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Optical Injection Locking을 이용한 반도체 레이저의 비선형성 향상
Non-linearity Improvement in Semiconductor Lasers with Optical Injection-Locking

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Abstract

Numerical analysis and experimental measurement were performed on the non-linear characteristics of semiconductor lasers that are optically injection-locked. It is shown that optical injection locking provides significant reduction in the inter-modulation products when semiconductor lasers are directly modulated with two-tone RF signals.

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 (LD) is used for transmitting signals multiplexed by RF-range sub-carriers. Consequently, the LD non-linearity becomes a key issue in the system performance because it can impose signal distortions by inter-channel interference, which limit the number of channels as well as transmission distance [1].

One method of overcoming the LD non-linearity problem is using the optical injection locking (OIL) technique [1], where light from an external laser (master laser, ML) is injected into the signal transmitting laser (slave laser, SL) as shown in Fig 1. When SL is locked to ML, it can have modulation bandwidth enhancement and chirp/noise reduction [2]. In this paper, we perform numerical analysis of injection-locked lasers to show that injection-locking improves LD non-linear characteristics and experimentally confirm it. We believe that this confirmation is done for the first time.

The numerical analysis of injection-locked lasers is based on Lang's equations [3] in which the laser nonlinear characteristics are described with the gain suppression term in the rate equations. The simulation parameters are obtained from [4]. For the simulation, two rf-sources (f_1 = 2.5 GHz and f_2 = 2.7 GHz) with the same amplitude (I_{rf}) are used in order to directly modulate the SL. The SL output spectrum is obtained by fast-Fourier-transforming the output power of SL laser calculated by the Runge-Kutta integration of Lang's equations.

Figure 2 shows the amplitudes for fundamental and harmonic components of LD output spectra as function of I_{rf} for (a) free-running (no optical injection) and (b) injection-locked (R = -7.9 dB, Δf = -15 GHz) lasers. R is the power injection ratio defined as the ratio of ML's power just outside the SL's facet to SL's emitting power under no optical injection. 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. This is shown in Figure 3 where the amplitudes of several frequency components are compared for free-running and OIL cases. It is found from Figure 3 that the external optical injection suppresses the third-order IMP, $2f_2-f_1$, by 6~25 dB within the range of 2~4 GHz.

Figure 4 shows the experimentally measured spectral amplitudes at f_1, f_1+f_2, $2f_1$, and $2f_2-f_1$ for varying RF currents (f_1 = 2.5 GHz, and f_1 = 2.7 GHz). For the measurement, an external-cavity tunable LD is used for ML and a DFB-LD (Samsung SDL24-B1-3) without isolator is used for SL. SL is dc-biased at $2\times I_{th}$ (I_{th} = 7 mA). We have not yet quantified the input current loss due to impedance mismatching. Figure 4 illustrates LD non-linearity improvement of OIL (estimated R = -3 dB, $\Delta\lambda$ = 0.078 nm) over free-running case. As the applied current is increased, the spectral amplitudes of the free-running laser get saturated because, we believe, over-modulation clips LD output. In the meanwhile, OIL amplitudes over the same current modulation do not saturate itself. We believe that this is related with the decrease of LD threshold current with the injection locking [5].

Figure 5 shows the measured *rf*-spectra for I_{rf} of 5 dBm. The OIL fundamental modulation product and third IMPs are smaller than free-running ones as expected from the numerical results. Theoretical and experimental results are in the qualitative agreement although the parameters used in the simulation do not reflect the parameters for the LD used in the experiment.

We believe that the IMP suppression with OIL can find useful applications in optical analog transmission systems. Future works are in progress in order to identify the exact cause for non-linearity reduction with optical injection.

