Technical Brief #8

Fiber Space (De)Multiplexer based on Photonic Lantern

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This note is one of a series of technical briefs developed from customer FAQs and intended to answer the majority of questions concerning the operation of Phoenix products. They are targeted at engineers to assist in incorporating Phoenix products into designs. Any detailed technical questions should be forwarded to Phoenix support.

Mode multiplexer/demultiplexer for Space Division Multiplexing (SDM).

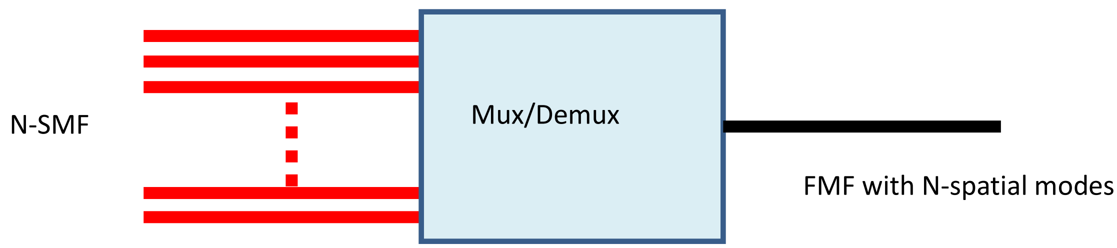
The concept of the mode multiplexer is to provide a smooth transition from a single mode in a single fiber to one or more modes in a single multimode fiber. In general the input fibers are single mode (SMF) and the output few mode (FMF). Optimum performance is achieved when the number of input SMF's is equal to the number of modes supported by the FMF.

Mode multiplexers can either couple from a single mode fiber directly to specific modes of an FMF or couple to a full set of modes with each generated set mutually orthogonal [1]. The Photonic Lantern is the latter type of multiplexer.

The modes are fully mixed and can be unraveled with the use of multiple-input multiple-output (MIMO) signal processing techniques [2].

Photonic Lantern

The Photonic Lantern couples the power from N-individual single mode fibers (SMFs) to a multimode fiber. The performance parameters are optimized when the number of inputs fibers is equal to the number of modes. Although originally developed for astronomical applications [3], the lantern is ideal for multiplexing from N-SMF's to N-mode few mode fiber (FMF) in space division multiplexing (SDM) systems [4]

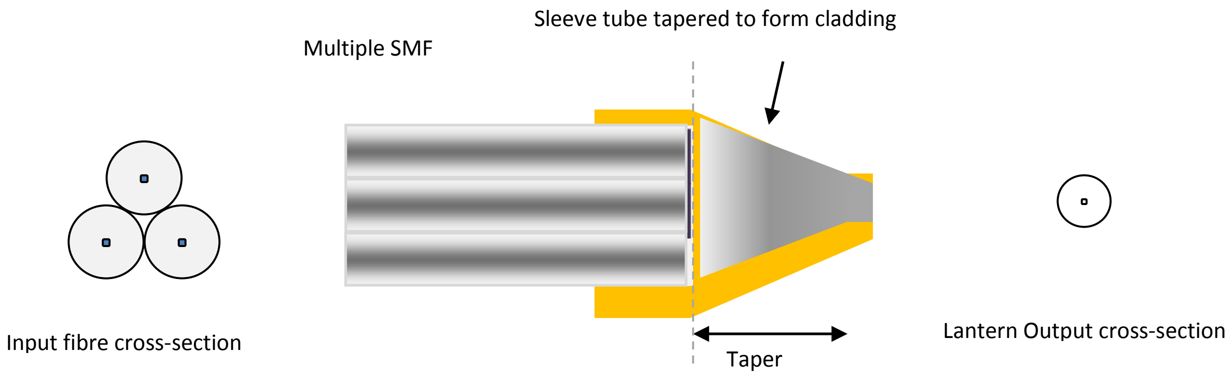


Schematic of photonic lantern in which N-input SMFs are coupled into the modes of an N-mode fiber.

The Phoenix Photonic Lantern is an adiabatic taper that provides a low loss transition from the input fibers to the modes supported by the waveguide at its output. In general, the taper output FMF does not match that of the system FMF, which will create both insertion loss (IL) and mode dependent loss (MDL). Therefore, mode matching is important to optimize the performance from SMF's to system FMF. Incorporated within the Phoenix Photonic Lantern is matching between the multimode taper output to the transmission FMF.

