High spectral efficient W-band optical/wireless system employing Single-Sideband Single-Carrier Modulation

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Abstract: With broader available bandwidth, W-band wireless transmission has attracted a lot of interests for future Giga-bit communication. In this article, we experimentally demonstrate W-band radio-over-fiber (RoF) system employing single-sideband single-carrier (SSB-SC) modulation with lower peak-to-average-power ratio (PAPR) than orthogonal frequency division multiplex (OFDM). To overcome the inter-symbol interference (ISI) of the penalty from uneven frequency response and SSB-SC modulation, frequency domain equalizer (FDE) and decision feedback equalizer (DFE) are implemented. We discuss the maximum available bandwidth of different modulation formats between SSB-SC and OFDM signals at the BER below forward error correction (FEC) threshold (3.8×10^{-3}). Up to 50-Gbps 32-QAM SSB-SC signals with spectral efficiency of 5 bit/s/Hz can be achieved.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation; (060.5625) Radio frequency photonics.

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1. Introduction

With the increasing demand of broadband wireless communications, millimeter wave communication such as V-band (57-64 GHz) and W-band (75-110 GHz) have attracted a lot of interests to provide more than 10-Gbps wireless applications due to larger bandwidth. However, the nature phenomenon of electromagnetic wave operating as high frequency will suffer high attenuation during wireless transmission. Therefore, radio-over-fiber (RoF) technology has been nominated as one of promising solutions for optical/wireless network to not only extend the coverage of V/W-band wireless signals but also to release the system complexities from base station to central office. Thus, V-band RoF systems with 7-GHz unlicensed band have been demonstrated by several methods [1,2]. Moreover, W-band with broader utilized bandwidth has also become a candidate to pursuit higher data rate. Recently, several W-band RoF systems have been proposed and experimentally demonstrated by using remote up-conversion with photonic transmitter-mixer, self-coherent heterodyne, and multi-input multi-output (MIMO) technology with coherent heterodyne or polarization division multiplexing [3–7]. Among the above literatures, 20-Gbps OOK wireless signal (from 83 to 103 GHz) by utilizing active near-ballistic uni-traveling-carrier photodiode was achieved with 25-km fiber transmission [4]. The maximum data rate in single-input single-output (SISO) was achieved to 40 Gbps by self-coherent heterodyne system [5]. To enhance the spectral efficiency, MIMO technique with coherent heterodyne and polarization division multiplexing were also demonstrated to achieve 108 Gbps and 120 Gbps with the same spectral efficiency of 4 bit/s/Hz, respectively [6,7]. Recently, OFDM-RoF employing direct-detection (DD) technology was proposed to not only reduce the complexities of system but also to achieve high spectrally-efficient signals transmission [8]. Nevertheless, OFDM signals have higher peak-to-average-power ratio (PAPR), which results in performance degradation.

In this paper, we propose single-sideband single-carrier (SSB-SC) modulation [9,10]. The SSB-SC signals not only has better spectral efficiency than double-sideband single-carrier (DSB-SC) signals but also has lower PAPR than OFDM signals. Hence, the higher average power can be provided by the SSB-SC signals within the linear modulation region of the W-band RoF system. Moreover, frequency domain equalizer (FDE) and decision feedback equalizer (DFE) are implemented to overcome inter-symbol interference (ISI) caused by W-band frequency response and the SSB-SC modulation. With 32-QAM SSB-SC signals occupied from 98 to 108 GHz, up to 50-Gbps data rate with the bit error rate (BER) below forward error correction (FEC) threshold (3.8×10^{-3}) can be achieved following 25-km fiber and 2-m wireless transmission. To the best authors' knowledge, the highest spectral efficiency of 5 bit/s/Hz can be attained in W-band RoF communication system.

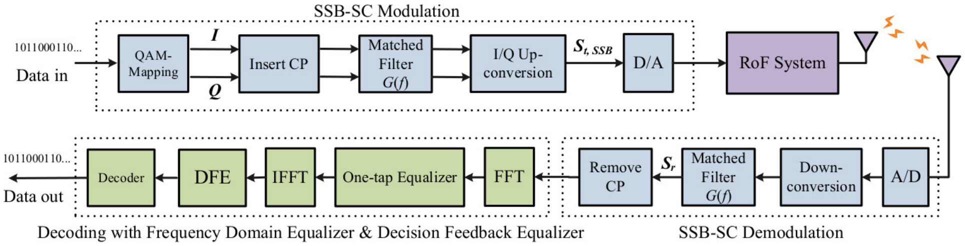

Fig. 1. The block diagrams of the SSB-SC signals generation. D/A: digital to analog convertor. A/D: analog to digital convertor. (I)FFT: (Inverse) fast Fourier transform.

