All-optical sub-THz signal generation using two mutually coupled semiconductor lasers

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Abstract: This study proposes a novel all-optical approach for sub-THz signal generation. Sub-THz signals ranging from 100 to 300 GHz with a 3-dB linewidth below 2 kHz and a SPSR of about 47 dB are generated.

1. Introduction

High-frequency microwaves with a narrow linewidth and low phase noise are essential for a wide variety of technological applications, such as precise foreign object debris detection, high-resolution adaptive cruise control radars, next-generation (6G) mobile communication, and high-capacity radio-over-fiber networks, due to their wide transmission bandwidth and high directivity. To pursue a higher resolution or faster transmission rate, there has been growing research interest in microwave generation over the sub-THz range as the Federal Communications Commission in the United States has released the spectrum from 95 to 330 GHz for experimental use for over-the-air investigation [1]. One key figure-of-merit for sub-THz signal generation is the phase noise. For instance, the minimum phase noise requirement for wireless communication carrying 64-QAM data is −96 dBc/Hz at 1-MHz frequency offset in WiGig/IEEE802.11ad [2]. Therefore, how to develop low phase-noise sources for sub-THz signal generation is a significantly challenging issue.

In recent years, photonic microwave generation techniques have attracted much attention because they offer attractive benefits compared to their electronic counterparts, such as simplicity of high-frequency microwave generation, ease of broadband frequency tunability, and low propagation loss over long-distance fiber transmission. High-frequency microwaves can be generated by using, for example, optoelectronic oscillators [2], external modulators [3], and optical heterodyne between two lasers. However, microwaves generated by the first technique suffer from significant phase-noise degradation due to the frequency multiplication process. Even though such a multiplication penalty is avoided in the second technique, specific electronic devices, such as microwave amplifiers and filters, are required. Thus, the generation of sub-THz signals becomes difficult and/or expensive to implement using the second technique, which is probably why microwave generation of only up to 94.5 GHz has been reported up to now [2]. The third technique generates sub-THz signals without suffering from the electronic bandwidth limitation. However, the poor coherence between two lasers deteriorates the spectral purity, restricting the scope of practical applications.

This study proposes an all-optical approach for sub-THz signal generation using period-one (P1) nonlinear dynamics excited in two mutually coupled semiconductor lasers with highly asymmetric coupling powers between the two lasers [4]. Sub-THz signals ranging from 100 to 300 GHz with a linewidth below 2 kHz and a side-peak suppression ratio (SPSR) of about 47 dB are generated all-optically. The phase noise at the 1-MHz frequency offset is −110 dBc/Hz, which meets the criterion set by WiGig/IEEE802.11ad [2]. The highest experimentally demonstrable frequency is mainly restricted by the bandwidth of the photodetector used in this study, not by the proposed scheme. Signal generation at a frequency higher than 300 GHz with similar high spectral purity is expected to be feasible.

2. Experimental Setup

An experimental configuration of the proposed sub-THz signal generation system consisting of two distributed feedback semiconductor lasers, LD1 and LD2 (Furukawa FRL15DCW5-A81), is illustrated in Fig. 1(a). The red or blue route shows that the two lasers are mutually coupled through optical injection from one to the other via an optical circulator. Under a fixed bias current of 70 mA and a stabilized temperature of 18.9°C, the free-running LD2 oscillates at 193.28 THz with an output power of 15.48 mW and a relaxation resonance frequency of approximately 10 GHz. For LD1, the bias current is fixed at 70 mA, and the output power is approximately 13.43 mW. The detuning frequency, f_i, defined as the frequency difference between the free-running oscillation frequency of LD1 and 193.28 THz, is adjusted by tuning the temperature of LD1. A variable optical attenuator

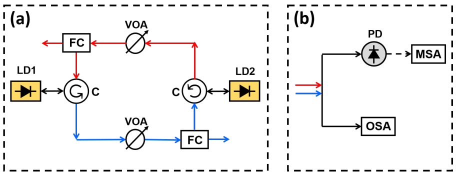

Fig. 1. Schematic diagram of (a) the mutual injection system and (b) the detection system. LD1, laser diode 1; LD2, laser diode 2; FC, fiber coupler; C, circulator; VOA, variable optical attenuator; PD, photodetector; OSA, optical spectrum analyzer; MSA, microwave spectrum analyzer.

