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High-frequency microwave generation using period-one dynamics of two mutually coupled semiconductor lasers

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Abstract—This study investigates an all-optical microwave generation scheme using a semiconductor laser operating at period-one nonlinear dynamics. In particular, a novel all-optical stabilization approach based on highly asymmetric mutual injection is introduced to improve the phase quality of such generated microwaves. As a result, microwave generation at 55 GHz with a side-peak suppression ratio above 45 dB and a 3-dB linewidth below 3.6 kHz is generated. The stabilized microwave generation across the entire V-band (40-75 GHz) and W-band (75-110 GHz) can be achieved by tuning the frequency and power of optical injection using our proposed scheme.

1. Introduction

High-frequency microwave generation with high spectral purity plays an essential role in many contemporary applications, such as high-speed wireless communication [1], high-specificity sensing, and high-resolution radar [2]. Over the past decades, photonic microwave generation has attracted much research interest since they offer many attractive advantages compared to electronic counterparts, such as simplicity of high-frequency generation, ease of wide frequency tunability, and low transmission loss over long-distance propagation. Many photonic approaches have been investigated for microwave generation, including optical heterodyne between two lasers [3], optoelectronic oscillators [4, 5], external modulators [6, 7], and mode-locked lasers [8].

Recently, period-one (P1) nonlinear dynamics excited by a semiconductor laser subject to continuous-wave (CW) optical injection has been studied for microwave generation [9–16] due to the continuous and broad-band frequency tunability. Microwave generation from tens to hundreds of gigahertz can be obtained by simply controlling the power and frequency of optical injection without suffering from the limitation of electronic device bandwidth. However, due to the intrinsic spontaneous emission noise of semiconductor lasers, the 3-dB linewidth of the photo-detected microwaves is typically on the order of 0.1 to 10 MHz, limiting the scope of practical applications. A few all-optical stabilization techniques have been proposed to improve the phase quality of the generated microwaves [10–12, 14]. For example, Zhang *et al.* [10] have proposed a dual-loop optical feedback scheme for such microwave stabilization. Microwaves were produced at a frequency up to 45 GHz with a 3-dB linewidth below 50 kHz.

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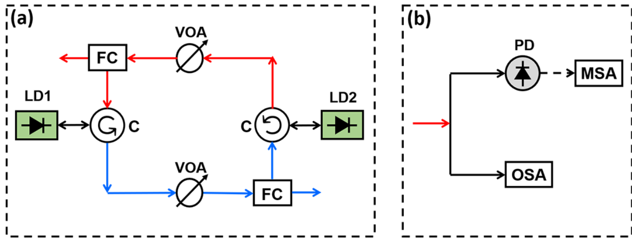

Fig. 1. Schematic diagram of (a) the mutually delay-coupled laser system and (b) the detection system. LD1, laser diode 1; LD2, laser diode 2; FC, fiber coupler; C, circulator; VOA, variable optical attenuator; PD, photodetector; OSA, optical spectrum analyzer; MSA, microwave spectrum analyzer.

This study investigates a novel photonic microwave generation scheme based on P1 dynamics of two mutually coupled semiconductor lasers under highly asymmetric coupling strength [17]. The proposed scheme applies P1 dynamics for high-frequency and stabilized microwave generation with a simplified configuration. As a result, a 55-GHz microwave with a 3-dB linewidth below 3 kHz and a side-peak suppression ratio (SPSR) above 45 dB, even better than the stabilized one in the dual-optical feedback scheme [10], is achieved.

2. Experimental Setup

A schematic configuration of two distributed feedback semiconductor lasers, LD1 and LD2 (Furukawa FRL15DCW5-A81), subject to mutually coupling, is illustrated in Fig. 1(a). The red or blue curve shows the coupling path from one laser to the other through an optical circulator in each injection route. Under a fixed bias current of 70 mA and a stabilized temperature of 18.9°C, the free-running LD2 works at 193.28 THz with an output power of 15.48 mW and a relaxation resonance frequency of about 10 GHz. Under the same bias current, the oscil-

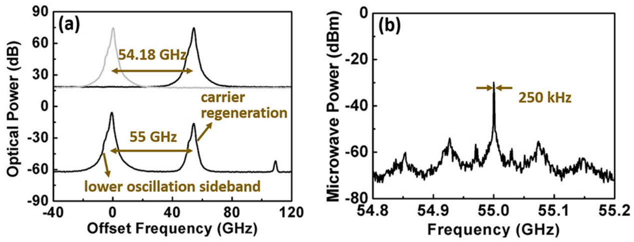

Fig. 2. (a) Optical spectra and (b) microwave spectrum of the P1 dynamical state at (ξ_{12}, f_i) = (0.264, 54.18 GHz) when ξ_{21} = 0. The axis in (a) is relative to 193.28 THz.

lation frequency of LD1 is detuned by f_i from 193.28 THz through controlling the temperature of LD1 to excite high-frequency P1 dynamics. Meanwhile, a variable optical attenuator (VOA) embedded into each coupling path is used to adjust the coupling strength from one laser to the other independently. Throughout the study, the coupling strength for the field injected into LD2, ξ_{12}, defined as the square root of the power ratio between the injected field from LD1 and the free-running LD2, is used. Similarly, the coupling strength for the field injected into LD1, ξ_{21}, is described as the square root of the power ratio between the injected field from LD2 and free-running LD1. Polarization maintaining fibers are used for all the optical devices in Fig. 1(a) to keep the polarization state of the system unchanged. Both red and blue routes shown in Fig. 1(a) have approximately the same fixed length, suggesting that the coupling delay time between the two lasers is equally 40.15 ns. For investigating the spectral features of LD2 output, the output signal of the red path from fiber coupler is sent to the detection system consisting of an optical spectrum analyzer (Advantest Q8384) and a microwave spectral analyzer (Keysight PXA N9030A) following a 100-GHz photodetector (Fraunhofer HHI) with a harmonic mixer (Keysight M1970W), as Fig. 1(b) presents.

