Novel WDM-PON architecture for simultaneous transmission of unicast data and multicast services

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We propose a novel wavelength-division multiplexed passive optical network (WDM-PON) to simultaneously transmit unicast data and multicast services with upstream data re-modulation in optical network units (ONUs). For each wavelength channel in the optical line terminal (OLT), the downstream unicast data are applied to one arm of a dual-parallel Mach-Zehnder modulator (DPMZM) to generate baseband unicast non-return-to-zero (NRZ) signal. A radio frequency (RF) control signal is applied to the other arm to present two un-modulated sidebands for multicast data modulation in a differential phase-shift keying (DPSK) format. The flexible and dynamic multicast services are realized by simply switching the RF control signal on or off. The proposed scheme is experimentally demonstrated with 1.25-Gb/s downstream unicast, multicast, and upstream data.

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Wavelength-division multiplexed passive optical network (WDM-PON) is regarded as a promising broadband access solution because of its almost unlimited bandwidth, network security, simple management, and upgradeability[1,2]. In WDM-PON, some customers may subscribe to diverse services, such as high-definition television (HDTV) and video-on-demand (VoD), for a particular period of time. The simultaneous delivery of point-to-multipoint multicast video services and conventional unicast data in WDM-PON has been studied[3−7], and reports are grouped into two categories: in-band transmission, where the multicast data are orthogonally modulated onto unicast signals by adjusting extinction ratios (ERs) of the unicast signals[3,4], or dynamically converting unicast data modulation format[5], which requires complicated timing and synchronization, and out-of-band transmission. In the latter category, multicast data in the sub-carrier multiplexing (SCM) format are overlaid on the baseband unicast data with the amplitude shift keying (ASK) modulation in the same wavelength channel by adjusting dynamically the ER of the unicast ASK signals[6,7] which requires high-frequency electronic components at both the transmitter and receiver sides.

In this letter, we propose and demonstrate a novel WDM-PON to deliver the downstream unicast data and multicast services simultaneously along with upstream data re-modulation in optical network units (ONUs). For each wavelength channel in the optical line terminal (OLT), the downstream unicast data are applied to one arm of a dual-parallel Mach-Zehnder modulator (DPMZM) to generate unicast non-return-to-zero (NRZ) signal carried on the optical baseband carrier, and a radio frequency (RF) control signal is applied to the other arm to produce two un-modulated optical sidebands for subsequent multicast data modulation in differential phase-shift keying (DPSK) format. By simply switching the RF control signal on or off in each wavelength channel, the multicast data can be enabled to realize a flexible and dynamic multicast overlay. The upstream data re-modulation based on the downstream baseband NRZ unicast signal is also demonstrated experimentally in ONUs.

The proposed WDM-PON architecture with SCM multicast overlay is shown in Fig. 1. In the OLT, the downstream carrier of each wavelength channel is generated by a continuous-wave (CW) laser and is modulated using a DPMZM[8]. The DPMZM consists of a pair of x-cut $LiNbO_3$ Mach-Zehnder modulators (MZMs) embedded in the two arms of a main MZM structure. The DPMZM has three bias ports that belong to the two sub-MZMs and the main modulator. The downstream unicast data are then applied to one arm of a DPMZM, to generate a downstream unicast NRZ signal with a lower ER, and a RF control signal is applied to the other arm of the DPMZM to switch two un-modulated optical sidebands on or off. These optical double-sideband signals in all wavelength channels are then coupled using an arrayed waveguide grating (AWG) and subsequently modulated through a phase modulator (PM), which is driven by the multicast data to overlay a multicast DPSK signal on the optical sub-carriers. The multicast data are also superimposed onto the optical baseband carrier in the baseband carrier; however, the multicast data are not recovered in the ONU. Hence, the multicast and unicast data transmissions differ in both frequency and modulation formats, thereby avoiding the bit synchronization between them.

