Using single side-band modulation for colorless OFDM-WDM access network to alleviate Rayleigh backscattering effects

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Abstract: In this investigation, we demonstrate a new colorless orthogonal-frequency-division-multiplexing (OFDM) wavelength-division-multiplexing passive optical network (WDM-PON) system with Rayleigh backscattering (RB) noise mitigation. Here, only a single laser source at the central office (CO) is needed to produce the downstream signal and distributed continuous-wave (CW) carrier, which will then be modulated at the optical networking unit (ONU) to produce the upstream signal. Single side-band (SSB) modulation is used to wavelength-shift the distributed CW carrier, which will be launched into a reflective semiconductor optical amplifier (RSOA) based ONU for directly modulation of 5.15 Gbps OFDM upstream signal. To avoid the radio-frequency (RF) power fading and chromatic fiber dispersion, the four-band OFDM modulation is proposed to generate a 40 Gbps downstream when a Mach-Zehnder modulator (MZM) with −0.7 chirp parameter is used. Hence, the RB circumvention can be centralized in the CO. Moreover, the signal performances of downstream and upstream are also studied and discussed in this measurement.

OCIS codes: (060.2330) Fiber optics communications; (060.4250) Networks.

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1. Introduction

Due to the rapid growth of internet, video and data services, broadband fiber access networks with higher data rates and better quality of services develop continuously [1]. The passive optical network (PON)-based access technologies are the promising choice [2, 3]. Presently, Gigabit (G)-PON and Ethernet (E)-PON have been deployed worldwide for broadband services, providing aggregated bandwidth up to 2.5 Gbps [4, 5]. To meet the ever increasing bandwidth requirements from end-users, next generation 10G PONs (i.e. XG-PON and 10G-EPON) with 10 Gbps data capacity have been standardized and deployed [6, 7]. Moreover, future generation of broadband optical access technologies have been proposed and studied with the traffic rate of 40 Gbps and beyond, such as the wavelength-division-multiplexed (WDM)-PON, time- and wavelength-division-multiplexed (TWDM)-PON, orthogonal-frequency-division-multiplexed (OFDM)-PON, or hybrid access PONs [8–11].

Among different access technologies, carrier-distribution is attractive since there is no need of laser source in the cost-sensitive optical networking unit (ONU). However, carrier-distribution would result in the Rayleigh backscattering (RB) and Fresnel reflection (FR) interferometric beat noises, and cause the impairment at the central office (CO) [11, 13]. Therefore, to mitigate the RB noise in colorless WDM access system, several RB mitigation methods have been proposed, such as applying double laser bands source [14], employing wavelength shifting skill [15], utilizing the phase and bias-current dithering [16], or using advanced modulation technique [17]. Generally, these proposed techniques of RB noise mitigation were focused and used in ONU side. However, it would increase the cost for colorless WDM access operation.

In this paper, we propose a new colorless WDM-OFDM PON access architecture to reduce the RB beat noise. In this work, only a single laser source at the CO is needed to produce the downstream signal and distributed continuous-wave (CW) carrier, which will then be modulated at the ONU to produce the upstream signal. Single side-band (SSB) modulation is used to wavelength-shift the distributed CW carrier, which will be launched into a reflective semiconductor optical amplifier (RSOA) based ONU for directly modulation of 5.15 Gbps OFDM upstream signal. To avoid the radio-frequency (RF) power fading and chromatic fiber dispersion, the four-band OFDM modulation is proposed to generate a 40 Gbps downstream when a Mach-Zehnder modulator (MZM) with −0.7 chirp parameter is used. Hence, the RB circumvention can be centralized in the CO, and can reduce the complexity of the ONU when compared with [15]. Besides, a single SSB modulator is needed to wavelength-shift all the distributed CW carriers. Moreover, the signal performances of downstream and upstream are also studied and discussed in this measurement.

