A WDM passive optical network enabling multicasting with color-free ONUs

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Abstract: We propose a wavelength-division-multiplexed (WDM) passive optical network (PON) to provide conventional unicast data and downstream multicast function. At the optical line terminal (OLT), for each WDM channel, a dual-drive Mach-Zehnder modulator (DDMZM) is used to generate a sub-carrier double-sideband differential-phase-shift-keying (DPSK) signal. All the central carriers are separated and subsequently modulated to deliver the multicast data, while the remaining sub-carrier DPSK signals carry the downstream unicast traffic. In the optical network units (ONUs), part of the downstream unicast signal power is re-modulated for upstream transmission, which enables source-free ONUs. The proposed scheme is experimentally demonstrated with 1.25-Gb/s downstream unicast, multicast and upstream data.

OCIS codes: (060.4510) Optical communications; (060.4255) Networks, multicast; (060.5060) Phase modulation.

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1. Introduction

The wavelength-division-multiplexed (WDM) passive optical network (PON) has been recognized as an attractive solution to provide broadband access for the next-generation networks. These networks need to provide diverse services such as video-on-demand and

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high-definition television (HDTV) broadcasting. Recently, several approaches have been proposed to enable broadcasting [1-6] or multicasting [7-9] function in WDM-PONs. The broadcast service can be multiplexed with conventional unicast traffic by time-division multiplexing, which suffers from complicated scheduling and reduced bandwidth. Additional light sources can also be used for the broadcast capability [1-4, 7], which increase the cost and complexity. In [5], a number of WDM multiplexers and interleavers are required in the optical line terminal (OLT) and the remote node (RN). Other schemes are proposed by using subcarrier multiplexing [6, 8] or hybrid modulation format [9], requiring high-frequency electrical components at the optical network unit (ONU), or experiencing the interference between the two formats in downstream delivery, respectively.

In this paper, we propose and demonstrate a novel selective broadcasting or multicasting capable WDM-PON with colorless ONUs. In the OLT, for each WDM channel, the downstream unicast data mixed with a clock is applied to one arm of a dual-drive Mach-Zehnder modulator (DDMZM), to generate a downstream sub-carrier differential-phase-shift keying (DPSK) signal; while a control signal is applied to the other arm of the DDMZM to switch on/off the optical carrier for multicast modulation. The optical carriers in all WDM channels are separated by a single interleaver and then modulated by an intensity modulator (IM) to deliver the downstream multicast data. At the ONU side, the received unicasting sub-carrier DPSK signal is re-modulated as the upstream carrier before sent back to the OLT [5], which eliminates the need of laser sources or colored components in the ONUs.

This proposed scheme shows several attractive features: (1) it provides a flexible multicast overlay over the conventional unicast service in WDM-PON; (2) no high-frequency electrical components are needed in the ONUs; (3) the multicast function supports fast and dynamical reconfiguration with centralized control in the OLT; (4) the downstream multicast and unicast data transmissions differ in both frequency and modulation format, which reduces the inference between them.

2. Operation Principle of Proposed WDM-PON

Figure 1 shows the architecture of the proposed WDM-PON with multicast function. In the OLT, the downstream carrier of each wavelength channel is generated by a continuous-wave (CW) laser, and then modulated by a DDMZM. The alternating current (AC) coupled downstream data is mixed with a radio frequency (RF) clock to produce an electrical sub-carrier multiplexed (SCM) signal, which drives one arm of the DDMZM. On the other arm a control signal is applied to switch the multicasting carrier on or off.

