Towards High-Density Space Division Multiplexed Transmission Systems

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Spatial division multiplexing (SDM) is increasingly become the next logical step in extending the capacity within a single fiber through the transmission of multiple spatial channels either in a multi-core or multi-mode fiber. Further enabled by multiple-input multiple-output (MIMO) digital signal processing (DSP), emerging low-loss (de)multiplexers are discussed for providing high-density SDM transmission of >1TB/s per channel over a single fiber.

Introduction

The recent interest in mode-division multiplexed transmission over multi-mode/core fibers is due to the dramatic increase in the capacity of a single optical fiber by exploiting the spatial dimension. To this end, ongoing developments have been focused on achieving low, or compensated, differential group delay (DGD) few mode fibers (FMF) [1], multi-mode amplifiers [2] and integrated mode couplers [3]. The latter is of primary importance, as low-loss and effective coupling into and out of the FMFs can be achieved. In earlier subsystems focused on 3 mode transmission, phase plates were proposed and exhibited losses in the order of 8-10dB at the multiplexer (MUX) and demultiplexer (DEMUX) [4]. In state-of-the-art FMFs where losses are 0.19dB/km [1], losses of 20dB at both the MUX and DEMUX side could equate to about 100km less transmission capability. In addition to low loss launching, to support the scalability to higher number of mode channels, appropriate technologies are being considered which are capable of exciting all spatial modes of the FMF. Several technologies have been investigated within the ongoing European FP7 project MODEGAP based on spot-based mode couplers [5], waveguides [6], and silicon on insulator multiplexers [3] and photonic lanterns. These have been realized and demonstrated to realize MUX and DEMUX features in transmission systems [5,7]. In this work, the principle of the MUX/DEMUX techniques are discussed with their design optimised currently for 3-mode operation. These technologies are evaluated in transmission systems. Finally we provide an overview of the emerging techniques likely to allow the expansion to higher number of modes channel transmitted over a single fiber.

Spot Launching Techniques

According to [8], various spot arrangements can be constructed by adding a spot for each non-degenerate mode and two spots of degenerate modes. The 3-mode coupler is the simplest for investigation. In this work, the excitation of linearly polarized (LP) modes, LP_{01}, LP_{11a} and LP_{11b} are of primary focus, where the latter two are degenerate modes. Hence to generate the three modes, three spots carrying the light beams are arranged in a triangular shape in order to achieve the optimum performance. Based on the free-space setup, a single 3-surface prism is used to combine the collimated beams. Two vertical surfaces of the prism are perpendicular and the top surface is 45 degrees with respect to the horizon.

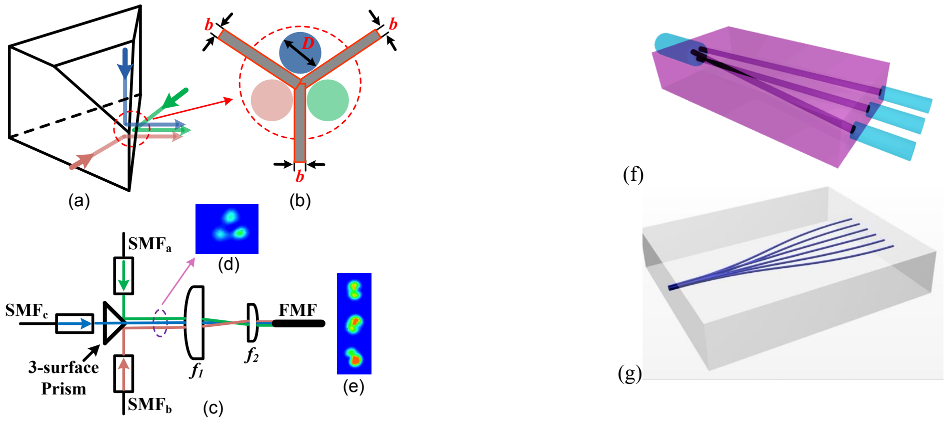

Fig 1: (a) 3-surface prism for combining 3 light beams; (b) prism bevels; (c) the setup of the 3-surface prism based 3-spot mode coupler; (d) The3 combined light beams and (e) FMF output fields (f) 3D waveguide design for a 3-mode spot launcher, (g) A design allowing scalability to 6 modes

