High-Frequency Microwave Signal Generation in a Semiconductor Laser under Double Injection Locking

Yi-Chun Chen, Yu-Shan Juan, and Fan-Yi Lin

Institute of Photonics Technologies, Department of Electrical Engineering,
National Tsing Hua University,
Hsinchu 300, Taiwan

ABSTRACT

We numerically investigate high-frequency microwave signal generation utilizing a double injection locking technique. A slave laser (SL) is strongly injected by a master laser 1 (ML1) and a master laser 2 (ML2) optically. Stable locking states are observed when the SL is subject to optical injection by either the ML1 or the ML2 individually. By utilizing the hybrid scheme consists of double optical injections, the advantages of each individual dynamical system are added and enhanced. Comparison of the performances of the spectral width, power fluctuation, and frequency tunability between the signal generated in the double injection locking scheme and the similar period-one (P1) oscillation signal generated in a conventional single injection scheme is studied. A 3-fold linewidth reduction is achieved by utilizing the double injection locking scheme benefitted by the strong phase-locking and high coherence when operating at the stable injection locking state. Moreover, for the double injection locking scheme, a wide continuous tuning range of more than 100 GHz is obtained by adjusting the detuning frequency of the two master lasers. The performances of narrow linewidth, wide tuning range, and frequency continuity show the great advantages of the high-frequency microwave signal generated by the double injection locking technique.

Keywords: semiconductor lasers, nonlinear dynamics, optical injection

1. INTRODUCTION

High-frequency microwave signal generated using optical techniques have been extensively studied in the recent years.[1–3] Conventionally, using electric circuits to generate the microwave signal may require many stages of frequency multiplexing to achieve the desired frequency.[4] The disadvantages in the system cost, complexity, and short transmission distance limit the system performance. On the contrary, signals with higher frequencies can be generated using optical techniques while reducing the system cost and the transmission loss.[5]

In the optical techniques, the microwave signals are first generated in the optical domain using optical hybrid scheme.[6] The two optical waves with different wavelengths are then beat at a photodetector to produce an electric beat frequency corresponding to the frequency spacing of the two optical waves. To get a high-performance microwave signal, the phases of the two optical sources must be highly coherent. Numerous techniques have been proposed and demonstrated in the last few years to generate low-phase-noise microwave signal with the two optical wave being locked in phase. The phase coherence can be realized by using optical injection locking[7] and optical phase-locked loop.[6] In a conventional single cw injection scheme[8] and a P1 injection scheme,[9] the frequency of the microwave signal generated is corresponding to the oscillation frequency of the P1 state. The frequency of the generated signal typically can be tuned in a range from about 10 to 23 GHz by varying the injection strength and the detuning frequency between the master laser the the injected slave laser.

In this study, we investigate the microwave signal generation by nonlinear dynamics of a semiconductor laser[10, 11] based on a double injections locking technique. The phase-locking is realized by using optical injection locking without any external RF modulation.[12] The high-frequency microwave signals generated by the double injection locking technique show great performances of narrow linewidth, wide tuning range, small power fluctuation, and enhanced modulation response.

Further author information: (Send correspondence to Fan-Yi Lin)
Fan-Yi Lin: E-mail: fylin@ee.nthu.edu.tw, Telephone: +886-3-5162185

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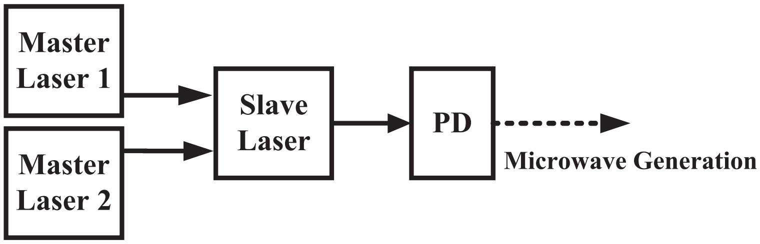

Figure 1. Schematic setup of the double injection-locked semiconductor laser for high-frequency microwave generation. PD: photodetector.

