Analyses of Characteristics for Direct Intensity Modulation Scheme

Jung-Tae Kim, *Member, KIMICS*

Abstract**—**We have investigated the spectral characteristics of the semiconductor lasers locked to the sidebands of the master laser in this paper, 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. We analyses characteristics of direct intensity modulation.

Index Terms**—**Direct Intensity Modulation, Optical modulation.

I. INTRODUCTION

A fiber-optic millimeter-wave uplink system can be classified as baseband, microwave IF (Intermediate Frequency) subcarrier and millimeter-wave radio frequency subcarrier according to subcarrier frequencies of signals transmitted in an optical fiber link. In the baseband transmission, influence of the fiber dispersion effect is negligible, and the base station configuration is the most complex. To use this method without a subcarrier frequency, it has no choice but to adopt time-division or code-division multiplexing. This requires higher-speed electrical processors. In the IF subcarrier transmission, the fiber dispersion effect does not cause a serious problem. Subcarrier miltiplexing can be employed, but downconversion from a millimeter-wave to an IF band is required at the base station. In the RF (Radio Frequency) subcarrier transmission, the base station configuration can be simplified only if a millimeter-wave optical external modulator and a high-frequency photodiode are respectively applied to the electric-to-optic (E/O) and the optic-to-electric (O/E) converters. For a simple base station configuration the millimeter-wave optical external modulation technique will be one of the best solutions [4]. A basic configuration is shown in Fig. 1(c). It consists of millimeter-wave link by using fiber-optic to deliver millimeter-wave signal transmission technique. Data transmitted in central station through millimeter-wave link is transmitted into base station by using fiber-optic link. And, it spreads out by wireless data through the antenna in base station. A fiber-optic millimeter-wave system can be classified as baseband, IF subcarrier and millimeter-wave radio frequency subcarrier. In baseband configuration, a signal in control station is transmitted into base station through fiber link. The transmitted signal is upconverted to an IF band signal. IF signal is modulated with LO (Local Oscillator) generating millimeter-wave frequency and transmitted into air by an antenna. This method is very difficult to handle because of complexity of base station. IF subcarrier configuration is shown in Fig. 1(b), the signal is transmitted after modulating with IF baseband in control station. Then signal is upconverted to millimeter-wave with local oscillator in base station. Compared to baseband system, the base station is simpler. In millimeter-wave radio frequency subcarrier system, it is possible for the base station to consist of only three simple components: a photodiode, millimeter-wave amplifier, and millimeter-wave antenna. This system has two advantages in leading to a simple base station configuration. One is that no millimeter-wave sources are required at the base station. The other is that no millimeter-wave mixer is needed [1].

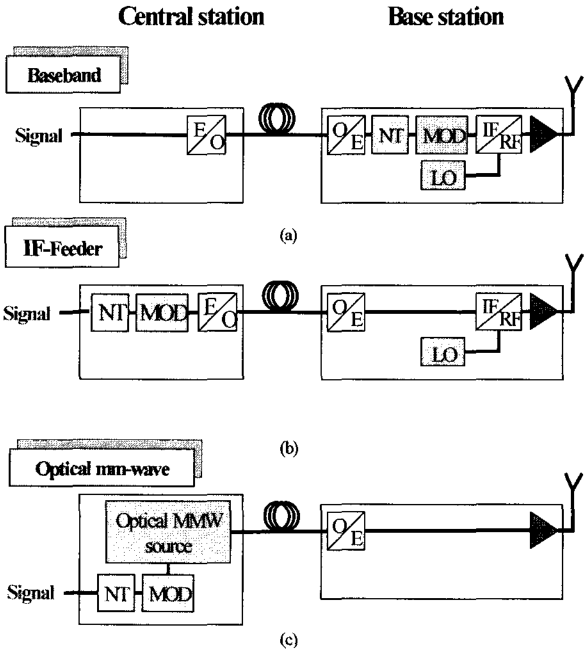


Fig. 1 Millimeter-wave link using fiber-optic configuration

Manuscript received July 6, 2006.

Jung-Tae Kim is with the Mokwon University, Department of Information Electronics & Imaging Engineering (phone: 82-42-829-7657, fax: 82-42-829-7653, e-mail: jtkim3050@mokwon.ac.kr)

