DMT-16QAM photonic-wireless link in W-band enabled by an integrated MLL chip

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Abstract *A lens-free DMT-16QAM W-band photonic-wireless system using an integrated MLL chip and a mixer-based receiver is demonstrated. The on-chip single-light-source MLL generates W-band signals and simplifies the transmitter. The wireless signal's SNR is improved by phase-coherent optical carriers both modulated with data beating in PD.*

Introduction

The coming 6G and Internet of Things are driving a lot of broadband wireless applications, such as smart city, wireless high definition stream and so on. The high-speed photonic-wireless networks are hence foreseeable to play a key role in the future to meet the exponentially increasing global wireless traffic[1]. In addition, high-speed photonic-wireless networks also have great advantages of being compatible with the optical fiber network, facilitating wireless-over-fiber technology for long-distance distribution of wireless signals[2]. Following this trend, the wireless carrier frequencies for communication have been increasing progressively to support the larger bandwidth demands[3-4].

The frequencies below 60 GHz have been almost fully exploited[5], and the wireless carrier frequencies beyond 60 GHz such as millimeter wave (MMW) band have been exploited for the larger available bandwidth[6-7]. The W-band (75-110 GHz), as a candidate of MMW band, providing wireless communications with high data rate has attracted extensive research interests[8-14]. However, further reducing the complexity of the system and realizing integrated transmitter are highly desirable[2, 15]. The on-chip single light source-based intensity modulation and direct detection (IM-DD) photonic-wireless links with the advantages of low cost, small footprint and simple configuration are more desirable for practical broadband wireless applications[16-17]. The discrete multi-tone modulation (DMT) has been proposed for the IM-DD systems and can simplify the transmitter[18].

In this paper, we experimentally demonstrate a DMT-16QAM (quadrature amplitude modulation) photonic-wireless link in the W-band based on a monolithically integrated mode-locked laser (MLL). The integrated MLL is used as a single light source to generate W-band wireless signal and simplify the transmitter. The DMT-16QAM modulation is employed to realize intensity modulation and use a mixer-based receiver for detection. Then, the two phase-coherent optical carriers with 80-GHz spacing selected from the MLL are modulated with data simultaneously, to increase the signal-to-noise ratio (SNR) when beating in the broadband photodiode (PD), while saving an extra optical local oscillator (LO). The wireless link is free-space transmission without using any lenses, thus more practical for actual applications. The mixer-based DMT-16QAM photonic-wireless system with a line data rate up to 38.1 Gbit/s is desirable and suitable for the future wireless applications with low cost and simple transmitter configuration.

Experimental setup

The experimental setup is shown in Fig. 1(a). A monolithically integrated MLL is used to generate a phase-coherent optical frequency comb (OFC) with 40 GHz frequency spacing, as shown in Fig. 1(b). The integrated MLL is a multi-section laser comprising an active and passive laser waveguide based on GaInAsP material system and operates in passive mode-locking regime with direct current (DC) biased gain and absorber section, as seen in Fig. 1(e). The gain current (I_{gain}) and absorber voltage (V_{SA}) can be used to fine tune the repetition frequency f_{pass} of the passively mode-locked MLL to the desired frequency[20-21]. Here, we chose a set of operation parameters (in particular I_{gain} = 70 mA, V_{SA} = -1 V), and the corresponding repetition frequency is around 40 GHz.

The OFC with 40-GHz frequency spacing generated from the MLL is launched into a wavelength selective switch (WSS) and two phase-coherent tones with 80-GHz spacing are selected and equalized, which are then both fed into an intensity modulator (IM) for modulation. A 65 GSa/s arbitrary waveform generator (AWG) is utilized to generate DMT-16QAM signals. Note that, here modulating the two comb lines

