3D Waveguide and All-Fiber “Photonic Lantern” Spatial Multiplexers

Nicolas K. Fontaine

Bell Laboratories/Alcatel-Lucent, 791 Holmdel Rd., Holmdel, NJ 07733, USA

Abstract—Space-division multiplexing requires spatial-multiplexers that support over 10 modes with low insertion loss and low mode-dependent loss. Photonic lantern spatial multiplexers provide a lossless interface between N single-mode fibers and the N modes of a multi-mode fiber. Devices fabricated using all-fiber technology and 3D waveguide technology have enabled transmission in multi-mode fibers supporting 12 spatial and polarization modes.

I. INTRODUCTION

A “photonic lantern” is an adiabatic mode-converter which merges N single-mode waveguides into a multi-mode waveguide that supports N modes [1–5]. If the taper is long enough (i.e., adiabatic), the fundamental mode on each single-mode waveguide excites an orthogonal combination of the N modes supported by the multi-mode waveguide. Historically, the photonic lantern was developed for astronomy, which required a way to collect light with a large aperture (i.e., multi-mode fiber) and fan it out into high-resolution instrumentation which required single-mode interfaces. Lanterns have been fabricated using laser inscribed 3D waveguide technology which allows for flexible waveguide layout [6], and in all-fiber technology which enables a very low loss direct transition between single-mode fibers and the multi-mode fiber. Devices for astronomical applications have been demonstrated with up to 61 fibers [7], or 121 3D waveguides [8].

Recently, photonic lanterns have found new uses in space-division multiplexing (SDM) which uses the N modes of a multi-mode fiber to increase the capacity carried by a single fiber. Compared to using parallel fibers, using the spatially overlapping modes of a multi-mode fiber enables building components and devices that act on all modes simultaneously

Fig. 1. Space-division multiplexing system using multi-mode fiber. Photonic lanterns can be used as the spatial-multiplexer, inside of the amplifiers, and inside the wavelength switches (WSS).

Fig. 2. (a) Two 6 mode (5+1) all-fiber photonic lanterns connected to a multi-mode fiber. (b) Propagation constants vs. inner diameter of capillary during the taper.

which can reduce system costs. While photonic lanterns designed for astro-photonics only require low insertion loss (IL), the lanterns for SDM must also have low mode-dependent loss (MDL) which requires careful control of the waveguide geometry inside the taper [3]. Figure 1 shows such an SDM system which contains photonic lantern spatial-multiplexers (SMUX) that provide a lossless interface back and forth between single-mode fibers and multi-mode fibers. In addition to the SMUXes, photonic lanterns can be used in the routing elements, such as wavelength selective switches (WSS), to minimize modal dependencies by first demultiplexing the modes into separate freespace beams [9] or separate fibers [10] and then passing them through identical single-mode components. Multiple-input multiple-output (MIMO) signal processing is used to undo any mode-mixing that occurs in the SDM system. Since mixing and scrambling occur in the multi-mode fiber, amplifiers, and routing elements, it is not necessary for the photonic lantern SMUX to excite individual modes, which simplifies its design and enables scaling to a large number of modes.

Fig. 3. 3D waveguide photonic lantern.

Fig. 4. Fabricated six-mode lantern showing an image of the output facet and the output intensity when exciting each SMF input.

Devices supporting 12 spatial and polarization modes (i.e., six input SMFs) have enabled transmission over 177 km of few-mode fiber [11], and 17 km transmission over a conventional 50 μm graded-index fiber [12]. In this paper, we will explain the operation principle of the 3D waveguide and fiber based photonic lantern.

II. THREE-DIMENSIONAL WAVEGUIDE PHOTONIC LANTERN

Figure 3 shows a 3D waveguide photonic lantern that consists of six single-mode waveguides which are slowly merged until they almost touch (i.e., a coupled-core waveguide). Figure 5 shows the modes and their propagation constants during the taper. At the input, the modes are degenerate, they have a Gaussian shape, and are in separate waveguides. At the coupled-core output, the modes are almost identical to the multi-mode fiber modes and have different propagation constants (i.e., non-degenerate). If the taper is adiabatic and has the correct geometry, the Gaussian beams slowly evolve from have Gaussian shape into the multi-mode fiber modes.

III. ALL-FIBER PHOTONIC LANTERN

A fiber lantern [Figure 2(a)] is built by placing multiple SMFs into a low refractive index capillary tube. The structure is tapered until the SMF index capillary tube. The SMF claddings become the new multi-mode core, and the low-index capillary becomes the multi-mode fiber cladding. Figure 2(b) shows the modal analysis of the fiber lantern which shows the originally degenerate SMF input modes evolving into the MMF modes. In contrast to the 3D waveguide lantern, the fiber lantern has cladding modes (red curves) which can be inadvertently excited if the taper is too fast. Figure 4 shows the output patterns of a fabricated six-mode lantern

Fig. 5. (a) Mode evolution in the 3D waveguide photonic lantern. (b) Mode effective indexes and (c) calculated IL and MDL.

when each SMF core is excited. The output patterns are orthogonal combinations of the multi-mode fiber modes rather than individual fiber modes.

IV. CONCLUSIONS

We have shown all-fiber and 3D-waveguide based photonic lantern spatial multiplexers. These SMUXes are scalable to 50+ modes and can enable high capacity SDM.

ACKNOWLEDGEMENTS

The author thanks Sergio Leon-Saval, Roland Ryf, Binbin Guan, and Haoshuo Chen. This work was partly supported by the IT R&D program of MKE/KEIT. [10043383, Research of Mode-Division-Multiplexing Optical Transmission Technology over 10 km Multi-Mode Fiber].

REFERENCES

- [1] S. G. Leon-Saval *et al.*, *Optics Letters* **30**, 2545–2547 (2005).
- [2] S. Yerolatsitis *et al.*, *Optics Express* **22**, 608–617 (2014).
- [3] N. K. Fontaine *et al.*, *Optics Express* **20**, 27,123–27,132 (2012).
- [4] S. G. Leon-Saval *et al.*, *Optics Express* **22**, 1036 (2014).
- [5] I. Giles *et al.*, in *Optical Fiber Communication Conference Tu3D.1*, (2014).
- [6] P. Mitchell *et al.*, in *Optical Fiber Communication Conference M3K.5*, (2014).
- [7] D. Noordegraaf *et al.*, *Optics Express* **18**, 4673 (2010).
- [8] R. R. Thomson *et al.*, *Optics Letters* **37**, 2331–2333 (2012).
- [9] N. K. Fontaine *et al.*, in *Optical Fiber Communication Conference Th4A.7*, (2014).
- [10] J. A. Carpenter *et al.*, in *Optical Fiber Communication Conference Th4A.2*, (2014).
- [11] R. Ryf *et al.*, in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013 PDP5A.1*, (2013).
- [12] R. Ryf *et al.*, in *Optical Fiber Communication Conference: Postdeadline Papers Th5B.1*, (2014).