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Demonstration of using multi-band 16-QAM OFDM modulation with direct-detection in 10 GHz bandwidth for 37.3-Gb/s PON

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Abstract We propose and experimentally demonstrate a 37.3 Gb/s passive optical network using four-band orthogonal-frequency-division-multiplexing (OFDM) channels within 10 GHz bandwidth. Here, the required sampling rate and resolution of digital-to-analog/analog-to-digital (DA/AD) converter are only 5 GS/s and 8 bits to accomplish the 40 Gb/s OFDM downstream rate. Moreover, to reduce the power fading and fiber chromatic dispersion issues, a −0.7 chirp parameter Mach-Zehnder modulator is used for the four-band OFDM modulation scheme. Downstream negative power penalty of −0.37 dB can be obtained at the bit error rate of 3.8×10^{-3} after 20 km standard single mode fiber transmission without dispersion compensation.

Keywords 40Gbps PON · Optical OFDM · Multi-band · Pre-chirp

1 Introduction

Passive optical network (PON) is the promising access system to provide the wide bandwidth to end users economically [1]. However, in future next generation (NG)-PON, the downstream traffic rate of 40 Gb/s or even beyond is required due to the demand of broadband multi-services [2]. For the future 40 Gb/s PON, the on-off keying (OOK) modulation on single wavelength is no longer feasible owing to the constrains of fiber chromatic dispersion, polarization mode dispersion (PMD), and expensive 40 GHz transceiver [3]. Thus, there is a great challenge to upgrade the present 2.5 or 10 Gb/s/wavelength PON to 40 Gb/s/wavelength.

To obtain the higher traffic rate cost-effectively, the high spectral efficiency of orthogonal frequency division multiplexing–quadrature amplitude modulation (OFDM-QAM) could be used for accessing networks [4]. Hence, the optical OFDM-PON has been proposed [2,5,6]. Recently, 40 Gb/s optical OFDM-PON has also been experimentally investigated using broadband OFDM signal [7,8]. However, they required the higher sampling rate (at least 12-GS/s) and resolution of digital-to- analog / analog-to-digital (DA/AD) conversion for OFDM signal processing. A multi-band OFDM system separates the signal in several sub-bands, and each sub-band only requires using the low-speed DA/AD convertor, and thus, the cost and system would be easily reduced and implemented [9]. However, the OFDM subcarriers would also be affected in the higher frequency due to the chromatic dispersion and RF power fading. Therefore, using the positive chirp modulator would enhance the effect of the dispersion and power fading. The pre-chirp technique can improve the bandwidth in the dispersion channel.

In this paper, we investigate a 40 Gb/s (including 7 % overhead, and the effective data rate is 37.3 Gb/s) OFDM-PON by using four-band OFDM channels within 10 GHz bandwidth. Each OFDM channel is modulated at 16-QAM format. Then, the four-band OFDM channels are used in 10 GHz bandwidth Mach-Zehnder modulator (MZM) with −0.7 alpha chirp parameter to generate the 40 Gb/s OFDM downstream rate in the transmitter (Tx). Direct-detection is used to reduce

