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40-Gbps vestigial sideband half-cycle Nyquist subcarrier modulation transmission experiment and its comparison with orthogonal frequency division multiplexing

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Abstract. We experimentally demonstrate the superior performance of a 40-Gbps 16-QAM half-cycle Nyquist subcarrier modulation (SCM) transmission over a 100-km uncompensated standard single-mode fiber using dual-drive Mach-Zehnder modulator-based vestigial sideband intensity modulation and direct detection. The impact of modulator chirp on the system performance is experimentally evaluated. This Nyquist-SCM technique is compared with optical orthogonal frequency division multiplexing in both back-to-back and 100-km transmission experiments, and the results show that the Nyquist system has a better performance. [DOI: 10.1117/1.OE.53.9.096114]

Keywords: vestigial sideband; direct detection; half-cycle Nyquist subcarrier modulation; chirp of modulator; orthogonal frequency division multiplexing.

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1 Introduction

With the fast-growing demand for higher transmission speed and information capacity, alternative modulation techniques such as optical orthogonal frequency division multiplexing (OFDM) modulation and Nyquist subcarrier modulation (Nyquist-SCM) are attractive to long-reach passive optical networks, metro transport networks and flexible optical wavelength division multiplexing (WDM) networks.[1–3] Optical OFDM has been widely explored in systems with both coherent detection and direct detection (DD) due to its advantages in overcoming transmission impairments such as chromatic dispersion (CD) and polarization-mode dispersion. Nyquist modulation is well known from communication theory and has been widely studied in coherent Nyquist-WDM systems in recent years, but is relatively new in DD systems.[2] For short reach applications (<100 km), the cost and complexity make coherent detection less justifiable. A more practical solution is to use an intensity modulation and direction detection (IMDD) scheme. However, an optical IMDD system will meet two challenges: dispersion-induced power fading and nonlinear distortion caused by square-law photodetection.[1] A vestigial sideband (VSB) filter has been used early in single-carrier systems to improve CD tolerance and the spectral efficiency of a dense WDM system.[4] Our previous work has also shown that the VSB filter in an IMDD OFDM system could mitigate the power fading, improve the available signal bandwidth, and increase the network capacity.[5]

In order to overcome the performance degradation caused by power fading, a fiber Bragg grating (FBG) is used in our system as a VSB filter to destroy the symmetry of the double-sideband (DSB) optical spectrum caused by intensity modulation. We experimentally demonstrate a 40-Gbps, 16-QAM, dual-drive Mach-Zehnder modulator (MZM)-based optical VSB-IMDD half-cycle Nyquist-SCM transmission over a 100-km uncompensated standard single-mode fiber (SSMF) link by using cost-effective 10-GHz bandwidth electronic devices. The 16-QAM Nyquist signal with zero roll-off is modulated onto an electrical subcarrier with a frequency equal to half the symbol rate.[2] Modulator chirp is usually an important factor limiting system performance, which can be introduced in the transmitter through devices such as directly modulated distributed feedback laser and electro-absorption modulator. We evaluate and discuss the impact of modulator chirp on the Nyquist-SCM signal by setting different optical phase modulation amplitudes on the two arms of the dual-drive MZM. Finally, we discuss the comparison with the DD-OFDM technique based on the same experimental setup with a special emphasis on the application in a short reach scenario. The results indicate that Nyquist-SCM has a better performance than OFDM; and the reason for this is analyzed.

2 Experimental Setup

The experimental setup for a 40-Gbps dual-drive MZM-based VSB-IMDD half-cycle Nyquist-SCM transmission system over a 100-km SSMF is shown in Fig. 1. The electrical Nyquist baseband signal is generated by an Agilent® arbitrary waveform generator (AWG M8190A) using the MATLAB® program. Nevertheless, since the sampling rate of the AWG is only 12 GSa/s, we use an electrical-optical-electrical (E/O/E) conversion architecture to generate a 40-Gbps electrical Nyquist-SCM signal. Two sinusoidal signals divided from the same oscillator at 5 GHz are combined with the real and imaginary parts of Nyquist baseband signals, respectively. Then, the two combined signals are

