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Invited Papers

Characterization and applications of spatial mode multiplexers based on Multi-Plane Light Conversion

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ABSTRACT

Multi-Plane Light Conversion (MPLC) enables novel beam shaping devices, and in particular highly mode-selective spatial mode multiplexers. MPLC-based multiplexers can combine up to 10 spatial modes with cross-talk of −26 dB and insertion loss below 4 dB. These multiplexers are versatile and can be used in many applications, including long haul mode division multiplexing, short reach mode group division multiplexing, multi-mode optical amplification, and their mode conversion capabilities can be used for optimizing wavelength selective switches.

1. Introduction

Due to the ever increasing data capacity requirement in optical fibers and to the approaching non-linear Shannon limit for single-mode fibers (SMFs), space division multiplexing (SDM) [1] has been proposed as a means to increase fiber capacity. Parallel spatial paths can be exploited through multiple modes of a multi-mode fiber (MMF) [2], multiple cores of a multi-core fiber (MCF) [3], or a combination of both [4]. In the case of transmission in a MMF, one of the key elements in the transmission system is the spatial multiplexer (MUX), capable of converting N SMFs into N spatial channels of the MMF, and the spatial demultiplexer (DEMUX) performing the inverse operation.

Two strategies exist for handling the spatial channels of the MMF. On the one hand, one can launch the input channels into a random set of orthogonal combination of the Eigenmodes of the MMF [2]. The channels are thus strongly coupled, and demultiplexing the channels requires full modal diversity at the receiver and complex digital signal processing (DSP). On the other hand, one can use fibers and components in which spatial modes are weakly- or un-coupled, therefore limiting the DSP to the joint detection of degenerate mode groups [5].

In both strategies, there is an interest in mode-selective MUX and DEMUX: indeed, weakly coupled technique requires that the modal cross-talks generated by the MUX/DEMUX stay small enough, while mode selectivity insures low mode-dependent loss (MDL) and possibility to compensate differential mode group delay [6], which relieve the complexity of DSP in strongly coupled transmissions. Other important features for mode MUX and DEMUX are low insertion loss (IL) and large bandwidth of operation for compatibility with wavelength division multiplexing.

Several techniques have been proposed for mode selective MUX. Primarily, binary phase plate converters [7] have been widely used due to their simplicity, but they suffer from large intrinsic IL. Another technique largely investigated is mode-selective photonic lantern [8] using dissimilar input SMFs, which presents the possibility of very low IL; however experimentally achieved mode selectivity remains low due to the complexity of fiber engineering. Other techniques based on fused couplers [9,10] have also been reported.

Here we demonstrate a highly mode-selective, 10-mode MUX and DEMUX based on Multi-Plane Light Conversion (MPLC). This technique has been previously reported for 6-mode multiplexers and used in various transmission experiments [4,5]; we present here the extension of these results to 10 modes, with good IL and high selectivity over the full C + L band. We also show several applications enabled by the high efficiency of Multi-Plane Light Conversion.

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2. Mode multiplexer/demultiplexer based on Multi-Plane Light Conversion

2.1. Multi-Plane Light Conversion

Multi-Plane Light Conversion (MPLC) is a technique that allows to perform any unitary spatial transform. Theoretically, any unitary spatial transform can be implemented by a certain succession of transverse phase profiles separated by optical Fourier transforms (OFT). In particular, the conversion of N separate input Gaussian beams into N orthogonal propagation modes of a fiber, i.e. spatial multiplexing, can be considered as a unitary spatial transform and therefore can be achieved with MPLC [11]. An example of spatial multiplexing for 3 modes is shown in Fig. 1. The unitarity of the transform insures that there is no intrinsic loss in the mode conversion. Losses in a MPLC only occur due to imperfect optical elements (e.g. coating). The inverse unitary transform, given by using the MPLC in the reverse direction, implements the demultiplexing operation of the same modes.

In order to reduce the footprint of the MPLC as well as decreasing the complexity of aligning free-space optical elements, the MPLC is experimentally implemented using a multi-pass cavity, in which the successive phase profiles are all printed on a single reflective phase plate. The cavity is formed by a mirror and the reflective phase plate, and performs the successive phase profiles and optical transforms.

