# Optical Coupling Components for Spatial Multiplexing in Multi-Mode Fibers

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**Abstract:** Space-Division Multiplexing for long distance transmission over multi-mode fibers requires mode-multiplexers with high mode selectivity and capable of exciting all fiber modes in a controlled way. We present an architecture for mode-multiplexers and its experimental demonstration for a three mode fiber.

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## 1. Introduction

Single-mode fibers (SMF) have dominated long distance transmission over the last 2 decades, during which the capacity has been steadily increased by 3 orders of magnitude [1]. This was achived by introducing wavelength-division multiplexing (WDM), polarization-division multiplexing (PDM), and more recently higher order modulation formats. However, studies [2] show that the capacity over single-mode fiber is rapidly approaching a limit imposed be the combination of fiber nonlinearity and the the Shannon formula. The introduction of space-division multiplexing (SDM) [3] has been proposed to overcome this limit. Multimode fibers (MMF) support spatial multiplexing and are widely used in optical communication, however suffer from strong mode coupling in combination with a large modal differential group delay (DGD), which limits their application to shorter reach [4]. However reduction of the number of modes supported by the fiber makes it possible to, either reduce the coupling between the modes, or reduce the DGD. Both approaches have been recently demonstrated in [5] and [6], respectively. In both cases mode couplers with mode selectivities > 20 dB, low coupling loss, and having the ability to selectively excite all fiber modes are required. We present mode couplers using phase holograms based either on fixed photolithographically manufactured phase plates or liquid crystal on silicon (LCOS) phase modulators. The first approach offers the advantage of having lower loss, and being inherently polarization independent. The second approach however offers the possibility to dynamically adapt to different types of fiber and modes, and compensate for aberrations in the coupler optics. We present experimental results for both approaches, including mode profile generation to couple into a three mode fiber (3MF), and validation in a 6 channel SDM tr... signal processing (DSP) for crosstal...

## 2. Thin hologra...

Mode-multiplexer ... and combine them such that every inc... MMF are orthogonal, in theory it s... izing beam splitter

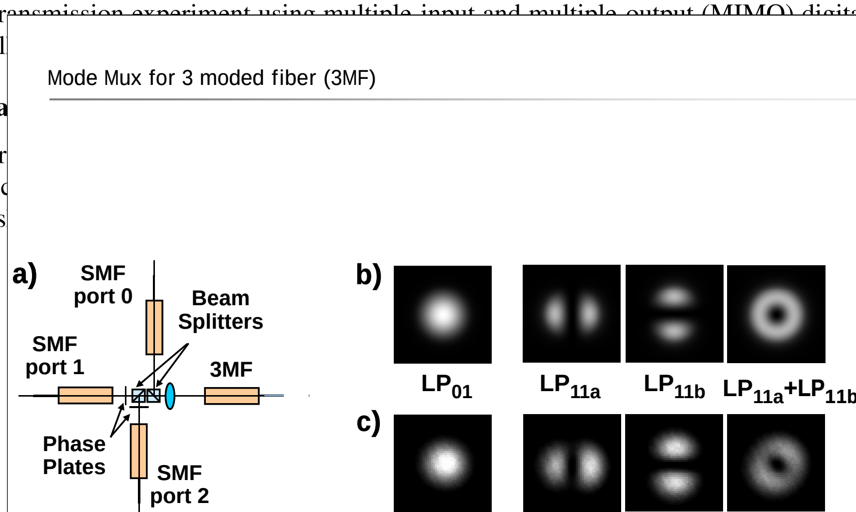


Fig. 1. a) Architecture of the 3 mode coupler b) Theoretical intensity profiles c) Measured intensity profile after 2 m of 3MF.

for PDM or a grating fo … ne fiber mode at a time, therefore beam splitters … holograms. The resulting loss is given by $1/N_{pol}$, … acceptable if the number of modes $N_{pol}$ is small. T … Port 0 is directly coupled into the $LP_{01}$ mode of th … l path, in order to launch the corresponding $LP_{11}$ … e in Fig.2. Generally the

