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Optical double-locked semiconductor lasers

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ABSTRACT

Self-sustained period-one (P1) nonlinear dynamics of a semiconductor laser are investigated when both optical injection and modulation are applied for stable microwave frequency generation. Locking the P1 oscillation through modulation on the bias current, injection strength, or detuning frequency stabilizes the P1 oscillation. Through the phase noise variance, the different modulation types are compared. It is demonstrated that locking the P1 oscillation through optical modulation on the output of the master laser outperforms bias-current modulation of the slave laser. Master laser modulation shows wider P1-oscillation locking range and lower phase noise variance. The locking characteristics of the P1 oscillation also depend on the operating conditions of the optical injection system

Introduction

Stable photonic microwaves are anticipated for many applications. These application include optical beam forming, radio-over-fiber (RoF) communication, broadband wireless access networks, photonic microwave signal processing, radar system, and integrated circuits [1–3]. Semiconductor lasers can generate photonic microwaves when properly perturbed [4]. A semiconductor laser can be perturbed in a variety of ways such as in strong current modulation [5], optical feedback [6], optoelectronic feedback [7], and optical injection [8]. The injection of an optical field into the semiconductor laser alters the coupling characteristics of the circulating optical field in the laser cavity and the free carriers in the gain medium of the semiconductor laser. This subsequently changes the resonant frequency and damping of the laser, causing instabilities. The instabilities causes the laser to undergo various useful dynamics such as stable locking, limit-cycle oscillations of period one and period two (P2), and chaotic oscillations [9].

The P1 oscillation induced by optically injected lasers is a prime candidate for photonic microwave generation. It can reach high microwave frequencies, with broadband frequency tunability, single sideband optical spectrum, and relatively low phase noise. Recently, extensive research efforts showed numerous techniques to further stabilize the P1 oscillations induced by an optically injected semiconductor laser [10–18].

The optically injected semiconductor laser system has three operational parameters. Those parameters are the bias current of the slave laser, the injection power of the master laser, and the detuning frequency between the master and slave lasers. Modulating one of the operational parameters can enhance the performance of the optical injection system. An Injection-locked laser, operating in the stable locking region, showed an enhanced modulation bandwidth when modulating the output of the master laser as opposed to modulating the bias current of the slave laser [19]. The P1 oscillation generated by an injection-locked semiconductor laser can be further locked by modulating the bias current of the slave laser by a microwave signal at or near the P1 frequency [10]. Double locking the semiconductor laser has been also demonstrated using subharmonic modulation [20,21]. A recent study on the performance of a double-locked semiconductor laser operating in P1 dynamic region for uplink transmission in Rof communication showed better SNR and BER as compared to a free-running or a stable injection-locked laser [22]. The optically injected laser undergoing chaotic oscillations showed significant increase in the chaotic bandwidth by modulating the output intensity of the master laser [23].

In this work, double locking the semiconductor laser by an optical injection signal and an applied reference microwave modulation is investigated. The P1 oscillations generated by an injection-locked semiconductor laser are locked by applying a reference microwave modulation to the bias current of the slave laser or to the output of the master laser. Microwave modulation on the bias current, Injection strength, or detuning frequency have different locking and phase noise characteristics when applied to the P1 oscillation of an optically injection-locked laser. Furthermore, the P1 oscillations at different operating conditions of the optical injection system have different modulation locking characteristics for the various modulation types. To show the locking characteristics of the P1 oscillation to optical modulation on the output of the master laser, we first revisit the locking characteristics of the P1

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oscillation to bias-current modulation on the slave laser. Modulating the P1 oscillation through the output of the master laser outperforms modulating the bias current of the slave laser by having a wider modulation locking range and lower phase noise variance. However, at points of low injection strengths and small frequency offsets, modulating the bias current of the slave laser shows better phase noise performance although with a narrower modulation locking range of the P1 oscillation.

The paper is organized as follows, after this introductory section; the theoretical model used in this work is presented in Section 2. Section 3 shows characteristics of the P1 oscillation when no modulation is applied. The locking characteristics of the P1 oscillation when modulation is applied on the bias current, injection strength and detuning frequency are reported in Section 4. Finally, in Section 5, a short conclusion is given summarizing our results.

Theoretical model

A schematic of the optical injection setup with modulation on the bias current of the slave laser or the output of the master laser is shown in Fig. 1.

The output of the master laser optically injects the slave laser through an optical circulator, a variable attenuator, and a polarization controller. The variable attenuator or the polarization controller can adjust the optical injection strength, ξ. The detuning frequency between the master and slave lasers, f, can be adjusted by varying either the bias current or the temperature of the master laser. In this work, the injection strength and detuning frequency are adjusted such that the laser operates in the P1 region. When the system operates in the P1 region, a photonic microwave is generated showing a microwave frequency signal on the microwave spectrum analyzer after the photodetector. To stabilize the generated microwave oscillation, a reference modulation signal at or near the generated P1 frequency is added. Through a microwave synthesizer, the dc-bias current of the slave laser is modulated. An optical intensity or frequency modulator is inserted into the optical path to modulate the injection strength or detuning frequency, respectively.

