IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 4, Number 5, October 2012

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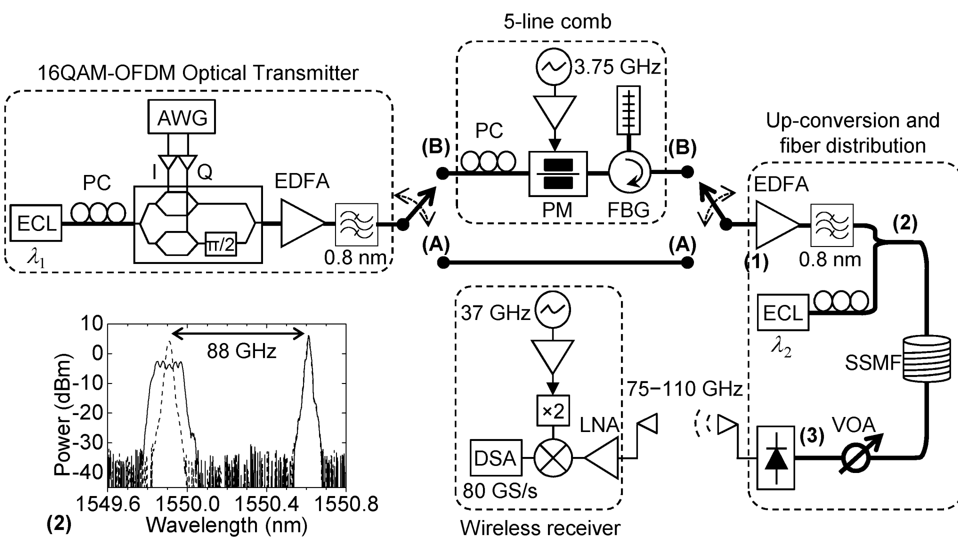

DOI: 10.1109/JPHOT.2012.2223205

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DOI: 10.1109/JPHOT.2012.2223205
1943-0655/$31.00 ©2012 IEEE

Manuscript received September 28, 2012; accepted October 3, 2012. Date of publication October 9, 2012; Date of current version October 18, 2012. This work was supported in part by the European Commission through the Seventh Framework Program (FP7) ICT-249142 FIVER Project, by the Spain Plan Nacional I+D+I project TEC2009-14250 ULTRADEF, by the National 863 Program of China under Grant 2009AA01A347, by Tektronix, Agilent Technologies, Radiometer Physics GmbH, Rohde&Schwarz, and u²t Photonics, and by the Danish Project OPSCODER. Corresponding author: M. Beltrán (e-mail: mbeltran@ntc.upv.es).

Abstract: The photonic generation of electrical orthogonal frequency-division multiplexing (OFDM) modulated wireless signals in the 75–110 GHz band is experimentally demonstrated employing in-phase/quadrature electrooptical modulation and optical heterodyn upconversion. The wireless transmission of 16-quadrature-amplitude-modulation OFDM signals is demonstrated with a bit error rate performance within the forward error correction limits. Signals of 19.1 Gb/s in 6.3-GHz bandwidth are transmitted over up to 1.3-m wireless distance. Optical comb generation is further employed to support different channels, allowing the cost and energy efficiency of the system to be increased and supporting different users in the system. Four channels at 9.6 Gb/s/ch in 14.4-GHz bandwidth are generated and transmitted over up to 1.3-m wireless distance. The transmission of a 9.6-Gb/s single-channel signal occupying 3.2-GHz bandwidth over 22.8 km of standard single-mode fiber and 0.6 m of wireless distance is also demonstrated in the multiband system.

Index Terms: Microwave photonics signal processing, frequency combs, heterodyning, fiber optics systems, orthogonal frequency division multiplexing.

1. Introduction

Wireless communication links supporting very high capacity are required to provide access network services such as 10-gigabit Ethernet (10 Gb/s), Super Hi-Vision (SHV)/Ultra High Definition (UHD) TV data (> 24 Gb/s), OC-768/STM-256 data (43 Gb/s), and 100-gigabit Ethernet (100 Gb/s), and also for close-proximity bulk data transfer [1]. Millimeter-wave wireless systems at around 60 GHz and higher frequencies can provide bandwidth enough to easily support multi-Gb/s communications, being a potential solution for future seamless integrated optical/wireless access, as well as for mobile backhauling [2]. The 60-GHz band has been widely studied as a wide bandwidth has been regulated in many countries for unlicensed use with a high equivalent isotropic radiated power

TABLE 1

Photonic Wireless Systems in the 75–110 GHz Band (MLL: Mode-locked laser, NBUTC-PD: Near-ballistic uni-travelling-carrier photodiode, IQ: In-phase/quadrature electrooptical modulator, DP-QPSK: Dual-polarization QPSK modulator, MZM: Mach–Zehnder modulator)

