

16×10Gb/s symmetric WDM-FOFDM-PON realization with colorless ONUs

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Abstract: A novel symmetric WDM-PON scheme with colorless ONU is proposed. The baseband 4-ASK Fast-OFDM signal is upconverted by an intermediate frequency carrier, reserving a frequency gap between the FOFDM signal and the optical carrier. After distributing different wavelengths to corresponding ONU by AWG, periodic BPFs are employed to extract the optical carriers for upstream transmission, achieving colorless ONUs. A WDM-PON system with 16 colorless ONUs is established, and 10-Gb/s symmetric transmission for each ONU is also realized. Experiment shows that the system tolerance to the intrachannel crosstalk is greatly improved when the crosstalk signal locates at relatively higher frequency band.

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1. Introduction

With the great increment of personal communication demand, wavelength-division-multiplexing passive optical network (WDM-PON) technique has been proposed as a promising candidate for the next generation high speed access optical access network [1–3]. However, the optical network units (ONUs) should be colorless (in other words, no ONU is wavelength specific) to decrease the costs of operation, administration, and maintenance functions, as well as the production cost [4], thus, many kinds of schemes for wavelength-reuse (or colorless ONU) are proposed [5–7]. Nowadays, optical orthogonal frequency division multiplexing (OFDM) technique has been introduced into PON applications for its high spectral efficiency (SE) and adaptability to various complex modulation formats [8]. Several schemes have been proposed to apply the OFDM to WDM-PON systems [9–11]. The scheme proposed in [11] skillfully utilizes the steep spectrum edge of OFDM signal and the frequency gap between the intermediate frequency (IF) OFDM signal and optical carrier to transmit the upstream signal, greatly simplifying the ONU structure and avoiding arranging laser source in the ONU. However, since the downstream IF OFDM signal occupies some of the frequency band, the available bandwidth for upstream transmission is greatly limited. Although the 16-QAM modulation format is employed in the 10Gb/s downstream transmission, the bitrate of the upstream OOK signal is only 2.5Gb/s. The asymmetric transmission limits the application of the PON system.

To overcome the disadvantage, in this paper, an optical band pass filter (BPF) is applied in the ONU to suppress the IF downstream signal, so the available bandwidth for upstream transmission is enlarged, as a result, the bitrate for upstream transmission can be greatly increased. To release the requirement for the BPF, fast orthogonal frequency division multiplexing (FOFDM) is for the first time introduced into PON system. Since FOFDM has double SE than conventional OFDM [12], the bandwidth of the baseband FOFDM signal can be half reduced and the frequency gap between the IF FOFDM signal and the optical carrier can also be enlarged. Moreover, the optical BPFs for all ONUs are designed the same with periodic pass bands aligning with the positions of the optical carriers, making the ONUs colorless. Based on the proposed scheme, a WDM-Fast-OFDM-PON system with symmetric 10-Gb/s transmission and 16 colorless ONUs is experimentally demonstrated. Both the downstream and upstream transmission performance in back-to-back (B2B) and 25-km standard single mode fiber (SSMF) situations is evaluated. Experiment also shows that the system tolerance to the intrachannel crosstalk is greatly improved when the crosstalk signal locates at relatively higher frequency band. To the best of our knowledge, this is the first experimental demonstration of the WDM-PON system with so many colorless ONUs and such high symmetric transmission bitrates.