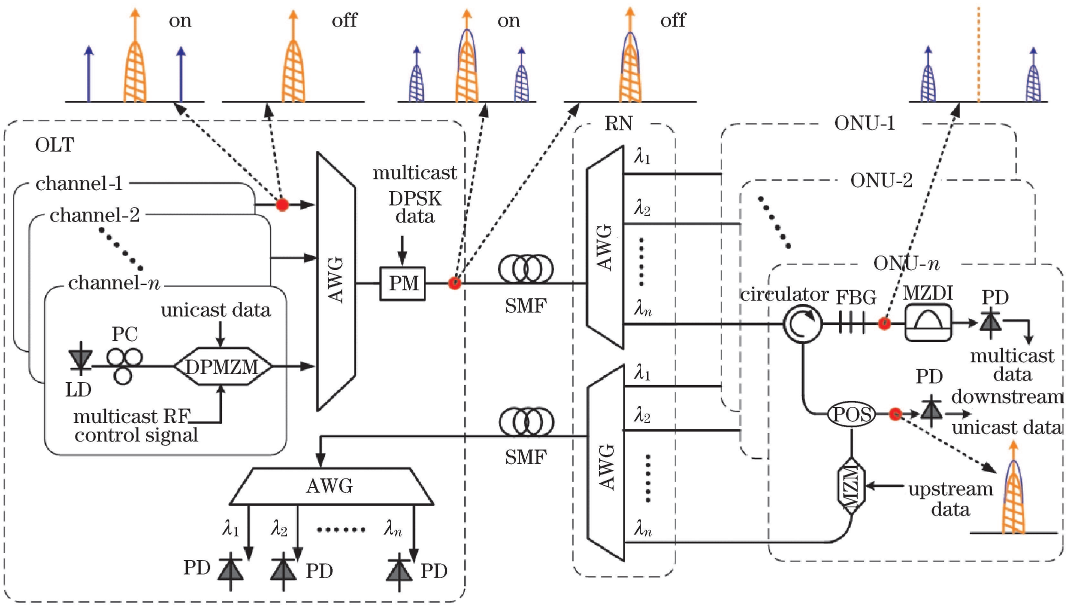

Fig. 1. Schematic diagram of the proposed WDM-PON architecture with SCM multicast overlay. PC: polarization controller; LD: laser diode; SMF: single mode fiber; POS: power of splitter.

When an ONU on a wavelength makes a request for multicast services, the RF control signal on the corresponding wavelength channel is switched on, allowing the simultaneous modulation of multicast data on the optical sub-carriers. To disable the multicast data for a designated ONU user, the RF control signal can be simply switched off and consequently, the optical sub-carriers for multicast data modulation do not exist. Thus, the multicast data can be transmitted to destined ONU users flexibly and dynamically by simply switching the RF control signal on or off in the OLT.

After transmission, an AWG in the remote node (RN) is used to de-multiplex the downstream wavelengths and route them to individual ONUs. At the ONU, a circulator and fiber Bragg grating (FBG) are used to separate the downstream unicast NRZ data and the multicast DPSK data on different spectra. The multicast data are demodulated using a 1-bit Mach-Zehnder delay interferometer (MZDI) followed by a low-speed photo-detector (PD). The baseband optical carrier is then filtered and split into two parts, one is detected using a PD receiver for downstream unicast data, while the other part of the baseband carrier power is fed into a single drive MZM for upstream data re-modulation and is sent back to the OLT through another feeder fiber. In this way, an ONU module without a light source deployment, which is an attractive feature of PON deployment, could also be implemented. All the multicast control intelligence data are deployed at the OLT by simply switching the RF control signal on or off. Given that the RF control signal is transparent to all ONUs, the system can thus be considered a cost-effective solution.

To verify the feasibility of the proposed WDM-PON with SCM multicast overlay, we performed an experiment shown in Fig. 2. In the OLT, a CW light with the wavelength of 1561.16 nm was fed into a DPMZM. One arm of the DPMZM was biased at the transmission null point and was driven by 1.25-Gb/s data with a pseudo-random bit sequence (PRBS) length of $2^{31}-1$ to generate downstream unicast NRZ signal with the lower ER around 3 dB. The 12.5-GHz RF control signal was applied on the other arm of DPMZM also biased at the

