitigate microwave power fading over fiber distribution. However, owing to the laser intrinsic noise, the linewidth of the photodetected microwaves is typically on the order of tens to hundreds of megahertz, limiting the scope of their practical applications.

A few microwave stabilization approaches have therefore been proposed. Simpson et al. demonstrated [13] that, by directly modulating the optically injected semiconductor laser at the same microwave oscillation frequency, the P1 dynamics can be locked to an electronic microwave reference. While the microwave linewidth can be reduced below 1 kHz, the highest locked microwave frequency is restricted to about 17 GHz due to the limited laser response to direct modulation. To eliminate the need of an electronic microwave reference, Chan et al. suggested [15] the use of the optoelectronic feedback of the P1 dynamics as the microwave reference. While a similar reduced linewidth can be achieved for microwaves up to 23 GHz, a photodetector, an electronic microwave amplifier, and an electronic microwave attenuator, which operate at the same microwave oscillation frequency, are required in the feedback loop. As noted, both approaches become increasingly difficult and expensive to implement for increasingly high-frequency microwave generation. To bypass the bandwidth restriction of electronics, lately, it was demonstrated [20-22] that the optical feedback of the P1 dynamics can work as the self-reference for stabilization of microwaves up to 45 GHz. However, owing to significant frequency jitters, the microwave linewidth can only be reduced below 50 kHz. In this work, an approach based on optical modulation sideband injection locking is investigated to stabilize the P1 microwave oscillation. A linewidth of 1 Hz can be achieved for microwaves up to 40 GHz or higher using an electronic microwave reference of only one-tens or lower of the P1 oscillation frequency.

2. Experimental Setup

Figure 1 presents a schematic of the experimental apparatus using typical single-mode distributed-feedback semiconductor lasers in a master-salve configuration. The slave laser (Furukawa FRL15DCW5-A81) is current-biased at about 6.15 times its 13-mA threshold and temperature-stabilized at 25^{o}C. Under the free-running condition, the slave laser oscillates at 193.33~THz with a power of 10.83 mW at its fiber-pigtail output and with a

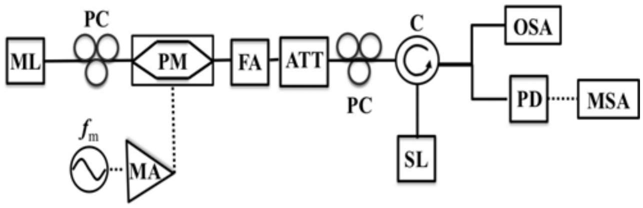

Fig. 1. Schematic of the experimental apparatus. ML, master laser; SL, slave laser; PC, polarization controller; PM, phase modulator; MA, microwave amplifier; FA, fiber amplifier; ATT, attenuator; C, circulator; OSA, optical spectrum analyzer; MSA, microwave spectrum analyzer; PD, photodiode.

relaxation resonance frequency of 12.1 GHz. The output of the master laser (Lucent D2525P33) is directed toward the slave laser through a circulator. To excite the P1 dynamics, the frequency of the optical injection is detuned, through adjusting either the temperature or the bias current of the master laser, by f_i from the free-running frequency of the slave laser. In addition, the power of the optical injection is varied using an attenuator and a fiber amplifier, and is measured at the output port of the circulator connected to the slave laser. To indicate the injection strength received by the slave laser, an injection ratio ξ_i, defined as the square root of the power ratio between the optical injection and the free-running slave laser, is used. A polarization controller aligns the polarization of the optical injection with that of the slave laser. A 10-GHz phase modulator (EOspace PM-0K5-10) superimposes an electronic microwave reference (Agilent E8257D) on the optical injection, yielding a comb of modulation sidebands offset from the master laser by integral multiples of the reference frequency f_m. An electronic microwave amplifier (Picosecond Pulse Labs 5882) operating at its saturation adds extra nonlinear distortion to the microwave reference for the generation of a broader modulation sideband comb. The spectral features of the slave laser output are displayed on an optical spectrum analyzer (Advantest Q8384), and also on a microwave spectrum analyzer (Agilent N9030A PXA) following a 50-GHz photodiode (u2t Photonics XPDV2120R).