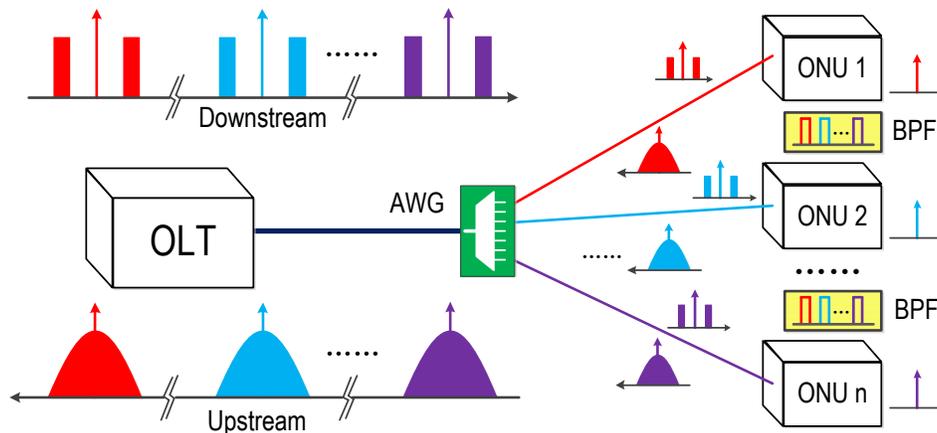


Fig. 1. The architecture of the proposed Fast-OFDM WDM-PON scheme with colorless ONU and symmetric transmission (OLT: optical line terminal, ONU: optical network unit, AWG: arrayed waveguide grating)

2. Principle

The principle of the proposed architecture is described in Fig. 1. The laser sources with equal frequency spacing are used in the optical line terminal (OLT). The baseband FOFDM signal is modulated to an IF carrier before electrical-optical conversion. The bandwidth of the IF FOFDM signal is only half of the conventional OFDM signal, and the frequency gap between IF FOFDM signal and optical carrier is larger. After fiber transmission, an arrayed waveguide grating (AWG) is used to deliver the signal on different wavelengths to the corresponding ONUs. As mentioned above, there is a periodic BPF in every ONU with pass bands aligning with the carrier wavelengths used in OLT. So no matter which wavelength is assigned to the ONU, the optical carrier of the downstream signal will be extracted for generating upstream signal with OOK modulation format. Since the IF FOFDM signal of downstream signal is suppressed by the periodic BPF, there is efficient bandwidth for symmetric upstream transmission. The upstream signals from different ONUs is combined by the AWG and processed in the OLT separately.

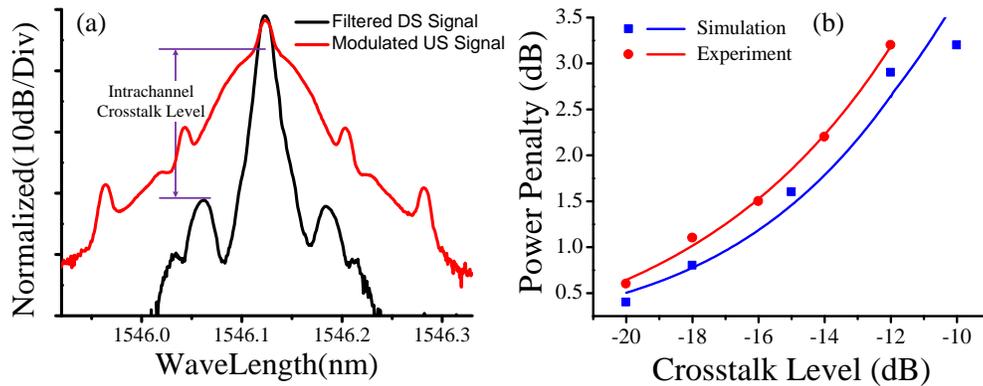


Fig. 2. The impact of the residual intermediate frequency FOFDM signal on the upstream transmission performance. (a): The spectral of the filtered downstream signal and modulated upstream signal (DS: downstream, US: upstream), (b): Upstream BER under different residual upstream signal power

In this scheme, although the frequency gap is enlarged by applying the FOFDM method, after BPF filtering, actually, there will still be some residual power left. Since the residual IF FOFDM signal locates at the same frequency band with the upstream OOK signal, as Fig. 2(a) shows, it can be treated as intrachannel crosstalk which will certainly affect the upstream transmission performance. It is generally believed that the power of the intrachannel crosstalk should be more than 25 dB lower than the signal power to guarantee the signal correctly detected [13] (at the power penalty of about 1dB). In this scheme, to simplify the structure of the ONU, the upstream signal is OOK modulated, while the downstream signal is processed with 4-ASK FOFDM method, so even with same bitrate, the bandwidth of the downstream and upstream signal are quite different. For the OOK upstream signal, the major signal power is located at the lower frequency band, as the red spectrum shown in Fig. 2(a). And because of the application of the IF carrier in the downstream transmission, after BPF in the ONUs, the residual downstream signal will be on the relatively higher frequency band, as the black spectrum shown in Fig. 2(a). In Fig. 2(a), the spectra of both the filtered downstream signal and re-modulated upstream signal on the same wavelength are overlaid, where the power difference between the peaks of the residual downstream signal and re-modulated upstream signal, which is marked in Fig. 2(a), is defined as the intrachannel crosstalk level (in dB). In the experiment, Finisar WaveShaper is employed as a programmable BPF. As the bandwidth of the BPF is turned narrower and narrower, the power of the residual downstream signal also becomes lower and lower. The power penalty in different crosstalk level is measured in both simulation and experiment situations by changing the BPF bandwidth. From Fig. 2(b) it is