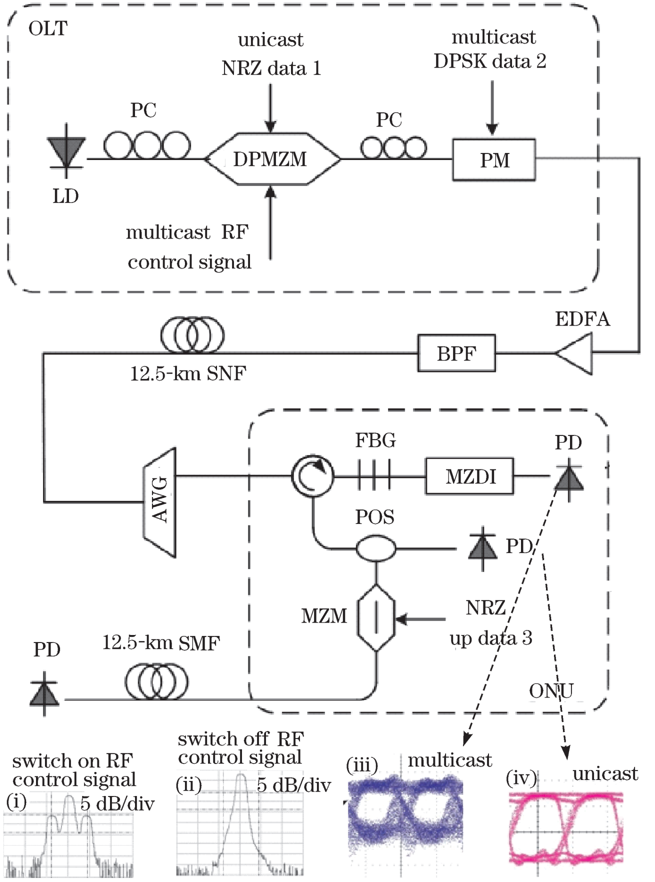

Fig. 2. Experimental setup of the proposed WDM-PON with SCM multicast overlay.

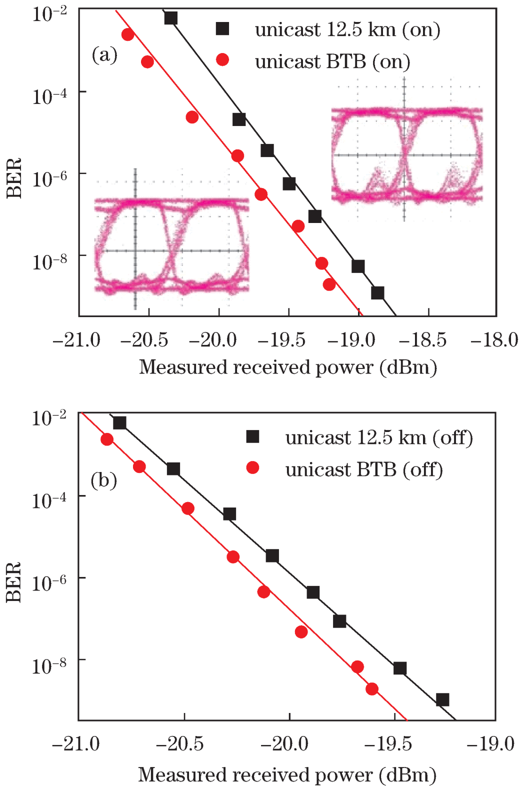

Fig. 3. BER curves and eye diagrams: downstream unicast NRZ signals when the RF control signal is (a) switched on and (b) switched off.

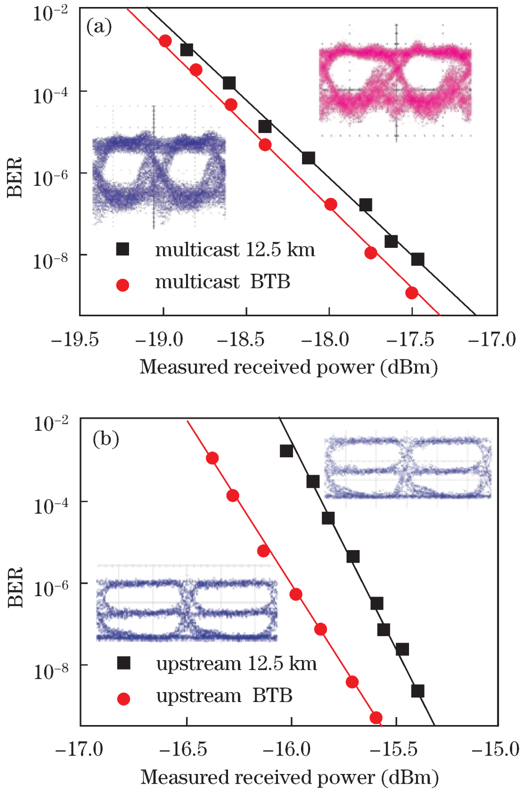

Fig. 4. BER curves and eye diagrams: (a) multicast DPSK data and (b) upstream re-modulated NRZ signal.

transmission null point; switching it on or off made it easy to control the presence of two un-modulated sub-carriers. The bias of main MZM structure was adjusted to obtain zero phase difference between the two arms of the modulator. The two signals from two sub-MZMs were combined constructively to achieve a double-sideband signal at the output port of the main modulator. Another PM was driven by another 1.25-Gb/s $2^{31}-1$ PRBS to generate multicast DPSK signal carried on the two optical sidebands. When the RF control signal was switched on, an optical double-sideband signal, including a baseband carrier and two sub-carriers, was turned out and the sideband-to-carrier ratio (SCR) was nearly 10 dB (Fig. 2, inset (i)). Otherwise, only the optical baseband carrier was displayed with the multicast services switched off (Fig. 2, inset (ii)). Given that the unicast and multicast data differ in optical spectra, the synchronization between both data was not necessary. The output from the PM was amplified by an erbium-doped fiber amplifier (EDFA) and filtered by a tunable band-pass filter (BPF) with the bandwidth of 0.4 nm before a 12.5-km single mode fiber (SMF) transmission.

