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Invited Papers

Recent progress in mode-division multiplexed passive optical networks with low modal crosstalk

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ABSTRACT

Recently, mode-division multiplexing (MDM) has been investigated in transmission systems and optical access networks for capacity enhancement. In this paper, recent progress in MDM optical passive networks (PONs) enabled by low-modal crosstalk few-mode fibers (FMFs) and optical components is reviewed. All-fiber mode multiplexer/demultiplexers (MUX/DeMUX) composed of mode-selective couplers (MSCs) are introduced to simultaneously multiplex or demultiplex multiple modes. Few-mode circulators (FMCs) are employed to realize bidirectional MDM-PON transmission. Direct detection without complex multiple-input–multiple-output (MIMO) digital signal processing (DSP) is applied. Moreover, multidimensional PONs by cascading MDM optical distribution network (ODN) with conventional time-division multiplexing (TDM) and wavelength-division multiplexing (WDM) ODNs are proposed and experimentally demonstrated.

1. Introduction

In recent years, a variety of passive optical network (PON) technologies have been proposed and discussed for next-generation optical access networks beyond 10G [1–4]. Most of the commercially deployed PONs such as Ethernet PONs (EPON) and gigabit PONs (GPON) are time-division multiplexed PONs (TDM-PON), in which different optical network units (ONUs) transmit/receive signals at different time slots and a power splitter is utilized to broadcast/combine signals for all of the ONUs. Beyond the current commercial TDM-PONs [1], several alternative approaches have been proposed, such as PON architectures based on wavelength-division multiplexing (WDM-PON) [2], orthogonal frequency-division multiplexing (OFDM-PON) [3], and optical code-division multiplexing (OCDM-PON) [4]. These multiplexing techniques can also be combined to form multidimensional PON architectures [5–15]. In particular, the hybrid WDM and TDM PON (WDM-TDM-PON) architecture uses the cascading of wavelength MUX/DeMUX and power splitters to expand the ODN. ONUs in the same TDM ODN share a wavelength in the time domain. This architecture significantly improves the data capacity of TDM-based PON systems.

As the bandwidth demand of end-customers continues to increase, additional multiplexing dimensions are expected to be combined to realize larger-scale PONs supporting higher transmission speed and/or more users. Recently, mode-division multiplexing (MDM) [16,17], as an alternative technique for expanding transmission capacity, has been extensively investigated for high-speed optical transmission to break capacity limit of single-mode fibers. All reported work on MDM long-haul transmission uses complex coherent detection and computationally-intensive MIMO DSP [18–23] to undo mode crosstalk that is inevitable during long-haul fiber transmission. For examples, Ryf et al. [22] reported 72-Tb/s transmission over 179-km all-Fiber 6-Mode span with two cladding pumped in-line amplifiers. Chen et al. [23] achieved a total capacity of 67.5 Tbits/s with 30 wavelength channels by applying 30-Gbaud 16-QAM over an 87-km multi-mode fiber span composed of hybrid 10- and 15-mode fibers with 20×20 MIMO DSP. However, these expensive and complex schemes involving coherent detection and MIMO DSP are not suitable for PONs.

There have also been reports on MDM short-reach transmission system [24–26]. For examples, Franz and Bulow [24] reported mode-group multiplexing in a 5-km standard graded-index multimode fiber with OOK modulation and direct detection, in which a mode converter consisting of a phase mask is used to excite the

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desired modes. Gasulla and Kahn [25] used four groups of modes in a 1-km FMF to transmit four different digital data signals modulated using OOK with direct detection. Simonneau et al. [26] realized 4 × 50-Gb/s transmission over 4.4-km of multimode OM2 fiber with mode group multiplexing and direct detection. These works imply that low mode crosstalk is achievable in the short-reach transmission systems. Meanwhile, it has been proposed that spatial modes could be used to enhance upstream transmission of conventional TDM-PON to accommodate more ONUs [27]. But it should be pointed out that under this mode-enhanced architecture only one ONU can transmit signal to the optical line terminal (OLT) at a specific time slot. It is preferred to greatly suppress mode crosstalk in the ODN, including the transmission FMF and mode MUX/DeMUX, to achieve independent spatial mode transmission.

There are several approaches to realize mode multiplexing/demultiplexing. Free-space bulk optical components, such as phase plates [28–30], are incompatible with optical fiber-based transmission link because of their bulkiness. In the planar lightwave circuit (PLC) platform, multimode interference devices (MMI) [31–33], asymmetric Y-junctions [34–36], T-shaped couplers [37] and multipass cavity [38] have been proposed. The third method is to realize mode multiplexing/demultiplexing in the optical fiber platform. Unlike previous work such as mechanically-induced long-period fiber gratings [39–42] or photonic lanterns [43–46], we focus on the suppression of mode crosstalk. We utilize all-fiber fused mode couplers [47–50,25] to construct low mode-crosstalk MUX/DeMUX for MDM-PON. Compared with other mode multiplexers, optical fiber-based fused mode coupler is compatible with current PON systems, and has low loss, compactness and efficient mode conversion with low modal crosstalk.

In this paper, we discuss the concepts of multidimensional PONs based on MDM and review some recent results. We start by introducing the principles of multidimensional PONs based on MDM including MDM-PON, MDM-TDM-PON, MDM-WDM-TDM-PON in Section 2. Passive components (all-fiber mode MUX/DeMUX and FMCs) for multidimensional PONs are described in Section 3. Section 4 presents experiment demonstrations for MDM-PON, MDM-TDM-PON, and MDM-WDM-PON transmission. Then we summarize and conclude this paper.

