

# Microwave Frequency Division and Multiplication Using an Optically Injected Semiconductor Laser

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**Abstract**—Nonlinear dynamics of semiconductor lasers is applied for microwave frequency division. Optical injection is used to drive a slave laser into the dynamical period-two state. A fundamental microwave frequency and its subharmonic are generated in the power spectrum. Both frequencies will be simultaneously locked when an external microwave near either frequency is applied on the bias. In our experiment, precise microwave frequency division is demonstrated by modulating the laser at the fundamental of 18.56 GHz. A locked subharmonic at 9.28 GHz with a low phase variance of  $0.007 \text{ rad}^2$  is obtained from a 10-dBm input. A large locking range of 0.61 GHz is measured under a 4-dBm modulation. Similarly, precise frequency multiplication is demonstrated by modulating at 9.65 GHz. At an input power of  $-5 \text{ dBm}$ , a multiplied signal at 19.30 GHz is obtained with a phase variance of  $0.027 \text{ rad}^2$  and a locking range of 0.22 GHz.

**Index Terms**—Frequency conversion, injection-locked oscillators, microwave, nonlinear dynamics, optical injection, semiconductor lasers.

## I. INTRODUCTION

MICROWAVE frequency division is an important element in communication systems. In the optical time division multiplexing (OTDM) system, the clock at the aggregated data rate must be divided in order to demultiplex an individual channel. Photonic devices have been widely studied for such application. In one approach, an optical pulse train is sent into a terahertz optical asymmetric demultiplexer (TOAD), which is an optical loop mirror based on a semiconductor optical amplifier (SOA) [1]. The output is amplified and feedback after a delay to control the switching of the loop mirror. Due to the slow nonlinearity of the SOA, an output pulse train at half the original repetition rate is obtained. All-optical clock division from 20 to 10 GHz has been demonstrated [2], among some of its variants [3], [4]. Despite the advantage of being integrable into a chip, the speed of this approach is limited by the lifetime of the SOA. In another approach, one can use an optoelectronic oscillator (OEO), which is essentially a microwave oscillator with its energy stored as an optical wave inside a long fiber [5]. An OEO can generate high-quality microwave oscillation and can be injection locked to an externally applied modulation. When the free-running OEO frequency is close to the subharmonic of the external modulation, it can be locked to the subharmonic frequency. Clock division from 160 GHz to 40 GHz has been demonstrated [6], together with some similar

experiments [7], [8]. Injection locking into the subharmonic of an external frequency has also been investigated in devices such as a passively modelocked external-cavity laser diode [9], a passively modelocked fiber ring laser [10] and a twin-section self-pulsating laser diode [11].

Direct generation of subharmonic frequency can also be realized by harnessing the nonlinear dynamics of semiconductor lasers. One simple approach uses semiconductor lasers under strong microwave current modulation. When the modulation is strong enough to invoke period-doubling bifurcation, the subharmonic frequency at half of the modulation frequency is generated [12], [13]. The process can be controlled optically [14], [15] and the modulation can be done through optical injection [16], [17]. All-optical clock division has been demonstrated at 19.6 GHz [18]. However, a deep modulation is often necessary, driving the laser into the gain-switching mode with a broad optical spectrum.

In this work, we report on an alternative scheme for frequency division and multiplication by the semiconductor laser nonlinear dynamics. An optical injection system is investigated, where a slave laser is subject to a continuous-wave (CW) optical injection from a master laser. As the injection strength increases, the slave laser is first destabilized to oscillate at a fundamental microwave frequency. It then undergoes period-doubling bifurcation to generate the subharmonic frequency [19], [20]. The frequencies can be simultaneously injection locked to a weak external current modulation, similar to the pioneering work by Simpson and Doft [21]. When the modulation matches the fundamental frequency, the locked subharmonic becomes the frequency-divided signal. On the other hand, when the modulation matches the subharmonic frequency, the locked fundamental becomes the frequency-multiplied signal [22]. While the optical injection is responsible for generating the microwave frequencies, the weak current modulation is only responsible for injection-locking the microwave.

Following this introduction, the experimental setup is described in Section II. The experimental results for frequency division and multiplication are presented in Section III and Section IV, respectively, followed by the discussions in Section V and the conclusion in Section VI.

## II. EXPERIMENTAL SETUP

The schematics for the experiment on the optical injection system is shown in Fig. 1. The lasers used are  $1.3\text{-}\mu\text{m}$  single-mode distributed feedback (DFB) semiconductor lasers (Bookham Technology LC131). The master laser (ML) is biased at 111.6 mA, which is 7.44 times the threshold, and is temperature stabilized at  $15.40 \text{ }^\circ\text{C}$ . The slave laser (SL) is

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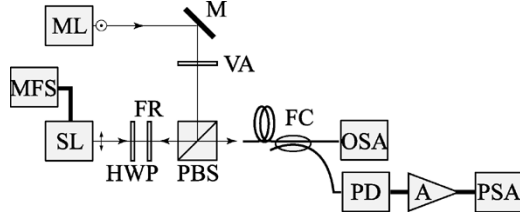


