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2018

Zhang, X., Zhang, C., Chen, C., Jin, W., Zhong, X., & Qiu, K. (2018). Digital chromatic dispersion pre-management for SSB modulation direct-detection optical transmission systems. *Optics Communications*, 427551-556. doi:10.1016/j.optcom.2018.07.026

<https://hdl.handle.net/10356/105585>

<https://doi.org/10.1016/j.optcom.2018.07.026>

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Digital Chromatic Dispersion Pre-management for SSB Modulation Direct-Detection Optical Transmission Systems

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Abstract:

Recently, single-side-band (SSB) modulation direct detection (DD) based optical transmission systems have attracted great interest due to their capability of electronic chromatic dispersion (CD) compensation. In this paper, we investigate the digital chromatic dispersion pre-management for optical SSB signals which are generated by radio frequency (RF) tone based on I/Q modulator and optical carrier based dual-drive Mach-Zehnder modulator (DDMZM) with DD at the C-band via numerical simulations. The impact of CD, self-phase modulation (SPM) and phase-to-amplitude noise on such a SSB DD optical transmission system with I/Q modulator based virtual carrier assisted, and the DDMZM based optical carrier are investigated. The simulation results have successfully demonstrated the transmission of a 224-Gb/s Nyquist 16-ary quadrature amplitude modulation (16QAM) signal over 75-km standard single mode fiber (SSMF) with bit error rate (BER) less than 3.8×10^{-3} in a SSB-DD system by using digital CD pre-management. It is shown that the SPM induced impairment can be optically mitigated by the residual positive CD of the SSMF link.

Key words: single-side-band (SSB), direct detection (DD), electronic dispersion compensation, DDMZM, virtual-carrier-assisted, Kramers-Kronig (KK).

1. Introduction

To satisfy the ever-increasing demand of the bandwidth-limited links for data centers, optical access networks and other optical communication systems, high spectral efficiency (SE) per wavelength channel transmission becomes more and more important. In the past few years, the advanced modulation formats and the polarization division multiplexing (PDM) with coherent detection have already achieved great success to provide excellent solutions for the high-speed optical transmission and fiber-wireless system [1-3]. However, compared with the intensity modulation and direct detection (IM/DD) systems, the coherent systems involve a number of sophisticated electrical and optical components/devices, such as several of digital-to-analog converters (DACs)/analog-to-digital converters (ADCs), local oscillator (LO) laser, 90° optical hybrids and four pairs of balanced photodiodes (PDs). Therefore, coherent optical transmission systems have relatively high power consumption, high cost and computation complexity. On the contrary, high-capacity optical transmission systems using direct-

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detection (DD) has the advantages of low power consumption, low cost and low computation complexity. DD systems become more and more attractive for cost-sensitive application scenarios such as optical access/metro network and data center [4, 5].

Recently, many advanced modulation techniques have been proposed to achieve high SE in DD optical transmission systems [6-8], such as discrete multi-tone (DMT) [9-11], carrier-less amplitude and phase (CAP) modulation [12-15], quadrature amplitude modulation (QAM) subcarrier modulation (SCM) [16-20], and pulse-amplitude modulation (PAM) [21-24]. Especially, single-side-band (SSB) signal modulation including SSB-PAM4, SSB-DMT and SSB-CAP become very promising scheme since they can not only overcome the inherent chromatic dispersion-induced power fading effect associated with the double-sideband (DSB) system, but also improve the SE. So far, there are four approaches widely utilized to generate optical SSB signals: 1) using an optical SSB filter to wipe off one of the signal side bands at the transmitter end [25]; 2) employing a DDMZM with two small driving signals with a phase difference of $\pi/2$, which are a pair of Hilbert signals [21]; 3) adopting an I/Q modulator with a pair of baseband driving signals while adding a separate optical tone at the transmitter (Tx) or receiver (Rx) as a local oscillator [26, 27]; 4) adding a digital RF tone acting as a virtual carrier together with the transmitted signal at the Tx digital signal processing (DSP) and only need two DACs and one I/Q modulator [28].