2. MODEL

Figure 1 shows the schematic setup of the double injection-locked semiconductor laser for high-frequency microwave generation. The slave laser (SL) is optically injected by a master laser 1 (ML1) and a master laser 2 (ML2). By controlling the injection strengths and the detuning frequency of the master laser 1 and 2, the slave laser can be simultaneously locked by the two master lasers. High-frequency microwave signals with frequencies corresponding to the detuning frequencies can be generated in the slave laser after detecting by the photodetector. The simulation is done by using the following coupled rate equations:[13]

$$\begin{aligned}
\frac{da}{dt} &= \frac{1}{2}\left[\frac{\gamma_c\gamma_n}{\gamma_s\tilde{J}}\tilde{n} - \gamma_p(2a+a^2)\right](1+a) + \xi_1\gamma_c\cos(\Omega_1 t+\phi) + \xi_2\gamma_c\cos(\Omega_2 t+\phi) + F_a \\
\frac{d\phi}{dt} &= -\frac{b}{2}\left[\frac{\gamma_c\gamma_n}{\gamma_s\tilde{J}}\tilde{n} - \gamma_p(2a+a^2)\right] - \frac{\xi_1\gamma_c}{1+a}\sin(\Omega_1 t+\phi) - \frac{\xi_2\gamma_c}{1+a}\sin(\Omega_2 t+\phi) + F_y \\
\frac{d\tilde{n}}{dt} &= -\gamma_s\tilde{n} - \gamma_n(1+a)^2\tilde{n} - \gamma_s\tilde{J}(2a+a^2) + \frac{\gamma_s\gamma_p}{\gamma_c}\tilde{J}(2a+a^2)(1+a)^2, \qquad (1)
\end{aligned}$$

where a is the normalized optical field, ϕ is the optical phase difference, and $\tilde{n}$ is the normalized carrier density. $\tilde{J}$ is the normalized dimensionless injection current parameter, γ_c is the cavity decay rate, γ_n is the differential carrier relaxation rate, γ_p is the nonlinear carrier relaxation rate, b is the linewidth enhancement factor, γ_s is the spontaneous carrier relaxation rate, and n is the effective refractive index. The dimensionless injection parameters ξ_1 and ξ_2 are the normalized strength of the injection field received by the slave laser from master laser 1 and master laser 2, respectively. The Ω_1 and Ω_2 are the frequency detuning from the ML1 and ML2 to the SL. The spontaneous emission noise is added to the amplitude and the phase with F_a and F_y, respectively. The laser parameters used here are $\tilde{J} = 1/3$, $\gamma_{\rm c} = 5.36\times10^{11}{\rm s}^{-1}$, $\gamma_{\rm n} = 5.96\times10^{9}{\rm s}^{-1}$, $\gamma_{\rm p} = 7.53\times10^{9}{\rm s}^{-1}$, $\gamma_{\rm s} = 19.1\times10^{9}{\rm s}^{-1}$, and $b = 3.2$. The relaxation resonance frequency of the lasers used in this simulation are $f_r = 10.25$ GHz. F_a and F_y are the normalized noise related to the spontaneous emission rate of the semiconductor laser. By varying the operational parameters, such as ξ_1, ξ_2, Ω_1, and Ω_2, we can get microwave signals with high-frequency, high stability, and continuous tunability.

3. RESULTS AND DISCUSSIONS

Figures 2(a) and (b) show the optical spectra of the SL when it is injected independently by the ML1 and the ML2, respectively. The detuning frequencies of the ML1 and ML2 relative to the SL are −50 and −20 GHz and the injection strengths of the ML1 and ML2 to the SL are 0.8 and 0.3, respectively. With the injection, the SL is injection-locked by either of the master lasers and oscillates at the frequencies of the master lasers. To generate high-frequency microwave signals, a double injection locking technique is used that the SL is injected simultaneously by the ML1 and the ML2. The optical and power spectra of the SL under the injections from both the ML1 and the ML2 seen in Figs. 2(a) and (b) are shown in Figs. 2(c) and (d), respectively. As can be seen, a microwave signal with a frequency of 30 GHz corresponding to the detuning frequency between the ML1 and ML2 is generated.

