Characteristics of Semiconductor Laser Using Optical Injection Locking Scheme

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Abstract— We have investigated the spectral characteristics of semiconductor lasers locked to the external light injected from a modulated laser. The numerical model for semiconductor lasers under the external 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. In this paper, we have analyzed characteristics of semiconductor laser using optical injection locking

I. INTRODUCTION

The demand for new services and the increasing number of sub-carrier requiring high-speed digital data transmission have pushed carrier frequencies from the microwave towards the millimeter-wave range. In broadband networks based on the inherent advantages of the millimeter-wave range, wider radio frequency channels can be allocated. Wireless connection of subscribers significantly reduces maintenance and installation costs, and allows mobile applications. However, due to the high atmospheric attenuation of millimeter-wave signals, it is straightforward to employ fiber-optic for the feed of the base station.

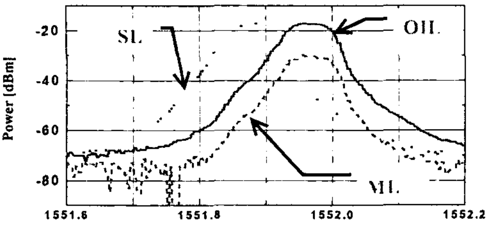
Several methods have been reported for the generation of modulated RF optical carriers for implementing fiber-wireless systems. These include optical heterodyne and self-heterodyne techniques such as dual-mode semiconductor laser and fundamental and harmonic signal generation using pulsed lasers. However, the simplest technique for the optical generation and distribution of the RF signal modulation is an intensity modulation scheme via direct or external modulation of a laser. Since direct modulation suffers from the effects of laser frequency chirp, externally modulated optical fiber links are the preferred choice.

II. Overview of Injection Locking

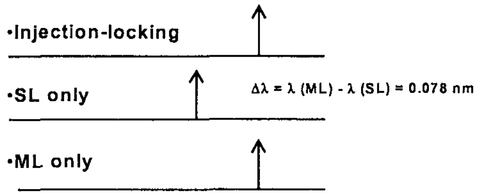
Although the direct current modulation of semiconductor lasers is simple and compact, it is not suitable to the high-speed applications. It is because the lasing frequency-shift, or chirp, during the direct current modulation combined with the fiber dispersion, causes the system performance degradation. This degradation becomes more serious when the transmission speed increases. One method of overcoming the chirp and subsequent fiber dispersion problems is to use optical injection locking (OIL). OIL provides such advantages such as the reduction of chirp, linewidth, and noise, modulation bandwidth enhancement, and other functions such as wavelength conversion, and optical generation of mm-wave signals. Fiber-optic transmission experiments using OIL technique has been successfully demonstrated in the modulation speed less than 500 Mbps, but not much analytical work has been done over the effect of optical injection on transmission performance.

The optical injection locking technique with semiconductor laser diodes (LDs) is widely used in chirp and linewidth reduction, measurement of the laser dynamics, wavelength conversion, and optical microwave generation. In particular, the optical microwave signal generation technique with injection locked lasers is very promising for many applications because it can easily produce high frequency signals with low phase noise. In the sideband injection-locking scheme, the master laser (ML) is electrically modulated and two of the resulting sidebands having the desired frequency separation are injected into two slave lasers (SLs). When these two injection-locked SLs beat each other in the photodiode (PD), the desired microwave signal is generated. Using this method, Braun *et al.* has recently reported the successful demonstration of 60 GHz beat signal generation.

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 influence the resulting microwave signals. The unselected sidebands can produce the unwanted beat signals around the desired beat signal, which degrade the overall system performance. The reduction in the incident light power helps in suppressing the unwanted beat signals, but it also reduces the locking range causing the stability problem. In this paper, we investigate the influence of the ML sidebands on the spectral characteristics of sideband injection-locked semiconductor lasers numerically and experimentally. The numerical models for the sideband injection-locked slave lasers are based on extended Lang's model, which includes the influence of multiple ML sidebands expressed by the Bessel function [1]. With multiple ML sidebands, the large-signal analyses for the SL spectra are performed. Finally, we investigate the influence of the unselected sidebands on the SL spectral properties for the different ML injection powers.