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2. Experiment and results

Figure 1 presents the proposed colorless WDM-OFDM PON system for the 40 Gbps four-band OFDM downstream and 5.15 Gbps OFDM upstream transmissions. In the CO, a DFB laser (CW laser) of 1545.04 nm (f_0) connects to a 1 × 2 optical coupler (OCP) for power division into two paths, as illustrated in Fig. 1. Here, the upper part is used to generate a carrier-distributed wavelength to launch into the RSOA-based ONU for upstream modulation. The upper CW wavelength transmits through a WDM multiplexer and a single-sideband modulator (SSB-MOD), which is a commercially available dual-parallel MZM (MZM_1), as seen in Fig. 1(blue line), with the distributed CW carrier is wavelength-shifted by 10 GHz (f_s) away from the original wavelength.

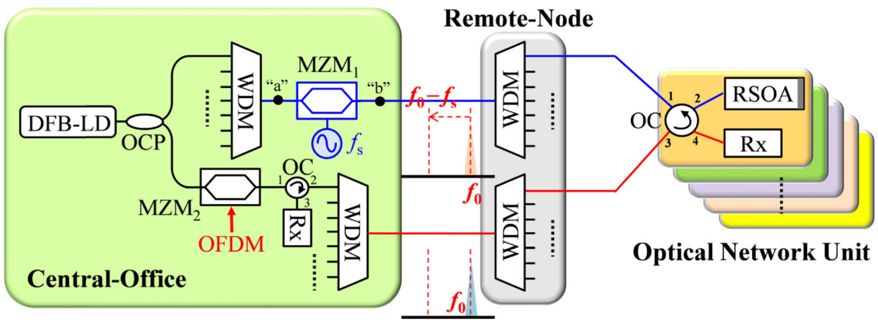

Fig. 1. Experimental setup of proposed colorless WDM-OFDM PON system.

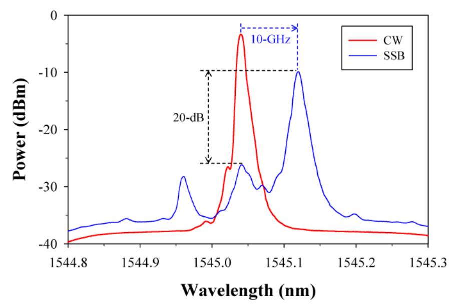

Fig. 2. The output spectra of original CW and SSB carrier-distributed wavelengths.

Figure 2 shows the output spectra of original CW and SSB carrier-distributed wavelengths, which are measured at the points "a" and "b" in the experimental setup of Fig. 1. Here, we can observe the SSB carrier-distributed is wavelength-shifted to 1545.12 nm. Moreover, the side-mode suppression ratio (SMSR) can achieve 20 dB after SSB modulation. Then, the SSB carrier-distributed wavelength could be utilized to launch into each RSOA-based ONU via a 4-ports optical circulator (OC) for upstream modulation, as illustrated in Fig. 1. Therefore, the RSOA can be directly modulated with OFDM-QAM modulation for upstream traffic by employing optical external-injected mechanism. Based on the proposed PON access architecture, the upstream signal could transmit through the lower fiber (red line) via the OC to mitigate RB noise, as also seen in Fig. 1. For simplicity, in this paper, the discrete (Fresnel) reflection is not considered in this work.

Another part of the CW signal generated by the DFB laser in the CO is used to produce the downstream signal. Here, we propose the four-band OFDM modulation applying on MZM_2 to generate 40 Gbps data rate. In the measurement, the band 1 OFDM signal has the bandwidth of 1.526 GHz. The band 2 to band 4 have the same bandwidth of 2.813 GHz and are up-converted in the frequencies of 3.164, 6.055, and 8.945 GHz by employing in-phase