2. Single-Sideband Single-Carrier Modulation

Figure 1 depicts the block diagrams of the SSB-SC signals generation and demodulation, which are mainly composed of three parts: SSB-SC modulation/demodulation, RoF transmission system, and decoding with the equalizers. The binary data streams are generated and mapped to QAM formats which consist of in-phase (I) and quadrature-phase (Q) signals

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at baseband, which can be represented as $S(t)=I(t)+jQ(t)$. $S(t)$ can be rewritten with discrete time as:

$$S(nT)=I(nT)+jQ(nT)=\sum_{n=-\infty}^{\infty} b_{I,n}\delta(t-nT)+j\sum_{n=-\infty}^{\infty} b_{Q,n}\delta(t-nT) \qquad (1)$$

where $b_{I,n}$ and $b_{Q,n}$ represent the *I* and *Q* signals in discrete time, respectively. To realize SSB-SC signals generation, a SSB-SC matched filter composed of the suitable filter and its Hilbert transform term is required to eliminate half spectrum of the DSB-SC signal. After I/Q signal up-conversion [9,10], the generated SSB-SC signals, $S_{t,SSB}(f)$, can be expressed as following equations:

$$\begin{aligned} S_{t,SSB}(f)=&\left[G(f-f_{RF})I(f-f_{RF})+jG(f-f_{RF})Q(f-f_{RF})\right]\left[1+j\,\mathrm{sgn}(f-f_{RF})\right] \\ &+\left[G(f+f_{RF})I(f+f_{RF})+jG(f+f_{RF})Q(f+f_{RF})\right]\left[1-j\,\mathrm{sgn}(f+f_{RF})\right] \end{aligned} \qquad (2)$$

where

$$1+j\,\mathrm{sgn}(f-f_{RF})=\begin{cases}2, f\geq f_{RF}\\ 0, f<f_{RF}\end{cases} \qquad (3)$$

and

$$1-j\,\mathrm{sgn}(f+f_{RF})=\begin{cases}0, f\geq -f_{RF}\\ 2, f<-f_{RF}\end{cases} \qquad (4)$$

where *G*(*f*) is the frequency domain representation for the impulse response of the root-raised cosine filter after Fourier transformation. The root-raised cosine filter is utilized as an ideal rectangular filter with the roll-off factor of 0. -*j*sgn(*f*) and sgn(*f*) represent Hilbert transform and the sign function in the frequency domain after Fourier transformation, respectively. *I*(*f*) and *Q*(*f*) are frequency domain representations of in-phase and quadrature-phase signals. The spectra of 20-GHz DSB-SC, 10-GHz SSB-SC, and 10-GHz OFDM signals with the same data rate are shown in the insets of (a) to (c) in the Fig. 2. These three signals are up-converted to the center frequency of f_{RF} (i.e. f_{RF} = 21.5 GHz) by I/Q up-conversion. Normally, compared with the DSB-SC signals, the SSB-SC signals can carry the same data information with the half of bandwidth. The spectral efficiency of SSB-SC signals will be higher than the DSB-SC signals. Figure 2(d) shows the simulated complementary cumulative distribution function (CCDF) of 16-QAM SSB-SC and OFDM signals with 10-GHz bandwidth. The subcarrier number of the OFDM signal is 426. At the probability of 10^{-3} in CCDF of PAPR, the SSB-SC signals have lower PAPR value of 3.5 dB than the OFDM signals. Hence, the SSB-SC signals can has less signal distortion from the nonlinear effect of the RoF system. For SSB-SC signals demodulation, the received signals are down-converted and demodulated by the corresponding SSB-SC matched filter. The signal can be expressed [9,10] as:

$$S_r(f)=\left|G(f)\right|^2\left[1+\mathrm{sgn}(f)\right]\left[I(f)+jQ(f)\right]=\frac{1}{2}\Phi(f)\left[I(f)+jQ(f)\right] \qquad (5)$$

where $\Phi(f)$ is the transfer function of the matched filter, which is related with the impulse response of the SSB matched filter in the frequency domain [9]. The signal can be rewritten in the discrete time and expressed as:

$$\begin{aligned} S_r(nT)&=\sum\nolimits_{n=-\infty}^{\infty}(b_{I,n}+jb_{Q,n})(\Re\{\phi_{\Delta k}\}+j\Im\{\phi_{\Delta k}\}) \\ &=\sum\nolimits_{n=-\infty}^{\infty} b_{I,n}\Re\{\phi_{\Delta k}\}-b_{Q,n}\Im\{\phi_{\Delta k}\}+j\sum\nolimits_{n=-\infty}^{\infty} b_{Q,n}\Re\{\phi_{\Delta k}\}+b_{I,n}\Im\{\phi_{\Delta k}\} \end{aligned} \qquad (6)$$