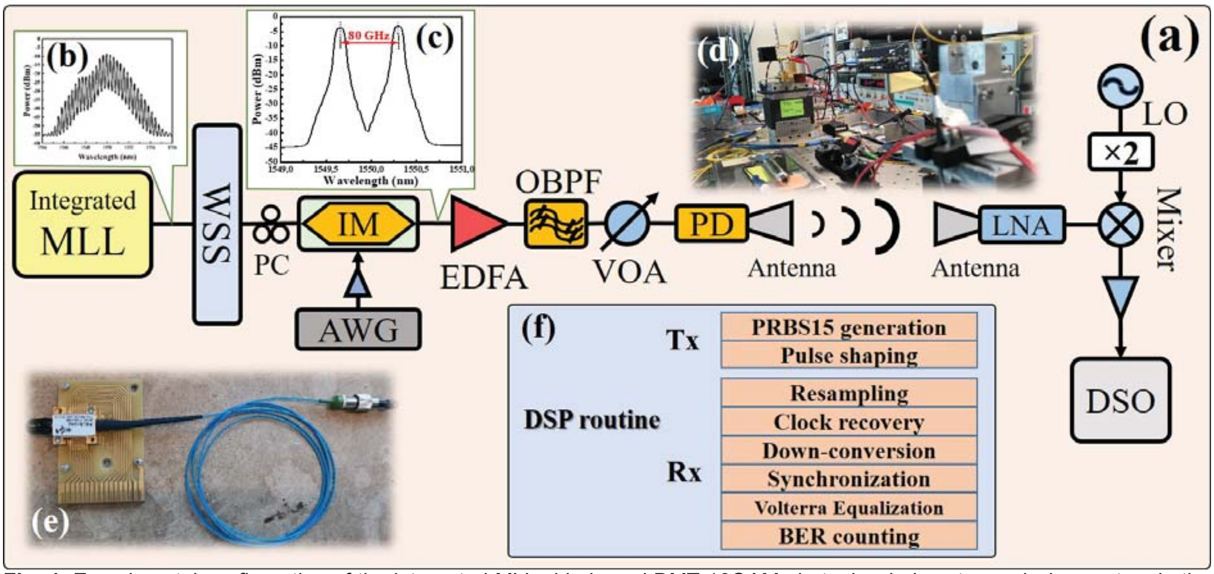

Fig. 1. Experimental configuration of the integrated MLL chip-based DMT-16QAM photonic-wireless transmission system in the W-Band: (a) The experimental setup of the overall system. (b) The optical spectrum of the frequency comb generated from MLL. (c) The optical spectrum of the selected two 80-GHz spaced tones both modulated with 20-GHz DMT-16QAM signal. (d) The picture of the actual wireless link. (e) The picture of the actual MLL. (f) The structure of the digital signal processing (DSP) routine. WSS: wavelength selectable switch, PC: polarization controller, IM: intensity modulator, AWG: arbitrary waveform generator, EDFA: erbium-doped fiber amplifier, OBPF: optical band pass filter, VOA: variable optical attenuator, PD: photodiode, LNA: low noise amplifier, LO: local oscillator, DSO: digital sampling oscilloscope.

with same data signals simultaneously can increase the SNR of the generated W-band wireless signal and save an extra optical local oscillator (LO), compared to the traditional scheme of using one line for modulation and the other one for the LO[3]. The two phase-coherent optical carriers both modulated with DMT-16QAM are amplified by an EDFA followed by an optical band-pass filter (OBPF) to remove out-of-band amplified spontaneous emission noise. Then, a variable optical attenuator (VOA) is used to accurately control the optical power sent into the broadband photodiode (PD, XPDV 4120R, 3-dB bandwidth of 90 GHz) for photo-mixing. At the output of the PD followed by a horn antenna, a single-channel DMT-16QAM wireless signal centered at ~80 GHz is generated and emitted into a 0.5-m free-space wireless link without any lenses. Fig. 1(d) shows the photo of the actual wireless link in the system. The other horn antenna is used to receive the wirelessly transmitted signal, and the received W-band signal is amplified by a low noise amplifier (LNA, 75-110 GHz) with a 40-dB gain. Then after the LNA, a mixer operating in the W-band is used to down-convert the W-band signal to the intermediate frequency (IF), which is driven by a 2-time frequency multiplied electrical LO. The output IF signal is amplified by a RF amplifier with 40 GHz bandwidth, and then fed into a broadband real-time digital sampling oscilloscope (DSO, Keysight DSOZ334A Infiniium Oscilloscope) with 80 GSa/s sampling rate and 33 GHz analog bandwidth, for analog-to-digital conversion, demodulation and communication performance analysis. The digital signals are processed and analyzed offline with a specifically designed digital signal processing (DSP) routine.