Fig. 1. Schematics of the experimental setup. ML: master laser; SL: slave laser; M: mirror; VA: variable attenuator; PBS: polarizing beam splitter; FR: Faraday rotator; HWP: half-wave plate; FC: fiber coupler; OSA: optical spectrum analyzer; PD: photodiode; A: amplifier; PSA: power spectrum analyzer; and MFS: microwave frequency synthesizer.

biased at 40.0 mA, which is 2.22 times the threshold, and is temperature stabilized at 18.00 °C. It emits an optical power of about 4.5 mW and has a relaxation resonance frequency at around 10 GHz. The combination of the polarizing beam splitter (PBS), the Faraday rotator (FR) and the half-wave plate (HWP) acts as an optical circulator by manipulating the polarizations. As a result, light is injected from the ML to the SL, while the output of the SL is transmitted through the PBS into an optical fiber. It is then split by a 3-dB fiber coupler (FC). The optical spectrum of the electric field is monitored by an optical spectrum analyzer (OSA) (Newport SR-260-C). The power spectrum of the intensity is monitored by a power spectrum analyzer (PSA) (HP E4407B) after detection by a 35-GHz photodiode (PD) (Discovery Semiconductors DSC 20S-3-FC) and amplified by a 26.5-GHz 20-dB amplifier (A) (HP 83 006A). A microwave frequency synthesizer (MFS) (HP 83 620A) can be used to apply a current modulation of power  $P_m$  and frequency  $f_m$  onto the SL.

The nonlinear dynamics of the SL is first invoked by the optical injection alone, without the current modulation. The dynamics depends on both the injection detuning and strength [19]. The injection detuning, defined as the ML's frequency offset from the SL's free-running frequency, is fixed at 13.91 GHz under our operating conditions. The injection strength  $\xi_i$ , defined as a normalized field injection rate [19], is varied by adjusting the variable attenuator (VA). The value of  $\xi_i$  is varied from 0 to 0.1, which corresponds to an injection power from 0 to 9.89 mW incident on the facet of the SL. Fig. 2 shows the optical and power spectra of the output of the SL at different values of  $\xi_i$ . In Fig. 2(a),  $\xi_i$  is 0; the SL is oscillating at its free-running frequency [Fig. 2(a-i)]. No modulation is observed in the power spectrum [Fig. 2(a-ii)]. In Fig. 2(b),  $\xi_i$  is increased to 0.036; the SL is locked to the ML injection frequency at an offset of 13.91 GHz with respect to the SL free-running frequency, together with a period-one (P1) oscillation at an offset of  $-2.92$  GHz [Fig. 2(b-i)]. The power spectrum in Fig. 2(b-ii) shows that the SL oscillates in the P1 state at a fundamental frequency  $f_0$  of 16.83 GHz, corresponding to the beating of the two optical frequencies. When  $\xi_i$  is further increased to 0.058 [Fig. 2(c)],  $f_0$  increases to 18.56 GHz. A period-doubling bifurcation into a period-two (P2) state has occurred. The subharmonic frequency  $f_0/2 = 9.28$  GHz is generated, as seen in the power spectrum [Fig. 2(c-ii)]. It also appears on the optical spectrum (Fig. 2(c-i)) as peaks at  $-13.93$  GHz and  $4.63$  GHz around the main oscillation frequency of  $-4.65$  GHz. In Fig. 2(d),  $\xi_i$  is

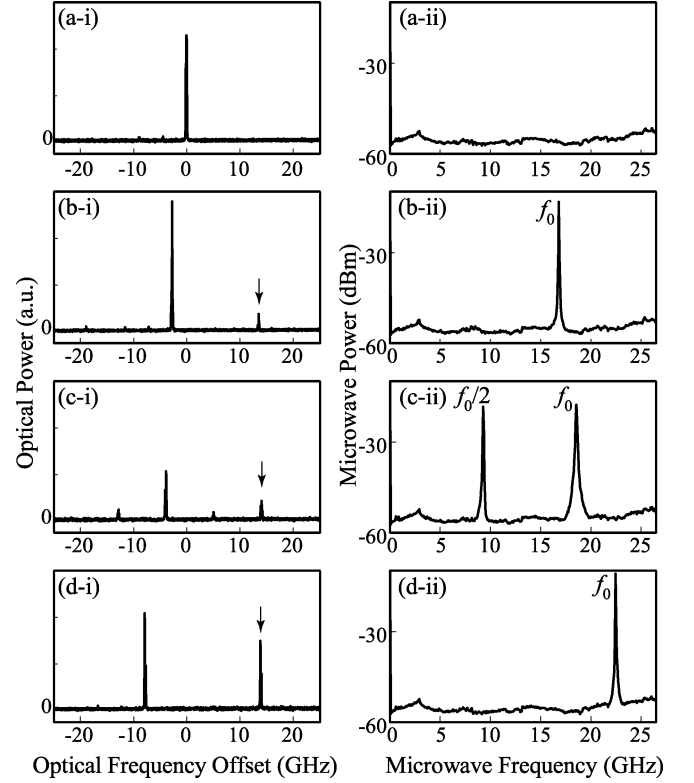


Fig. 2. Output of the SL under optical injection only. (i) Optical spectrum offset to the free-running frequency of the SL, and (ii) power spectrum. The data for different  $\xi_i$  are plotted: (a) 0; (b) 0.036; (c) 0.058; and (d) 0.100. The arrows indicate the injection frequency.

increased to 0.1; the SL returns to a P1 state. While  $f_0$  is increased to 22.46 GHz,  $f_0/2$  disappears from the spectrum.