(a) Optical spectra



(b) comparison of wavelength by generating OIL

Fig. 1. Optical spectra and comparison of wavelength by optical injection locking

III. MODELING OF SINGLE MODE RATE EQUATION UNDER EXTERNAL LIGHT INJECTION

OIL configuration consists of two lasers, where the CW power generated from master laser (ML) is injected into slave laser (SL) with frequency offset (Δf) in between the ML's lasing frequency (f_{ML}) and the SL's lasing frequency at threshold (f_{SL}). We limit our investigation to the SL emitting power of 3 dBm for numerical simulation to avoid the undesired nonlinear effect of the optical fiber, such as stimulated Brillouin scattering. Since the sidemodes of DFB lasers in general are strongly suppressed, SL under external injection can be modeled based on the single-mode longitudinal rate-equations, in which ML's light is taken into account, as shown in reference [1,2].

$$\frac{dP}{dt}=\left[\frac{\Gamma g_0}{1+\varepsilon P}(N-n_t)-\frac{1}{\tau_p}\right]P+\frac{\Gamma\beta}{\tau_n}N+2K_C\sqrt{P_{in}P}\cos(\Phi_{ML}-\Phi) \tag{1}$$

$$\frac{d\Phi}{dt}=-2\pi\Delta f+\frac{1}{2}\alpha\left[\Gamma g_0(N-n_t)-\frac{1}{\tau_p}\right]+K_C\sqrt{\frac{P_{in}}{P}}\sin(\Phi_{ML}-\Phi) \tag{2}$$

$$\frac{dN}{dt}=\frac{I}{qV_a}-\frac{g_0}{1+\varepsilon P}(N-n_t)P-\frac{N}{\tau_n} \tag{3}$$

where, P and N are the photon and carrier density in the active layer, Φ is the optical phase, Γ is the confinement factor, n_t is the transparent carrier density, τ_p and τ_n are the photon and carrier lifetimes, β is the fraction of spontaneous emission coupled to the lasing mode, $K_C = c/2n_gL_a$ is the coupling rate with c the light velocity in vacuum, n_g is the group refractive index, L_a is the active cavity length, P_{in} and Φ_{ML} are the injected photon density and phase of ML, g_0 is the differential gain, ε is the gain suppression factor, I is the applied current, q is the electron charge, and V_a is the volume of the active layer. α is the linewidth enhancement factor, which is directly related to the optical lasing frequency chirp. Here, we define the injection power ratio as $R = P_{inj} / P_{out}$, where P_{inj} is the ML's injecting power just outside the SL facet, and P_{out} the SL emitting power. The rate-equations without the light injection terms, P_{in} and Δf, are same as those of the free-running laser [3].

When SL becomes locked at the steady-state, $\frac{dP}{dt}=\frac{d\Phi}{dt}=0$, the locking range is bounded within

$$\Delta f(=f_{ML}-f_{SL})\le\frac{K_C}{2\pi}\sqrt{\frac{P_{in}}{P}(1+\alpha^2)} \tag{4}$$

where, the gain suppression and spontaneous emission terms are neglected for simplicity. This locking range can be classified into two regimes: stable-locking regime and unstable-locking one. In the stable-locking regime, the emitting power variation converges to its steady-state level after the short excitation by small perturbation. In the unstable locking one, however, the power does not converge to the steady state but makes the self-sustained oscillation after the small perturbation. The multiple sidebands due to the oscillation cause the system performance degradation. Thus, we limit our analysis to the stable locking.

