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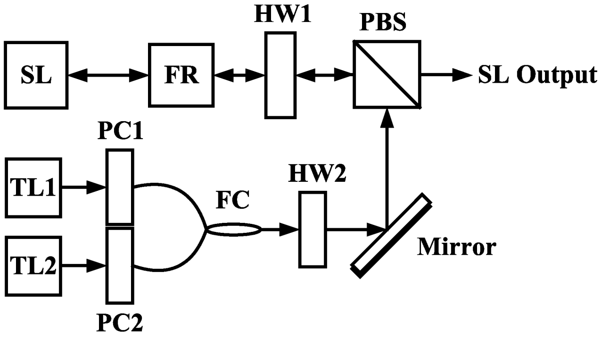
Yu-Shan Juan
Fan-Yi Lin



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Photonic Generation of Broadly Tunable Microwave Signals Utilizing a Dual-Beam Optically Injected Semiconductor Laser

Yu-Shan Juan and Fan-Yi Lin

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

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Abstract: We propose and study photonic generation of broadly tunable microwave signals utilizing a dual-beam optically injected semiconductor laser. By injecting a slave laser with two detuned master lasers at the stable locking states, microwave signals with frequencies corresponding to the frequency spacing of the master lasers can be generated. Without the need for a microwave reference source, the dual-beam optical injection scheme has the advantages of low cost and less system complexity. Moreover, without the limitations of period-doubling bifurcation and Hopf bifurcation, by utilizing the period-one oscillation state with a single-beam injection scheme, the microwave signals generated with the proposed scheme have a much broader tuning range. In this paper, optical and power spectra of the microwave signals generated with the dual-beam optical injection scheme are compared with those generated with the optical mixing, the single-beam injection, and the unlocked dual-beam injection schemes. Generation of tunable microwave signals up to 120 GHz is demonstrated, which is currently limited by the locking range of the slave laser determined by the frequency difference between the Hopf (higher frequency) and the saddle node (lower frequency) bifurcation curves.

Index Terms: Semiconductor lasers, instabilities and chaos, optical injection.

1. Introduction

Photonic generations of high-frequency microwave signals have been studied extensively in recent years [1]–[5]. Compared with the conventional electric circuitries that require several stages of frequency multiplexing to generate a desired frequency, photonic generations have the advantages of less system complexity, lower cost, longer transmission distance, and the ability to generate tunable microwave signals with higher frequencies.

Several photonic schemes have been studied to generate the microwave signals. The simplest scheme is the optical mixing (optical heterodyning), where two optical waves detuned at a desired frequency beat directly at a photodetector to generate the microwave beat signal [6]. However, the beat signal typically has large phase noise since the phases of the two optical waves from two free-running lasers are in general not correlated. To improve the phase coherence between the two optical waves, techniques with optical injection locking or optical phase lock loop have been used [7]–[9]. However, a microwave reference source is needed for sideband generation and phase stabilization in these techniques, which significantly increases the cost and complexity of the system. Other schemes utilizing external intensity or phase modulation have also been studied to

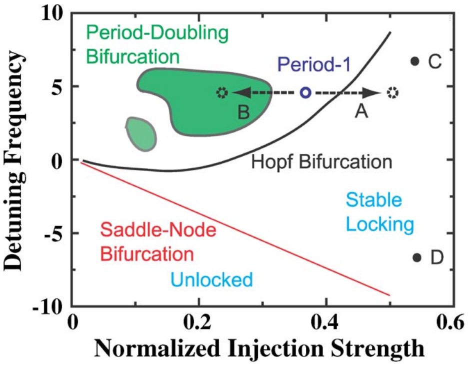

Fig. 1. Schematic drawing of the bifurcation diagram typically seen in an optically injected semiconductor laser.

generate high-quality microwave signals [10], [11]. However, while a tunable optical filter must be used to generate tunable microwave signals, a microwave reference source together with an expensive high-speed electro-optic modulator is also required.

By using dual-wavelength ultranarrow transmission-band fiber Bragg gratings (FBGs), a dual-wavelength fiber ring laser has been demonstrated to generate microwave signals without the need for the microwave reference source [12], [13]. However, with the fixed frequency spacing between the transmission bands of the FBGs, the frequency of the microwave signal generated is difficult to be tuned. To generate tunable narrow-linewidth microwave signals without the need for a microwave reference source, a single-beam optical injection scheme utilizing the nonlinear laser dynamics has been studied [14]–[16]. By optically injecting a slave laser with a master laser, the slave laser can be operated in the period-one (P1) oscillation states where the corresponding microwave signals can be converted from the slave laser output using a photodetector [17]–[19]. By varying the injection strength from the master laser to the slave laser, tuning of the oscillation frequency of the P1 state in a range from 10 to 23 GHz has been demonstrated. With the aid of an optoelectronic feedback loop to stabilize the slave laser, the linewidths of the generated signals reducing from 40–120 MHz to 10–160 kHz have been shown. However, although tunable, the tuning range of the microwave signals generated is limited to just a few tens of gigahertz due to the limited P1 region in the parameter space.