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where $\Re\{\varphi_{\Delta k}\}$ and $\Im\{\varphi_{\Delta k}\}$ are the real part and the imagine part of transfer function $\varphi_{\Delta k}$ in the discrete time domain, respectively. Δk means other discrete time from the other symbols. From the Eq. (6), the in-phase and qudrature-phase signals of the received signals will be inherently influenced by each other, which depends on the design of the SSB-SC matched filter. Although we can choose suitable filter for SSB matched filter to reduce the inherent ISI, it cannot be removed completely. In this work, two kinds of equalizers (i.e. FDE and DFE) are implemented to mitigate the ISI at receivers [11].

3. Experimental setup

Figure 3 shows the experimental setup of the 103-GHz RoF system. The optical transmitter is composed of two single-electrode Mach-Zehnder Modulator (SD-MZMs) and an electrical I/Q mixer [8]. The I- and Q-channel of the SSB-SC signals are generated at baseband by an arbitrary waveform generator (AWG) with a sampling rate of 12-GHz. The generated SSB-SC signals are up-converted to 21.5-GHz via an electrical I/Q mixer, and then combined with 38.5-GHz sinusoidal signal as driving signal of 1st SD-MZM. The bias voltage of 1st SD-MZM is set at the null point to achieve the optical double-sideband with carrier suppression scheme as shown in the inset (i) of Fig. 3. In order to overcome power fading induced by fiber dispersion, a 50/100 interleaver is utilized as an optical filter to remove non-required optical sidebands as shown in the inset (ii) of Fig. 3. After an Erbium-doped fiber amplifier (EDFA), the optical SSB-SC signals and the rest of optical carriers are modulated with 21.5-GHz sinusoidal signal to achieve frequency multiplication by the 2nd SD-MZM as shown in the inset (iii) of Fig. 3.

After 25-km fiber transmission and photo detection (PD) at remote unit, the beating term of one optical SSB-SC signal and one optical carrier will contribute to the electrical SSB-SC signal at the center frequency of 103-GHz. After amplifier, the signal is fed into rectangular waveguide-based standard horn antenna with 24-dBi gain for 2-m wireless transmission. The wireless signal is received by the same kind of horn antenna at wireless receive unit and then down-converted to 8.5-GHz via an electrical mixer with 94.5-GHz sinusoidal signal. The down-converted signal is captured by the oscilloscope with 80-GHz sampling rate. The corresponding spectrum is shown in inset (iv) of Fig. 3. Subsequently, the SSB-SC signals are demodulated by the off-line Matlab® DSP programs. The bit error rate (BER) is determined by error counting.

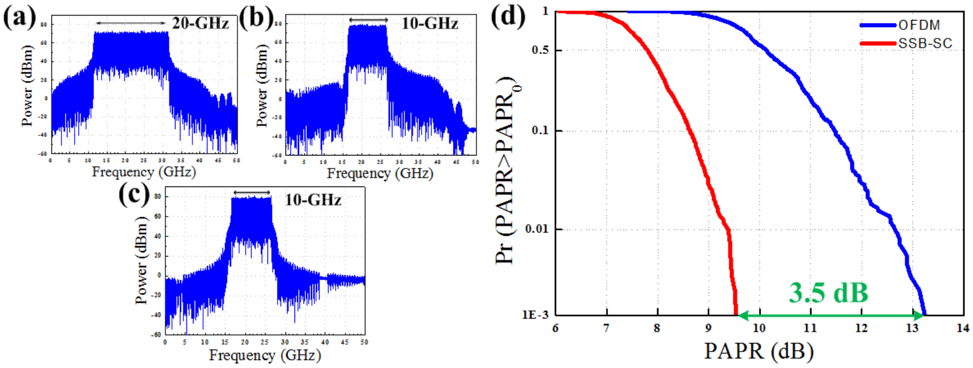

Fig. 2. The generated spectra of (a) DSB-SC, (b) SSB-SC and (c) OFDM modulations after I/Q signal up-conversion. (d) CCDF diagrams of PAPR for the OFDM and the SSB-SC signals.

