Optimization of Transmission Performance of 10-Gb/s Optical Vestigial Sideband Signals Using Electrical Dispersion Compensation by Numerical Simulation

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***Abstract*—We analyze the transmission performance of vestigial sideband (VSB) signals with electrical dispersion compensator (EDC) by numerical simulations. Optimizing the dispersion and bandwidth of EDC, and the extinction ratio and chirp of the modulator, we can improve the dispersion tolerance of VSB signals. VSB signals with negative chirp have better transmission performance while VSB signals with positive chirp are advantageous to the implementation of EDC due to low optimum dispersion in EDC. VSB transmission with EDC can be a very cost-effective solution for 10-Gb/s single-channel systems with the maximum transmission distance of 320 km.**

***Index Terms*—Chirp modulation, compensation, optical fiber communications, optical fiber dispersion, optical modulation, simulation.**

I. Introduction

FIBER chromatic dispersion mainly limits the transmission distance in 10-Gb/s fiber-optic communication systems. In general, an optical dispersion compensator (ODC) using dispersion compensating fiber (DCF) can perfectly compensate chromatic dispersion in 10-Gb/s single-channel transmission systems. Although DCF has the best dispersion-compensating performance, it is too expensive to be used in metro systems using single-channel or coarse wavelength-division multiplexing (CWDM). To improve chromatic dispersion tolerance without expensive ODC, the several schemes like prechirping [1], duobinary [2], multilevel signalling [3], single sideband (SSB) [4], and vestigial sideband (VSB) [5]–[8] have been introduced.

Not only can SSB and VSB signals improve the spectral efficiency [7] and dispersion tolerance [8] but also can electrically compensate fiber dispersion using dispersive electrical waveguides such as microstrip lines and coaxial cables [5]. For double sideband (DSB) signals, linear fiber dispersion is converted into nonlinear distortion after square-law detection in photodiode (PD), and nonlinear electrical dispersion compensator (EDC) is needed for fiber dispersion compensation in electrical domain [9]. However, both SSB and VSB signals offer the advantage that linear fiber dispersion is not changed into nonlinear distortion after square-law detection. Therefore, fiber dispersion can be compensated using linear and dispersive electrical waveguides after detection in PD [4].

The transmitters for SSB signals are difficult to realize since the generation of SSB signals needs complex electrical signal processing to implement the Hilbert transformer [4], while the transmitters for VSB signals can be more easily implemented using optical bandpass filters (OBPFs) [5], [6]. However, the transmission performance of VSB signals is degraded due to nonideal characteristics of OBPF. Because the frequency response of OBPF is not perfectly rectangular in shape, one sideband of DSB signals cannot be filtered out totally. The large group delay variation at the edge of OBPF also distorts the signals after VSB filtering.

In addition to the nonideal characteristics of OBPF, the limited bandwidth of EDC can degrade the system performance of VSB signals with EDC. The large dispersion in EDC is required to extend the transmission distance and it is difficult to obtain the sufficient bandwidth of EDC.

In previous work [4], it was reported that VSB signals with EDC could be transmitted for the distance over 225 km through the standard single-mode fiber (SSMF). However, they did not perform the optimization of the parameters for EDCs and modulators. We can extend the transmission distance of VSB signals with EDC through the optimization of EDC and modulators.

In this paper, we numerically calculate the system performance of 10-Gb/s VSB signals with EDC. We focus on 10-Gb/s single-channel transmission links using SSMF for metro systems without ODC. To extend the transmission distance up to 320 km, we optimize the dispersion and bandwidth of EDC, and the chirp and extinction ratio of modulators.

This paper is organized as follows. In Section II, the system configuration and device modeling is clearly described. In Section III, we compare the transmission performance between DSB and VSB signals and optimize the parameters for VSB transmitters and EDCs. Finally, a brief conclusion is given in Section IV.

II. System Configuration and Device Modeling

VSB transmission systems consist of a continuous-wave (CW) laser, Mach–Zehnder modulator (MZM), VSB filter,

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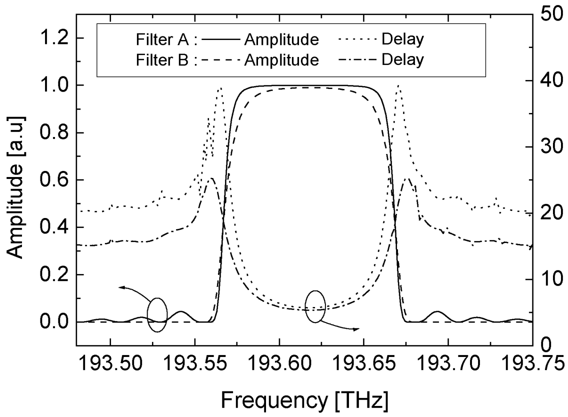

Fig. 1. Frequency responses of FBG filters.

