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Abstract: We demonstrate the first few-mode-fiber based passive optical network, effectively utilizing mode multiplexing to eliminate combining loss for upstream traffic. Error-free performance has been achieved for 20-km low-crosstalk 3-mode transmission in a commercial GPON system carrying live Ethernet traffic. The alternative approach of low modal group delay is also analyzed with simulation results over 10 modes.

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1. Introduction

Time-division multiplexed (TDM) passive optical networks (PON) (e.g. GPON and EPON) are currently being widely deployed worldwide to satisfy the traffic demand in access networks. There is an increasing interest in PONs towards longer reach and larger splitting ratios to increase coverage and reduce overall cost. To do so, the power budget needs to be improved using innovative solutions. In most practical systems, a large power loss is incurred at collector locations by optical splitters that combine/split signals from/to the optical network units (ONUs). The downstream power splitting enables the essential one-to-many function from the optical line terminal (OLT) to ONUs and thus the splitting losses are unavoidable, but the excess upstream combining loss incurred in one-to-one communication from an ONU to the OLT is neither necessary nor fundamental and can be reduced in a variety of ways. There has been much effort aiming to eliminate the upstream combining loss, such as the use of a multi-mode combiner (MC) [1, 2]. The MC solution, however, requires multiple feeder fibers as shown in Fig. 1(a), which defeats one of the main purposes of fan-out improvement using splitters, that is, the reduction of the total amount of fibers needed in the network.

Recently, we proposed the use of space-division multiplexing (SDM) in a single few-mode fiber (FMF), acting as the feeder fiber in the optical distribution network (ODN), to effectively eliminate the upstream combining loss [3]. Moreover, this concept has been realized by using a commercial GPON system carrying live Ethernet traffic, achieving the first reported few-mode GPON [4]. In this paper, we discuss different approaches to achieve TDM few-mode PON, including the previously demonstrated low-crosstalk method and the low modal group delay (MGD) method. The experimental setup and results of the few-mode GPON system are presented in more depth and details. Future work in this area such as mode-division multiplexing for PON is also discussed.

It should be noted that the application of FMF to access is not simply the transplantation of a long distance optical transport technique to access. Instead, it focuses on the unique requirements of optical access. While in optical transport the usual goal is to maximize spectral efficiency and total information throughput, in access it is most important to maximize the loss budget and split ratio, and reduce cost per subscriber. While throughput is important, it must be balanced against other factors. This brings us to different design strategies which leverage better fiber designs to enable simple direct detection schemes.
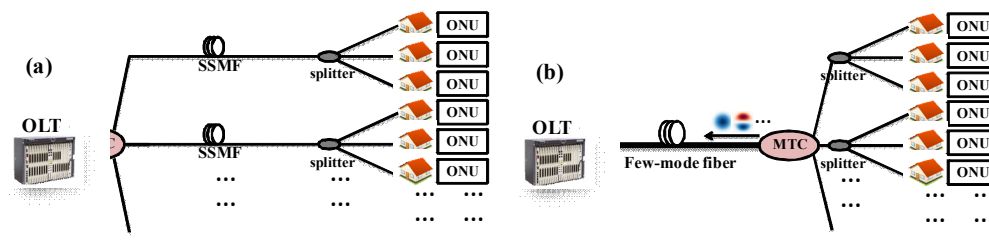

Fig. 1. PON architectures with low upstream loss using (a) multiple feeder fibers and a multimode combiner (MC); and (b) a single FMF with a mode transforming coupler (MTC).

2. Principle of few-mode PON

Figure 1(b) shows the proposed few-mode PON architecture which consists of a FMF and a mode-transforming coupler (MTC) in place of a traditional single-mode combiner/splitter in standard PON systems. The MTC couples multiple single-mode fibers (SMFs) into the FMF. The MTC can combine signals from feeder fibers with negligible losses [5–8] and thus is able to increase the fan-out number by a factor equal to the number of the spatial modes, including the degenerate modes. The critical challenge is from inter-mode crosstalk generated in the MTC as well as along the FMF, and the modal group delay (MGD). In long-haul SDM transmission, inter-mode crosstalk and MGD are equalized by using sophisticated joint coherent detection of all the modes, followed by multiple-input-multiple-output (MIMO) signal processing [9, 10]. For PON applications, coherent detection and MIMO are undesirable due to their high complexity and cost. Fortunately, one can utilize the unique feature of TDM-PON that only one ONU is active upstream at any given time and preserve direct detection in the PON architecture. Given $I_s(t)$ is the only signal transmitted at a time, the detected signal hence can be written as below

