Photonic-Lantern-Based MDM Devices

Grüner-Nielsen, Lars; Mathew, Neethu Mariam; Galili, Michael; Rishøj, Lars Søgaard; Rottwitt, Karsten

Published in:
Proceedings of 2023 Optical Fiber Communications Conference and Exhibition

Link to article, DOI:
10.23919/OFC49934.2023.10116116

Publication date:
2023

Document Version
Peer reviewed version

Citation (APA):
Grüner-Nielsen, L., Mathew, N. M., Galili, M., Rishøj, L. S., & Rottwitt, K. (2023). Photonic-Lantern-Based MDM Devices. In *Proceedings of 2023 Optical Fiber Communications Conference and Exhibition* IEEE. https://doi.org/10.23919/OFC49934.2023.10116116

Photonic-Lantern-Based MDM Devices

Lars Grüner-Nielsen,[1,2,*] Neethu Mariam Mathew,[2] Michael Galili,[2] Lars Søgaard Rishøj,[2] and Karsten Rottwitt[2]

[1] *Danish Optical Fiber Innovation, Åvendigen 22A, 2700 Brønshøj, Denmark*
[2] *DTU Electro, Technical University of Denmark, Ørsteds Plads 343, 2800 Kongens Lyngby, Denmark*

[*] *lars@dofi.dk*

Abstract: Results for air clad photonic lanterns are presented including new results for a 6-mode photonic lantern. Results for cross talk dynamics in a 1.6 km link versus both time and wavelengths are presented.

1. Introduction

Mode multiplexers are essential components for mode division multiplexed (MDM) systems [1]. Nowadays, the most common techniques for mode multiplexers are: 1. Multi-plane light converters (MPLC) [2], 2. Fused couplers [3], and 3. Photonic lanterns (PL). Very impressive results have been obtained using MPLC including MDM transmission of 55 spatial modes over 26 km [4]. PL for up to 61 spatial modes have been demonstrated [5], however, in this case, it was a non-mode selective lantern. For mode selective PL, lanterns with three and six modes has been demonstrated with good mode selectivity. Mode selective PL with 10 and 15 spatial modes have been demonstrated but the mode selectivity was not that good in these cases [6]. Compared to MPLC, mode selective PL has only been demonstrated for fewer modes but has the advantage of being an all fiber component and very compact in size. Basically, a PL is simply a bundle of single mode fibers, which are tapered down over a few cm and spliced to a few mode fiber. PL in general also have lower loss than MPLC [1].

The focus in our research group has been on photonic lanterns for intensity modulated direct detection systems. We have developed mode selective air clad PL for three spatial modes [7, 8] and here we report the first result for a six mode air clad PL.

2. Air Clad Photonic Lanterns and their use for MDM

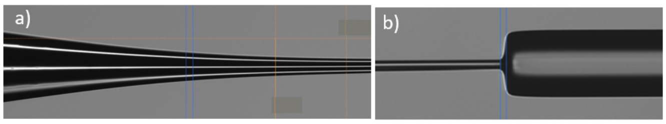

Fig. 1. Lantern fabrication. a) Three fiber taper (Normally much longer), b) taper end spliced to a few mode fiber.

The principle of an air clad photonic lantern is illustrated in fig. 1. An example of a three fiber taper is shown in fig. 1.a. The basic principle of a PL is that when the fibers are tapered down, the modes of the three single mode fibers expand and transform into higher order modes guided in the original silica cladding with the surrounding air now acting as the cladding. For illustration the taper length in fig. 1.a is only around 2 mm. For actual PL, taper lengths of 20 to 40 mm are used to assure an adiabatic transition from the input single mode fiber modes to the modes at the taper end. Fig. 1.b shows the splice from the taper end to the few mode fiber. The taper ratio is optimized to get highest possible overlap between the few mode fiber modes and the modes at the taper end.

