Numerical analysis on fiber-nonlinearity compensation for 4ASK 100-km SSMF transmission by using electrical butterfly operation for received signal sidebands

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Abstract: We investigated a novel demodulation technology based on our proposed electrical butterfly operation scheme which compensates for optical nonlinear distortion of conventional single-sideband (SSB) signals. In the scheme, phase-conjugated twin signals are transmitted as lower sideband (LSB) and upper sideband (USB) components of a dual sideband (DSB) signal modulated by a simple Mach-Zehnder modulator (MZM). The performance was evaluated by numerical simulation of 4-ary amplitude shift keying (4ASK) signals transmitted over a 100-km standard single mode fiber (SSMF). The error vector magnitude (EVM) was improved by about 20% when the input power was 10 dBm, compared with a conventional SSB-4ASK signal.

Keywords: optical nonlinearity compensation, SSB modulation, phase-conjugated twin waves

Classification: Fiber-Optic Transmission for Communications

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1 Introduction

Optical single sideband (SSB) modulation has been attracting attention due to its high spectral efficiency and dispersion-tolerant characteristics [1, 2, 3, 4, 5]. However, the high peak-to-average power ratio (PAPR) of an optical SSB signal induces waveform distortion caused by optical nonlinearities such as self-phase modulation (SPM) [2]. Consequently, SSB schemes require some nonlinear compensation to enable long-haul transmission [5]. A method using phase-conjugated twin waves is one of the important candidates for mitigating the optical nonlinear effects [6]. In this method, a phase-conjugated optical signal is polarization multiplexed or time-division multiplexed with the original signal [7, 8]. In our study, we proposed a novel phase-conjugated twin scheme where the original optical SSB signal and the phase-conjugated SSB signal are multiplexed as a lower sideband (LSB) and upper sideband (USB) in the form of a twin-SSB optical signal [9]. A similar kind of phase-conjugated twin-signal method has been proposed by Sakamoto et al. [10].

In our proposed scheme, however, subcarrier modulation is not needed because the LSB and USB are completely demultiplexed by an electronic butterfly operation. In this paper, besides our former study in [9], we investigated the performance of the proposed scheme with varying input optical power to the optical fiber, and compared the performance with that of the conventional SSB scheme. The results show the optical-nonlinearity-tolerant characteristics of the proposed scheme.

2 Principle of nonlinearity compensation of SSB signal

Compared with a double sideband (DSB) signal, an SSB signal has dispersion-tolerant characteristics due to the narrower bandwidth of the occupied spectrum. A twin-SSB signal conveys two independent signals as an LSB and a USB, as shown in Fig. 1(a). The twin-SSB scheme can achieve higher spectral efficiency because two different spectra can be arranged side by side without any spectral spacing [11, 12, 13]. Furthermore, the two independent signals on the LSB and USB are modulated using a single optical modulator, allowing a cost-effective transmitter to be realized. Figure 1(b) shows the structure of our proposed twin-SSB receiver consisting of homodyne detection and an electronic butterfly operation with a Hilbert transform [13]. By using this butterfly operation, the signals on the LSB and USB can be demultiplexed without using optical filters. The twin-SSB signal, $s(t)$, can be expressed as

$$s(t) = \cos(\omega_C - \omega_{SL})t + \cos(\omega_C + \omega_{SU})t \quad (1)$$

where ω_{SL} and ω_{SU} are the angular frequencies of the baseband signals for the LSB and USB, respectively, and ω_C is the optical carrier frequency. When homodyne detection is performed on this signal, the two outputs of the optical 90°-hybrid, $r_1(t)$ and $r_2(t)$, are expressed as

$$r_1(t) = \frac{1}{2} \{ \cos(\omega_{SL}t) + \cos(\omega_{SU}t) \}, \quad (2)$$

$$r_2(t) = \frac{1}{2} \{ \sin(\omega_{SL}t) - \sin(\omega_{SU}t) \}, \quad (3)$$

When a Hilbert transform is performed on $r_2(t)$, the result, $r_3(t)$, is expressed as

$$r_3(t) = \frac{1}{2} \{ -\cos(\omega_{SL}t) + \cos(\omega_{SU}t) \}, \quad (4)$$

Fig. 1. Principle of modulation and demodulation.

By performing a butterfly operation on $r_1(t)$ and $r_3(t)$, the baseband signals of the LSB and USB can be retrieved as

$$r_1(t) - r_3(t) = \cos(\omega_{SL}t), \quad (5)$$

$$r_1(t) + r_3(t) = \cos(\omega_{SU}t). \quad (6)$$

In the proposed scheme, the original signal and the phase-conjugated signal are multiplexed and transmitted in the form of twin-SSB. It is known that this type of the modulated signal can be easily achieved by DSB intensity modulation using a single Mach-Zehnder modulator (MZM), as shown in Fig. 1(c) [10]. When the baseband signal and the optical carrier are expressed as $\cos(\omega_s t)$ and $\cos(\omega_c t)$, respectively, the modulated signal $s(t)$ can be expressed as