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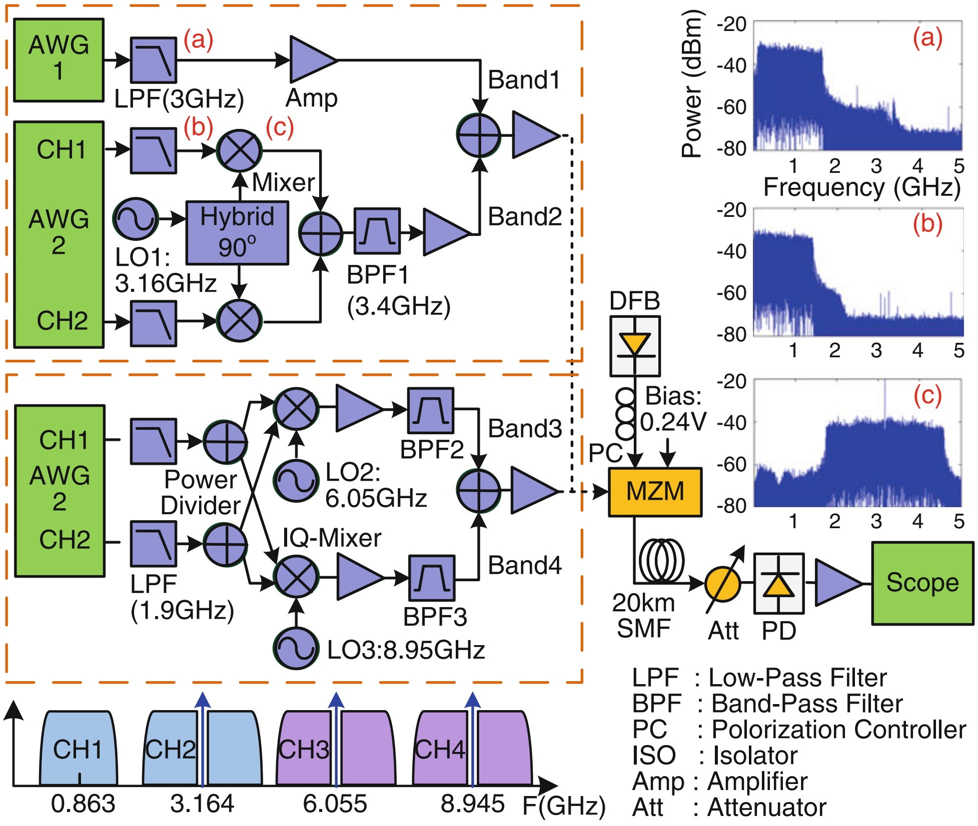

Fig. 1 Experimental setup and frequency allocation of each OFDM bands and the electrical spectrum of **a** channel 1 baseband signal, **b** channel 2 baseband signal and **c** up-converted channel 2 signal

the cost of receiver (Rx). Each 16-QAM OFDM channel only requires the 5 GS/s sampling rate and 8 bits resolution for DA and AD conversions; hence, the Tx and Rx modules could be cost-effective for PON. From the experimental results, the downstream power penalty of −0.37 dB can be measured at the bit error rate (BER) of 3.8×10^{-3} (forward error correction (FEC) threshold) [10] after 20 km fiber transmission due to pre-chirp characteristic of MZM.

Table 1 The detailed parameters of four-band OFDM channels

Parameters of the 40Gb/s OFDM signal	
Tx sampling rate (GS/s)	12
Rx sampling rate (GS/s)	50
FFT/IFFT size	512
CP	8
Modulation format	16 QAM
Carrier number of band 1	40 (3rd–42th)
Carrier number of band 2	72 (45th–117th, excluding the LO of 81th)
Carrier number of band 3	72 (119th–191th, excluding the LO of 155th)
Carrier number of band 4	72 (193th–265th, excluding the LO of 229th)

2 Experiment and discussions

Figure 1 shows the experimental setup of the proposed PON architecture by using four-band OFDM channels. The insert of Fig. 1 is the schematic spectra of the four-band OFDM channels for downstream transmission. Here, the channel 1 OFDM signal has the bandwidth of 1.526 GHz. The channels 2–4 are with the same bandwidth of 2.813 GHz and are up-converted in the frequencies of 3.164, 6.055 and 8.945 GHz by using I–Q modulation, respectively. Here, we used the 4-port IQ mixer from Hittite. And, the RF bandwidths and conversion losses of IQ mixers from bands 2 to 4 are 1 MHz–6 GHz, 4–8.5 and 6–10 GHz, and 7, 7.5 and 7 dB, respectively. Moreover, the channel separations are 0.1315, 0.078 and 0.077 GHz, respectively. The more detailed parameters are listed in Table 1. In this experiment, due to the limitation of available equipments, the measurement of the four-band OFDM channels are separated into two parts, as shown in Fig. 1. In the first part, band 1 and band 2 are generated by AWG1 and AWG2. In the second part, band 3 and band 4 share the same AWG2. The total OFDM bandwidth is

10.3515 GHz, which can fit into the modulation bandwidth of our 10 GHz MZM. We have stated explicitly that only 2 bands are transmitted at a time due to the limited equipments of our laboratory. Since the carrier numbers and locations of each band are setting to orthogonal, there is almost no interference between each band. The main impact would be output optical power from the modulator. When the input continuous-wave (CW) optical power to the optical modulator is fixed, the output optical power of four band signal would be lower than the two band signal; thus, the receiver sensitivity would be lower in the case of four band signal.