in each route is used to independently adjust the injection power from one laser to the other. Here, the coupling strength, ξ_{12} (ξ_{21}), is defined as the square root of the power ratio between the optical injection from LD1 (LD2) to the free-running LD2 (LD1). Polarization-maintaining fibers are used for all the optical devices in Fig. 1(a) to keep the polarization state of the system unchanged. The red and blue routes have approximately the same fixed length, and a coupling delay time between the two lasers is estimated to be 40.15 ns. The output of either LD1 or LD2 is sent to a detection system consisting of an optical spectrum analyzer and a microwave spectrum analyzer following a 100-GHz photodetector to investigate spectral features, as Fig. 1(b) shows.

3. Results and Discussion

For a sub-THz signal generation, a P1 dynamical state is first excited by sending a continuous-wave optical input from LD1, shown as the black curve of Fig. 2(a), to LD2 at (ξ_{12}, f_i) = (0.268, 100.4 GHz) when ξ_{21} = 0. For comparison, the free-running LD2 output is also presented as the gray curve of Fig. 2(a). Note that the frequency axes of all optical spectra are relative to 193.28 THz in this study. As observed in Fig. 2(b), the optical input regenerates itself at an offset frequency of 100.4 GHz due to the injection pulling effect [4]. In addition, two oscillation sidebands appear, which are equally separated from the regeneration by an oscillation frequency of f_0 = 101.2 GHz, with the lower one much stronger than the upper one in intensity because of the red-shifting effect [4]. The beating between the spectral components in Fig. 2(b), mainly the regeneration and the lower oscillation sideband, gives rise to a sub-THz signal with poor spectral purity that jitters around 101.2 GHz, as Fig. 2(c) presents. By fitting the spectral profile of the sub-THz signal in Fig. 2(c) with a Lorentzian curve, a 3-dB linewidth of about 170.4 kHz is estimated. The poor spectral purity of the generated signal originates from the poor phase correlation between LD1 and LD2.

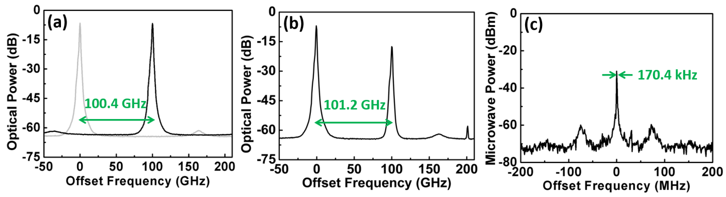

Fig. 2. (a)(b) Optical spectra and (c) microwave spectrum of the P1 dynamics at (ξ_{12}, f_i) = (0.268, 100.4 GHz) when ξ_{21} = 0. The axes in (a) and (b) are relative to 193.28 THz, and the axis in (c) is relative to 101.2 GHz.

To stabilize the sub-THz signal, a small fraction of the LD2 output is sent back to LD1 at the same (ξ_{12}, f_i) = (0.268, 100.4 GHz) when ξ_{21} = 0.015, and the corresponding optical spectrum is presented in Fig. 3(a). Considering the power of optical injection from LD2 to LD1 is about two orders of magnitude smaller than that from LD1 to LD2, the spectral features of Fig. 3(a) are closely similar to those presented in Fig. 2(b). As Fig. 3(b) shows, photodetection of such a LD2 output generates a sub-THz signal at 101.2 GHz with side peaks equally separated by integral multiples of 12.45 MHz, which equals the reciprocal of the round-trip delay time in the proposed mutual injection system. A SPSR of about 47 dB, defined as the power ratio between the sub-THz signal and the strongest side peak around it, is achieved. The 3-dB linewidth of less than 2 kHz is estimated by fitting the sub-THz signal in Fig. 3(b) with a Lorentzian curve. Compared with the sub-THz signal before stabilization in Fig. 2(c), the linewidth is narrowed by more than 85 times when ξ_{21} = 0.015. The phase quality of the generated sub-THz signal in Fig. 3(b) is analyzed by estimating the single-sideband (SSB) phase noise, defined as the power ratio of a frequency component at a non-zero offset frequency to that at the zero offset frequency, as illustrated in the black curve of Fig. 3(c). Compared with the sub-THz signal without stabilization when ξ_{21} = 0, the SSB phase noise is significantly improved by at least 10 dB over the frequency range under study when ξ_{21} = 0.015.