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and quadrature-phase (I-Q) modulation, respectively, as illustrated in Fig. 3(a). And, the RF bandwidths and conversion losses of I-Q mixers from bands 2 to 4 are 1 MHz to 6 GHz, 4 to 8.5 GHz and 6 to 10 GHz, and 7, 7.5 and 7 dB, respectively. Moreover, the OFDM band separations are 0.1315, 0.078 and 0.077 GHz, respectively. Four-band OFDM signals are utilizing the same 16-QAM OFDM modulation 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. Here, the sampling rate and DA/AD resolution are only 5 GS/s and 5-bit respectively to achieve 40 Gbps traffic within 10 GHz bandwidth. The band 1 OFDM signal is consisted of 40 OFDM subcarriers to inhabit 1.526 GHz bandwidth from 82 MHz to 1.626 GHz for creating 6.25 Gbps data rate. The band 2 to band 4 OFDM signals are with 72 subcarriers occupying 2.813 GHz bandwidth to produce the traffic rate of 11.25 Gbps, respectively. Therefore, 40 Gbps total downstream can be accomplished by the proposed four-band OFDM modulation.

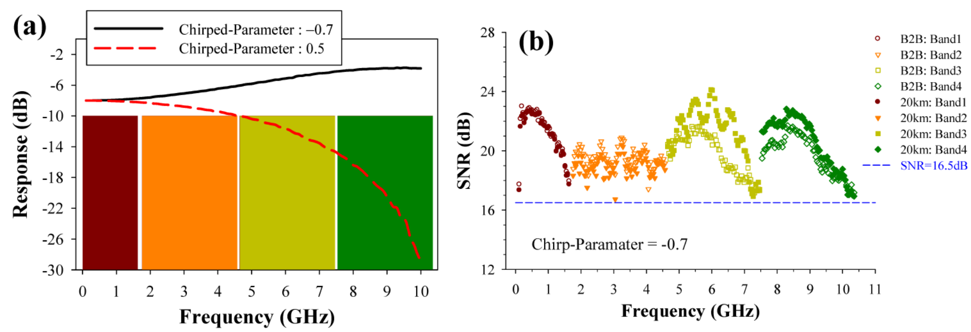

Fig. 3. (a) The observed RF response spectra in 10 GHz frequency bandwidth for four-band OFDM signal, when the 0.53 and −0.7 chirp parameters are used. (b) Measured SNR spectra of 40 Gbps downstream four-band OFDM signal in the B2B and 20 km SMF transmission, while a −0.7 chirp parameter MZM_2 is used.

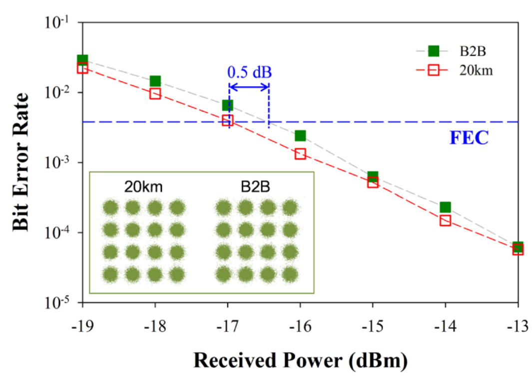

Fig. 4. Measured BER performance of 40 Gbps four-band OFDM downstream traffic at the B2B status and after 20 km SMF transmission. Insets are the corresponding constellation diagrams.

To overcome the power fading and fiber dispersion effects, the MZM_2 with a chirped parameter of −0.7 is employed to enhance the OFDM signal performance. Figure 3(a) presents the numerical analysis of power fading in the frequency range of 0 to 10 GHz, under the chirp parameters of 0.53 and −0.7, respectively, in a 20 km single-mode fiber (SMF) transmission. We observe that the power fading would affect the SNR performance of band 3 and band 4 OFDM signals when a 0.53 chirp parameter is employed, as shown in the dash red line of Fig. 3(a). Hence, the power fading could be improved in a higher frequency range