As shown in Fig. 1, the first part includes band 1 and band 2 (Ch1 and Ch2) signals, and the second part includes band 3 and band 4 signals for the practical downstream OFDM measurements. The four-band OFDM signals are using the same modulation of 16-QAM with a fast Fourier transform (FFT) size of 512 and cyclic prefix (CP) size of 8. The OFDM signals are generated by arbitrary waveform generator (AWG) by using the Matlab® program. The sampling rate and DA/AD resolution of 5 Gs/s and 8 bit are used in this experiment, respectively. As shown in Fig. 1, base band OFDM signal of channel 2, 3 and 4 are IQ modulated by the IQ mixer.

In the first part, the band 1 OFDM signal is generate by AWG1. It consists of 40 OFDM subcarriers that occupying 1.526 GHz bandwidth from 82 MHz to 1.626 GHz to produce a total data rate of 6.25 Gb/s. The band 2 OFDM signal consists 72 subcarriers that occupying 2.813 GHz bandwidth to generate a data rate of 11.25 Gb/s. In the second part, the band 3 and band 4 OFDM signals are generated by using AWG2, and each band also consists of 72 OFDM subcarriers that occupying 2.813 GHz bandwidth producing a data rate of 11.25 Gb/s. As a result, the total data rate of 40 Gb/s can be obtained by the proposed four-band OFDM channels. The OFDM signal is applied to the MZM with the alpha chirp parameters of −0.7 and the EAM with the alpha chirp parameters of 0.53 in turn in the experiment, respectively. Here, one 3 GHz bandwidth LPFs is used for band 1, four 1.9 GHz bandwidth LPFs are employed for band 2 to band 4, and three BPFs with 3.4 GHz bandwidth are used for band 2 to band 4, as shown in Fig. 1. A continuous-wave (CW) optical signal at 1550.0 nm is launched into the modulator to produce the optical OFDM signal, as illustrated in Fig. 1. The electrical spectra of different parts have been included in insets of Fig. 1. After 20 km single mode fiber (SMF) transmission, the 40 Gb/s OFDM signal is directly detected by a PIN photo receiver (Rx). It has a 3-dB bandwidth of 12 GHz. It has the responsivity of 0.9 A/W at wavelength of 1,550 nm. The dark current is about 5 nA. A real-time scope is used to capture the received electrical data for off-line analysis. Moreover, there are two methods that can achieve single side band optical signal. The first is using optical IQ modulator which is much expensive than a MZM. The second method is using optical filter. And the signal needs guard band due to the non-ideal transition edge of the filter; it would reduce the bandwidth efficiency and increase the cost of the system.

In this measurement, the signal processing of the OFDM transmitter (Tx) constructed by serial-to-parallel conversion, QAM symbol encoding, inverse fast Fourier transform (IFFT), CP insertion, and DA conversion. The received downstream OFDM signal is captured by using Matlab® programs for signal demodulation. To demodulate the vector signal, the off-line DSP program is employed. And the demodulation process includes the synchronization, FFT, one-tap equalization, and QAM symbol decoding. As a result, the bit error rate (BER) would be calculated according to the observed signal-to-noise ratio (SNR) of each OFDM subcarrier. Due to the limitation of available equipment, the channel 3 and channel 4 are generated simultaneously. We copy the base band real and imaginary signal by the electrical splitter and then up-convert them by two different IQ mixers. At the receiver side, the signals are sampled by the scope with sampling rate of 50 GS/s, and the each channel is down convert and filtered by the digital low-pass filter in the Matlab. Only the channel 1 is generated with real value OFDM signal. Each OFDM band is demodulated separately and independently.