Although, SSB or vestigial sideband (VSB) modulations can overcome the CD introduces power fading in DD systems. CD, fiber loss and self-phase modulation (SPM) are still three major factors which limit the transmission distance and capacity of DD systems. Che *et al.* proposed signal carrier interleaved direct detection (SCI-DD) [29] and stokes vector direct detection (SV-DD) [30] schemes to avoid the dispersion induced power fading and hence achieve higher SE. However, the above two methods require several photo-detectors at the receiver to eliminate the signal-to-signal beat interference (SSBI). In [31], Gao *et al.* proposed the use of degenerate four-wave mixing (DFWM) to mitigate the CD induced power fading effect in high-speed and short-reach CAP based DD systems. In [24], Fu *et al.* have identified that the SPM effect arising in the standard single mode fiber (SSMF) transmission can be optically mitigated by the residual positive CD of the link.

In this paper, we investigate the interaction effect of the SPM and CD for SSB-based DD systems through numerical simulations, where the optical SSB signals are generated by using DDMZM and I/Q modulator, respectively. The DDMZM-based SSB signal inherently carries the optical carrier, while the I/Q modulator-based SSB signal has a virtual-carrier which is added via DSP in the transmitter. We also study the performance of CD pre-management SSB signal which is generated by an optical I/Q modulator and DDMZM, respectively. We have demonstrated the transmission of a 224-Gb/s Nyquist 16-ary quadrature amplitude modulation (16QAM) signal over 75-km SSMF with bit error rate (BER) less than 3.8×10^{-3} in a SSB-DD system by using digital CD pre-management. The simulation results show that SPM induced impairment can be optically mitigated by the residual positive CD of the SSMF link. The research work not only effectively provides an approach to mitigate the channel impairment of the SPM by utilizing the residual positive CD, but also allows the utilization of low-cost optical components without comprising the overall system performance. The demonstrated SSB system can provide a promising technique for relative low-cost long-reach optical access networks with direct detection.

2. Principle of generating SSB signal

Fig. 1 shows the different techniques for generating the optical SSB signal. Fig. 1(a) depicts that the optical SSB signal can be generated by using an intensity modulator (IM) and an optical filter, which is the simplest approach to achieve a SSB signal, but a sharp optical filter is required [25]. Fig. 1(b) shows an illustration of the generation optical SSB signal by using a DDMZM. The transmitted optical SSB signal can be written as

$$S_{out}(t) = \frac{E_{in}(t)}{2} \left[\exp\left(j\pi \frac{V_{RF1} + V_{bias1}}{V_{\pi}}\right) + \exp\left(j\pi \frac{V_{RF2} + V_{bias2}}{V_{\pi}}\right) \right] \quad (1)$$

where $E_{in}(t)$ is the input optical field, V_{bias1} and V_{bias2} are the DC bias voltage of two parallel phase modulators (PMs), V_{π} is the half-wave voltage of the two electrodes, and V_{RF1} and V_{RF2} are two up-converted signals which are expressed by

$$V_{RF1} = \text{real}[s(t) \cdot \exp(j2\pi f_{b/2}t)] \quad V_{RF2} = \text{imag}[s(t) \cdot \exp(j2\pi f_{b/2}t)] \quad (2)$$

where $s(t)$ represents the baseband signal with the symbol rate of f_b and $f_{b/2}$ corresponds to the central frequency of the up-converted $s(t)$. By setting $V_{bias1} = -V_{\pi}/2$ and $V_{bias2} = 0$, the output of DDMZM can be expressed as [21]

$$S_{out}(t) = \frac{E_{in}(t)}{2} \left[\exp\left(j\pi \frac{V_{RF1} - V_{\pi}/2}{V_{\pi}}\right) + \exp\left(j\pi \frac{V_{RF2}}{V_{\pi}}\right) \right] \quad (3)$$

When V_{RF1} and V_{RF2} are the small signals, Eq. (3) can be approximated as

$$\begin{aligned} S_{out}(t) &\approx \frac{E_{in}(t)}{2} \left[-j \left(1 + \frac{j\pi}{V_{\pi}} V_{RF1} \right) + 1 + \frac{j\pi}{V_{\pi}} V_{RF2} \right] \\ &= \frac{E_{in}(t)}{2} \left[1 - j + \frac{\pi}{V_{\pi}} (V_{RF1} + jV_{RF2}) \right] \end{aligned} \quad (4)$$

In Eq. (4), it is obvious that the electrical complex signal $T_x = V_{RF1} + jV_{RF2} = s(t) \exp(j2\pi f_{b/2}t)$ is linearly converted to the optical domain. The SSB signal generation is also achievable by employing modulation procedures similar to those reported in [21], but it is not identical theoretically. In addition, some researches are also conducted on exploring the SSB signal with DD based on optical I/Q modulator with optical tone added at the Tx [26] as illustrated in Fig. 1(c), where an additional laser is required to produce the optical tone which however greatly increases the system over-all cost.