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while the negative chirp parameter of −0.7 is utilized, as seen in the black line of Fig. 3(a). Therefore, the negative chirp modulator is very imperative for the proposed four-band OFDM modulation to moderate power fading after 20 km SMF transmission. In this measurement, Fig. 3(b) presents the related SNR spectra of 40 Gbps downstream four-band OFDM signal in the back to back (B2B) and 20 km SMF transmission, when a −0.7 chirp parameter MZM_2 is utilized at the −10 dBm received power. By reason of the negative-chirp MZM_2 in this experiment, the measured SNR of each OFDM subcarrier in the band 3 and band 4 are better than that of B2B state, as illustrated in Fig. 3(b). As a result, the obtained SNRs of four-band OFDM signals are larger than the forward error correction (FEC) threshold (SNR = 16.5 dB).

Figure 4 shows the bit error rate (BER) measurement of 40 Gbps four-band OFDM downstream at the B2B status and after 20 km SMF transmission. The receiver sensitivity of −17.4 and −17.0 dBm are obtained at the B2B status and 20 km SMF transmission, respectively. Moreover, the insets of Fig. 4 are the corresponding constellation diagrams at B2B and after 20 km transmission under the FEC threshold (BER = 3.8×10^{-3}). The negative power penalty of −0.4 dB is measured after 20 km SMF transmission when a −0.7 chirp parameter of MZM_2 is employed for four-band OFDM modulation. Use of four-band OFDM signal not only can reduce the power consumption of AD/DA converter, but also can enhance the BER performance due to the better power gain in the higher frequency range. Therefore, the received sensitivity of downstream signal can be enhanced to 0.4 dB after a 20 km SMF transmission. Moreover, the measured back-reflected RB generated by a 20 km SMF is about −30 dB when compared with the input signal. However, as there are insertion losses from the WDM mux/demux at the remote node (or sometimes a fiber splitter is added before each ONU to implement the WDM-TDM-PON), the upstream signal power will be much lower and can be affected by the RB. Hence, the proposed RB mitigation scheme is useful. The more analysis of the bi-directional WDM-PON has also been studied [18].

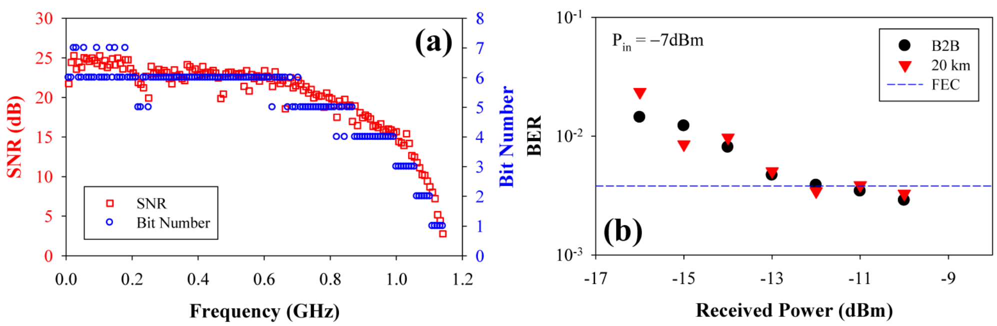

Fig. 5. (a) Measured SNR and bit-number spectra in the 1.1406 GHz frequency bandwidth. (b) Measured BER of upstream signal at the B2B and 20 km SMF transmission, when a −7 dBm injected power launches into RSOA.

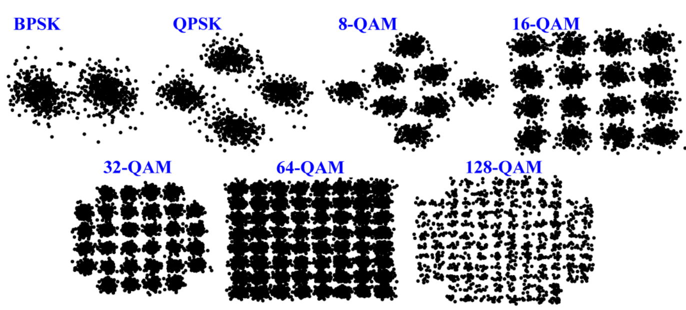

Fig. 6. Related constellation diagrams form BPSK to 128-QAM OFDM formats after a 20 km SMF transmission when the bit-loading OFDM signal is used.

