A 40-Gb/s OFDM PON System Based on 10-GHz EAM and 10-GHz Direct-Detection PIN

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***Abstract*—This letter demonstrates a 40-Gb/s optical double-sideband (ODSB) orthogonal frequency-division multiplexing passive optical network (OFDM-PON) system using a cost-effective 10-GHz-bandwidth electroabsorption modulator (EAM). By employing a subcarrier-adaptive modulation format and pre-emphasis, we successfully achieve 20-km EAM-based single-mode-fiber (SMF) transmission.**

***Index Terms*—Electroabsorption modulator (EAM), orthogonal frequency-division multiplexing (OFDM), passive optical network (PON).**

I. Introduction

PASSIVE optical network (PON) technology has been considered to be one of the most promising candidates for future broadband wired access. Currently, the gigabit PON (GPON) provides 2.5-Gb/s downstream and 1.25-Gb/s upstream services based on the nonreturn-to-zero (NRZ) modulation format [1]. Nevertheless, for future 40-Gb/s (and beyond) PON, NRZ format is no longer feasible due to constrains such as fiber dispersion, polarization mode dispersion (PMD), and expensive 40-GHz wideband electronics at transmitters and receivers, to name just a few. Although wavelength division multiplexing PONs (WDM-PONs) provide dedicated channel to each user, the high complexity and cost of WDM lasers and multiplexers urge researchers to yield an alternative and feasible solution.

Thanks to the advance in digital signal processing technology, orthogonal frequency-division multiplexing (OFDM)-PON has been envisioned as a prominent candidate for future cost-effective and flexible PONs [2]–[8]. With the flexibility of using higher order quadrature amplitude modulation (QAM) [4], [8], OFDM-PON effectively achieves high spectral efficiency and ultimately lowers the bandwidth requirement of components. Recently, 40-Gb/s optical single-sideband (OSSB) OFDM PON has been proposed and experimentally demonstrated [4]–[7]. OSSB OFDM is achieved by employing an optical I/Q modulator and two different wavelength external cavity lasers (ECLs) [4] or an optical interleaver [5]–[7]. However, the use of optical I/Q modulator and ECLs is expensive and complicated, and using optical interleaver requires precise wavelength control, hence increasing the cost. Both methods are not suitable for cost-sensitive access networks.

Optical double-sideband (ODSB) OFDM-PON with directly modulated Distributed Feedback (DFB) laser (DML) or electroabsorption modulator (EAM) with DFB laser provides an economical alternative, but it gives rise to two hurdles that need to be crossed. First, ODSB OFDM signals result in power fading after fiber transmissions [9]. Second, the positive chirp of DMLs or EAMs has a detrimental effect on the maximum transmission distance over conventional fibers [10].

In this letter, to clear these hurdles we propose and demonstrate a 40-Gb/s ODSB OFDM PON, and we focus on the theoretical and experimental studies of the transmission performance of 10-GHz EAM. By using a subcarrier-adaptive modulation format and pre-emphasis, 40-Gb/s EAM-based 20-km standard single mode fiber (SMF) transmission is successfully achieved. We also investigate that adding erbium-doped fiber amplifier (EDFA) in the transmitter can improve the optical power budget to 21.5 dB, which can support 20-km SMF and 1:16 optical splitter in an ODSB OFDM PON.

II. Theoretical Analysis of DML-Based Transmission

Notice that both DML and EAM follow similar E/O characteristics. Namely, the output optical power is proportional to the input electrical signal, and additional frequency chirp will be generated after modulation. We hence choose DML to study the physical impairments induced by direct modulation. Based on our previous work [10], after square-law direct detection in the receiver, the normalized received signal after L SMF transmission distance is

$$|E(L)|^2 \cong 1 + 2\sqrt{1+\alpha^2} \cdot \sum_{n=1}^{N} x_n \cos(n\omega t + \theta_n)\cos(n^2\theta_D - \theta_\alpha),$$

where α is the chirp parameter, N is the subcarrier number, and x_n and θ_n are the encoded amplitude and phase information of the n^{th} subcarrier, θ_D and θ_α are dispersion-induced and chirp-induced phase shifts, respectively. The second term at

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the RHS of above equation corresponds to the desired OFDM signal and the n^{th} subcarrier power is proportional to $(1 + \alpha^2)\cos^2(n^2\theta_D - \theta_\alpha)$, the well-known formula of power fading [11]. Owing to positive α, the power fading is intensified by an extra factor of $(1 + \alpha^2)$, and therefore, the transmission bandwidth of DML-based OFDM signals is degraded by its positive chirp. In this work, subcarrier-adaptive modulation format and pre-emphasis are adapted to compensate the power fading. The modulation formats of subcarriers are adaptively adjusted based on the measured channel response by the OFDM training symbols. In the receiver, the measured signal to noise ratio (SNR) of n^{th} subcarriers, which is proportional to $(1+\alpha^2)\cos^2(n^2\theta_D - \theta_\alpha)$, is used to calculate the pre-emphasis parameters, $p(n) = 10^{-SNR_n/20}$. Thus, $p(n)$ is inversely proportional to the received SNR and can be used to adjust the power levels x_n of transmitted subcarriers to homogenize the received SNRs of subcarriers. For example, subcarriers with poor SNRs will get extra power in the transmitter due to higher pre-emphasis parameters $p(n)$. In the next section, we show the experimental results and demonstrate that using subcarrier-adaptive modulation format and pre-emphasis improves the performance of 40-Gb/s ODSB OFDM signal transmission.