The structure of the DSP routine is shown in Fig. 1(f). To generate the DMT data, 16-QAM signal is modulated on 2000 out of 8192 subcarriers. It is noted that the fast Fourier transform (FFT) size is configured as 8192, and the low-frequency 2000 subcarriers are chosen as payload considering the conjugate symmetry of DMT and the bandwidth limitation of AWG. The sampling rate for the DMT signal is 20.48 and 40.96 GSa/s for 10-GHz and 20-GHz double-sideband (DSB) signal, respectively. The overhead caused by cyclic prefix (CP) is 5%. With the CP added, the signal is resampled to match the sampling rate of the AWG. At the receiver side, the captured waveform is firstly resampled and clock recovery is implemented. In the mixer based receiver, a digital down-conversion with 15.62624-GHz LO is employed according to the IF signal at the mixer output. After the synchronization, channel estimation is applied for the DMT-16QAM demodulation. Then a Volterra equalizer is used to equalize the signal. The signal decision is then made for bit-error-rate (BER) counting.

Experimental results

We employ spectrally efficient modulation format of DMT-16QAM and investigate two modulation bandwidths of 10 GHz and 20 GHz, to increase

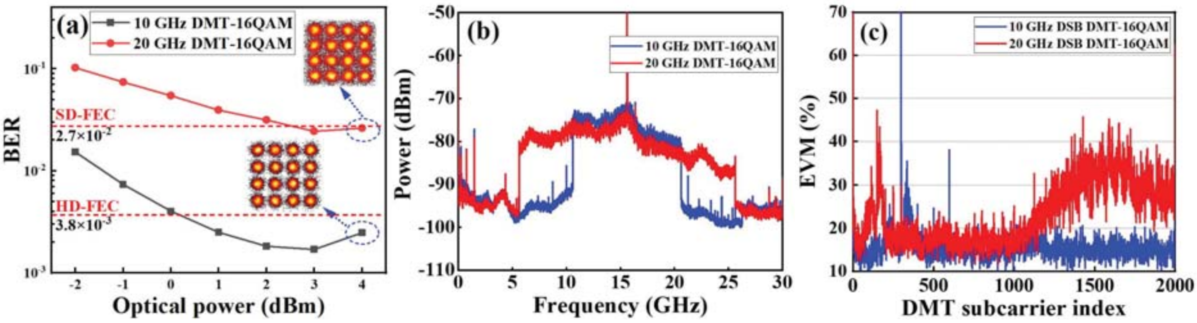

Fig. 2. (a). The BER performances of 10-GHz and 20-GHz W-band wireless DMT-16QAM signal transmission using mixer-based receiver. Insets: The constellations both measured at 4 dBm input optical power. (b). The electrical spectra of the 10-GHz and 20-GHz DMT-16QAM signal after the down conversion. (c). Detailed error vector magnitude (EVM) on each subcarrier of the DMT-16QAM signals for two modulation bandwidths (10 GHz and 20 GHz) using the mixer-based receiver, and 2000 subcarriers are loaded with data for both cases.

the overall capacity of the photonic-wireless system based on intensity modulation and the mixer-based receiver. The BER performances for the two cases have been measured as a function of optical power launched into the PD. As shown in Fig. 2(a), the DMT-16QAM signal with 10 GHz bandwidth has achieved BER performance below the hard-decision forward error correction (HD-FEC) threshold of 3.8 × 10^{-3} with 7% overhead, resulting in a line rate of 19.05 Gbit/s and a net rate of 17.8 Gbit/s. Fig. 2(a) also shows that the DMT-16QAM signal with 20 GHz bandwidth has obtained the BER performance below the soft-decision FEC threshold of 2.7 × 10^{-2} with 20% overhead (20%-OH SD-FEC)[22], leading to a line rate of 38.1 Gbit/s and a net rate of 31.75 Gbit/s. The corresponding signal constellations measured at 4-dBm optical power for both cases are shown in the insets of Fig. 2(a).