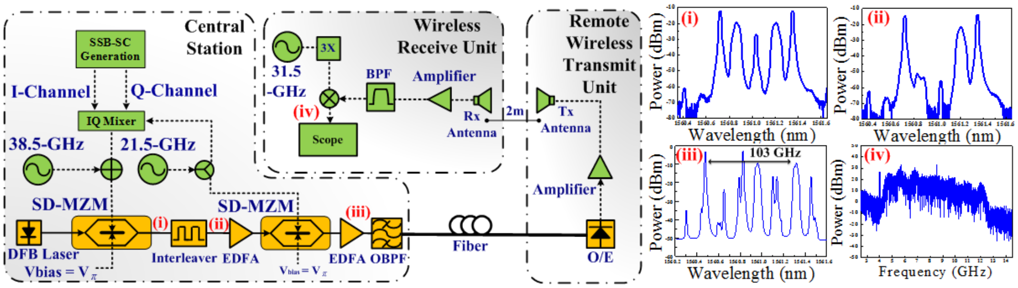

Fig. 3. Experimental setup of 103-GHz DD-RoF system with SSB-SC modulation scheme and optical spectrums of (i) After 1st SD-MZM. (ii) After interleaver. (iii) After interleaver and 2nd SD-MZM. (iv) Electrical spectrum after down-conversion.

4. Experimental results

Figure 4 shows the BER curves of 16-QAM SSB-SC and OFDM signals with 10-GHz bandwidth. Both signals have the same data rate of 40 Gbps and can achieve the BERs below FEC threshold of 3.8×10^{-3}. Moreover, there are no significant power penalties for both SSB-SC and OFDM signals after 25-km fiber transmission. Notably, the SSB-SC signals have 3.5 dB better in power sensitivity than the OFDM signals at the BER of 3.8×10^{-3}. This is because the SSB-SC signals have lower PAPR as shown in Fig. 2, resulting in higher signal to noise ratio (SNR). The corresponding constellation diagrams of SSB-SC and OFDM signals for BTB case and 25-km fiber transmission are shown in the insets (a) to (f) of Fig. 4. For the SSB-SC signals, the FDE and DFE are utilized to mitigate the ISI. Figures 4(c) and 4(e) show the constellation diagrams for the demodulated SSB-SC signals only with FDE. Figures 4(d) and 4(f) show the constellation diagrams with FDE and DFE. To achieve higher spectral efficiency, higher order data format is further investigated. Figure 5 shows the BER curves of SSB-SC and OFDM signals by using 32-QAM data format. For the SSB-SC signals, they can achieve the BER below FEC threshold with 10-GHz bandwidth. The attained data rate is 50-Gbps following 25-km fiber transmission. However, for the OFDM signals, if the bandwidth is more than 7.3 GHz, they cannot achieve the BER below FEC threshold. Therefore, the maximum bandwidth of the 32-QAM OFDM signals is 7.3 GHz, and the corresponding data rate is 36.5 Gbps. For the BTB case and 25-km fiber transmission, Figs. 5(a) and 5(b) show the corresponding constellation diagrams for the OFDM signals, and Figs. 5(c) to 5(f) show the corresponding constellation diagrams for the SSB-SC signals with the equalizers

To discuss the maximal data rate for the SSB-SC and OFDM signals in the proposed W-band RoF system, we study the BERs versus different bandwidths and modulation formats (16 QAM, 32 QAM, and 64 QAM) at optimal optical received power following 25-km fiber transmission as shown in Fig. 6(a). For the same bandwidth of 10 GHz, the highest data formats for the SSB-SC and the OFDM signals below the BER FEC threshold are 32 QAM and 16 QAM, respectively, and the corresponding data rates are 50 Gbps and 40 Gbps, respectively. Consequently, due to lower PAPR, the SSB-SC signals have better SNR to support one higher order of data format than OFDM signals with the same bandwidth. In order to increase the spectral efficiency, higher data formats are utilized. Since higher data formats require higher SNR requirements, the maximum bandwidths below FEC threshold need to be decreased. For the 32-QAM OFDM signals, the available bandwidth is 7.3 GHz, and the data rate is 36.5 Gbps. For the SSB-SC signals, 64-QAM data format can be used within 7-GHz bandwidth, and the data rate is 42 Gbps. Notably, there is only 0.3-GHz bandwidth difference between 64-QAM SSB-SC and 32-QAM OFDM signals.

