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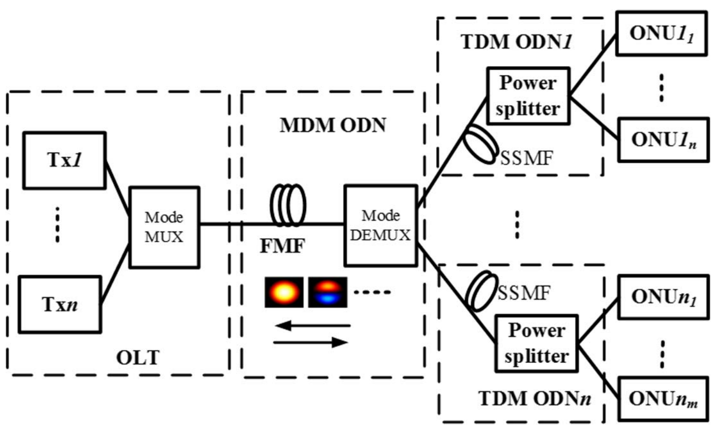

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Cascaded Mode-Division-Multiplexing and Time-Division-Multiplexing Passive Optical Network Based on Low Mode-Crosstalk FMF and Mode MUX/DEMUX

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Abstract: We propose cascaded mode-division-multiplexing and time-division-multiplexing passive optical network (MDM-TDM-PON) based on low mode-crosstalk few-mode fiber (FMF) and all-fiber mode multiplexer/demultiplexer (MUX/DEMUX), in which optical network units communicate with the optical line terminal utilizing different time slots and specific optical linearly polarized spatial modes. An MDM optical distribution network (ODN) is cascaded with multiple conventional TDM ODNs to effectively extend a larger scale of current commercial PON systems based on TDM. The upgrade from TDM-PON to the cascaded MDM-TDM-PON is simple and cost-effective. No multiple-input–multiple-output (MIMO) digital signal processing is required to eliminate the mode crosstalk. The all-fiber mode MUX/DEMUXs are composed of mode selective couplers, which simultaneously multiplex or demultiplex multiple modes. We experimentally demonstrate MDM-PON transmission over 10 and 55 km two-mode FMFs and cascaded MDM-TDM-PON transmission over a 10-km two-mode FMF and a 10-km standard single-mode fiber with 10-Gb/s optical on–off keying (OOK) signal and direct detection.

Index Terms: Mode-division multiplexing (MDM), time-division multiplexing (TDM), passive optical network (PON), mode selective coupler (MSC).

1. Introduction

In recent years, next-generation passive optical network (PON) technologies at traffic of 40-Gb/s or above have been widely discussed, owing to growing bandwidth demand. Besides current commercial PON based on time-division-multiplexing (TDM) [1], several alternative approaches have been proposed, such as PON architecture based on wavelength-division-multiplexing (WDM-PON) [2] and orthogonal frequency-division-multiplexing (OFDM-PON) [3]. Basically, these approaches utilize only one multiplexing dimension. There are also some multi-dimensional PON architectures [4]–[6], such as the hybrid of TDM, WDM, or OFDM. In particular, wavelength-division-multiplexing and time-division-multiplexing PON (WDM-TDM-PON) architecture [6] 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 the end-customers increases gradually, more multiplexing dimensions are expected to be combined to realize larger-scale PON with much higher transmission speed and supporting more users. Recently, mode-division multiplexing (MDM) [7], [8], as an alternative technique for expanding transmission capacity, has been widely investigated for high-speed optical transmission to break through the capacity crunch by use of FMFs instead of single-mode fibers (SMFs). Comparing to the transmission over multiple parallel SMFs, MDM-PON allows reducing power consumption and incrementally incorporating upgrades to existing single-mode infrastructure, which offer cost advantages in PON application. Meanwhile, comparing to other space-division multiplexed fiber like multicore or multi-element fibers, the FMF is more potential to facilitate integration and to be reverse-compatible in the current PON systems. The various reported works on MDM transmission in long-distance transmission use computation-complex coherent detection and multiple-input–multiple-output (MIMO) DSP, because the mode crosstalk is inevitable during long-distance fiber transmission. For example, Ryf *et al.* [9] report simultaneous transmission of six spatial and polarization modes, each carrying quadrature-phase-shift-keyed (QPSK) channels over 96 km of a low-differential group delay few-mode fiber, in which the channels are recovered by offline MIMO DSP after coherent detection. Chang *et al.* [10] demonstrate transmission of three spatial modes with polarization division multiplexing (PDM)-QPSK signals over 15 km of four mode fiber by using 6×6 MIMO digital signal processing. However, the expensive scheme with coherent detection and MIMO DSP are not applicable for optical access network.

