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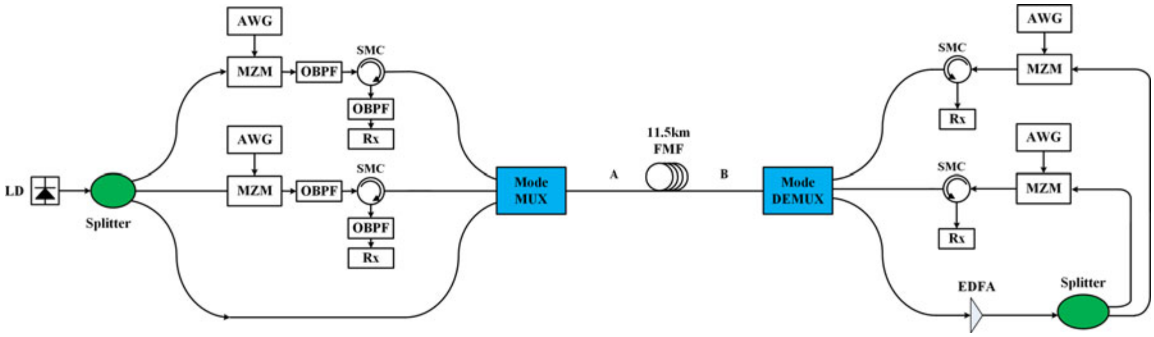

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Abstract: Wavelength reuse has been proposed as an effective solution to realize colorless optical network units (ONUs) for next-generation passive optical network with simplified maintenance and reduced cost. In this paper, we propose a wavelength reused mode-division-multiplexing (MDM) scheme for bidirectional short-reach optical access network with low mode-crosstalk multiplexer/demultiplexer (MUX/DEMUX) and few-mode fiber (FMF). In downstream (DS) transmission, one of the spatial modes in FMF is used to transmit optical carriers, while the others are used as DS signal channels. In upstream (US) transmission, the carrier is split to all the ONUs for US remodulation. By utilizing low mode-crosstalk mode MUX/DEMUX and FMF, the carrier and each signal channel can be effectively separated. Compared with other wavelength reused schemes in which the DS and US transmission are modulated in orthogonal dimension, the signal qualities on two transmission directions are independent in the proposed scheme, and symmetrical bidirectional transmission without residual remodulation crosstalk can be achieved. What is more, to reduce bidirectional Rayleigh backscattering noise, we propose to use different optical sidebands for DS and US transmission. With the proposed scheme, we experimentally demonstrate symmetrical bidirectional 2 × 12.5-Gb/s quadrature phase-shift keying (QPSK) orthogonal-frequency-division-multiplexing (OFDM) intensity-modulation and direct-detection transmission over 11.5-km four-mode FMF. With Rayleigh backscattering noise mitigation, a Q-factor improvement of 2 dB is achieved for the US signal at the DS signal-to-carrier power ratio of −27 dB.

Index Terms: Wavelength reuse, mode-division-multiplexing (MDM), Rayleigh backscattering.

1. Introduction

With the continuous increase of service demand from end-customers, the future access networks need to accommodate over Gigabit data rates both in upstream (US) and downstream (DS) transmission [1]. The passive optical network (PON) has been considered as a dominant solution to realize Gigabit access due to the advantages of cost effectiveness, energy savings, and service transparency [2], [3]. In next generation PONs for fiber-to-the-home (FTTH) deployment, bidirectional transmission of symmetrical US and DS data capacity will be increasingly important due to the growth of intrinsically bidirectional services such as interactive on-line games and peer-to-peer multimedia services [4], [5]. In bidirectional wavelength-division-multiplexing (WDM) PON transmission system, wavelength reuse can effectively reduce the cost and achieve colorless operation at the ONUs [6]–[8]. Previously, wavelength reused schemes including self-seeded reflective semiconductor optical amplifier (RSOA), reflective electro-absorption modulator with SOA (REAM-SOA) and Fabry-Perot laser diode (FPLD) have been proposed [9]–[14]. However, the RSOA-based wavelength reused scheme is limited by its modulation bandwidth. In the REAM-SOA and WRC-FPLD scheme, the quality of US signal depends much on the modulation depth of DS signal, which makes symmetrical bidirectional transmission challenging.