Meanwhile, the SSB signal can also be generated in a simple but effective way, by generating a digital tone acting as a virtual carrier, which is added to the transmitted signal in the digital domain at the Tx, as shown in Fig. 1(d). Similar to the Fig. 1(c), the I/Q modulator biased at the null-point is adopted to suppress the optical carrier. The transmitted optical SSB signal with virtual carrier can be written as

$$S_{out}(t) = [A \exp(j2\pi f_{RF}t) + s_1(t)] \exp(j2\pi f_c t) \quad (5)$$

where A denotes the amplitude of the digital tone, $s_1(t)$ represents the baseband signal, f_{RF} corresponds to the central radio frequency (RF) of the virtual carrier and $\exp(j2\pi f_c t)$ is the optical carrier. From Eq. (5), the carrier-to-signal power ratio (CSPR) can be calculated as

$$CSPR = 10 \log \frac{P_{Carrier}}{P_{Signal}} = 10 \log \frac{A^2}{E\{|s_1(t)|^2\}} \quad (6)$$

where the operation $E\{\cdot\}$ stands for the mathematical expectation. Compared with the SSB signal generation approach illustrated in Fig. 1(b), we can find that in the virtual carrier-assisted system, dynamic CSPR adjustment can be easily achievable through adjusting the amplitude of the digital tone.

Fig. 1. Block diagrams of generation the optical SSB signal (a) using an electrical I/Q mixer with intensity modulation and optical filter; (b) using a DDMZM with up-conversion; (c) using optical I/Q modulator with optical tone added at the Tx; (d) using optical I/Q modulator with digital tone added in the DSP.

At the receiver side, the received SSB signal with virtual carrier after direct detection can be expressed as

$$i_{ph}(t) = S_{I_{out}}(t)S_{I_{out}}^*(t) = As_1(t)\exp(-j2\pi f_{RF}t) + s_1(t)s_1^*(t) + A^2 + As_1^*(t)\exp(j2\pi f_{RF}t) \quad (7)$$

In (7), the first term is the desired electronic signal, which can be obtained using a simple filtering operation; the second term corresponds to the SSBI component which can be removed by the Kramers-Kronig (KK) receiver [32, 33]; the third term is the DC component which is blocked at the receiver. Here, the other transmission impairments such as noise, CD and fiber nonlinearity are not considered in (7). However, for long-reach optical access networks with fiber transmission distance more than 40 km and high launch optical powers, the interplay between the CD and the SPM should be considered. In short, for method (a) of Fig.1, a guard band between the optical carrier and the signal is needed to remove one of the side bands, which reduces the system spectrum efficiency. For method (c), since an extra laser is needed, the cost of the system is higher than methods (b) and (d). More specifically, this work focuses on the digital CD pre-compensation for SSB DD system in low-cost long-reach PONs. Thus, here we focus on investigating the generation methods (b) and (d).

3. Simulation Setup

To investigate the interplay between CD and SPM for the SSB systems with DD during the SSMF transmission, two optical SSB signal generation methods including the use of an optical I/Q modulator with RF added in the Tx DSP and the use of a DDMZM are considered.