2. Principles of MDM-PON and its cascading structures

2.1. MDM-PON architecture

Fig. 1 shows the schematic structure of the proposed bidirectional MDM-PON [51], which is similar to current WDM-PON, except that the MDM-PON is based on dedicated mode, but not wavelength as WDM-PON is. For downstream transmission, signals from n transmitters (Tx1,...,Txn) at the OLT side are converted to different spatial modes and multiplexed together by a mode MUX, then launched into the FMF. After FMF transmission, different modes are converted back to the fundamental mode in a standard single-mode fiber (SSMF), demultiplexed and distributed to n ONUs (ONU1,...,ONUn) by a mode DeMUX. For upstream transmission, signals from each ONU are multiplexed by another mode MUX. After FMF transmission, signals are demultiplexed by another mode DeMUX and received at the OLT side. The bidirectional transmission is enabled by a pair of few-mode circulators (FMCs) on both ends of the FMF. Compared with TDM-PON and WDM-PON architecture, the proposed MDM-PON can adopt conventional TDM-PON transceivers and does not require colorlessness solution in WDM-PON. Moreover, it's compatible with current PON architecture and can be cascaded with deployed TDM-PON and WDM-PON.

2.2. MDM-TDM-PON architecture

The schematic of cascaded MDM-TDM-PON architecture [52] is shown in Fig. 2. At the OLT side, TDM signals from all the transmitters (Tx1,...,Txn) are combined and converted to specific modes of a FMF by a mode MUX. Then the light beam carrying multiple modes is launched into the FMF. After the FMF transmission, the signals are demultiplexed by a mode DeMUX and launched into each SSMF in conventional TDM-PONs. If the mode crosstalk is very low, each TDM-PON is allocated with a specific mode without affecting each other. The upgrade from TDM-PON to the cascaded MDM-TDM-PON is simple and cost-effective, and no modification is required for the deployed TDM ODNs and ONUs. Therefore, the cascaded MDM-TDM-PON can be utilized to effectively extend the scale of current PONs while achieving compatibility to legacy systems.

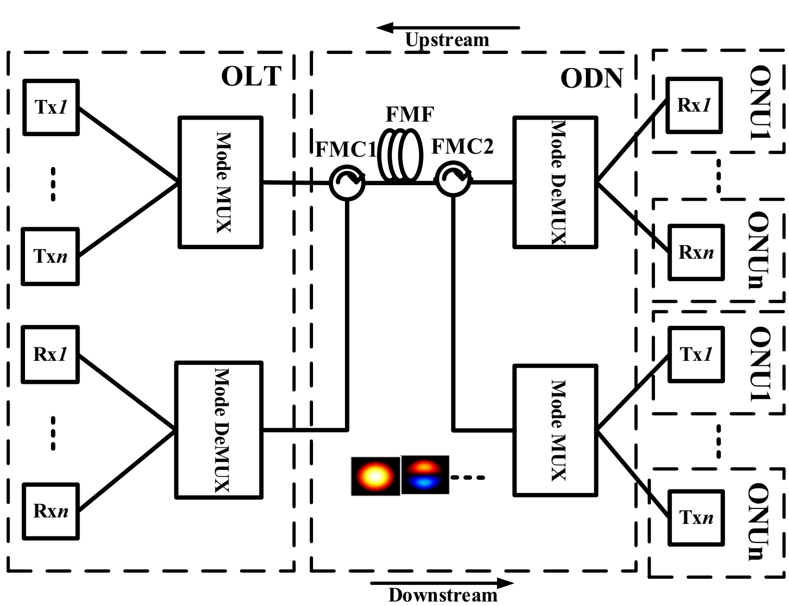

Fig. 1. Schematic of a proposed bidirectional MDM-PON architecture.

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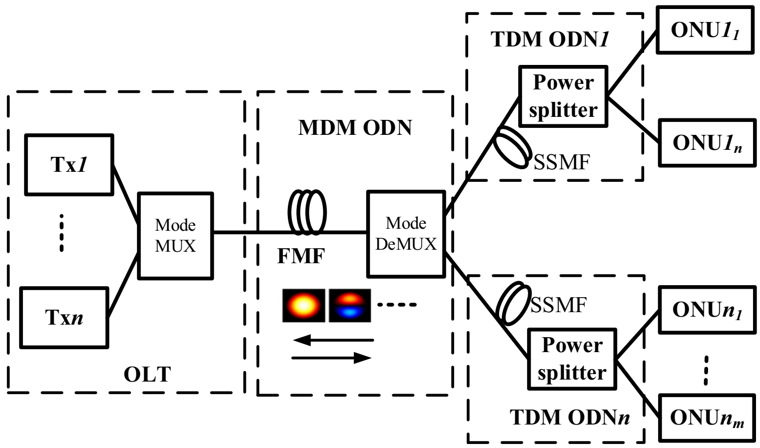

Fig. 2. Schematic of a proposed cascaded MDM-TDM-PON architecture.

2.3. MDM-WDM-TDM-PON architecture

The proposed bidirectional MDM-WDM-TDM-PON architecture [53] is as shown in Fig. 3. Compared with conventional WDM-TDM-PON architecture, a MDM ODN is cascaded, which consists of a low modal-crosstalk FMF and a MDM MUX/DeMUX. In the Mode MUX/DeMUX, multiplexing is enabled by converting each signal in the SSMF into a specific mode in the FMF, while demultiplexing is the reverse. Each output port of MDM MUX/DeMUX is connected with a WDM-TDM ODN. At the OLT side, a MDM MUX/DeMUX and a FMC are also configured. If low modal crosstalk is guaranteed for the FMF, FMC and MDM MUX/DeMUX, the signals in multiple MDM-TDM ODNs will not interference with each other. Thus conventional WDM-TDM-PON architecture can be preserved and a smooth evolution from WDM-TDM-PON to MDM-WDM-TDM-PON can be achieved, which will be cost-effective in PON upgrading. It should be pointed out that in this cascading structure, the order of multiplexing can be changed, however, changing the order of MDM will require that all the components in its cascading structure have FMF input/output ports and support MDM, which are not compatible with deployed PONs based on SMF. The bidirectional MDM transmission is enabled by a FMC in the MDM ODN and a single-mode circulator (SMC) in each ONU. For a typical SMC, there are two faraday rotators (FRs) and two half-wave plates with a structure of Mach–Zehnder interferometer (MZI) [54], and the MZI structure is made of SMF. A FMC can be realized by replacing the MZI SMF with FMF. The FRs and half-wave plates generally will not induce appreciable modal crosstalk. If the FMF has low modal-crosstalk, high isolation can be achieved for all the modes in the FMC.