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*Address all correspondence to: Na Liu, E-mail: liunana@bupt.edu.cn used to drive an in-phase/quadrature modulator. The generated optical signal is a virtual single-sideband optical signal.[6] A 10-GBaud Nyquist-SCM signal is obtained after photoelectric conversion. Since the Nyquist-SCM signal after O/E conversion suffers from distortions caused by hardware imperfections and signal-to-signal beating interference, two methods are adopted to mitigate the distortions and interference in this paper. First, the carrier-to-signal-power ratio (CSPR) is increased, which is the power ratio of the radio frequency tone to the Nyquist baseband signal. Second, the baseband signal after QAM mapping is predistorted. The ideal time domain signal after QAM mapping can be written as $\vec{V} = [V_1, V_2 \dots V_N]^T$. The received signal after E/O/E conversion can be written as $\vec{R} = [R_1, R_2 \dots R_N]^T$, which can be further expressed as $\vec{R} = \Gamma\{\vec{V}\}$, where $\Gamma\{\cdot\}$ is the channel transfer function of the E/O/E conversion process, assuming the received signal after E/O/E is the desired ideal signal and the transmitted signal should be predistorted, $\vec{V} = \Gamma\{\vec{Y}\}$, where $\vec{Y} = [Y_1, Y_2 \dots Y_N]^T$ are the predistortion values. Iteration is used to increase the signal quality, $\vec{Y}^{(i)} = \vec{Y}^{(i-1)} + \eta[\vec{V} - \Gamma\{\vec{Y}^{(i-1)}\}]$, where the superscript, i, denotes the number of iterations, $\vec{Y}^{(0)} = \vec{V}$ is the initial value, and η is the scaling parameter. The CSPR, the iteration number and η are set to be 15 dB, 2 and 0.9, respectively, in the following experiment.

Based on the E/O/E architecture shown in Fig. 1, the signal processing program in the transmitter consists of a bit to QAM symbol mapping, predistortion, two times up-sampling and Nyquist pulse shaping. Zero roll-off raised-cosine pulse shaping is performed to produce Nyquist 4 level in-phase (I) and quadrature (Q) baseband signals. After E/O/E conversion, a 10-GBaud Nyquist-SCM signal is split in two by a Balun and used to drive a dual-drive MZM to generate an optical DSB signal. The chirp parameter of the intensity modulator could be simulated by setting different optical phase modulation amplitudes on the two arms. The chirp parameter, α, can be written as $\alpha \approx (m_1 + m_2)/(m_1 - m_2)$, where m_1 and m_2 are the modulation amplitudes on the upper and the lower arms.[7] A commercial FBG is used as VSB filter with a temperature compensation and a profile of a 1.35th order Gaussian, whose 3-dB bandwidth is 21.7 GHz. The optical power difference before and after the VSB filter is used as feedback to precisely adjust the central frequency of the laser, then the central frequency offset of the VSB filter relative to the optical carrier could be stabilized at 11 GHz. The insertion loss of the FBG filter is ~3.5 dB. The optical spectra before and after the FBG filter are shown in Figs. 1(a) and 1(b), which are measured by a conventional optical spectrum analyzer with a 0.02-nm resolution. The launch power is 4 dBm, and an erbium doped fiber amplifier with a 16-dB gain is inserted after 70-km SSMF transmission. After the 100-km transmission, an optical attenuator is used to adjust the received power. The received electrical signal is captured by a LeCroy® digital oscilloscope WaveMaster813ZI-A with a 40-GSa/s sampling rate and processed off-line by MATLAB® digital signal processing program. The received signal is down converted to the baseband to produce separate I and Q signals.[2] The linear distortion is compensated by the overlap frequency-domain equalization (O-FDE)[8] method with a fast Fourier transform size of 1024 (512 symbols as a block) and 8 overlap symbols, followed by symbol to bit mapping, error vector magnitude calculation, and bit error counting.

To compare the performance with a VSB-IMDD OFDM system, we provide a brief description of the OFDM system configuration used in our previous works.[5] Table 1 shows the comparison of the main parameters in two experiments. The OFDM signal contains 107 data subcarriers (1 to 54 and 76 to 128) with a 16-QAM format with an inverse fast Fourier transform (IFFT) size of 128, then the signal after E/O/E conversion is equivalent to a baseband OFDM real-valued signal containing 107 data subcarriers with an IFFT size of 256 and digital-to-analog converter sampling rate of 24 GSa/s. A cyclic prefix of 1/8 is used. The 16-QAM signals before IFFT are predistorted. The optimum optical modulation

