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Photonic microwave generation and transmission using direct modulation of stably injection-locked semiconductor lasers

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ABSTRACT

Direct modulation of a semiconductor laser subject to stable injection locking is capable of generating microwave subcarriers that are broadly frequency-tunable, more than 4 times its free-running relaxation resonance frequency, and are highly sideband-asymmetric, more than 22 dB. The latter characteristic makes the laser system particularly attractive for radio-over-fiber applications. Therefore, such modulation sideband asymmetry, its underlying mechanism, and its effect on chromatic dispersion-induced microwave power variation are extensively studied, in particular, over a broad range of injection conditions. Mappings showing integrated and global understandings of the modulation sideband asymmetry together with the modulation frequency enhancement are obtained accordingly. Interestingly, it is found that the microwave frequency can be tuned over a broad range while keeping a similar level of modulation sideband asymmetry and vice versa, either of which is achieved by simply changing the injection condition. This, therefore, considerably adds the flexibility and re-configurability to the laser system. The cavity resonance shift due to injection locking is responsible for not only the enhanced modulation frequency but also the modulation sideband asymmetry, where a modification in its previous interpretation is obtained for explanation. The modified modulation characteristics are strong functions of the linewidth enhancement factor, making it possible to choose lasers with proper values of the factor for different photonic microwave characteristics.

1. Introduction

Microwave photonics has attracted great attention over the past years [1]. This is particularly due to the strong demand in distributing microwave subcarriers over long distances through fibers for broadband wireless access networks [2,3]. Such radio-over-fiber systems adopt an architecture where microwave subcarriers are generated in the optical domain at a central office and next transmitted to remote base stations through fibers. Microwave subcarriers are converted to the electrical domain at the base stations using photodetectors, which are next radiated by antennas over small areas. Therefore, certain characteristics of such generated microwave subcarriers are necessary to simultaneously satisfy the requirements in both the optical domain and the electrical domain. They include high microwave frequency, low phase noise, broadband frequency tunability, and optical single-sideband (SSB) modulation [1,4]. A variety of different schemes have therefore been proposed to simultaneously achieve these photonic microwave characteristics [5–12].

Direct modulation of a semiconductor laser is the simplest scheme for photonic microwave generation and transmission. However, the highest relaxation resonance frequency experimentally demonstrated so far is only around 25 GHz, limiting the highest frequency and the tunable range of the generated microwave subcarriers [13,14]. Besides, the spectral signature of the relaxation resonance is symmetric, suggesting optical double-sideband (DSB) modulation characteristic [15,16]. These inherent properties of the laser make the direct modulation scheme difficult to achieve the above-mentioned photonic microwave characteristics. Operating the laser under stable injection locking by introducing an external optical field, however, offers an attractive solution. Based on a linearized analysis [17], the relaxation resonance of the laser can be radically modified due to stable injection locking, predicting considerable enhancement in relaxation resonance frequency and strong asymmetry in direct modulation sidebands. More than 3-fold enhancement in relaxation resonance frequency has been experimentally observed in a number of different lasers [18–22], demonstrating that direct modulation of a stably injection-locked laser is feasible for very high frequency and broadband tunable microwave generation. The shift of the cavity resonance due to optical injection has been proposed to be responsible for such an enhancement [17,23–26]. Optical SSB modulation

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characteristic was observed in recent experiments [27–31], where modulation sideband asymmetry of up to 21.4 dB was found. This characteristic makes direct modulation of a stably injection-locked laser even more attractive for applications where fiber transmission of microwave subcarriers to remote areas is necessary.

As noted, while studies on direct modulation of a stably injection-locked laser have focused mainly on the enhanced relaxation resonance frequency and its underlying mechanism, there have been few or no discussions on the modulation sideband asymmetry, its underlying mechanism, and its effect on dispersion-induced microwave power variation. Particularly, how they behave over a broad range of injection conditions and key laser parameters have not yet been addressed. These discussions are important as they help to better understand the laser system from a global viewpoint and in determining whether the laser system is practically useful. Therefore, the main purpose of this work is to numerically study these issues based on a set of coupled, nonlinear rate equations for the stably injection-locked laser [17,32]. The laser intrinsic noise is considered in the numerical calculation as a broadband optical probe. The corresponding noise spectra not only reveal how the stably injection-locked laser would response to direct modulation [13,18], but also help to study the underlying mechanisms leading to the modified modulation characteristics. Even though the enhanced relaxation resonance frequency of the laser system has been extensively investigated, it is again discussed here briefly to obtain an integrated picture of the overall photonic microwave characteristics of the laser system with our understanding of its modulation sideband asymmetry. While it is not the focus of this study, an interesting phenomenon is observed accordingly, that is, reduction, not enhancement, in the relaxation resonance frequency is found over a range of operating conditions. Such reduction has actually been both experimentally observed [17,18] and numerically verified [25,33] but has not been much emphasized. This, however, stimulates us to revisit the previously proposed underlying mechanism, resulting in the modification of its interpretation.