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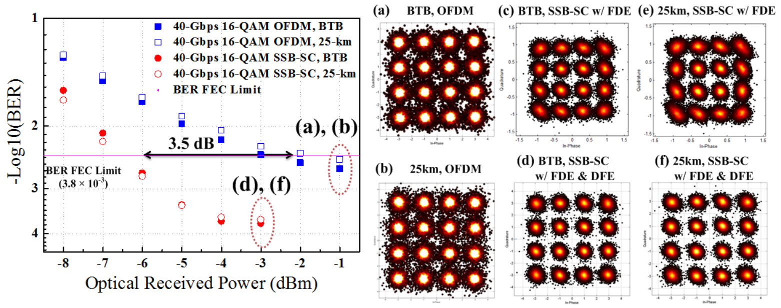

Fig. 4. BER curves of 10-GHz 16-QAM SSB-SC signal and OFDM signal with and without 25-km fiber transmission. (a) BTB, OFDM. (b) 25-km, OFDM. (c) BTB, SSB-SC w/ FDE. (d) BTB, SSB-SC w/ FDE & DFE. (e) 25-km, SSB-SC w/ FDE. (f) 25-km, SSB-SC w/ FDE & DFE.

Figure 6(b) shows the attained data rates versus different signal bandwidths for OFDM and SSB-SC signals following 25-km fiber transmission. According to Fig. 6(a), the maximum data rate can be achieved by selecting the optimal data format in each bandwidth. For the SSB-SC signals, the maximum data rates are from 36 Gbps to 50 Gbps as the bandwidths range from 6 GHz to 10 GHz. The corresponding data rates of the OFDM signals are from 30 Gbps to 40 Gbps. Moreover, the bit-loading with water-filling algorithm can be applied to adjust the power weighting factors and re-allocate the data formats among the subcarriers of the OFDM signals. Therefore, the maximal data rate of 10-GHz OFDM signal with bit-loading and water-filling algorithm can be improved from 40 Gbps to 46.4063 Gbps [8]. Compared with the data rate of OFDM signals, the data rate of SSB-SC signals is still 3.5937-Gbps higher than that. Consequently, up to 50-Gbps data rate by using SSB-SC signals can be achieved, and the corresponding spectral efficiency is 5 bit/s/Hz.

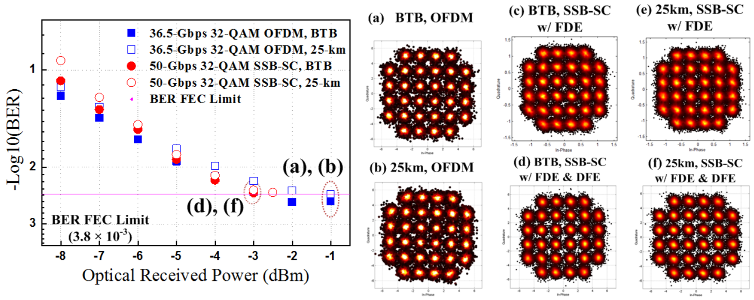

Fig. 5. BER curves of 7.3-GHz 32-QAM OFDM and 10-GHz 32-QAM SSB-SC signal with and without 25-km fiber transmission. (a) BTB, OFDM (b) 25-km, OFDM. (c) BTB, SSB-SC w/ FDE. (d) BTB, SSB-SC w/ FDE & DFE. (e) 25-km, SSB-SC w/ FDE. (f) 25-km, SSB-SC, w/ FDE & DFE.

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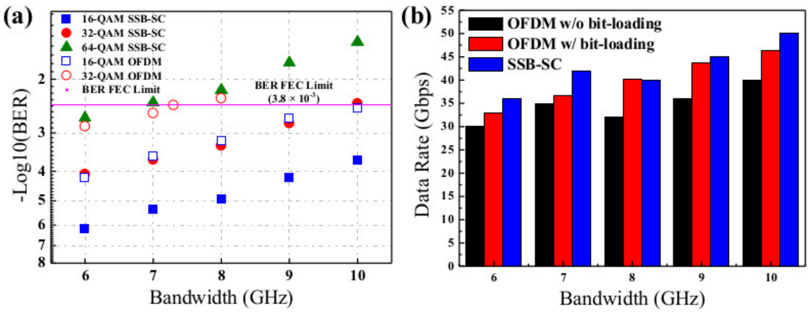

Fig. 6. (a) BER curves of OFDM and SSB-SC signals with 16-QAM, 32-QAM and 64-QAM data format within 6-GHz to 10-GHz bandwidth. (b) Maximum data rates for SSB-SC and OFDM signals versus different bandwidths with the BER below FEC limit (3.8×10^{-3}).

5. Conclusion

In this paper, we experimentally demonstrate the SSB-SC signals transmission in W-band RoF system. Since the SSB-SC signals have lower PAPR than OFDM signals, the SSB-SC signals have better SNR to support one higher order of data format than OFDM signals without bit loading in the same bandwidth. After 25-km fiber and 2-m wireless transmission, the maximum data rate of 50-Gbps with 5 bit/s/Hz spectral efficiency can be attained by using 10-GHz 32-QAM SSB-SC signals at the center frequency of 103 GHz.

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