The optical spectrum of the two optical carriers with 80-GHz spacing and both modulated with 20-GHz DSB DMT-16QAM signal is shown in Fig. 1(c). Fig. 2(b) shows the electrical spectra of the 10-GHz and 20-GHz DMT-16QAM IF signals after the down conversion using the mixer. The IF frequencies for the two cases are both set to be around 15.6 GHz, when the mixer is driven by a 2-time frequency multiplied 32.2-GHz electrical LO. Note that the performance difference between the two cases can also be found from the spreading clusters of the corresponding 16QAM constellations. With higher optical power fed into the PD than 3 dBm, BER performances cannot be further improved, which is mainly attributed to the saturation of the mixer in the receiver.

In addition, we have investigated the detailed error vector magnitude (EVM) on each subcarrier of the DMT-16QAM signals for two modulation bandwidths (10 GHz and 20 GHz) using the mixer-based receiver, as shown in Fig. 2(c). For the DMT-16QAM signal with 20-GHz bandwidth, the signal quality of the subcarriers in the higher frequency band becomes much worse, which is consistent with the power distribution of the 20-GHz DMT-16QAM IF signal as shown in the electrical spectrum (Fig. 2(b)). This is mainly because the IF response of the receiver including the mixer and following RF amplifier becomes worse in the higher frequency band.

Conclusions

We have demonstrated a lens-free W-band MMW photonic-wireless transmission of the intensity modulated DMT-16QAM signal with 10 GHz and 20 GHz bandwidth, by using an integrated MLL chip in the transmitter and a mixer-based receiver. The integrated MLL acts as an on-chip single light source to generate wireless signal and simplify the transmitter. The two filtered 80-GHz spacing tones are both modulated with the DMT-16QAM data to enhance the SNR of the wireless signal generated by the beating of the two modulated tones in the broadband PD. Such a photonic-wireless system with simple configuration will be suitable for future broadband wireless applications.

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References

[1] J. Yu, X. Li, and W. Zhou, “Tutorial: Broadband fiber-wireless integration for 5G+ communication,” APL Photon., Vol. **3**, p. 111101 (2018).

[2] T. Nagatsuma, et al., "Advances in Terahertz Communications Accelerated by Photonics," Nature Photon., Vol. **10**, p. 371 (2016).

[3] S. Jia, et al., “0.4 THz Photonic-Wireless Link With 106 Gb/s Single Channel Bitrate,” J. Lightw. Technol., Vol. **36**, p. 610 (2018).

[4] R. Sabella, "Silicon photonics for 5G and future networks," IEEE J. Sel. Topics Quantum Electron., Vol. **26**, p. 8301611 (2020).

[5] J. Federici and L. Moeller, "Review of terahertz and subterahertz wireless communications," J. Appl. Phys., Vol. **107**, p. 111101(2010).

[6] S. Jia, L. Zhang, S. Wang, W. Li, M. Qiao, Z. Lu, N. M. Idrees, X. Pang, H. Hu, X. Zhang, L. K. Oxenløwe, and X. Yu, "2×300 Gbit/s line rate PS -64QAM-OFDM THz photonic-wireless transmission," J. Lightw. Technol., **DOI 10.1109/JLT.2020.2995702** (2020).

[7] W. Zhou, L. Zhao, J. Zhang, K. Wang, J. Yu, Y. Chen, S. Shen, R. Shiu and G. Chang, "135-GHz D-band 60-Gbps PAM-8 wireless transmission employing a joint DNN equalizer with BP and CMMA," J. Lightw. Technol., **DOI 10.1109/JLT.2020.2979070** (2020).

[8] X. Pang, A. Caballero, A. Dogadaev, V. Arlunno, R. Borkowski, J. S. Pedersen, L. Deng, F. Karinou, F. Roubeau, D. Zibar, X. Yu, I. T. Monroy, “100 Gbit/s hybrid optical fiber-wireless link in the W-band (75–110 GHz),” Opt. Express, Vol. **19**, p. 24944 (2011).

[9] X. Li, J. Yu, J. Zhang, Z. Dong, F. Li, and N. Chi, “A 400G optical wireless integration delivery system,” Opt. Express, Vol. **21**, p. 18812 (2013).