As shown in Fig. 1(b), to influence the spacing between the spots, the widths of the bevels on the prism are less than 10μm which is 50 times smaller than the collimated light beam with a diameter of 500μm. Therefore, the influence from the bevels becomes negligible. A telecentric setup composed of two lenses with focal length of f_1=150mm and $f_{2=}$2.7mm are utilized to image the 3 spots into the FMF, as shown in Fig. 1(c). Fig. 1(d) shows the captured light beams. The tested coupler inserted loss (CIL) of the 3-spot mode coupler as a mode MUX and DEMUX is 3.9dB and 2.8dB, respectively, for a step-index FMF with a core diameter of 19.4μm. Fig. 1(e) shows the output fields excited for each spot. For a graded-index FMF with a core diameter of 11μm, the best CIL at the mode MUX and DEMUX achievable is 3.7dB and 3.5dB, respectively [5]. As the proof of principle is based on 3-mode propagation using free-space techniques, the scalability to higher number of modes as suggested in [9], is not investigated with free-space spot arrangement. To scale to a higher number of modes, the spots from the free space launcher can be further optimized and placed closer by using 3D silica waveguides inscribed by femto-second pulsed lasers [6,8]. Each input excites a different orthogonal set of modes, which are fully mixed when propagated along a few-mode fiber. The key consideration for the design of such waveguides is the placement of the spots such that the supermodes approximate the modes of the few-mode fiber with minimum CIL and mode dependent loss (MDL). As shown in Fig 1(f) and (g) it becomes relatively easy to scale to higher number of spots.

An Silicon on Insulator Integrated Multiplexer

In contrast to bulky free space components discussed, photonic integration provides the possibility for the (de)multiplexer to be placed with local oscillator lasers, modulators and photodetectors. This is key if these are to be combined and realised cost effectively in a transponder. To this end, a photonic integrated mode coupler based on Silicon-on-insulator device was designed and fabricated. The device utilizes push-pull and center launch to excite LP_{11} and LP_{01} mode. Supporting 6 channels (both polarizations of 3 modes), the device creates two Gaussian-like spots with a phase difference $\Delta\varphi$ of π, since LP_{11} mode has a bipolar field distribution. As shown in Fig. 2(a), to create such bipolar field for LP_{11} mode coupling, two 2D grating couplers, push-pull driven with opposite phase are employed. To further illustrate this concept Fig. 2(b) shows full 6-channel integrated mode coupler where the center 2D grating coupler is for launching or channeling the LP_{01} mode for reception. The mode coupler connects 6 individual SMFs

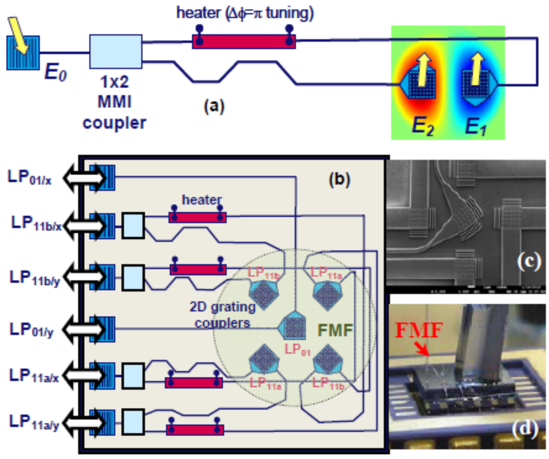

Fig 2: Push-pull scheme realized by a pair of grating couplers for LP11 mode excitation; (b) circuit for multiplexing LP01 and LP11 modes; (c) Scanning electron microscope image of the five vertical grating couplers and (d) The packaged integrated mode coupler

through one-dimensional grating couplers to the five 2D grating couplers for coupling into the few-mode fiber. The five small 2D vertical grating couplers, as shown in Fig. 2(c), excite 6 channels: the x- and y polarization of LP_{01} and two orthogonal LP_{11} modes (LP_{11a} and LP_{11b}). Fig. 2(d) shows the picture of the packaged mode coupler.

Experimental Validation – Spot Launcher and SOI Multiplexer

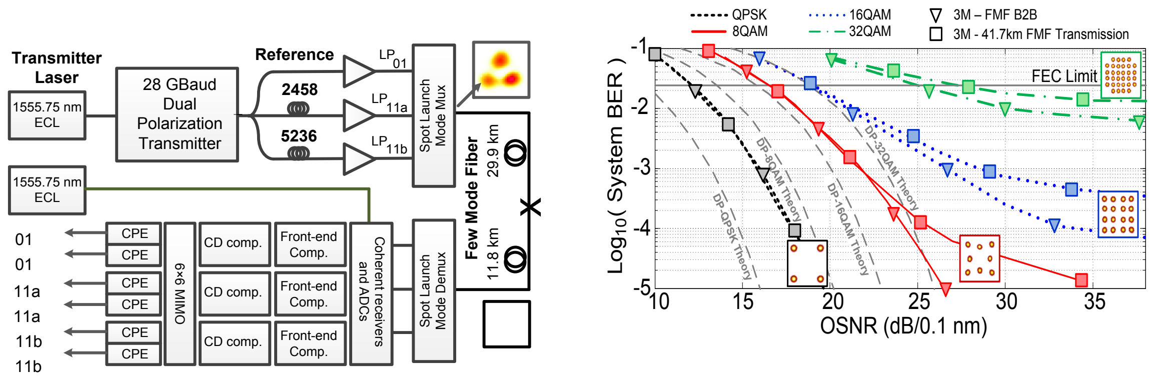

Fig 3(a): The experimental setup verifies the performance of the spot Launch Mux/Demux (inset: measured spot alignment).(b) Results