Fig. 2 shows the simulation setup and the key simulation parameters are summarized in Table 1. The simulation is conducted by using VPItransmissionMaker 9.1 and MATLAB. At the transmitter side, a data stream with a pseudo random bit sequence (PRBS) length of $2^{20}-1$ is mapped into 16QAM symbols. After that, 16QAM symbols with a symbol rate of 56 Gbaud are first up-sampled and subsequently pass through a Nyquist filter with a roll-off factor of 0.005 to generate the 16QAM Nyquist signal. Then for the Tx1 after the digital CD pre-management in the frequency domain, a RF tone with the frequency of 28.15GHz is added, which locates at the left edge of the signal band. And for the Tx2, the baseband 16-QAM Nyquist signal is up-converted by multiplexing $\exp(j2\pi f_{b/2}t)$, where the frequency of $f_{b/2}$ is 28.15 GHz, and then digital CD pre-management is implemented. Subsequently, the real and imaginary parts of Tx1 and Tx2 are fed into a DDMZM biased at its quadrature bias point and an I/Q modulator biased at its null-point to linearly modulate the light from external cavity laser (ECL), respectively. The central wavelength of the ECL is set as 1552.52 nm, and the dispersion coefficient at 1552.52 nm is 17 ps/nm/km. An erbium-doped fiber amplifier (EDFA) with a noise figure of 4 dB is utilized to boost the launch power of the optical signal. The SSMF has an attenuation coefficient of 0.2 dB/km, a dispersion slope of 0.08 ps/nm²/km, a Kerr coefficient of 2.6×10^{-20} m²/W and an effective core area is 80.0 μm^2 . In the receiver, an EDFA and a Gaussian-shape optical band-pass filter (OBPF) with 80-GHz bandwidth are used to compensate the fiber loss and remove the out-of-band optical noise, respectively. The optically filtered signal is then detected by a PIN photodiode with a bandwidth of 70 GHz and a responsivity of 0.8 A/W. Then, the received electrical signal is further processed via Matlab. The sampling rate and the resolution of the DAC/ADC are 112 GSa/s and 8 bits, respectively. The bandwidths of the DAC/ADC are larger than the signal bandwidth and thus the bandwidth influence can be neglected. The Rx DSP including pre-filtering, SSBI mitigation with KK, equalization, QAM demodulation, and BER counting as shown in Fig. 2. To optimize the system performance, pre-filtering with an ideal filter is performed to remove the out-of-band noise. The received signal is up-sampled to 4 samples per symbol before KK receiver due to the logarithm and square root operation.

Fig. 2. Digital chromatic dispersion pre-management for single-sideband modulation direct-detection system.

Table 1 Simulation Parameters

Parameter	Value
DAC/ADC sampling rate	112 GS/s
DAC/ADC bit resolution	8 bits
ECL laser operation wavelength	1552.52 nm
Chromatic dispersion	17 ps/nm/km
SSMF attenuation	0.2 dB/km
Dispersion slope	0.08 ps/nm ² /km
Kerr coefficient	2.6×10^{-20} m ² /W
Effective core area	80.0 μm^2
Noise figure of EDFA	4 dB
OBPF type	Gaussian
OBPF bandwidth	80 GHz
PIN detector bandwidth	70 GHz
PIN detector responsivity	0.8 A/W
PIN detector sensitivity	-19 dBm

4. Results and Discussions

Fig. 3(a) shows optical spectrum at the transmitter with virtual carrier and I/Q modulator. We first investigate the BER performance versus optical modulation index (OMI) for SSB system based on DDMZM and the BER performance as a function of the CSPR for the virtual-carrier-assisted SSB system, as shown in Fig. 3(b). The results show that the virtual-carrier-assisted SSB system has the optimum CSPR of about 13 dB, while the best OMI for the SSB system based on DDMZM is about 0.132. In this paper, OMI is defined as $OMI = V_{RF}^{rms} / V_{\pi} \cdot V_{RF}^{rms}$ corresponds to the root-mean-square (RMS) of the electrical input to the DDMZM, V_{π} is the half-wave voltage of the DDMZM. Fig. 3 (d) shows an illustration of the optical spectrum of the SSB signal based on the DDMZM.

Fig. 3. (a) Spectrum of the SSB optical signal with virtual carrier; (b) BER versus CSPR or OMI in back-to-back systems; (c) Spectrum of the SSB optical signal based on DDMZM.

The phase noise introduced by the ECL can degrade the system performance due to the combining effect of the chromatic dispersion and the spectrum boarding. The ECL phase noise can be modeled by a Wiener process with zero mean and variance of $t\Delta\nu/(2\pi)$, where t represents the time and $\Delta\nu$ is the laser linewidth. As shown in Fig. 4, for different laser linewidths, we calculate the BER performances of the 16-QAM SSB signals after transmitted over 50km SSMF, which are plotted as a function of the received optical power. The linewidth of the laser varies from 0.2 to 1 MHz. For the virtual carrier assisted SSB system, the receiver sensitivities at the forward-error-correction (FEC) limit of $BER = 3.8 \times 10^{-3}$ are approximately -9, -8.2 and -6 dBm, when $\Delta\nu = 0.2, 1$ and 2 MHz, respectively. The

differences of receiver sensitivity for these SSB signals are mainly because of the laser phase noise. While for the SSB system based on the DDMZM, due to the laser phase noise effect, 2-dB receiver sensitivity degradation is observed at a BER of 3.8×10^{-3} when enlarging $\Delta\nu$ from 0.2MHz to 1 MHz. It is worth mentioning that the CW laser with a linewidth of 1 MHz is employed in the following simulations.