[10] X. Li, Z. Dong, J. Yu, N. Chi, Y. Shao, and G. K. Chang, “Fiber-wireless transmission system of 108 Gb/s data over 80 km fiber and 2 × 2 multiple-input multiple-output wireless links at 100 GHz W-band frequency,” Opt. Lett., Vol. **37**, p. 5106 (2012).

[11] J. Yu, X. Li, J. Zhang, and J. Xiao, “432-Gb/s PDM-16QAM signal wireless delivery at W-band using optical and antenna polarization multiplexing,” 2014 Eur. Conf. Opt. Commun., We.3.6.6 (2014).

[12] X. Li, J. Yu, J. Zhang, F. Li, Y. Xu, Z. Zhang, and J. Xiao, “Fiber wireless-fiber link for 100-Gb/s PDM-QPSK signal transmission at W-band,” IEEE Photon. Technol. Lett., Vol. **26**, p. 1825 (2014).

[13] J. Xiao, X. Li, J. Yu, Y. Xu, Z. Zhang, and L. Chen, “40-Gb/s PDM-QPSK signal transmission over 160-m wireless distance at W-band,” Opt. Lett., Vol. **40**, p. 998 (2015).

[14] X. Pang, A. Caballero, A. Dogadaev, V. Arlunno, L. Deng, R. Borkowski, J. S. Pedersen, D. Zibar, X. Yu, and I. T. Monroy, “25 Gbit/s QPSK hybrid fiber-wireless transmission in the W-Band (75–110 GHz) with remote antenna unit for in-building wireless networks,” IEEE Photon. J., Vol. **4**, p. 691 (2012).

[15] B. Yu, Y. Ye, X. Ding, Y. Liu, Z. Xu, X. Liu, and Q. J. Gu, “Ortho-mode sub-THz interconnect channel for planar chip-to-chip communications,” IEEE Trans. Microw. Theory Techn., Vol. **66**, p. 1864 (2018).

[16] Y. Yang, Y. Yamagami, X. Yu, P. Pitchappa, J. Webber, B. Zhang, M. Fujita, T. Nagatsuma, and R. Singh, “Terahertz topological photonics for on-chip communication,” Nature Photon., Vol. **14**, p. 446 (2020).

[17] L. Wu, J. Cheng, Z. Zhang, J. Dang, and H. Liu, “Low-complexity spatial modulation for IM/DD optical wireless communications,” IEEE Photon. Technol. Lett., Vol. **31**, p. 475 (2019).

[18] K. Zhong, X. Zhou, T. Gui, L. Tao, Y. Gao, W. Chen, J. Man, L. Zeng, A. P. T. Lau, and C. Lu, “Experimental study of PAM4, CAP-16, and DMT for 100 Gb/s short reach optical transmission systems,” Opt. Express, Vol. **23**, p. 1176 (2015).

[19] C. Tsai, C. Lin, C. Lin, Y. Chi, and G. Lin, "60-GHz millimeter-wave over fiber with directly modulated dual-mode laser diode," Sci. Rep., Vol. **6**, p. 27919 (2016).

[20] R. Kaiser and B. Huttl, “Monolithic 40-GHz mode-locked MQW DBR lasers for high-speed optical communication systems,” IEEE J. Sel. Topics Quantum Electron., Vol. **13**, p. 125 (2007).

[21] B. Huettl, H. Hu, R. Ludwig, R. Kaiser, C. Schmidt-Langhorst, A. G. Steffan, C. Schubert, “Linewidth investigation of monolithically integrated 40 GHz mode-locked laser diodes for high-speed RZ-DQPSK transmission,” 2008 Eur. Conf. Opt. Commun., Th.1.C.7 (2008).

[22] S. Jia, M. Lo, L. Zhang, O. Ozolins, A. Udalcovs, D. Kong, X. Pang, X. Yu, S. Xiao, S. Popov, J. Chen, G. Carpintero, T. Morioka, H. Hu and L. K. Oxenlewe, “Integrated Dual-DFB Laser for 408 GHz Carrier Generation Enabling 131 Gbit/s Wireless Transmission over 10.7 Meters,” 2019 Optical Fiber Conference, Th1C.2 (2019).