Our air clad PL for three spatial modes consists of three fibers fused together, down tapered, and spliced to an OFS two mode step index fiber (TMSIF). The TMSIF guides two LP modes, equivalent to three spatial modes. The taper is made using one large core and two small core single mode fibers (SMF). The large core SMF is for coupling to the fundamental mode of the TMSIF and the two small core SMF are for coupling to the LP_{11a} and LP_{11b} mode group. The large core fiber is a Thorlabs SM2000 fiber and the small core fibers are OFS ClearLite 16 fibers. Three-fiber multiplexing lanterns have been fabricated with insertion losses of 0.7 and 1.6 dB for the LP_{01} and LP_{11} inputs respectively. The maximum polarization dependent cross talks were -15 and -18 dB for the LP_{01} and LP_{11} inputs respectively. Three-fiber demultiplexing lantern has been fabricated with insertion losses of 1.5 and 3 dB and maximum polarization dependent cross talks of -11 and -9 dB for the LP_{01} and LP_{11} inputs respectively [8]. These lanterns has been used for various successful MDM transmission experiments including transmission over 20 km two mode fiber [7], and 1.6 km of standard multimode fiber [8].

Recently, we have also started to work on PL for six spatial modes. One Thorlabs SM2000 fiber, two standard single mode fibers, two Corning HI1060, and finally one OFS ClearLite 16 fiber for coupling to LP_{01}, LP_{11}, LP_{21} ,and LP_{02} respectively are used. Furthermore, a single core less fiber is used to fill out the geometry [9]. A maximum polarization dependent multiplexing cross talk for all four modes of -8 dB was measured.

3. Cross talk dynamics

The cross talk of mode multiplexers is in general not constant but vary with the input polarization. For demultiplexing, it depends both on the polarisation and for degenerate modes as well on the power distribution between the two degenerate modes. There has so far not been much study on the dynamics of these cross talk variations. This can for example be of importance for design of DSP for cross talk compensation as suggested by Yankov et al. [10].

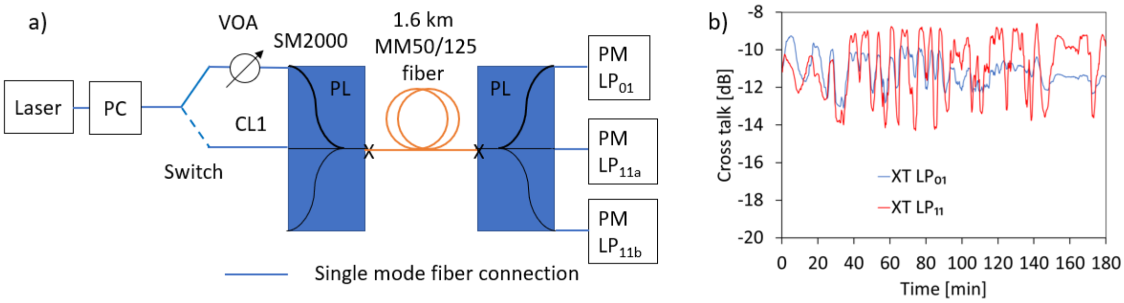

Fig. 2. a. Set up for measuring Cross talk dynamics. PC: Polarization Controller, VOA: Variable Optical Attenuator, PL: Photonic Lantern, PM: Power Meter. b. Measured cross talk versus time.

To examine the dynamics of the cross talk, we have used the setup of 2.a. A tunable laser is via a polarization controller and an optical switch connected to the multiplexing lantern. The multiplexing lantern is connected to the demultiplexing lantern via 1.6 km of standard graded index 50/125 μm multimode (MM) fiber. The lanterns and the MM fiber are the same as used for successful MIMO free MDM transmission [8]. The powers out of the three fibers of the demultiplexing lantern are measured with three power meters. As also done in the transmission experiment, the LP_{11} power is detected as the sum of powers out of the two LP_{11} ports. A variable attenuator in the SM2000 input arm is used to adjust to the same cross talk level for the two modes. This is similar to what is done in transmission experiment, where the input powers are adjusted for best performance [8].

