OFDM system implementation using compatible SSB modulation with a dual-electrode MZM

Zhenbo Xu,[1,*] Maurice O'Sullivan,[2] and Rongqing Hui[1]

[1]*Information and Telecommunication Technology Center, The University of Kansas, Lawrence, Kansas 66045, USA*
[2]*Nortel, Ottawa Carling Campus, 3500 Carling Avenue, Nepean, Ontario, Canada K2H 8E9*
Corresponding author: zhenbo@ittc.ku.edu

Received January 27, 2010; accepted February 17, 2010;
posted March 5, 2010 (Doc. ID 123322); published April 15, 2010

Single-sideband (SSB) direct-detection optical orthogonal frequency division multiplexing (OFDM) transmission is experimentally demonstrated in a system with 125 km fiber length, which does not need a guard band between the carrier and the OFDM band. The waveforms of compatible SSB modulation are analytically derived and realized through a single dual-electrode Mach–Zehnder modulator. The required optical signal-to-noise ratios for different modulation indices on the OFDM band are discussed for optimal operation. © 2010 Optical Society of America

OCIS codes: 060.2630, 060.2330, 060.4080.

Orthogonal frequency division multiplexing (OFDM) for optical transmission has been realized with both direct [1] and coherent [2] detections. While coherent detection has the advantage of better receiver sensitivity, direct detection is still attractive for short and medium distance transmissions due to its relaxed laser linewidth requirement and receiver simplicity. However, a guard band between the optical carrier and the OFDM sideband is usually required to avoid inter-modulation-induced waveform distortion in the direct-detection process [1]. This guard band, which equals the OFDM bandwidth, reduces the spectral efficiency of the system. Several techniques have been proposed to eliminate the guard band [3,4]. One way is to use a compatible single-sideband (SSB) modulation, where the OFDM signal is carried as the exponential envelope [5]. The implementation of a compatible SSB requires a complex in-phase/quadrature (I/Q) modulator in order to independently manipulate the optical amplitude and phase. Although theoretical analysis and numerical simulations have been performed [5], an experimental demonstration of this technique has not been reported. In this Letter, we demonstrate our OFDM transmission system implementation using a compatible SSB modulation. A commercial optical transmitter initially designed for 10 Gbits/s electrical-domain dispersion compensation (eDCO) [6–8] is used for this experiment, which includes two 22 Gs/s digital/analog converters (DACs) and a dual-electrode Mach–Zehnder modulator (MZM). Negligible degradation with regard to the required OSNR was found after transmission over 125 km standard single-mode fiber. Although the eDCO transmitter card used in the experiment would allow a 20 Gbit/s transmission for this OFDM implementation, we chose 10 Gbits/s data rate, because the ADC used in our receiver only has 6 GHz analog bandwidth.

In a previous numerical analysis of the OFDM transmission using a compatible SSB modulation [5], an I/Q modulator was proposed for the transmitter. Given our implementation, which is based on a simple dual-electrode MZM, appropriate signal waveforms have to be derived for the input to the two electrodes of the MZM. For a real value OFDM signal $\sigma(t)$ obtained from the Hermitian symmetry, $\sigma(t)+jH(\sigma(t))$ is used for the SSB modulation, where $H[\ ]$ denotes Hilbert transform. In the compatible SSB modulation, the OFDM information is applied as the exponential coefficient for the envelope of the defined optical field $E_0(t)$ as below [5],

$$E_0(t)=\exp\{\sigma(t)+jH[\sigma(t)]\}=A(t)e^{j\Phi(t)}, \tag{1}$$

where $A(t)=\exp[\sigma(t)]$ is the amplitude and $\Phi(t)=H[\sigma(t)]$ represents the phase, and the OFDM signal is carried only by the amplitude of the optical field. In the receiver, the OFDM signal can be recovered through amplitude detection by $\sigma(t)=\ln[A(t)]$. With a dc bias set at the quadrature point, in order to realize the desired amplitude and phase modulation on the dual-electrode MZM, we use the dual-arm MZM field transfer function as

$$E_0(t)=2E_i e^{j\omega t}e^{j\varphi_0(t)}\sin[\Delta\varphi(t)], \tag{2}$$

where E_i and E_0 are the input and output optical fields, and

$$\varphi_0(t)=[\varphi_1(t)+\varphi_2(t)]/2,\quad \Delta\varphi(t)=[\varphi_1(t)-\varphi_2(t)]/2, \tag{3}$$

with $\varphi_1(t)$ and $\varphi_2(t)$ as the phases of the two arms.