There are also some discussions for spatial multiplexing in short-distance transmission system [11], [12]. For examples, Franz *et al.* [11] report spatial multiplexing using mode group in a 5 km standard graded-index multimode fiber with on–off keying (OOK) modulation and direct detection, in which a mode converter consisting of a phase mask is used to excite the desired modes. Gasulla *et al.* [12] use four groups of modes in a 1 km FMF to transmit four different digital data signals modulated using OOK with direct detection. These works imply that low mode crosstalk is achievable in the short-distance transmission systems. Meanwhile, it has been proposed that spatial mode could be used to enhance upstream transmission of conventional TDM-PON to accommodate more ONUs [13], but it should be pointed out that under this mode-enhanced architecture only one ONU can transmit signal to the OLT at a specific time slot. It is preferred to greatly restrict the 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 [9], [14], [15], always have large volume incompatible with optical fiber-based transmission link. In the planar lightwave circuit (PLC) platform, multimode interference devices (MMI) [16], asymmetric Y-junctions [17], and T-shaped couplers [18] have been proposed. Third method is to realize mode multiplexing/demultiplexing in optical fiber platform. Unlike previous work such as mechanically-induced long-period fiber gratings [19], [20] or photonic lanterns [21], we focus on the suppression of mode crosstalk. We utilize all-fiber fused mode coupler [22]–[25] to construct low mode-crosstalk MUX/DEMUX for MDM-PON, which is attractive for its low-loss, compactness and efficient mode conversion.

In this paper, we propose cascaded MDM-TDM-PON architecture based on low mode-crosstalk FMF and all-fiber mode MUX/DEMUX, in which each TDM-PON is allocated with a specific LP spatial mode without influencing each other. An MDM ODN is cascaded with multiple conventional TDM ODNs to effectively extend larger scale of current commercial PON systems based on TDM. We fabricate low mode-crosstalk 2-mode FMF and all-fiber 2-mode MUX/DEMUX. By experiment, we successfully demonstrate MDM-PON transmission over 10-km and 55-km 2-mode FMF, and cascaded MDM-TDM-PON transmission over 10 km 2-mode FMF and 10 km SSMF. Coherent detection and MIMO DSP are replaced by simple direct detection for

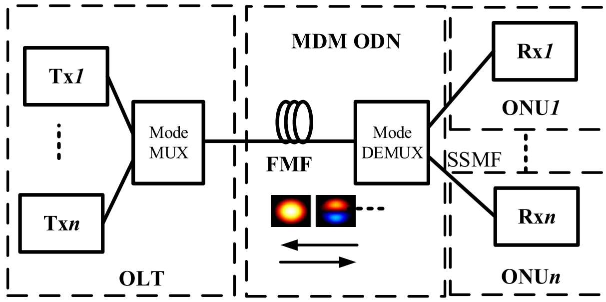

Fig. 1. Schematic of an architecture of proposed MDM-PON.

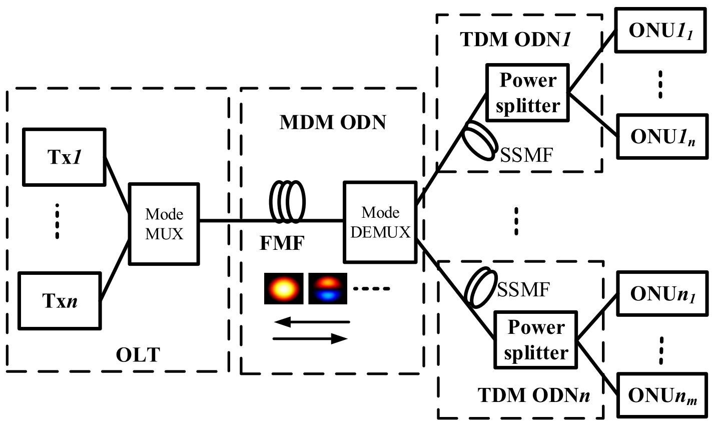

Fig. 2. Schematic of an architecture of proposed cascaded MDM-TDM-PON.

