High spectral efficient W-band OFDM-RoF system with direct-detection by two cascaded single-drive MZMs

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Abstract: W-band wireless transmission has attracted a lot of interest due to its wider available bandwidth (i.e. 75-110 GHz). In this article, we propose a direct-detection orthogonal frequency division multiplexing radio over fiber (OFDM-RoF) system via two cascaded single-drive MZMs at center frequency of 103 GHz. We discuss maximum bandwidth of different modulation formats under forward error correction (FEC) threshold (3.8×10^{-3}). Up to 40-Gbps 16-QAM OFDM signals is achieved over 25-km fiber and 2-m wireless transmission. To overcome the penalty from uneven frequency response, bit-loading algorithm is applied to discuss data rate and spectral efficiency with signal bandwidth from 5 to 10 GHz. With 10-GHz bandwidth, 46.4-Gb/s data rate and 4.64-bit/s/Hz spectral efficiency was achieved. To achieve 40-Gbps data rate, the required bandwidth of OFDM signal with bit-loading is 2 GHz less than that without bit-loading.

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

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1. Introduction

Recently, V-band and W-band have attracted a lot of interest due to its larger available bandwidth, compared with WIFI and LTE [1–8]. To extend wireless coverage and reduce the cost, radio-over-fiber (RoF) system, which minimizes the cost of the base station and shifts the system complexity to central office, is a promising candidate as the transmission medium due to almost unlimited bandwidth of fiber. V-band RoF systems with 7-GHz unlicensed band from 57 to 64 GHz have been demonstrated by several methods [1,2]. To provide higher data rate, W-band with more bandwidth from 75 to 110 GHz have attracted lots of attentions. However, one of the challenges is how to practically generate high data rate W-band signal. Recently, several W-band RoF systems have been proposed and experimentally demonstrated by using remote up-conversion with photonic transmitter-mixer [4], self-coherent heterodyne [5], and coherent heterodyne [6–8]. 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]. Self-coherent heterodyne was utilized to perform the W-band RoF system with data rate of 40 Gbps (from 87.5 to 97.5 GHz) [5]. Moreover, multi-input multi-output technology with coherent heterodyne was used to further improve capacity, and the data rate can reach 108 Gbps (from 86.5 to 113.5 GHz) [4]. In these works, however, either advanced spectrally-efficient modulation could not be applied [4], or narrow-linewidth laser is required [5–8].

In this paper, we propose and experimentally demonstrate W-band orthogonal frequency division multiplexing RoF (OFDM-RoF) system employing direct-detection (DD) technology, which is based on optical carrier suppression scheme [9]. The W-band DD-system was achieved via cascading two single-drive Mach-Zehnder modulators (SD-MZMs) with a commercial distributed feedback (DFB) laser source. Since optical OFDM-modulated subcarrier and un-modulated beating subcarrier were generated from the same laser source, the computing complexity induced from laser phase estimation can be mitigated at the receiver end. With 16-QAM OFDM signal occupied from 98 to 108 GHz, 40-Gbps with bit error rate (BER) under forward error correction (FEC) threshold (3.8×10^{-3}) can be achieved over 25-km fiber and 2-m wireless transmission. Moreover, with bit-loading technology to lessen the penalty of un-even frequency response at W-band, the data rate can achieve 46.4 Gbps. To the best authors' knowledge, the highest spectral efficiency of 4.64 bit/s/Hz with more than 40-Gbps W-band wireless communication is attained in this work.