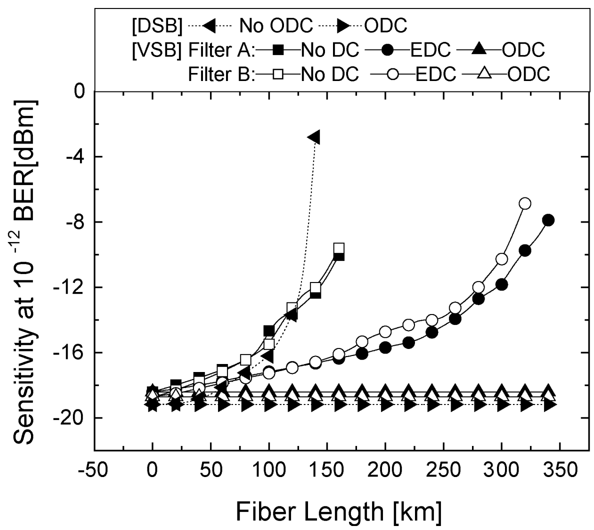

Fig. 2. Receiver sensitivities of DSB and VSB signals with and without dispersion compensation as a function of fiber length (extinction ratio $= 12$dB and chirp parameter $= 0$).

optical fiber, receiver, and EDC. We applied nonreturn-to-zero (NRZ) pseudorandom bit sequence (PRBS) signals to MZM. MZM converted electrical NRZ signals into optical NRZ-DSB signals. Optical NRZ-VSB signals were obtained by filtering out the one side of DSB signals with VSB filters. In our simulation, we chose fiber Bragg grating (FBG) filters for VSB filtering. We took a model of FBG filters using transfer matrix methods (TMMs) [10]. FBG filters have Gaussian-shaped apodization to reduce sidelobes. To take a look at the effect of group delay response of VSB filters, we considered the phase response as well as the amplitude response of VSB filters. Fig. 1 shows the frequency response of FBG filters. We used two FBG filters with different grating length. The steepness of the edge and the group delay difference are typical nonideal characteristics of OBPF, degrading transmission performance of VSB signals. Because Filter A had longer grating length than Filter B, Filter I had steeper edge and higher group delay difference than Filter B.

VSB signals were transmitted over the SSMF. The optical signal propagation was calculated by solving the nonlinear Schrödinger equation. For SSMF, dispersion (D), dispersion slope $(dD/d\lambda)$, nonlinear coefficient (n_2), and effective core area $(\mathrm{A_{eff}})$ were set to be 17 ps/nm/km, 0.059 36 ps/nm^2/km, 3×10^{-20} m^2/W, and 78 μm^2, respectively. Because we focused on the performance degradation by fiber dispersion, the fiber launching power was set to 0 dBm to exclude the signal distortions by fiber nonlinear effects. When the fiber launching power was 0 dBm in our simulation conditions, the results including fiber nonlinear effects were nearly the same as the results without including fiber nonlinear effects.

After optical VSB signals were converted into electrical signals in the receiver, EDC mitigated the fiber dispersion. For receiver models, the frequency response from PIN photodiode to EDC was assumed as fourth-order Bessel–Thomson filter. The circuit noise assumed to be 17 pA/$\sqrt{Hz}$ with the Gaussian distribution. The phase response of the EDC using microstrip delay line was modeled as

$$\angle H(f) = -j\pi D_{eq} f^2 \tag{1}$$

where D_{eq} is total dispersion in EDC [4].

