Dispersion-Tolerant Transmission of 155-Mb/s Data at 17 GHz Using a 2.5-Gb/s-Grade DFB Laser With Wavelength-Selective Gain From an FP Laser Diode

Hye-Seung Ryu, Young-Kwang Seo, and Woo-Young Choi

***Abstract*—We present a novel scheme of overcoming laser diode (LD) intensity modulation bandwidth limitation by effectively improving modulation depth and simultaneously generating optical single sideband for radio-on-fiber applications. Our scheme uses wavelength-selective amplification characteristic of an LD under modulated light injection. The 17-GHz optical single sideband signals are generated with a 2.5-Gb/s-grade distributed feedback laser with wavelength-selective gain from a Fabry–Pérot LD. The 155-Mb/s data transmission at 17 GHz is successfully achieved.**

***Index Terms*—Intensity modulation, light injection, radio-on-fiber (RoF) system, semiconductor laser diode (LD).**

I. Introduction

RADIO-ON-FIBER (RoF) systems have attracted much attention for the future cellular radio access network and indoor wireless local area network applications [1]. This is mainly because RoF systems allow flexible network design by linking central offices and remotely located antenna units with optical fiber. A simple and cost-efficient approach for transmitting microwave signals over optical fiber is to employ intensity modulation of laser diodes (LDs). However, the LD modulation bandwidth is limited by its relaxation frequency, and although LDs with very high modulation speeds have been reported [2], their commercial availability is limited, especially for RoF applications.

In order to overcome the LD modulation bandwidth limitation, various schemes have been investigated such as strong external light injection [3] and harmonic enhancement with external optical feedback [4]. Although these methods can efficiently enhance the modulation bandwidth, several sidebands are produced in the optical spectra of RF modulated LDs, and these sidebands can cause the dispersion-induced power degradation problem when they are transmitted over the dispersive fiber [5]. Ideally, the transmitter spectra should have a single sideband separated from the optical carrier peak by the required RF carrier frequency. Although it is possible to filter out undesired modes by a fiber Bragg grating [6], this causes additional loss and the required filter resolution is very high.

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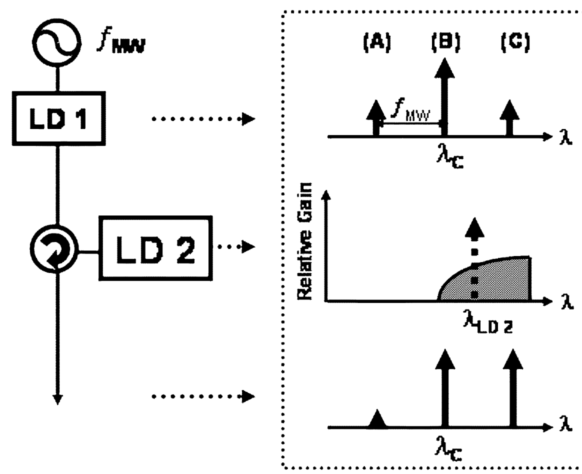

Fig. 1. Configuration for our scheme and schematic optical spectra for RF modulated LD1 and after passing through LD2. λ_{LD2} is the wavelength of free-running (without any injection) LD2.

In this letter, we propose and demonstrate a new scheme which can overcome the LD modulation bandwidth limitation by effectively improving modulation depth and, at the same time, produce the desired single sideband spectrum. Our scheme uses the wavelength-selective amplification characteristics of an LD under the modulated light injection. These characteristics have been previously investigated for producing an optical single sideband from double sidebands generated by an MZ modulator [7]. In this letter, our focus is on overcoming LD modulation bandwidth limitation by enhancing the intensity of the weak sideband and producing single sideband at the same time. We demonstrate transmission of single sideband 155-Mb/s data on a 17-GHz RF carrier by using a commercial 2.5-Gb/s-grade distributed feedback (DFB) laser along with a Fabry–Pérot laser diode (FP-LD).