$$I_{\text{det}}(t) = a \cdot I_s(t) + \sum_i b_i \cdot I_s(t - \tau_i) + \sum_j c_j \cdot I_s(t - \tau_j) + \cdots, \quad \tau_{i,j} \leq \tau_{MGD} \qquad (1)$$

where the first term is the signal carried by the desired mode while the other terms represents crosstalk from the other modes generated at different locations. Equation (1) reveals two different approaches for successful TDM-PON operation. One is to reduce MGD to be much less than a symbol period and thus the crosstalk becomes part of the signal. The other approach is to suppress the modal crosstalk to be low enough that MGD would no longer be an issue. For the first approach, one needs to design FMF with very low MGD or apply the MGD-compensation method using FMFs of positive and negative MGDs [11, 12]. For the second approach of crosstalk suppression, note that direct detection of all the FMF modes actually relaxes the requirement for crosstalk as mode crosstalk becomes incoherent in intensity detection due to mode orthogonality. Here we first demonstrate the low-crosstalk approach combined with the low-MGD approach for the real experiment on a 20km 3-mode fiber. Because among the three modes, the MGD between the two degenerate LP11 modes is close to zero while between the LP01 and LP11 modes modal crosstalk of the FMF can be low but the MGD is usually large. Therefore the problem is reduced to suppress the crosstalk between the LP01 and LP11 modes for both the MTC and along the FMF. In Section 5 we present simulation results to introduce the possibility of using the low-MGD approach for 10 Gb/s 10-mode transmission without the need of suppressing mode crosstalk.

3. Low-crosstalk few-mode ODN

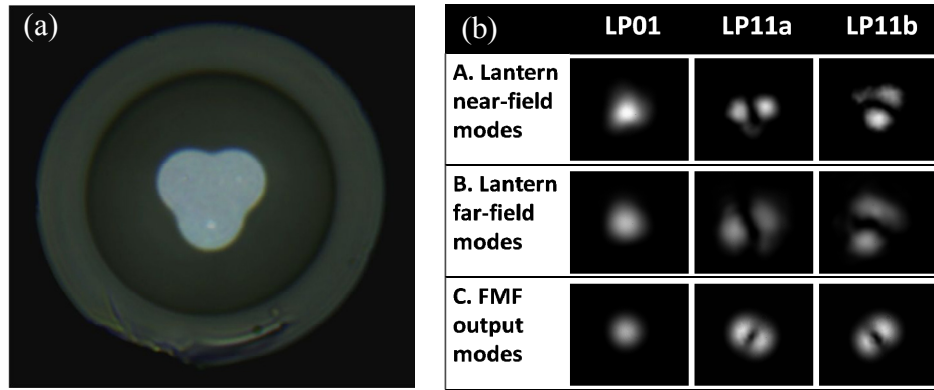| (b)	LP01	LP11a	LP11b
A. Lantern near-field modes			
B. Lantern far-field modes			
C. FMF output modes			

Fig. 2. (a) The cross-section of the mode-selective lantern output; (b) measured LP01, LP11a & LP11b intensity patterns at the lantern near-field, far-field and the end of lantern-to-20km FMF.