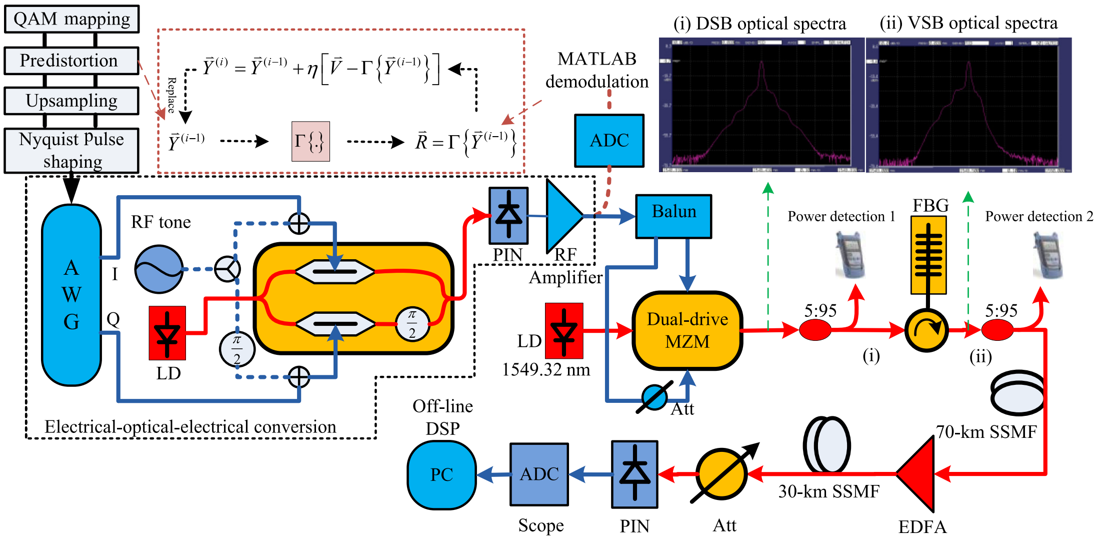


Fig. 1 Experimental setup of fiber Bragg grating (FBG)-based vestigial sideband (VSB)-IMDD half-cycle Nyquist-subcarrier modulation (SCM) transmission system and the optical spectra (a) before and (b) after FBG filter.

Table 1 Parameter comparison between Nyquist-subcarrier modulation (SCM) and orthogonal frequency division multiplexing (OFDM) system.

	Nyquist-SCM	OFDM
QAM format	16-QAM	16-QAM
Frequency of radio frequency-tone (GHz)	5	5.0625
Raw data rate (Gbps)	40	40.125
Number of data symbols	49,600	400
Optical modulation index	~0.32 (optimum)	~0.23 (optimum)

index (OMI) values for Nyquist-SCM and OFDM system are ~0.32 and ~0.23, respectively. The setting of the FBG filter is the same as that in the Nyquist system. Specially designed training symbols[6] with subcarrier interleaving, which can protect the training symbols from being affected by the signal-to-signal intermixing interference (SSII), are used for channel estimation in both experiments.

3 Experimental Results and Comparison

In this section, we depict and analyze the experimental results of half-cycle Nyquist-SCM transmission, and then a comparison with DD-OFDM transmission is performed. Since the chirp of the intensity modulator is critical to the DD system performance, the impact of different chirp values on Nyquist-SCM signal transmission is explored. Herein, the system parameters are optimized under the condition of 100-km SSMF transmission with a bit error rate (BER) of 3.8×10^{-3} (the forward error correction limit), and the signal-to-noise ratio (SNR) is used to evaluate the signal quality. Figure 2 depicts the SNR as a function of modulator chirp at back-to-back (B2B), and after 60- and 100-km transmission.

The SNR at B2B with a VSB filter and chirp free is 19.7 dB and has a negligible penalty compared with that of the DSB. However, it would become slightly worse when the chirp deviates from the zero point. The SNR sharply declines after fiber transmission and the SNR penalties after 60- and 100-km transmission are 2 and 3.2 dB. The main bottleneck in the VSB-IMDD Nyquist-SCM system is dispersion-induced nonlinear distortion, since linear distortion has been compensated by the O-FDE. Compared with the SNR curves of positive chirp after fiber transmission, the negative chirp in the VSB scheme has a better performance, similar to the case of the DSB scheme, because the power null point caused by power fading with a negative chirp could be shifted to higher frequencies in the DSB system.[9] The imperfect VSB filter (relatively smaller sideband suppression ratio) could not completely inhibit this effect. The constellations at B2B with chirp free in the DSB scheme and that after 100-km transmission in the VSB scheme are shown in Figs. 2(b) and 2(c).

To give an analogy of both modulation techniques, the dual-drive MZM is operated at a push-pull mode ($\alpha = 0$) and the SNRs at B2B are all fixed to 19.7 dB. The BER performance of each subcarrier after fiber transmission is not exactly the same in the OFDM system, since the imperfect VSB filter and SSII may induce the fluctuation of the SNR value.[5] In order to guarantee a fair comparison between OFDM and Nyquist systems, SNR is used to assess the system performance. It is the averaged value of all subcarriers in the OFDM system, as shown in Fig. 3(a).

