Analysis of Spectral Characteristics of Semiconductor Lasers under Strong Optical Injection Locking for Tens of Giga Hz Signal Generation

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***Abstract*—we have analyzed tens of Giga pulse signal generation using sideband injection locking scheme. The numerical model for semiconductor lasers under the strong optical injection is based on the Lang's equation and has been extended in order to take into account the simultaneous injection of the multiple sidebands of the current-modulated laser. The numerical simulation results show that the unselected sidebands will affect the optical and RF-spectral characteristics even though the semiconductor laser is locked to the target sidebands.**

***Index Terms*— Frequency detuning, Optical injection locking, Millimeter-wave**

I. INTRODUCTION

As transmission capacity of existing microwave band is saturated these days, Millimeter Wave (MMW) system with wide frequency band is now required. The new technology using MMW is developing in the field of wide band wireless communication system which supports multimedia communication in wireless network in the future. The fusions of MMW technology and fiber-optic technology have a lot of advantages in the aspect of supporting the more wide frequency band, capacity of transmission and low loss. Therefore, much work is developed based on radio over fiber system. Intelligent traffic system, indoor communication, remote antenna, and beam forming including conventional mobile communication are needed for higher carrier frequency band. It makes the MMW system an interesting field. For example, MMW is essential in pico-cellular broadband wireless communication, because the connection configuration between the central station and base station is necessary to obtain wide band, and its system is made up with optical feeder link. Optical feeding of base stations in these systems is an attractive approach because it enables a large number of base stations to share the transmitting and processing equipments remotely located from the customer serving area. A number of techniques for the generation, modulation, and distribution of millimeter-wave modulated optical carriers for fiber-wireless systems have been developed [1]. One of the methods for generating a signal for micro wave and millimeter wave band is optical injection locking (OIL) technique. Recently much related work has developed in this area. Using this method, Hyuk-Kee Sung et al. has recently reported that A 622 Mb/s data transmission on a 20 GHz subcarrier is demonstrated over an 80 km fiber link [2]. Our recent study on FM sideband injection locking has shown that when SLs are locked to the target sidebands of the directly modulated ML, the presence of the unselected sidebands influences the resulting microwave signals [3]. The unselected signals can produce the unwanted beat signals around the desired beat signal, which degrade the overall system performance.

II. OPTICAL INJECTION LOCKING SCHEME

One method of generating optical /mm-wave signals is to use the optical injection locking (OIL) technique [4]. In this technique, the master laser (ML) is directly RF-modulated and has multiple optical sidebands which are separated by the modulation frequency, fm. Two slave lasers (SL's) are then injection-locked by two sidebands separated by the desired frequency offset, generating two coherent optical signals which can produce the desired beat frequency signal in the photodetector. In order to obtain high frequency signals, the rf-modulated ML should provide a large number of sidebands that are widely separated. The sideband generation, however, sensitively depends on the modulating RF-power and frequency. A technique that does not require external RF source would be highly desirable.

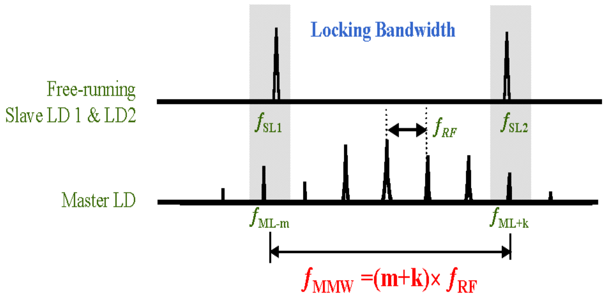

Fig. 1 Spectrum of beating signal between SL

Manuscript received July 16, 2010; revised July 17, 2010; accepted July 29, 2010.