In order to demonstrate the low-crosstalk few-mode PON, we first establish the low-loss and low-crosstalk few-mode segment of the optical distribution network (ODN) consisting of the transmission FMF and the MTC. The implementation of the low-loss and low-crosstalk MTC can be done in several ways. Generally speaking, all low-loss mode-division multiplexers that are mode-group selective is suitable for this application, including directional couplers [13], free-space phase-selective devices [14] and mode-group selective photonic lanterns [5–8]. Here the MTC is a mode-selective photonic lantern which converts three single-mode inputs from SSMFs into the LP01, LP11a and LP11b modes of the FMF. The photonic lantern was fabricated by inserting three input fibers into a fluorine-doped capillary with an index difference of 4×10^{-3} and then tapering the entire structure adiabatically. Of the three input fibers, two of them are SMF-28 fibers with propagation constant matched to LP11 modes of the photonic lantern while the other has a slightly larger core of ~15μm and an index difference of 5×10^{-3} so that its propagation constant is matched to that of LP01 mode of the photonic lantern to achieve mode selectivity. The cross-section of the lantern output has a near-triangular core of a diameter of ~27μm as shown in Fig. 2(a). The FMF has a depressed cladding index profile that supports 3 modes, the fundamental LP01 mode and two degenerate LP11 modes, at 1310nm, the upstream wavelength of GPON. Additionally, the LP11 modes are near cut-off at 1550nm and thus become very lossy. The attenuations of the LP01 and LP11 modes at 1310nm are 0.33dB/km and 0.35dB/km respectively while at 1550nm the attenuation of the LP11 mode is 0.192dB/km, all comparable to those of SSMF. The FMF modes are about half sizes of the lantern modes. In order to reduce the coupling loss due to the mode-size mismatch, a lens combination was used for free-space lantern-to-FMF coupling. The near-field and far-field output mode intensity patterns of the photonic lantern and those at the end of the 20km FMF are shown in Fig. 2(b), demonstrating excellent mode selectivity. The insertion loss of the photonic lantern including the splice loss to the single-mode input fibers was 1.3dB, 0.8dB and 1.4dB for the LP01, LP11a and LP11b mode, respectively, representing an average 3.5 dB improvement in the combining loss compared to conventional single-mode splitters. The coupling loss from the lantern output to the FMF, mainly due to mode mismatch between the lantern and the FMF as well as the scattering, was estimated to be 2.4dB for LP01 and 6.7dB, 6.2dB for LP11a&b. Those coupling losses can be substantially decreased by using a photonic lantern better matched to the FMF [3]. The crosstalk of the
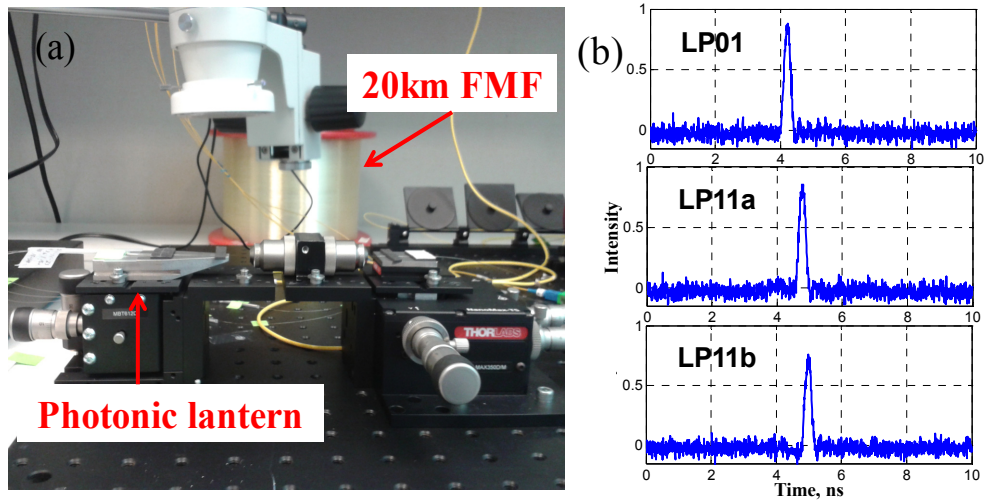
Fig. 3. (a) Picture of the few-mode segment of the ODN; (b) measured LP01, LP11a and LP11b impulse responses of the few-mode ODN segment.

entire few-mode segment shown in Fig. 3(a) was measured by the impulse-response method. In order to do so, a narrow pulse was sent into each input port of the photonic lantern, transmitted through 20km FMF and received by a high-speed free-space-coupled photo-detector. The crosstalk levels were optimized to be less than 9dB for all the three inputs, as shown in Fig. 3(b). The MGD between the LP01 and LP11 modes was characterized at the same time to be ~0.6ns over 20km FMF.