Mod. format	Data rate (Gb/s)	Frequency range (GHz)	Fiber length (km)	Wireless distance (m)	Technology		Ref.
					Transmitter	Receiver	
OOK	20 BER<10^{-12}	85.5–100.5	25	0.2	MLL+NBUTC-PD	Power detector	[10]
Optical QPSK-OFDM	40 BER<10^{-2}	70–95	–	–	MZM comb+IQ+ECL heterodyning	Optical detection	[13]
16-QAM	40 BER<$2\cdot10^{-3}$	82.5–102.5	–	0.03	Two-tone optical generator+DP-QPSK +UTC-PD	Electrical heterodyne	[11]
16-QAM PolMux	100 BER<$2\cdot10^{-3}$	75–100	–	1.2	IQ+ECL heterodyning	Electrical heterodyne	[12]
Three-band QPSK-OFDM	8.3 /ch BER<$2\cdot10^{-3}$	79.25–94.25	22.8 0.01	0.5 2	MZM comb+IQ+ECL heterodyning	Electrical heterodyne	[22]
Three-band 16-QAM-OFDM	15.1 /ch BER<$2\cdot10^{-3}$	78.5–93.5	0.01	0.6	IQ+MZM comb+ECL heterodyning	Electrical heterodyne	[23]
16-QAM-OFDM	19.1 BER<$2\cdot10^{-3}$	77.4–83.8	0.01	1.3	IQ+ECL heterodyning	Electrical heterodyne	This work
Four-band 16-QAM-OFDM	9.6 /ch BER<$2\cdot10^{-3}$	78.9–93.3	0.01	1.3	IQ+PM comb+ECL heterodyning	Electrical heterodyne	This work

(EIRP) of higher than 40 dBm allowed [3]. A number of standards in the 60-GHz band have recently been proposed, including WirelessHD, ECMA-387, IEEE 802.15.3c, and WiGig. These technologies target to provide up to 7-Gb/s data rates at short-range indoor wireless distances of up to 10 m. Standard devices of 60 GHz are also available for wireless display connectivity, for HD audio/video streaming from the consumer electronics, personal computing, and portable devices to HDTVs. In addition, other higher frequency millimeter-wave bands can potentially offer larger bandwidths to support higher capacities, as well as lower atmospheric loss to extend wireless transmission distances as compared to the 60-GHz band [4]. Of particular interest, the 71–76/81–86 GHz paired band has been allocated for commercial use in the United States, Europe, and other countries, and permits point-to-point communications over distances of several kilometers. Commercial equipment is easily available in the 71–76/81–86 GHz band supporting 1.25-Gb/s Gigabit Ethernet connectivity. Electronic-based millimeter-wave wireless links at frequencies higher than 100 GHz have also been demonstrated providing up to 20 Gb/s with polarization multiplexing (PolMux) over the kilometer distance [5].

Radio-over-fiber technology combined with millimeter-wave wireless systems is seen as a fast deployable and cost-effective solution for providing seamless integrated optical/wireless access at $>$ 10 Gb/s [2]. Radio-over-fiber systems operating within 7-GHz bandwidth in the 60-GHz band have been reported to provide capacities higher than 10 Gb/s when spectrally efficient electrical orthogonal frequency-division multiplexing (OFDM) modulation based on quadrature amplitude modulation (QAM) and electrooptical modulation for upconversion are employed, such as 27 Gb/s for 2.5-m wireless distance employing 16-QAM-OFDM [6], 21 Gb/s for 500-m standard single-mode fiber (SSMF) transmission and 10-m (or 2.5 m in bidirectional system) wireless transmission employing 8-QAM-OFDM [7], 26.5 Gb/s for 100-km SSMF and 3-m wireless distance employing adaptive-level QAM-OFDM in amplified long-reach networks [8], and 50 Gb/s for 4-m wireless distance employing 16-QAM-OFDM and multiple-input multiple-output (MIMO) spatial multiplexing [9]. In addition, radio-over-fiber systems in the 75–110 GHz band (W-band) are recently attracting increasing interest to deliver 40 Gb/s and beyond. A number of photonic wireless transmission systems in the 75–110 GHz band have been demonstrated, as summarized in Table 1. A system providing error-free 20 Gb/s with on–off keying (OOK) modulation and simple RF power detection has been demonstrated including 25 km of fiber transmission [10]. Spectral efficient modulation formats have also been employed, at 20 Gb/s and 40 Gb/s based on quadrature phase-shift keying (QPSK) and 16-QAM formats, respectively [11], and up to 100 Gb/s based on 16-QAM with PolMux [12]. A system based on optical OFDM with optical detection has also been demonstrated [13]. For fixed wireless access over the kilometer distance, photonic wireless links in the 75−110 GHz band have been reported at $<$ 10 Gb/s employing differential phase-shift keying modulation [14]. Finally, millimeter-wave systems operating at frequencies higher than 110 GHz based on photonic generation have been demonstrated to provide error-free $>$ 20 Gb/s at 300 GHz with OOK modulation [5].

