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Hybrid bidirectional radio-over-fiber-based orthogonal frequency division multiple access-passive optical network supporting 60/120 GHz using offset quadrature phase shift keying

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Abstract. A hybrid bidirectional orthogonal frequency division multiple access-passive optical network (OFDMA-PON) based on offset quadrature phase shift keying (OQPSK) to support 60- and 120-GHz radio-over-fiber system is proposed. The system can support wired/wireless applications and enable the dynamic bandwidth allocation according to a subscriber's application. It is successfully achieved by using the millimeter waves (MMWs) generation and the carrier-reuse technique. In the proposed scheme, the MMW bands used for downlink (DL) and uplink transmissions are generated at the optical line terminal by the dual-arm Mach-Zehnder modulators. Both 60- and 120-GHz MMWs are obtained for the transmission of the high bit-rate services in source-free optical network units (ONUs), only using a single 15-GHz sinusoidal wave source. The Rayleigh backscattering effect is considered in the proposed OQPSK-based OFDMA-PON. For DL transmission over a 30-km single-mode fiber, the power penalties are less than 0.8 and 1 dB for the OQPSK-OFDM wired data at 10 Gb/s and the OQPSK-OFDM wireless data at 5 Gb/s, respectively. © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.54.9.096108](https://doi.org/10.1117/1.OE.54.9.096108)]

Keywords: radio-over-fiber; orthogonal frequency division multiple access-passive optical network; offset quadrature phase shift keying; dual-arm Mach-Zehnder modulator.

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1 Introduction

Next-generation passive optical networks (NG-PONs) need to meet the increasing demand of broadband connectivity for end users for both wired and wireless services.¹ Radio over fiber (RoF) is the combination technology of optical and wireless systems.² It is a promising approach to meet the requirements of the future broadband wireless system, and has attracted great interest for increasing the capacity and mobility of future access networks.³ Optical orthogonal frequency division multiple access (OFDMA) has been widely considered as one of the strongest contenders for NG-PONs with its high spectral efficiency and robust dispersion tolerance to improve system capability and transmission distance over both fiber and air links.^{4,5} Consequently, the OFDMA-based PON (OFDMA-PON) can simultaneously support the wired and wireless services with its integration of the RoF systems.³ However, the main impairments of the OFDMA-PON providing bidirectional transmission over a single-mode fiber is the Rayleigh backscattering (RB) effect which could distort the desired signal.⁶ To settle this problem, Cvijetic et al.⁷ have reported a solution by which the RB effect can be mitigated by the optical-carrier-suppressed (OCS) modulation of the upstream OFDM data and the coherent detection.

Moreover, in the integration of OFDMA-PON and RoF systems, millimeter wave (MMW) generation is one of the key techniques and has triggered much attention. Due to the

high extinction ratio and low insertion loss, the dual-arm Mach-Zehnder modulator (MZM) has attracted our interest for its application in the all-optical generation of MMW with a relatively stable phase.⁸ Recently, intensive investigations have been conducted on the RoF systems using a 60-GHz MMW band, since it is the attenuation peak of air, it has a globally available 7 to 9-GHz unlicensed bandwidth, and a negligible interference with current low radio-frequency (RF) wireless services.^{8–10} However, it is insufficient for 60-GHz MMW to transmit the high bit-rate services such as uncompressed pictures or HD videos, so we have the need to develop certain higher carrier frequency MMW to cover its shortage.¹¹ Similarly, 120 GHz is another attenuation peak of air and it has a huge available bandwidth compared with 60 GHz. Therefore, 120 GHz can be an excellent candidate for the transmission of high bit-rate services in the future optical wireless access networks and its transmission characteristics have been well studied in Ref. 12.