4. Demonstration of few-mode GPON system

We then demonstrate the world's first few-mode GPON system by seamlessly integrating the few-mode ODN in a commercial GPON system with one Huawei OLT and four Echolife ONUs, as shown in Fig. 4. To enable the integration between the few-mode ODN and the otherwise SSMF-based PON optical components, a novel reach extender was added before the OLT to separately detect the upstream data from the FMF in burst mode and to regenerate the data onto a single-mode fiber because the current OLT SFP optical module only accepts single-mode input. Two stages of splitters were created to imitate a real PON network. The WDM filters separate 1310nm and 1490 nm light for the upstream and downstream flow. Since our focus is combining loss for upstream traffic, downstream signals were transmitted over SMF ODN. Modification of the OLT transmitter is required if downstream signals needs to be transported in the few-mode ODN. For upstream, data streams from different ONUs were coupled into the FMF by the 3-mode photonic lantern and transmitted over 20km FMF link. The variable attenuators before the photonic lantern were used to equalize and monitor the power levels. The reach extender regenerates and interleaves upstream and downstream signals, and finally connects to the OLT. Gigabit/s real traffic was monitored by an Ethernet tester.
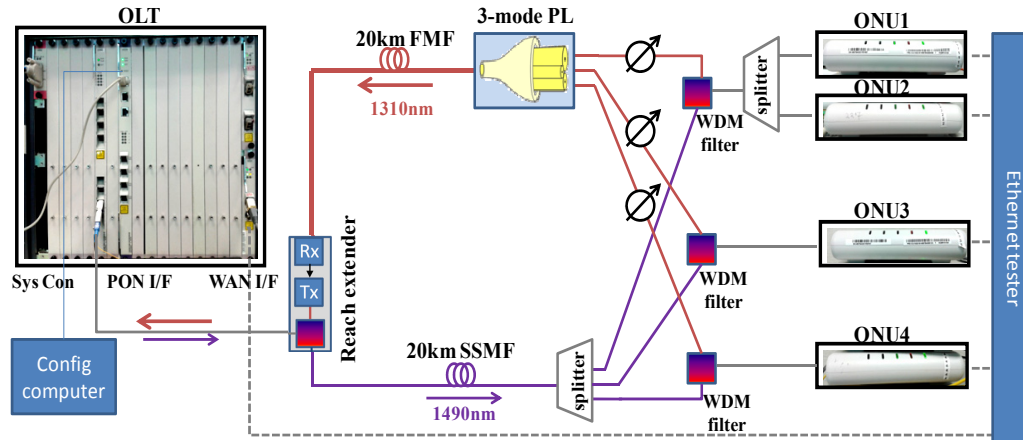
Fig. 4. Schematic of a few-mode GPON system using a 20km FMF and a mode-selective lantern for upstream transmission. OLT: commercial optical line terminal; ONUs: commercial optical network units.

The upstream transport performance through the few-mode ODN was characterized via bit-error-rate (BER) measurements at 1.25 Gb/s using a 1.3μm DFB laser and an APD ROSA without limiting amplification and clock data recovery. The transmitter output was switched to the three photonic lantern input ports one at a time to test each mode. The BER results are plotted in Fig. 5(a). The back-to-back (B2B) receiver sensitivity at a BER of 10^{-3} is −30 dBm. The B2B eye diagram and those after 20km transmission for each mode are shown as Fig. 5(b). The eye diagrams of LP01 and B2B cases are almost identical. The LP11s have slightly degraded performance. Nevertheless, all the modes can achieve a BER of $<10^{-9}$, which is good enough for successful commercial GPON operation. Compared to B2B, the LP11a and LP11b modes exhibit power penalties of 1.5 dB and 2.7 dB, respectively. We attribute these moderate implementation penalties to imperfect matching between the LP11 modes and the free-space-coupled photo-detector area, which was matched to SSMF inputs. This penalty is expected to be eliminated using a properly designed photo-detector. The error-free performance of the few-mode ODN allowed us to carry live Ethernet traffic in the few-mode GPON system using a commercial Ethernet tester. Long-term measurement was done with no packet loss observed over tens of millions of Ethernet packets received.
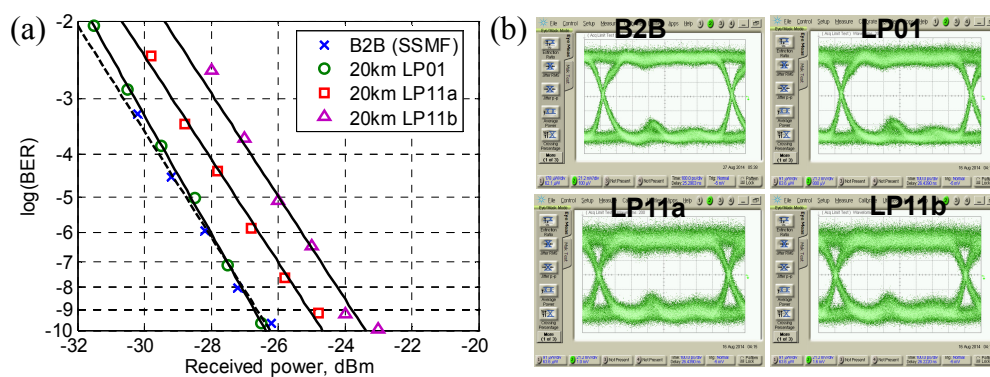

Fig. 5. (a) BER measurements of the few-mode ODN segment; (b) eye diagrams of the cases of B2B (with SSMF), 20km LP01, LP11a and LP11b transmission.