3. Results and Analyses

A continuous-wave optical injection at (ξ_i, f_i) = (1.06, 30 GHz), presented in Fig. 2(a), excites a P1 dynamical state of the slave laser, as Fig. 2(b) shows. For comparison, the spectrum of the free-running slave laser is also presented in Fig. 2(a). While the optical injection regenerates [23], oscillation sidebands sharply appear, which are equally separated from the regeneration by f_0 = 40 GHz. Attributed to the red-shift of the laser cavity resonance caused by the optical injection [4], the lower oscillation sideband is resonantly enhanced as opposed to the upper one. As a result, the lower oscillation sideband is not only 23 dB stronger than the upper one but also has an intensity close to the regeneration, only 5 dB weaker. Effectively, the optically injected laser system at the P1 dynamics functions as a two-tone optical oscillator, leading to a feature of optical single-sideband modulation. After photodetection, as shown in Fig. 2(c), the beating between the spectral components generates a microwave signal jittering around 40 GHz, over a range of 151 MHz for a time period of 100 s, with a 3-dB linewidth of about 1.7 MHz. While the broad linewidth results from the laser intrinsic noise [22], the significant jitter arises from relative fluctuations in the operating conditions of both lasers due to unavoidable slight variations in current, temperature, and even polarization [5].

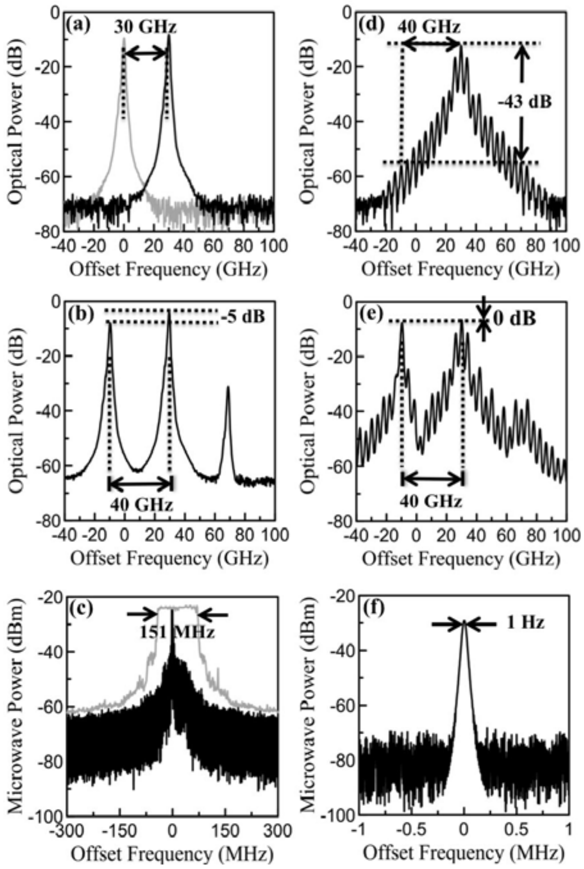

Fig. 2. Optical spectra of (a) continuous-wave injection and (d) comb-like injection. Optical spectra of P1 dynamics under (b) continuous-wave injection and (e) comb-like injection. (c)(f) Microwave spectra of (b) and (e), respectively, centering at 40 GHz with a resolution of 1 MHz and 30 kHz, respectively. The optical spectrum of the free-running slave laser (gray curve) is also shown in (a). The frequency jitter of P1 dynamics (gray curve) is also presented in (c). The x-axes of all optical spectra are relative to the free-running frequency of the slave laser. The injection condition is fixed at (ξ_i, f_i) = (1.06, 30 GHz). When measuring the microwave linewidth of (f), the highest resolution of 1 Hz is used.

To stabilize the P1 oscillation, a microwave reference at f_m = 4 GHz, distorted by the saturated microwave amplifier, now phase-modulates the optical injection. A comb of more than 10 modulation sidebands on either frequency side therefore appears, as shown in Fig. 2(d), which are offset from the optical carrier by integral multiples of f_m and which are highly correlated to each other. By injecting this entire optical comb into the slave laser at the same (ξ_i, f_i) = (1.06, 30 GHz), a globally similar P1 dynamical state is excited by the optical carrier, as Fig. 2(e) presents, with its lower oscillation sideband, 40-GHz lower, phase-locked to the 10th harmonic of the lower modulation sidebands. Consequently, as demonstrated in Fig. 2(f), a stable microwave generation at 40 GHz with a linewidth of 1 Hz, same as the microwave reference, is achieved. Note that when

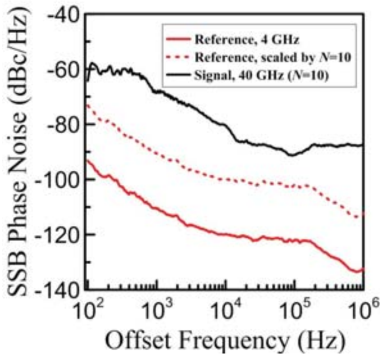

Fig. 3. Single-sideband (SSB) phase noise as a function of microwave offset frequency for generated 40-GHz microwave signal (black solid curve), 4-GHz microwave reference (red solid curve), and 4-GHz microwave reference scaled by N = 10 (red dotted curve).

measuring the microwave linewidth of Fig. 2(f), the highest resolution of 1 Hz is used.