II. Operation Principle

The configuration of the proposed scheme is shown in Fig. 1. LD1 is directly modulated with an RF source and several sidebands [Fig. 1(A), (b), and (C)] are produced. When these are injected into LD2, it is possible that the lasing modes of LD2 are suppressed and injected modes experience different amounts of loss and gain from LD2. One or several modes [specifically, Fig. 1(B) and (C)] that are within a certain wavelength range receive gain and others [for example, Fig. 1(A)] loss. The gain wavelength range is related to the injection-locking range of

LD2, and it is determined by several factors such as the free-running lasing (without injection) wavelength and power of LD2 and the injected light power [8].

In addition, among the modes that receive gain, the one [Fig. 1(C)] at the longer wavelength receives larger gain than the one [Fig. 1(B)] at shorter wavelength [9], which is quite useful for enhancing the weak sideband. This is related to the fact that, in an injection-locked LD, an external mode at the longer wavelength produces larger locked output power [9]. Consequently, only two dominant modes are produced resulting in the single sideband spectrum and, with the larger enhancement of the weak sideband located at the longer wavelength, the modulation depth is effectively enhanced and the modulation bandwidth limit of LD1 is overcome.

III. Experiments and Results

In order to demonstrate the feasibility of our scheme, we directly modulated a commercial 2.5-Gb/s-grade DFB laser (LD1) with a 17-GHz RF source and injected the resulting modulated light into a commercial FP-LD (LD2) without an isolator, as shown in Fig. 2(a). The DFB laser was biased at 30 mA $(1.8 \times I_{\rm th})$, and its modulation response including packaging effects are shown in inset of Fig. 2(a). The FP-LD was biased at 13 mA $(2.6 \times I_{\rm th})$. The injection power level was about -8 dB. An FP-LD can be used here since, with the external light injection, all the undesired lasing modes can be greatly suppressed. The use of an FP-LD is especially beneficial because it is cheap and has many modes providing easier selection of the desired mode for the wavelength-selective amplification process. By controlling temperature of the FP-LD, the gain region is brought to the desired location.

The insets in Fig. 2(b) and (c) shows the measured optical spectra for intensity-modulated signals, before and after passing through the FP-LD. Since the resolution of the optical spectrum analyzer available for measurement was not sufficient to clearly resolve the sidebands, a heterodyne spectrum analysis was performed by beating signals of interest (S1, S2, and λ_C) with additional light having $\lambda_{\rm Ex}$ lower than λ_C by 3 GHz and observing the resulting RF spectrum, as schematically shown in Fig. 2(a). Fig. 2(b) and (c) shows the RF spectra, before and after passing through the FP-LD. In Fig. 2, the optical modes that produce the beating signals are identified. The sidemode suppression ratio of 30–43 dB was achieved with the FP-LD. For the case shown in Fig. 2(b) and (c), the desired sideband has a gain of about 20 dB and the carrier is suppressed by 12 dB. As shown in Fig. 2(c), the peak at 20 GHz, corresponding to S2, is larger than the peak at 14 GHz, corresponding to S1, by more than 20 dB, clearly indicating the successful generation of the single sideband spectrum. In addition, with the amplification of S2, the technique overcomes the modulation bandwidth limitation by effectively improving modulation depth. The additional sideband shown in the inset of Fig. 2(c) is due to the four-wave mixing but its effect is not significant for the present study.

In order to make sure that our scheme is tolerant to fiber chromatic dispersion, signals produced with and without the