5. Low-MGD approach and design

Even though the low-crosstalk approach has been demonstrated successfully for three-mode transmission, crosstalk suppression for both the MTC and the FMF is still difficult in general, especially when it scales to larger number of modes. On the other hand, the alternative approach only requires the FMF to have low-MGD between all the modes. As a result the requirement for MTC relaxes to be simply low insertion loss, which can be easily achieved [15]. In this section we consider the alternative low-MGD approach when the number of modes scale to 10 (i.e., LP01, LP02 and degenerate LP11s/ LP21s/ LP12s/ LP31s modes). Based on previous works for fewer modes [16, 17], trench-assisted graded-index profile has been found to be useful for MGD optimization and hence will be applied here as well. The inset of Fig. 6 shows the graded-index profile, with a cladding trench for low MGD, given by

$$n(r) = \begin{cases} n(0) \cdot [1 - \Delta_1 \cdot (r / a_1)^{\alpha_n}]^{1/2}, & (r \le |a_1|) \\ n_{cl}, & (|a_1| < r \le |a_2|) \\ n_{cl} \cdot (1 - \Delta_2), & (|a_2| < r \le |a_3|) \\ n_{cl}, & (r > |a_3|) \end{cases} \qquad (2)$$

where α_n is the power coefficient of the GI profile. With fiber parameters chosen as $a_1 = 15.32\,\mu m, a_2 = 17.2\,\mu m, a_2 = 22.12\,\mu m, \Delta_1 = 0.4375\%$ and $\Delta_2 = 0.33\%$, the differential modal group delay of a 10-mode GI FMF (referenced to the average modal group delay) at 1310 nm as a function of the power coefficient is shown in Fig. 6. The maximum MGD (between the fastest and slowest mode) is less than 7 ps/km, achieved near $\alpha_n = 2.0$. This fiber design should be able to support few-mode transmission of reach up to 20 km for standard PON (data rate of 2Gb/s) in presence of mode crosstalk. The high sensitivity of MGD to the power coefficient and other fiber parameters should be studied and improved, possibly using different fiber structures.
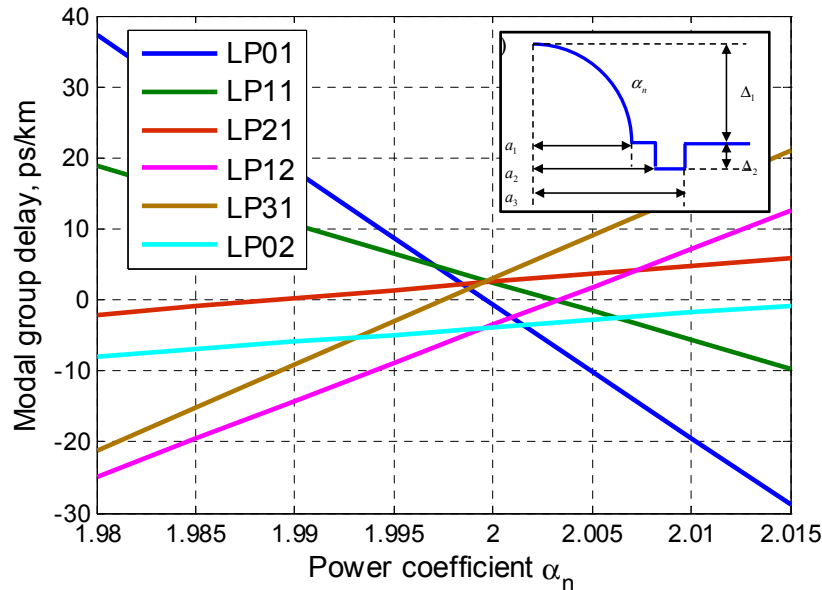

Fig. 6. Simulation results of modal group delay for 10-mode fiber design of trench-assisted graded-index profile. Inset: the FMF index profile with parameters indicated.

6. Discussion and conclusions

We demonstrate, for the first time, a few-mode PON that utilizes mode multiplexing to eliminate the combining losses for upstream traffic. Seamless integration between a few-mode ODN and a commercial GPON system carrying live Ethernet traffic is achieved without any packet loss. Simulation results also indicated the possibility of using the alternative low-MGD approach. The current demonstration represents the most immediate benefits of introducing FMF into PON network. If mode-division demultiplexing is implemented at the OLT, the upstream capacity can be increased, in addition to increases of the fan-out number, by using mode-division multiplexing (MDM). In principle, if the crosstalk of FM ODN is low enough, MDM can be implemented with direct detection by adding a low-crosstalk mode-group multiplexer at the OLT. The crosstalk requirement for MDM FM PON is expected to be higher than for TDM FM PON. The beneficial combination of SDM and PON may open exciting opportunities for future research, development, and commercialization.