This paper focuses on applying the P2 state for frequency division and multiplication. The existence of the state depends on the dynamical and operational parameters in a complicated manner [23], but the P2 frequencies are usually on the order of the relaxation resonance frequency. A faster SL can be used if a higher operational frequency is desired. In the current setup, the state exists when  $\xi_i = 0.054$  to  $0.065$ , which gives  $f_0 = 17.49$  to  $19.61$  GHz. However,  $\xi_i$  will be fixed at 0.058 [as in Fig. 2(c)] in the following discussions, unless otherwise specified.

### III. FREQUENCY DIVISION

The linewidths of the microwave frequencies generated by the nonlinear dynamics are rather broad due to noise. By applying an external microwave modulation, the linewidths can be substantially narrowed and locked [21]. In order to demonstrate the frequency division, modulation at  $f_m = f_0 = 18.56$  GHz is applied to the SL, while  $P_m$  is varied. Fig. 3 shows the power spectra zoomed into a 1.6-GHz span, centered at  $f_0/2$  and  $f_0$ , respectively. When  $P_m = -43$  dBm, the modulation is too weak to have any observable effect on the spectrum [Fig. 3(a)]. The fluctuating spectrum is essentially the same as that generated by optical injection alone. As  $P_m$  is increased to  $-18$  dBm, the external microwave starts to injection-lock the oscillation [Fig. 3(b)]. A narrow peak appears at  $f_m$  with a suppression of the sidebands [Fig. 3(b-ii)]. Since the subharmonic is related to the fundamental through the nonlinear dynamics, a narrow

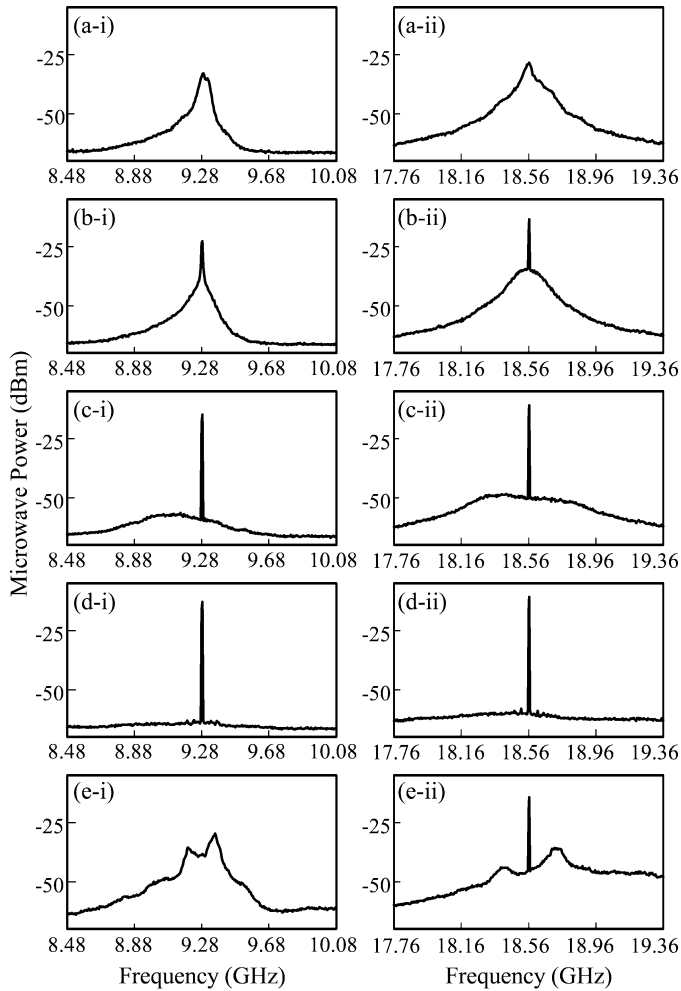


Fig. 3. Power spectrum under modulation at  $f_m = f_0$ , (i) centered at  $f_m/2 = 9.28$  GHz, and (ii) centered at  $f_m = 18.56$  GHz, while  $P_m$  is varied: (a)  $-43$  dBm; (b)  $-18$  dBm; (c)  $-4$  dBm; (d)  $10$  dBm; and (e)  $14$  dBm. (Span =  $1.6$  GHz. Resolution bandwidth =  $300$  kHz.)

peak also appears at  $f_m/2$  as shown in Fig. 3(b-i). The spectra are shown in Fig. 3(c) and (d) as  $P_m$  is increased to  $-4$  dBm and then to  $10$  dBm, respectively. The locking improves as  $P_m$  increases, thus achieving frequency division from  $18.56$  GHz to  $9.28$  GHz. However, there is an upper limit for  $P_m$ , above which the modulation will severely affect the SL's dynamics [12], [13]. This is shown in Fig. 3(e) at  $P_m = 14$  dBm, corresponding roughly to  $32$  mA of current modulation. The deep modulation is sufficient to drive the SL below the threshold, hence modifying its dynamics and grossly degrades the locking [Fig. 3(e)]. Therefore, it is important to choose an optimum  $P_m$  to suppress the frequency fluctuation while keeping the SL in a P2 state.

