Multi-spot based mode (de)multiplexer for mode division multiplexing over few-mode fiber

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Multiple-Gaussian-spot based mode multiplexers are investigated in this paper for Mode Division Multiplexing over Few-mode Fiber. A structure of five spots for exciting 3 spatial modes: LP01 and degenerate LP11 with high mode extinction ratio is discussed and realized by a silicon-on-insulator integrated circuit. Test results are presented. Moreover, a spot-based solution scalable to support more modes is introduced and simulated. It is demonstrated low insertion loss and mode-dependent loss can be achieved but with sacrificing mode extinction ratio. A variety of compact solutions can be used to realize these multi-spot schemes, such as photonic integration, photonic lantern and 3D-waveguide.

Introduction

Due to the rapidly increasing concern about the exhausting capacity of single mode fiber (SMF) links, Mode Division Multiplexing (MDM) [1] by using Few-mode fibers (FMFs) in optical networks came in the spotlight recently. By using each mode as a separate channel, MDM could reduce the impact from modal dispersion to signal quality, if each signal is purely propagated in one mode [2]. In the case with strong mode coupling, Digital Signal Processing (DSP) can help to recover the mixed signals [1]. MDM has the potential to enhance optical network's capacity *N*-fold to avert network gridlock. To realize MDM in an FMF, the widely-used free space scheme is to convert a fundamental mode output profile from a SMF into the profiles of different higher order modes of the FMF. For such mode convertor functions, phase plates [1], spatial light modulators (SLM) [2] and long period gratings (LPG) [3] have been used. In this paper, Multiple-Gaussian-spot based mode multiplexers (MUX) with different designs are investigated in detail for MDM over FMF. It is demonstrated that low Coupler Insertion Loss (CIL) and low Mode-Dependent Loss (MDL) or high mode extinction ratio can be achieved with multi-spot launching schemes. A variety of compact solutions can be used to realize multi-spot schemes, such as with photonic integration [4], photonic lantern [5] and 3D-waveguide [6].

Mode Division Multiplexing

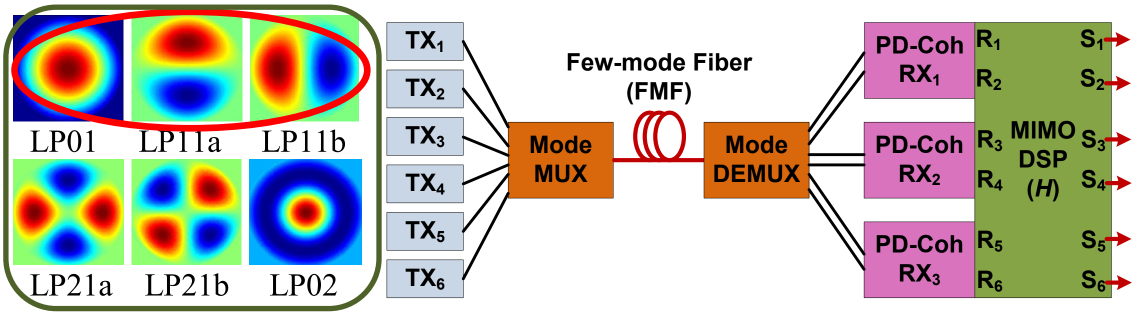


Figure 1. (a) 6 lower order spatial modes; (b) schematic MDM setup for 3 spatial modes.

Mode profiles for 6 lower order spatial modes are given in Figure 1(a). Compared to the SMF system, parallel transmission with several channels in one optical fiber is realized. Figure 1(b) shows the schematic MDM setup for 3 spatial modes: LP01 and two degenerate LP11 modes. The mode MUX couples the light from different transmitters to one corresponding mode or a group of modes. At the receiving side, the mode demultiplexer (DEMUX) separates the power of the different modes and these modes are detected by polarization division multiplexed coherent receivers. MIMO compensation based DSP is used to recovered the mixed signals due to the mode coupling through the propagation.