Photonic millimeter-wave wireless links have been reported using the wide RF bandwidth in a single channel. A different approach is to allocate multiple channels of lower data rate signals to serve different users in the system. The multiband approach also enables flexible bandwidth allocation by aggregating channels, thus relaxing the power and bandwidth requirements of electrooptical equipment such as digital-to-analog/analog-to-digital converters (DAC/ADC) for energy-efficient and cost-effective systems. Combined optical access and wireless transmission of multiband OFDM-based signals in the 60-GHz band has been demonstrated based on subcarrier multiplexing (SCM) [3]. Wavelength division multiplexing (WDM) architectures can also be employed, where multiple wavelengths produced by an optical frequency comb or by a continuous-wave laser array support the different channels [15].

A number of approaches have been demonstrated for optical comb generation. Mode-locked lasers provide stable and sharp spectral components over a wide bandwidth with low noise qualities. In addition, optical frequency combs based on electrooptic modulators driven by large-amplitude sinusoidal signals permit arbitrary wavelength spacing by adjusting the frequency of the sinusoidal signals [16]–[18]. Although this technique can provide a relatively flat optical comb, it can be limited by the insertion loss of the modulator together with the modulation efficiency. Finally, gain-switched pulsed lasers can be employed for simple and cost-efficient multicarrier generation [19]. Additionally, the number of comb wavelengths can be increased without influencing optical bandwidth by applying an adequate time-domain periodic multiphase modulation on the laser pulse train [20].

In this paper, we experimentally demonstrate the optical generation, wireless transmission, and electrical heterodyn detection of multiband OFDM-based wireless signals in the 75−110 GHz band. The proposed system has the following advantages: 1) Electrical OFDM modulation with a high number of subcarriers has been widely used in optical and wireless communications systems to benefit from its high spectral efficiency, flexibility, and robustness against fiber dispersion impairments and wireless multipath fading [3], [21]. 2) Seamless allocation of multiple channels in the wide RF bandwidth is demonstrated enabled by optical comb generation [22]. 3) Optical heterodyn mixing enables seamless optical frequency upconversion, highly scalable in RF frequency [13]. The phase and frequency drift originated from the wireless signal generation, and detection is compensated by baseband digital signal processing (DSP) at the receiver, thus avoiding the need for phase-locking techniques. Based on this approach, we have demonstrated the combined SSMF and wireless transmission of a three-channel QPSK-OFDM signal at 8.3 Gb/s/ch with a bandwidth of 5 GHz/ch (15-GHz total RF bandwidth) [22], as summarized in Table 1. The wireless transmission of three-channel signals has also been demonstrated employing 16-QAM-OFDM [23], as summarized in Table 1. In this paper, the wireless transmission of four-channel 16-QAM-OFDM signals [24] is compared with that of the signal generated in a single-band system, with a bit error rate (BER) performance within the standard forward error correction (FEC) limit of $2 \cdot 10^{-3}$, as summarized in Table 1. After removing the 7% overhead for FEC, the effective data rates are 17.8 Gb/s and 8.9 Gb/s/ch with a spectral efficiency of 2.8 b/s/Hz and 2.8 b/s/Hz/ch, respectively.

2. Theoretical Description

Considering the line-of-sight (LOS) case in the wireless link, the signal-to-noise ratio (SNR) at the receiver side can be calculated in dB using the link power budget equation [25]

$$\mathrm{SNR} = P_T + G_T + G_R - L_{FS} - L_I - (N_o + 10\log(B) + NF) \quad (1)$$

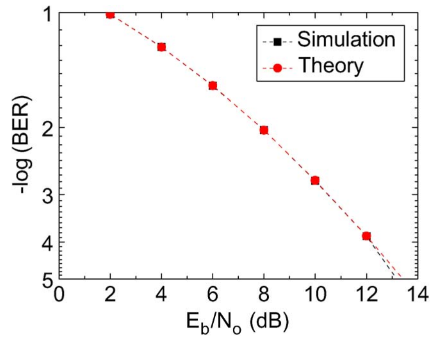

Fig. 1. Bit error probability curve for 16-QAM-OFDM in AWGN.

where P_T is the transmitter power, G_T and G_R are the transmitter and receiver antenna gain, respectively, I_L is the implementation loss of the link, N_0 is the thermal noise in 1 Hz of bandwidth, B is the system bandwidth, and NF is the noise figure of the receiver. L_{FS} represents the free space loss as given by $L_{FS} = 20\log(4\pi fd/c)$, where c is the light speed, f is the signal frequency, and d is the wireless distance in the far field.