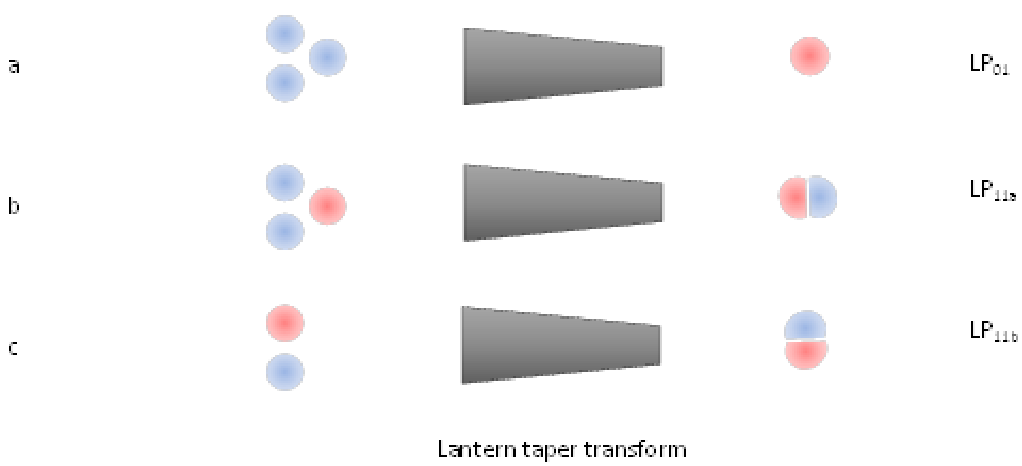
Fiber Photonic Lantern

The fiber Photonic Lantern consists of a set of SMFs contained in an outer capillary tube with refractive index below that of Silica. The combined structure is adiabatically tapered to a diameter such that the resulting waveguide supports the number of modes equal to the number of input SMFs.



Schematic of fiber photonic lantern showing taper of three SMFs in outer lower index capillary tube.

The modes evolve along the fiber from a single mode input to a combination of modes at the taper output [4]. The taper for a 3-mode fiber is shown in the following diagram, launching the supermodes of the structure in correct amplitude and phase relationships from the SMFs generates the LP_{01}, LP_{11a} and LP_{11b} modes at the lantern output.



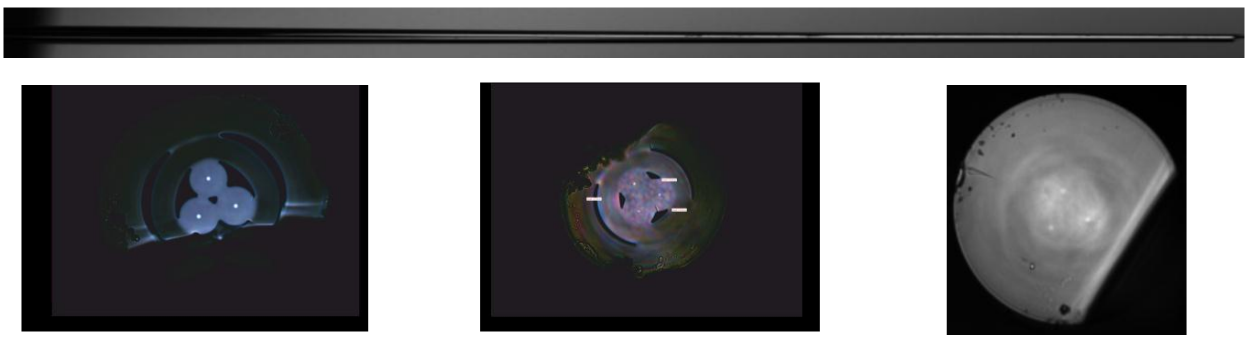
Supermode launch into a 3-fiber taper, the two colors represent the relative phase relationship (0, π)

Launching into individual fibers creates a combination of modes specific to each input fiber at the output FMF.

For an ideal adiabatic taper and optimum output taper diameter the conversion from SMF to FMF is lossless with zero mode dependent loss (MDL).

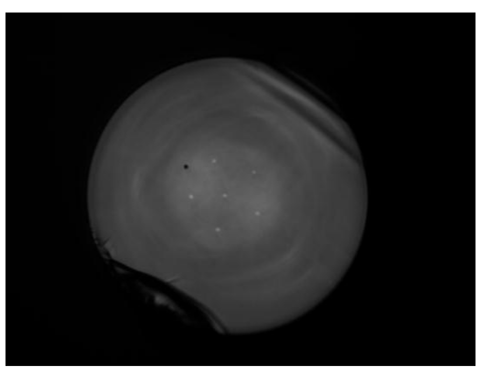
Phoenix Fiber Lanterns

Phoenix Photonics fabricates photonic lanterns in-house based on the fuse/taper concept. This approach, as shown by theoretical modeling, provides the lowest loss and lowest MDL combination giving optimum system performance. The set of photographs below shows a typical 3-fiber taper and the evolution of the waveguide along the taper from three individual fibers lightly fused to the capillary tube to the final fused FMF waveguide in which the three original fibers form the core and the capillary tube the cladding of the 'new' FMF waveguide.