To further demonstrate the stability of the generated 40-GHz microwave signal, its single-sideband phase noise, estimated as the ratio of the power at a non-zero frequency offset to that at the zero, is compared with that of the 4-GHz microwave reference itself, as shown in Fig. 3. Note that the single-sideband phase noise scales with multiplication of frequency by N as $20[\log_{10}(N)]$ = 20 dB for N = 10. For fair comparison, the scaled phase noise up to the 10th harmonic of the microwave reference is also presented. Even though excess phase noise of approximately 9 to 25 dB is observed over the offset frequency range under study, the phase noise level of the stabilized microwave generation is highly comparable to the ones that are possibly the lowest found in the literature. This verifies that the proposed approach effectively and considerably improves the poor stability of the P1 oscillation at f_0 up to an extent similar to the stability of the microwave reference at $f_m = f_0/N$, where N = 10 in this demonstration. A lower f_m for a fixed f_0 or a higher f_0 for a given f_m is feasible if a higher-order harmonic of the lower modulation sidebands emerges with a power adequate to stably lock the lower P1 oscillation sideband. This can be achieved, for example, by using a phase modulator of the same speed with a slower roll-off at high frequencies, or of a higher speed, such as 40 GHz. For the 10th harmonic shown in Fig. 2(d), a power of 43-dB weaker than the optical carrier is strong enough to achieve stability, suggesting an upper limit of the lowest required power for a harmonic to lock the lower P1 oscillation sideband under study.

Various P1 dynamical states similar to the one shown in Fig. 2(b) with different f_0 can be excited over a wide range of ξ_i and f_i [3,16], leading to a continuously tunable f_0 from a few up to tens or even hundreds of gigahertz through a simple all-optical adjustment [6,11,12,20]. By adopting different N, f_m, or their combinations of the modulation sideband injection locking approach, broadly tunable yet highly stable microwave generation with constant power can therefore be achieved using the P1

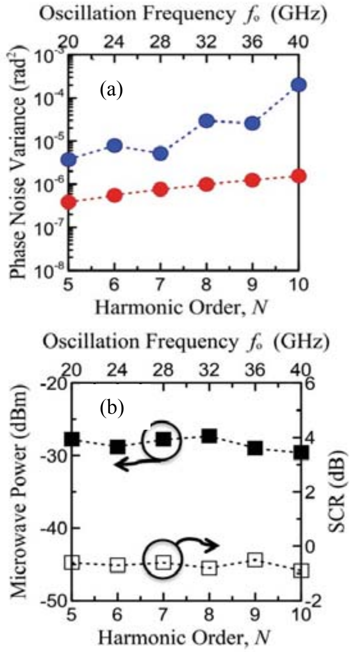

Fig. 4. (a) Phase noise variance in terms of N for generated microwave signals (blue symbols) and scaled microwave references (red symbols), and (b) microwave power and SCR in terms of N when f_m = 4 GHz. The corresponding values of f_0 are also marked in the upper x-axis of (b).

dynamics scheme. For example, at (ξ_i, f_i) = (0.95, 3 GHz), a P1 dynamical state of f_0 = 20 GHz is excited, the lower oscillation sideband of which can be locked to the 5th harmonic of the optical comb of f_m = 4 GHz shown in Fig. 2(d). A stabilized microwave generation at 20 GHz with a 1-Hz linewidth is therefore obtained. Figure 4(a) demonstrates similar noise performance between such stabilized microwave generation at $f_0 = 4N$ and the 4-GHz microwave reference, scaled by N, by comparing their phase noise variance estimated by integrating the single-sideband phase noise from the frequency offset of 100 Hz to 1 MHz. As shown in Fig. 4(b), each P1 dynamical state of different f_0 demonstrated in Fig. 4(a) is so chosen that the power ratio of the lower oscillation sideband to the optical carrier, referred to as the sideband-to-carrier ratio (SCR), is about the same, around −0.5 dB. This leads to a similar microwave power level over a broad frequency range of microwave generation, as also shown in Fig. 4(b), if the same optical power is received by the photodiode. The microwave power can be maximized for any received optical power if SCR approaches zero.

4. Conclusion

This study investigates P1 nonlinear dynamics of a semiconductor laser for photonic microwave generation with the help of modulation sideband injection locking to achieve microwave stabilization. Highly stable, down to a 3-dB linewidth of 1 Hz, and broadly tunable, up to 40 GHz, microwave generation with constant power is demonstrated using an electronic microwave reference at a small fraction, such as one-tens, of the P1 oscillation frequency. The highest demonstrable frequency is mainly restricted by the bandwidth of the devices used in this study, not by the proposed microwave generation and stabilization scheme. Stabilized microwave generation at a higher frequency, such as 100 GHz or more, is feasible.

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