Recently, mode-division-multiplexing (MDM) as an alternative technique to expand transmission capacity has been widely investigated for high-speed optical transmission and optical access networks by using few-mode fibers (FMFs) instead of single-mode fibers (SMFs) [15]–[17]. In long-haul backbone networks, due to the inevitable mode crosstalk during long-distance fiber transmission, computation-complex coherent detection and multiple-input-multiple-output (MIMO) digital signal processing (DSP) are required at the receiver [18]–[20]. While in short-distance access systems, by appropriately suppressing mode crosstalk, mode could be operated as an independent dimension and the signal at each optical network units (ONUs) can be individually detected without MIMO DSP [21]. Compared with WDM technology, the MDM-based system is naturally colorless and it may be a good candidate for short-distance access application.

In this paper, we propose a wavelength reused MDM scheme for bidirectional short-reach access network. At the optical line terminal (OLT) side, one of the spatial modes is used for US signal carrier while the others are used for DS signal channels. After FMF transmission, the signal carrier is firstly mode demultiplexed and then split to each ONU as US signal re-modulation carrier. With the proposed scheme, we demonstrate 2 × 12.5-Gb/s quadrature phase-shift keying (QPSK) orthogonal frequency division multiplexing (OFDM) intensity-modulation and direct-detection (IM-DD) transmission over 11.5-km 4-mode FMF. We utilize LP_{01} for carrier transmission while LP_{11} and LP_{02} for signal transmission. The DS receiver sensitivity for LP_{11} and LP_{02} is -25 dBm and -23 dBm, respectively. The US receiver sensitivity for LP_{11} and LP_{02} is -20.4 dBm and -18.1 dBm, respectively. To reduce bidirectional Rayleigh backscattering noise, single sideband (SSB) transmission and receiving of OFDM signal is employed. We use upper sideband for DS transmission and lower sideband for US transmission. The results show that the variation of DS receiver sensitivity is small when adopting SSB scheme due to the relatively small backscattering power, whereas for US transmission, the receiver sensitivity of LP_{11} and LP_{02} is -21.2 dBm and -18.9 dBm, respectively. Compared with conventional double sideband (DSB) transmission, a receiver sensitivity improvement of up to 0.8 dB is achieved for US signal due to reduced Rayleigh back-scattering. In addition, we investigate the DS signal to carrier power ratio (SCR) to the performances of bidirectional transmission. It is shown that the SSB scheme can alleviate the impact of high DS SCR to the performance of US signal. A Q-factor improvement of 2 dB is achieved at the DS SCR of -27 dB.

2. Technique Principle

The proposed symmetrical bidirectional wavelength reused MDM-PON is shown in Fig. 1. A laser diode (LD) is power-split to n branches and sent to different transmitters (Tx) for DS transmission. n-1 branches are respectively intensity modulated by n-1 transmitters to generate DSB signals while one branch is used as re-modulation carrier for US transmission. A SSB filter is cascaded to each Mach-Zehnder modulator (MZM) to generate SSB signal. After single mode circulator (SMC), the modulated DS signals and the carrier are combined by a mode MUX and converted from LP_{01} mode into specific modes in the FMF. After the FMF transmission, the signals and carrier are mode demultiplexed and converted to the LP_{01} mode. At each ONU, the DS signal is sent to the respective receiver for direct detection while the carrier is power-split by a 1:n-1 splitter and then sent to each transmitter as US re-modulation carrier. A single-mode-fiber (SMF) erbium-doped fiber amplifier (EDFA) can be utilized to compensate for the loss of the remodulation carrier at the input of the 1:n-1 splitter. Different with DS transmission, the US SSB filter is located at the input of the receiver