2. Experimental setup

Figure 1 schematically depicts the experimental setup of the W-band DD OFDM-RoF system with two cascaded SD-MZMs biased at null point. A commercial DFB laser with 3-dB bandwidth of 10.9 MHz was utilized. The driving signal for the 1st SD-MZM consists of two electrical signals: an OFDM-modulated signal at 21.5 GHz and a sinusoidal signal at 38.5 GHz. The baseband OFDM signal was generated by an arbitrary waveform generator (AWG) with a sampling rate of 12 GHz. The length of FFT size was 512. The OFDM signal was up-converted to 21.5 GHz via electrical I/Q mixer, and then combined with a 38.5-GHz sinusoidal signal before being sent into the 1st SD-MZM, and the optical spectrum of output was consist of optical subcarrier: two OFDM-modulated subcarrier and two un-modulated subcarrier as shown in inset (i) of Fig. 1. After an Erbium-doped fiber amplifier (EDFA), the generated optical OFDM signal composed of four optical subcarriers was up-converted by the 2nd SD-MZM modulated by 21.5-GHz sinusoidal driving signal. Hence, the generated optical signal consists of 7 wavelength envelopes, as shown in inset (ii) of Fig. 1. After photo detection, two beating terms of one OFDM-modulated subcarrier and one un-modulated subcarrier will contribute to the electrical OFDM signal at the center frequency of 103 GHz. To avoid dispersion-induced RF fading and increase the sensitivity of photo detection, an interleaver was used to filter out non-required optical subcarrier as shown in inset (iii) of Fig. 1. In addition, the input power of fiber was fixed in −5 dBm.
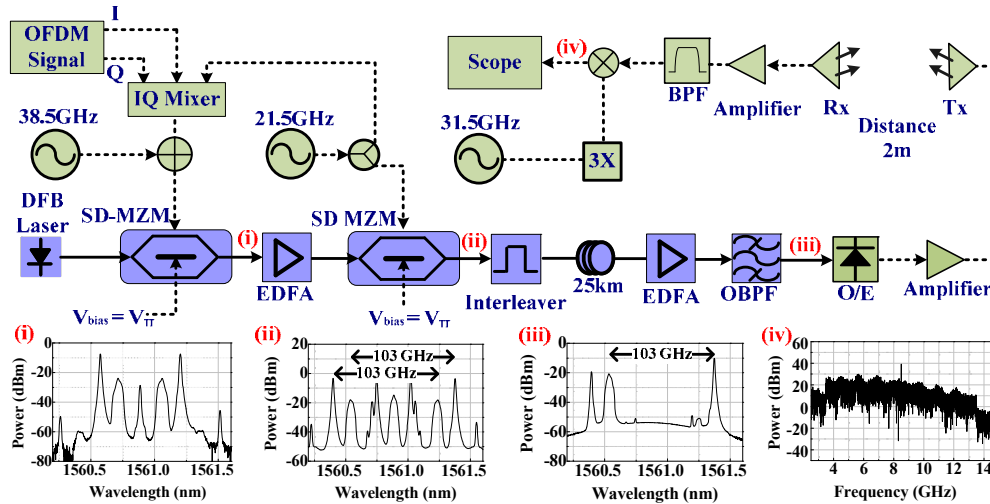
Fig. 1. Experimental setup of DD OFDM-RoF system at 103 GHz.

After 25-km fiber transmission, optical signal was received via photo detector to generate desired W-band signal. After amplifier, the signal was fed into rectangular waveguide-based standard gain horn antenna with 24-dBi gain. Note that the amplifier includes a low noise amplifier and a power amplifier, which the gain was about 20 dB and 13 dB, respectively. In addition, the saturated output power of power amplifier in transmitter and receiver ends were 12 dB and 14.5 dB, respectively. After 2-m wireless transmission, the OFDM signal was down-converted to 8.5 GHz via an electrical balanced mixer with 94.5-GHz LO signals, and received by an oscilloscope of 80-GHz sampling rate as shown in inset (iv) of Fig. 1. An off-line digital signal processing (DSP) program, including down-conversion and I/Q imbalance compensation, was used to demodulate the received signal. The BER was determined via error counting. Take 10-GHz 16-QAM OFDM signal for example, we collected 204480 bits for BER measurement.