III. Simulation Results and Discussions

A. Comparison Between DSB and VSB Transmissions

We compared the transmission performance between DSB and VSB signals. Fig. 2 shows receiver sensitivities of DSB and VSB signals as a function of fiber length. ODC was used for both DSB and VSB signals, while EDC was used for VSB signals because fiber dispersion cannot be compensated with EDC for DSB signals. The receiver sensitivity was defined as required optical power at the receiver to achieve 10^{-12} bit error rate (BER). The extinction ratio and chirp parameter were fixed at 12 dB and zero, respectively. We filtered out the lower frequency sideband of DSB signals with two different types of FBG filters, as shown in Fig. 1. Adjusting the wavelength of CW lasers, the filtering loss of VSB signals was set to 6 dB for both Filter I and II. The dispersion in EDC was set to the same value of fiber dispersion with the opposite sign.

Before transmission, DSB signals had better receiver sensitivity than VSB signals since VSB filtering distorted the output signals. As the fiber length was extended, the fiber dispersion degraded DSB signals more rapidly than VSB signals because of the broader spectral width of DSB signals. Before EDC was used, transmission performance of VSB signals was not improved dramatically due to nonideal characteristics of FBG filters. VSB signals using Filter I and II had the similar transmission performance due to the tradeoff between the steepness of the edge and group delay difference. When ODC was used for both DSB and VSB signals, the fiber dispersion can be perfectly compensated and the receiver sensitivities after transmission is nearly the same as the sensitivities at back-to-back.

After applying EDC, the receiver sensitivities of VSB signals were dramatically improved. When Filter I was used for the generation of VSB signals, better transmission performance was achieved. One sideband of VSB signals using Filter I was suppressed more perfectly, and the detected signals were electrically compensated well. Therefore, the steepness of the edge is a more important factor than group delay difference for the performance of EDC. We used Filter I for all following simulations.

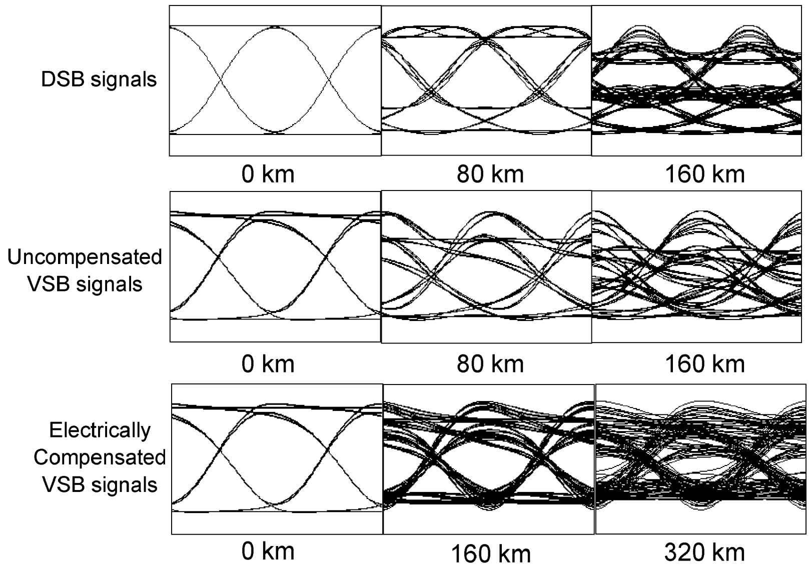

Fig. 3. Eye diagram of DSB, uncompensated VSB, and electrically compensated VSB signals with different distances (extinction ratio = 12 dB and chirp parameter = 0).

Fig. 3 shows the eye diagrams for DSB, uncompensated VSB, and compensated VSB signals for transmission distances. The eye diagram for both DSB and uncompensated VSB signals closed severely for the distance up to 160 km. On the other hand, the eye diagram of compensated VSB signals did not close for the distance up to 160 km. VSB signals with EDC can be partially compensated for fiber dispersion for distances over 320 km.

B. *Optimization of Dispersion in EDC*

Fig. 4 shows the receiver sensitivities as a function of fiber lengths. We used two different values of the dispersion in EDC. One is the same value as fiber dispersion with the opposite sign and the other is the optimum value. When the dispersion in EDC was optimized, we could reduce the signal distortion by non-ideal characteristics of FBG filters. The receiver sensitivity with an optimum dispersion in EDC was enhanced by 3 dB at the transmission distance of 320 km.

The optimum value of the dispersion in EDC is higher than the same value of fiber dispersion with the opposite sign since more dispersion is necessary to compensate the group delay variation of FBG filters. As the transmission distance was extended, the difference of sensitivities between two cases became larger.