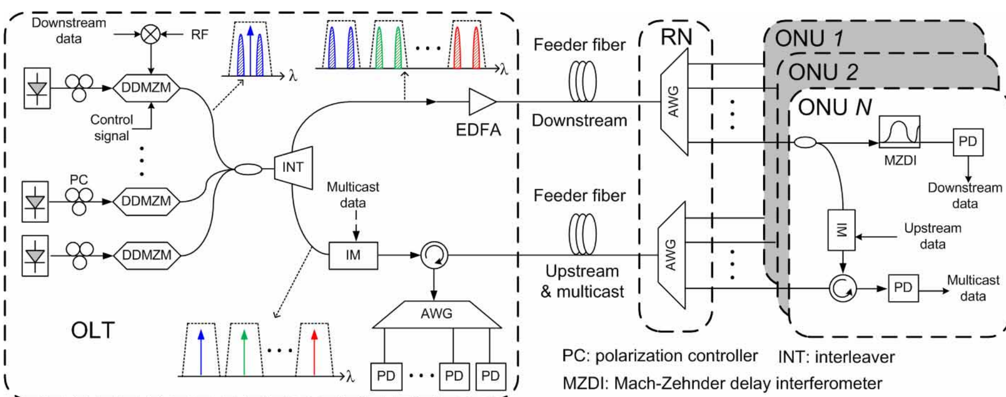

Fig. 1. Architecture of the proposed WDM PON with multicasting capability.

Figure 2 depicts the operation principle of the downstream signal generation and control employing the DDMZM. As each arm of the DDMZM is a phase modulator, if one arm is driven by a mixed signal of bipolar data and RF clock signal, an optical double-sideband

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(DSB)-DPSK signal is generated, as shown in Fig. 2. The other arm of the DDMZM is driven by a direct current (DC) control voltage to obtain an un-modulated optical carrier. If there is a phase difference of π between the optical carrier from the lower arm and the central carrier of the DSB-DPSK signal from the upper arm, after destructive interference the output of the DDMZM is an optical carrier suppressed (OCS)-DPSK format. Consequently, by simply adjusting the DC voltage, it can dynamically control the presence of the central optical carrier; thus switch the output between the DSB-RF-DPSK and the OCS-DPSK signal.

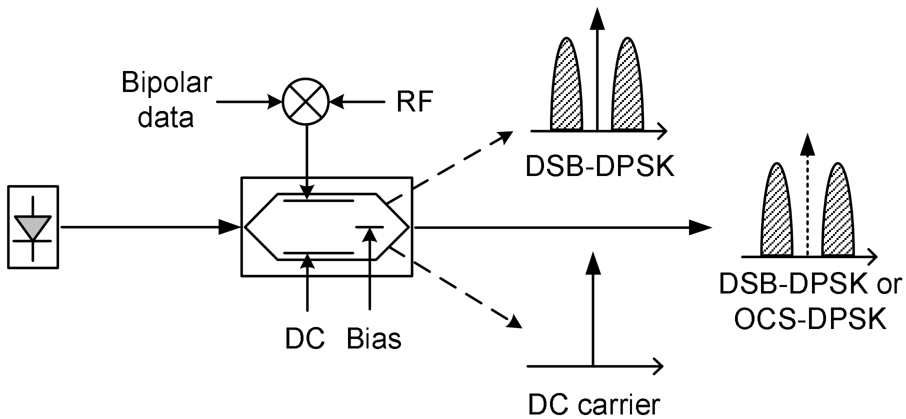

Fig. 2. Principle of the downstream signal generation and control.

The generated downstream signals from all the WDM channels are combined and coupled into one fiber through an arrayed waveguide grating (AWG) or an N×1 coupler as shown in Fig. 1, and subsequently sent into an interleaver. The un-modulated optical carrier in each channel is separated from the subcarrier DPSK signal and then modulated by the multicast data. Through a circulator, the multicast signals are launched into a feeder fiber shared by the upstream and the multicast traffic. After transmission they are demultiplexed in the RN and then routed to the ONUs. Therefore, when the multicast optical carriers of some channels are switched on in the OLT, the corresponding ONUs are able to receive the multicast signals. On the other hand, the multicast signals for certain ONU users can be disabled by simply switching off their multicast optical carriers. Thus, the multicast signals can be selectively and dynamically delivered to end users. The fast switchable multicast overlay enables more flexible services in the WDM-PON. For example, several HDTV programs can be time-division multiplexed into a stream of high-speed multicast data; with proper control the OLT can deliver each program to its subscribers in individual time slot.