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Then, we evaluate the upstream signal performance when the SSB carrier-distributed signal is launching into a RSOA. Here, the 1.2 GHz RSOA (produced by *CIP*) is employed and the bias current is set at 60 mA. To achieve the better upstream data traffic, the injected power of carrier-distributed signal is set at −7 dBm. Besides, we utilize the OFDM modulation signal with bit-loading algorithm applying onto RSOA via a bias-tee (BT) for direct upstream modulation. First, we use the 16-QAM OFDM format onto RSOA to measure the related SNR performance. Here, the 146 subcarriers of 16-QAM OFDM format occupy ~1.1406 GHz modulation bandwidth with a fast-Fourier transform (FFT) size of 512 and CP of 8. Then, the upstream wavelength signal could be direct detected via a 2.5 GHz PIN Rx. The received OFDM signal is captured by a real-time sampling oscilloscope for signal demodulation. Figure 5(a) presents the measured SNR spectrum in the 1.1406 GHz frequency bandwidth. The obtained SNR of >20 dB is observed between 0 and 0.8047 GHz. And then, the SNR would be dropped rapidly after the frequency of 0.8047 GHz. According to the measured result, we can utilize bit-loading OFDM format within 1.1406 GHz bandwidth for enhancing upstream traffic. Thus, Fig. 5(a) also shows the obtained bit number of 1 to 7 in the effective frequency bandwidth of RSOA, while the OFDM-QAM with bit-loading is applied. This means that the binary phase shift keying (BPSK) to 128-QAM formats can be used for upstream modulation. As a result, the total upstream rate of 5.15 Gbps is completed in this experiment.

Figure 5(b) shows the measured BER performance of upstream signal at the B2B state and after a 20 km SMF transmission, when a −7 dBm injected power launches into RSOA. The received sensitivities of −11.9 and −12.2 dBm are measured at the B2B and after a 20 km SMF transmission. Hence, the 0.3 dB power penalty is achieved for upstream transmission. In this measurement, if the optical injected power is below −7 dBm, the obtained BER could not achieve FEC threshold. In this upstream signal measurement, the measured BER curves of Fig. 5(b) are very close, since the upstream OFDM signal only occupies a 1.1 GHz spectrum. Hence the fiber chromatic dispersion and the power fading effect can be negligible. Here, Fig. 6 shows the related constellation diagrams form BPSK to 128-QAM OFDM formats after a 20 km SMF transmission when the bit-loading OFDM signal is used. Besides, we observe that the measured constellations are close and clear.

3. Conclusion

In summary, we proposed and demonstrated a new colorless WDM-OFDM PON system together with RB noise mitigation. Here, in the CO, only a single laser source was needed to produce the downstream signal and the distributed CW carrier. The SSB modulation was employed to generate a wavelength-shifted CW carrier. 40 Gbps downstream traffic was achieved by using proposed four-band OFDM modulation format. A −0.7 chirp parameter MZM was utilized to compensate the RF power fading and fiber dispersion; and −0.4 dB of negative penalty of downstream could be obtained after a 20 km SMF transmission for enhancement. Moreover, the CW carrier-distributed signal was launched into RSOA-based ONU to directly modulate 5.15 Gbps OFDM upstream with bit-loading. The penalty of upstream traffic was 0.3 dB while the injected power of −7 dBm was launched into RSOA. In this proposed scheme, the RB circumvention can be centralized in the CO, and can reduce the complexity of the ONU. Besides, only a SSB modulator is needed to wavelength-shift all the distributed CW carriers.

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