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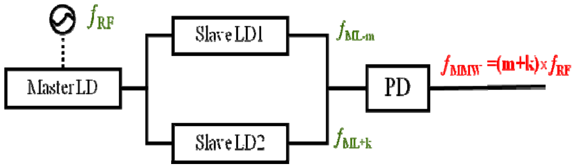


Fig. 2 Block diagram of the proposed OIL technique

III. ANALYSES OF OPTICAL INJECTION SCHEME

When optical output which is generated from ML is injected to SL, locking characteristics of the laser are classified into 3 regions. These characteristics consist of unlocking, dynamically stable locking and dynamically unlocking regions. These characteristics depend on injected optical output and lasing of frequency offset between ML and SL. Assuming DFB lasers with negligible side modes are used for both ML and SL, the SL under the influence of external light injection can be described by the following single mode rate equations shown below [3].

$$\frac{dP}{dt}=\left[\frac{\Gamma g_0}{1+\varepsilon P}(N-n_t)-\frac{1}{\tau_p}\right]P+\frac{\Gamma\beta}{\tau_n}N+2K_C\sqrt{P_{in}P}\cos(\Phi_{ML}-\Phi)$$
$$\frac{d\Phi}{dt}=-2\pi\Delta f+\frac{1}{2}\alpha\left[\Gamma g_0(N-n_t)-\frac{1}{\tau_p}\right]+K_C\sqrt{\frac{P_{in}}{P}}\sin(\Phi_{ML}-\Phi) \quad (1)$$
$$\frac{dN}{dt}=\frac{I}{qV_a}-\frac{g_0}{1+\varepsilon P}(N-n_t)P-\frac{N}{\tau_n}$$

In the above equations, P_{in} and Φ_{ML} represent the density and the phase of the injected photons and K_C (= $\upsilon_g/2L_a$) means the coupling rate between ML and SL. Other parameters have the usual meanings. The numerical values for the laser parameters used are obtained from reference [3].

TABLE 1
PARAMETERS USED

Symbol	Parameter	Value	Unit
Λ	lasing wavelength	1550	nm
Γ	confinement factor	0.4	
n_t	transparent carrier density	1.0 x 10^{18}	cm^{-3}
τ_p	photon lifetime	3.0 x 10^{-12}	sec
τ_n	carrier lifetime	1.0 x 10^{-9}	sec
β	spontaneous emission factor	3.0 x 10^{-5}	
υ_g	group velocity	8.5 x 10^{9}	cm/sec
g_0	differential gain	12.7 x 10^{-7}	cm^{3}/sec
ε	gain suppression factor	5.0 x 10^{-17}	cm^{3}
V_a	volume of active layer	1.5 x 10^{-10}	cm^{3}
α	linewidth enhancement factor	5	
η_{ex}	LD differential quantum efficiency	0.4	

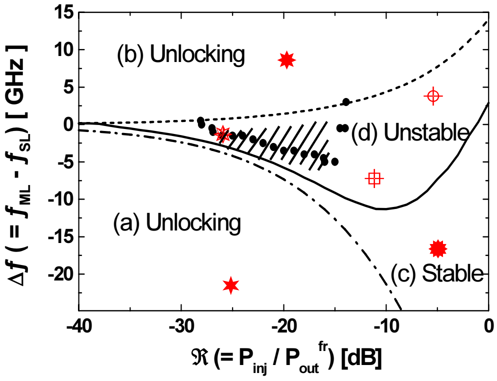


Fig. 3 Locking range versus injection power ratio

IV. TRANSIENT RESPONSE AND SPECTRUM FOR LOCKING REGIME

Recent studies on OIL have found that the modulation bandwidth of a semiconductor laser can be significantly enhanced under the strong optical injection [4]. However, the locking properties under the strong optical injection have not been fully analyzed outside the dynamically stable locking range, where effects such as undamped relaxation oscillation and chaos can occur. We analyze the spectral characteristics of semiconductor lasers under strong optical injection, and show that the generation of multiple optical sidebands having large frequency separation is possible. By feeding these sidebands into two SL's, as shown in Fig. 2, it is possible to generate optical μ/mm-waves without using any external RF source. From the steady-state analysis of the rate equations, Fig. 3 shows the locking and unlocking regions as function of Δf and ℜ. Here, injection power ratio ℜ is defined as P_{inj}/P_{out}, where P_{inj} is the injected optical power just outside the SL facet and P_{out} is SL output power. For the results shown in Fig. 2, SL output power is fixed at 2mW. If the gain suppression and the spontaneous emission terms are ignored, the range of Δf that allows locking can be determined as follows [5].