In the OLT, from the other output port of the interleaver, all the downstream unicast signals in OCS-DPSK format are pre-amplified and then injected into the downstream feeder fiber. Through the RN, the downstream unicast channels are demultiplexed and delivered to the corresponding ONUs. In the ONU, the received OCS-DPSK signal is firstly split into two parts: one is demodulated by a 1-bit Mach-Zehnder delay interferometer (MZDI) followed by a low-speed photodetector (PD); the other part of the unicasting power is fed into an MZM for upstream data remodulation and redirected to the OLT through a circulator. Thus no lasers or colored components are needed for upstream transmission. Note that the upstream and the multicast signal travel in opposite directions in the same feeder fiber. However, since the upstream data are carried on the two sidebands, while the multicast data are on the baseband, they do not experience interference from Rayleigh backscattering. The bandwidth of the multicast data is limited by the spacing between the two sidebands, i.e. the frequency of the RF signal, to avoid overlapping in spectrum.

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3. Experiment

In this section, we experimentally demonstrate the feasibility of the proposed WDM-PON enabling multicasting to ONUs.

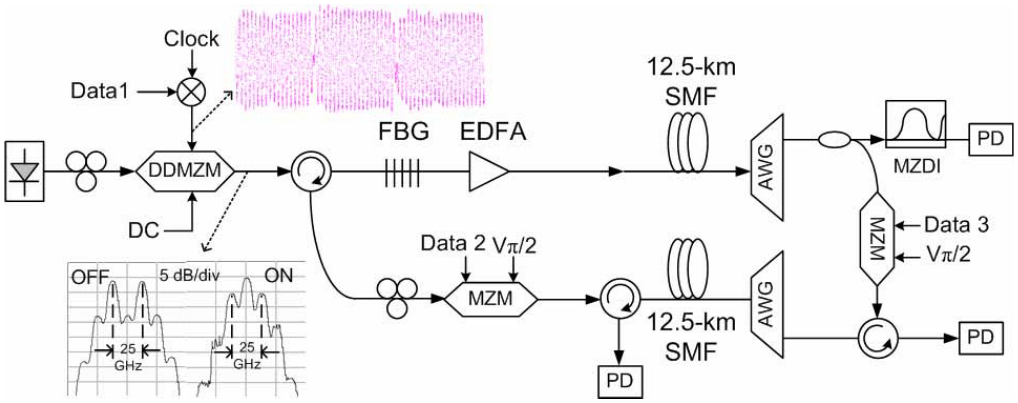

Fig. 3. Experimental setup.

Figure 3 shows the experimental setup. The downstream unicast, multicast and upstream data, are marked as Data 1, Data 2 and Data 3 in Fig. 3, respectively. All the three signals are 1.25-Gb/s non-return-to-zero (NRZ) data streams with a pseudo-random bit sequence (PRBS) length of 2^{31}-1 from three independent sources. The bipolar unicast data is mixed with a 12.5-GHz clock signal to generate an electrical SCM signal, whose waveform is the inset in Fig. 3. Then it drives one arm of the DDMZM to obtain an optical DSB-DPSK signal. By changing the DC voltage on the other arm of the DDMZM, it is easy to control the central carrier amplitude in order to switch the multicasting on or off. In the inset spectra in Fig. 3, when the central carrier is suppressed, the power decreases nearly 15 dB compared with when it is on. Since the spacing between the two sidebands is 25 GHz, a 12.5/25 GHz interleaver is needed to separate the carriers from the sideband signals. Here we use a fiber Bragg grating (FBG) with a 3-dB bandwidth of 0.114 nm and connected with a circulator to mimic the filtering effect of an interleaver for one WDM channel. In practice, RF carrier with higher frequency could be used to increase the downstream unicasting data bandwidth and relax the narrow bandwidth requirement on the interleaver.