Specific Mode Excitation

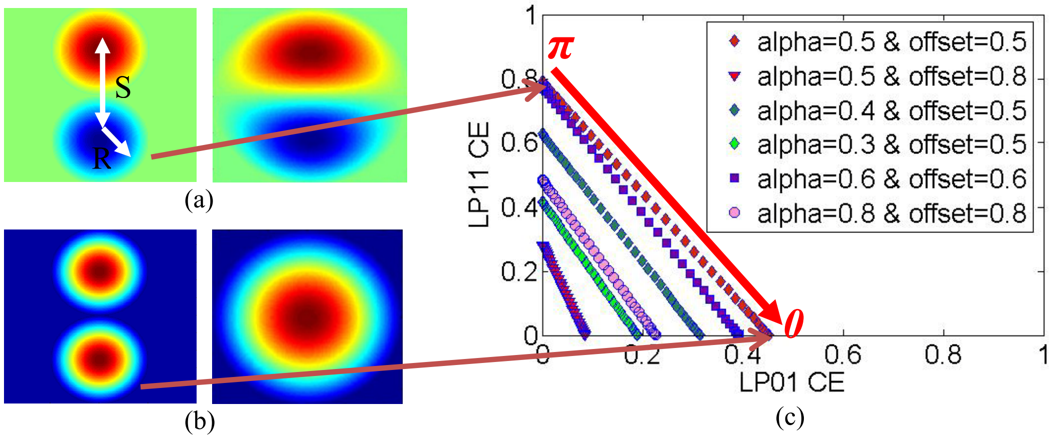
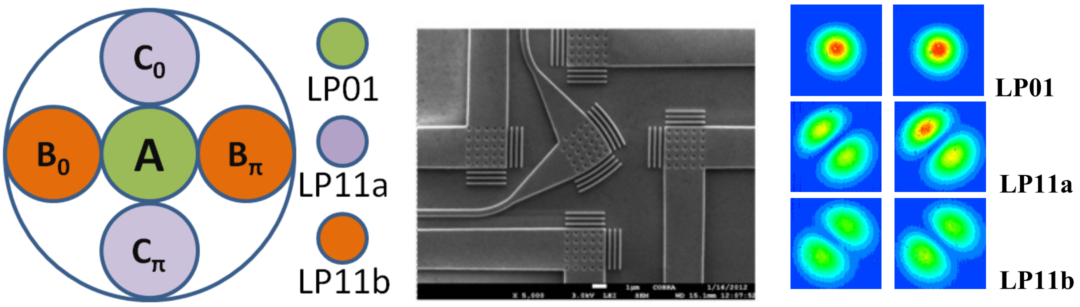


Figure 2. Push-pull solution for exciting (a) LP11 and (b) LP01 mode; (c) coupling efficiency for LP01 and LP11 modes with different alpha, offset and phase difference of two spots.

The LP01 mode field is unipolar, and the LP11 mode has a bipolar field distribution. The LP11a and LP11b mode fields are orthogonal, and rotated over $\pi/2$ with respect to each other in the core cross-section area, see Figure 1(a). The multi-spot based solution to generate the LP11 mode is illustrated in Figure 2(a) which uses two Gaussian spots with a spacing of *S* and a radius of *R*, but with a phase difference of π (push-pull). Figure 2(c) shows the Coupling Efficiency (CE) between the two Gaussian spots and the LP01 and LP11 modes with different alpha, offset and phase difference, where alpha=*R/D* and offset=*S/2D*. *D* is the radius of the FMF. More than 80% CE for LP11 mode can be achieved with a high mode extinction ratio to the LP01 mode. Based on this two spots based push-pull solution, a structure with 5 spots to generate all 3 lower order spatial modes is proposed, as shown in Figure 3(a). The spot at the center is utilized to excite the LP01 mode. This sacrifices the CE for the LP11 mode since the *R* has to be minimized to give the space for the center spot. However, high mode extinction ratio and CE>40% for the LP11 can still be achieved as alpha=0.3, offset=0.5 and fine phase tuning of π, see Figure 2(c).

Paper [4] shows the realization of this structure with a SOI integrated circuit. 2-dimensional (2D) grating couplers are utilized to realize vertical-out-of-plane coupling. Since the 2D grating couplers support two polarizations and with a large 3dB bandwidth, this SOI integrated solution is compatible with Wavelength Division Multiplexing (WDM) and Polarization Division Multiplexing (PDM). The thermo-optic phase tuner provides the correct π phase difference to drive the two grating couplers. Figure 3(b) shows a Scanning Electron Microscope (SEM) image of the section with the 5 2D grating couplers. Figure 3(b) shows the excited mode profiles in the test [4]. The thermo-optic phase tuner provides the correct π phase difference for the excitation of LP11 modes. This proposed structure uses both intensity and phase to launch different modes so can achieve high mode extinction ratio and low CIL simultaneously. Theoretically, this solution can scale up to support more modes, i.e. using four spots for LP21 modes excitation. However to support higher order modes, more spots, phase fine tuners, power splitters and tapers are required, which increase the difficulty for chip layout and phase controlling in practice.



(a) (b) (c)

Figure 3. (a) A structure with 5 spots to serve for a FMF with 3 spatial modes; (b) the realization of this structure with a SOI integrated solution (A SEM image of the structure) and (c) Excited 3 spatial mode profiles with two polarizations.