As we know, the SNR of OFDM subcarrier would drop seriously in high frequency after fiber transmission due to the RF fading [7]. Here, to realize the relationship of chirp effect and OFDM signal, first we use a 0.53 chirp parameter of EAM to experiment. Figure 2a shows the measured electrical power of bands 3 and 4 with 16-QAM OFDM modulation at the received power of −10 dBm at the back-to-back (B-t-B)

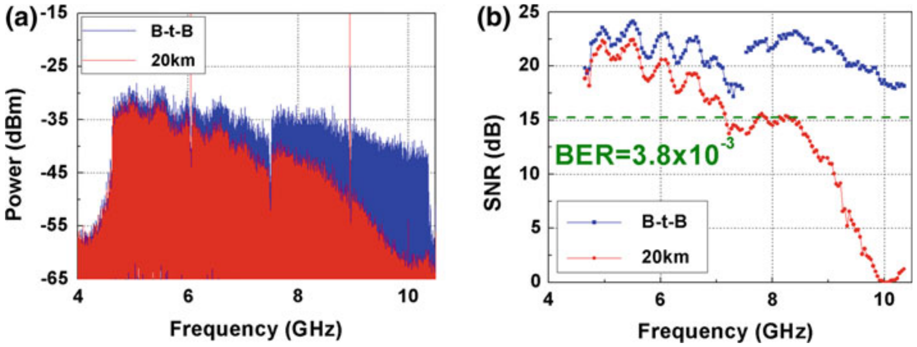

Fig. 2 Using MZM with 0.53 chirp parameter. **a** Electrical spectrum of four-band OFDM channels at B-t-B and after 20 km single mode fiber, and **b** SNR of each OFDM subcarrier at received power of −10 dBm

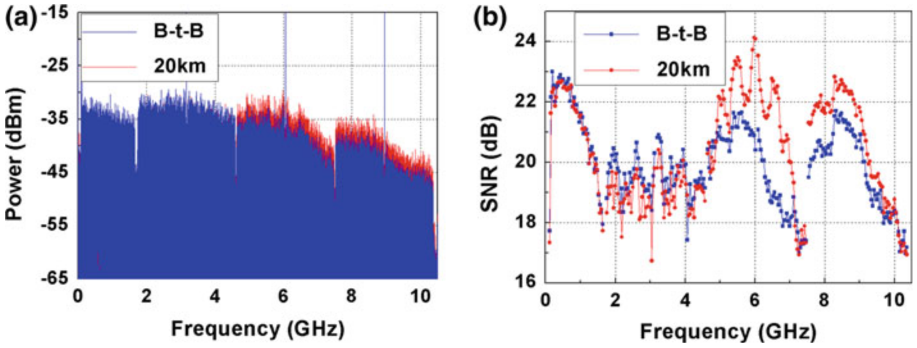

Fig. 3 Using MZM with −0.7 chirp parameter. **a** Electrical spectrum of optical back-to-back and after 20 km single mode fiber and **b** SNR of each OFDM subcarrier at received power of −10 dBm

status and 20 km fiber transmission. And Fig. 2b presents the measured SNR of each OFDM subcarrier. After 20 km transmission, the measured electrical power and SNR of bands 3 and band 4 become worse due to the fiber chromatic dispersion. As shown in Fig. 2b, the SNR cannot achieve the forward error correction (FEC) threshold (SNR = 16.5 dB; BER of 3.8×10^{-3}), when the OFDM subcarrier frequency is larger than 7.2 GHz. Therefore, the total downstream rate cannot accomplish 40 Gb/s in 20 km fiber transmission due to the worse SNRs of bands 3 and band 4.

In order to upgrade to 40 Gb/s PON while maintaining the 20 km reach of the standard PON, a 10 GHz MZM with −0.7 chirp parameter is used as the Tx. The MZM (from *Eospace*) is Z-cut with a fixed pre-chirp alpha chirp parameter of −0.7. The insertion loss and the V_{pi} of the MZM are 3 dB and 4 V respectively. Figure 3a, b show the four-band 16-QAM OFDM electrical spectrum and SNR of each OFDM subcarrier at the B-t-B and 20 km fiber transmission when the received power is −10 dBm. Due to the pre-chirp of MZM in the experiment, the power gain in the OFDM signal of bands 3 and 4 can be enhanced after 20 km fiber transmission, as shown in Fig. 3a. Moreover, after 20 km transmission, the measured SNRs of OFDM subcarriers in band 3 and band 4 are better than that of B-t-B, as seen in Fig. 3b. The measured SNRs of all the four-band OFDM channels are larger than FEC level.