Fig. 1 shows a schematic drawing of the bifurcation diagram typically seen in an optically injected semiconductor laser [15]. The detuning frequency is the frequency difference between the master and the slave lasers and the normalized injection strength is defined as the ratio of the injection power from the master laser to the output power of the slave laser. As can be seen, when the injection strength is raised to increase the P1 oscillation frequency, the SL will reach the Hopf bifurcation curve after certain strength and become stably locked with the injection laser (arrow A). This limits the highest P1 frequency that can be generated, which is about three-fold of the resonance oscillation frequency of the slave laser used. Moreover, when the injection strength is reduced to decrease the P1 oscillation frequency, the SL will enter other high-order periodic oscillation states and chaos through the period-doubling bifurcation (arrow B). This period-doubling bifurcation point sets the lowest P1 frequency, which is bounded at about the resonance oscillation frequency [15], [18]. As the result, a tuning range of about or less than two-fold of the resonance oscillation frequency is typically seen for the microwave signal generation utilizing the P1 oscillation state with a single-beam injection scheme [17].

Therefore, to generate broadly tunable microwave signals, we propose and study a dual-beam optical injection scheme where a slave semiconductor laser is stably locked by two detuned master lasers (e.g., Operate at points C and D of the stable locking region bounded with the Hopf bifurcation and the saddle-node bifurcation curves as seen in Fig. 1). Without the need for a microwave reference source, the cost and complexity of the system can be significantly reduced. Moreover, without the boundaries set by the period-doubling bifurcation and the Hopf bifurcation of

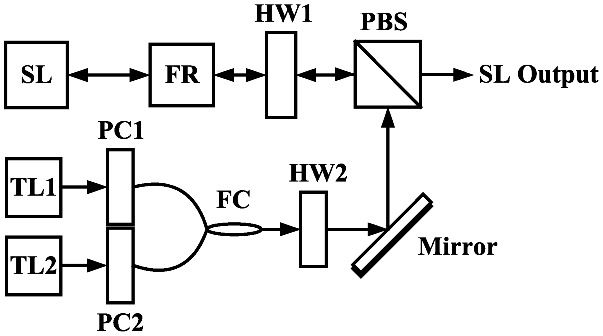

Fig. 2. Schematic setup of the dual-beam optically injected semiconductor laser for photonic generation of the tunable microwave signals. The slave laser (SL) is optically injected by two tunable master lasers (TL1 and TL2) simultaneously. PC: polarization controller, FC: fiber coupler, HW: half-wave plate, PBS: polarizing beamsplitter, and FR: Faraday rotator.

the P1 oscillation state in the single-beam injection scheme, the microwave signal generated in the dual-beam optical injection scheme can have a much broader tuning range.

2. Experimental Setup

Fig. 2 shows the schematic setup of the dual-beam optically injected semiconductor laser for photonic generation of the tunable microwave signals. A 1.4-μm single-mode distributed feedback (DFB) semiconductor laser is used as the slave laser (SL), which is optically injected by two tunable master lasers (TL1 and TL2) at different detuning frequencies with different injection strengths. By optically injecting the SL with both the TL1 and TL2, a microwave signal with a frequency corresponding to the frequency spacing between the TL1 and TL2 can be generated. By varying the frequency spacing between the TL1 and TL2, the frequency of the microwave signal generated can be continuously tuned accordingly. A free-space circulator formed by two half-wave plates (HW1 and HW2), a polarizing beamsplitter (PBS), and a Faraday rotator (FR) is used to separate the SL output from the injection beams. When biased at 32.6 mA, the SL has an output power of 9.3 mW and a relaxation oscillation frequency of about 8 GHz. A linewidth enhancement factor of about 2.2 for the SL is estimated with a four-wave mixing method [22]. The tunable lasers used are Santec TSL210 (TL1) and Yenista Tunics P100S-O (TL2) with maximum power of 10 mW and linewidths of 1 MHz. The electrical power spectra of the SL output are detected by a photodetector (Discovery Semiconductor DSC30S) and an electric amplifier (MITEQ AFS6-00102000-30-10P-6) with 3-dB bandwidths of 20 GHz and recorded using a power spectrum analyzer (Agilent E4407B) with a bandwidth of 26.5 GHz. The optical spectra are measured by an optical spectrum analyzer (Advantest Q8384) with a 10-pm resolution.