For link budget analysis, the most important aspect of a given modulation technique is the SNR necessary for a receiver to achieve a specified level of reliability in terms of BER. BER is a function of the energy per bit relative to the noise power E_b/N_o. In the additive white Gaussian noise (AWGN) channel, single carrier and OFDM have approximately the same performance in terms of E_b/N_o, and the theoretical BER of 16-QAM-OFDM is shown in Fig. 1 [25]. The corresponding curve simulated for the 16-QAM-OFDM signal employed in the experimental work exhibits slight differences with the theoretical curve, as shown in Fig. 1. Note that E_b/N_o is independent of the system data rate R_b. SNR and E_b/N_o can be related by

$$\text{SNR} = (E_b/N_o) \cdot (R_b/B). \quad (2)$$

In addition, considering the resistance load and the responsivity of the photodetector employed in the experimental work, P_T can be related to the received optical power P_{opt} by

$$P_T(\text{dBm}) = 2P_{\text{opt}}(\text{dBm}) - 22. \quad (3)$$

3. Experimental Setup

Fig. 2 shows the schematic of the experimental setup. At the optical OFDM transmitter, a baseband OFDM signal is generated employing a two-channel arbitrary waveform generator (Tektronix AWG7122C) and in-phase/quadrature (IQ) electrooptical modulation. The OFDM signal comprises a data stream consisting of a pseudorandom bit sequence (PRBS) of length $2^{15} - 1$ mapped onto 72 16-QAM subcarriers, which, together with eight pilot subcarriers, one zero power dc subcarrier, and 47 zero-power edge subcarriers, are converted to the time domain via an inverse fast Fourier transform (IFFT) of size 128. A cyclic prefix of length 13 samples is employed, resulting in an OFDM symbol size of 141. To facilitate OFDM frame synchronization and channel estimation, ten training symbols are inserted at the beginning of each OFDM frame that contains 150 data symbols. The real and imaginary parts of the complex OFDM signal are clipped and converted to analog signals at the outputs of the AWG. The two filtered signals are amplified and applied to an IQ modulator connected to an external-cavity laser (ECL) at $\lambda_1 = 1549.9$ nm with 100-kHz linewidth. The IQ modulator reduces to half the bandwidth requirement of the DAC, although it introduces high transmission loss as it is biased at the minimum transmission point. In this way, an optical OFDM signal is generated, which is amplified by an erbium-doped fiber amplifier (EDFA). An optical bandpass filter with 0.8-nm bandwidth is employed to filter noise.

The optical OFDM signal is expanded by optical comb generation based on an electrooptic phase modulator (PM) [16] to form five OFDM channels. The output from the comb is further filtered by a

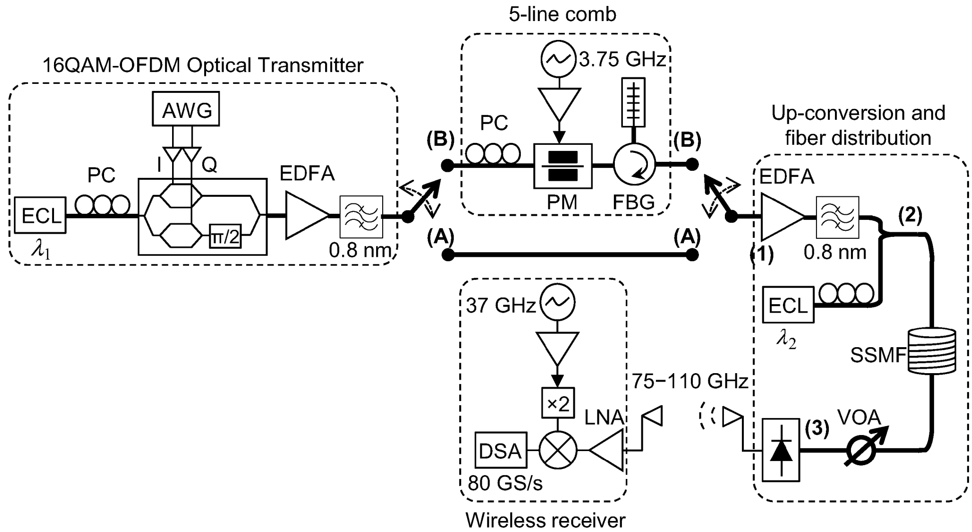

Fig. 2. Experimental setup of an OFDM photonic wireless system in the 75–110 GHz band. Configuration (A): single-band system. Configuration (B): multiband system employing optical comb generation. PC: Polarization controller, VOA: Variable optical attenuator.