3. Low-modal crosstalk components

Optical components in the MDM ODN should have low modal crosstalk, because high modal crosstalk will reduce system performance significantly. For conventional TDM-PON, the power budget is an important issue, which should be larger than the sum of the splitting loss and transmission loss in optical fiber for every ONU-OLT link, so that the received signal power is larger than the minimum received power at which the BER is the forward error correction (FEC) limit. The modal crosstalk acts like receiver noise and will degrade the signal-to-noise ratio (SNR). The tolerable modal crosstalk depends on the SNR requirement of the receiver. In this paper, we introduce low modal crosstalk few mode fiber,

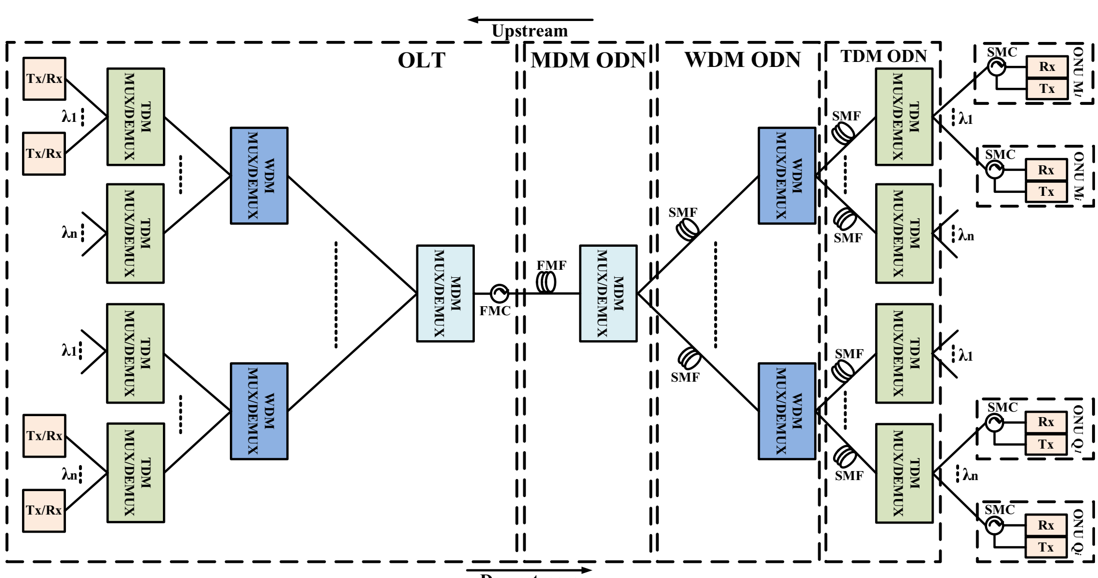

Fig. 3. Schematic of a proposed MDM-WDM-TDM-PON architecture.

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mode MUX/DeMUX and FMCs. The all-fiber mode MUX/DeMUX simultaneously multiplex or demultiplex multiple modes. The FMCs are employed to realize bidirectional transmission.

3.1. Low modal crosstalk few mode fiber

To realize low modal crosstalk in few mode fiber, the difference of the propagation constant of modes should be large, which means the difference of the effective refractive index of modes should be large. Generally, the difference of the effective refractive index of modes in step index fiber is larger than that in graded index fiber, although they may adopt the same design and fabrication method. For all the experiments in this paper, the FMF is the same and the parameters are as follows: the diameters of the fiber core and cladding are 13.6-μm and 125-μm, respectively, and the normalized frequency V is 3.24. The FMF can support only the LP_{01} and LP_{11} modes.

3.2. All-fiber mode MUX/DeMUX

Our mode MUX/DeMUX are realized in the form of fused couplers. The MSC is fabricated by heating and tapering a SMF and a FMF together so as to achieve the phase-matching condition [45,46]. At a specific tapering ratio, the launched fundamental LP_{01} mode in the SMF can be converted into the LP_{11} mode in the FMF over a broad wavelength range around 1550-nm. Fig. 4(a) and (b) shows the mode MUX and DeMUX that are composed of MSCs. Mode intensity profiles at the output ports of the mode MUX are monitored by an infrared CCD camera to ensure mode conversion and multiplexing. Fig. 4(c) and (d) shows the measured mode intensity profiles from the output ports of the mode MUX when optical power is injected to each input port of the mode MUX. The coupling ratio of the MSC from LP_{01} mode to LP_{11} mode is measured to be up to 66% in the wavelength range of C-band, which can be further enhanced by precisely controlling the tapering geometry. The mode extinction ratio is about 15 dB, which is measured using a mode stripper. The modal crosstalk of the mode MUX is measured to be about −22 dB while about −20 dB of the mode DeMUX. The optical insertion losses of the mode MUX are measured to be 0.3 dB for the LP_{01} mode and 1.8 dB for the LP_{11} mode at the wavelength of 1550-nm. The insertion losses of the mode DeMUX are measured to be 0.5 dB for the LP_{01} mode and 2.5 dB for the LP_{11} mode. The mode MUX/DeMUX operate well in the C-band. Wavelength-dependent performance of fiber-fused mode selective coupler can be found in [45].

