Analysis and Suppression of Dynamic Nonlinear Distortions in Semiconductor Laser Diodes

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Abstract

In analog optical communication systems, the optical source linearity is one of key elements that determine system performance. We analyze nonlinear distortions of directly modulated DFB laser diodes and examine optical injection locking technique as a way of suppressing them.

Introduction

There is a strong need for analog optical communication systems [1, 2]. One example is the radio-on-fiber system in which high frequency carriers and sub-carrier multiplexed data are simultaneously transmitted through a single fiber [2]. In Korea, such systems are widely used for optical repeaters for mobile communication systems. In these systems, one of the key elements that determine the total system performance is optical source linearity. Direct modulation of semiconductor laser diodes is the simplest and most economical solution but linearity of the laser diode is often not sufficient for many applications. This is especially the case for next generation mobile systems, which require much higher carrier frequencies. Consequently, it is of significant importance to understand the causes for nonlinearity in laser diodes and to come up with ways of suppressing it. In this paper, we present an accurate method for analyzing signal distortions due to laser diode nonlinearity. In addition, we investigate the injection locking technique that can be used for suppressing laser diode nonlinearity.

When laser diodes are directly modulated, there are several causes for nonlinearity. In sub-carrier multiplexed systems, which usually have many channels in the range of a few hundred MHz, static nonlinear L-I characteristics and clipping are the main causes for distortion [3]. For dynamic nonlinearity, which becomes more important as the modulation frequency increases, approximate [4] and numerical [5] distortion models have been reported. However, these approaches do not include distortions in frequency modulation. For a more accurate model of nonlinear distortions in analog optical links, we analyze nonlinear dynamics of laser diodes and consider their effects in both intensity and frequency modulation. We confirm the results of our analysis with measurement of second harmonic distortions in a wide frequency range.

To overcome distortion problems due to laser diode nonlinearity, several methods have been reported such as electro-optic feedback [6], feedforward compensation [7], predistortion [8, 9], and optical injection locking [10, 11]. Among them, the optical injection locking technique is attractive because it can provide other benefits such as narrow laser linewidth [12], chirp reduction [13, 14], and low mode partition noise [15]. We examine the influence of the injection locking on nonlinear distortions and show that the lasing frequency of the injected light has significant influence on the nonlinear distortion suppression.

Nonlinear distortion of laser diode

Intrinsic dynamic nonlinearity in a laser diode is caused by the interaction between carriers and photons in laser cavity. This can be analyzed based on the rate equations [16, 17]. The rate equations used in our analysis are shown below.

$$\begin{aligned}
\frac{dS(t)}{dt} &= 1 g_0 \frac{N(t)-N_t}{1+\varepsilon S(t)} S(t) - \frac{S(t)}{\tau_p} + \frac{1\beta}{\tau_n} N(t) \\
\frac{dN(t)}{dt} &= \frac{I(t)}{qV} - \frac{N(t)}{\tau_n} - g_0 \frac{N(t)-N_t}{1+\varepsilon S(t)} S(t) \\
\frac{d\phi(t)}{dt} &= \frac{\alpha}{2}[\Gamma g_0 (N(t)-N_t) - \frac{1}{\tau_p}] \\
v(t) &= \frac{1}{2\pi}\frac{d\phi(t)}{dt}
\end{aligned} \tag{1}$$

S is photon density, N is carrier density, Γ is confinement factor, N_t is carrier density at transparency, τ_p is photon lifetime, τ_n is carrier lifetime, ε is gain compression factor, g_0 is gain slope, q is electron charge, V is volume of active region, and α is linewidth enhancement factor. Since any quantitative investigation based on the rate equations requires numerical values for the parameters used in equations, we extracted numerical values for the parameters of the laser used in our investigation following the procedure given in [18].