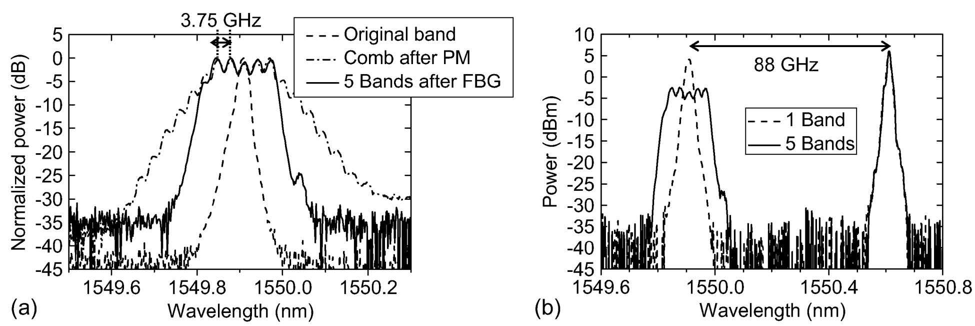

Fig. 3. (a) Optical spectra measured at various points in Fig. 2. (b) Optical spectra measured at point (2) in Fig. 2. (Resolution bandwidth: 0.01 nm).

fiber Bragg grating (FBG) with 25-GHz bandwidth operating in reflection to reduce crosstalk penalty from the edge comb lines, as shown in Fig. 3(a). The comb wavelength spacing is set to 3.75 GHz to minimize crosstalk penalty while maximizing spectral efficiency. It should be noted that the optical comb repeats the same OFDM signal. The effect of crosstalk when independent data bit streams are coded for each OFDM channel should be further investigated for the application in reality. This could be done by using different optical carriers and modulate each of them in a different I/Q modulator by each OFDM data signal. The modulated optical carriers would then be optically combined to generate an optical multiband OFDM signal, as shown in [15]. Decorrelation of adjacent channels at least has usually been considered for emulation of a real system, e.g., by employing frequency shifting and optical delay [21] or two modulators for odd and even channels [15].

To perform optical frequency upconversion, the optical OFDM signal at point (1) in Fig. 2 is amplified and combined with an unmodulated continuous-wave optical carrier from an ECL with 100-kHz linewidth at λ_2 located at the desired RF carrier apart. Fig. 3(b) shows the spectrum of the combined signal at point (2) in Fig. 2. The combined signal is transmitted over fiber to a remote antenna site where the optical ODFM signal and the unmodulated carrier are heterodyn mixed in a 100-GHz photodetector (u^{2}t Photonics, XPDV4120R). The photodetected signal is an OFDM signal at the desired RF carrier in the 75−110 GHz band, which is fed to a rectangular horn antenna in the 75−110 GHz band with 24-dBi gain.

After wireless transmission, the RF OFDM signal is received by a similar antenna with 25-dBi gain and amplified by a low-noise amplifier (LNA; Radiometer Physics, 75−105 GHz) with 25-dB gain. An electrical mixer (75−110 GHz RF and 1−36 GHz IF) driven by a local oscillator (LO) signal at 74 GHz is employed for frequency downconversion. The LO signal is generated by frequency doubling a 37-GHz signal from a signal generator (Rohde&Schwarz, SMF100A). The downconverted signal is digitized by a digital signal analyzer at 80 GS/s with 32-GHz real-time bandwidth (Agilent, DSAX93204A) and demodulated by offline DSP.

In the receiver DSP, each OFDM channel is demodulated individually after frequency downconversion and low-pass filtering (LPF). For each baseband OFDM channel, time synchronization, frequency and channel estimation, pilot-assisted phase estimation, data recovery by symbol mapping and serialization, and BER test are performed. To mitigate the dispersion and nonlinearity effects induced by fiber and wireless transmission, one-tap equalizer and an effective algorithm combining intrasymbol frequency-domain averaging [26] and digital phase-locked loop are employed for channel estimation. The effect of the algorithm can be observed in the constellation diagrams in [23]. The pilot-assisted phase estimation consists of estimating the common phase error due to the laser phase noise, as described in [27]. BER is evaluated by counting the number of errors considering 42 912 bits. Note that the frequency/phase estimation algorithm (frequency and channel estimation and pilot-assisted phase estimation) can track the frequency jitter of the ECL lasers provided that a maximum frequency offset is not exceeded; otherwise, advanced algorithms may be employed [13].