clear that in our system, since the crosstalk signal is located at higher frequency band, the tolerance to intrachannel crosstalk of upstream transmission is increased to about -18dB at the power penalty of about 1dB .

3. Experiment setup and results

The schematic diagram of the proposed WDM-PON system is shown in Fig. 3. In the optical line terminal (OLT), the laser source of the downstream transmission for the 16 ONUs is generated by a 16-channel multi-wavelength laser (MWL) with 100GHz channel spacing. The 10-Gb/s 4-ASK FOFDM downstream baseband data is first pre-processed in digital domain and then generated by the Tektronix arbitrary waveform generator 7122B with the sample rate of 20GS/s . A Mach-Zehnder Modulator (MZM) is used to complete the E/O conversion. The spectrum draft of the downstream signal for 16 ONUs is also inserted in Fig. 3. After erbium-doped optical fiber amplifier (EDFA) amplification, the downstream signal for 16 ONUs is coupled into the fiber link. After 25-km SSMF transmission, the signal carried on different wavelengths is separated and delivered to corresponding ONUs by an arrayed waveguide grating (AWG). At each ONU, the received downstream signal is separated into two uneven parts by a $10:90$ coupler. The minority is lead to the PD for downstream signal demodulation after sampled by the Tektronix digital phosphor oscilloscope 72004B with the sample rate of 50GS/s . And the majority is reused by the periodic BPF for upstream transmission. The 10-Gb/s upstream NRZ signal is directly modulated onto the reused optical carrier and sent back to the OLT. After upstream transmission, another EDFA is used to compensate the power loss, and a second AWG is employed to separate the upstream signal on different wavelength from different ONU. At last the BER of the upstream signal for every ONU is calculated by the BER tester (BERT) after PD detection.

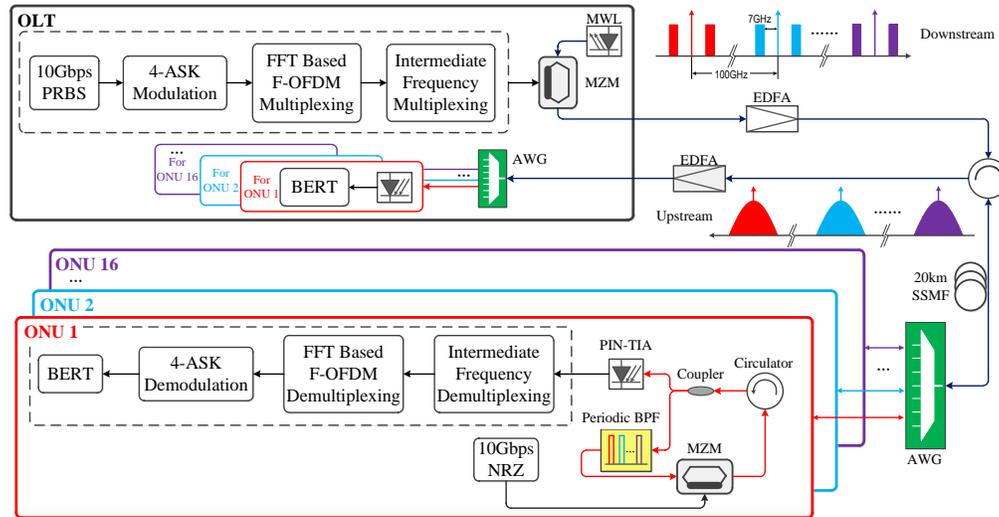


Fig. 3. Experiment setup (ASK: Amplitude Shift Keying, BPF: Band Pass Filter, MZM: Mach-Zehnder Modulator, NRZ: non-return zero, BERT: bit error rate tester, SSMF: standard single mode fiber, EDFA: erbium-doped optical fiber amplifier, MWL: Multi-wavelength laser)