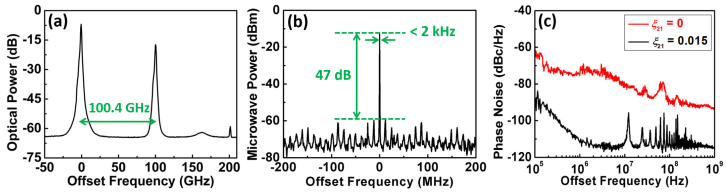

Fig. 3. (a) Optical spectrum and (b) microwave spectrum of the generated sub-THz signal at 101.2 GHz after stabilization when (ξ_{12}, f_i) = (0.268, 100.4 GHz) and ξ_{21} = 0.015. (c) SSB phase noise of the generated sub-THz signal before (red curve) and after (black curve) stabilization.

The frequency of the P1 oscillation, or equivalently the generated sub-THz signal, can be tuned from a few to hundreds of gigahertz by simply increasing ξ_{12} and/or f_i using an all-optical approach. As an example, Fig. 4(a) shows the optical spectrum of a P1 dynamical state at f_0 = 300 GHz with stabilization when (ξ_{12}, ξ_{21}, f_i) = (0.268, 0.015, 299 GHz). High spectral purity for such a tunable sub-THz signal can still be achieved by taking advantage of the same asymmetric mutual coupling technique demonstrated above. Limited by the bandwidth of the photodetector used in this study (i.e., 100 GHz), however, the corresponding microwave spectrum for the generated sub-THz signal at 300 GHz cannot be obtained experimentally. Nevertheless, by using the well-known Lang-Kobayashi laser rate equations, which have been demonstrated to numerically reproduce all experimentally observed phenomena in the laser system not only qualitatively but also quantitatively [4], the corresponding microwave spectrum is numerically obtained and presented in Fig. 4(b). As observed, a SPSR of about 45 dB, similar to the one shown in Fig. 3(b), is achieved. A 3-dB linewidth of less than 2 kHz is estimated by fitting the sub-THz signal with a Lorentzian curve, as Fig. 4(c) shows. Note that the experimental results shown in Figs. 2 and 3 for the sub-THz signal at 101.2 GHz are similarly obtained through a numerical calculation using the same set of laser rate equations. This suggests that the generated sub-THz signal at 300-GHz with high spectral purity presented in Figs. 4(b) and 4(c) is realized experimentally.

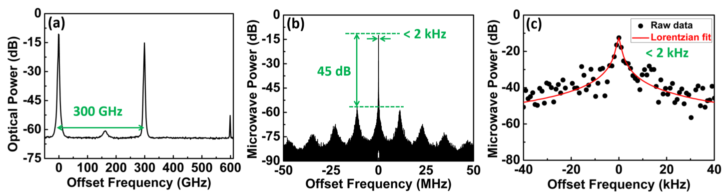

Fig. 4. (a) Optical spectrum (experimental measurement) and (b)(c) microwave spectra (numerical calculation) of the generated sub-THz signal at 300 GHz.

4. Conclusion

This study proposes a novel all-optical approach for sub-THz signal generation using P1 dynamics of two mutually coupled semiconductor lasers with highly asymmetric coupling powers between the two lasers. Sub-THz signals ranging from 100 to 300 GHz with a linewidth below 2 kHz and a SPSR of about 47 dB are generated all-optically. The highest experimentally demonstrable frequency is mainly limited by the bandwidth of the photodetector used in this study, not by the proposed approach. Signal generation at a frequency higher than 300 GHz with similar high spectral purity is expected to be feasible.

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