Here, the RF power fading of 0.53, 0 and −0.7 chirp parameters are also numerical analyzed, respectively. Figure 4 presents the numerical result of the power fading under the frequencies from 0 to 10 GHz, when the chirp parameter is 0.53, 0 and −0.7, respectively, after 20 km fiber transmission. As shown in Fig. 4, the RF fading can be improved in the higher frequency when the negative chirp parameter is used. When the frequency is 10 GHz under the 0.53, 0 and −0.7 chirp parameters, respectively, the RF fading can be observed in −28.8, −10.1 and −3.8 dB. If only considering the fading effect, the chirp of 0 is enough for 20 km transmission experiment. However, the channel responses of high-frequency bands are worser than that of low-frequency bands. Hence, the gain of the transmission response of the negative chirp is important for improving the SNR and sensitivity. As a result, the pre-chirp MZM is very crucial for the proposed multi-band OFDM-PON to mitigate power fading in 20 km standard reach SMF transmission.

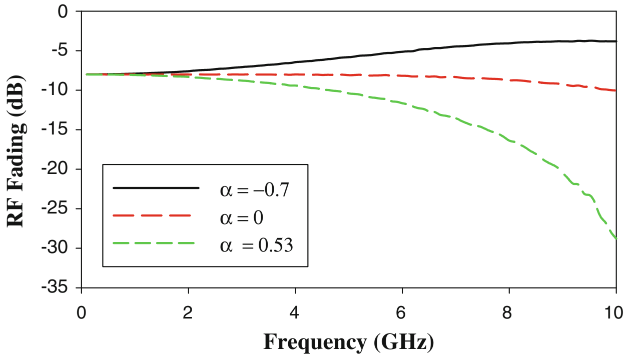

Fig. 4 RF power degradation under the frequencies of 0–10 GHz, when the chirp parameter is 0.53, 0 and −0.7, respectively

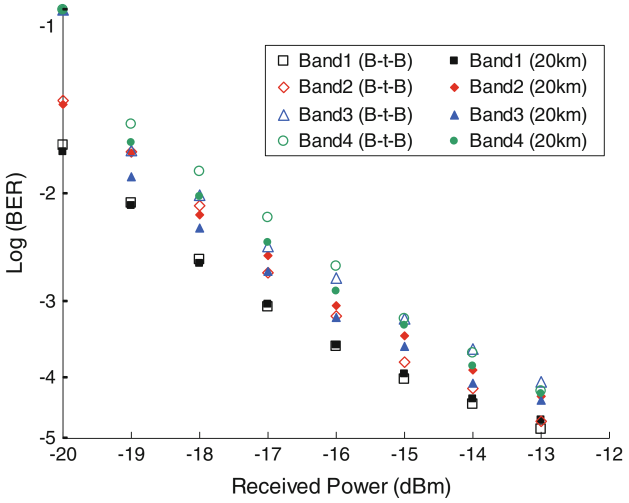

Fig. 5 BER curves of band 1 to band 4 at different received power, while the chirp of MZM is −0.7

Figure 5 presents the BER performances of each 16-QAM OFDM band at the B-t-B and 20 km SMF transmission, respectively, using the proposed scheme with −0.7 alpha chirp parameter MZM. In Fig. 5, we can obtain the receiver