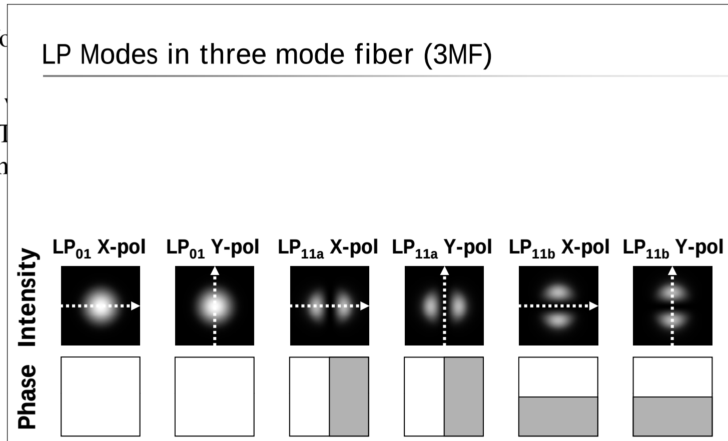


Fig. 2. a) Intensity and b) phase profile of the LP modes of a three mode fiber.



thin holograms can be inserted in two different locations along the path, corresponding either to an image plane or a Fourier plane of the end facet of the MMF. The spatial Fourier transform of the fiber mode profiles have the interesting properties of being similar to their originating profile [7]. In particular the phase structure is maintained and also the intensity profile is similar. Therefore also the holograms required for mode conversion will be similar, and the most convenient optical arrangement can be selected. There are multiple ways to generate optimized holograms for mode converters [7]. A very simple method is to use holograms that have the same phase profile as the corresponding LP modes as shown in Fig.2 b). In this case, no hologram is required for the $LP_{01}$ mode, whereas for the $LP_{11}$ the hologram consists of two half planes with a constant phase difference of $\pi$. Rotating the mask by 90° will produce the second $LP_{11}$ mode mask. Such simple masks however are not capable of creating intensity profiles matching the corresponding $LP_{11}$ modes of the fiber, nevertheless because of the symmetry of the $LP_{01}$ and $LP_{11}$ modes, it can be shown that the masks produce a complex amplitude distribution that can be coupled only into the desired mode. The resulting mode conversion loss can be additionally reduced by optimizing the magnification of the optical imaging system that images the facet of the incident SMF on the facet of the MMF fiber. The mode conversion loss from a conventional SMF into a step index MMF with normalized frequency $V = 3.92$ and core diameter $d = 17\ \mu$m, was calculated to be 1.1 dB for the $LP_{11}$ mode and 0.1 dB for the $LP_{01}$ mode. Combining the conversion loss with the splitting loss, and after reoptimizing the splitting ratios of the beam splitters, we obtain a theoretical minimal loss of 5.5 dB. Although smaller losses are desirable, the loss is acceptable considering the simplicity of the optical arrangement.