For the nonlinear distortion analysis, we used the perturbation method in which a sinusoidal input current of small magnitude with modulation frequency ω is assumed, and output photon density and carrier density have their harmonic responses varying around the mean values. In equations, this can be expressed as following:

$$
\begin{aligned}
&I = I_0 + \frac{1}{2}(\Delta I_1 e^{j\omega t} + \Delta I_1^* e^{-j\omega t}) \\
&S = S_0 + \frac{1}{2}(\Delta S_1 e^{j\omega t} + \Delta S_1^* e^{-j\omega t}) + \frac{1}{2}(\Delta S_2 e^{j2\omega t} + \Delta S_2^* e^{-j2\omega t}) + \cdots \qquad (2) \\
&N = N_0 + \frac{1}{2}(\Delta N_1 e^{j\omega t} + \Delta N_1^* e^{-j\omega t}) + \frac{1}{2}(\Delta N_2 e^{j2\omega t} + \Delta N_2^* e^{-j2\omega t}) + \cdots \\
&\Delta v = v_0 + \frac{1}{2}(\Delta v_1 e^{j\omega t} + \Delta v_1^* e^{-j\omega t}) + \frac{1}{2}(\Delta v_2 e^{j2\omega t} + \Delta v_2^* e^{-j2\omega t}) + \cdots
\end{aligned}
$$

Inserting Eq. (2) to Eq. (1), we can find relationships for first order terms as given in Eq. (3) and second order terms in Eq. (4).

$$
\begin{aligned}
&a_{11} \times \Delta S_1 + a_{12} \times \Delta N_1 = 0 \\
&a_{21} \times \Delta S_1 + a_{22} \times \Delta N_1 = \Delta I_1 \qquad (3) \\
&\Delta v_1 = -a_{32} \times \Delta N_1
\end{aligned}
$$

$$
\begin{aligned}
&b_{11} \times \Delta S_2 + b_{12} \times \Delta N_2 = K_1 \\
&b_{21} \times \Delta S_2 + b_{22} \times \Delta N_2 = K_2 \qquad (4) \\
&\Delta v_2 = -b_{32} \times \Delta N_2
\end{aligned}
$$

In the above equations, each coefficient is function of lower order terms and ω. If we measure ΔS_1 as functions of ω, values for all other terms can be determined.

For analyzing second harmonic distortions after fiber transmission, the E-field can be expressed as shown in Eq. (5) that fully considers laser diode dynamics. Values for both magnitude and phase indices can be obtained as shown in Eq. (6).

$$
\begin{aligned}
E(t, z=0) \equiv P_0^{1/2}&(1 + m_{IM1}\cos(\omega \cdot t + \varphi_{IM1}) + m_{IM2}\cos(2\omega \cdot t + \varphi_{IM2}))^{1/2} \qquad (5) \\
&\cdot \exp(i \cdot m_{FM1}\cos(\omega \cdot t + \varphi_{FM1}) + i \cdot m_{FM2}\cos(2\omega \cdot t + \varphi_{FM2}))
\end{aligned}
$$

$$
\begin{aligned}
&m_{IM1} = \Delta S_1 / S_0, m_{IM2} = \Delta S_2 / S_0 \\
&\varphi_{IM1} = \arg(\Delta S_1), \varphi_{IM2} = \arg(\Delta S_2) \qquad (6) \\
&m_{FM1} = \Delta v_1 / f, m_{FM2} = \Delta v_2 / 2f \\
&\varphi_{FM1} = \arg(\Delta v_1), \varphi_{FM2} = \arg(\Delta v_2)
\end{aligned}
$$

In order to model the influence of fiber dispersion, the fiber transfer function given in Eq. (7) can be used.

$$H(f) = e^{j\pi \cdot \lambda^2 \cdot D \cdot L \cdot f^2} \qquad (7)$$

Experiments are performed in order to verify the accuracy of our model for a fixed link length (40km) with varying modulation frequencies and at a fixed modulation frequency (4GHz) for varying fiber lengths. Fig. 1 shows measured fundamental signals and second harmonic distortions. Calculated results with our model are shown in solid lines. Good agreement with the measured results can be seen. For comparison, calculated results with previously reported models are shown in dashed [4, 5] and dotted lines [19, 20] respectively. Accurate modeling is possible for the entire frequency ranges and transmission distances.