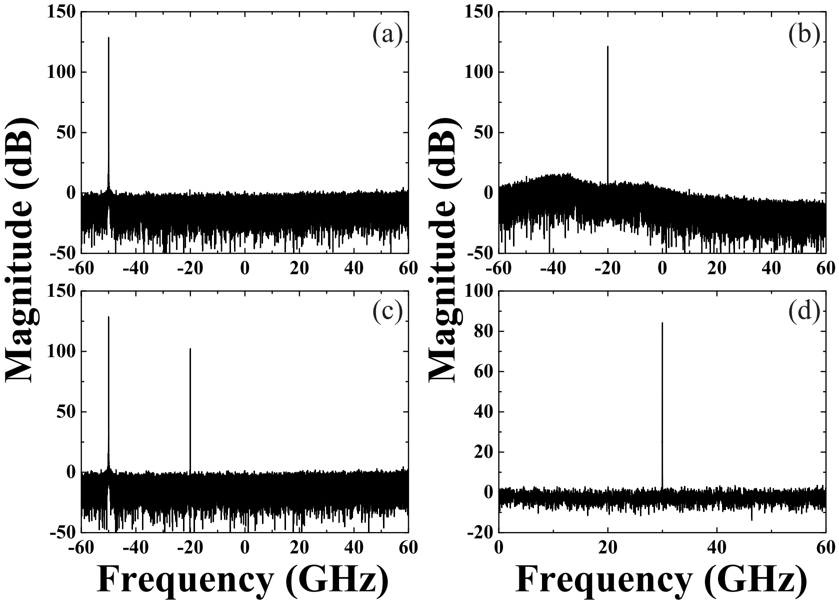

Figure 2. The optical spectra of the SL subject to optical injection from (a) the ML1 and (b) the ML2. The (a) optical and (b) power spectra of the SL subject to optical injections from both the ML1 and ML2. The detuning frequencies of the ML1 and ML2 relative to the SL are -50 and -20 GHz and the injection strengths of the ML1 and ML2 to the SL are 0.8 and 0.3, respectively.

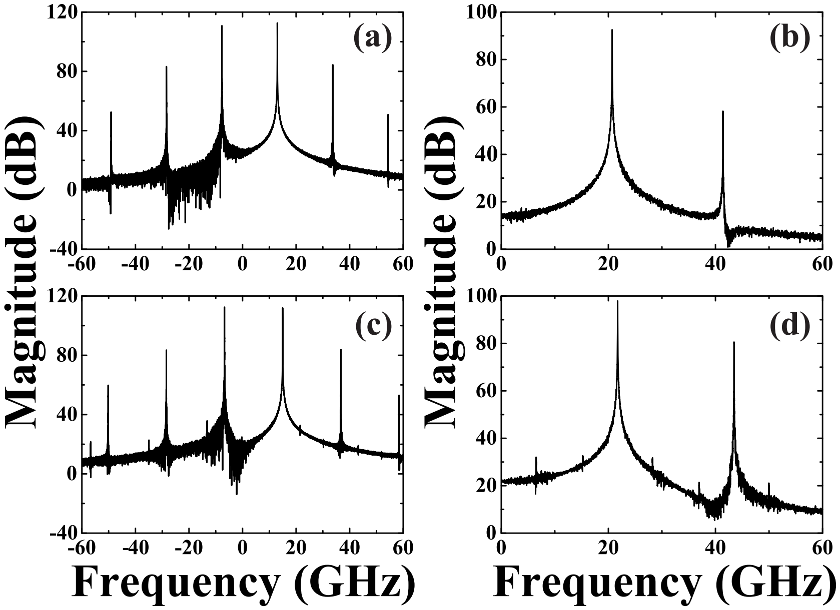

Figure 3. Optical and power spectra of the SL with the (a)-(b) single injection and (c)-(d) P1 injection schemes, respectively.