Two multiplexers supporting 10 spatial modes are fabricated using an implementation with 14 reflections on the phase plate. The multi-pass cavity for a 10-mode multiplexer is shown in Fig. 2. The system converts light from 10 input SMFs into the 10 modes of a graded-index few-mode fiber [12]. Fig. 3 shows the output modes in free-space (before coupling into a MMF) when using a super luminescent diode (SLD) centered at 1550 nm as light source. The optical losses, from input SMF to free-space output, are below 2 dB.

2.2. Method of characterization

We characterize the 10-mode multiplexers using the setup shown in Fig. 4: characterization setup: light source is either a SLD or a tunable DFB. After an optical isolator and a polarization scrambler, an optical switch and a multi-channel optical power meter (PM) are used to characterize the system. The transmission matrix of a back-to-back system comprising a MUX, 10 m of MMF and a DEMUX is measured using an optical switch and a multi-channel optical power meter. Two types of input light sources are used: a SLD, centered at 1550 nm with FWHM bandwidth of 50 nm, and a tunable distributed feedback laser (DFB) able to cover full C + L band (1530 nm–1630 nm). Measurements with low coherence SLD source are not affected by multi-path interferences; therefore they are more stable and they do not fluctuate with fiber position. These measurements give similar results as measurements with DFB averaged across the C-band.

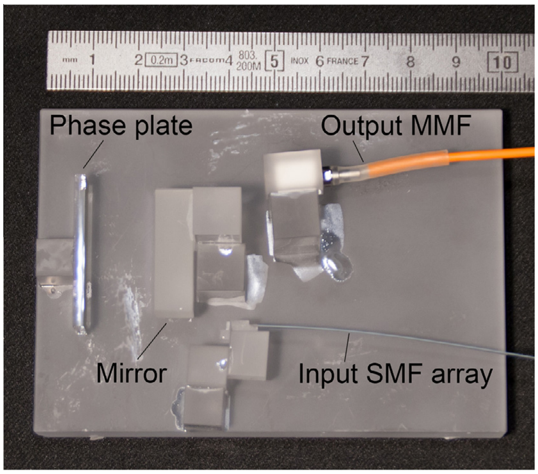

Fig. 2. Photo of a 10-mode MUX based on MPLC.

We measure the matrix of output powers $P_{i,j}\psi$ for power in output j when light is on input i, allowing to retrieve the coupling efficiency and the modal cross-talk for all modes. In order to remove the effect of intra-mode group mixing inside the fiber in the calculation of MUX performance, for one input of a mode group we consider its output power as the sum of all the outputs of the same mode group. For example, the coupling efficiency of $\mathrm{LP}_{11\mathrm{a}}\psi$input is given by

$$\eta(LP_{11a}) = \frac{(P_{LP_{11a},LP_{11a}} + P_{LP_{11a},LP_{11b}})}{P_{in}},$$

where P_{in} is the input power, equal for all input fibers. In the same way, the cross-talk is averaged between outputs of the same mode group. For example, the cross-talk from input LP_{01} to mode group LP_{11} is given by

$$XT(LP_{01} \to LP_{11a}) = XT(LP_{01} \to LP_{11b}) = \frac{(P_{LP_{01},LP_{11a}} + P_{LP_{01},LP_{11b}})}{2P_{LP_{01},LP_{01}}}.$$

2.3. Results

Table 1 shows the measured cross-talk matrix and Table 2 the coupling efficiency for a back-to-back system using SLD source. Assuming that the MUX and DEMUX are identical, the average

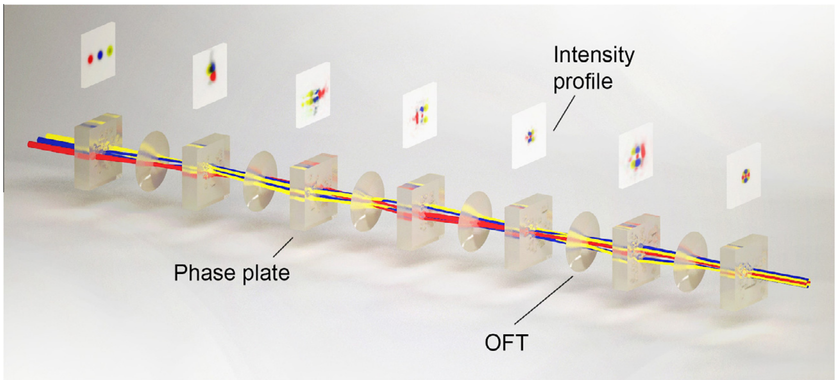

Fig. 1. Schematics of a 3-mode MUX based on MPLC.

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