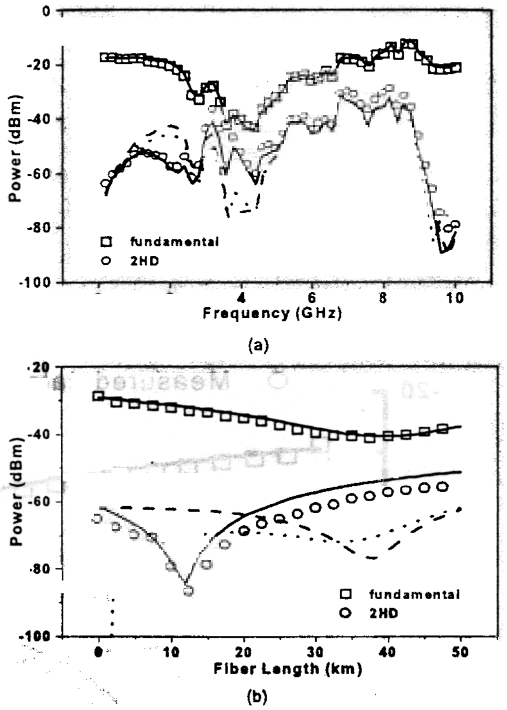

Fig. 1. Fundamental signals and 2nd harmonic distortions after transmission. Dotted lines; measured results, solid lines; calculated results with Eq. (5), dashed and dotted lines; calculated with models previously reported.

Nonlinear distortion suppression by optical injection locking.

Optical injection locking occurs when external light from Maser Laser (ML) is injected into Slave Laser (SL) and the SL characteristics are controlled by the ML. For the stable injection locking, the frequency difference between ML and SL as well as injection power ratio should satisfy certain stability conditions. It has been reported that injection-locked laser diodes have significantly reduced dynamic nonlinear distortions [10, 11]. The mechanism for distortion reduction can be explained as following. When locking occurs, the relaxation oscillation frequency of the SL increases. Since the nonlinear distortions are more pronounced as the modulation frequency approaches the relaxation oscillation frequency, the injection-locked laser with the increased relaxation oscillation frequency suffers less from nonlinear distortions. However, the amount of distortion suppression can be influenced by the locking conditions such as injection wavelength. Our investigation is aimed at understanding this dependence and determining the optimal locking condition.

In order to determine the dependence of distortion suppression on injection wavelength, the amounts of IMD2 (second order intermodulation distortion) suppression are measured at various injection wavelengths that are within the sable locking range. The SL is modulated with 2.8 GHz and 2.9 GHz RF signals, and the modulation power is adjusted to the free-running (no optical injection) modulation power. The ML wavelength is swept from 1550.15 nm to 1550.30 nm. Fig. 2 shows the experimental results with 2dBm injection power. When frequency detuning is small, IMD2 is suppressed very much. On the other hand, when frequency detuning is large, IMD2 is not suppressed enough.

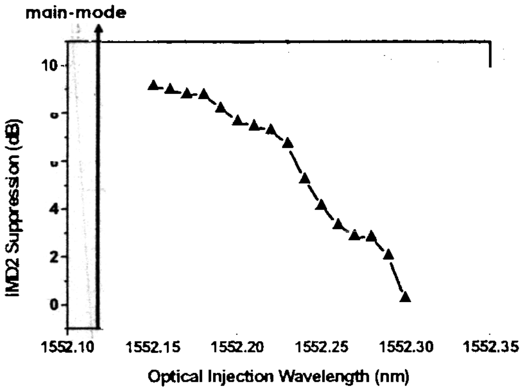

Fig. 2. IMD2 suppression as function of injected wavelength. IMD2 Suppression is defined as IMD2 at free-running state – IMD2 at the locking state

To investigate this result, the laser frequency responses according to the optical injection wavelength are simulated. Fig. 3 is the frequency response simulation results. The rate equations including external light effects are used for this simulation [21].