In the ONU, an optical circulator was connected to a FBG with a 3-dB bandwidth of 0.15 nm and a 90% reflection ratio. The FBG was used to reflect the baseband optical carrier of unicast NRZ data and bypass the two sideband optical carriers for multicast DPSK data. After being demodulated by 1-bit MZDI, followed by a low speed PD with a 2.5-GHz bandwidth, the 25-GHz oscillation of the SCM multicast data was filtered, and the electrical eye diagrams of multicast data are displayed (Fig. 2, inset (iii)). The reflected optical power of the baseband NRZ signal was split into two parts using a power of splitter (POS). One half was converted into an electrical signal using a 2.5-GHz PD receiver. The detected electrical eye diagrams of downstream unicast NRZ data are shown in Fig. 2, inset (iv). The other half of baseband power was used for 1.25-Gb/s upstream data re-modulation in the NRZ format with the higher ER of around 10 dB and then sent back to the OLT, where it was detected by a PD.

The bit-error-rate (BER) measurement results are presented in Figs. 3 and 4. For the downstream unicast NRZ data when the RF control signal is switched on and off, the power penalties are ~0.27 and ~0.23 dB, respectively. The detected electrical eye diagrams are also respectively provided in insets of Fig. 3 in the two transmission cases. For the multicast DPSK signal on the two optical sidebands, the power penalty is ~0.2 dB; the eye diagrams are shown in Fig. 4(a). The BER performance of upstream re-modulated NRZ signal shown in Fig. 4(b) indicates that the upstream transmission suffered a ~0.35-dB penalty due to the dispersion. The eye diagram of upstream data for back-to-back (BTB) transmission and after the 12.5-km SMF transmission are also displayed in the inset of Fig. 4(b).

To verify the feasibility of the downstream link, a power budget analysis for the downstream unicast and multicast data was carried out using the modulated optical power of around −14 and −16 dBm, respectively (Table 1). In this analysis, EDFA gain reached about 30 dB in the OLT. The total losses consist of a 3-dB BPF loss, a 6-dB insert loss for phase modulator, a 5-dB insert loss for AWG, a 2.8-dB transmission loss for a 12.5-km optical fiber, a 0.8-dB insert

Table 1. Power Margin Calculation for Downstream and Upstream Data

	Downstream Unicast Data	Multicast Data	Upstream Unicast Data
Modulated Power at OLT (dBm)	−14	−16	–
Modulated Power at ONU (dBm)	–		−19
EDFA Amplifier Gain (dB)	30	30	30
BPF Loss (dB)	3	3	3
Phase Modulator Loss (dB)	6	6	–
AWG Insertion Loss (dB)	5×2[a]	5×2[a]	5×2[a]
12.5-km SMF Loss (dB)	2.8	2.8	2.8
Circulator Insertion Loss (dB)	0.8	0.8	–
FBG Insertion Loss at ONU (dB)	0.6	0.6	–
Splitter Insertion Loss at ONU (dB)	3	–	–
MZDI Insertion Loss at ONU (dB)	–	6	–
Insertion Loss (dB)	26.2	29.2	15.8
Receiver Sensitivity (dBm)	−18.85	−17.25	−15.35
Power Margin (dB)	8.65	2.05	10.55

[a] "×2" means the optical singal experiences the loss twice.

loss for the optical circulator, a 0.6-dB FBG insert loss, a 6-dB insertion loss for MZDI, and a 3-dB splitter insertion loss at ONU. Consequently, in the upstream power budget analysis, a re-modulated upstream unicast signal showed an optical power of around −19 dBm, according to the received downstream power. According to the experiment data, the receiver sensitivity of the downstream unicast data, multicast data, and upstream unicast data are −18.85, −17.25, and −15.35 dBm, respectively (Figs. 3(a), 4(a), and 4(b)). The power margin of about 8.65, 2.05, and 10.55 dB are obtained for downstream unicast data, multicast data, and upstream signal, respectively, indicating the feasibility of the larger transmission scope in the proposed WDM-PON.

In conclusion, we propose a novel WDM-PON to transmit conventional unicast data and point-to-multipoint multicast services simultaneously using upstream data re-modulation in ONUs. The baseband optical carrier bears the downstream unicast NRZ data, and the two optical sub-carriers only carry multicast DPSK data. The multicast function for all wavelength channels can be reconfigured quickly and dynamically through simple and centralized management in the OLT. The feasibility of the proposed WDM-PON architecture is demonstrated experimentally with 1.25-Gb/s downstream unicast/multicast data and 1.25-Gb/s upstream re-modulated signal.

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