2. Theoretical model

The optical injection system consists of one master laser and one slave laser, as shown in Fig. 1. The output of the former is directed to the latter using a free-space circulator arrangement that consists of two half-wave plates, one polarizing beam splitter, and one Faraday rotator [34,35]. Additionally, optical isolators can be used to increase the extent of isolation. For a fiber-based system, such an arrangement can be replaced simply by a fiber circulator. The output of the slave laser is sent to a detection system to obtain both optical and microwave spectra. Depending on the level and frequency of the injection from the master laser, the slave laser can undergo a variety of different dynamical states [32,35–38], such as stable injection locking, periodic oscillations, and chaos. For our interest in this study, the laser system is operated under stable injection locking. For photonic microwave

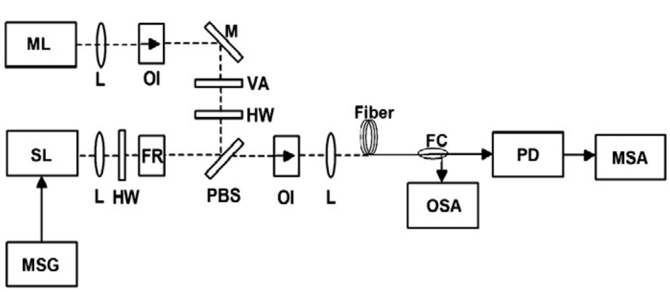

Fig. 1. Schematic of the laser system. ML: master laser; SL: slave laser; L: lens; PBS: polarizing beam splitter; M: mirror; HW: half-wave plate; FR: Faraday rotator; VA: variable attenuator; OI: optical isolator; FC: fiber coupler; PD: photodiode; OSA: optical spectrum analyzer; MSA: microwave spectrum analyzer; MSG: microwave signal generator.

generation, the stably injection-locked slave laser is directly modulated by a microwave signal at the required frequency. For photonic microwave transmission, the output of the directly modulated, stably injection-locked slave laser is sent through fibers, where the chromatic dispersion effect on microwave power is investigated.

The laser system can be characterized by the following rate equations of a single-mode semiconductor laser subject to both optical injection and direct modulation [17,32]:

$$\frac{dA}{dt} = -\frac{\gamma_c}{2}A + i(\omega_0-\omega_c)A + \frac{\Gamma}{2}(1-ib)gA + \eta A_i e^{-i\Omega t} + F_{sp} \quad (1)$$

$$\frac{dN}{dt} = \frac{J+J_m\cos(\Omega_m t)}{ed} - \gamma_s N - gS. \quad (2)$$

Here, $A=|A|e^{i\phi}$ is the total complex intracavity field amplitude at the free-running oscillation frequency ω_0, ϕ is the optical phase relative to the injection field, γ_c is the cavity decay rate, ω_c is the angular frequency of the cold cavity, Γ is the confinement factor describing the spatial overlap between the gain medium and the optical mode, b is the linewidth enhancement factor relating the dependence of the refractive index on changes in the optical gain [39], g is the optical gain parameter which is a function of the charge carrier density N and the intracavity photon density S, $F_{sp}=F_r+iF_i$ is the complex field noise characterized by a spontaneous emission rate [40,41], η is the injection coupling rate, A_i is the injection field amplitude, $f=\Omega/2\pi$ is the detuning frequency of the master laser from the free-running frequency of the slave laser, J is the bias current density, J_m is the modulation current density, $f_m=\Omega_m/2\pi$ is the modulation frequency, e is the electron charge, d is the active layer thickness, and γ_s is the spontaneous carrier decay rate. The photon density is related to the field by

$$S = \frac{2\epsilon_0 n^2}{\hbar\omega_0}|A|^2 \quad (3)$$

where ϵ_0 is the free-space permittivity, n is the refractive index, and $\hbar$ is the reduced Plank's constant. Under a steady state, free-running operating condition of the slave laser determined by J, setting Eqs. (1) and (2) equal to zero without considering the field noise, optical injection, and microwave modulation results in $\Gamma g_0=\gamma_c$, $\omega_0-\omega_c=b\gamma_c/2$, and $N_0/S_0=\gamma_c/\Gamma\gamma_s\tilde{J}$, which are used in the following derivations. Note that g_0, S_0, N_0 are the free-running values of g, S, and N, respectively, and $\tilde{J}=(J/ed-\gamma_s N_0)/\gamma_s N_0$ is the normalized bias level above the laser threshold. For the following derivations and discussions, Eq. (1) is further separated into the real and the imaginary part, respectively, as

$$\frac{1}{|A|}\frac{d|A|}{dt} = \frac{1}{2}\Gamma(g-g_0) + \eta\frac{|A_i|}{|A|}\cos(\Omega t+\phi) + \frac{F_r\cos\phi + F_i\sin\phi}{|A|} \quad (4)$$

$$\frac{d\phi}{dt} = -\frac{b}{2}\Gamma(g-g_0) - \eta\frac{|A_i|}{|A|}\sin(\Omega t+\phi) + \frac{F_i\cos\phi - F_r\sin\phi}{|A|} \quad (5)$$

For the purpose of numerical calculation, Eqs. (2), (4), and (5) are recast about the steady-state, free-running operating point of the slave laser, where A and N are normalized to their corresponding free-running values, A_0 and N_0, respectively [32,37]:

$$\frac{da}{dt} = \frac{1}{2}\left[\frac{\gamma_c\gamma_n}{\gamma_s\tilde{J}}\tilde{n} - \gamma_p\left(2a+a^2\right)\right](1+a) + \xi\gamma_c\cos(\Omega t+\phi) + F_a \quad (6)$$

$$\frac{d\phi}{dt} = -\frac{b}{2}\left[\frac{\gamma_c\gamma_n}{\gamma_s\tilde{J}}\tilde{n} - \gamma_p\left(2a+a^2\right)\right] - \frac{\xi\gamma_c}{1+a}\sin(\Omega t+\phi) + \frac{F_\phi}{1+a} \quad (7)$$