10-Gb/s OOK signals. The rest of the paper is organized as follows. The following section describes the principle of MDM-PON architecture. The third section introduces the principle of cascaded MDM-TDM-PON architecture. The fourth section discusses MDM-PON experiment over 10 km and 55 km two-mode FMF with OOK modulation and direct detection. The fifth section investigates cascaded MDM-TDM-PON experiment, in which both downstream MDM transmission and upstream MDM-TDM transmission are experimentally demonstrated over 10 km FMF and 10 km SSMF with error-free performance. We then summarize and conclude this paper.

2. Principle of MDM-PON Architecture

The schematic of 1-D MDM-PON architecture is shown in Fig. 1. Only downstream transmission is depicted for simplification and better understanding, which can be extended to bi-directional transmission similar with bi-directional WDM-PON. At the OLT side, signals from all transmitters 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 into individual signals all of which are converted to the LP_{01} mode and launched into SSMF. Neither the FMF transmission nor mode MUX/DEMUX will generate strong crosstalk among the modes, so the signal at each OUN can be individually detected without MIMO DSP.

3. Principle of Cascaded MDM-TDM-PON Architecture

The schematic of cascaded MDM-TDM-PON architecture is shown in Fig. 2. At the OLT side, TDM signals from all the transmitters $(\mathrm{Tx}1, \ldots, \mathrm{Tx}n)$ 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 and launched into each

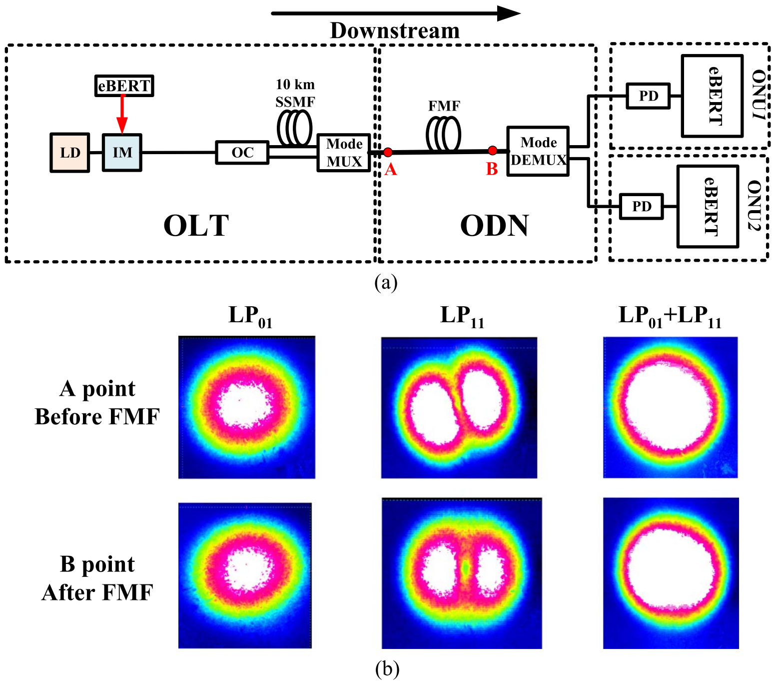

Fig. 3. (a) Experimental setup for two-mode PON transmission over the FMF. (b) Measured far-field mode intensity patterns at the points A and B in MDM-PON system. LD: laser diode; IM: intensity modulator; OC: optical coupler.

SSMF in different conventional TDM-PONs. If the mode crosstalk is very low, each TDM-PON is allocated with a specific mode without influencing 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 PON and achieve good compatibility to legacy systems.