$$\begin{aligned} s(t) &= \frac{1}{2} \{ \cos(\omega_C - \omega_S)t + \cos(\omega_C + \omega_S)t \} \\ &= \frac{1}{2} \text{Re} \{ (e^{-j\omega_s t} + e^{j\omega_s t}) \cdot e^{j\omega_c t} \}, \end{aligned} \quad (7)$$

where $e^{-j\omega_s t}$ and $e^{j\omega_s t}$ are the complex amplitudes of the LSB and USB, respectively. The two complex amplitudes are in a phase-conjugate relationship. This signal on LSB and the phase-conjugated signal on USB are transmitted as a DSB. The multiplexed LSB and USB signals can be demultiplexed by the butterfly operation explained above. The nonlinear distortion can be compensated for by superimposing the LSB and USB components, because the nonlinear distortions of the phase-conjugated twin waves are anticorrelated [6].

3 System setup

The performance of the scheme was investigated by numerical simulations with a transmission system shown in Fig. 2. 10-Gsymbol/s 4-ary amplitude shift keying (4ASK) DSB modulation was performed using a single MZM. The single MZM was biased at the null point so that the optical carrier was suppressed. The LSB and USB components of the DSB signal were in a phase-conjugate relationship, as explained above. We used PRBS $2^{11} - 1$ data. The modulated signal was transmitted by a 100-km standard single mode fiber (SSMF). The loss parameter and dispersion coefficient were 0.2 dB/km and 16.75 ps/nm/km, respectively. The input power to the optical fiber was adjusted from 0 to 10 dBm using an optical attenuator (ATT). The noise figure of the erbium-doped fiber amplifiers (EDFAs) was 5 dB. On the receiver side, we performed homodyne detection using a local oscillator (LO) with

Fig. 2. System setup.

Fig. 3. Results of numerical simulations.

an optical power of 10 dBm. Here, we assumed that the LO was ideally synchronized to the optical signal. The thermal power density of balanced-photodiodes (BPDs) was 1.0×10^{-22} [W/Hz]. The LSB and USB components were demultiplexed by the electronic butterfly operation. Nonlinear compensation was performed based on the scheme of phase-conjugated twin waves.

4 Results and discussion

Figures 3(a) to (e) show the eye diagrams of the received signal when the input power to the optical fiber was 10 dBm. The received optical power was -20 dBm. Figure 3(a) shows the result of a standard SSB signal transmission demonstrated for comparison. The waveform of the LSB signal was completely distorted by SPM due to the large PAPR of the signal. Figure 3(b) shows the result of a normal homodyne detection of the DSB signal, and the waveform was distorted principally by chromatic dispersion. Figures 3(c) and (d) show the eye diagrams of the demultiplexed LSB and USB components of the DSB signal, respectively. Figure 3(e) shows the eye diagram

after the nonlinear compensation. It was confirmed that eye opening was improved compared with the SSB signal due to the nonlinear compensation based on phase-conjugated twin waves. Figure 3(f) shows the error vector magnitude (EVM) versus the received optical power when the input optical power was 10 dBm. Here, we calculated EVM values at the optimum timings when the values became minimum. In the case of SSB, the EVM characteristics were more highly degraded by nonlinear effects compared to the DSB signal. By using the proposed scheme, however, the EVM was improved by about 20% compared to SSB and by about 9% compared to DSB. In the range of the lower received optical power, the EVM was degraded by the ASE noise of EDFAs and the thermal noise of BPDs. Figures 3(g) to 3(i) show the eye diagrams after the nonlinear compensation when the input optical power was changed from 0 dBm to 10 dBm. Thanks to the optical nonlinearity tolerant characteristics of the proposed scheme, we did not observe a significant change of the eye opening. Figure 3(j) shows the EVM versus the input power to the optical fiber. When the input power was low enough, the EVM of the SSB signal was about 5% better than DSB due to the dispersion tolerant characteristics. When the input power was large, however, the EVM of the SSB signal was seriously degraded by nonlinear effect. On the other hand, in the case of our proposed scheme, the EVM degradation caused by the large input power of 10 dBm was small, at less than about 3%. Additionally, even when the input power was low, we observed dispersion-tolerant characteristics. When the input power was 0 dBm, the EVM was improved by about 7% compared to conventional SSB. Finally, the mainlobe bandwidth of the 10-Gsymbol/s 4ASK DSB modulation was 20 GHz, giving a spectral efficiency of 1.0 bit/s/Hz. SSB modulation can double the spectral efficiency, achieving 2.0 bit/s/Hz. However, the spectral efficiency of the proposed scheme becomes 1.0 bit/s/Hz as in the case of DSB.

5 Conclusions

We proposed a novel nonlinear compensation scheme for SSB signals. The scheme may be categorized as one type of phase-conjugated twin wave scheme. The modulation can be performed simply by using a single MZM. Demultiplexing is performed in the digital domain without using costly additional optical components. This simple construction of the proposed scheme is a major advantage over other methods.