C. *Effect of Extinction Ratio on Transmission Performance of VSB*

Fig. 5 shows the optimum dispersion in EDC and sensitivities as a function of extinction ratios. The chirp parameter was set to zero. Before transmission, VSB signals with the highest extinction ratio have the best receiver sensitivity. However, the optimum extinction ratio was about 7 dB after 320 km transmission. The optimum dispersion in EDC after 320 km transmission hardly changed with different extinction ratios. VSB signals with low extinction ratio have an advantage for long-distance transmission, which is similar to DSB signals [1].

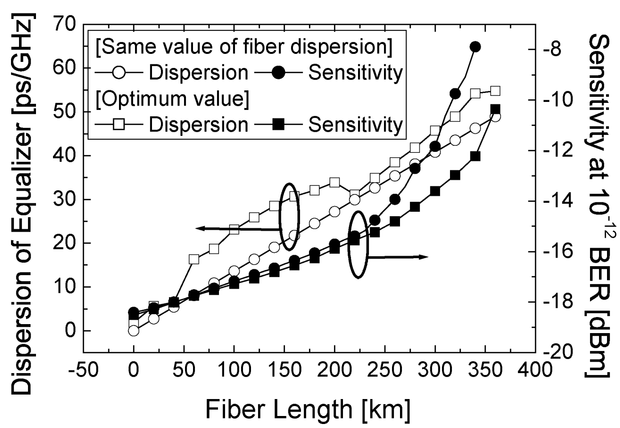

Fig. 4. Receiver sensitivity of electrically compensated VSB signals as a function of fiber length when the dispersion in EDC is set to the optimum value and same value as fiber dispersion (extinction ratio = 12dB and chirp parameter = 0).

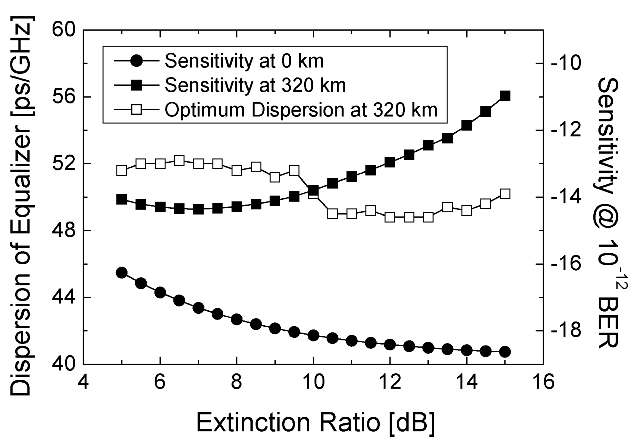

Fig. 5. Optimum dispersion in EDC and sensitivities for electrically compensated VSB signals as a function of extinction ratio (chirp parameter = 0).

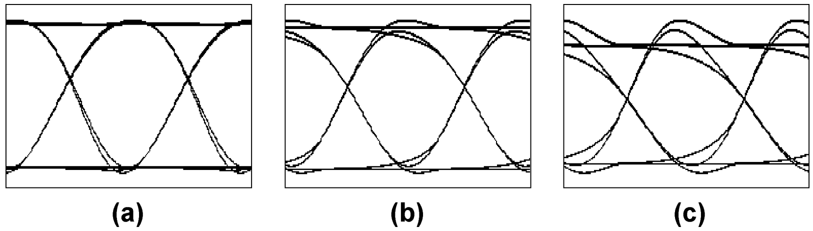

Fig. 6. Eye diagrams of VSB signals before transmission with (a) chirp parameters of two, (b) chirp parameters of zero, and (c) chirp parameters of -2. (Extinction ratio $= 8.2$dB).

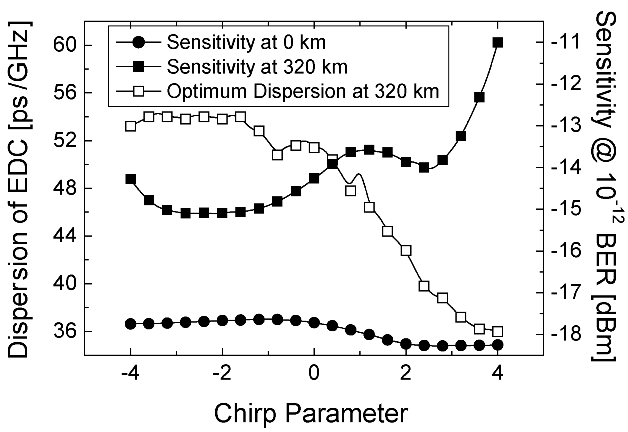

Fig. 7. Optimum dispersion in EDC and sensitivities for electrically compensated VSB signals as a function of the chirp parameter (extinction ratio $= 8.2$dB).