The dynamics of the optically injected slave laser shown in Fig. 1 are described by the normalized intracavity optical field amplitude $a_\mathrm{r} + \mathrm{i}a_\mathrm{i}$ and the normalized charge carrier density $\tilde{n}$. The rate equations for a single-mode semiconductor laser under optical injection and modulation are as follows [24–26]:

$$\frac{da_\mathrm{r}}{dt} = \frac{1}{2}\left[\frac{\gamma_\mathrm{c}\gamma_\mathrm{n}}{\gamma_\mathrm{s}\tilde{J}}\tilde{n}(a_\mathrm{r} + ba_\mathrm{i}) - \gamma_\mathrm{p}(a_\mathrm{r}^2 + a_\mathrm{i}^2 - 1)(a_\mathrm{r} + b'a_\mathrm{i})\right] + \xi[1 + m_\xi\cos(2\pi f_\xi t)]\gamma_\mathrm{c}\cos(2\pi ft + m_f\sin(2\pi f_f t))$$

$$\frac{da_\mathrm{i}}{dt} = \frac{1}{2}\left[\frac{\gamma_\mathrm{c}\gamma_\mathrm{n}}{\gamma_\mathrm{s}\tilde{J}}\tilde{n}(-ba_\mathrm{r} + a_\mathrm{i}) - \gamma_\mathrm{p}(a_\mathrm{r}^2 + a_\mathrm{i}^2 - 1)(-b'a_\mathrm{r} + a_\mathrm{i})\right] - \xi[1 + m_\xi\cos(2\pi f_\xi t)]\gamma_\mathrm{c}\sin(2\pi ft + m_f\sin(2\pi f_f t))$$

$$\frac{d\tilde{n}}{dt} = -[\gamma_\mathrm{s} + \gamma_\mathrm{n}(a_\mathrm{r}^2 + a_\mathrm{i}^2)]\tilde{n} - \gamma_\mathrm{s}\tilde{J}(a_\mathrm{r}^2 + a_\mathrm{i}^2 - 1) + \frac{\gamma_\mathrm{s}\gamma_\mathrm{p}}{\gamma_\mathrm{c}}\tilde{J}(a_\mathrm{r}^2 + a_\mathrm{i}^2)(a_\mathrm{r}^2 + a_\mathrm{i}^2 - 1) + \gamma_\mathrm{s}m_{\tilde{J}}(1 + \tilde{J})\cos(2\pi f_{\tilde{J}}t)$$

where γ_c is the cavity decay rate, γ_s is the spontaneous carrier relaxation rate, γ_n is the differential carrier relaxation rate, γ_p is the nonlinear carrier relaxation rate, b is the linewidth enhancement factor, b' is the gain saturation factor, and $\tilde{J}$ is the normalized bias above the threshold current. The modulation indices, $m_{\tilde{J}}$, m_ξ, and m_f, and the modulation frequencies, $f_{\tilde{J}}$, f_ξ, and f_f, represent the modulation added to the system with the subscripts $\tilde{J}$, ξ, and f, respectively, indicating bias-current modulation on the slave laser, injection-strength modulation on the master laser output, and detuning-frequency modulation on the master laser output. To simulate spontaneous emission noise, Langevin source terms are incorporated into the equations characterized by spontaneous emission rate R_sp [27].

The intrinsic parameters adopted in this work are all experimentally determined for a InGaAs/InP semiconductor laser using a four-wave mixing technique [28]. They are $\gamma_\mathrm{c} = 5.36 \times 10^{11}\ \mathrm{s}^{-1}$, $\gamma_\mathrm{s} = 5.96 \times 10^{9}\ \mathrm{s}^{-1}$, $\gamma_\mathrm{n} = 7.53 \times 10^{9}\ \mathrm{s}^{-1}$, and $\gamma_\mathrm{p} = 1.91 \times 10^{10}\ \mathrm{s}^{-1}$, $b = b' = 3.2$, $R_\mathrm{sp} = 2.34 \times 10^{18}\ \mathrm{V}^2\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$ for a normalized bias current of $\tilde{J} = 1.222$. The rate equation model with the experimentally extracted intrinsic parameters of the laser used in this work and other lasers showed excellent qualitative and quantitative agreement between theory and experiment [24,29,30]. A second-order Runge-Kutta integration is carried out on the rate equations with a duration of 1.25 μs for each time series and an integration time step of 2.4 ps. Fourier transform of the time series is taken to find the optical and power spectra of the slave laser output.

P1 oscillation

The P1 oscillation induced by an optically injected laser is a result of undamping the relaxation resonance of the semiconductor laser. This nonlinear dynamic appears when the injection strength, detuning frequency, or bias current is tuned to a critical point where the system undergoes a Hopf bifurcation [9].

Fig. 2 shows the P1 dynamics region, identified above the stable locking region separated by the Hopf bifurcation line shown as a thick black curve. The contour curves above the Hopf bifurcation line in Fig. 2 signify the P1 frequency, f_0, in GHz. The black areas in Fig. 2 are regions of complex dynamics. The blue and red contour

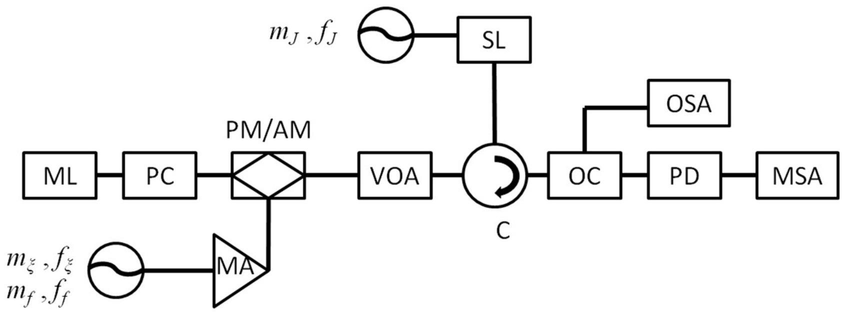

Fig. 1. Schematic of the experimental apparatus. ML, master laser; SL, slave laser; PC, polarization controller; PM/AM, phase/amplitude optical modulator; MA, microwave amplifier; VOA, variable optical attenuator; C, circulator; OC, optical coupler; OSA, optical spectrum analyzer; MSA, microwave spectrum analyzer; PD, photodiode.