Fig. 4. BER performances of the SSB signals after transmitted over 50-km SSMF under different laser linewidth conditions for (a) virtual carrier assisted system and (b) DDMZM-based system.

Figs. 5(a)-(c) show the constellations diagrams of the virtual carrier assisted SSB signal after 75-km SSMF transmission with the launch powers of -4, 6, and 10 dBm at the residual CD of 0 ps/nm, respectively. Obviously, an extreme lower optical launch power leads to the SSB signal with a weakened tolerance to the system noise, which mainly contributed from the amplified spontaneous emission (ASE) noise, so the constellation is ambiguous as shown in Fig. 5(a). However, when the optical launch power is larger than 6 dBm, the constellation begins to blur due to the occurrence of SPM. Therefore, SPM induced transmission impairments need to be taken into consideration.

Fig. 5. Constellation diagram of SSB signal after 75-km SSMF transmission with the launch power of (a) -4, (b) 6, and (c) 10 dBm at the residual CD of 0 ps/nm.

Furthermore, we investigate the effect of residual CD on BER performance by the interplay between CD and the SPM effect as shown in Fig. 6. The optical signal launch power being fixed at 8 dBm. In comparison with the complete CD pre-compensation, residual positive CD is capable of improving the BER performance. However, excessive residual positive CD definitely degrades the BER performance due to CD-induced inter-symbol interference (ISI). In particular, we can obtain that the optimal residual CD values of the two SSB systems are 17 and 34 ps/nm for 50 and 75 km SSMF transmission, respectively. Obviously, when prolonging SSMF transmission fiber link with an enhancing SPM effect, the optimum residual positive CD is enlarged in order to mitigate the SPM effect.

Fig. 6. Optimal residual CD identification for various SSMF lengths. (a) For SSB signal with virtual carrier assisted; (b) For SSB signal based on DDMZM.

The optical power launched into the fiber link has a straight-forward influence on the achievable system power budget. Fig. 7 explores the relationship between system BER performance and optical launch power, under the conditions of with or without residual positive CD after 75km SSMF transmission. Due to the effect of SSBI, the BER without KK is relatively high as show in Fig. 7(a). After adopting KK to cancel SSBI, as shown in Fig. 7(b), the optimum launch powers of the SSB system with virtual carrier at BER of 3.8×10^{-3} are 8 and 7 dBm with and without residual positive CD, respectively. For the SSB system based on the DDMZM, due to the residual CD of the SSMF link enabled substantial SPM mitigation, there exists about 1 dB power improvement compared with the case of without employing CD pre-management. Then, we compare the BER performance of the SSB system based on virtual carrier and DDMZM. It can be seen that the virtual carrier assisted SSB system has a better performance after applying the CD pre-management.

Fig. 7. BER performance after 75-km SSMF transmission for the SSB signal (a) without KK receiver and (b) with KK receiver.

5. Conclusion

In this paper, we have demonstrated the SSB transmission of 224 Gb/s Nyquist 16QAM signal with digital CD pre-management over 75-km SSMF with DD operating at the C-band via numerical simulations. We have theoretically explored and compared the principles of various SSB signal modulation approaches and also numerically verify the feasibility of utilizing the residual positive CD to mitigate the SPM effects in long reach SSB-based DD systems. Simulation results show that the optimum launch power is improved by approximately 1 dB after 75-km SSMF transmission with the residual positive CD in both virtual carrier assisted SSB system and DDMZM-based SSB system. In addition, both of

above-mentioned SSB-based DD systems are relative low-cost, due to the expensive optical/electrical components are not required in each transceiver. At the receiver side, two SSB systems can effectively utilize the KK receiver to remove the SSBI, thereby resulting in relatively high SE. Compared with the DDMZM based SSB system, the virtual carrier assisted SSB system has a better performance after applying the CD pre-management to mitigate the nonlinearity of SPM. Therefore, the virtual carrier assisted SSB system is a more promising cost-efficient solution for future relative low-cost long-reach optical access networks with direct detection.

6. Acknowledgment

This work was supported in part by the National High Technology Research and Development Program (2015AA015501), Program for Joint Research of UESTC and Salton Tech (2018STKY001), 111 Project (B14039).

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