The time variation of the cross talk is measured for a fixed wavelength of 1550 nm and a fixed position of the polarization controller. The powers are measured every 15 second for the two positions of the switch and the cross talk for the LP_{01} mode is calculated as the difference of the power measured with the LP_{01} power meter for the switch connected to the SM2000 input port (which launch LP_{01} into the MM fiber) and the power measured with the switch connected to the CL1 port (which launch LP_{11} into the MM fiber). The cross talk for the LP_{11} mode is measured in the same way, looking at the sum of the powers of the LP_{11} power meters for the switch in the two positions. Measured cross talk versus time over 3 hours is shown in fig. 2.b. A Fourier transform of the measurement for the LP_{01} mode is shown in fig. 3.a. It is observed that the variation of the cross talk happens with a period greater than 3 minutes and most of the variations happens with a period larger than 5 minutes. The Fourier transform of the variation for LP_{11} looks very similar. The distribution of the cross talk for both modes are shown in fig. 3.b and 3.c. A worst case cross talk of -9 dB is observed for both modes. The distribution for the LP_{11} mode is somewhat broader than for LP_{01}.

For comparison, the cross talk versus wavelength has been measured for 10 randomly selected position of the polarization controller. The wavelength is scanned in 0.002 nm steps in a 0.2 nm range. The measurement time for one wavelength scan is around 2 minutes, that is around 20 minutes for all 10 polarizations. The result for the LP_{01} mode is shown in fig. 3.d. A clear beat period of 0.024 nm is observed, corresponding to the differential group delay of 330 ps between LP_{01} and LP_{11} in the used 1630 m MM fiber. The distribution of the cross talk for all wavelengths and all polarizations for both modes are shown in fig. 3.d and 3.e. When comparing the distribution for cross talk versus time and cross talk versus wavelength, they look pretty similar except for that the cross talk distributions for the wavelength scan has a low cross talk tail.

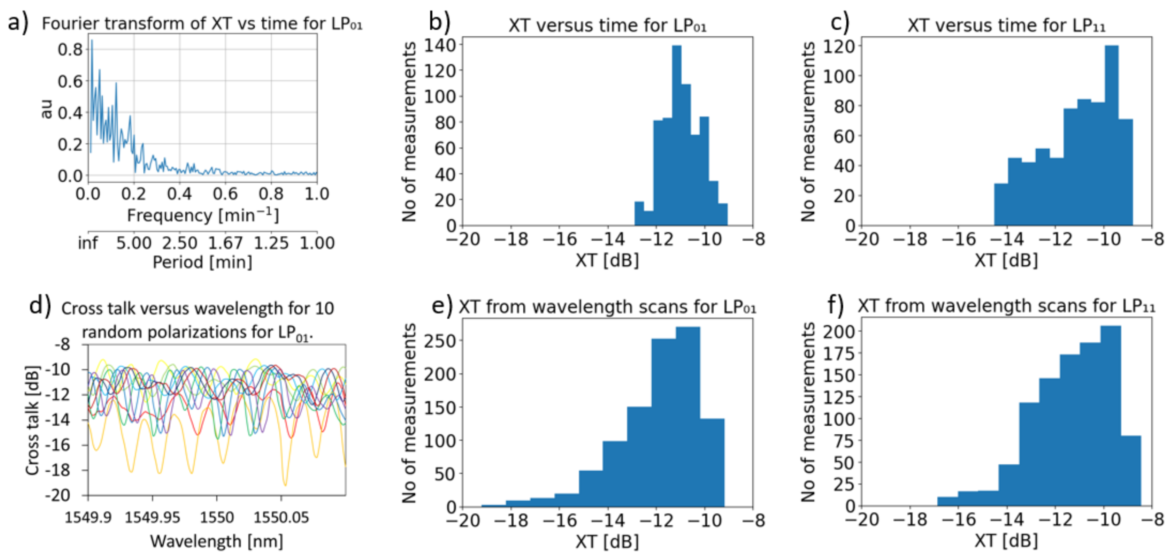

Fig. 3. Results Cross talk dynamics

4. Conclusion

Results for cross talk dynamics in a few mode system has been presented. The variation over time observed is rather slow with periods above 5 minutes. Cross talk variation over time show quite similar distribution as cross talk measured versus wavelength and input polarization.