In order to quantify the locking behavior, the phase noise is analyzed. Assuming the noisy sidebands in Fig. 3 come mainly from small phase fluctuations, the phase noise variance is estimated by integrating from  $3$  MHz to  $1$  GHz the normalized single sidebands. The results are plotted against  $P_m$  in Fig. 4. The phase variances decrease for both the  $f_m$  and the  $f_m/2$  components as  $P_m$  increases, until the P2 state is disrupted at  $P_m > 10$  dBm. Thus, the highest quality frequency division occurs at  $P_m = 10$  dBm [Fig. 3(d)], where minimum phase

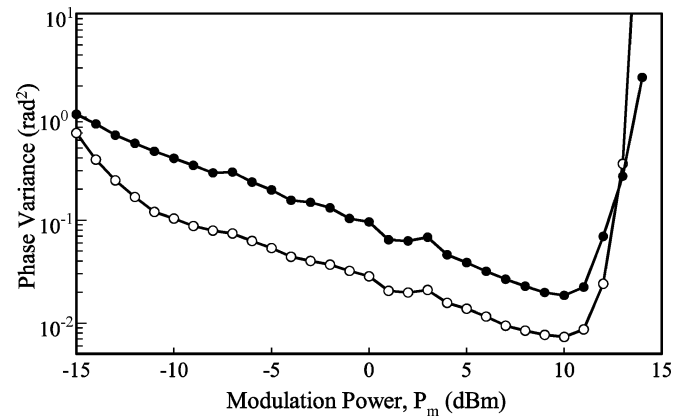


Fig. 4. Phase variance versus  $P_m$  when  $f_m = f_0$ . Closed symbol: fundamental at  $f_m$ . Open symbol: subharmonic at  $f_m/2$ .

variances of  $0.019$  rad<sup>2</sup> and  $0.007$  rad<sup>2</sup> are found for the  $f_m$  and the  $f_m/2$  components, respectively. When the P2 state is locked, the subharmonic always has a lower phase variance than the fundamental. This is also observed in systems involving period-doubling [16], [18] and is commonly found in electrical regenerative frequency dividers.

The microwave injection locking tolerates large frequency detuning. Fig. 5 shows the spectrum at  $P_m = 4$  dBm when  $f_m$  is tuned across  $f_0$ . In Fig. 5(a),  $f_m$  is detuned far away from  $f_0$  by  $0.78$  GHz. The fundamental oscillation is pulled away from  $f_0$  toward  $f_m$  [Fig. 5(a-ii)] and is about to be locked. As the detuning is reduced to  $0.54$  GHz, Fig. 5(b-ii) shows that the fundamental starts to be locked to  $f_m$ . However, the locking is not strong enough to enable locking at  $f_m/2$  [Fig. 5(b-i)]. When the detuning reduces to  $0.42$  GHz, narrow peaks are observed at both  $f_m$  and  $f_m/2$  in Fig. 5(c), suppressing the sidebands. The locking trend continues as the detuning decreases to  $0.18$  GHz [Fig. 5(d)]. Both  $f_m$  and  $f_m/2$  are best locked when the detuning becomes  $-0.12$  GHz [Fig. 5(e)], with the phase variances of  $0.027$  rad<sup>2</sup> and  $0.012$  rad<sup>2</sup>, respectively. The best locking is not found at the zero detuning because the original  $f_0$  is being shifted by the modulation. A similar shifting of the intrinsic resonance frequency in a modulated self-pulsating semiconductor laser has been reported [24]. Further reduction of the detuning degrades the locking, as shown in Fig. 5(f) at  $-0.20$  GHz. The SL eventually falls out of locking at a detuning of about  $-0.60$  GHz, resulting in merely mixing frequencies of  $f_0$ ,  $f_0/2$  and  $f_m$  [Fig. 5(g)].

The phase variance is shown in Fig. 6 against the detuning. Locking behavior is clearly observed as a sharp reduction of phase variance within a locking range. The fundamental has a larger locking range than the subharmonic because it is directly under modulation. However, a locked subharmonic is necessary for frequency division purposes. If we define the locking range as the frequency detuning range where the phase variance is less than  $0.5$  rad<sup>2</sup>, then the subharmonic has a locking range of  $0.61$  GHz ( $-0.21$  to  $0.40$  GHz). This is consistent with the observations made in Fig. 5. The large locking range of our system is inherent from the absence of any microwave feedback loop, thus allowing a relatively broad oscillation spectrum that is sustained by the optical injection alone.