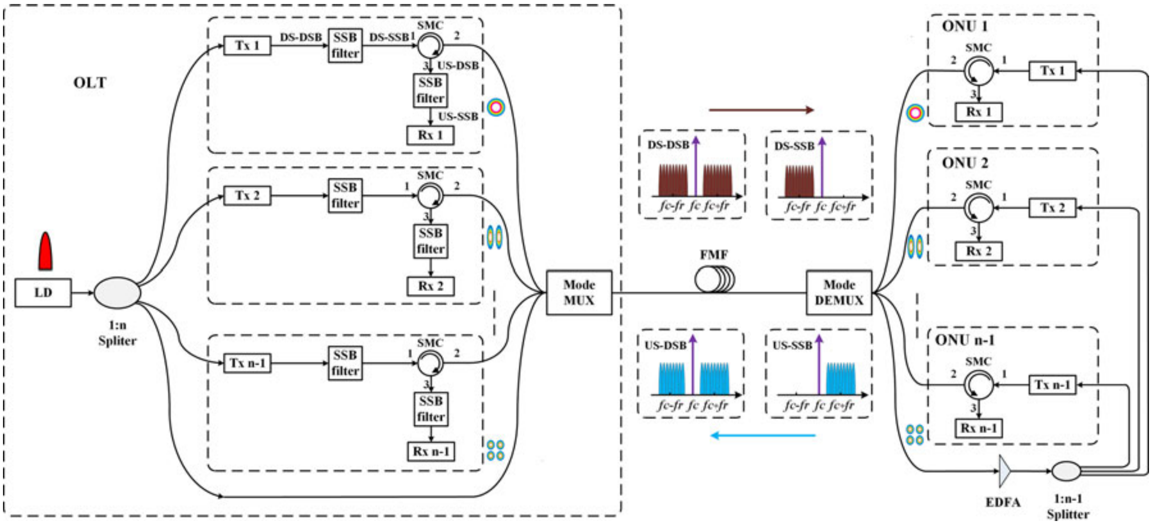

Fig. 1. Operating principle of wavelength reuse for short-reach optical access network utilizing MDM.

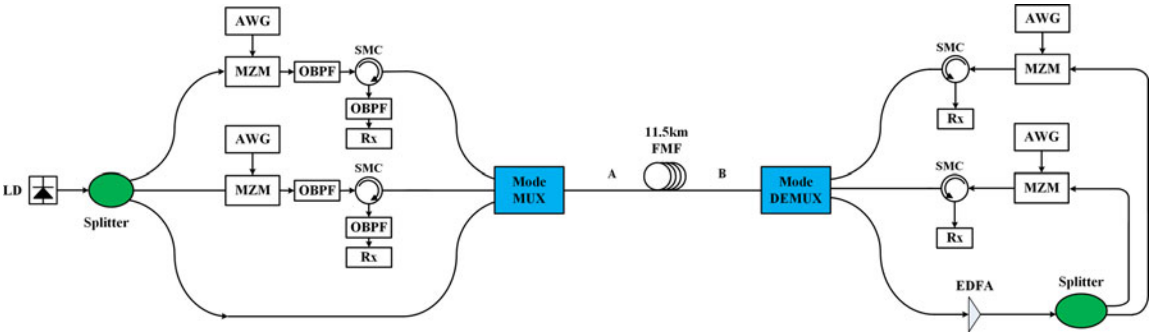

Fig. 2. Experiment setup for wavelength reuse for short-reach optical access network utilizing MDM.

(Rx) at OLT to filter out the other sideband. In the proposed scheme, the DS and US signals occupy different spectrum, thus the Rayleigh backscattering noise will not overlap each other. Meanwhile, no filtering device is located at ONUs, which could achieve colorless operation. Furthermore, due to the larger effective core area of FMF compared with the SMF, the power input FMF can be enhanced without additional nonlinear impairments to increase bidirectional power budget. Compared with DSB scheme, even though the cost and complexity of the whole system increase in SSB scheme, the ONU still keep simple. What is more, the SSB modulation can be realized by IQ modulator together with Hilbert transform, which can remove the optical band-pass filters [22]. The proposed scheme is a promising alternative solution for future access network.