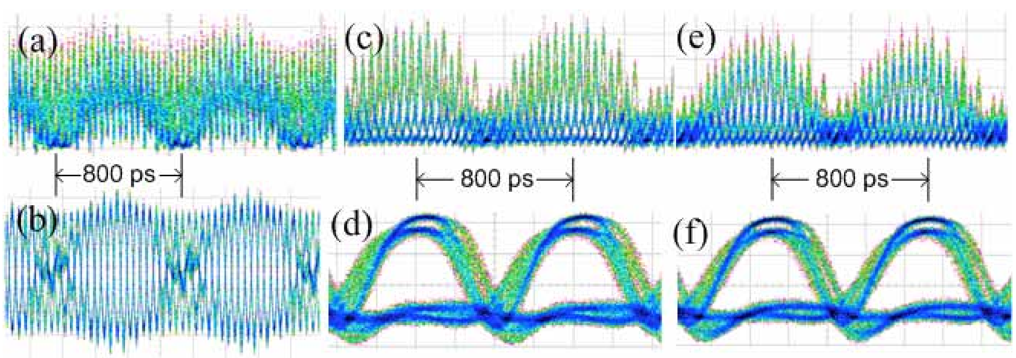

Fig. 4. Eye diagrams of (a) the OCS-DPSK signal and (b) the electrical driving signal after mixing; back-to-back eye diagrams of the demodulated OCS-DPSK (c) before detection and (d) after detection; eye diagrams of the demodulated OCS-DPSK through transmission and (e) before detection and (f) after detection.

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After the filtering, the downstream OCS-DPSK signal with a 25-GHz repetition rate is obtained (Fig. 4(a)). The intensity envelope shows a periodicity of 800 ps, equaling to the period of one bit of the 1.25-Gb/s data. Figure 4(c) indicates the eye diagram at the destructive output port demodulated by an MZDI. After detection by a low-speed PD with a 2.5-GHz bandwidth, the 25-GHz oscillation is filtered and a clear electrical eye diagram is obtained in Fig. 4(d). Figure 4(e) and (f) provide the corresponding optical and electrical eye diagrams after 12.5-km transmission, respectively. When the multicasting signal switches off, the sideband-to-carrier ratio (SCR) of the OCS-DPSK signal is more than 17 dB. Otherwise, the SCR decreases to 10 dB with the multicasting signal on. The bit-error-rate (BER) performances in Fig. 5(a) indicate that less than 0.5-dB penalty is caused by the transmission in both cases, and the performance degradation induced by the SCR reduction is less than 0.5 dB. Furthermore, we investigate the influence by the SCR on the performance of the OCS-DPSK signal. Figure 5(b) shows the sensitivity of the OCS-DPSK signal for various SCRs. The results indicate that the sensitivity is degraded by ~1 dB with an SCR of 5 dB, and the penalty increases to ~3 dB as the SCR decrease to 0 dB. When the SCR decreases, more power is allocated to the central carrier rather than the OCS-DPSK signal. Therefore the received power to achieve the same BER performance increases.