4. Transmission Performance

The feasibility of the photonic generation and wireless transmission of 16-QAM-OFDM signals in the 75–110 GHz band has been evaluated. The performance of single-band signals generated by IQ modulation and optical heterodyn upconversion, configuration (A) in Fig. 2 is first evaluated. Wireless transmission performance is further evaluated when the RF bandwidth is used in multiple channels employing optical comb generation, configuration (B) in Fig. 2. The performance of the single-channel signal in the multiband system when the RF signal driving the PM in Fig. 2 is off is also evaluated.

4.1. Single-Band System

In the single-band system, configuration (A) in Fig. 2, the AWG operates at 10 GS/s, resulting in an optical OFDM signal at 19.14 Gb/s $(10\ \text{GS/s} \cdot \log_2(16) \cdot 72/141 \cdot 150/160)$ with a bandwidth of 6.328 GHz $(10\ \text{GS/s} \cdot 81/128)$. Two antialiasing LPF with 3.4-GHz bandwidth are employed at the AWG outputs. The RF carrier frequency is set at 80.6 GHz by tuning λ_2 in Fig. 2.

Fig. 4(a) shows the BER performance of the 19.14-Gb/s single-band 16-QAM-OFDM signal as a function of the received optical power at point (3) in Fig. 2 for different wireless transmission distances compared with the theoretical slope for 16-QAM-OFDM in AWGN. The receiver sensitivities at the FEC limit of $2 \cdot 10^{-3}$ are -2.1 dBm, -0.7 dBm, and 1.7 dBm for 0.5 m, 0.75 m, and 1.3 m of wireless distance, respectively. Fig. 4(b) shows received constellations confirming the BER performance shown in Fig. 4(a). The electrical spectrum of the 19.14-Gb/s signal after digitization at the receiver is shown in Fig. 4(c).

The difference in the receiver sensitivity at 0.5 m and 0.75 m or at 0.75 m and 1.3 m is near the theoretical values of 1.75 dB or 2.4 dB, respectively. From (1) and (3), the difference in the received optical power P_{opt} required for a given BER at different wireless distance due to the increased free space loss L_{FS} is given by $\Delta P_{\text{opt}} = \Delta L_{FS}/2$. In addition, the signal does not exhibit an apparent BER floor, and it is not expected to be significantly limited by the residual phase error after pilot-assisted phase estimation considering an estimated phase error variance of 0.0179 rad^2 for a combined laser linewidth of 200 kHz and a symbol rate of 70.2 MSymbol/s [28].

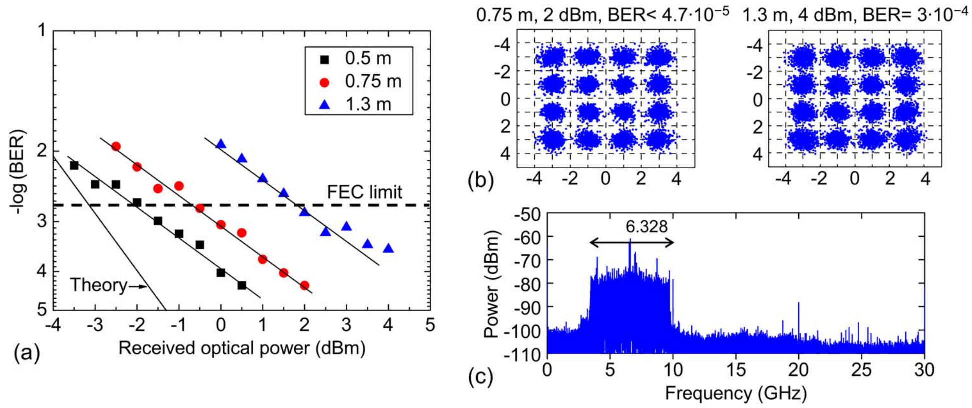

Fig. 4. (a) BER performance of the 19.14 Gb/s single-band system, configuration (A) in Fig. 2, as a function of the received optical power and wireless distance. (b) Constellation diagrams. (c) Electrical spectrum after digitization at the receiver at 2 dBm received optical power and 0.75 m wireless distance.