In addition to the modulation bandwidth enhancement above, OIL can provide the great reduction of the large-signal chirp as well. The significant reduction in frequency chirp comes from optical injection. When $g_0/(1+\varepsilon P)$ in Equation (1) is simplified into $g_0(1-\varepsilon P)$ using the Taylor expansion, the OIL frequency chirp, δv, can be written by rearranging Equation (1) and (2) as

$$\begin{aligned}2\pi\delta\nu&=\frac{d\Phi}{dt}=\frac{\alpha}{2}\left[\Gamma g_0(N-n_t)-\frac{1}{\tau_p}\right]-2\pi\Delta f+\kappa\sin\theta\\&=\frac{\alpha}{2}\left[\frac{1}{P}\frac{dP}{dt}+\varepsilon\Gamma g_0(N-n_t)P-\frac{\beta\Gamma N}{\tau_n P}\right]-2\pi\Delta f-\alpha\kappa\cos\theta+\kappa\sin\theta\end{aligned} \tag{5}$$

where, $\theta\left(=\Phi_{ML}-\Phi_{SL}\right)$ is the phase difference, and the coupling coefficient κ is $K_C\sqrt{P_{in}/P}$ Equation (5) can be rewritten as

$$\begin{aligned}2\pi\delta\nu&=\frac{\alpha}{2}\left[\frac{d\ln P}{dt}+\varepsilon\Gamma g_0(N-n_t)P-\frac{\beta\Gamma N}{\tau_n P}\right]\\&\quad-2\pi\Delta f-\kappa\sqrt{(1+\alpha^2)}\cos\left(\theta+\tan^{-1}\frac{1}{\alpha}\right)\end{aligned} \tag{6}$$

The analytical equation of frequency chirp is same as one of free running case except for the contribution of the external light. The first term above corresponds to the dynamic frequency chirp or transient chirp, expressed as the derivative of power fluctuation with time. And the second and third terms describe the DC frequency chirp by the gain suppression and spontaneous emission, respectively. They contribute to the lasing frequency difference between the ON and OFF state during current modulation. The large gain suppression causes the large frequency difference in two steady-state power levels. The last two terms are the contribution of the external optical injection to δv. Since δv is proportional to $-\sqrt{P_{in}}$, δv can be reduced by injected photon density.

Another reason for OIL chirp reduction comes from the changes of carrier density, which determines the DC chirp. OIL needs less carrier density than free-running for a certain optical power level. This point becomes clear from the steady-state analysis of Equation (1) and (2), $\frac{dP}{dt} = \frac{d\Phi}{dt} = 0$. When the steady-state photon density is known, the steady-state carrier density is related with P_{in} as follows.

$$N = \left[\Gamma g_0 (1 - \varepsilon P) n_t + 1/\tau_p - 2\kappa \cos\theta\right] \Big/ \left[\Gamma g_0 (1 - \varepsilon P) + \frac{\Gamma\beta}{\tau_n P}\right] \qquad (7)$$

This equation shows that the steady-state carrier density is also proportional to $-\sqrt{P_{in}}$. Therefore, strong optical injection into SL causes much less carrier density, and decreases significantly the frequency difference DC chirp between the ON and the OFF state.

IV. Non-linearity Improvement with Optical Injection Locking

The optical analog transmission of GHz range signals is recently attracting much interest for WLL (Wireless Local Loop), CATV, and satellite system applications. In these applications, direct modulation of a semiconductor laser diode is used for transmitting signals multiplexed by RF range subcarriers. Consequently, the LD (Laser Diode) non-linearity becomes a key issue in the system performance because it can interfere and limit the number of channels as well as transmission distance [3]. One method of overcoming the LD non-linearity problem is using the optical injection locking (OIL) technique, where light from an external laser (Master laser) is injected into laser in the signal transmitted (Slaver laser). When slave laser is locked to master laser, it can have modulation bandwidth enhancement and chirp/noise reduction. We perform numerical analysis of injection locked lasers to show that injection locking improves LD non-linearity characteristics and experimentally confirms it. The numerical analysis of injection locked lasers is based on Lang's equations in which the laser nonlinearity characteristics are described with the gain suppression term in the rate equations. The simulation parameters are obtained from reference [1,4]. For the simulation, two rf-sources (f_1=2.5GHz and f_2=2.7GHz) with the same amplitude are used in order to directly modulate the slave laser. The slave laser output spectrum is obtained by fast-Fourier-transforming the output power of slave laser calculated by the Runge-Kutta integration of Lang's equations.