$$\left|\Delta f(=f_{ML}-f_{SL})\right|\le\frac{K_C}{2\pi}\sqrt{\frac{P_{in}}{P}(1+\alpha^2)} \quad (2)$$

When light from ML is injected into SL, the locking characteristics can be classified into three distinctive regimes: unlocking, dynamically stable locking, and dynamically unstable locking. Both dynamically stable and unstable locking regimes can be grouped together as the static locking regime. These characteristics are determined based on the injected optical power and the lasing frequency offset between ML and SL. For the analysis, the laser rate-equations including injected light are used for a sample LD whose parameters are obtained from [3]. Figure 3 maps the characteristic regimes determined from the rate-equation analysis. In the figure, Δf is the frequency difference between the ML (f_{ML}) and SL lasing frequency (f_{SL}), and the injection power ratio, $\Re$, is the ratio between the injected ML optical power (P_{inj}) and SL optical power ($P_{\mathrm{out}}^{\mathrm{fr}}$) without optical injection. The boundaries for the static locking regime can be obtained from the steady-state solutions of the OIL rate equations. Within the static locking regime, the stability analysis of the linearized transfer function determines the dynamically stable locking regime. The calculated power spectra at the operating points (c) in Fig. 3 are illustrated in Fig. 5. These are obtained by Fourier transforming the SL output power at the steady-state determined from the large-signal numerical analysis of the rate-equations. In the case of signal response, waveform is depicted under injected step-like current from $1.01I_{th}$ to $1.5I_{th}$ at 2ns. Each value is normalized by high values obtained from FFT outputs in the case of free-running state. We can estimate all optical power of SL locked in ML frequency in stable locking. The theoretical power spectra were calculated by taking the fast Fourier Transform (FFT) of the steady-state slave intracavity electric field over a given time window. The power spectrum of region (a) in Fig. 3 is typical for the unlocking regime. Unlocked power exists only at f_{SL}. On the other hand, the power spectrum for another unlocking region (b) at Fig. 3 shows positive Δf. Here, the injected light is amplified and beats the SL light. This causes the four-wave mixing between ML and SL light and generates multiple conjugate sidemodes. The sidemode separation, $\Delta\nu$, equals Δf but this region is not useful for optical μ/mm-wave signal generation because the conjugate sidemodes are not coherent. The region (c) in Figure 3 shows the power spectrum at the dynamically stable regime. Here, SL is locked to ML and has power spectrum only at f_{ML}. The dynamically unstable locking regime is characterized by undamped relaxation oscillation and chaos as shown region (d) in Fig 3. Figure 5(d) shows the case of chaos, where the spectrum is densely spread. We find that chaos occurs when $\Re$ is less than about -14 dB, as indicated by shades in figure 3. This agrees with the experimental and analytical results [3]. When $\Re$ > -14 dB, the undamped relaxation sidebands appear and their separation becomes larger by increasing $\Re$ and Δf. The maximum possible $\Delta\nu$ as function of $\Re$ is illustrated in Fig. 4. When two SL's are locked to two of the sidebands generated in the dynamically stable regime shown in Fig. 5(c), they can act as frequency filters and suppress other undesired sidesmodes. Then, two SL's output light will be two coherent signals separated by a multiple of $\Delta\nu$ and the beat signals at the multiple of $\Delta\nu$ can be generated at the photodiode to have the desired signal. This technique allows $\Delta\nu$ as large as 15.4 GHz at $\Re$= 0 dB in the present analysis. For example, if two sidebands indicated by arrows in Fig. 5(e) and (f) are selected, the beat frequencies of 58 GHz ($\Delta\nu$ = 7.25 GHz), and 100.8 GHz ($\Delta\nu$ = 12.6 GHz) can be obtained.