This paper proposes a hybrid bidirectional optical offset quadrature phase shift keying OQPSK-OFDMA-PON scheme supporting 60 and 120-GHz RoF systems. Based on dual-arm MZMs and a single 15-GHz sinusoidal wave source, 120-GHz frequency is, for the first time, integrated with conventional 60-GHz frequency in a hybrid radio over a PON system. 5-Gb/s OQPSK-OFDM wireless data on both 60- and 120-GHz MMW and 10-Gb/s OQPSK-OFDM wired data are transmitted over the downlink (DL) 30-km

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Fig. 1 Principle of the proposed offset quadrature phase shift keying (OQPSK)-based optical orthogonal frequency division multiple access-passive optical network (OFDMA-PON) system supporting 60- and 120-GHz radio-over-fiber (RoF) system. OLT: optical line terminal, ONU: optical network unit, DL: down-link, UL: uplink, OC: optical circulator, OS: optical splitter, PD: photodiode, Tx: transmitter, Rx: receiver, SMF: single-mode fiber, EDFA: erbium-doped fiber amplifier.

single-mode fiber (SMF) only using a single 15-GHz sinusoidal wave RF source. In the uplink (UL), 5-Gb/s OQPSK-OFDM wired data are successfully transmitted by the reused carrier with the mitigation of the RB effect. OQPSK is used in the system due to its low sidelobe level and better tolerance against fiber nonlinearity. By using the carrier-reuse technique, the complexity and cost of each optical network unit (ONU) is reduced, thus the proposed bidirectional OFDMA-PON system is much more cost-effective than a system using an independent laser in each ONU. The system can dynamically allocate bandwidth among ONUs with different wavelengths and support heterogeneous ONUs with different bandwidths. ONUs can be easily added or reduced without reconfiguring any hardware. The system is also resistant to most dispersion in the frequency domain due to the fiber or components; the system utilizes multiple wavelengths to transmit so it can have a larger capacity and longer transmission distance.

2 Principle of the Proposed Scheme

Figure 1 depicts the principle of our proposed optical OQPSK-OFDMA-PON supporting the 60- and 120-GHz

RoF system. At an optical line terminal (OLT), a distributed feedback laser with a central wavelength of 1553.5992 nm, and an average power of 1 mW is used as the continuous-wave (CW) light source. The 45-GHz sinusoidal wave is generated by a 15-GHz RF source with an electrical power of 22 dBm together with a frequency tripler. It drives the first dual-arm MZM-1 to perform the optical double sideband (ODSB) modulation.

The expander figure of the DL OQPSK-OFDMA in Fig. 1(a) shows the OQPSK-OFDM principle in the OLT, where the input signal is first sent into S/P, then each output signal of the S/P is modulated into OQPSK. The OQPSK is a modified form of QPSK, which splits the input signal streaming into two roads and in a quadrate. The difference between OQPSK and QPSK is that OQPSK staggers a half symbol period between the in-phase and quadrature-phase. OQPSK can overcome the 180-deg phase jump in QPSK. No crosstalk will be produced between the in-phase and quadrature-phase channels at matched filter sample times.

Figure 2(a) shows the power transfer function of the dual-arm MZM with different bias voltages at the extinction ratio (ER) of $\text{Inf}(\infty)$, 30, 20, and 10 dB, respectively. When ER

Fig. 2 (a) Power transfer function of the dual-arm Mach-Zehnder modulator (MZM) with different bias voltages at the extinction ratio (ER) of Inf , 30, 20, and 10 dB. (b) Power ratio of the first-order sideband to carrier with different amplitudes of the radio-frequency (RF) signal.

reaches 30 dB, the power ratio of the output to input signal is 0.9396 at the bias voltage of zero, which is very close to 1. The power transfer function of the dual-arm MZM is given by

$$\frac{P_{\text{out}}}{P_{\text{in}}} = \frac{1}{4} \left[1 + \gamma^2 + 2\gamma \cos\left(\frac{\pi}{V_\pi} V_{\text{bias}}\right) \right] \quad \gamma = \frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1}, \quad (1)$$

where V_π is the half-wave voltage (about 5 V) and V_{bias} is the bias voltage between the two arms. γ is the split ratio of the lower arm, while ε is the ER. The intrinsic extinction ratio of the common MZM is usually in the 30 to 40 dB range.