To compare with the microwave signals generated by the period-one (P1) oscillation of a single injection scheme, the optical and power spectra of the SL under a P1 state and the SL optically injected by a P1 state are shown in Figs. 3(a)-(d), respectively. Although similar high-frequency microwave signals can be generated, the linewidths of the generated signals are much broader than the signal generated by the double injection-locked system as can be seen in Fig. 2(d).

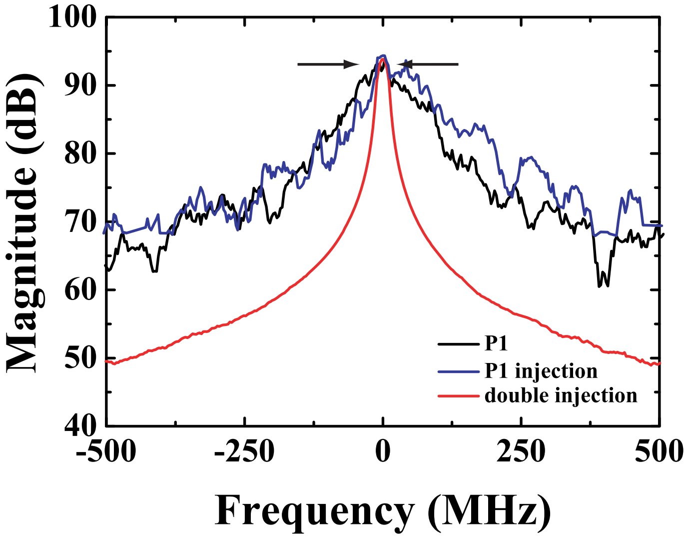

Figure 4. Linewidths of the microwave signals generated by the double injection-locked, single injection, and the P1 injection schemes.

Figure 4 shows the linewidths of the high-frequency signals generated by the double injection-locked, single injection, and the P1 injection schemes. 3-dB Linewidths of 66.4 MHz, 50.6 MHz, and 19.2 MHz are obtained for the single injection, the P1 injection, and the double injection-locked schemes, respectively. As the result, through double injection locking, a 3-fold reduction in the linewidth can be achieved in microwave signal generation compared to the conventional single injection and the P1 injection schemes.[15]

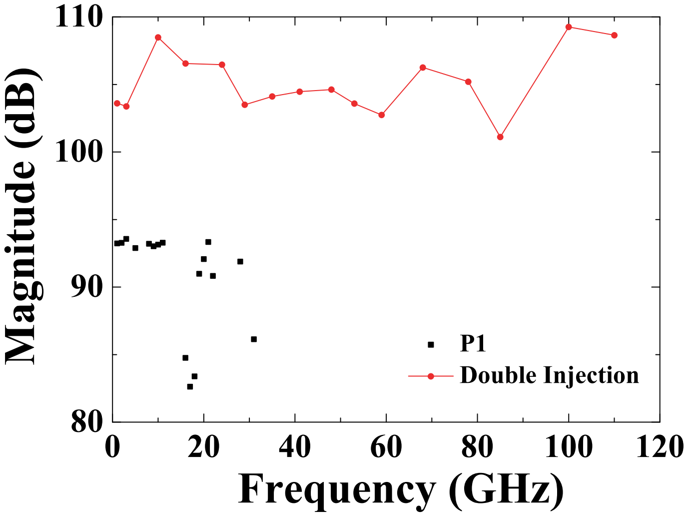

Figure 5. Tunability of the microwave signals generated by the P1 state (black square) and the double injection locking (red line)

Figure 5 shows the tunability of the microwave signals generated by the double injection-locked and the single injection schemes. For the single injection scheme, the frequency of the generated P1 state can only reach about 30 GHz. With stronger injection, the SL becomes stably locked. With larger detuning, the SL becomes unlocked. Moreover, the generation of the P1 state is not continuous and is interrupted by other dynamical states such as chaos. On the contrary, the frequency of the microwave signal generated by the double injection-locked scheme can be tuned continuously up to more than 100 GHz. The magnitudes of the signals vary less than ±5 dB.