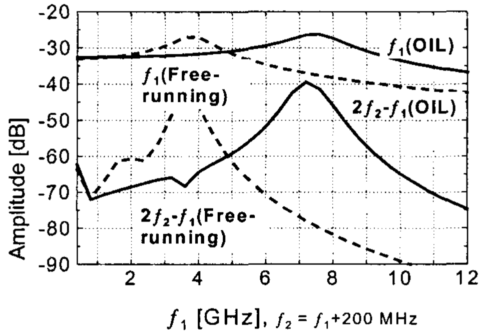


Fig 2. Simulated modulation frequency responses at f_1 and $2f_2$-f_1 for free-running and injection locked lasers

Figure 2 shows the amplitudes for fundamental and harmonic components of LD output spectra as function of amplitude for (a) free-running and (b) injection locked lasers. The second inter-modulation products (IMPs) at f_1+f_2 and $2f_1$, and third IMP at $2f_2$-f_1 are smaller for injection locked LD than for free-running LD. The slight difference in the amplitude of the fundamental term (f_1) is due to the change in LD dynamic characteristics caused by injection locking. Amplitudes of several frequency components are compared for free-running and OIL cases as shown in Figure 2.

V. Direct Modulation Bandwidth Enhancement by Strong Injection Locking

There are renewed research efforts for injection-locked laser diodes (LDs) as they can provide enhanced performance for various applications. The single mode rate equations for injection locked lasers are employed as follows.[5]

$$\frac{dS}{dt} = (G - \gamma)S + \frac{1}{L}\upsilon_g S_i \sqrt{\frac{S_i}{S}} \cos\theta + R \qquad (8)$$

$$\frac{d\Phi}{dt} = (\omega_i - \omega_o) + \frac{1}{2L}\upsilon_g \sqrt{\frac{S_i}{S}} \sin\theta \qquad (9)$$

$$\frac{dN}{dt} = -\frac{N}{\tau_e} - GS + \frac{I}{q} \qquad (10)$$

Here, where time-varying phase difference between master laser (ML) and slave laser (SL) is taken into accounts, S_i is the photon number injected into SL from ML through the optical isolator between them, and S is the photon number in the cavity of SL. By the small-signal analysis of these equations, the third order system function for injection-locked frequency response can be obtained. For free running LDs, the frequency response system function is of the second order.

We first found the allowed maximally phase detuning range between ML and SL. In order for the system to be stable, its poles should be located in the left plane in S-domain. Figure 3 shows the allowed phase detuning range for varying injection levels. The allowed maximum phase detuning value becomes larger as the injected photon number gets increased. It shows clearly that a stronger injection locking can provide larger direct modulation bandwidth. For example, the modulation bandwidth of an injection-locked laser at $(S_i/S) = -5$ dB is about three times larger than that of a free-running laser. The resonance frequency of the injection- locked laser is plotted for several injection-levels within each allowed frequency detuning range. The frequency detuning, $\Delta\omega = \omega_{SL} - \omega_{ML}$, can be determined from the following equation.

$$\begin{aligned}\Delta\omega &= \omega_M - \omega_{SL} \\ &= \frac{1}{2}\alpha\left[\Gamma v_g a_o (N - n_t) - \frac{1}{\tau_p}\right] + K_c\sqrt{\frac{P_{in}}{P}}\sin\theta\end{aligned} \tag{11}$$

Here, α is the linewidth enhancement factor. The modulation response is a strong function of applied injection level and phase/frequency detuning values.

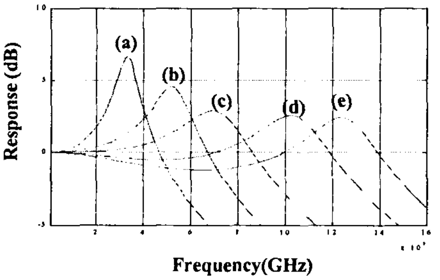


Fig 3. Modulation response for several injection levels with allowed phase detuning values

V. Conclusion

In conclusion, we have investigated 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. In this paper, we have shown that the characteristics of semiconductor laser using optical injection locking have nonlinearity improvement and modulation bandwidth enhancement.

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