III. Experimental Setup and Results

In the experiment, the OFDM signals are generated by an arbitrary waveform generator (AWG, Tektronix AWG7102) using the Matlab program. The OFDM transmitter consists of serial-to-parallel conversion, QAM modulation, inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion, and digital-to-analog conversion (DAC). The sampling rate and digital-to-analog converter resolution of the AWG are 12 GS/s and 8 bits, respectively. Other detailed parameters of generated OFDM signals include: FFT size = 512, CP size = 8, and every 100 OFDM symbols is added with 10 training symbols for channel response detection. Besides, the driving signal consists of an OFDM signal of 23.4375-MSym/s 128-QAM symbol that is encoded at channels 6–98 with a bandwidth of 2.18 GHz (band 1) and a total data rate of 15.2578 Gb/s. Another OFDM signal of the same symbol rate but with 64-QAM format is encoded and up-converted to 4.406 GHz which occupies from channels 99–186 and 200 to 287 with a combined data rate of 24.75 Gb/s (band 2). Combining these two OFDM bands, we achieve a total data rate of 40 Gb/s, including the training-symbol, CP, and 7% forward error correction (FEC) overhead, or 32.84 Gb/s excluding the overhead.

Fig. 1 shows the experimental setup with the insets displaying the corresponding OFDM electrical spectra without pre-emphasis. Two streams of electrical signals are generated from channels 1 and 2 of AWG, respectively. The channel-2 signal is amplified and up-converted to 4.406 GHz. Notably, since the channel number of the AWG is only 2, this up-converted signal is used to emulate band-2 signal which should be realized by independent I- and Q-channels in practice. Through a directional coupler, both signals are then combined and passed to a 10-GHz EAM. An EDFA is used in the transmitter to compensate the optical power loss induced by the SMF transmission and optical splitter, and an optical variable attenuator (Att1) is allocated after EDFA and used to avoid the nonlinear effects. The optical splitter is emulated by

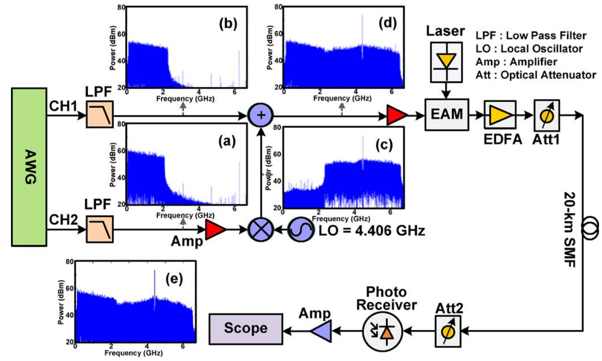

Fig. 1. Experimental setup with electrical spectrum illustration. (a) Channel 2; (b) channel 1; (c) channel 1 after up-conversion; (d) combination of channels 1 and 2; and (e) combination of channels 1 and 2 after receiving.

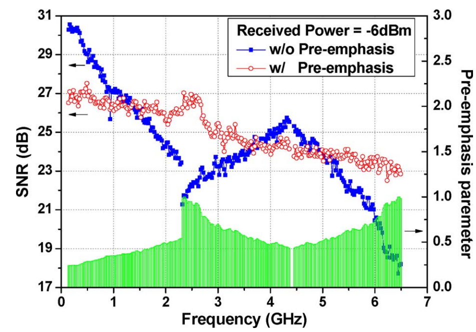

Fig. 2. Subcarrier SNR before and after pre-emphasis and the pre-emphasis parameters.

Att2. Following 20-km SMF transmission, the optical signal is received by a 10-GHz PIN photo-detector. After square-law photo detection, the waveform is amplified and captured by a digital oscilloscope (Tektronix DPO 71254) with a 50-GS/s sampling rate and a 3-dB bandwidth of 16 GHz. Due to the limited buffer size of oscilloscope, 1000 OFDM symbols with 1.707 Megabits are captured. An offline Matlab digital signal processing program is employed to demodulate the OFDM signal. This demodulation process includes synchronization, fast Fourier transform (FFT), one-tap equalization, and QAM symbol decoding. From the constellations of the OFDM signal, we measure the SNR and in turn calculate the bit error rate (BER).