The small, signal approximation condition is valid when $\Delta\varphi(t)+\pi/2\ll\pi$; the output optical field is then

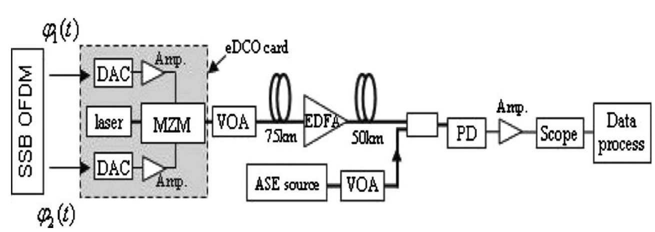

Fig. 1. System schematics of compatible SSB OFDM modulation on a dual-electrode MZM: PD, photodetector; VOA, variable optical attenuator; DAC, digital/analog converter.

0146-9592/10/081221-3/$15.00

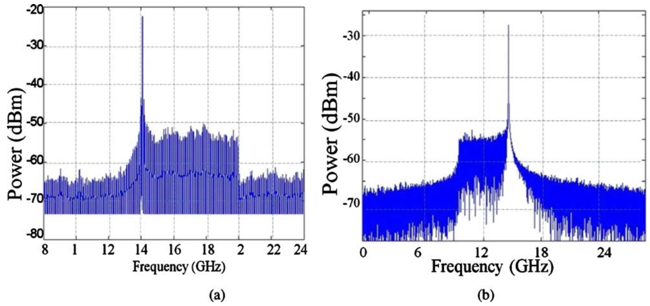

Fig. 2. (Color online) (a) Compatible SSB optical spectrum measured by coherent heterodyne detection. (b) Simulated optical spectrum.

$$E_0(t) \approx 2E_i e^{j\omega t} e^{j\varphi_0(t)}(\Delta\varphi(t)). \tag{4}$$

In order to satisfy the SSB condition, Eq. (4) should represent Eq. (1), that is,

$$(\Delta\varphi(t))e^{j\varphi_0(t)} = A(t)e^{j\Phi(t)}. \tag{5}$$

Therefore,

$$\Delta\varphi(t) = A(t), \quad \varphi_0(t) = \Phi(t). \tag{6}$$

Combining Eqs. (3) and (6), we obtain the required phase shifts of the two MZM arms and the relation to the OFDM signal $\sigma(t)$ by

$$\varphi_1(t) = H[\sigma(t)] + e^{\sigma(t)}, \tag{7a}$$

$$\varphi_2(t) = H[\sigma(t)] - e^{\sigma(t)}. \tag{7b}$$

Practically, $\varphi_1(t)$ and $\varphi_2(t)$ are digital representations of the required electrical waveforms on the two electrodes to synthesize the SSB OFDM optical signal without the guard band.

The experimental schematic is illustrated in Fig. 1. A Nortel commercial eDCO card was used as the OFDM transmitter, which is equipped with two 22 Gs/s DACs with a six-bit resolution and a balanced dual-electrode MZM. A 10 Gbit/s data stream was partitioned into 64 OFDM subcarriers with a QPSK modulation format, and the total OFDM signal bandwidth was about 5.8 GHz. The length of the cyclic prefix was 4% of the fast Fourier transform (FFT) size. The Hermitian symmetry was adopted in the FFT matrix to guarantee the real value of the original OFDM signal. The digital OFDM data were converted into analog signals by two DACs based on Eq. (7) to ensure the SSB optical spectrum, and the signals were amplified before feeding to the two electrodes of the MZM. To minimize the optical carrier component and maximize the modulation index, we had to adjust the dc levels of the driving electrical waveforms $\varphi_1(t)$ and $\varphi_2(t)$ so that the MZM operated in the linear region. The gain of the electrical amplifiers that drive the MZM was controlled to obtain the desired modulation index.