II. CHARACTERISTICS OF DIRECT MODULATION METHOD

2.1. Direct Intensity Modulation

Fiber-optic microwave and millimeter-wave links which are subject to a still increasing interest can be implemented either by the use of direct detection techniques or heterodyne detection techniques. Many such links have been proposed, analyzed, and experimented. In the direct detection, the millimeter-wave signal is intensity modulated onto the optical carrier from a laser. The optical signal is then transmitted through the optical fiber, and the millimeter-wave signal is recovered by direct detection in a photodiode. In the remote heterodyne detection links, two phase correlated optical carriers are generated in a dual-frequency laser transmitter with a frequency offset the same as to the desired millimeter-wave frequency. Further, one of the optical carriers is modulated by the information to be contained in the millimeter-wave signal. Both optical signals are then transmitted through the optical fiber, and the millimeter-wave signal is generated by heterodyning the two optical signals in a photodiode. In both approaches the chromatic fiber dispersion becomes a limiting factor for the transmission distance when the microwave signals are in the above 20 GHz regime. In an Intensity Modulation Direct Detection link (IMDD), the millimeter-wave signal is carried as a lower and upper sideband on the optical carrier. Due to the dispersion and the large frequency offset between the side bands and the optical carrier, the phase of each of the spectral components of the transmitted optical signal has experienced a differential change. After detection, this results in a power reduction of the recovered millimeter-signal and thereby decreasing its carrier to noise ratio (CNR). The dispersion induced CNR penalty on the recovered millimeter-wave signal with the carrier frequency is found by comparing the signal power of millimeter-wave signal which is recovered by square law detection of the optical signal. Power shift of millimeter-wave signal is characterized by function of fiber distance due to the chromatic dispersion effect in fiber. IM-DD link and shift of optical spectrum by external modulation technique is shown in Fig. 2.

2.2. Non-linearity Improvement

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.

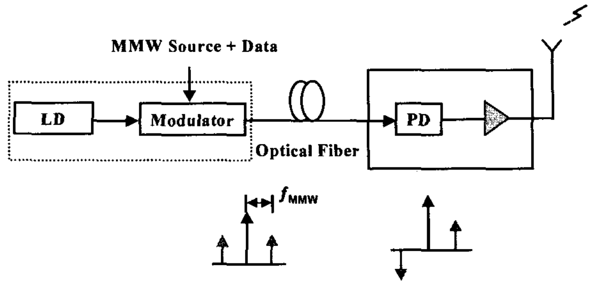


Fig. 2 Optical spectrum shift and IM-DD link using external modulation method

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 the signal transmitting laser (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. The numerical analysis of injection locked lasers is based on Lang's equations in which the laser non-linearity characteristics are described with the gain suppression term in the rate equations. The simulation parameters are obtained from reference. For the simulation, two RF-sources (f1 = 2.5 GHz and f2 = 2.7 GHz) 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. Figure 3 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 f1 + f2 and 2f1, and third IMP at 2f2 - f1 are smaller for injection locked LD than for free-running LD. The slight difference in the amplitude of the fundamental term (f1) 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 in Fig. 3.

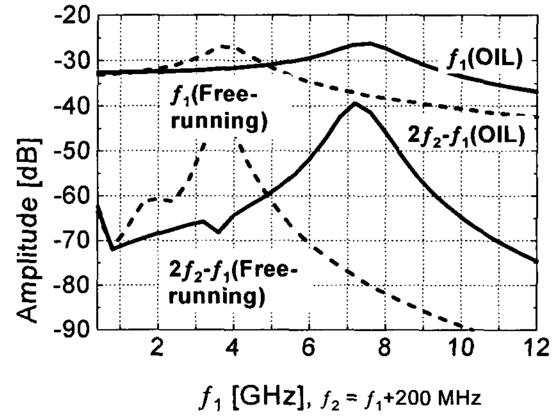


Fig. 3 Simulated modulation frequency responses at f1 and 2f2 - f1 for free-running and injection-locked lasers

2.3 Direct Modulation Bandwidth Enhancement

There are renewed research efforts for injection-locked laser diodes as they can provide enhanced performance for various applications. The single mode rate equations for injection locked lasers are employed as follows [2,3].

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

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

$$\frac{dN}{dt}=-\frac{N}{\tau_e}-GS+\frac{I}{q} \qquad (3)$$

where Si 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 laser diodes, the frequency response system function is of the second order. We first found the maximally allowed phase detuning range between ML and SL. In order to be stable for the system, its poles should be located in the left plane in s-domain. Figure 3 shows the allowed phase detuning range for a fixed injection levels. The maximally allowed phase detuning value becomes larger as the injected photon number gets increased. Figure 4 shows the direct modulation response for several injection levels at the allowed maximum phase detuning values. 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 (Si /S) = -5 dB is about three times larger than that of a free-running laser. Figure 5 shows modulation response for several phase detuning values with injection level fixed at –5 dB. Larger modulation bandwidth can be achieved by detuning the ML's phase. The resonance frequency of the injection-locked laser can be obtained for several injection-levels within each allowed frequency detuning range. The frequency detuning, Δω = ωML - ωSL, can be determined from the following equation.

$$\begin{aligned}\Delta\omega&=\omega_{ML}-\omega_{SL}\\&=\frac{1}{2}\alpha\left[\Gamma v_g a_o(N-n_t)-\frac{1}{\tau_p}\right]+K_c\sqrt{\frac{P_{in}}{P}}\sin\theta\end{aligned} \qquad (4)$$