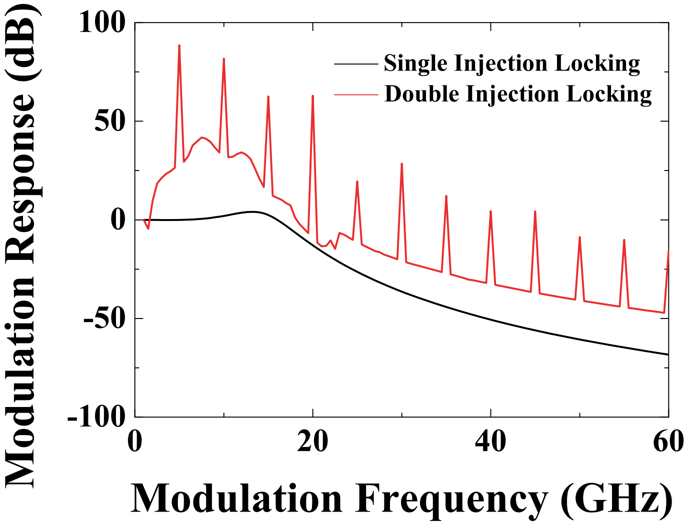

Figure 6. Modulation response of the double injection-locked and the single injection schemes.

Figure 6 shows the modulation response of the double injection-locked and the single injection schemes. As can be seen, with an injection strength of 0.2, the modulation bandwidth of the single injection scheme is enhanced to about 20 GHz compared with the 10.25 GHz relaxation oscillation frequency. With the same total injection strength from both the ML1 and the ML2, higher modulation response is obtained in the double injection-locked scheme as can be seen. About 20 dB gain is found in most part of the spectrum compared to the single injection scheme.

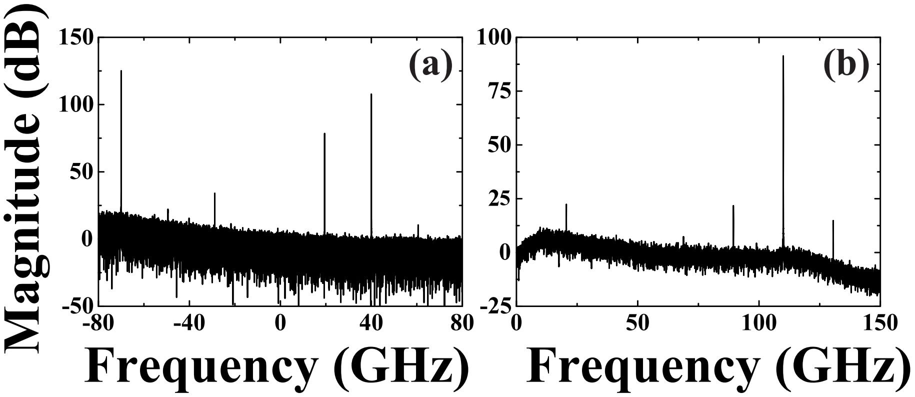

Figure 7. (Color online) Optical and power spectra of a 110 GHz high-frequency microwave signal generated with $\Omega_1 = 40$, $\Omega_2 =$ -70, $\xi_1 = 0.8$, and $\xi_2 = 0.85$.

With detuning frequencies of $\Omega_1 = 40$ and $\Omega_2 = -70$ GHz and injection strengths of $\xi_1 = 0.8$ and $\xi_2 = 0.85$, a microwave signal of 110 GHz is generated. The optical and power spectra of the generated signal are shown in Figs. 7(a) and (b), respectively. Although some side modes are seen in the power spectra, they have the magnitudes of more than 60 dB below the high-frequency signal generated.

