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Experimental Demonstration of 6-Mode Division Multiplexed NG-PON2: Cost Effective 40 Gbit/s/Spatial-Mode Access Based on 3D Laser Inscribed Photonic Lanterns

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Abstract *We report the first space-division-multiplexed based symmetric NG-PON2 network by efficiently transmitting 40 Gbit/s/spatial-mode. Error free transmission (BER of 10^{-9}) is obtained for all the downstream and upstream data tributaries over 1-km 6-spatial-mode FMF without using MIMO DSP.*

State of the Art

Space division multiplexing (SDM) based on either multi-core fibers (MCFs) or few-mode fibers (FMFs) enables capacity escalation beyond that of single-mode fibers (SMFs)[1] by transmitting multiple data streams over spatial paths[2]. During last few years there have been concerted efforts invested in FMFs for long-haul transmission[2]. The spatial modes generally exhibit differential mode group delay (DMGD) and differential modal loss/gain. To mitigate these linear impairments, equalization by multiple-input multiple-output (MIMO) digital signal processing (DSP) is required at receiver. On the contrary, there is an increasing interest in SDM-PONs, as summarized in Fig. 1, towards larger splitting ratios (SRs) to increase coverage and reduce overall cost[3,4] by incorporating low-modal-crosstalk fiber so that discrete spatial modes can be detected individuality without using MIMO DSP[5–7].

In most practical systems, the limitation of having higher SRs is the power budget due to the fact that characteristically SMF splitters have an unavoidable bi-directional loss[8]. In order to avoid these losses, multiple feeder fibers are needed. This up-gradation will cause congestion in the installation ducts and laborious maintenance[9]. As

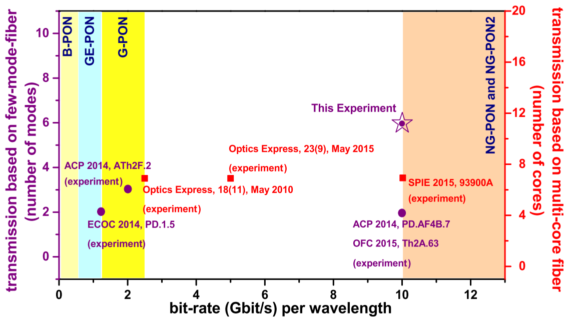


Fig. 1: Recent demonstrations of FMF and MCF based PON networks vs. deployable bit-rates. [●=FMF and ■=MCF]

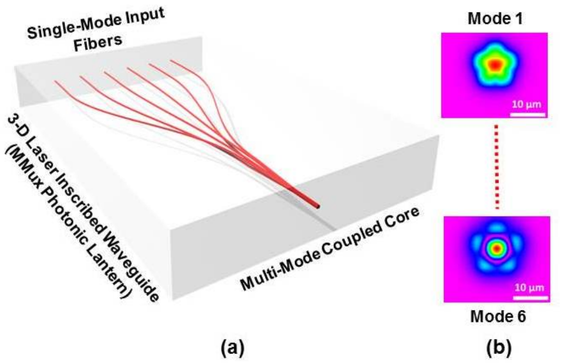


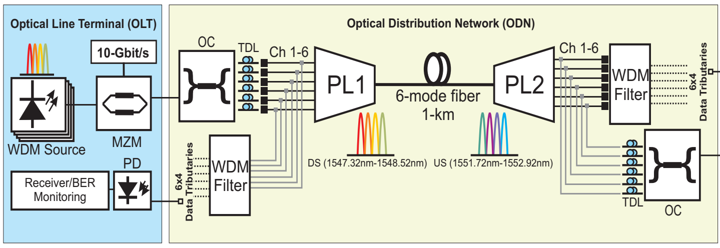
Fig. 2: (a) 3D Laser inscribed 6:1 photonic lantern and (b) Typical super-mode profiles at the output of photonic lanterns.

an alternative, FMF-PONs have been demonstrated[5,6] with 2-LP modes (LP_{01}, LP_{11}) and bit-rates of 1.25 Gbit/s and 10 Gbit/s, respectively.

In this article, we report the first SDM based next-generation passive optical network stage-2 (NG-PON2), ITU-T G.989, that is capable of transmitting 6-spatial-modes with 40 Gbit/s/mode bit-rate employing 3D laser inscribed photonic lanterns as mode multiplexers (MMuxs). Both downstream (DS) and upstream (US) transmission performances are experimentally analyzed over 1-km of 6-spatial-mode FMF.