## 3. Experimental mode coupler demonstration

We built an MMUX according to the arrangement shown in Fig.1. We used 3 collimators with a nominal beam diameter of 500 $\mu$m. The collimators were imaged on the end facet of a 3MF by means of two lenses, the first with a focal length of 75 mm and the second, an aspheric lens, with focal length of 3.9 mm placed in front of the 3MF. The 3MF was a depressed cladding index profile fiber with a normalized frequency $V = 5$ at 1550 nm, designed such that the $LP_{11}$ mode was reliably guided, whereas the next-higher modes ($LP_{21}$ and $LP_{02}$) were cut off. The fiber also showed a very small DGD between modes of $< 60$ ps/km across the C-band, which is necessary for tractable MIMO processing. The fiber had a loss of 0.2 dB/km at 1550nm and the effective areas of the $LP_{01}$ and $LP_{11}$ modes were approximately 155 $\mu m^2$ and 320 $\mu m^2$, respectively. The phase plates were made of 0.5 mm thick Borosilicate glass, and a photolithographic process was used to create the phase pattern, which was subsequently time etched into the glass, in order to achieve a 1.7 $\mu$m thickness difference. The 3 beams were combined using two splitters with a non ideal splitting ratio of 37/63 and a coupling loss of 8.3 dB, 10.6 dB and 9.0 dB was measured for the $LP_{01}$ and the two $LP_{11}$ modes, respectively. An excess loss of $\sim 3$ dB for the $LP_{11}$ modes was observed and found to be related to a mismatch between the incident beam diameter and the $LP_{11}$ mode diameter. To evaluate the crosstalk, two MUXs were connected between 2 m of 3MF. We launched power into the port corresponding to the $LP_{01}$ mode in the first coupler and measured the power in the ports of the second coupler. We found that the crosstalk suppression defined as the power ratio between the power detected in the port corresponding to the $LP_{01}$ mode and the highest power measured in the ports corresponding to the $LP_{11}$ mode was $> 28$ dB. Fig.1c) shows pictures of the modes measured with an infrared camera at the end of the 2 m fiber. Simulated images are reported as reference in Fig.1b) showing a very good qualitative match between theory and experiment. Note that when launching power into one of the two $LP_{11}$

modes, the output mode distribution changes over time or as the fiber is moved. The two degenerate $LP_{11}$ modes show strong polarization-dependent coupling. Whereas when the $LP_{01}$ mode is launched, moving the 3MF had no impact on the profile of the output mode. Repeating the crosstalk measurements with 10 km of 3MF shows a typical crosstalk fluctuating around -20 dB, confirming mode separation between $LP_{01}$ and $LP_{11}$ even over longer distances. In contrast, the two $LP_{11}$ modes were continuously mixing along propagation in the fiber as a result of being linear combinations of the true (non-LP) fiber modes [8].

Using the MMUX, we simultaneously launched 6 independent data streams at the same wavelength into the 6 polarization- and spatial modes supported by 10 km of 3MF. We used 14-Gbaud QPSK test signals with a De Bruijn sequence of order 11. The transmitted signals were detected by 3 polarization-diversity coherent receivers, and a copy of the signal laser was used as a local oscillator in a self-homodyne arrangement. The captured signals were subsequently analyzed by off-line MIMO digital signal processing [6] and all channels were recovered to a bit error rate $< 10^{-3}$.

## 4. Dynamic h

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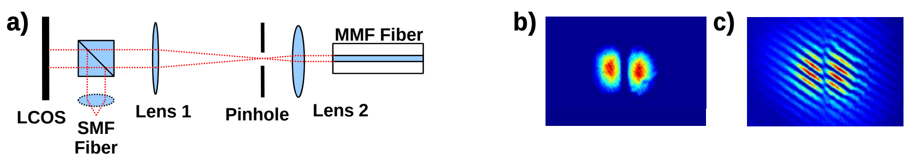


Fig. 3. a) Experimental setup for phase and amplitude shaping using LCOS, b) Intensity and Interferogram of produce $LP_{11}$ mode profile.

coupler that can be reprogrammed to couple different modes during operation, or correct for aberration and misalignments of the optical components. Furthermore, LCOS-based SLMs can be used to modify both phase and amplitude profile in the fiber plane, if phase contrast methods, that are well known in photolithography [9], are applied. Fig.3a) shows and LCOS-based arrangement where a pinhole provides the amplitude modulation capability and Fig.3b) and c) show the intensity measurement and interferogram of the produced $LP_{11}$ like light distribution. The interferogram in Fig.3c) clearly shows the characteristic $\pi$ phase shift between left and right half-planes.



## 5. Conclusion

We have presented novel mode couplers for 3MF. The couplers can selectively launch a full set of modes of a 3MF offering a high selectivity of $> 28$ dB. The couplers were used to successfully demonstrate 6-channel SDM transmission over a 10 km 3MF using MIMO digital signal processing.

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