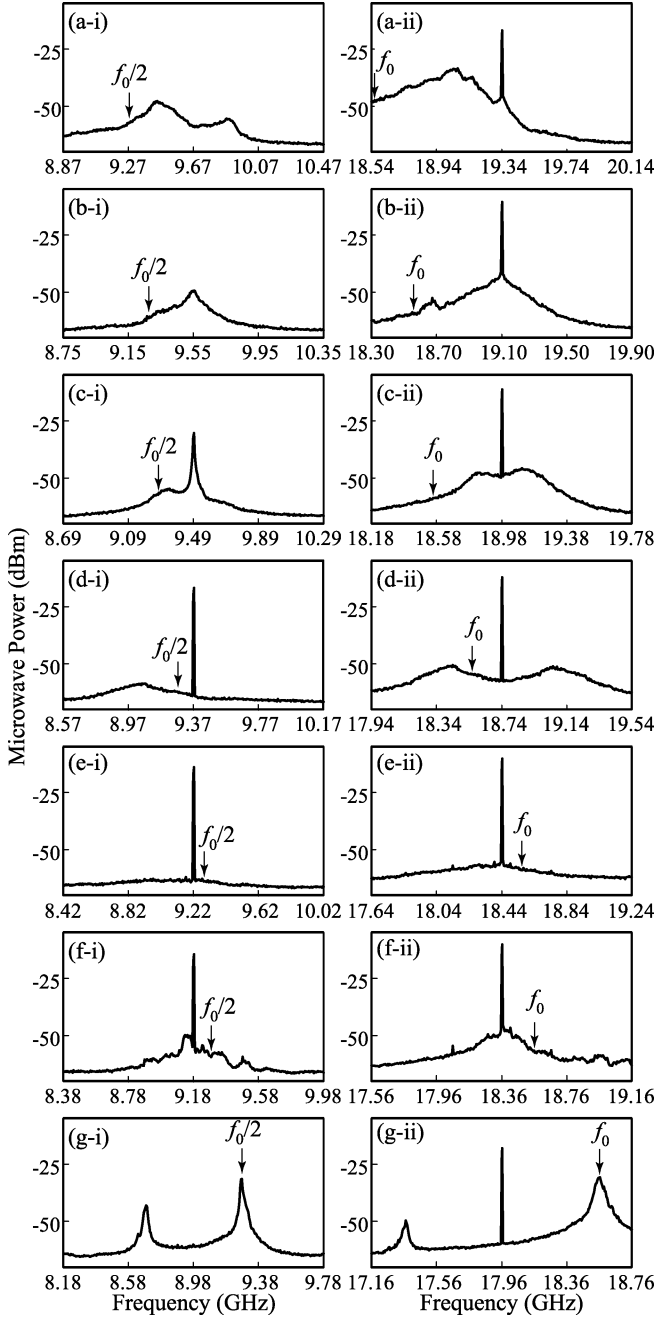


Fig. 5. Power spectrum under modulation at  $f_m$  near  $f_0$ , (i) centered at  $f_m/2$ , and (ii) centered at  $f_m$ , while  $P_m$  is fixed at 4 dBm. The detuning frequency,  $f_m - f_0$ , is varied: (a) 0.78 GHz; (b) 0.54 GHz; (c) 0.42 GHz; (d) 0.18 GHz; (e) -0.12 GHz; (f) -0.20 GHz; and (g) -0.60 GHz. (Span = 1.6 GHz. Resolution bandwidth = 300 kHz.)

In addition, the locking range increases with the strength of the modulation. As shown in Fig. 7, the locking range expands linearly with the modulation index, and it is asymmetric around the zero detuning. Theoretical work on the microwave injection locking of a dynamically oscillating semiconductor laser is relatively rare [25], but an analytical explanation of the locking is beyond the scope of this paper.

Nonetheless, we have experimentally demonstrated the frequency division by applying microwave injection locking to the fundamental of an optically injected semiconductor laser under

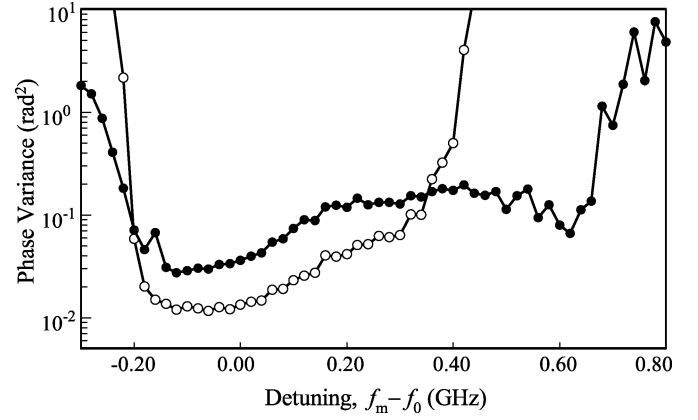


Fig. 6. Phase variance versus detuning,  $f_m - f_0$ , at  $P_m = 4$  dBm. Closed symbol: fundamental at  $f_m$ . Open symbol: subharmonic at  $f_m/2$ .