3. Experimental Setup

A symmetrical 2 × 12.5-Gb/s direct-detection OFDM transmission over 11.5-km 4-mode FMF is demonstrated to verify the feasibility of our proposed scheme, as shown in Fig. 2. For downstream transmission, a LD operating at the center wavelength of 1546.31 nm is power-split into three branches. The upper two branches are modulated by MZM which is utilized to convert the baseband OFDM signal to DSB optical signal, while the un-modulated lower branch is used as US carrier. A tunable optical band-pass filter (OBPF) with a bandwidth of 10-GHz serves as SSB filter. The OBPF is based on liquid crystals on silicon (LCoS) with highly flexible program and fine control

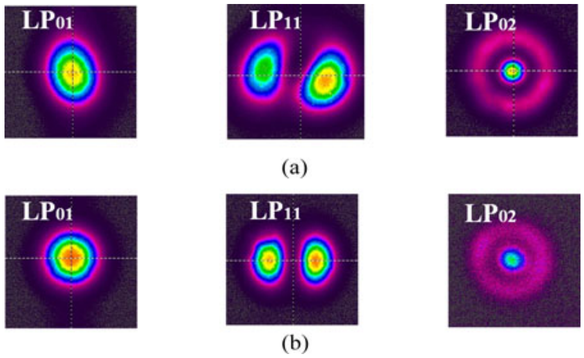

Fig. 3. Mode intensity profiles at the (a) point A and (b) and point B.

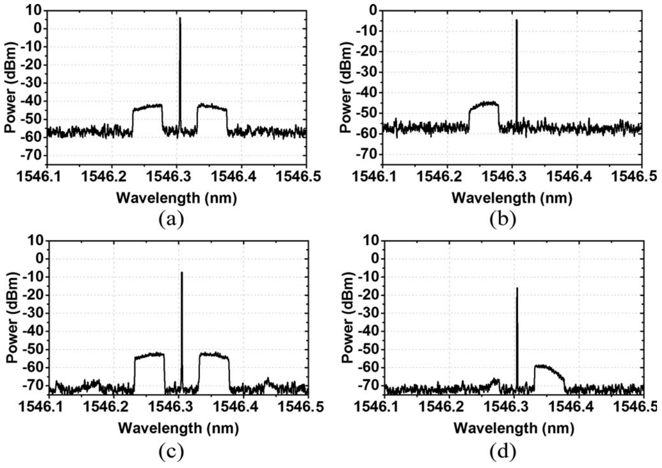

Fig. 4. Optical spectra for (a) DS signal before OBPF, (b) DS signal after OBPF, (c) US signal before OBPF, and (d) US signal after OBPF.

capacity, which applies to practical applications. An arbitrary waveform generator (AWG 70002A) with sampling rate of 25 GS/s generates baseband OFDM signal. The baseband OFDM signal is up-converted to 6.25-GHz by digital I-Q modulation. The DFT size is 1024, from which 968 subcarriers are used for data transmission. The cyclic prefix (CP) size is 16. QPSK is used as modulation format and the bit rate of a single channel is 12.5 Gb/s. Then, the three branches are multiplexed into a mode MUX, in which the two modulated signals are, respectively, converted from LP_{01} mode to LP_{11} and LP_{02} mode while the carrier is LP_{01} mode for FMF transmission. The signal power launched into FMF per channel is 4 dBm, and the carrier power is 8 dBm. The FMF is an 11.5-km low mode-crosstalk step-index fiber with a core diameter of 18.3 μm, a cladding diameter of 125 μm, and refractive index difference (Δn) of 4.52×10^{-3} between core and cladding. The normalized frequency V is 5.1. Thus the FMF supports LP_{01}, LP_{11}, LP_{21} and LP_{02} modes transmission. The effective index difference between LP_{21} and LP_{02} is 5.55×10^{-4}, which may cause large mode crosstalk by strong mode coupling between them. Therefore, in our experiment setup, we only excite LP_{01}, LP_{11} and LP_{02} for transmission. After mode MUX, FMF transmission and mode DEMUX, the crosstalk from LP_{01} to LP_{11}, LP_{01} to LP_{02}, LP_{11} to LP_{01}, LP_{11} to LP_{02}, LP_{02} to LP_{01}, LP_{02} to LP_{11} is -16 dB, -23 dB, -17 dB, -22 dB, -30 dB, and -16 dB, respectively. To extend the scheme to support more modes, elliptical-core FMFs that break the circular symmetry can be used [23]. The MUX/DEMUX can also be realized by asymmetric fused coupler to excite and extract specific mode in one mode groups [24]. Ring-assisted fiber with ultra-low inter-mode crosstalk without obvious degradation on other characteristics can also be utilized to expand the