Passive MUX/DEMUXs are indispensable for both MDM-PON and WDM-PON when cascading with TDM-PON structures. Since the mode MUX/DEMUX consisting of MSCs has similar insertion loss with an arrayed-waveguide grating (AWG) in WDM-PON, the MDM-PON will not induce serious influence on power budget of the TDM-PON, just like the WDM-PON. It should be pointed out that in WDM-TDM-PON, the wavelength of ONUs should be tunable to achieve colorless upstream transmission, which will greatly increase the ONU cost. On the contrary, cascaded MDM-TDM-PON does not need wavelength-tunable module and the upstream transmission is naturally colorless. Therefore, the MDM-PON is a better approach than the WDM-PON to be cascaded with conventional TDM-PON to achieve larger-scale PON. It is expected that the number of independent spatial modes of FMF should be increased while keeping low crosstalk among modes, which will raise a new requirement of fiber design.

4. MDM-PON Experiment

We first investigate the transmission performance of MDM-PON. Experimental setup of proposed MDM-PON transmission system is shown in Fig. 3(a). At the OLT side, a laser diode (TeraXion, PureSpectrum-NLL) with a wavelength of 1550 nm is used, and a 10-Gb/s optical OOK signal is generated using an optical intensity modulator (IM). The IM is driven by $2^{15}-1$ pseudo-random binary sequence (PRBS) data generated by the transmitter of a bit-error-ratio tester (eBERT-15G). The optical signals are split into two beams by a 3-dB power optical coupler (OC). The upper branch is delayed by 10 km SSMF for decorrelation. Then the two decorrelated signals are multiplexed by the mode MUX, in which one of them is converted from LP_{01} mode to LP_{11} mode, and the other one is LP_{01} mode for FMF transmission. The fabrication

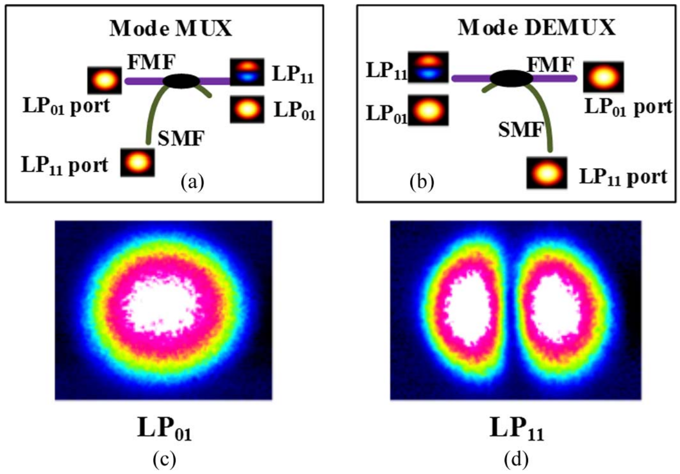

Fig. 4. (a) All-fiber mode MUX. (b) All-fiber mode DEMUX. (c) and (d) Output mode intensity profiles of the mode MUX when signal power is injected to each port of LP_{01} mode (c) and LP_{11} mode (d).

parameters of this FMF for transmission are as follows: the core/cladding diameters of the fiber are 13.5 μm and 125 μm, respectively, and the normalized frequency V is 3.24. Thus, the FMF only supports LP_{01} and LP_{11} modes transmission. After the FMF transmission, these MDM signals are demultiplexed with a mode DEMUX and then are launched into two SSMFs. At the ONU side, the signals are detected by a photodetector (CONQUER, 20G), and then, the bit error rate is measured online by the receiver of bit-error-ratio tester (eBERT-15G).

In the experiment, the mode MUX/DEMUX are realized in the form of fused-type coupler. The MSC is fabricated with a SMF and a FMF by heating and tapering according to phase-matching condition [22]–[24]. At a specific coupler diameter, the launched fundamental LP_{01} mode in the SMF arm can be converted into the higher order mode LP_{11} in the FMF arm 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 the mode conversion and multiplexing. Fig. 4(c) and (d) shows the measured mode intensity profiles from 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 coupler cross-section geometry. The mode extinction ratio is about 15 dB, which is measured using a mode stripper. The sum of degenerate modes (LP_{11a} and LP_{11b}) is considered as a mode (LP_{11}). The optical insertion losses of the mode MUX are measured to be 0.3 dB for LP_{01} mode, 1.8 dB for LP_{11} mode excitation at the wavelength of 1550 nm. The insertion losses of the mode DEMUX are measured to be 0.5 dB for LP_{01} mode, 2.5 dB for LP_{11} mode. The mode MUX/DEMUX operates well in C-band. Further discussion for wavelength dependent performance of fiber-fused mode selective coupler can be found in [23]. The measured far-field mode patterns at the points A and B in MDM-PON system are shown in Fig. 3(b). 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.