During the experiment, the spectrum of the 16-channel downstream signal is shown in Fig. 4(a). As analyzed in [14], only the real part of the subcarriers in FOFDM signal is orthogonal, so the 10-Gb/s baseband pseudo-random bit sequence (PRBS) signal is 4ASK modulated, guaranteeing the data after baseband modulation still real. To reduce the computational complexity, FFT is applied in FOFDM multiplexing, as the scheme proposed in [14], and the odd and even terms of the 4ASK sequence are separated and processed with IFFT respectively. Then, the two parts are combined after introducing a frequency shift to form the

FOFDM signal. The total number of the subcarriers of the FOFDM signal is 1024, and cyclic prefixes with length of 10 are added at the head of every frame to combat with the chromatic dispersion originated from the fiber transmission. Since the bandwidth of the downstream signal is much narrower than the upstream, to improve the upstream transmission performance, as analyzed in section 2, an 8-GHz digital IF carrier is used to upconvert the baseband FOFDM signal, reserving a frequency gap between the optical carrier and IF FOFDM signal. The spectrum of the downstream signal on carrier of 1552.52 nm is shown in Fig. 4(b). The bitrate of the downstream baseband signal is 10 Gb/s, after 4ASK modulation and FOFDM, the bandwidth of the FOFDM downstream signal is only 2.5 GHz. As a result, the frequency gap between the optical carrier and IF FOFDM signal is about 7 GHz and at the ONUs the optical carrier can be easily extracted by a narrow bandwidth BPF. The normalized spectrum of the periodic BPF is shown in Fig. 4(c), which is achieved by Finisar WaveShaper in this system. The 10-dB bandwidth of the periodic BPF is about 10 GHz and the pass bands of the periodic BPF just align with the positions of the optical carriers. So the ONUs can work independently with wavelength and in this way colorless ONU is achieved. Figure 4(d) shows the spectrum of the downstream signal after periodic BPF on the carrier of 1552.52 nm, where although the downstream signal is filtered by the BPF, the residual downstream IF FOFDM signal still can be observed. But compared with Fig. 4(b), the residual intrachannel crosstalk level is less than -25 dB, so it will have little effect on the upstream transmission. The 10-Gb/s upstream NRZ signal is directly modulated onto the reused optical carrier, and the spectrum of the 16-channel upstream signal is shown in Fig. 4(e). The spectrum of the upstream signal on the carrier of 1552.52 nm is shown in Fig. 4(f), whose bandwidth is 20 GHz.

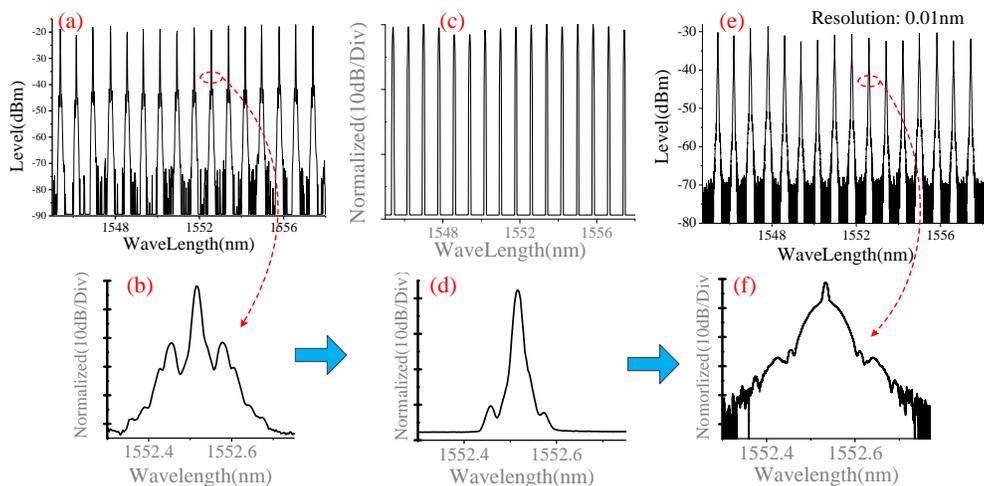


Fig. 4. Spectra of the signals and the periodic BPF in the system. (a): spectrum of the 16-channel downstream signal; (b): spectrum of the downstream signal on the carrier of 1552.52 nm; (c): normalized spectrum of the periodic BPF; (d): spectrum of the filtered downstream signal on the carrier of 1552.52 nm; (e): spectrum of the 16-channel upstream signal; (f): spectrum of the upstream signal on the carrier of 1552.52 nm