3. Results and Discussion

For high-frequency microwave generation, the P1 dynamical state is first excited by sending CW optical injection presented in the upper trace of the black curve in Fig. 2(a) to LD2 at (ξ_{12}, f_i) = (0.264, 54.18 GHz) when ξ_{21} = 0. For comparison, the output signal from free-running LD2 is also presented as the gray curve in Fig. 2(a). Note that the frequency axes of all the optical spectra shown here are relative to 193.28 THz. Due to the injection pulling effect [16], the regeneration of the optical input oscillates at an offset frequency of 54.18 GHz, as the lower trace in Fig. 2(a) demonstrates. In addition, two oscillation sidebands sharply emerge, which are separated from the regeneration by an oscillation frequency of f_0 = 55 GHz. The lower oscillation sideband is much stronger in intensity than the upper one because of the cavity resonance red-shifted effect [16]. After photodetection, the beating between the

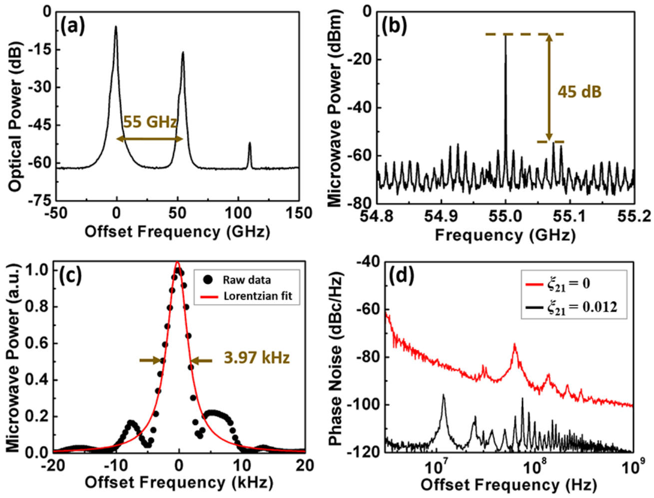

Fig. 3. (a) Optical spectrum and (b)(c) microwave spectra at (ξ_{12}, f_i) = (0.264, 54.18 GHz) when ξ_{21} = 0.012, and (d) phase noise estimation of the generated microwaves. The axis in (a) is relative to 193.28 THz, and the axes in (c) and (d) are relative to 55 GHz.

spectral components, mainly by the regeneration and the lower oscillation sideband, generates a microwave signal jittering around 55 GHz, as presented in Fig. 2(b). The corresponding 3-dB microwave linewidth of about 250 kHz is estimated by fitting the central peak of Fig. 2(b) with the Lorentzian curve. The poor quality of the generated microwave is caused by the poor phase correlation between the regeneration and the lower oscillation sideband.

A small fraction of optical injection from LD2 to LD1 is introduced to stabilize the phase fluctuation of the generated microwave. Figure 3(a) shows the corresponding optical spectrum at the same (ξ_{12}, f_i) = (0.264, 54.18 GHz) when ξ_{21} = 0.012. Since the injection power from LD2 to LD1 is about two orders of magnitude smaller than that from LD1 to LD2, the optical spectrum is closely similar to the one shown in the lower trace of Fig. 2(a). As Fig. 3(b) shows, photodetection of such an optical spectrum gives rise to a microwave at 55 GHz with side peaks separated by multiples of 12.45 MHz, which equals the reciprocal of the round-trip delay time in the proposed mutual injection system. A SPSR of 45 dB, even better than the dual-loop optical feedback system [10], is achieved. The 3-dB linewidth of about 3.97 kHz is estimated by the Lorentzian curve fitting of the central peak shown in Fig. 3(b), as Fig. 3(c) presents. Note that the frequency axes of Figs. 3(c) and 3(d) presented here are relative to 55 GHz. Considering the resolution bandwidth of the microwave spectral analyzer used in this study is limited by 3.6 kHz, it can be regarded that the 3-dB linewidth of the stabilized microwave is below 3.6 kHz, which reduces by more than 70 times compared with Fig. 2(b). The stability and spectral purity of the generated microwave shown in Fig. 3(b) are analyzed by measuring the single-sideband (SSB) phase noise, which is defined as the power ratio between the frequency component at a non-zero offset frequency to the central peak, as the black curve of Fig. 3(d) illustrates. Compared with the P1 oscillation without stabilization $\xi_{21} = 0$ (red curve), the phase noise is well suppressed when $\xi_{21} = 0.012$ (black curve). Moreover, the phase noise variance, which is estimated by integrating the SSB phase noise from the offset frequency of 3 to 100 MHz in Fig. 3(d), is significantly improved by more than 758 times after stabilization.

4. Conclusion

This study proposes a novel all-optical photonic microwave generation and stabilization approach based on the P1 dynamics of two mutually coupled semiconductor lasers operating at highly asymmetric coupling strength. As a result, microwave generation at 55 GHz with a 3-dB linewidth below 3.6 kHz and a SPSR above 45 dB is generated. The stabilized microwave generation across the entire V-band (40-75 GHz) and W-band (75-110 GHz) can be achieved by controlling the frequency and power of optical injection using such a simplified configuration.

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