3D MMux Photonic Lantern Waveguide

Photonic lantern (PL), i.e. conventional or mode selective, is one of the several breakthroughs that are revolutionizing SDM transmission[10]. A few other MMuxs have been proposed including spatial light modulators (SLMs) and phase plates. But these are comparatively expensive, especially in case of PONs where cost-effectiveness is enviable. In contrast to phase-plate based MMuxs that launch and detect signals directly from a particular linearly polarized (LP) mode, 3D MMuxs launch signal power equally into a linear combina-



(a)

Total Insertion Loss (dB) including delay lines + PL1 + PL2 + 6-mode fiber + all splices	
Channels	Loss (dB)
1	4.6
2	5.8
3	6.1
4	5.4
5	5.3
6	4.4

(b)

Fig. 3: (a) Experimental setup for 40 Gbit/s/spatial-mode WDM-NG-PON2 network based on 3D laser inscribed photonic lanterns and (b) Summary of the insertion loss test for ODN. [PD: photo-detector, OC: optical coupler, TDL: tunable optical delay lines, Ch: channel, PL: photonic lantern, MZM: Mach-Zehnder modulator]

tion of modes[10]. The design of MMuxs based on 3D waveguide is economical and complementary to conventional PL, as shown in Fig. 2(a). This geometry brings 6 SMF cores (channels) together such that they couple and the resultant 6 super-modes of the coupled array very closely approximate the FMF modes[10], as shown in Fig. 2(b).

For this experiment, ultrafast laser inscription (ULI)[11] is used to fabricate waveguides with a 4 μm^2 cross-section and refractive index contrast (Δn) of 0.7%, which support a single mode at a wavelength of 1550 nm. ULI enables 3D routing of these waveguides into an adiabatically tapered, centered-pentagonal geometry which gradually couples the single mode waveguides such that the resultant super-modes couple strongly with the guided modes of the FMF. The fiber to fiber insertion loss from SMF-28 to a commercially available OFS graded index FMF (4 LP modes, or 6-spatial-modes) was 2.0 dB or less across the 6 channels of the PL. Polarization dependent loss (PDL) was measured to be less than 0.1 dB for all 6-spatial channels.

Experimental Setup

The experimental setup for SDM based NG-PON2 is shown in Fig. 3(a). A distributed feedback laser (DFB) bank is used to generate 2 sets of 4 wavelength-division-multiplexed (WDM) channels with 50 GHz channel spacing. WDM filters are incorporated to separate and identify the channels; i.e., (a) for optical line terminal (OLT): 1547.32 nm, 1547.72 nm, 1548.12 nm, 1548.52 nm as downstream (DS) and (b) for optical network unit (ONU): 1551.72 nm, 1552.12 nm, 1552.52 nm, 1552.92 nm are used as upstream (US) data tributaries for experimental demonstrations. Each of the WDM signal is modulated via a Mach-Zehnder modulator (MZM) and 10 Gbit/s On-Off keying (OOK) signal with 2^{31}-1 pseudo-random sequence length is generated. The resulted signal is further split into 6 paths with a relative delay of 3-symbols between the subsequent paths, by using tunable optical delay lines (TDL). This relative delay is optimized so as to produce 6 fully de-correlated signal copies at the input of PL. Each of the input port of PL has an aggregated data rate of 40 Gbit/s. The delayed signal copies are fed to the ingress section of optical distribution network (ODN) connected to FMF by 3D MMUX. The ODN comprises of 2 PLs and 1 km 6-spatial-mode FMF having cladding diameter of 125$\pm$0.7 μm and a maximum differential group delay of +0.14 ps/m between all the modes. The attenuation loss (α) of all the modes in the fiber is $<$0.22 dB/km. The insertion loss is measured for all PL channels and is enlisted in Fig. 3(b).

After transmission through ODN, the received signal is sent into ONU, that comprises of pre-amplified receiver for BER measurements. Due to the equipment limitation, DS and US signals are monitored sequentially, nevertheless during all measurements DS and US data tributaries are transmitted in the ODN. At ONU, all the modes are de-multiplexed and individually detected without using complex MIMO DSP due to fact that each mode group has a significantly different propagation constant due to TDL in addition to the low modal crosstalk (XT) fiber.

Results and Discussion

We first measure the receiver sensitivity of DS signals. After the optimization of WDM filter at ONU, we have 24 data tributaries (6-modes $\times$ 4λ) to receive. The results for 1547.32 nm wavelength for all the 6-modes are plotted in Fig. 4.