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

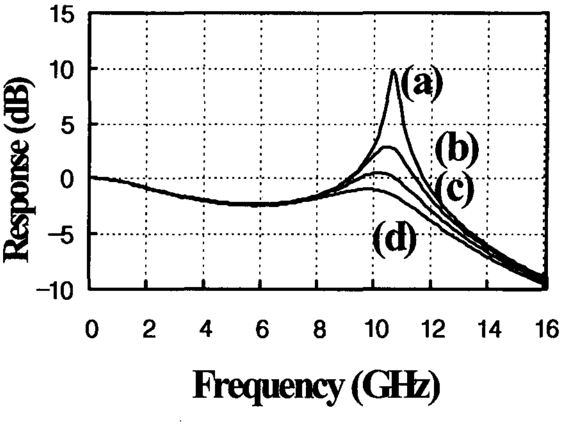


Fig. 4 Modulation response at a fixed injection level of –5 dB over phase detuning values, such as (a) 83 deg., (b) 80 deg., (c) 70 deg., and (d) 60 deg

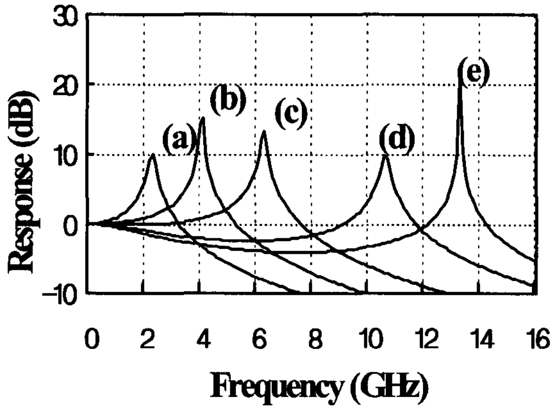
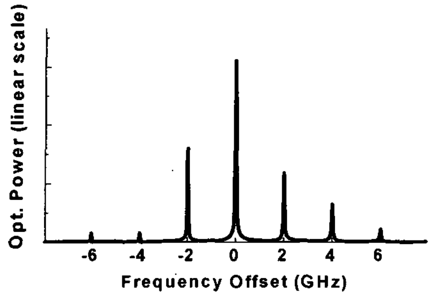


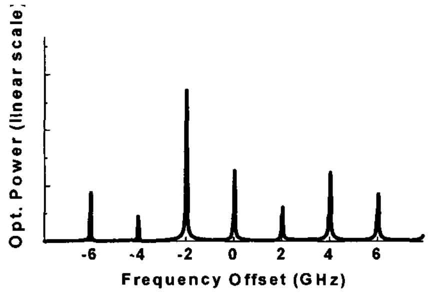
Fig. 5 Modulation response for several injection levels with allowed phase detuning values, such as (a) free running laser, (b) (Si/S) = -15 dB (θ = 48 deg.), (c) (Si/S) = -10 dB (θ = 71 deg.), (d) (Si/S) = -5 dB (θ = 83 deg.), and (e) (Si/S) = -3 dB (θ = 85 deg.)

2.4 Dependence of the Optical Spectrum for the ifferent Modulation Powers

The complex electrical amplitude of each sideband of the directly modulated semiconductor laser can be denoted in Eq. (1-3). Equation (1-3) shows the asymmetric sidebands in the optical spectrum since the IM response is superimposed on the FM response. The magnitude and quantity of the sidebands are determined directly by the FM index, m_{FM}, which has the relation with the intrinsic laser frequency chirp and increases with the modulation current as shown in Fig. 6. The increase of m_{FM} can make the target sideband power increase so that its power becomes larger than the center lasing peak power in the optical spectrum as illustrated in Fig. 6. In Fig. 6, it is assumed that the LD is biased at 1.5 times threshold at the modulation frequency of 3 GHz.



(a) $I_{mod} = 4mA$



(b) $I_{mod} = 8mA$

Fig. 6 Dependence of the optical spectrum for the different modulation Powers

III. CONCLUSION

We have analyzed the characteristics of direct intensity modulation and injection locking scheme. From the proposed scheme, we can apply the characteristics of scheme for millimeter wave application especially pico-cell wireless communication.

REFERENCES

[1] M. Gagnaire, "An overview of broad-band access technologies," *Proc. Of IEEE*, Vol. 85, No. 12, 1997, pp. 1958-1972.

[2] Gnitaboure Yabre and Jean Le Bihan, "Reduction of nonlinear distortion in directly modulated semiconductor lasers by coherent light injection," *IEEE J. Quant. Electron.*, Vol. 33, No. 7, July 1997, pp. 1132-1140.

[3] J. Le Bihan and G. Yabre, "FM and IM intermodulation distortions in directly modulated single-mode semiconductor lasers," *IEEE J. Quant. Electron.*, Vol. 40, No. 40, April 1994, pp. 899-904.

[4] Jung-Tae Kim et al., "Spectral characteristics of semiconductor lasers locked to external light injection from a current-modulated laser," *SPIE's Optoelectronics 2001*, January 2001, pp. 54-55.

Jung-Tae Kim

He received his B.S. degree in Electronic Engineering from Yeungnam University in 1989 and M.S. and Ph.D. degrees in Electrical and Electronic Engineering from the Yonsei University in 1991 and 1996, respectively. From 1991 to 1996, he joined at ETRI, where he worked as Senior Member of Technical Staff. In 2002, he joined the department of Electronic and Information security Engineering, Mokwon University, Korea, where he is presently professor. His research interest is in the area of Information security system technology that includes Network security system design, Chaos Cryptosystem and Wireless Communication.