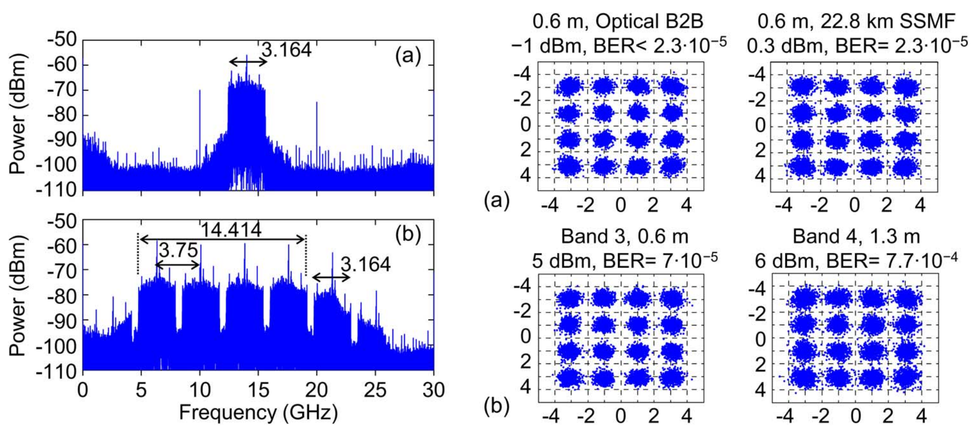

Fig. 5. Electrical spectra after digitization at the receiver at 4.5 dBm received optical power for optical B2B and 0.6 m wireless distance, and constellation diagrams, for configuration (B) in Fig. 2. (a) 9.57 Gb/s single-band OFDM signal. (b) 9.57 Gb/s/ch four-band OFDM signal.

4.2. Multiband System

In the multiband system, configuration (B) in Fig. 2, the AWG operates at 5 GS/s, resulting in an optical OFDM signal at 9.57 Gb/s $(5\ \text{GS/s} \cdot \log_2(16) \cdot 72/141 \cdot 150/160)$ with a bandwidth of 3.164 GHz $(5\ \text{GS/s} \cdot 81/128)$. Two antialiasing LPF with 2.5-GHz bandwidth are employed at the AWG outputs. The RF carrier frequency is set at 88 GHz by tuning λ_2 in Fig. 2.

Up to four RF OFDM bands out of the five optical OFDM bands can be demodulated within the FEC limits due to the frequency response of the photodetector. BER performance of the four OFDM channels at 9.57 Gb/s/ch has been evaluated and compared with the performance of the 9.57-Gb/s single-band OFDM signal. The performance of the single-band OFDM signal is evaluated when the RF signal driving the PM in Fig. 2 is off. Fig. 5 shows the electrical spectra of the single- and four-band OFDM signals after digitization at the receiver. Received constellations are also shown in Fig. 5, confirming the BER performance shown in Fig. 6. Fig. 6 shows the measured BER as a function of the received optical power at point (3) in Fig. 2. Fig. 6(a) shows BER performance of the 9.57-Gb/s single-band 16-QAM-OFDM signal for combined optical and wireless transmission compared with the theoretical slope for 16-QAM-OFDM in AWGN. The receiver sensitivity at the FEC limit of $2 \cdot 10^{-3}$ is -4.2 dBm and -0.6 dBm for optical back-to-back (B2B) and 0.6 m and 1.3 m

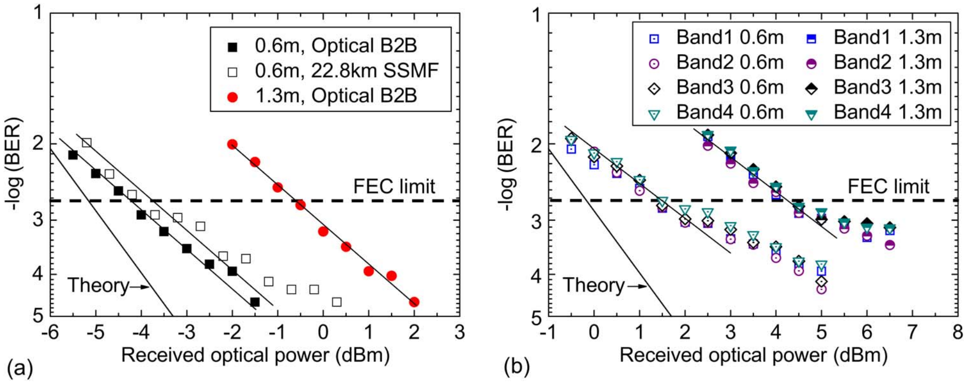

Fig. 6. BER performance of the multiband system, configuration (B) in Fig. 2, as a function of received optical power. (a) 9.57 Gb/s single-band OFDM signal as a function of optical and wireless transmission distance. (b) 9.57 Gb/s/ch four-band OFDM signal as a function of wireless distance for optical B2B.