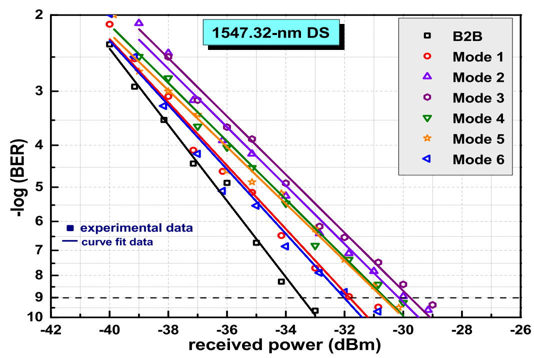


Fig. 4: Measured receiver sensitivity for downstream (DS) transmission for all 6 spatial modes.

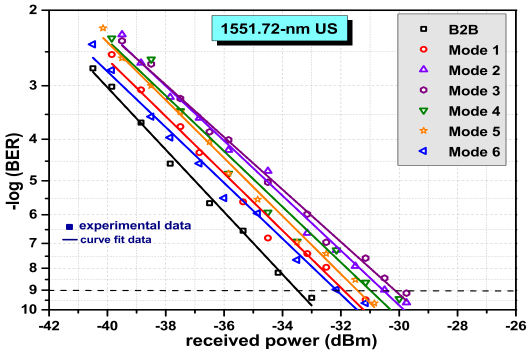


Fig. 5: Measured receiver sensitivity for upstream (US) transmission for all 6 spatial modes.

The back-to-back (B2B) receiver sensitivity at a BER of 10^{-9} is -33.60 dBm. The spatial modes that are generated from 3D MMux PL waveguide (mode 1-6) are compared with B2B performance. The power penalties at a BER of 10^{-9} are measured as 1.76 dB, 3.47 dB, 3.84 dB, 3 dB, 2.9 dB, 1.6 dB for modes 1-6 respectively. The variance in the power penalty among different modes are mainly due to the scattering and coupling losses between PL and 6-mode fiber. Nevertheless, all the spatial modes achieve a BER of $<10^{-9}$, which is advantageous for successful commercial and economical SDM-PON operation.

The US signals are de-multiplexed and respectively detected in OLT. The receiver sensitivity for the US signals for 1551.72 nm wavelength are plotted in Fig. 5. The B2B receiver sensitivity at a BER of 10^{-9} is -33.43 dBm. The power penalties at a BER of 10^{-9} are measured as 1.48 dB, 3.03 dB, 3.29 dB, 2.4 dB, 2.05 dB, 1.26 dB for modes 1-6 respectively. Furthermore, we analyzed all the 48 data tributaries for DS and US and plotted the receiver sensitivity at BER of 10^{-9} as shown in Fig. 6. We have observed negligible wavelength dependence on system performance for DS and US signals. It is also worth mentioning that in this experiment: (a) DS and US signals are transmitted by same 6-spatial-mode FMF as compared to the previous demonstration[5], where FMF is used for US and SMF is opted for DS data flow and (b) 3D laser inscribed photonic lanterns are incorporated in ODN, whereas free-space mode multiplexers and de-multiplexers are used in[6], which may be not easily integrated into commercially available transmitter and receiver.

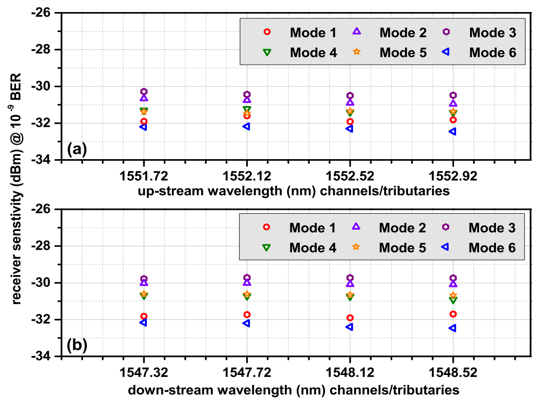


Fig. 6: Measured receiver sensitivity at BER of 10^{-9} of all SDM and WDM tributaries after 1-km transmission.

Conclusion

We successfully demonstrated the first SDM based symmetric NG-PON2 network by efficiently transmitting 40 Gbit/s/spatial-mode. Both DS and US signals are experimentally investigated to validate the architecture and error-free performance for all the SDM-WDM tributaries is achieved. The results show promising impact of SDM on NG-PON2 for incorporating higher split-ratio and increasing the transmission capacity at access network level.

Acknowledgments

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