3. Results and Discussions

To generate tunable microwave signals, the SL is optically injected by both the TL1 and TL2 simultaneously at the stable locking region. Fig. 3(a) and (b) shows the optical spectra of the SL when injection-locked with only the TL1 and only the TL2, respectively. As can be seen, with the normalized injection strengths of $\xi_1 = 0.816$ and $\xi_2 = 0.8$ (ξ is the ratio of the injection power from the ML to the output power of the SL), the SL originally oscillates at a wavelength of 1305.626 nm is locked to the wavelengths of the TL1 and TL2 at $\lambda_1 = 1306.65$ nm and $\lambda_2 = 1306.54$ nm, respectively. By simultaneously injecting both beams from the TL1 and TL2 to the SL, the SL is transformed into a dual-wavelength laser. Fig. 3(c) and (d) shows the optical and power spectra of the SL under dual-beam optical injection. As can be seen, a 20-GHz microwave signal corresponding to a wavelength spacing of 0.11 nm with more than -50-dB sidemode suppression ratio is obtained. Unlike the dual-wavelength fiber ring laser that can only generate microwave signals with fixed frequencies limited by the predesigned transmission bands of the FBGs used [12],

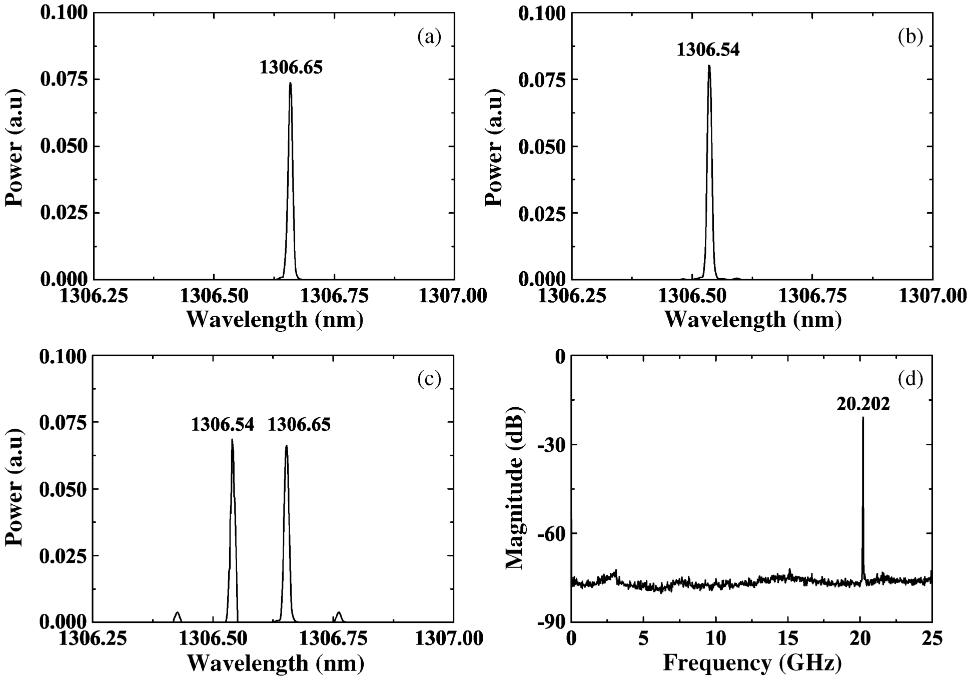

Fig. 3. Optical spectra of the SL when injection-locked by (a) TL1, (b) TL2, and (c) TL1 and TL2 simultaneously. (d) Corresponding power spectrum of the SL with dual-beam optical injection as shown in (c). The SL has a wavelength of 1305.626 nm, and TL1 and TL2 have wavelengths of 1306.65 nm and 1306.54 nm, respectively. The normalized injection strengths from the TL1 and TL2 to the SL are 0.816 and 0.8, respectively.