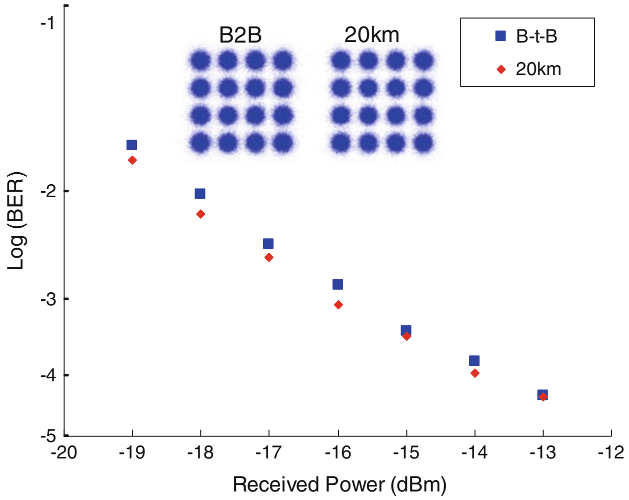

Fig. 6 Average BER measurement of the 4-OFDM bands for the proposed 37.3 Gb/s multi-band OFDM signals at B2B status and 20 km fiber transmission, respectively. The insets are the corresponding constellation diagrams at the FEC threshold

sensitivities of −18.33, −17.47, −17.09 and −16.5 dBm at the FEC threshold (BER of 3.8×10^{-3}) at the B-t-B status for the OFDM band 1 to band 4. After 20 km SMF transmission, there are almost no power penalties for the band 1 and band 2, and the power penalties of band 3 and band 4 are measured at −0.59 and −0.48 dB, respectively. The measured negative penalty is due to the pre-chirp characteristic as discussed before.

Figure 6 shows the BER performances of total 37.3 Gb/s OFDM signal at the B-t-B status and 20 km SMF transmission. The receiver sensitivity of B-t-B status and 20 km SMF transmission are −17.42 and −17.05 dBm, respectively. Besides, the insets are the corresponding constellation diagrams at B-t-B and 20 km transmission at FEC level. The negative power penalty of −0.37 dB is observed after 20 km fiber transmission by using a −0.7 chirp parameter of MZM. The optical power of the Tx is 6 dBm, the total fiber loss is 4 dB, and the proposed scheme can support 64 ONUs (18 dB loss emulated by the optical attenuator as shown in Fig. 1).

The sampling rate of AD/DA convertor in the ref. [8] was at least 12 GS/s. However, the sampling rate of AD/DA convertor in our purposed multi-band architecture is only 5 GS/s. Moreover, the modulation/demodulation DSP process can deal with in 4 lower speed parallel way. By comparing with ref. [8], the proposed multi-band operation needs more electrical components, but the cost of the electrical components could be much lower. Hence, the cost of the multi-band architecture would be more cost-effective, because the multi-band channel can use mature and low-cost electrical components.

Moreover, the ONU in the proof-of-concept demonstration would be complex and costly since the processing of aggregated 40 Gb/s signal is need. However, we believe that the idea of using lower- speed electronic processing to decompose part of the RF spectrum, such as that reported in ref. [11], could be used in our scheme. In our scheme, each wavelength carries 4-band OFDM signals; it is similar to the ref. [11], in which the FDM has 4 channels. For the OLT side, the data rates of sub-band are fixed in our proposal OLT, but the FDM bandwidth and subcarrier (SC) frequency could be varied in ref. [11].

3 Conclusion

We have proposed and experimentally investigated a 37.3 Gb/s OFDM-PON by using four-band OFDM channels in 10 GHz bandwidth. Here, each OFDM channel is modulated at 16-QAM format. And the four-band OFDM channels are applied to a 10 GHz bandwidth MZM with −0.7 chirp parameter to generate the 37.3 Gb/s OFDM downstream traffic rate. In the measurement, the direct-detection is used to reduce the cost of Rx. And each 16-QAM OFDM channel only requires the 5 GS/s sampling rate and 5 bits resolution for the DA and AD conversion. Negative penalty of −0.37 dB is measured experimentally at the BER of 3.8×10^{-3} after 20 km fiber transmission, when a −0.7 chirp parameter of MZM is used in the proposed four-band OFDM-PON. Experimental and numerical analysis of using commercially available EAM and MZM with 0.53 and −0.7 alpha chirp parameter are performed, respectively, showing the pre-chirp MZM is very crucial for the proposed OFDM-PON to mitigate RF power fading in 20 km standard reach SMF transmission.

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