The optical transmission system consisted of two spans of standard single-mode fibers of 75 and 50 km, respectively. An erbium-doped fiber amplifier was used between the two fiber spans to amplify the optical signal. A variable optical attenuator (VOA) adjusted the power level of the optical signal that launched into the fiber spool. In this system, approximately 4 dBm launched optical power appeared to give the best performance. In order to measure the required OSNR for a certain bit-error-rate (BER), amplified spontaneous emission (ASE) noise loading was applied before the optical receiver, which consists of an ASE noise source, a VOA, and an optical coupler that adds the extra ASE noise to the received optical signal as shown in Fig. 1. A wideband photodiode performed a direct detection of the optical signal. The electrical signal waveform was amplified and then digitized by a 20 Gs/s LeCroy digital oscilloscope. The reason that we chose the 5.8 GHz OFDM signal bandwidth in the experiment was because the 6 GHz maximum analog bandwidth of the oscilloscope. The digital signal waveform was recorded with the time duration three times the OFDM pattern length for synchronization and OFDM demodulation. The oscilloscope sampling offset was also corrected in the digital offline processing [8].

The typical spectrum of the generated compatible SSB optical signal is shown in Fig. 2(a), where the OFDM signal has a uniform spectral density from 10 MHz to 5.8 GHz, on one side of the optical carrier. Based on the system block diagram and the signal-processing algorithm described in [8], we have also developed a numerical simulation model including the dual-electrode MZM and the fiber model. The simulated optical SSB spectrum shown in Fig. 2(b) has the same bandwidth of 5.8 GHz.

For back-to-back operation without the fiber, the received OFDM signal experienced a significant spectral roll-off due to the low-pass characteristics of various radio frequency components used in the system. As the consequence, the constellation diagram became unrecoverable. To illustrate this effect, Fig. 3(a) shows the measured OFDM spectrum with 2.9 GHz bandwidth. The corresponding constellation diagram shown in Fig. 3(b) exhibits a significant amplitude variation. In order to maintain equal OSNRs in the receiver for all subcarriers, we had to apply a digital precompensation (a linear power tilt over frequency) on the OFDM spectrum at the transmitter side. In this way, the received baseband OFDM spectrum became flat as illustrated in Fig. 3(c). In our system, this precompensation eliminated the approximately 10 dB high frequency roll-off within the 5.8 GHz OFDM bandwidth, and the constellation diagram with precompensation is shown in Fig. 4(a). The simulated constellation diagram shown in Fig. 4(b) exhibits similar characteristics as the measured one, which indicates that the experimental system

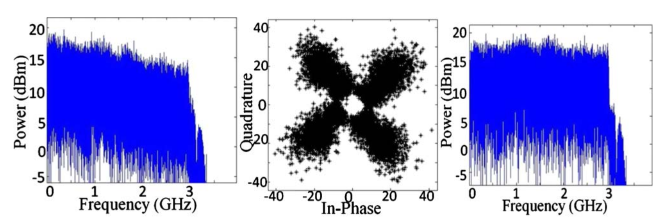

Fig. 3. (Color online) (a) SSB OFDM spectrum high-frequency roll-off, (b) constellation of SSB OFDM signal of (a), and (c) SSB OFDM after digital precompensation.

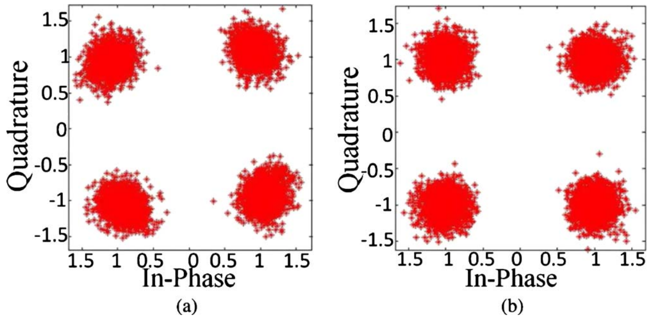

Fig. 4. (Color online) Back-to-back constellation for the SSB OFDM signal: (a) experimental result, (b) numerical result.