of wireless distance, respectively. As compared with the 9.57-Gb/s single-band OFDM signal in Fig. 6(a), the 19.14-Gb/s single-band OFDM signal in Fig. 4(a) exhibits 2.7-dB and 2.3-dB penalty in receiver sensitivity, respectively. Theoretically, it is expected that the single-band OFDM signal in Fig. 4(a) at twice the data rate and bandwidth have a near 1.5-dB receiver sensitivity penalty compared with the single-band OFDM signal in Fig. 6(a), as given by $10\log(2)/2$ from (1), (2), and (3). The difference between theory and experiment may be mainly ascribed to the higher optical SNR penalty due to residual laser phase noise, which is expected for the lower symbol rate signal in Fig. 6(a) with an estimated phase error variance of 0.0358 rad^2 [28]. The BER curves in Figs. 4(a) and 6(a) have similar slopes. In addition, optical transmission over 22.8 km of SSMF induces 0.4-dB receiver sensitivity penalty for 0.6-m wireless distance. BER is degraded for received optical power higher than 0.3 dBm due to fiber nonlinearity, corresponding to an optical power of 5.8 dBm at the input of the fiber. The fiber nonlinearity is the reason that the BER is not below the FEC limit for combined 22.8-km SSMF and 1.3-m wireless distance.

Fig. 6(b) shows the wireless transmission performance of the four OFDM bands for optical B2B compared with the theoretical slope for 16-QAM-OFDM in AWGN. There is negligible power penalty among the different OFDM bands when one OFDM subcarrier in the second band is removed during BER evaluation. The receiver sensitivity at the FEC limit of $2 \cdot 10^{-3}$ is 1.5 dBm and 4.3 dBm for 0.6 m and 1.3 m of wireless distance, respectively. The optical comb reduces the optical SNR; the maximum power spectral density decreases by 6.6−7.6 dB, as shown in Fig. 3(b), thus inducing a receiver sensitivity penalty of 5.7 dB and 4.9 dB for 0.6 m and 1.3 m of wireless distance, respectively. The four-band BER in Fig. 6(b) slope more gradually with received optical power than the single-band BER in Fig. 6(a) due to the increased optical noise. Although the SNR is dominated by electrical noise, decreasing the received optical power increases the BER, the optical noise affects performance. Reducing the channel spacing would increase the optical noise, thus reducing the slope, as shown in [23]. Furthermore, BER is degraded for received optical power higher than 5 dBm and 6 dBm due to receiver saturation. In addition, although it is expected that BER is degraded due to fiber nonlinearity from a higher received optical power for the multiband OFDM signal compared with the single-band OFDM signal [23], the BER is not below the FEC limit for combined 22.8-km SSMF and 0.6- or 1.3-m wireless distance.

Fig. 6 also indicates that the required received optical power to achieve BER $< 2 \cdot 10^{-3}$ is up to 5 dBm, corresponding to a maximum transmitter power of -12 dBm and a maximum EIRP of 12 dBm. The received RF power is approximately -36 dBm and -36.5 dBm for 2-dBm and 5-dBm received optical power at 0.6 m and 1.3 m of wireless distance, respectively. The wireless distance could be extended by employing a W-band high-power amplifier at the transmitter and a higher gain LNA at the receiver side.

As expected, the difference in the receiver sensitivity at 0.6 m and 1.3 m in Fig. 6(a) and in Fig. 6(b) is near 3.4 dB, as given by $\Delta P_{\text{opt}} = \Delta L_{FS}/2$.

The herein demonstrated system supports four channels in 14.4-GHz total bandwidth with 4.3-dBm receiver optical sensitivity for 1.3-m wireless distance as compared with three channels in 11.2-GHz or 9.4-GHz total bandwidth with 2.8 dBm or 3.2 dBm, respectively [23].

The demonstrated single-band transmission could be suitable for delivering 10-Gigabit Ethernet signals [see Fig. 6(a)] or UHDTV signals [see Fig. 4(a)] to a single user. Although with higher complexity and lower performance, the multiband system [see Fig. 6(b)] could be suitable for providing multiuser or higher capacity access, e.g., up to four 10-Gigabit Ethernet users and up to two UHDTV users or one OC-768/STM-256 user by aggregating channels.

5. Conclusion

The photonic generation and wireless transmission of electrical 16-QAM-OFDM signals in the 75−110 GHz band has been experimentally demonstrated using a single RF band and when the RF bandwidth is used in multiple channels. A single-band system at 17.8-Gb/s effective data rate in 6.3-GHz bandwidth has been demonstrated up to 1.3 m of wireless distance. This signal exhibits up to 2.7-dB penalty in receiver optical sensitivity as compared with a single band at 8.9 Gb/s effective data rate in 3.2-GHz bandwidth in a system supporting multiband generation. The transmission of the 8.9-Gb/s signal over combined 22.8-km SSMF and 0.6-m wireless distance has also been demonstrated. The transmission of up to four channels at an effective data rate of 8.9 Gb/s/ch in 14.4-GHz bandwidth has been demonstrated up to 1.3 m of wireless distance employing an optical comb. The proposed multiband radio-over-fiber approach can provide a cost- and power-efficient solution for high-capacity hybrid wireless/optical links supporting multiple users with flexible bandwidth allocation.

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