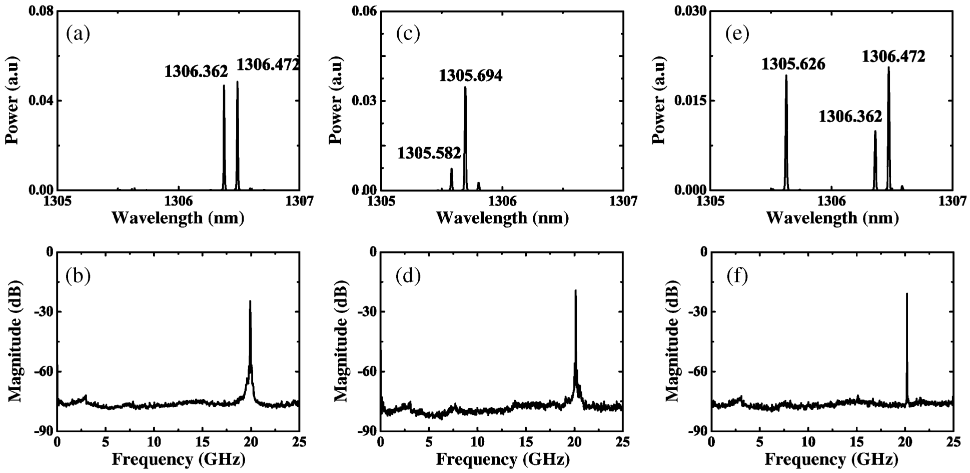

Fig. 4. Optical and power spectra of (a)–(b) optical mixing, (c)–(d) P1 oscillation state by single-beam injection, and (e)–(f) four-wave mixing state by unlocked dual-beam injection, respectively.

the frequency of the microwave signal generated with the dual-beam optical injection scheme can be easily tuned by adjusting the frequency spacing between the TL1 and TL2.

With the similar setup, microwave signals generated by mixing the beams from the TL1 and TL2 directly on a photodetector (optical mixing scheme), by injecting one of the beam from the master laser (TL1 or TL2) to the SL to generate the period-one (P1) oscillation state (single-beam injection scheme), and by injecting both the beams from the TL1 and TL2 to the SL but without locking (four-wave mixing state under unlocked dual-beam injection scheme) are shown in Fig. 4. Fig. 4(a)–(f)

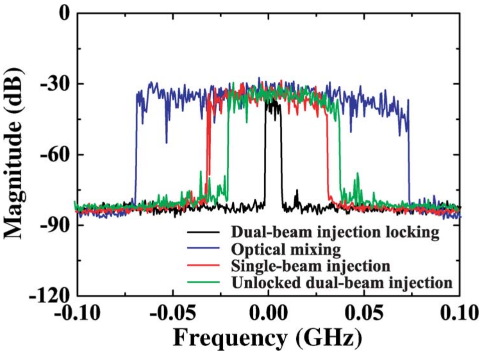

Fig. 5. Power spectra of the microwave signals generated by the dual-beam optical injection (black), optical mixing (blue), P1 oscillation state with single-beam injection (red), and four-wave mixing state with unlocked dual-beam injection schemes centered at the respective peak frequencies. The resolution bandwidth is 100 kHz, and the span is 200 MHz.

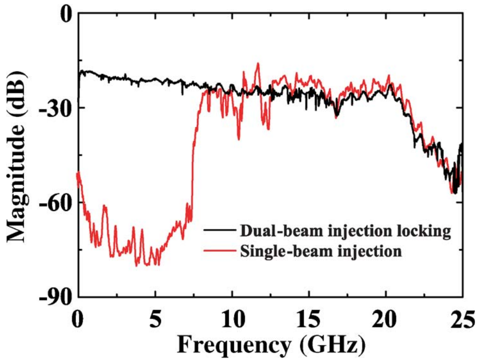

Fig. 6. Power of the microwave signals generated at different frequencies for the dual-beam optical injection (black) and the single-beam injection (red) schemes.

shows the optical and power spectra of the optical mixing, the single-beam injection, and the unlocked dual-beam injection schemes, respectively. As can be seen, all these schemes can generate microwave signals at about 20 GHz. However, compared with these benchmark schemes, the linewidths of the microwave signals generated in the dual-beam optical injection scheme are much narrower, as shown in Fig. 5.

Fig. 5 shows the power spectra of the microwave signals generated by the dual-beam optical injection (black), the optical mixing (blue), the single-beam injection (red), and the unlocked dual-beam injection schemes (green), as seen in Figs. 3(d) and 4(d)–(f), respectively. The spectra are obtained with a resolution bandwidth of 100 kHz and centered at the respective peak frequencies of the microwave signals generated. As can be seen, while the microwave signals generated by the optical mixing, the single-beam injection, and the unlocked dual-beam injection schemes have 3-dB bandwidths of 152, 69, and 56 MHz, respectively, the signal generated by the dual-beam optical injection scheme has a bandwidth of only 6.2 MHz. Clearly, the bandwidth of the microwave signal generated is significantly reduced benefited by the strong optical injections from the TL1 and TL2 [20], [21]. This bandwidth can be further reduced to the kilohertz range by applying an additional optoelectronic feedback loop on the SL as that has been utilized in the single-beam injection scheme [17].