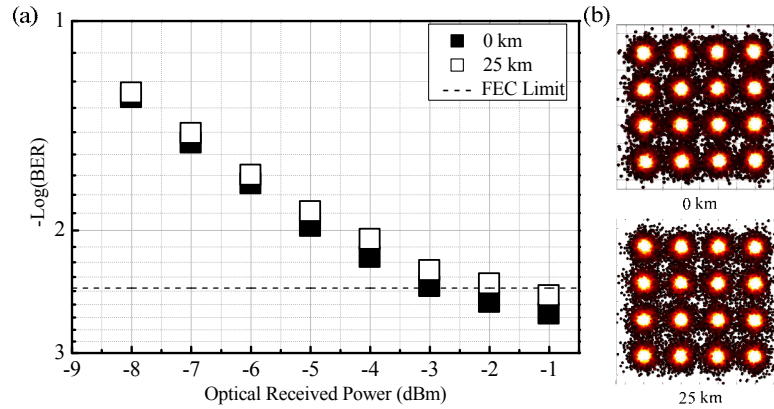## 3. Result and discussion

Fig. 2. (a) BER curves of 16-QAM OFDM signals. (b) 16-QAM OFDM constellations with optical received power of −1 dBm.
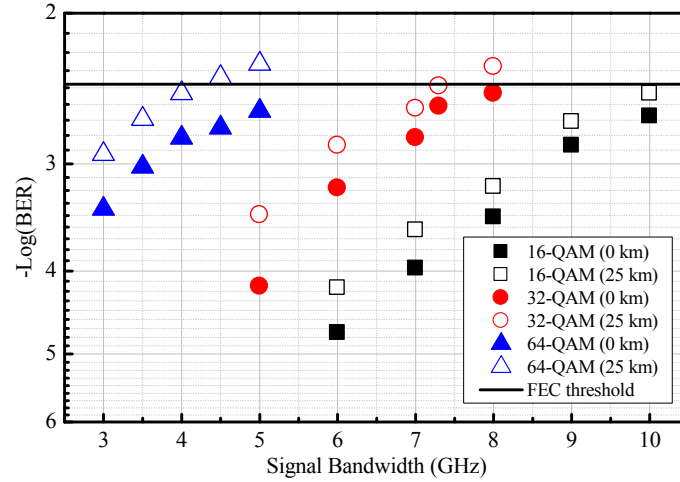
Fig. 3. BER versus different bandwidth with 16-QAM, 32-QAM, and 64-QAM modulated OFDM signal.
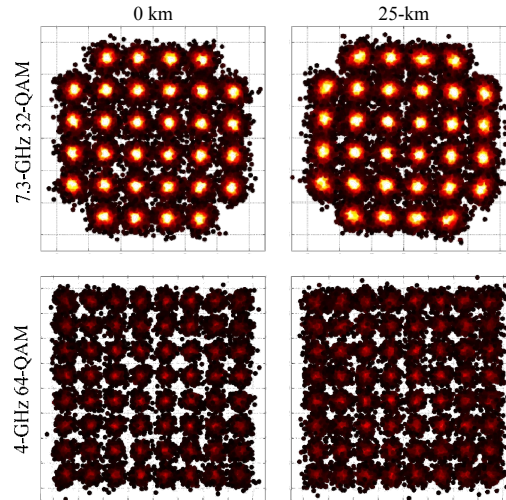

Fig. 4. 7.3-GHz 32-QAM and 4-GHz 64-QAM constellations with/without fiber transmission

Figure 2(a) shows the BER curves of 16-QAM OFDM signals with 10-GHz bandwidth at central frequency of 103 GHz. For the 10-GHz OFDM signal, 426 subcarriers were enabled and data rate was about 40 Gbps. Note that the optical received power was measured before PD input. For the cases with and without 25-km fiber transmission, both OFDM signals can meet the FEC threshold. Notably, although our proposed system has no power fading issue, there is still 1-dB penalty at FEC threshold after 25-km transmission. This is because of laser phase noise de-correlation of two optical subcarriers as shown in inset (iii) of Fig. 1 [10]. Figure 2(b) shows the constellations with and without 25-km fiber transmission. To discuss maximum bandwidth for different modulation formats (16-QAM, 32-QAM, and 64-QAM), we study the BER versus different bandwidth with optimal optical received power as shown in Fig. 3. Although high modulation format can improve spectral efficiency, it has higher SNR requirement. Hence, the maximum bandwidth will be decreased. With the BERs below the FEC threshold over 25-km fiber transmission, the acceptable bandwidth for modulation format of 16-QAM, 32-QAM, and 64-QAM are 10 GHz, 7.3 GHz, and 4 GHz, respectively,

and the corresponding data rate are 40, 36.5, and 24 Gbps, respectively. Figure 4 shows the constellations of 7.3-GHz 32-QAM and 4-GHz 64-QAM OFDM signals with and without 25-km fiber transmission.

As the carrier frequency increases, the frequency response of the components will have more deviations, especially for W-band devices. Therefore, the performance of W-band DD OFDM-RoF system is dominated by the subcarriers with the poorest BER. To mitigate the penalty, the adaptive power-loading and modulation format for each subcarrier is adopted in this paper. Rate-adaptive Levin-Campello loading algorithm is utilized to find the best corresponding power-loading and modulation format [11]. As a result, the data rate can be further improved. Figure 5 shows the bit-loading result of 10-GHz signal with fiber transmission. QPSK, 8-QAM, 16-QAM, 32-QAM, and 64-QAM formats were assigned depending on the corresponding SNR of each OFDM subcarrier. The constellations of different modulation format are shown in Fig. 6. The data rate of 46.4 Gbps can be achieved with the BER below the FEC threshold, and the spectral efficiency is 4.64 bit/s/Hz.
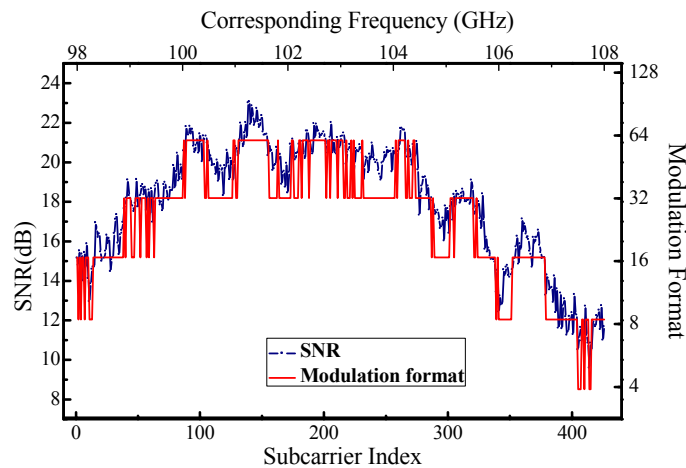