References

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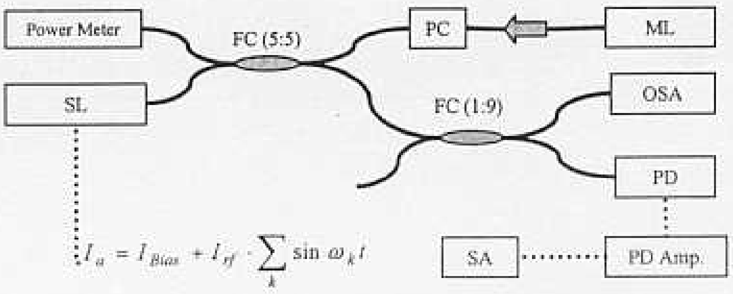

Figure 1. Basic block diagram for the experiment. The external cavity tunable laser and DFB-LD are used for ML and SL, respectively. PC denotes polarization controller, FC fiber coupler, OSA optical spectrum analyzer, PD high-speed photodiode, PD Amp PD amplifier (Gain ≈ 10 dB), and SA spectrum analyzer. The arrow indicates optical isolator (Samsung ISO-A115NO).

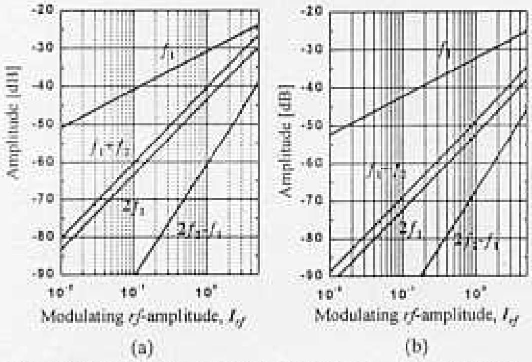

Figure 2. Simulated spectral amplitudes at f_1, $f_1 + f_2$, $2f_1$, and $2f_2 - f_1$ for (a) free-running (no optical injection) and (b) injection-locked (R= -7.9dB, Δf= -15 GHz) lasers (f_1 = 2.5 GHz and f_2 = 2.7 GHz).

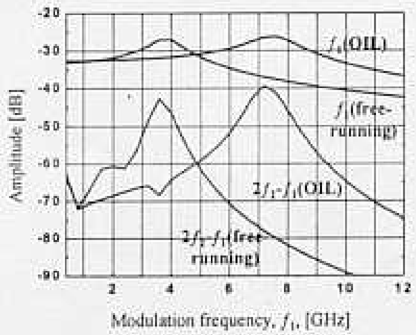

Figure 3. Simulated modulation frequency responses at f_1 and $2f_2 - f_1$ for free-running and injection-locked lasers ($f_2 = f_1$ + 200MHz, I_{rf} = 1 mA).

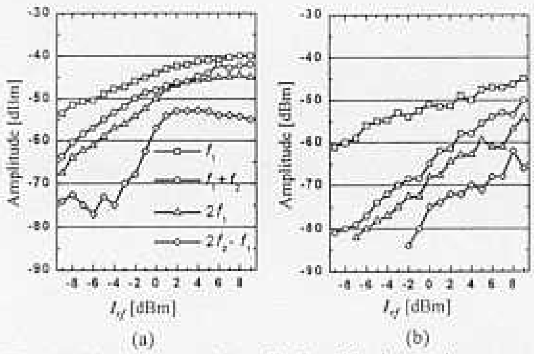

Figure 4. Measured spectral amplitudes of fundamental modulation, and second / third inter-modulation products for (a) free-running and (b) injection-locked (R = -3 dB, Δf= -9.75 GHz) lasers (f_1 = 2.5 GHz and f_2 = 2.7 GHz).

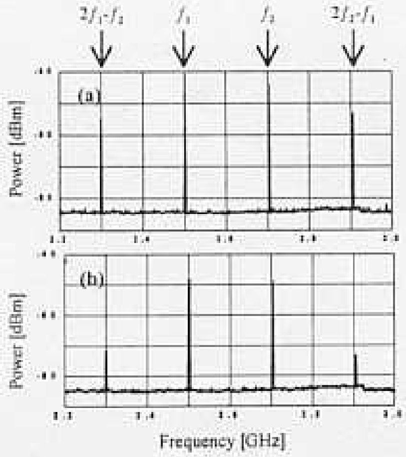

Figure 5. Measured rf-spectra of (a) free-running and (b) injection-locked lasers for I_{rf} = 5 dBm in Figure 4.