3.3. Few-mode circulator

Bidirectional transmission in multidimensional PON systems based on MDM is enabled by a pair of FMCs at both ends of the FMF. For a typical single-mode circulator (SMC), there are two faraday rotators (FRs) and two half-wave plates with a structure of Mach–Zehnder interferometer (MZI) [54] consisting of SMFs. A FMC can be realized by replacing the MZI SMF with FMF. The FRs and half-wave plates will not induce appreciable modal-crosstalk. Fig. 5(a) shows the schematic of a FMC. If the modal crosstalk of the FMF is low enough, high isolation can be achieved for all the modes in the FMC. Here the isolation is used to characterize the crosstalk between upstream and downstream signals and defined by the difference of the optical power of port 2 and port 1 of a circulator when light is launched at port 2 and received at port 1. Fig. 5(b) shows a picture of the fabricated FMCs. We have measured the insertion loss for the FMC. For FMC1, the insertion losses are 0.3 dB and 0.8 dB for the LP_{01} mode and LP_{11} mode from port 1 to port 2, respectively, while the insertion losses of the LP_{01} mode and LP_{11} mode from port 2 to port 3 are 0.8 dB and 1.0 dB, respectively. For FMC2, the insertion losses of the LP_{01} mode and LP_{11} mode from port 1 to port 2 are 0.2 dB and 0.5 dB, respectively, while the insertion losses of the LP_{01} mode and LP_{11} mode from port 2 to port 3 are 0.4 dB and 0.7 dB respectively. For both FMC1 and FMC2, isolation is larger than 28 dB for LP_{01} mode, while it is larger than 25 dB for LP_{11} mode. The return losses are both larger than 30 dB for FMC1 and FMC2. The modal crosstalk generated by FMC1 and FMC2 is less than −25 dB. The FMC operates well for wavelengths ranging from 1535-nm to 1560-nm.

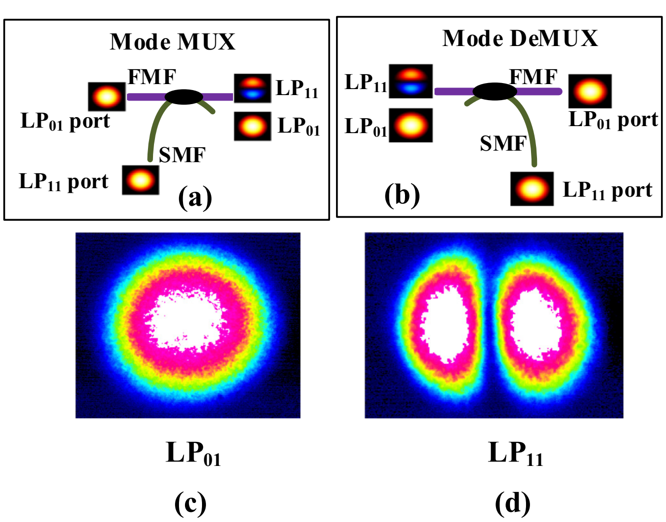

Fig. 4. (a) All-fiber mode MUX; (b) all-fiber mode DeMUX; (c) and (d) output mode intensity profiles of the mode MUX when signal power is injected to each port of LP_{01} mode (c) and LP_{11} mode (d).

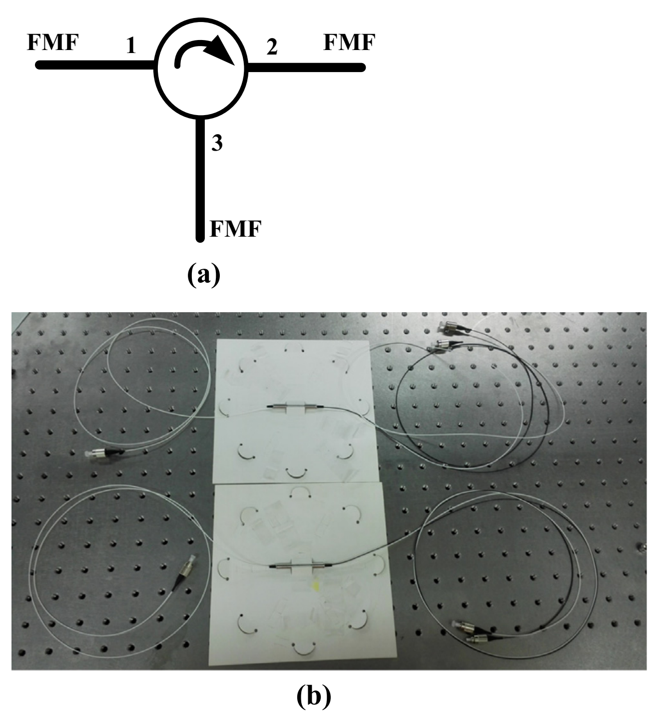

Fig. 5. (a) Schematic of a FMC and (b) picture of the fabricated FMCs with pigtails.