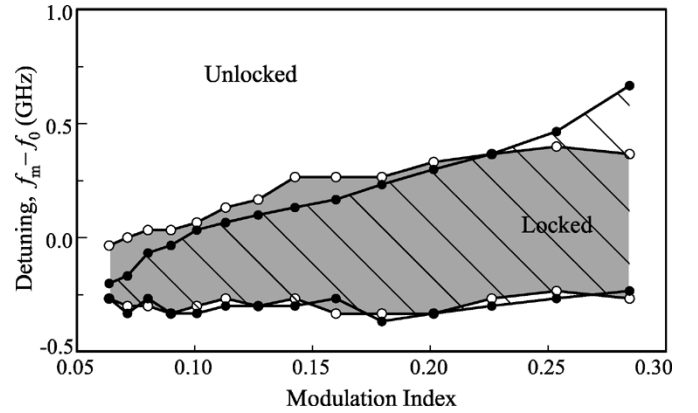


Fig. 7. Locking ranges when  $f_m$  is around  $f_0$ . Hatched region between closed symbols: fundamental at  $f_m$ . Shaded region between open symbols: subharmonic at  $f_m/2$ .

the P2 state. Both the locking quality and the locking range increase with the modulation power. In practice, extra tunability can be obtained by electrically changing the operating conditions of the lasers, such as the bias current level, thereby adjusting the fundamental frequency  $f_0$ .

#### IV. FREQUENCY MULTIPLICATION

Frequency multiplication is realized by applying a modulation around the subharmonic frequency of the P2 state, i.e.,  $f_m \approx f_0/2$ . When the modulation is strong enough, both the subharmonic and the fundamental will be locked to the modulation. Thus, the fundamental at  $2f_m$  can be regarded as a frequency-multiplied signal. The power spectrum evolves in a way similar to that presented in Figs. 3 and 5 when the modulation power and the detuning are respectively varied. At zero detuning, the change of the phase variance with respect to  $P_m$  is shown in Fig. 8. The locking quality is not as good as that in the frequency division experiment. It is because the SL exits the P2 state when  $P_m$  is above -21 dBm, before the microwave locking is established. However, when the detuning,  $f_m - f_0/2$ , is changed, a high-quality locking can be obtained. Fig. 9 shows the clear locking when the detuning falls within the 0.22-GHz (0.21 to 0.43 GHz) locking range at  $P_m = -5$  dBm. The best result is obtained for the 9.65 GHz to 19.30 GHz multiplication,

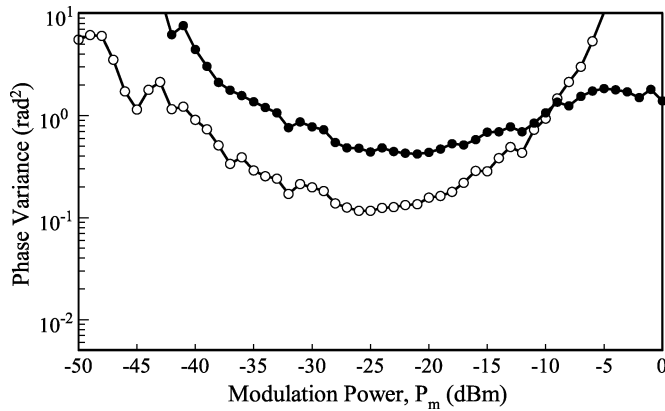


Fig. 8. Phase variance versus  $P_m$  when  $f_m = f_0/2$ . Closed symbol: fundamental at  $2f_m$ . Open symbol: subharmonic at  $f_m$ .

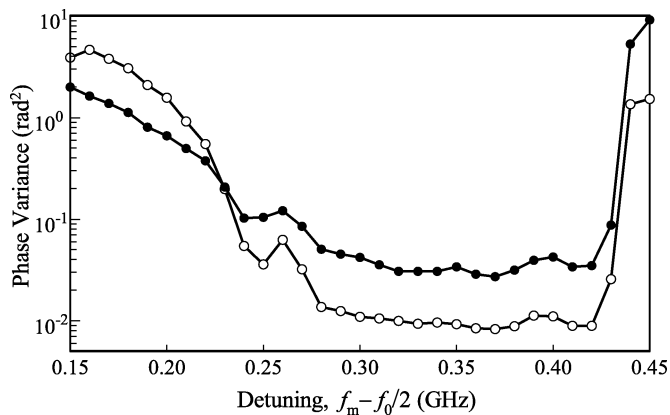


Fig. 9. Phase variance versus detuning,  $f_m - f_0/2$ , at  $P_m = -5$  dBm. Closed symbol: fundamental at  $2f_m$ . Open symbol: subharmonic at  $f_m$ .

with phase variances of  $0.008 \text{ rad}^2$  and  $0.027 \text{ rad}^2$  for the subharmonic and the fundamental, respectively. The locking range again increases with the modulation index, as shown in Fig. 10. The asymmetry around the zero detuning suggests a substantial modification of the P2 frequencies by the modulation. In some region outside the locking range, a few frequency-locked states are found. These states may also be utilized for frequency conversion of different rational ratios.