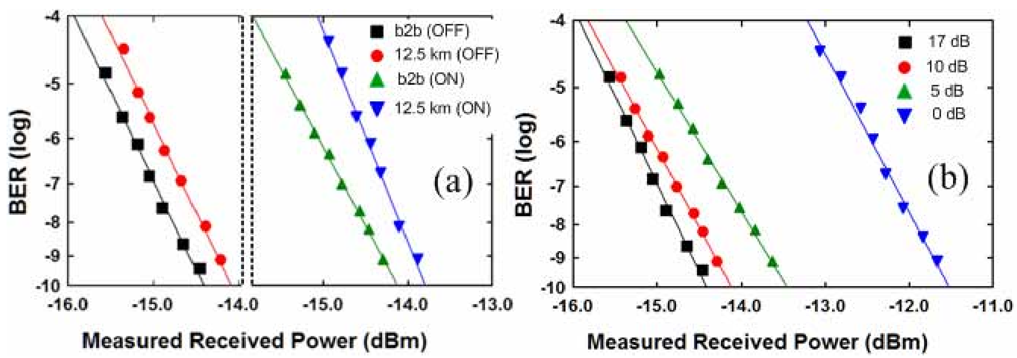

Fig. 5. (a) BER measurements of downstream unicast signal; (b) BER measurements of OCS-DPSK signal for various sideband-to-carrier ratios.

Figure 6(a) shows the BER measurements of the upstream signal. Due to the 25-GHz oscillation of the downstream OCS-DPSK signal, the upstream NRZ signal has a fluctuating '1' level as shown in the inset (i) of Fig. 6(a). After detection by a 2.5-GHz PD, the electrical eye diagram opens as provided in inset (ii) of Fig. 6(a). The inset (iii) and (iv) of Fig. 6(a) show the optical and electrical eye diagrams, respectively, after 12.5-km transmission. Less than 1-dB penalty is observed. In the ONU, a reflective semiconductor optical amplifier could be used to achieve polarization-insensitive modulation and power boosting [6].

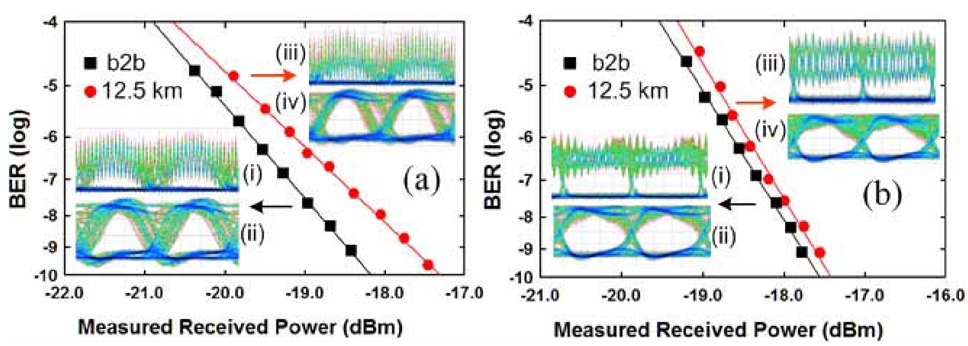

Fig. 6. BER measurement of (a) the upstream signals and (b) the multicast signals with eye diagrams.

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For the multicasting transmission, the residual modulation on the central carrier by the RF signals attributes to the fluctuations on the optical signals after the multicast NRZ modulation as shown in the inset (i) of Fig. 6 (b). Similar to the upstream case a 2.5-GHz PD filters out the high-frequency residual modulation as shown in the inset (ii) of Fig. 6 (b). After 12.5-km transmission in the feeder fiber, the optical and electrical eye diagrams are provided in Fig. 6(b) as inset (iii) and (iv). The BER performances in Fig. 6(b) depict that the multicast traffic suffers negligible penalty through the 12.5-km transmission. In the experiment, the multicast power is ~0 dBm before injected into the feeder fiber with multicasting function on. When the multicast is off, the received power is less than -18 dBm.

4. Conclusion

We have proposed and experimentally demonstrated a WDM-PON architecture to provide downstream multicasting service over the conventional unicast data service without additional light carrier. OCS-DPSK and NRZ formats are used for the downstream unicasting and multicasting transmission, respectively. The multicast function for all channels can be quickly and dynamically reconfigured with simple and centralized control in the OLT. By employing re-modulation technique, no light sources and colored components are needed in the ONUs, which effectively reduce the cost and complexity.

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