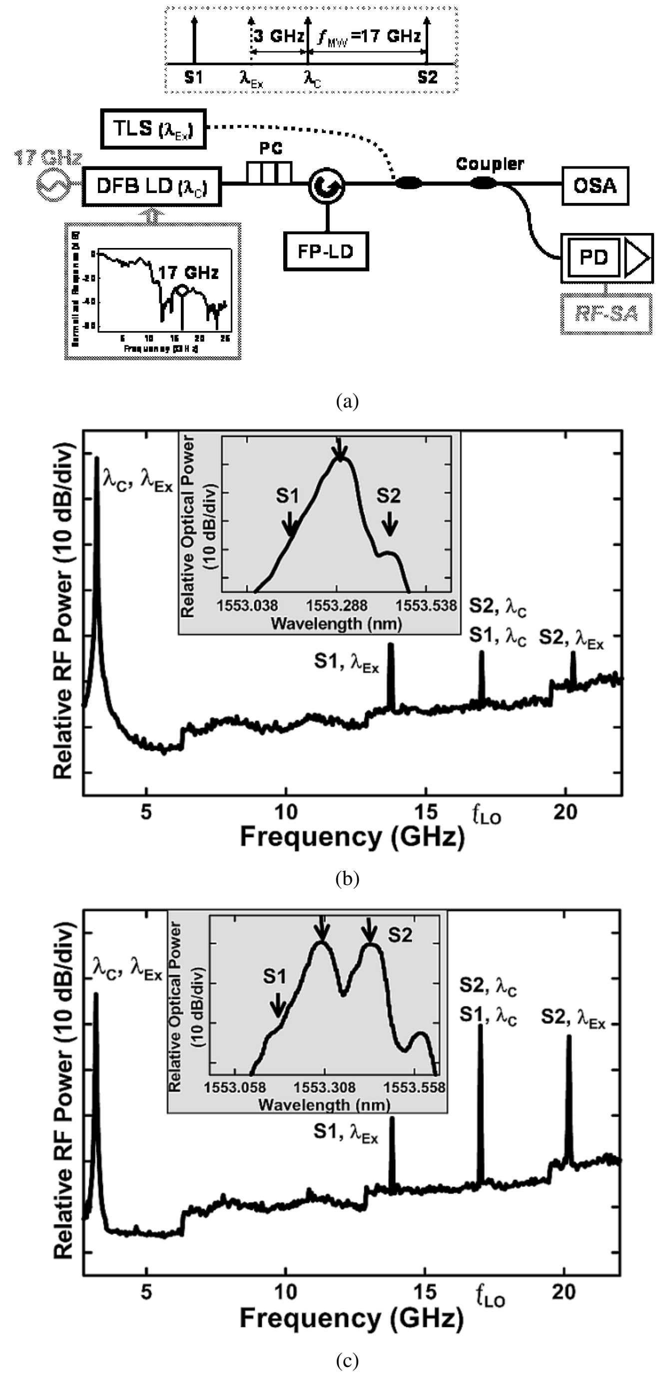

Fig. 2.(a) Experimental setup for measuring optical spectra before and after passing through FP-LD, and (b) and (c) the resulting spectra. PC, TLS, OSA, and RF-SA represent polarization controller, tunable light source, optical spectrum analyzer, and RF-spectrum analyzer, respectively.

FP-LD were sent over fibers having various lengths. The detected 17-GHz RF powers at the end of fiber were measured as function of fiber transmission length and the results are shown in Fig. 3. For the compensation of the optical loss in fiber transmission, a variable optical attenuator and an Erbium-doped fiber amplifier were employed. Without the FP-LD, detected powers are periodically suppressed due to the dispersion-induced power degradation problem. The solid line in the figure is obtained from curve-fitting the measurement results with theory [10]. The

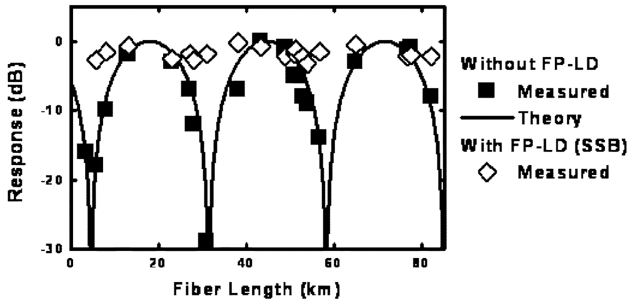

Fig. 3. Detected RF power versus fiber length for two different cases.