Both B2B and 25-km SSMF transmission experiments are carried out to evaluate the performance of the system. The signal on the carrier of 1552.52 nm is taken as an example for downstream transmission and the BER curves are depicted in Fig. 5(a). The special shape constellations of the 4ASK FOFDM signal are also inserted, where in horizontal the points are divided into four parts according to the 4ASK modulation, and in vertical the points are disordered because the imaginary part of the subcarriers in FOFDM is not orthogonal. The signals on the carriers of 1549.32 nm, 1550.12 nm, 1550.92 nm and 1551.72 nm are chosen for upstream and the BER curves are depicted in Fig. 5(b). The eye diagrams are also inserted,

the upper one is for B2B situation and the lower for 25-km transmission situation, which are good enough for detection. Since BER of the upstream signal is real-time tested by BERT, while the demodulation and analysis of the downstream signal is processed offline, limited by the memory depth of the DPO, the lower limit of the BER of downstream is about 10^{-6} .

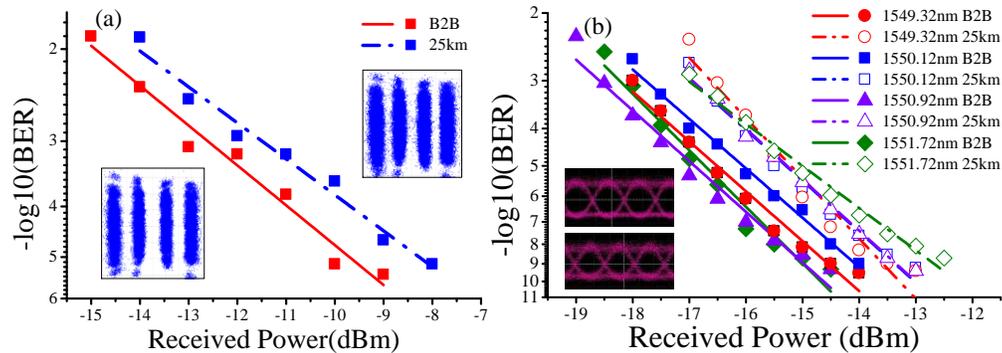


Fig. 5. BER curves of downstream signal and upstream signal in both back to back and 25km transmission situation

4. Conclusion

In this paper, a novel WDM-PON scheme with colorless ONU and symmetric transmission is proposed and experimentally demonstrated. An 8-GHz IF carrier is used to upconvert the FOFDM signal and reserve a 7-GHz frequency gap between the IF FOFDM signal and optical carrier, so the optical carrier be easily extracted. At the ONU, a periodic BPF with 10 dB bandwidth about 10 GHz and pass bands aligning with the positions of the optical carriers is employed and the downstream optical carrier is extracted and reused for upstream transmission, making the ONUs colorless. Based on the proposed scheme, a 10-Gb/s symmetric transmission system with 16 ONUs is successfully established. And the experiment also shows that the tolerance to intrachannel crosstalk of upstream transmission is greatly increased by upconverting the baseband FOFDM signal to higher frequency band.

In the demonstrated experiment setup, in order to change the bandwidth of the BPF flexibly, the BPF of the ONUs is achieved by Finisar Waveshaper, which is not very cost-effective in practical application. In fact, it is not difficult to realize a periodic BPF with 10dB bandwidth about 10GHz by F-P cave or fiber Bragg Gating (FBG). And what is more, the periodic BPFs for different ONUs are completely the same, which makes the fabricating of the BPF easier and cheaper. So it is expected that the proposed scheme will be more practical with cost-effective periodic BPFs.

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