The dual-arm MZMs used in our scheme have an ER of about 35 dB and we can assume that the power splitting ratio of the two arms is 50:50. The bias voltage consists of the RF source and the DC bias. The input CW carrier can be represented as $E_{\text{in}}(t) = A_c \cos(\omega_c t)$, while the RF driving signal can be shown as $V_{\text{RF}}(t) = A_{\text{RF}} \cos(\omega_{\text{RF}} t)$, where A_{RF} is the amplitude of the RF driving signal. The DC bias is set to $V_\pi/2$ in order to perform ODSB modulation. The electrical field at the output of the MZM is shown as follows:⁸

$$E_{\text{out}}(t) \approx \frac{\sqrt{\alpha} A_c}{2} \left\{ J_0\left(\frac{A_{\text{RF}}}{V_\pi} \pi\right) [\cos(\omega_c t) - \sin(\omega_c t)] \right. \\ \left. - J_1\left(\frac{A_{\text{RF}}}{V_\pi} \pi\right) [\cos(\omega_c - \omega_{\text{RF}})t + \cos(\omega_c + \omega_{\text{RF}})t] \right. \\ \left. + J_1\left(\frac{A_{\text{RF}}}{V_\pi} \pi\right) [\sin(\omega_c - \omega_{\text{RF}})t + \sin(\omega_c + \omega_{\text{RF}})t] \right\}. \quad (2)$$

Here, α is the insertion loss of the MZM. $J_0(x)$ and $J_1(x)$ are the zero and first orders of the first-kind Bessel function. The output optical power spectrum of the MZM is the Fourier transform of the output electrical field and it can be expressed as

$$P_{\text{out}}(\omega) \approx \frac{\alpha \pi A_c^2}{4} \left(J_0^2\left(\frac{A_{\text{RF}}}{V_\pi} \pi\right) \delta(\omega + \omega_c) + J_1^2\left(\frac{A_{\text{RF}}}{V_\pi} \pi\right) \right. \\ \left. \times \{ \delta[\omega + (\omega_c - \omega_{\text{RF}})] + \delta[\omega + (\omega_c + \omega_{\text{RF}})] \} \right). \quad (3)$$

Fig. 3 The corresponding spectra of (a), (b), (c), (d), (e), and (f) points in Fig. 1.

According to Eq. (3), we can obtain the power distribution of the first-order sideband and the carrier. Figure 2(b) shows the power ratio R_p of the first-order sideband to the optical carrier with a different amplitude of the RF signal, so we set the amplitude around $0.46 V_\pi$ to obtain a suitable sideband-to-carrier ratio (close to 1).

The MZM-1 has a 3 dB bandwidth of 20 GHz and insertion loss of 6 dB. After the ODSB modulation, we obtain an ODSB signal with three frequency bands centered at 193.055, 193.1, and 193.145 THz, respectively. A demultiplexer (DEMUX) is applied to separate these bands. The middle band with a central frequency of 193.1 THz is sent into an intensity MZM-2 to modulate with 10-Gb/s OQPSK-OFDM data which are generated by MATLAB® programs. 5-Gb/s OQPSK-OFDM baseband data are also produced by MATLAB programs and are mixed by a mixer with a 30-GHz sinusoidal wave, which is generated by the shared 15-GHz RF source and a frequency doubler. The mixed signal drives MZM-3 to perform another ODSB modulation on the 193.145 THz carrier, which is amplified by an erbium-doped fiber amplifier (EDFA) with a gain of 15 dB in advance. Thus, we obtain another ODSB signal with a central carrier frequency of 193.145 THz and two modulated sidebands at frequencies of 193.115 and

193.175 THz. After all the above operations, the 10-Gb/s OQPSK-OFDM data modulated band of 193.1 THz, the unmodulated band of 193.055 THz, and the new ODSB signals are combined together by a multiplexer (MUX). The combined signal is launched into the SMF after an optical circulator (OC) for the DL transmission.

After the transmission fiber, the transmitted signal is divided into two streams by an optical splitter (OS 50:50) and each stream is sent to the ONU supporting 60- or 120-GHz MMW, respectively. After an OC, the stream is amplified by an EDFA with a gain of about 15 dB in each ONU. A DEMUX is used to separate the bands of the received signal and the middle band with 10-Gb/s OQPSK-OFDM data at a central frequency of 193.1 THz is directly sent into the photodiode (PD1) for detection and demodulation. The unmodulated band of 193.055 THz and the 5-Gb/s OQPSK-OFDM data modulated band of 193.115 THz input the PD2 together to generate the 60-GHz MMW in the ONU, while the unmodulated band of 193.055 THz and the 5-Gb/s OQPSK-OFDM data modulated band of 193.175 THz input PD3 together to generate the 120-GHz MMW in the ONU. The unmodulated band of 193.145 THz is reused as the UL carrier and it is OCS modulated by the MZM with the 5-Gb/s OQPSK-OFDM data. Then it is sent back to OLT for the UL