In order to analyze the mode crosstalk between the two modes (LP_{01} and LP_{11}) using the mode MUX/DEMUX in the MDM-PON transmission system, we measure output power at the output ports of the mode DEMUX when the input power of 0 dBm is launched to each of the inputs of the mode MUX and the output port of the mode MUX is directly connected to the input port of the mode DEMUX (back to back configuration). The output powers at the output ports of the mode DEMUX are around -5.42 dBm for LP_{11} mode and around -27.3 dBm for LP_{01} mode respectively when the input signal is launched to the LP_{11} port of the mode MUX. When the input power is connected to the LP_{01} port of the mode MUX, the output powers are around -16.45 dBm for the LP_{11} mode and around -2.39 dBm for the LP_{01} mode at the output ports of

TABLE 1

Output power (dBm) with back to back and over 10 km and 55 km FMF transmission

Input port	Measured output port	Back to Back	Over 10 km FMF	Over 55 km FMF
LP_{01}	LP_{01}	-2.39	-4.41	-14.01
LP_{01}	LP_{11}	-16.45	-16.24	-24.04
LP_{11}	LP_{11}	-5.42	-8.82	-20.60
LP_{11}	LP_{01}	-27.3	-24.44	-32.64

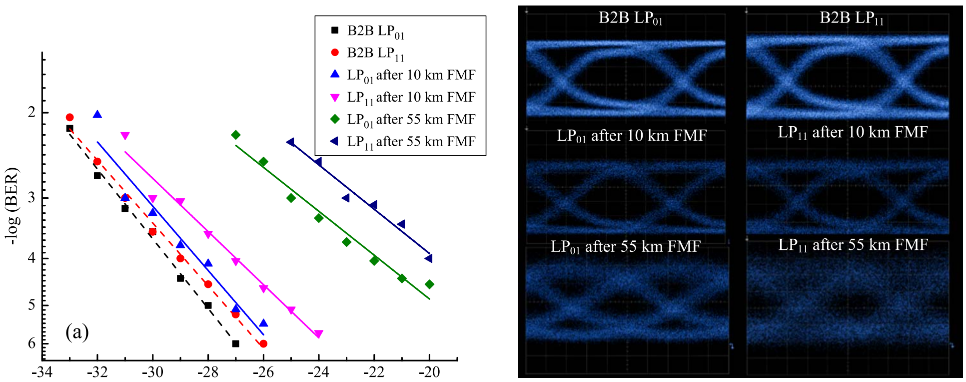

Fig. 5. (a) BER measurements of the two-mode PON transmission over 10 km and 55 km FMF. (b) Eye diagrams of B2B (LP_{01} and LP_{11}) and 10 km and 55 km FMF transmission (LP_{01} and LP_{11}).

the mode DEMUX. The mode crosstalk is considered to be generated at the MSCs and the fiber pigtail connections. In addition, the mode crosstalk in the FMF transmission is also analyzed. Table 1 shows the measured output power at the output ports of the mode DEMUX with back to back, over 10 km and 55 km FMF transmission configurations when the input power of 0 dBm is launched to either of two inputs of the mode MUX.