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4. Experiments on MDM-PON and its cascading structures

4.1. MDM-PON experiment

The experimental setup of the bidirectional MDM-PON is shown in Fig. 6. For downstream transmission, 10-Gb/s pseudo-random binary sequence (PRBS) with a period of $2^{15} - 1$ on–off keying (OOK) signal is generated using a laser diode (LD) at 1550-nm followed by an optical intensity modulator (IM). Then the light is split into two branches by a 50:50 optical coupler (OC). For the upper branch, a 10-km delay line is applied to eliminate the correlation between the two branches. At Mode MUX1, signals from the upper branch is converted to LP_{11} mode and multiplexed together with signals from the lower one. After a pair of fabricated FMCs and 10-km FMF transmission, we utilize Mode DeMUX1 to demultiplex signals and distribute them to the corresponding ONUs. In each ONU, a photodiode (PD) is used to detect signals and bit-error ratios (BER) are measured by the receiver of the eBERT. For upstream transmission, 10-Gb/s OOK signals at the wavelength of 1550-nm from ONU1 and ONU2 are converted to corresponding modes and multiplexed by Mode MUX2. 10-km delay line is also utilized. After a pair of FMCs and 10-km FMF transmission, signals are demultiplexed and distributed to different PDs by Mode DeMUX2 for detection and BER measurement. LP_{11} mode is a mode group which consists of two degenerate modes (LP11a and LP11b). In the experiment we excite only one LP11 mode, and the relative angle of the connectors at the input port of Mode DeMUX is manually adjusted to demultiplex the excited LP_{11} mode.

Fig. 7 shows the measured mode patterns of light beams at Point A and Point B in Fig. 6. We can see that the mode patterns are successfully preserved after 10-km of FMF transmission. Fig. 8 shows the eye diagrams for back-to-back (B2B), downstream and upstream transmission for both LP_{01} and LP_{11} modes. The eye diagrams after transmission are slightly degraded as compared to that of B2B, which can be attributed to the crosstalk between LP_{01} and LP_{11} modes during transmission and mode multiplexing/demultiplexing. Meanwhile, these results show that LP_{01} mode is successfully converted to LP_{11} mode and then converted back using mode MUX/DeMUX composed of MSCs.

Fig. 9 shows the measured BER performance of B2B, downstream and upstream transmission for both LP_{01} and LP_{11} modes. Since no FEC is applied in the experiment, we investigate the receiver sensitivity at the BER of 10^{-3}, which can be corrected to 10^{-12} when FEC is applied. The receiver sensitivity of LP_{01} mode for downstream and upstream transmission are about −27.8 dBm and −25.2 dBm, respectively, while they are −26.0 dBm and −24.5 dBm for LP_{11} mode, respectively. The power penalties of downstream and upstream transmission for LP_{01} mode are about 1.5 dB and 2.5 dB respectively, while they are 3.5 dB and 5.5 dB for LP_{11} mode. The results indicate that the performance of LP01 mode is better than that of LP11 mode, and high-order mode may require higher power budget than the LP01 mode.

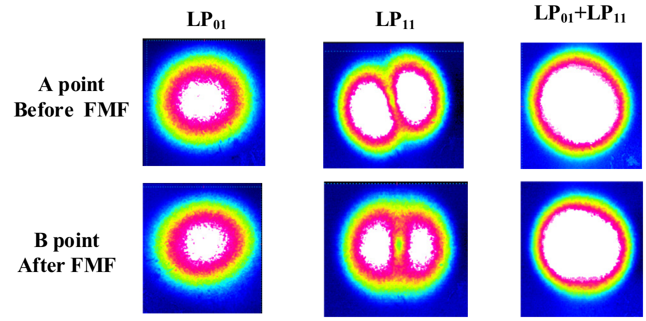

Fig. 7. The measured far-field mode intensity patterns at the points A and B before and after FMF transmission in MDM-PON system.

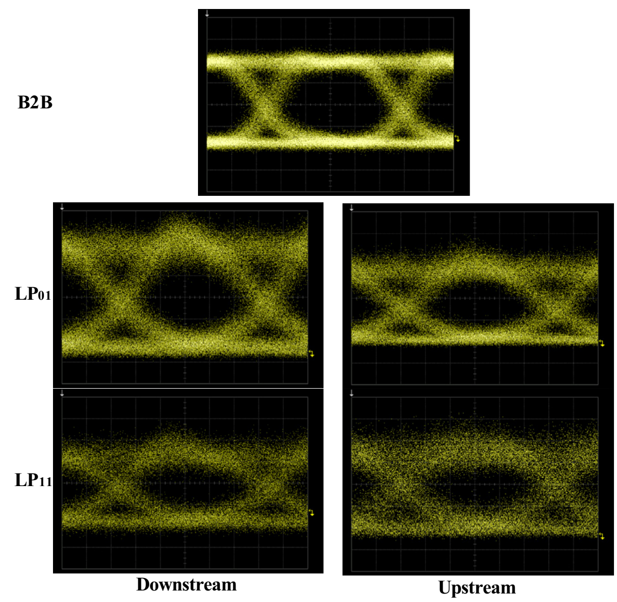

Fig. 8. Eye diagrams of B2B, LP_{01} and LP_{11} mode.

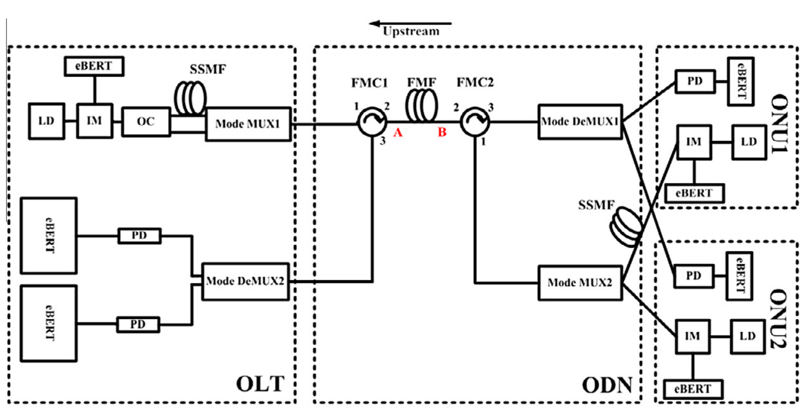

Fig. 6. Experimental setup of bidirectional MDM-PON.