## V. DISCUSSIONS

In the previous experiments, the input microwave signal is carried into the SL through current modulation. In fact, the microwave input can also be carried optically as sidebands of the optical injection. All-optical microwave frequency division and multiplication can thus be achieved without the need for optical/electrical conversion. The approach is demonstrated on a P2 state of  $f_0 = 18.73$  GHz by adjusting  $\xi_i$ . The ML, instead of the SL, is current-modulated at  $f_m = 18.56$  GHz to generate microwave sidebands. The microwave signal, carried by the optical injection, enters into the SL and locks the P2 oscillation. The resulting spectrum is similar to that in Fig. 3 and the phase variances reduce with the modulation power as shown in Fig. 11. When the ML is under a 10-dBm modulation, corresponding to relative sidebands power of less than 1%, we obtain

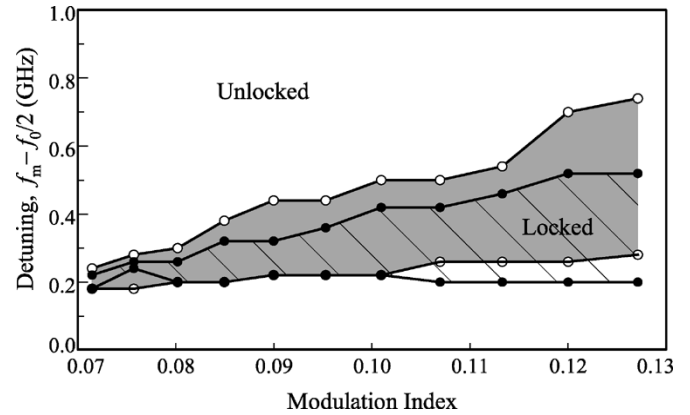


Fig. 10. Locking ranges when  $f_m$  is around  $f_0/2$ . Hatched region between closed symbols: fundamental at  $2f_m$ . Shaded region between open symbols: subharmonic at  $f_m$ .

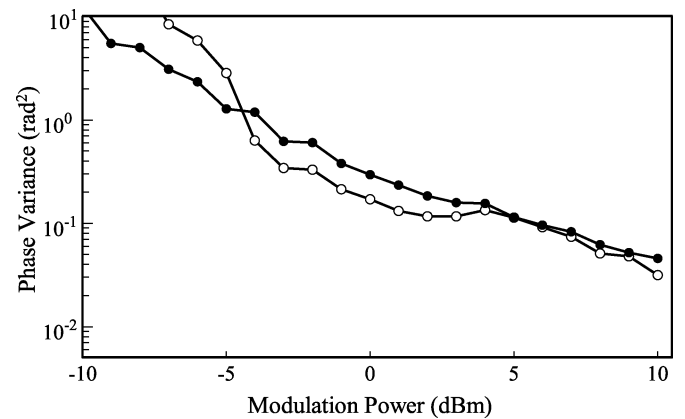


Fig. 11. Phase variance versus the modulation power on the ML. Closed symbol: fundamental at  $f_m$ . Open symbol: subharmonic at  $f_m/2$ .

a divided frequency at  $f_m/2 = 9.28$  GHz with a phase variance of  $0.032 \text{ rad}^2$ . Similar behavior is observed for frequency multiplication when the ML is modulated near  $f_0/2$ . If the optical injection is replaced by an optical data stream, the frequency component at the clock rate will be carried into the SL. The system is expected to be capable of all-optical clock division and multiplication.

## VI. CONCLUSION

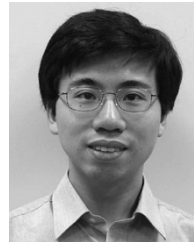
In conclusion, microwave frequency division and multiplication are demonstrated using semiconductor laser nonlinear dynamics. Optical injection to a slave laser generates a P2 state that consists of both a fundamental microwave frequency and its subharmonic. Microwave injection is then applied at either of the frequencies to lock both of them, hence, achieving frequency conversion.

Frequency division of 18.56 GHz to 9.28 GHz is demonstrated, with a phase variance of as low as  $0.007 \text{ rad}^2$  from a 10-dBm input. A large locking range of 0.61 GHz can be obtained from a 4-dBm input. Conversely, frequency multiplication of 9.65 GHz to 19.30 GHz is also demonstrated. Phase variance of  $0.027 \text{ rad}^2$  and locking range of 0.22 GHz at a low input power of  $-5$  dBm are achieved. With the current setup, the fundamental frequency can also be adjusted between 17.49 GHz

and 19.61 GHz. In the future, the locking quality can be improved using a phase-locked loop [22], the simple setup can be integrated, and the laser dynamical parameters can be tailored for applications at specific frequencies.