Fig. 5(a) shows the BER characteristics versus the received power of the LP_{01} and LP_{11} modes. The dashed and solid lines show the bit error rates (BERs) for back-to-back (B2B), 10 km and 55 km FMF transmissions, respectively. The BER performance is verified firstly with B2B configuration where the output of the mode MUX is connected to the input of the mode DEMUX directly by fiber connector, temporarily disconnecting the transmission FMF fiber. The B2B receiver sensitivity at the BER of 10^{-3} are around -31.2 dBm for LP_{01} mode and around -30.8 dBm for LP_{11} mode, respectively. After the 10 km FMF transmission, the receiver sensitivity for LP_{01} and LP_{11} modes are around -30.3 dBm and -29.3 dBm, respectively. After 55 km FMF transmission, the receiver sensitivity for LP_{01} and LP_{11} modes are around -24.6 dBm and -22.5 dBm, respectively. Fig. 5(b) shows the eye diagrams for B2B 10-Gb/s optical OOK signals and received signals after the 10 km and 55 km FMF transmission for two modes (LP_{01} and LP_{11}). As for MDM-PON transmission over 10 km FMF, the eye diagrams of LP_{01} mode after the transmission and B2B are similar, and the eye diagrams of LP_{11} mode after transmission have slightly degraded the BER performance. As for MDM-PON transmission over 55 km FMF, the eye diagrams of LP_{01} and LP_{11} modes after the transmission have obviously degraded the BER performance. Compared to B2B at the BER of 10^{-3}, the LP_{01} and LP_{11} modes after 10 km and 55 km FMF transmission exhibit power penalties of 0.9 dB and 1.5 dB as well as 6.6 dB and 8.3 dB, respectively. For the LP_{01} transmission, power penalty is mainly attributed to chromatic dispersion and crosstalk from the other mode. So the power penalty for the LP_{01} mode after 55 km FMF transmission is higher than that after 10 km FMF transmission. For the LP_{11} transmission, besides these reasons, phase mismatching between the LP_{11} and LP_{01} modes for mode MUX/DEMUX is also responsible for the penalty. This penalty is expected to be

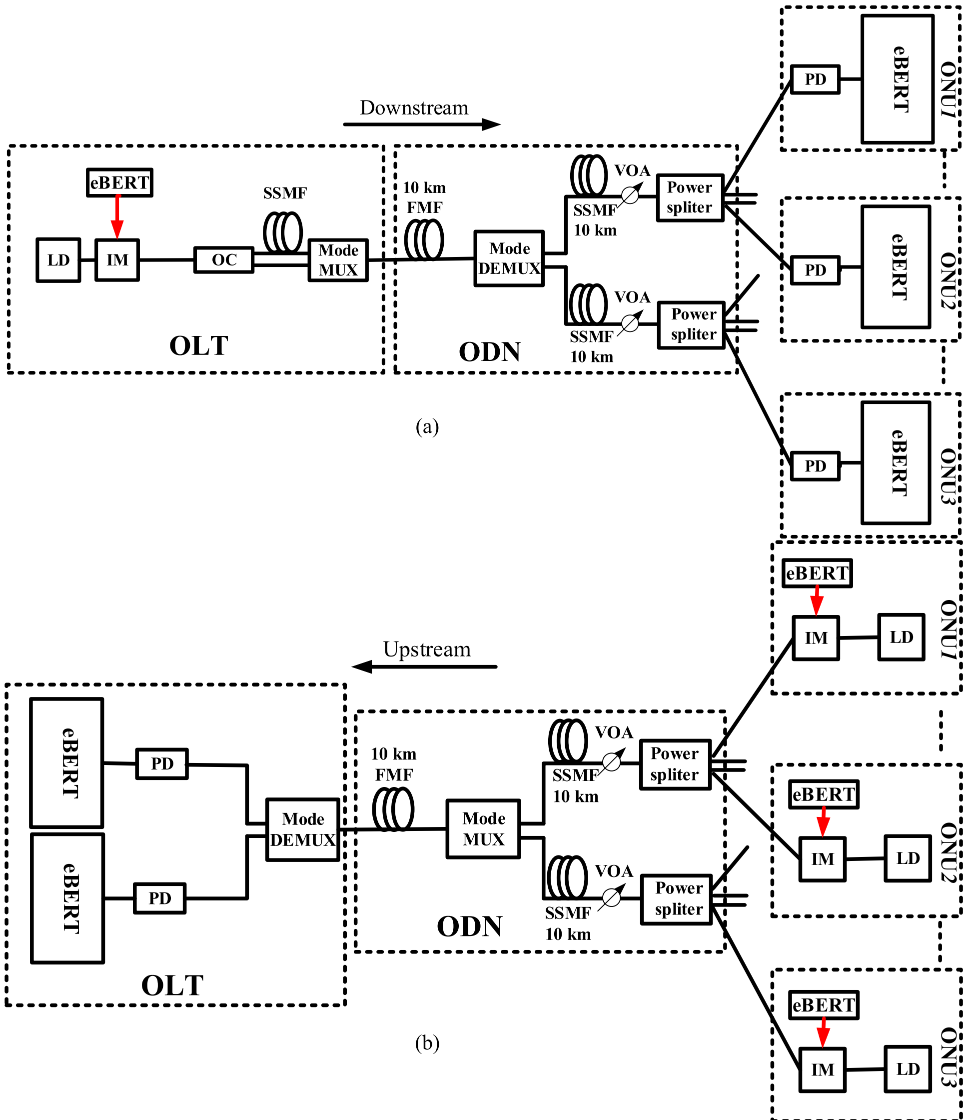

Fig. 6. Experimental setup of downstream (a) and upstream (b) transmission in MDM-TDM-PON.