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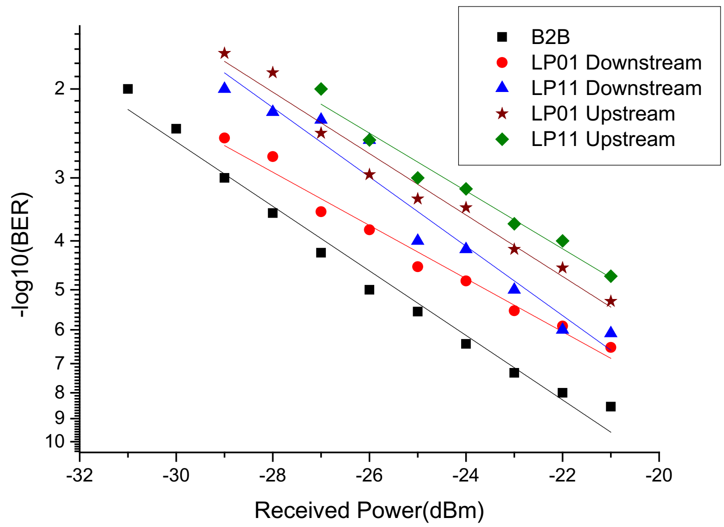

Fig. 9. BER performance of LP_{01} and LP_{11} modes.

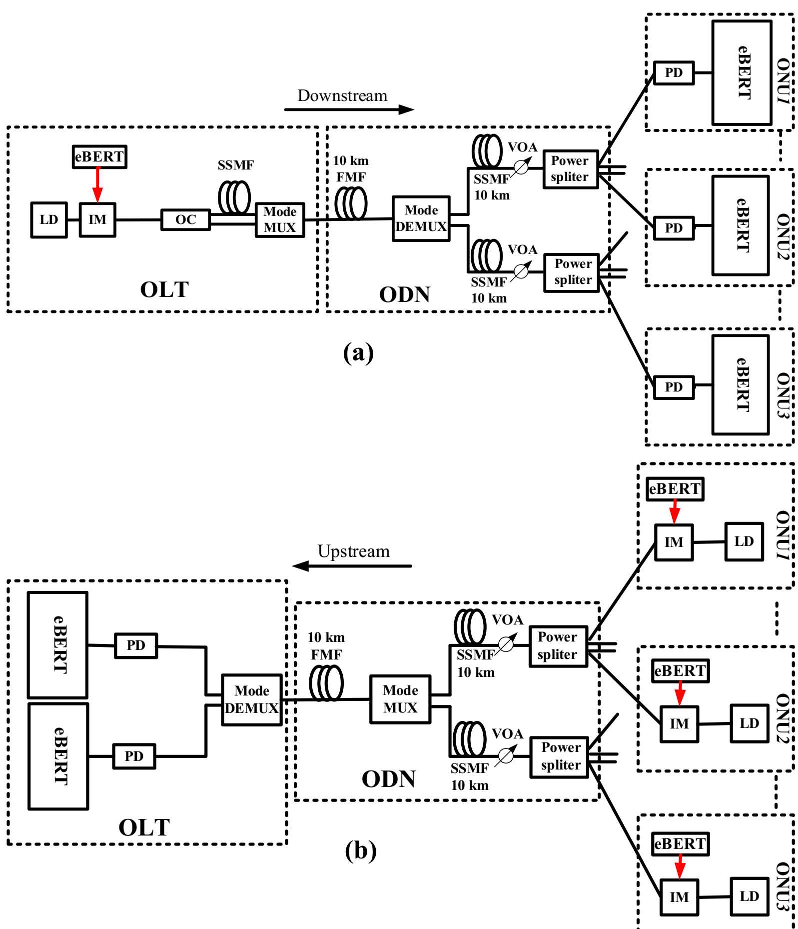

Fig. 10. Experimental setup of downstream (a) and upstream (b) transmission in MDM-TDM-PON.

4.2. MDM-TDM-PON experiment

The experimental setup of downstream transmission for cascaded MDM-TDM-PON is shown in Fig. 10(a). The OLT, MDM ODN and ONU are the same as those used in the MDM-PON experiment (Fig. 6). After MDM signals are demultiplexed with a mode DeMUX, the two output branches are respectively transmitted into 10-km SSMFs and a variable optical attenuator (VOA) before being coupled into a 1×4 power splitter. The experimental setup of upstream transmission is shown in Fig. 10(b). In each ONU, a LD at 1550-nm is used, and a 10-Gb/s optical OOK signal is generated using an optical IM. ONU1 and ONU2 generate signals with LP01

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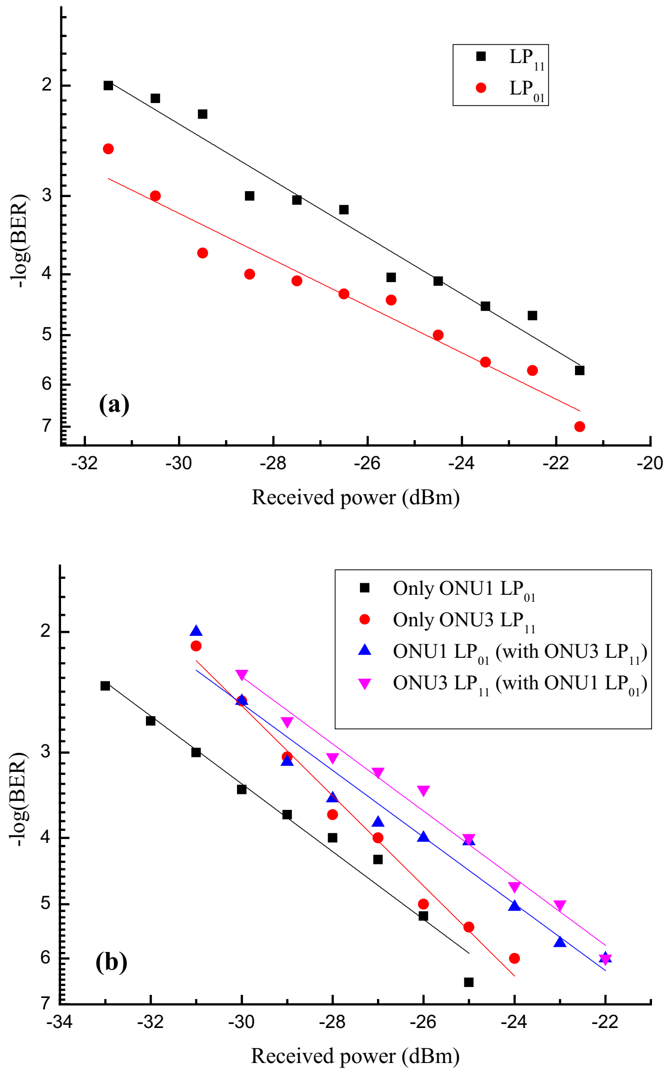