One important factor that limits the performance of EAM is the RF fading following fiber transmission. Because the generated optical signal exhibits double side bands, after fiber dispersion, the two side bands create different phase shifts resulting in signal power loss [9]. To overcome this problem, we employ a pre-emphasis algorithm. As shown in Fig. 2, we first display the SNR by the blue curve without power adjustment. Though some subcarriers maintain relatively high SNR, the subcarriers located at high frequency, nonetheless, suffer from RF fading that causes severe SNR degradation. After applying the pre-emphasis algorithm and parameters $p(n)$ as shown in the green lines, we attain a smoother SNR as shown in the red curve, hence an improved performance compared to that without the pre-emphasis algorithm.

On the basis of the theoretical model presented in the previous section, the chirp parameter α of EAM is measured [12] and equal to 0.7 when the bias is set at -1 V. In Fig. 3(a) and (b), we plot the theoretical and experimental results of power fading

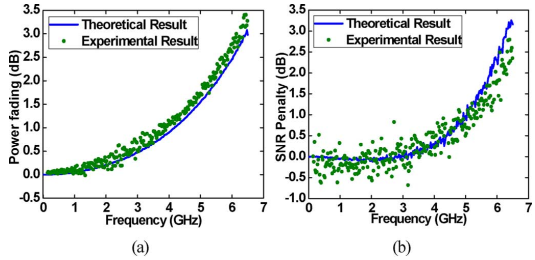

Fig. 3. Theoretical and experimental results of subcarrier ($\alpha = 0.7$, $L = 20$ km). (a) Power fading; (b) SNR degradation.

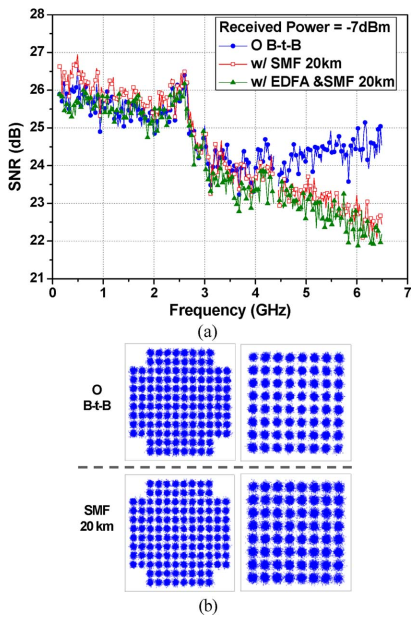

Fig. 4. (a) EAM SNR and (b) constellations before and after fiber transmissions.

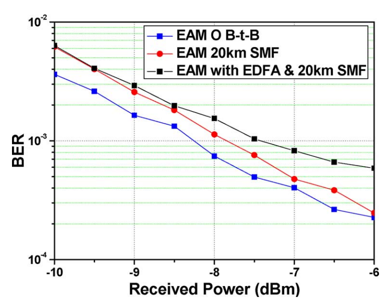

Fig. 5. BER before and after fiber transmissions.

and SNR penalty of each subcarrier after a 20-km SMF transmission. We observe that the experimental results are consistent with theoretical results.

Fig. 4(a) depicts the EAM SNR of each subcarrier at back-to-back and following 20-km SMF transmission with and without an EDFA. The RF fading is intensified after taking into account the frequency chirp from the EAM. Because the fading is more substantial at higher frequency, to compensate the power loss from fading, extra power is given to high-frequency subcarriers. Thus they exhibit better SNR as can be seen from the blue line of Fig. 4(a). However, in the case of 20-km SMF transmission, due to RF fading, the higher frequency subcarriers suffer most and exhibit the lowest SNR. In Fig. 4(b), we plot the constellation of band 1 (128-QAM) and band 2 (64-QAM) before and after fiber transmissions. Fig. 5 shows the BER of EAM at back-to-back and following 20-km of SMF transmissions with and without an EDFA, respectively. The BER of less than 10^{-3} can be obtained at both receiving powers of -8.3 dBm and -7.8 dBm. After using an EDFA, the received power (BER $= 10^{-3}$) is slightly reduced to -7.5 dBm. Furthermore, due to the use of the pre-emphasis algorithm, we observe a negligible transmission penalty. The optical power after Att1 is 14 dBm, thus 21.5-dB optical power budget is obtainable, which can support 20-km SMF and 1:16 optical splitter in an ODSB OFDM PON.

IV. Conclusion

In this letter, we have presented the theoretical study and experimental results of a 40-Gb/s ODSB OFDM transmission system that efficiently employs EAM of 10-GHz bandwidth. Experimental and theoretical results delineate that the power and SNR considerably deteriorate as a result of the frequency chirp from the EAM via the RF fading effect. To compensate the power and SNR degradations of higher frequency subcarrier, we have employed a pre-emphasis algorithm and subcarrier-adaptive modulation format at the transmitter. Experimental results then demonstrate that 40-Gb/s transmission of 20-km SMF and 1:16 optical splitter in an ODSB OFDM PON via EAM is successfully achieved. In the future, we will proceed to adopt the bit loading and pre-emphasis algorithms, which can further improve the bandwidth efficiency and mitigate subcarriers degradation at high frequency.

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