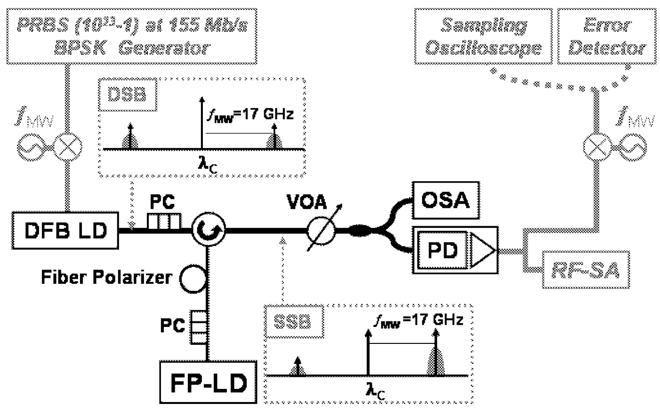

Fig. 4. Experimental setup for system demonstration.

optical single sideband signals produced with the FP-LD are not influence by fiber dispersion as expected.

For a system demonstration, we tried the transmission of a 155-Mb/s binary phase-shift keying (BPSK) data on a 17-GHz RF carrier with the experimental setup shown in Fig. 4. A pattern generator provided a nonreturn-to-zero data stream of $2^{23} - 1$ pseudorandom bit sequence at 155 Mb/s. The data were mixed with a 17-GHz RF carrier to generate BPSK data signals at 17 GHz. The resulting signals were then used to directly modulate a DFB laser. For comparison, the direct output of DFB laser as well as signals produced after passing through FP-LD were transmitted over fiber. The lasers used for this transmission measurement were the same lasers used for the previous measurement and biased at the same condition. At the end of transmission, the BPSK signals were down-converted to the baseband with a 17-GHz local oscillator and a mixer. The recovered 155-Mb/s data were then displayed on a digital sampling oscilloscope for eye diagrams, and sent to the digital data analyzer for the bit-error-rate (BER) measurement. By using a variable optical attenuator before PD, we measured the received BER as a function of received optical power, for both cases with and without passing through the FP-LD, and the results are shown in Fig. 5. For 10^{-9} BER, 11-dB improvement is obtained in receiver sensitivity by using the FP-LD as the wavelength-selective gain medium. The inset in Fig. 5 shows remarkably different eye diagrams for both cases at the received optical power of -7.8 dBm. It should be noted that the present demonstration of 155 Mb/s was limited by the receiver electronics available to us, and not by the scheme itself. In addition, the RF carrier frequency can be easily enhanced if sufficient RF power can be delivered to LD1 through its package.

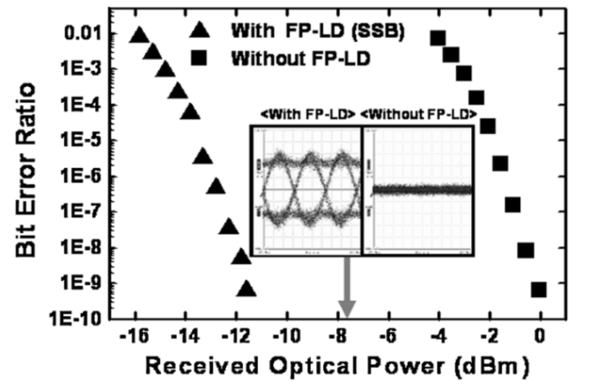

Fig. 5. Measured BER versus received optical power and received eye diagrams of 155-Mb/s data signal at the received optical power of -7.8 dBm for both cases.

IV. Conclusion

We have presented a new scheme of overcoming LD modulation bandwidth limitation by effectively increasing modulation depth and simultaneously generating single sideband spectrum for RoF applications. An FP-LD under modulated light injection is used as a wavelength-selective gain medium to enhance weakly modulated sideband and eliminate undesired sideband. The results of transmitting 155-Mb/s data on a 17-GHz RF carrier show that our scheme provides 11-dB improvement in receiver sensitivity. We believe this scheme can be useful for realizing cost-effective RoF systems that utilize directed-modulated LDs.

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