Fig. 11. BER measurements of downstream (a) and upstream (b) transmission.

mode, whereas ONU3 generates signal to be converted to LP_{11} mode. After propagating through TDM ODN and MDM ODN, the upstream signals are demultiplexed and respectively detected at the OLT side.

Fig. 11 shows the BER versus the received power of the LP_{01} and LP_{11} modes. The receiver sensitivity of downstream transmission is shown in Fig. 11(a). At the BER of 10^{-3}, the receiver sensitivity of LP_{01} mode is about −30.7 dBm, while the receiver sensitivity of LP_{11} mode is about −27.5 dBm. The receiver sensitivity of upstream transmission is presented in Fig. 11(b). In the scenario that only ONU1 operates and only ONU3 operates, the receiver sensitivity is about −30.9 dBm and −29 dBm. When ONU1 and ONU3 operate simultaneously, the receiver sensitivity is about −28.5 dBm for ONU1 and −27.8 dBm for ONU3. The penalty can be attributed to the non-zero crosstalk between the two modes.

4.3. MDM-WDM-TDM-PON experiment

The experimental setup to verify the MDM-WDM-TDM-PON architecture is shown in Fig. 12. For downstream transmission, at the ONU side, four LDs generate optical carriers with four wavelengths (1548-nm, 1549-nm, 1550-nm and 1551-nm). An IM is configured to generate 10 Gb/s OOK signal at each wavelength. Then the WDM channels are combined using a WDM MUX which consists of a 4 × 1 optical coupler (OC) and split into two branches by a 50:50 OC. For the upper branch, 10-km SSMF is utilized to decorrelate the two branches. In Mode MUX1, signals from the lower branch is converted to LP_{11} mode and multiplexed with signals from the upper branch. After a FMC and 10-km FMF transmission, Mode MUX/DeMUX2 and two WDM MUX/DeMUX are utilized to demultiplex the signals. Thus the FMF can support only LP_{01} and LP_{11} modes transmission. The TDM ODN consists of 10-km SSMF, a VOA and 1 × 2 OC. In each ONU, a SMC is used and BER is measured by the eBERT. For upstream transmission, 10-Gb/s optical OOK signals from all the ONUs are combined together by two WDM MUX/DeMUX and converted to corresponding modes and multiplexed by Mode MUX/DeMUX2 at the optical distribution network (ODN). After 10-km FMF transmission and a FMC, Mode DeMUX1 and two WDM DeMUX are applied to demultiplex and distribute the signals to the corresponding eBERT for BER measurement.

Figs. 13 and 14 depict the spectrum of the OOK signals for downstream transmission and the eye diagrams of both LP_{01} and LP_{11} modes for downstream transmission at 1550-nm. The results indicate that signals are successfully transmitted/received for 10-km FMF transmission.

Figs. 15 and 16 show the BER performance of downstream and upstream transmission. At the BER of 10^{-3}, the receiver sensitivity of the LP_{01} mode is about −27 dBm, and about −25 dBm of the LP_{11} mode at all four wavelengths for downstream transmission. For upstream transmission, the receiver sensitivity is also −27 dBm for the LP_{01} mode and −25 dBm for the LP_{11} mode at 1550-nm.

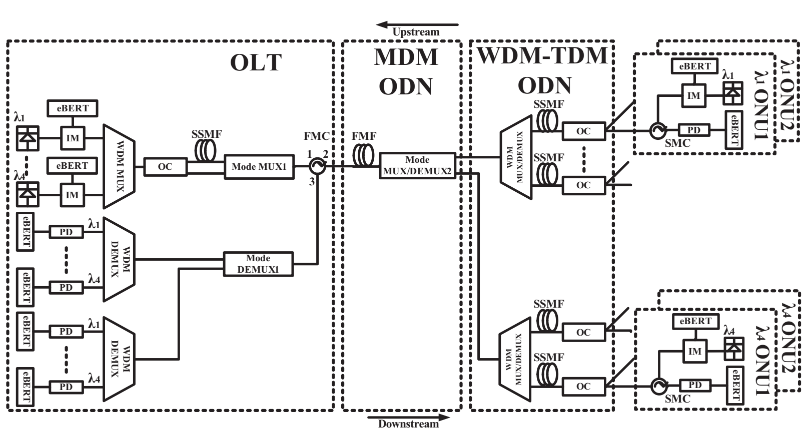

Fig. 12. Experimental setup of TDM-WDM-MDM-PON.