$$\frac{dS}{dt}=[\Gamma g_0\frac{(N-N_t)}{(1+\varepsilon S)}-\frac{1}{\tau_p}]S-R_{SP}+2Kc\sqrt{S_{inj}S}\cos\theta$$

$$\frac{d\Phi}{dt}=\frac{1}{2}\alpha[\Gamma g_0\frac{(N-N_t)}{(1+\varepsilon S)}-\frac{1}{\tau_p}]-(\omega_{inj}-\omega_0)+Kc\sqrt{\frac{S_{inj}}{S}}\sin\theta \qquad (8)$$

$$\frac{dN}{dt}=\frac{I}{qV}-\frac{N}{\tau_N}-g_0\frac{(N-N_t)}{(1+\varepsilon S)}S$$

With the perturbation method, the frequency responses after light injection are calculated. The injection power ratio is fixed at – 8 dB and the frequency detuning is changed from –5.5 GHz to –37 GHz. At small frequency detuning, the relaxation oscillation frequency increases very much with small damping. However, at large frequency detuning, the relaxation oscillation frequency does not increase much. Instead, damping is very large. These effects reduce the modulated signal power. When the frequency detuning is small, damping effects are so large that the modulation signal power is greatly degraded. Therefore, such modulated signal power degradation is the result of frequency response change, and affects the distortion suppression.

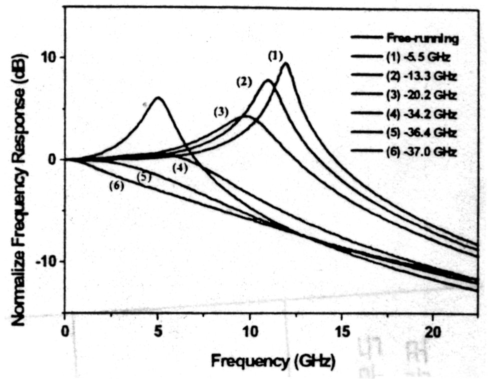

Fig. 3. Frequency responses of injection locked laser.

Then, to investigate the effects of modulated signal power degradation to the distortion suppression of the injection locked laser, the IMD2 suppression simulation is also done. Fig. 4 is the simulation results of IMD2 suppression and fundamental signal power degradation according to the injection wavelength. The injection locking conditions are same as the previous simulation conditions. Modulation frequencies are 2.8 GHz and 2.9 GHz and each modulation signal power is also adjusted to the free-running value. For numerical calculation of the IMD2 suppression at various injection wavelengths, the perturbation method is also employed. As shown in the figure, the simulation results are in good agreement with the experimental results. Moreover, the power degradation characteristics explain well the reason for IMD2 suppression results.

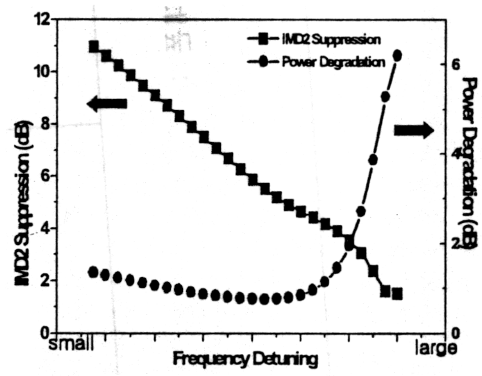

Fig. 4. Simulation results of the IMD2 suppression and fundamental signal power degradation according to the frequency detuning.

Conclusions

We analyzed the nonlinear distortions of the directly modulated laser diodes that can be used in analog optical links. For the accurate distortion model, intrinsic dynamic distortion is considered. In addition, for reducing the nonlinear distortions, we investigated optical injection locking. Because the injection wavelength influences the frequency response very much, distortion suppression is varied according to the injection wavelength. We believe the results of our investigation are useful for realizing high performance analog optical links that are based on the directly modulated laser diodes.

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