#### REFERENCES

- [1] J. P. Sokoloff, P. R. Prucnal, I. Glesk, and M. Kane, "A terahertz optical asymmetric demultiplexer (TOAD)," *IEEE Photon. Technol. Lett.*, vol. 5, no. 7, pp. 787–790, Jul. 1993.
- [2] A. E. Kelly, R. J. Manning, A. J. Poustie, and K. J. Blow, "All-optical clock division at 10 and 20 GHz in a semiconductor optical amplifier based nonlinear loop mirror," *Electron. Lett.*, vol. 34, pp. 1337–1339, Jun. 1998.
- [3] H. J. Lee and H. G. Kim, "Polarization-independent all-optical clock division using a semiconductor optical amplifier/grating filter switch," *IEEE Photon. Technol. Lett.*, vol. 11, no. 4, pp. 469–471, Apr. 1999.
- [4] R. J. Manning, I. D. Phillips, A. D. Ellis, A. E. Kelly, A. J. Poustie, and K. J. Blow, "All-optical clock division at 40 GHz using semiconductor optical amplifier based nonlinear interferometer," *Electron. Lett.*, vol. 35, pp. 827–829, May 1999.
- [5] X. S. Yao and G. Lutes, "A high-speed photonic clock and carrier recovery device," *IEEE Photon. Technol. Lett.*, vol. 8, no. 5, pp. 688–690, May 1996.
- [6] H. Tsuchida and M. Suzuki, "40-Gb/s optical clock recovery using an injection-locked optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 17, no. 1, pp. 211–213, Jan. 2005.
- [7] Z. X. Wang, T. Wang, C. Y. Lou, L. Huo, and Y. Z. Gao, "A novel approach for clock recovery without pattern effect from degraded signal," *Opt. Commun.*, vol. 219, pp. 301–306, Apr. 2003.
- [8] J. Lasri, P. Devgan, R. Y. Tang, and P. Kumar, "Ultralow timing jitter 40-Gb/s clock recovery using a self-starting optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 16, no. 1, pp. 263–265, Jan. 2004.
- [9] H. Yokoyama, Y. Hashimoto, H. Kurita, and I. Ogura, "Two-stage all-optical subharmonic clock recovery using modelocked semiconductor lasers," *Electron. Lett.*, vol. 36, pp. 1577–1578, Aug. 2000.
- [10] E. Tangdiongga, J. P. Turkiewicz, G. D. Khoe, and H. de Waardt, "Clock recovery by a fiber ring laser employing a linear optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 16, no. 2, pp. 611–613, Feb. 2004.
- [11] G. Farrell, P. Phelan, J. Hegarty, and J. A. Shields, "All-optical timing extraction with frequency division using a twin-section laser-diode," *IEEE Photon. Technol. Lett.*, vol. 5, no. 6, pp. 718–721, Jun. 1993.
- [12] Y. C. Chen, H. G. Winful, and J. M. Liu, "Subharmonic bifurcations and irregular pulsing behavior of modulated semiconductor lasers," *Appl. Phys. Lett.*, vol. 47, pp. 208–210, Aug. 1985.
- [13] H. F. Liu and W. F. Ngai, "Nonlinear dynamics of a directly modulated 1.55- $\mu\text{m}$  InGaAsP distributed feedback semiconductor laser," *IEEE J. Quantum Electron.*, vol. 29, no. 6, pp. 1668–1675, Jun. 1993.
- [14] Y. Matsui, S. Kutsuzawa, S. Arahira, Y. Ogawa, and A. Suzuki, "Bifurcation in 20-GHz gain-switched 1.55- $\mu\text{m}$  MQW lasers and its control by CW injection seeding," *IEEE J. Quantum Electron.*, vol. 34, no. 7, pp. 1213–1223, Jul. 1998.
- [15] K. K. Chow, C. Shu, and H. F. Liu, "Low-power optical control of period doubling in injection-seeded Fabry–Perot laser diode," *Electron. Lett.*, vol. 37, pp. 429–431, Mar. 2001.
- [16] Y. M. Yang, H. F. Liu, and Y. Matsui, "Scheme for all-optical clock division based on period doubling in semiconductor lasers," *Electron. Lett.*, vol. 36, pp. 1852–1854, Oct. 2000.
- [17] K. K. Chow, C. Shu, and H. F. Liu, "All-optical control of clock frequency division using injection-locked Fabry–Perot laser diode," *Electron. Lett.*, vol. 39, pp. 1136–1138, Jul. 2003.
- [18] K. K. Chow, C. Shu, Y. M. Yang, and H. F. Liu, "Optical control of period doubling in a gain-switched Fabry–Perot laser diode and its application in all-optical clock division," *Proc. IEE Optoelectron.*, vol. 150, pp. 239–245, Jun. 2003.
- [19] T. B. Simpson, J. M. Liu, K. F. Huang, and K. Tai, "Nonlinear dynamics induced by external optical injection in semiconductor lasers," *Quantum Semiclass. Opt.*, vol. 9, pp. 765–784, Oct. 1997.
- [20] S. Wieczorek, B. Krauskopf, and D. Lenstra, "A unifying view of bifurcations in a semiconductor laser subject to optical injection," *Opt. Commun.*, vol. 172, pp. 279–295, Dec. 1999.
- [21] T. B. Simpson and F. Doft, "Double-locked laser diode for microwave photonics applications," *IEEE Photon. Technol. Lett.*, vol. 11, no. 11, pp. 1476–1478, Nov. 1999.
- [22] T. B. Simpson, "Phase-locked microwave-frequency modulations in optically-injected laser diodes," *Opt. Commun.*, vol. 170, pp. 93–98, Oct. 1999.
- [23] S. K. Hwang and J. M. Liu, "Dynamical characteristics of an optically injected semiconductor laser," *Opt. Commun.*, vol. 183, pp. 195–205, Sep. 2000.
- [24] H. G. Winful, Y. C. Chen, and J. M. Liu, "Frequency locking, quasi-periodicity, and chaos in modulated self-pulsing semiconductor lasers," *Appl. Phys. Lett.*, vol. 48, pp. 616–618, Mar. 1986.
- [25] M. Nizette, T. Erneux, A. Gavrielides, and V. Kovanis, "Stability and bifurcations of periodically modulated, optically injected laser diodes," *Phys. Rev. E.*, vol. 63, p. 026 212, 2001.



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