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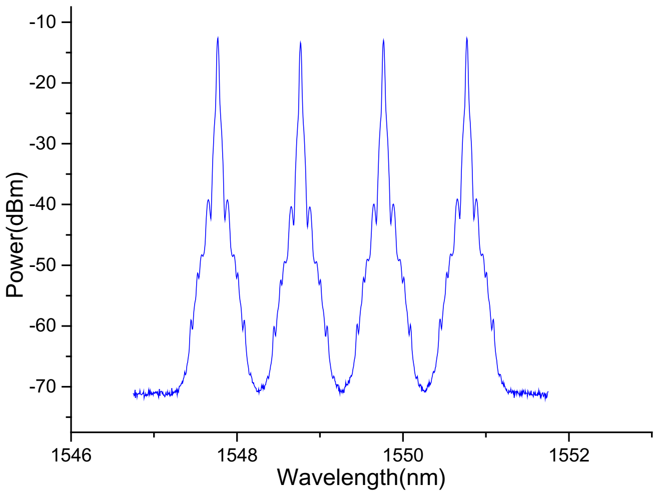

Fig. 13. Spectrum of downstream signals.

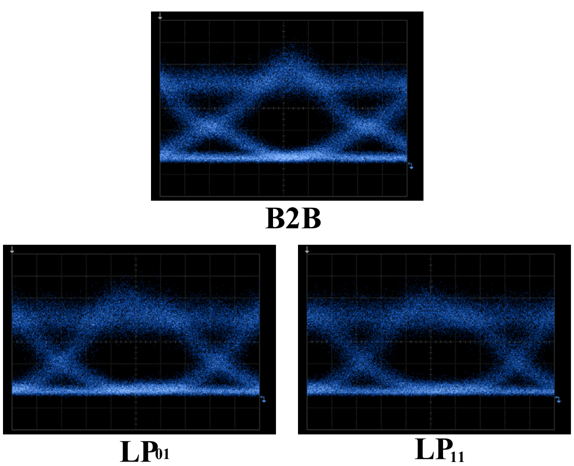

Fig. 14. Eye diagrams of downstream signals at 1550-nm.

The results of upstream transmission agree with that of downstream transmission.

5. Conclusion

In conclusion, we present the concepts of multidimensional -PONs based on MDM including MDM-PON, MDM-TDM-PON, MDM-WDM-TDM-PON and review recent results in this area. Direct detection is used in all the proposed PON systems based on MDM, which avoids the use of coherent detection and MIMO DSP. The all-fiber mode MUX/DeMUX are composed of MSCs, which simultaneously multiplex or demultiplex LP_{01} and LP_{11} modes. FMCs are realized by FMF MZI, which are used to realize bidirectional transmission.

Owing to low modal crosstalk for FMF transmission, mode MUX/DeMUX and FMCs, we successfully achieve bidirectional MDM-PON transmission, where two independent linearly polarized spatial modes are simultaneously transmitted over 10-km low-modal crosstalk two-mode FMF and demultiplexed without MIMO DSP.

We also report cascaded MDM-TDM-PON demonstration. Both downstream and upstream MDM-TDM transmissions are experimentally demonstrated over 10-km two-mode FMF and 10-km SSMF with error-free performance.

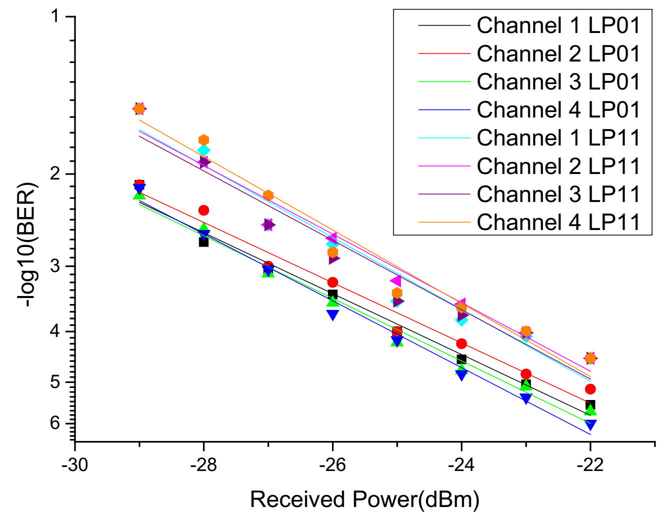

Fig. 15. BER performance for downstream transmission.

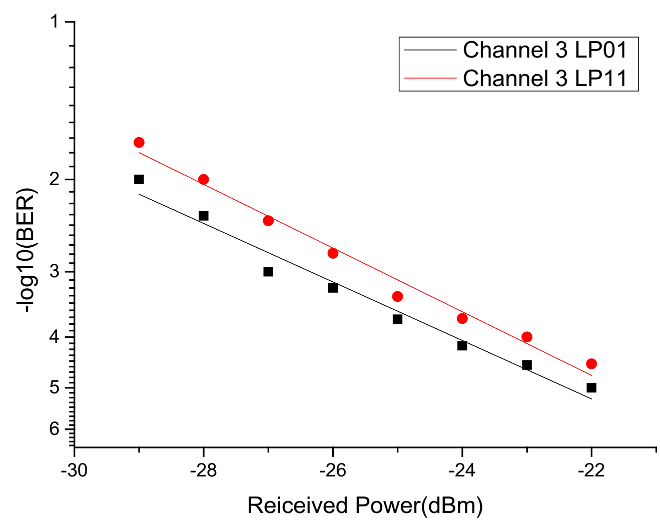

Fig. 16. BER performance for upstream transmission at 1550-nm.

Bidirectional MDM-WDM-TDM-PON architecture is also experimentally demonstrated. The bidirectional transmission is achieved by a FMC at the input port of the two-mode FMF for downstream transmission and a SMC in each ONU. The results indicate that this TDM-WDM-MDM-PON architecture is backward compatible with conventional WDM-TDM-PON and can be used to construct larger-scale access network.

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