Fig. 4 The corresponding waveforms of (I), (II), (III), (IV), and (V) points in Fig. 1.

transmission through an OC and detected by the coherent OFDM receiver in the OLT afterward. By using OCS modulation and coherent detection for UL transmission, the RB effect can be mitigated.⁷

3 Results and Discussions

The corresponding spectra of (a), (b), (c), (d), (e), and (f) points in Fig. 1 are shown in Fig. 3. It illustrates the corresponding output optical spectra of the various points in Fig. 1. Figure 3(a) is the spectrum of the output ODSB signal after dual-arm MZM-1 and the central carrier has a frequency interval of 45 GHz from the two adjacent first-order sidebands. The power of two first-order sidebands is almost the same to the central carrier at about -20 dBm and it is 20 dB higher than the power of the second-order sidebands. Figure 3(b) shows the spectrum of the output ODSB signal after the dual-arm MZM-3 and the power of two first-order sidebands is also 20 dB higher than the power of the second-order sidebands. The frequency components, which are sent into optical detectors to generate the 60- and 120-GHz MMWs, are shown in Figs. 3(c) and 3(d), respectively. Figures 3(e) and 3(f) depict the finally obtained 60- and 120-GHz wireless OFDM signals, both with the optical power of about -20 dBm.

Figure 4 gives the corresponding waveforms of points (I), (II), (III), (IV), and (V) in Fig. 1. Figures 4(I) and 4(II) are the

waveforms of the transmitted and received DL wired OFDM signals. Though the OFDM signal has some deterioration after transmission over the 30-km SMF, it still can be successfully demodulated to obtain the wired users' data. The waveforms of 30, 60, and 120 GHz OFDM signals are depicted in Figs. 4(III)–4(V), respectively. Figure 4(III) gives the waveform of the signal mixed with the baseband OFDM signal and a 30-GHz RF source, which is achieved by the single 15-GHz RF source and a frequency doubler. After the frequency beating in the optical detectors, the desired 60- and 120-GHz OFDM MMW signals are obtained. Then they are emitted into the wireless channel by antennas and received by the users.

Figures 5 shows the bit-error-rate (BER) values versus different received optical powers and the received constellations for both wireless and wired signals transmission. Figure 5(a) plots the BER performance and the received constellations of DL 60- and 120-GHz wireless signal transmission for back-to-back (B2B) and after 30-km SMF. We also find that the 120-GHz MMW signal is received at a higher optical power than the 60-GHz MMW signal, for example, 5 dB higher at the BER of about 10^{-6} . The inserts in Fig. 5(a) show the received constellations of the appointed situations for the 60- and 120-GHz wireless signals over the 30-km SMF. The BER performances and the received constellations of the DL and UL wired signals are given in Fig. 5(b) for B2B and after 30-km SMF at the same time. The inserts in Fig. 5(b) are the received constellations of the appointed situations.

4 Conclusion

We have proposed and demonstrated a hybrid bidirectional optical OQPSK-OFDMA-PON for wired and wireless OFDM signals. The system supports the wired and wireless applications and enables the bandwidth allocation according to the subscriber's application. The power penalties are less than 0.8 and 1 dB for the DL wired and wireless data transmission, respectively, while the power penalty for the UL wired data transmission is 0.3 dB. The key advantage of our proposed scheme is using OQPSK and a carrier-reuse technique to successfully realize a low-complexity and cost-effective hybrid bidirectional access network providing 60- and 120-GHz MMW for the transmission of high bit-rate services with low RB interference. Therefore, the introduced OQPSK-OFDMA-PON supporting 60- and 120-GHz RoF can be applied to provide the independent wired and wireless services with a high bit rate for the next-generation optical access networks.

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Fig. 5 (a) Measured bit-error-rate (BER) curves and the received constellations of the DL wireless OFDM signals and (b) measured BER curves and the received constellations of the DL and UL wired OFDM signals.

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