Scalable Solution

It is proposed in [7], that by arranging *N/2* spots in different positions in accordance with the symmetry of the modes of the FMF which supports *N* spatial and polarization modes, all the modes of the FMF can be excited or detected. This multi-spot solution has the scalability to support more modes, low CIL and low MDL. However this scheme cannot achieve high mode extinction ratio, since each spot is not designed for exciting one specific mode but for launching a set of modes. All spots generate an orthogonal linear combinations of all spatial modes which is a unitary transformation between the field of spots and fiber modes, so a DSP can recover all signals without system's outage.

To characterize and optimize this mode coupler, it is useful to introduce the *N X N* transfer matrix *H* which describes the coupling between the spots and the modes of the FMF. *N* is the number of modes and also the spots. The matrix entries $c_{i,j}$ of *H* are calculated through the amplitude overlap integral between the electrical field of the *j*-th spot and the *i*-th spatial mode. λ_n ($n=1$ to N) are eigenvalues of *H*. CIL and MDL are defined as:

$$\text{CIL}=\Sigma(\lambda_n^2)/N \qquad (1)$$

$$\text{MDL}=max(\lambda_n^2)/\,min(\lambda_n^2) \qquad (2)$$

Figure 4(a) and (d) shows the arrangement of the spots for supporting 3 and 6 spatial modes, respectively. Using equation (1) and (2), CIL and MDL for the 3-spot and 6-spot based solution are calculated with different spot radius and offset, respectively. For the 3-spot MUX, the optimal CIL=2dB and MDL=0.6dB can be achieved with $r_1=0.53R_1$ and $s_1=0.53R_1$. For the 6-spot case, the optimal CIL=1.9dB and MDL=1.7dB can be achieved with $r_2=0.4R_2$ and $s_2=0.6R_2$. R_1 and R_2 is the radius of the FMF which supports 3 and 6 spatial modes respectively. Figure 4(b) and (e) give the intensity patterns of the 3-spot and 6-spot MUX with the optimized radius and offset. Figure 4(c) and (f) show the covered CIL and MDL region as radius and offset are scanning.

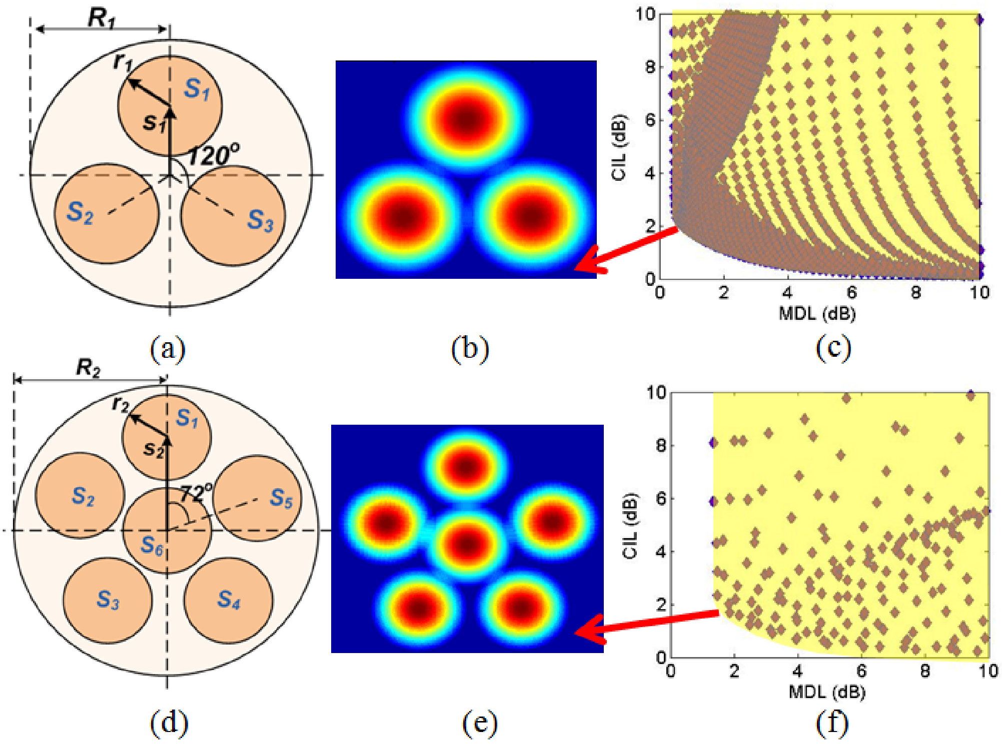


Figure. 4. The arrangement of spots and covered CIL and MDL region for a FMF (a)-(c) with 3 (N=2*3=6) spatial modes and (d)-(f) with 6 (N=2*6=12) spatial modes.

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