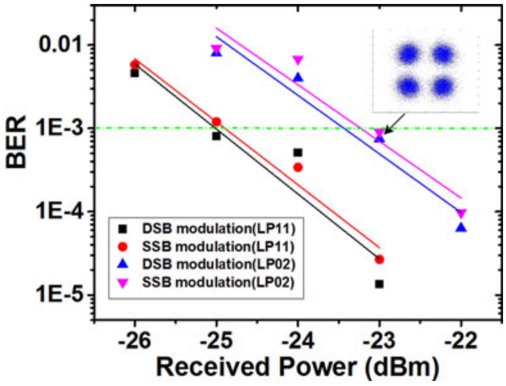

Fig. 5. BER performances versus the received power of DS signal.

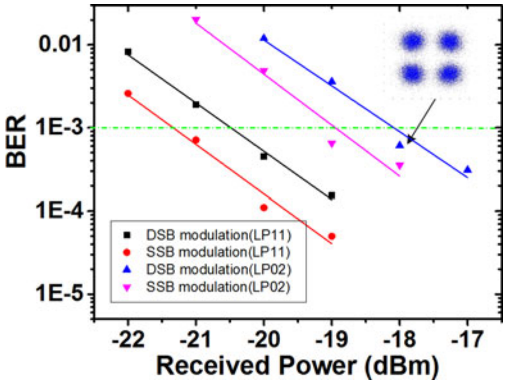

Fig. 6. BER performances versus the received power of US signal.

scale and up to 12 spatial modes operation can be achieved [25]. After FMF transmission, the MDM signals and carrier are demultiplexed by a mode DEMUX to achieve individual signal channel and carrier channel. The signal power is about -3 dBm and the carrier power is 2 dBm. The signal channel is sent to the receiver for direct detection with offline DSP while the carrier channel is sent to MZM for US re-modulation after power amplification by an EDFA. The receiver at ONU consists of an EDFA as optical pre-amplifier and a PIN photo-diode (PD). In practical PONs, the EDFA can be replaced by a compact and cost-effective semiconductor optical amplifier (SOA). The received electronic signal is sampled by a real-time digital storage oscilloscope operating at 50-GS/s. The sampled signal is down-converted to baseband and decoded by Matlab. The US transmission is similar to the DS. The insertion loss of the MZM is 8.1 dB. The optical power of the carrier input the MZM is 10 dBm and the US signal power into FMF per channel is -2 dBm. The OBPF at OLT is used to filter out the other sideband.

4. Experimental Results

To investigate the performance of mode MUX/DEMUX and FMF, we measure far-field mode patterns of the downstream transmission at the points A and B in MDM-PON system. The mode intensity profiles at the point A and B are shown in Fig. 3. It demonstrates that LP_{01} mode can be converted to LP_{11} and LP_{02} mode successfully by the MUX and then converted back by the DEMUX. To observe the filtering effect, we utilize optical spectrometer BOSA 300 CL with a minimum optical resolution of 0.08 pm to see the details of the optical spectrum. BOSA 300 CL is based on stimulated Brillouin scattering (SBS) and the optimal optical power input to optical spectrometer need exceed 0 dBm.