5. Acknowledgements

This work was supported by the Innovation Fund Denmark under Project GO-SENS 0224-00074B.

References

1. N. K. Fontaine, J. Carpenter, S. Gross, S. Leon-Saval, Y. Jung, D. J. Richardson, and R. Amezcua-Correa, “Photonic lanterns, 3-d waveguides, multiplane light conversion, and other components that enable space-division multiplexing,” Proc. IEEE pp. 1–14 (2022).
2. G. Labroille, B. Denolle, P. Jian, P. Genevaux, N. Treps, and J.-F. Morizur, “Efficient and mode selective spatial mode multiplexer based on multi-plane light conversion,” Opt. Express **22**, 15599–15607 (2014).
3. S. H. Chang, S.-R. Moon, H. Chen, R. Ryf, N. K. Fontaine, K. J. Park, K. Kim, and J. K. Lee, “All-fiber 6-mode multiplexers based on fiber mode selective couplers,” Opt. Express **25**, 5734–5741 (2017).
4. G. Rademacher, R. S. Luís, B. J. Puttnam, N. K. Fontaine, M. Mazur, H. Chen, R. Ryf, D. T. Neilson, D. Dahl, J. Carpenter, P. Sillard, F. Achten, M. Bigot, J. Sakaguchi, and H. Furukawa, “1.53 peta-bit/s c-band transmission in a 55-mode fiber,” in *European Conference and Exhibition on Optical Communication,* (Optica Publishing Group, 2022), p. Th3C.3.
5. D. Noordegraaf, P. M. W. Skovgaard, M. D. Maack, J. Bland-Hawthorn, R. Haynes, and J. Lægsgaard, “Multi-mode to single-mode conversion in a 61 port photonic lantern,” Opt. Express **18**, 4673–4678 (2010).
6. A. M. Velázquez-Benítez, J. E. Antonio-López, J. C. Alvarado-Zacarías, N. K. Fontaine, R. Ryf, H. Chen, J. Hernández-Cordero, P. Sillard, C. Okonkwo, S. G. Leon-Saval, and R. Amezcua-Correa, “Scaling photonic lanterns for space-division multiplexing,” Sci. Reports **8**, 8897 (2018).
7. N. M. Mathew, J. B. Christensen, L. Grüner-Nielsen, M. Galili, and K. Rottwitt, “Air-cladded mode-group selective photonic lanterns for mode-division multiplexing,” Opt. Express **27**, 13329–13343 (2019).
8. L. Grüner-Nielsen, N. M. Mathew, M. H. Nymann, M. Lillieholm, M. Galili, and K. Rottwitt, “Mode division multiplexing on standard 50/125 µm multi mode fiber using photonic lanterns,” in *Optical Fiber Communication Conference (OFC) 2021,* (Optica Publishing Group, 2021), p. W6A.41.
9. N. M. Mathew, L. Grüner-Nielsen, Z. Wang, L. S. Rishøj, and K. Rottwitt, “Broadband air-clad lp02 mode converter using a tapered mode transition,” Opt. Lett. **47**, 38–41 (2022).
10. M. P. Yankov, F. Da Ros, S. Forchhammer, and L. Grüner-Nielsen, “Capacity and achievable rates of fading few-mode mimo im/dd optical fiber channels,” in *ICC 2022 - IEEE International Conference on Communications,* (2022), pp. 769–774.