4. CONCLUSIONS

In conclusion, we have numerically investigated the high-frequency microwave signal generation utilizing a double injection locking technique. By double injections, the microwave signal generated can be continuously tuned within a range of more than 100 GHz. Compared with the microwave signals generated by the single injection and the P1 injection schemes, a more than 3-fold reduction in the spectral linedwidth is achieved due to the strong phase-locking and high coherence. Less power fluctuation and continuous tuning in the whole frequency range is obtained. Moreover, enhancements of about 20 dB in the modulation response compared with the single injection scheme is also achieved. Experimental demonstration of generating a 120 GHz high-frequency microwave signal with the proposed double injection-locked scheme has been realized and will be reported separately.

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REFERENCES

1. X. Chen, Z. Deng, and J. Yao, "Photonic generation of microwave signal using a dual-wavelength single-longitudinal-node fiber ring laser," *IEEE Trans Lightwave Technol.* **2,** 804-809, 2006.
2. Y. S. Juan and F. Y. Lin, "Microwave-frequency-comb generation utilizing a semiconductor laser subject to optical pulse injection from an optoelectronic feedback laser," *Opt. Lett.* **34,** 1636-1638, 2009.
3. Y. S. Juan and F. Y. Lin, "Ultra broadband microwave frequency combs generated by an optical pulse-injected semiconductor laser,"Opt. Express **17**, 18596-18605, 2009.
4. Jianjun Yu, "Cost-Effective Optical Millimeter Technologies and Field Demonstrations for Very High Throughput Wireless-Over-Fiber Access Systems," *J. Lightwwave Technol.* **28**, no.16 2376-2397, 2010.
5. Y. S. Juan and F. Y. Lin, "Demonstration of ultra-wideband (UWB) over fiber based on optical pulse-injected semiconductor laser," *Opt. Express* **18**, no.9 9664-9670, 2010.
6. A. C. Bordonaalli, C. Walton, and A. J. Seeds, "High-performance phase locking of wide linewidth semiconductor lasers by combined use of optical injection locking and optical phase-lock loop," *J. Lightwwave Technol.* **17,** 328-342, 1999.
7. L. Goldberg, H. F. Taylor, J. F. Weller, and D. M. Bloom, "Microwave signal generation with injection locked laser diodes," *Electron. Lett.* **19,** 491-493, 1983.
8. S. C. Chan, S.K. Hwang, and J.M. Liu, "Period-one oscillation for photonic microwave transmission using an optically injected semiconductor laser," *Opt. Exp.* **15,** 14921-14935, 2007.
9. S. C. Chan and W. K. S. Tang, "Chaotic Dynamics of Laser Diodes with Strongly Modulated Optical Injection", *J. of Bifurcation and Chaos* **19,** 3417-3424, 2009.
10. F. Y. Lin and J. M. Liu, "Harmonic frequency locking in a semiconductor laser with delayed negative optoelectronic feedback," *Appl. Phys. Lett.* **81,** 3128-3120, 2002.
11. F. Y. Lin and J. M. Liu, "Nonlinear dynamical characteristics of an optically injected semiconductor laser subjectto optoelectronic feedback," *Opt. Commun.* **221**, 173-180, 2003.
12. J. J. O'Reilly, P. M. Lane, R. Heidemann, and R.Hofstetter, "Optical generation of very narrowlinewidth millimeterwave signals," *Electron. Lett.* **28,** 2309V2311, 1992.
13. F. Y. Lin, S. Y. Tu, C. C. Huang, and S. M. Chang, "Nonlinear dynamics of semiconductor lasers under repetitive optical pulse injection," *IEEE J. of Sel. Top. Quantum Electron.* **15**, issue 3 604-611, 2009.
14. F. Y. Lin and J. M. Liu, "Diverse waveform generation using semiconductor lasers for radar and microwave applications," *IEEE J. of Quantum Electron.*, **40,** 682-689, 2004.
15. S. C. Chan and J.M. Liu, "Tunable narrow-linewidth photonic microwave generation using semiconductor laser dynamics", *IEEE J. of Sel. Top. Quantum Electron* **10,** 1025-1032, 2004.