If in detection we consider only the Gaussian noise and ignore the distortions and the other non-Gaussian interference, SNR = ~15.6 dB corresponds to a $\text{BER} = 3.8 \times 10^{-3}$ for a 16-QAM format.[10] Experimentally, the SNR of 15.6 dB for Nyquist and OFDM signals can be obtained at the received powers of −12.5 and −11.6 dBm at B2B, and −9.3 and −8.1 dBm after 100-km transmission. Accordingly, compared with OFDM signal, 0.9 and 1.2-dB receiver sensitivities are improved for the Nyquist signal in two cases. The measured BER versus the received power of both modulation schemes are also shown in Fig. 3(b). The major difference between the two schemes is that the Nyquist signal has a smaller peak-to-average power ratio (PAPR).

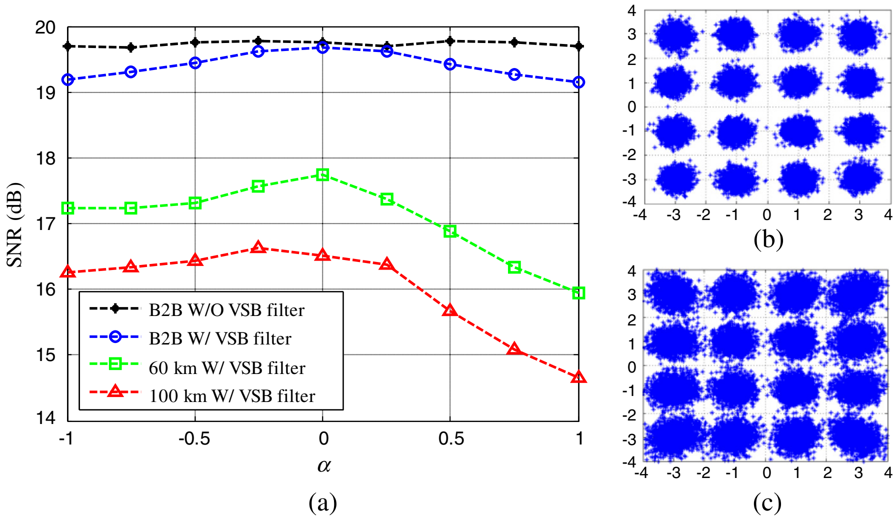
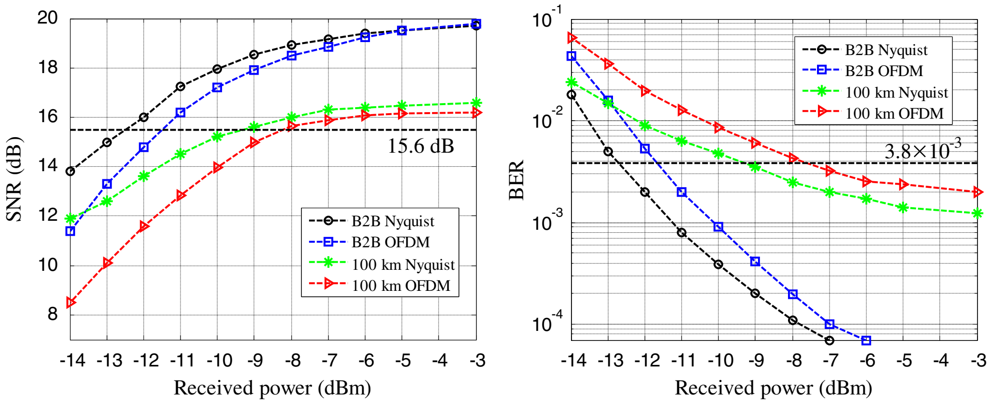


Fig. 2 (a) Measured signal-to-noise ratio (SNR) versus chirp parameter. (b) The constellations at B2B with chirp free and without VSB filter. (c) The constellations after 100-km standard single-mode fiber transmission with chirp free and with VSB filter.



(a) (b)

Fig. 3 (a) SNR versus received power at B2B and after 100-km transmission. (b) BER versus received power.

The signal with a smaller PAPR allows a larger OMI and suffers from smaller modulation nonlinearity.[11] The optimum OMI for the OFDM and Nyquist signals are ∼0.23 and ∼0.32, respectively. Therefore, for the Nyquist signal, there is more efficient signal power transmitting over the fiber with a smaller modulated distortion.

4 Conclusions

In this paper, a 40-Gbps VSB-IMDD half-cycle Nyquist-SCM transmission scheme over a 100-km SSMF is experimentally demonstrated using a cost-effective FBG to overcome the influence of power fading and improve the spectral efficiency. The impact of modulator chirp on the VSB-IMDD system is also evaluated. A simple comparison with the DD-OFDM system is performed with respect to the application in a short reach scenario. The results show that the half-cycle Nyquist-SCM outperforms OFDM.

Acknowledgments

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Na Liu received her bachelor's degree from Xi'an University of Posts and Telecommunications, China, in 2010. She is currently working toward her PhD degree in the State Key Lab of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications. Her current research interest is impairment compensation in intensity modulation and direction detection system.

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