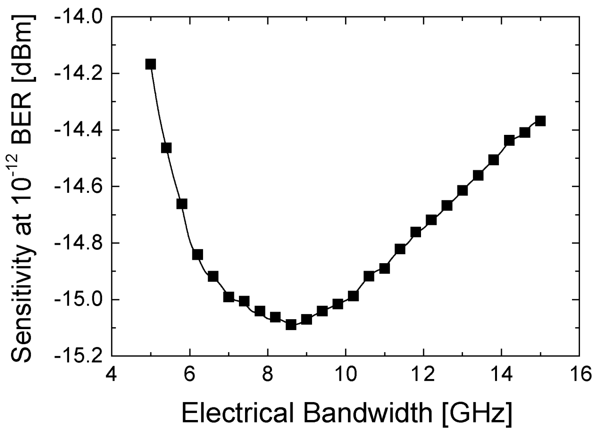

Fig. 8. Receiver sensitivities for electrically compensated VSB signals as a function of total electrical bandwidth of receivers (extinction ratio $= 8.2$dB and chirp parameter $= -2$).

D. Effect of Chirp Parameter on Transmission Performance of VSB

Fig. 6 shows the eye diagrams before transmission with the chirp parameter of 2, 0, and -2. The extinction ratio was set to 8.2 dB because low extinction ratio helps improve the transmission performance and ITU-T recommends that extinction ratio should be higher than 8.2 dB. The chirp parameter of transmitters affected the output signals of VSB filtering. After VSB filtering, the signals with positive chirp had the clearest eye diagram.

The chirp parameter of transmitters influenced the transmission performance as well as the output signals of VSB filtering. Fig. 7 shows the optimum dispersion in EDC and sensitivities as a function of the chirp parameter. Although VSB signals with negative chirp had lower sensitivities before transmission, the VSB signals with the chirp parameter of -2 have the best receiver sensitivity after 320 km transmission. The receiver sensitivity maintained below -15 dBm and the dispersion penalty was lower than 3 dB after 320 km transmission when the chirp parameter was optimized. On the other hand, the optimum dispersion in EDC was decreased with increasing the chirp parameter. The signals with positive chirp take advantage of the realization of EDC since EDC with low dispersion is easier to implement.

If an optical fiber has negative value of chromatic dispersion, these results on the chirp parameter will be reversed. When the total dispersion is a negative value, the signals with positive chirp parameter will have better transmission performance and the signals with negative chirp parameter will have smaller optimum dispersion in EDC.

E. Effect of Electrical Bandwidth of EDC

In VSB transmission systems with EDC, the other factor of limiting the system performance is the electrical bandwidth of EDC. Fig. 8 shows the sensitivities after 320 km transmission as a function of total electrical bandwidth of the receiver with the chirp parameter of -2 and the extinction ratio of 8.2 dB. The optimum bandwidth appears to be at 8.5 GHz. When the electrical bandwidth was narrower than 7 GHz, the sensitivity was degraded rapidly. To mitigate the intersymbol interference (ISI) penalty by the limited electrical bandwidth, the electrical bandwidth of receivers has to be maintained over 7 GHz.

IV. Conclusion

The transmission performance of 10-Gb/s VSB signals with EDC was theoretically estimated. To improve the dispersion tolerance of VSB signals, the dispersion and bandwidth of EDC, and the chirp parameter and extinction ratio of modulators, should be optimized. The steepness of the edge is a more important factor than group delay difference for the performance of EDC. VSB signals with negative chirp had the best transmission performance. On the other hand, VSB signals with positive chirp took advantage of the implementation of EDC due to the smaller optimum value of dispersion in EDC. To reduce the ISI penalty by limited electrical bandwidth of EDC, total electrical bandwidth of EDC had to be maintained over 7 GHz. Through optimization of EDC and modulators, VSB signals can be transmitted up to 320 km with the sensitivity below -15 dBm and the dispersion penalty below 3 dB. VSB signal with EDC will be a very cost-effective solution for 10-Gb/s metro systems with transmission distance of 320 km.

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