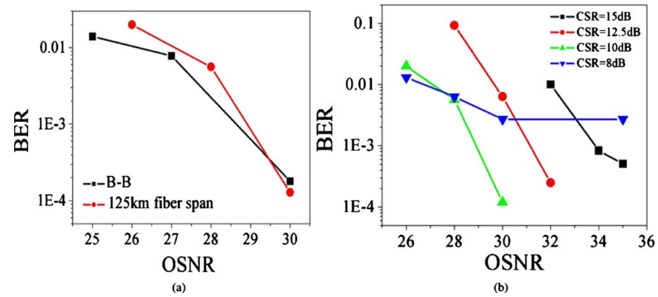

Fig. 5. (Color online) BER versus required OSNR for (a) back-to-back and after 125 km fiber span with CSR $=10$ dB and (b) after 125 km fiber span but with different CSR values.

was optimized. The ASE noise was then loaded to evaluate the BER as a function of the OSNR at the receiver.

Figure 5(a) shows the measured results for back-to-back as well as for the system with 125 km standard single-mode fiber. It is clear that the 125 km fiber in the system introduces negligible penalty in the transmission performance. In both cases, the required OSNR to achieve the BER of 10^{-3} was approximately 29 dB. This system using a compatible SSB modulation apparently demands a higher OSNR in comparison to the 17 dB required OSNR in previous OFDM systems reported using the same transmitter [8]. The reason is not completely clear at this point, but we postulate that by putting the OFDM signal into the exponential as indicated by Eq. (1), the peak-to-average ratio is increased and the effective modulation index is reduced, especially for the part of waveforms with small amplitudes. This is the price paid to improve the bandwidth efficiency by eliminating the guard band between the carrier and the OFDM sideband.

As an attempt to investigate the effect of the modulation index, we adjust the gain of the electrical amplifiers that drive the MZM. This allows us to vary the carrier-to-signal ratio (CSR), which is defined as the ratio between the powers in the optical carrier and in the OFDM sideband. The carrier linewidth was measured to be about 2 MHz, and the carrier power was calculated as the integration of the Lorentzian profile. In the MZM transfer function, when the modulation index is higher than 100%, power clipping will happen. On the other hand, if the modulation index is too small, the CSR will be very high and the system is vulnerable to the ASE noise. The trade-off between the two effects provided a guideline to find the optimized modulation index. Figure 5(b) shows the measured BER versus OSNR at the receiver for various CSR values corresponding to different modulation indices. The best modulation index corresponds to a CSR of 10 dB. When the modulation index is too low (for example, CSR $=15$ dB), the required OSNR to obtain a BER of 10^{-3} is as high as 34 dB. On the other extreme if the modulation index is too high (for CSR$=8$ dB), the BER value cannot reach 10^{-3} even for very high OSNRs. In this case, most of the errors were caused by clipping.

In conclusion, we have experimentally demonstrated the OFDM transmission using a compatible SSB modulation, in which the guard band between the optical carrier and the OFDM sideband is not required. The implementation uses a commercial Nortel eDCO transmitter card equipped with a simple dual-electrode MZM. Although the bandwidth efficiency is doubled in comparison to intensity-modulated OFDM systems, the major challenge is the increased peak-to-average ratio arising from the exponentiation of Eq. (1), which increases the required OSNR. Further investigations in nonlinear signal predistortion may help one to improve the system performance.

The work was supported by Nortel-Networks and National Science Foundation (NSF) under CNS043538.

References

1. A. J. Lowery and J. Armstrong, Opt. Express **14**, 2079 (2006).
2. W. Shieh and C. Athaudage, Electron. Lett. **42**, 587 (2006).
3. B. J. Schimidt, Z. Zan, L. Du, and A. Lowery, in *Proceedings of the OFC* (2009), paper PDP OWM4.
4. W. R. Peng, X. Wu, V. R. Arbab, B. Hamee, J. Y. Yang, L. C. Christen, K. M. Feng, A. E. Willner, and S. Chi, in *Proceedings of the OFC* (2008), paper OMU1.
5. M. Schuster, S. Randel, C. A. Bunge, S. C. Lee, F. Breyer, B. Spinnler, and K. Petermann, IEEE Photon. Technol. Lett. **20**, 670 (2008).
6. J. McNicol, M. O'Sullivan, K. Roberts, A. Comeau, D. McGhan, and L. Strawczynski, in *Proceedings of the OFC* (2005), paper OThJ3.
7. D. Walker and H. Sun, IEEE Photon. Technol. Lett. **17**, 2751 (2005).
8. Z. Xu, R. Hui, and O. Sullivan, Opt. Express **17**, 13479 (2009).