Firstly the performance of the free-space spot launcher is experimentally verified using the setup depicted in Fig. 3a. At the transmitter, the IQ-modulator is modulated at 28GBaud and driven by two digital-to-analog converters (DACs) for the in-phase and quadrature component of the transmitted constellation. The gray coded QPSK, 8, 16 and 32QAM constellations were used. By employing a number of gray coded, fully uncorrelated pseudo random bit sequences (PRBS) for the transmitted sequence in the digital domain each of length 2^{15}. The output of the IQ-modulator is split, and one arm is delayed by 1233 symbols for the emulation of polarization multiplexing. After recombining the two arms, the DP signal is noise loaded to characterize the optical signal to noise ratio (OSNR) system performance. To achieve 3 DP multiplexed transmission channels, the noise-loaded signal is split into three equal tributaries. Two arms are delayed for mode decorrelation by 2458 and 5236 symbols, respectively. As the single prism mode MUX is used, equal excitation of the three LP modes is expected to guarantee full mixing. For all inputs, the losses are approximately 3.7dB. The transmission link consists of two spans of graded index few-mode fiber with length of

41.7 km and a DMD of +3.82ns. A similar setup to the MUX is used for the DEMUX operation where the loss is 4.5 dB for each output.

In the digital domain, the optical front-end impairments are compensated. Then, the chromatic dispersion (CD) is removed. To invert the channel mixing effects, a 6×6 MIMO time-domain equalizer (TDE) with adaptive step size is used [12]. The weight matrix of the TDE is heuristically updated using the least mean squares (LMS) algorithm during convergence and decision-directed least mean squares (DD-LMS) during data transmission. One carrier phase estimation (CPE) block per output channel in the form of a digital phase locked loop is used to compensate for phase offset[11].
As shown in Fig 3b, at the FEC limit, the penalty is quite low for QPSK, 8/16 QAM.

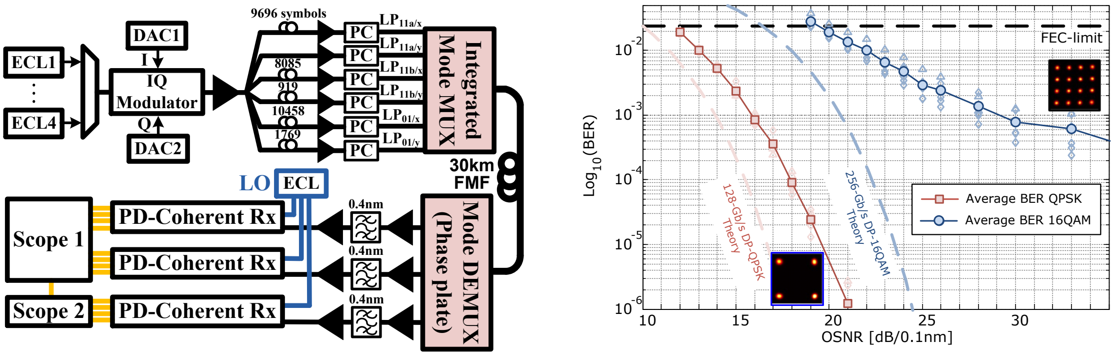

Fig 4(a): The experimental setup verifies the performance of the spot Launch Mux/Demux (inset: measured spot alignment).(b) Results

To validate the integrated multiplexer, the setup in Fig 4a is used. The 3dB wavelength bandwidth of the integrated MUX is larger than 40nm, which is sufficient for C-band [3]. Hence, 4 ECLs operated with 1THz frequency spacing are combined and modulated. In this particular test, the DACs are operated for QPSK or 16QAM symbols. Unlike the conventional method for polarization diversity (PD) through a polarization beam combiner with a delay line, the 2D grating coupler combines the two polarizations, the signal is directly split into six tributaries, which are amplified and input to the six ports of the integrated mode coupler. Polarization controller (PC) is used to maximum the diffraction efficiency of the grating couplers. The delays with respect to the $LP_{11a/b}$ port are decorrelated as in Fig 4a. After the DEMUX, the signals are sent into PD coherent receivers for capture and processing. Fig 4b. shows that with respect to theory, a penalty of 2dB and 3dB are observed for QPSK and 16QAM respectively

Conclusions

Within the MODEGAP project, various technologies have been shown to potentially offer a path to scalable mode multiplexing and coupling into emerging low-loss FMFs. Through integration and low-loss waveguides, a higher number of modes can enable 1Tb/s per wavelength channel transmission over single fibers.

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