Fig. 5. Each SNR and corresponding modulation format with bit-loading algorithm with 25-km fiber transmission
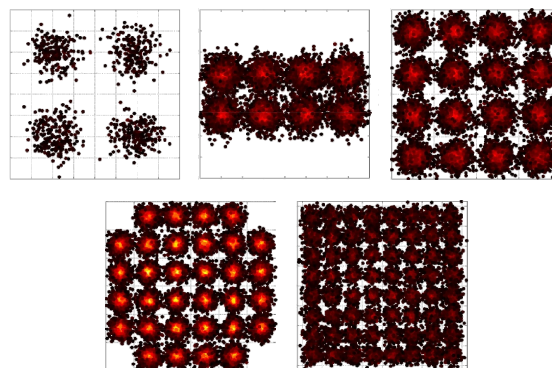

Fig. 6. Constellations with bit-loading algorithm over 25-km fiber transmission.

To further study the data rate and spectral efficiency with different signal bandwidths, the bit-loading algorithm was applied to W-band OFDM signals with bandwidth from 5 GHz to 10 GHz. Figure 7 shows the OFDM subcarrier numbers of different modulation formats and spectral efficiency versus different bandwidth over 25-km fiber transmission. With higher OFDM signal bandwidth, the subcarrier number of lower modulation format increased, which

caused lower spectral efficiency. Figure 8 shows the data rate and spectral efficiency versus different bandwidth. As the OFDM bandwidth increases from 5 to 10 GHz, the data rate increases from 28.29 to 46.4 Gbps but the spectral efficiency decreases from 5.66 to 4.64 bit/s/Hz. Note that the required bandwidths to achieve 40-Gbps OFDM W-band wireless transmission with and without bit-loading algorithm are 8 GHz and 10 GHz, respectively.
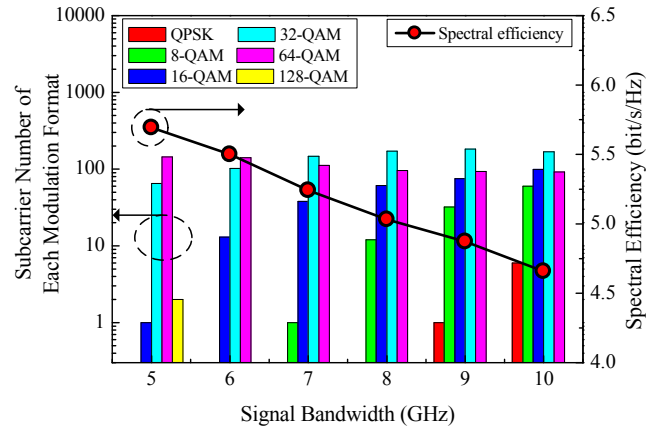

Fig. 7. Subcarrier number of each modulation format and corresponding spectral efficiency versus signal bandwidth from 5 GHz to 10 GHz.
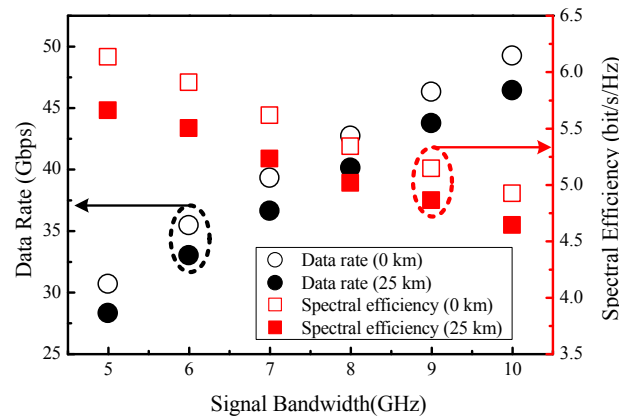

Fig. 8. Data rate and spectral efficiency in different bandwidth with/without 25-km fiber transmission.

4. Conclusion

In this paper, we experimentally demonstrated high spectral efficiency W-band DD OFDM-RoF system employing two cascaded SD-MZMs. 40-Gbps 16QAM OFDM signal over 25-km fiber and 2-m wireless transmission was achieved under FEC threshold. To further improve the data rate and spectral efficiency, the bit-loading algorithm was employed to mitigate the impact of W-band devices with higher frequency response deviation. Data rate and spectral efficiency with the same bandwidth of 10 GHz can be improved from 40 to 46.4 Gbps and from 4 to 4.64 bit/s/Hz, respectively. To achieve 40-Gbps data rate, the required bandwidth of OFDM signal with bit-loading is 2 GHz less than that without bit-loading.