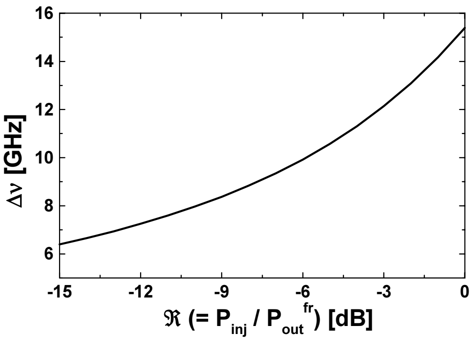
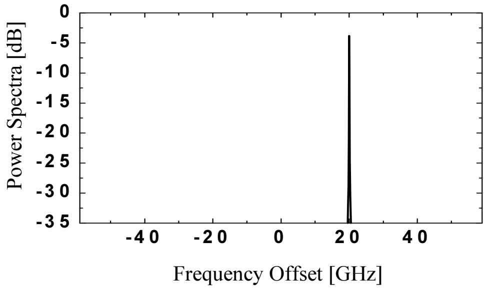
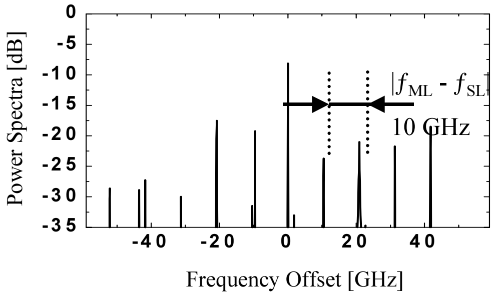


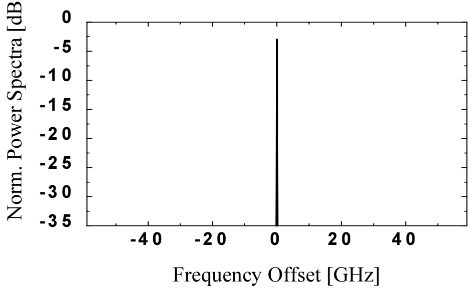
Fig. 4 Separation of sideband as function of boundary condition



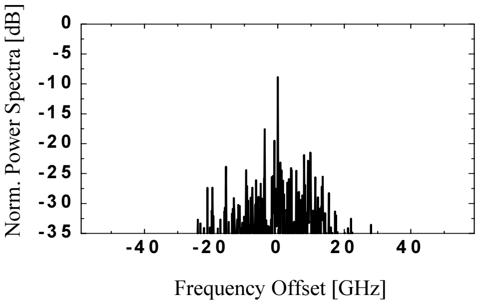
(a) Unlocking (Lower)



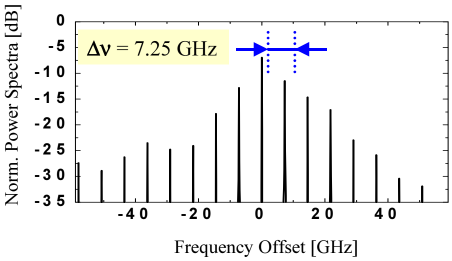
(b) Unlocking (Upper)



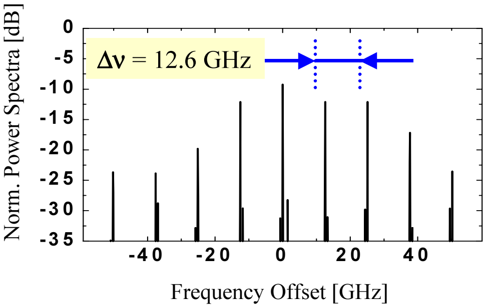
(c) Stable locking



(d) Chaos



(e) Unstable locking



(f) Unstable locking

Fig. 5 Optical output spectrum calculated at different power ratio (a) Unlocking (Lower) (b) Unlocking (Upper), (c) Stable locking (d) Chaos (e) Unstable locking (58 GHz) (f) Unstable locking (100.8 GHz)

V. CONCLUSION

In this paper, we have analyzed the spectral characteristics of the semiconductor lasers locked to the sidebands of the master laser, which were expressed by a series of the Bessel function. The numerical model for the semiconductor lasers based on the typical Lang's equation has been extended in order to take into account the simultaneous injection of the multiple sidebands of the directly modulated ML. The numerical simulations have showed that the unselected sidebands can affect the optical and RF-spectral characteristics even when the semiconductor laser is stable-locked to the target sidebands. Due to the presence of the unselected sidebands, the unwanted powers in the optical and RF-spectra will increase with the ML power, and be combined with the fiber chromatic dispersion so that they may degrade the overall system performance.

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