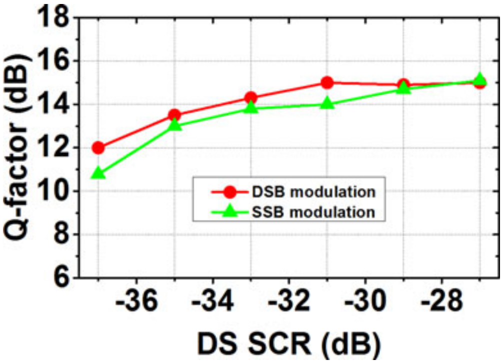

Fig. 7. Q-factor performances versus the DS SCR of DS signal.

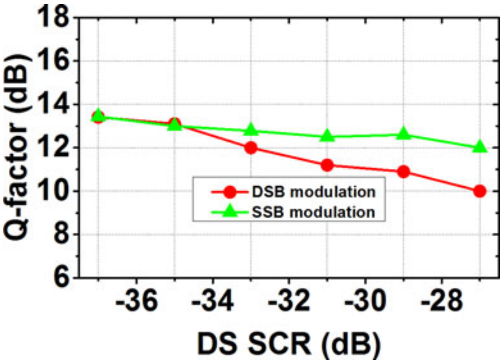

Fig. 8. Q-factor performances versus the DS SCR of US signal.

Fig. 4(a)–(d) shows the optical spectra of DS and US signal before and after OBPF. Only one signal sideband is left after OBPF. Compared with DS signal, the US signal spectrum degrades obviously is partly due to the optical filtering effect and partly due to the spectrum display by the optical spectrometer. Fig. 5 shows the BER performances for DS signal when DSB and SSB schemes are adopted for both DS and US transmission. It can be seen that DSB and SSB schemes have similar performances for both modes. Compared with SSB scheme, no obvious power penalty is observed for DS transmission when DSB scheme is adopted. That is because the upstream signal has relatively small power and the Rayleigh backscattering noise is weak. Meanwhile, LP_{11} has better performance than LP_{02} because of the smaller phase mismatching between the LP_{01} and LP_{11} than LP_{01} and LP_{02} modes of mode MUX/DEMUX. The receiver sensitivity of LP_{11} and LP_{02} is about -25 dBm and -23 dBm, respectively. Fig. 6 shows the BER performances of US signal when DSB and SSB schemes are adopted for both DS and US transmission. In DSB scheme, the US receiver sensitivity for LP_{11} and LP_{02} is -20.4 dBm and -18.1 dBm, respectively, whereas in SSB scheme, the US receiver sensitivity for LP_{11} and LP_{02} is improved to -21.2 dBm and -18.9 dBm, respectively. From the results, we can see the SSB scheme has up to 0.8 dB sensitivity improvement compared with DSB because of the reduced spectrum overlapping, which effectively mitigate Rayleigh backscattering.

Further, we adjust the electric power that input to MZM and investigate the DS SCR to the performances of the DS and US signal when DSB and SSB schemes are adopted. We measure the Q-factor of LP_{11} as reference. In DS transmission, the signals have similar performances when adopting DSB and SSB schemes, as shown in Fig. 7. After 11.5 km FMF transmission, the Q-factors of SSB and DSB are above 9.8 dB, which is BER limit of 10^{-3} for standard 7% FEC coding. When the DS SCR increases from -35 dB to -27 dB, a Q-factor improvement of about 3 dB is achieved.

That is because the higher SCR leads to a high OSNR of the signal. In US transmission, when the SCR of the DS signal increases, the Rayleigh backscattering noise caused by the overlapping spectrum is also enhanced, resulting in performance degradation, as shown in Fig. 8. Compared with DSB scheme, the variation of DS SCR has less impact on the US performance in the SSB scheme. When the SCR of DS is -27 dB, a Q-factor improvement of 2 dB is achieved. The results indicate that the SSB scheme can balance both the DS and US performances.

5. Conclusion

In this paper, we propose a cost-effective wavelength reused scheme for short-reach optical access network utilizing low mode-crosstalk MUX/DEMUX and FMF. We experimentally demonstrate symmetrical 2 × 12.5-Gb/s QPSK-OFDM IM-DD transmission over 11.5-km 4-mode FMF. Different sideband for US and DS transmission is verified to be effective for mitigating Rayleigh backscattering noise.

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