eliminated by improving the fabrication parameters of the mode MUX/DEMUX. In addition, the power fluctuations are smaller than 0.05 dB and 0.6 dB for the LP_{01} and LP_{11} modes, respectively.

5. Cascaded MDM-TDM-PON Experiment

The experimental setup of downstream transmission for cascaded MDM-TDM-PON is shown in Fig. 6(a). The parts of OLT, MDM ODN, and ONU are same with MDM-PON experiment [see Fig. 3(a)]. 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 1 $\times$ 4 power splitter. The experimental setup of upstream transmission is shown in Fig. 6(b). In each ONU, a laser diode with a wavelength of 1550 nm is used, and a 10-Gb/s optical OOK signal is generated using an optical IM. ONU1 and ONU2 generate signals with LP_{01} 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.

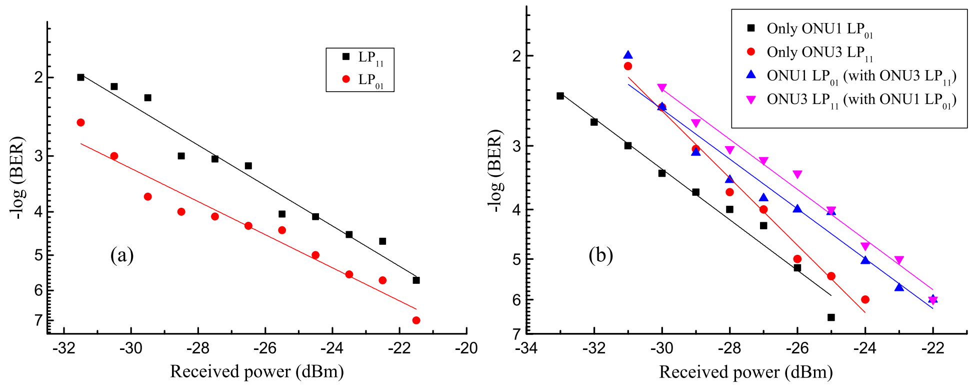

Fig. 7. BER measurements of (a) downstream and (b) upstream transmission.

Fig. 7 show the BER characteristics versus the received power of the LP_{01} and LP_{11} modes. The receiver sensitivity of downstream transmission is shown in Fig. 7(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. 7(b). In the scenario that only ONU1 operates and only ONU3 operates, the receiver sensitivity are about −30.9 dBm and −29 dBm. When ONU1 and ONU3 operate simultaneously, the receiver sensitivity are 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.

6. Conclusion and Discussion

In conclusion, cascaded MDM-TDM-PON based on low mode-crosstalk FMF and all-fiber mode MUX/DEMUX is investigated. Direct detection is used in this proposed cascaded MDM-TDM-PON system, which avoids the usage of DSP request for MIMO demultiplexing in coherent detection systems. The all-fiber mode MUX/DEMUX are composed of MSCs, which simultaneously multiplex or demultiplex LP_{01} and LP_{11} modes. Owing to low-mode crosstalk for FMF transmission and mode MUX/DEMUX, we successfully achieve MDM-PON transmission experiment, where two individual linearly polarized spatial modes are transmitted over 10 km and 55 km low-crosstalk two-mode optical fiber and demultiplexed without MIMO DSP. In addition, both downstream MDM transmission and upstream MDM-TDM transmission are also experimentally demonstrated over 10 km FMF and 10 km SSMF with error-free performance. The design and fabrication of FMF and mode MUX/DEMUX should be improved to realize more independent modes. Although the number of mode may be limited, it can be combined with multi-core technique to further enhance the scale of current PON. The design and fabrication of FMF and mode MUX/DEMUX should be improved to realize more independent modes. Although the number of mode may be limited, it can be combined with multi-core technique to further enhance scale of current PON.

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