Fig. 6 shows the power of the microwave signals generated at different frequencies for the dual-beam optical injection (black) and the single-beam injection (red) schemes. Limited by the 3-dB bandwidths of the photodetector and the amplifier used, we only show the tuning of the microwave signals below 20 GHz. As can be seen, for the single-beam injection scheme, the P1 oscillation

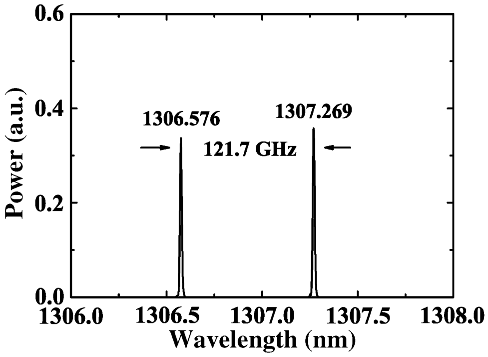

Fig. 7. Optical and power spectra of a 120-GHz high-frequency microwave signal generated with $\lambda_1 = 1306.576$ nm, $\lambda_2 = 1307.269$ nm, $\xi_1 = 0.81$, and $\xi_2 = 0.823$ for the TL1 and TL2, respectively.

states only exist while having sufficient power at frequencies higher than the resonance oscillation frequency of about 8 GHz. The SL enters high-order periodic oscillation states and chaos when the injection strength is lowered beyond the period-doubling bifurcation point (lowest injection strength). The highest P1 oscillation frequency that can be obtained with our setup is about 24 GHz. By further increasing the injection strength, the SL will be stably locked with the master laser after it reaches the Hopf bifurcation curve (highest injection strength). Similar results have been shown in [18] where the frequency of the P1 oscillation state is bounded in a range from 10 to 23 GHz. On the other hand, the frequency of the microwave signal generated by the dual-beam optical injection scheme can be tuned all the way down to just a few megahertz. It is limited by the stability of the lasers used when the wavelengths of the TL1 and TL2 are tuned to be very close. By increasing the frequency spacing between the TL1 and TL2, the frequency of the microwave signals can be continuously tuned up to the full locking range of the slave laser determined by the Hopf (higher frequency) and the saddle node (lower frequency) bifurcation curves. With a reasonable injection strength, the locking range can easily exceed ten-fold of the resonance oscillation frequency, and microwave signals with frequencies higher than 100 GHz can be obtained.

To demonstrate a very high frequency microwave signal generation, Fig. 7 shows the optical spectrum of the dual-beam optically injected semiconductor laser under injections from the TL1 and TL2 with $\lambda_1 = 1306.576$ nm, $\lambda_2 = 1307.269$ nm, $\xi_1 = 0.81$, and $\xi_2 = 0.823$, respectively. Due to the limited bandwidths of the photodetector and the power spectrum analyzer, only the optical spectrum of the SL output is shown. As can be seen, similar to the case shown in Fig. 3(c), the slave laser is locked with both TL1 and TL2 and a beat frequency of 121.7 GHz is successfully obtained. The current limitation of the highest frequency that can be generated is limited by the locking range determined by the maximum injection strengths of the TL1 and TL2. While the Hopf bifurcation boundary and therefore the stable locking region can differ from each laser with different intrinsic and operational parameters (e.g., the relaxation oscillation frequency, the linewidth enhancement factor, and the pump current), the locking range can in general be further extended with stronger injections.

4. Conclusion

In conclusion, we have proposed and studied the photonic generation of broadly tunable microwave signals utilizing a dual-beam optically injected semiconductor laser. Without the need for a microwave reference source, generation of microwave signals up to 120 GHz has been demonstrated. Compared with the microwave signals generated with the P1 oscillation state in a single-beam injection scheme in which the tuning range is confined by the period-doubling and the Hopf bifurcation curves, the tuning range of the dual-beam optical injection scheme can be significantly broader. In the dual-beam optical injection scheme, the tuning range is determined by the locking range of the injected SL defined by the frequency spacing between the Hopf and the saddle node bifurcation curves. It can be further extended by increasing the injection power from the master lasers. A linewidth of 6.2 MHz has been measured for the microwave signal generated with the dual-beam optical injection scheme, which is considerably narrower than the linewidths of the microwave signals generated with the optical mixing, the single-beam injection, and the unlocked dual-beam injection schemes.

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