Photographs of: Tapered lantern (top) and evolution from left to right along the taper showing the 3 SMF input fibers fusing together and eventually forming the core of the 'new' FMF taper output.

The above photographs show the 3-fiber lantern compatible with dual-mode fiber supporting three linearly polarized modes (LP_{01}, LP_{11a}, LP_{11b}). The same fabrication methods are used to produce higher fiber count lanterns as shown in the photograph below which is a 6-fiber lantern cross section designed for use with 4-mode fiber (LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, LP_{02}).



Photograph of cross section of 6-fiber lantern output compatible with 4-mode fiber

Connection to transmission FMF

The lantern output is a step index fiber the characteristics of which are defined by the core shape, the core dimensions and the cladding refractive index. The final core diameter is determined by the cut-off conditions for the unwanted modes and the loss for the desired modes. The mode field diameter (MFD) for each of the modes is different. In general this waveguide is not compatible with commercial FMF which may be step or graded index in profile and have differing MFD.

The lantern exhibits very low MDL and insertion loss and these characteristics should be transferred to the transmission fiber. Mismatch in MFD between modes in the two waveguides lead to increased MDL and/or IL during interfacing.

The primary method utilized in early research work was to have a free space launch to image the lantern output onto the FMF core using a telecentric configuration. This facilitates optimizing the launch for the specific system. Ideally the lantern should be fully packaged to provide a robust, broadband, wide operational temperature range device. To achieve this, the FMF in the Phoenix Lanterns is spliced directly to the lantern.

Optimization of the lantern is achieved by monitoring of MDL and IL during FMF pigtailing. Phoenix has developed techniques to improve MFD matching minimizing IL and to monitor MDL during splicing alignment.

The figure below shows direct splicing of a 3-fiber lantern to graded index dual mode fiber.

3-fiber photonic lantern on the left spliced into a graded index dual mode fiber to the right.

A direct splice gives in the region of 6.5 dB insertion loss, however using mode matching techniques this has been improved to between better than 4dB insertion loss.

Fiber Photonic Lantern technology benefits

The fiber Photonic Lantern offers an all-fiber solution to multiplexing and demultiplexing in mode division multiplexed (MDM) systems. The lantern is theoretically a lossless device and adiabatic tapering of the input fibers ensures low loss in a physical device. Utilizing mode matching techniques the insertion loss and MDL to the output FMF is minimized. The final devices are robust all-fiber components that are fabricated using standard, low cost fabrication methods. Alternative options such as 3-D inscribed waveguides offer a possible solution, but the process is expensive and the final device requires interfacing and matching to the fibers creating a transmission medium interface. Alternative free-space options such as the similar spot-launch are limited in scalability, losses introduced and mechanical alignment requirements.

Currently the all-fiber fabrication method offers the optimum approach to a Photonic Lantern based space multiplexer/demultiplexers.

Fiber lantern options

Phoenix Photonics offers both OEM targeted compact component fiber-in fiber-out components or robust modules for laboratory use in system development.

Fiber component

This compact component has either 3-SMF input to dual mode fiber output or 6-SMF input to 4-mode fiber output. The standard output fiber for the products is OFS dual mode or 4-mode FMF. Also devices can be fabricated with customer defined fiber outputs. The component device is designed to be compact for integration into a transmitter or receiver instrument.

Multiplexer/demultiplexer module

The module is a robust unit with connectors for SMF input and either connector output for FMF or a tail ready for splicing into the customer system. These robust modules are more convenient for undertaking experiments during system evaluation and design.

References

[1] 'Fiber based Multiplexing and Demultiplexing devices for Few Mode Fiber Space Division Multiplexed communications.'
Ian P. Giles, et al. OFC2014 Invited Paper

[2] 'MIMO capacities and outage probabilities in spatial multiplexed optical transport systems', P.J.Winzer et al. Optics Express Vol 19, no 17 2011.

[3] 'Multimode fiber devices with single-mode performance' S.G. Leon-Saval et al. Optics Letters, Vol.30, No.19 2005

[4] 'Geometric requirements for photonic lanterns in space division multiplexing', N.K.Fontaine et al., Optics Express Vol.20, no. 24 2012.