

# Integrated Power Splitters for Mode-Multiplexed Signals

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**Abstract:** An on-chip non-center-feed MMI power splitter for mode-multiplexed signals is proposed and experimentally demonstrated for the first time. © 2018 The Author(s)

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## Introduction

The successful implementation of few-mode fiber (FMF) communication systems will require mode-transparent passive devices. Such devices would be employed in networks where switching and routing of mode-multiplexed signals are performed. For example, a mode-transparent power splitter would find applications in wavelength-selective switches for mode-division multiplexed signals [1] and cross-talk compensation through efficient MIMO (multi-input multi-output) processing [2]. Mode-transparent devices should handle multiple modes with high efficiency and minimal distortion. Take the most basic device, the power splitter for example, it is generally believed that it can only be implemented in free space since integrated-optics implementations such as the Y junction and direction couplers are mode dependent. In this paper, the use of multimode interference (MMI) coupler as an integrated mode-transparent power splitter is proposed and experimentally demonstrated for the first time.

## Principles of Device Operation

Up to now, only single-mode input and output waveguides have been investigated for MMI devices. The operation of MMI couplers is based on the self-imaging theory [3, 4]. Center-feeding the MMI with the zeroth-order (fundamental) mode, as seen in Fig. 1(a), forms a single self-image at  $3L_\pi/4$  where  $L_\pi$  is the beat length between the two lowest order modes. In addition, images are also formed at  $Z = 3L_\pi/4N$  where  $N$  is an integer. Now, let's consider center-feeding the MMI with the first-order mode in the input waveguide. This leads to the splitting of the input modes into two parts located at the edges (See Fig. 1(b), point A). At locations B (1x2 split) and C (1x3 split), in addition to splitting at the edges, the two input modes form images at different lateral positions. Therefore, straightforward extension of the center-fed MMI is unsuitable for mode-transparent power splitting. The reason for this is that center launch only excited even modes in the MMI region, which is not suitable for splitting of modes with odd symmetry. So for a mode-transparent MMI splitter to work, the input modes must excite the same modal contents in the MMI. To accomplish this, we shift the input away from the lateral center of the MMI region. As shown in Fig. 1 (c) and (d), when the input waveguide is shifted to an appropriate location both the zeroth-order and first-order modes can be split. Our extensive simulation results show that the non-center-feed MMI splitter yields a very low crosstalk, and negligible insertion and mode dependent losses.

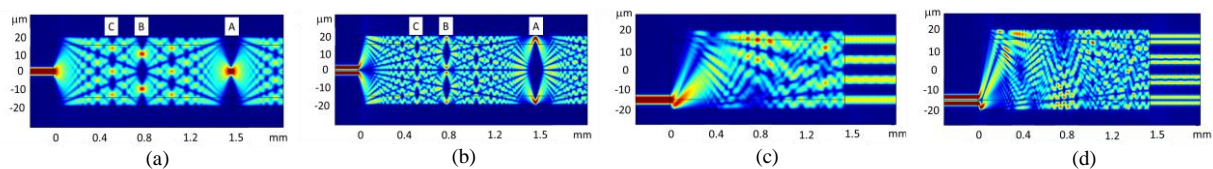


Fig. 1: Normalized field distribution for center-fed MMI for (a) 0<sup>th</sup> order input mode and (b) 1<sup>st</sup> order input mode (A: 1<sup>st</sup> self-image distance  $3L_\pi/4$ , B:  $3L_\pi/8$ , C:  $3L_\pi/12$ ). Normalized electric field evolution for a non-center-feed 1x4 MMI power splitter for the (c) 0<sup>th</sup> order input mode and (d) 1<sup>st</sup> order input mode.

## Device Fabrication

The device fabrication process is schematically shown in Fig. 2. The fabrication begins with a 3.75 μm silicon dioxide (SiO<sub>2</sub>) layer deposited on a silicon substrate by plasma-enhanced chemical vapor deposition (PECVD). The refractive index of the SiO<sub>2</sub> was measured to be 1.485 using an ellipsometer (M-2000, J.A. Woollam Co., Inc.). After that a 5 μm layer of silicon oxynitride (SiON) with a refractive index of 1.577 was deposited on the top of SiO<sub>2</sub> layer. Contact photolithography with negative photoresist was used to pattern the MMI structure. After

developing the photoresist, a layer of chromium was evaporated to serve as the etch mask for the SiON layer, followed by lift-off and reactive ion etching (RIE). Any remaining chromium was removed through immersion in a chromium etchant acid. Thereafter, the sample was capped by an 8.75 $\mu\text{m}$ -thick layer of SiO<sub>2</sub> using PECVD. Finally, the substrate was lapped down to a thickness of about 150  $\mu\text{m}$  and polished to a mirror finish. The device was then cleaved and mounted on a stage for testing.



Fig.2 Schematics of the main fabrication processes.

## Device Characterization

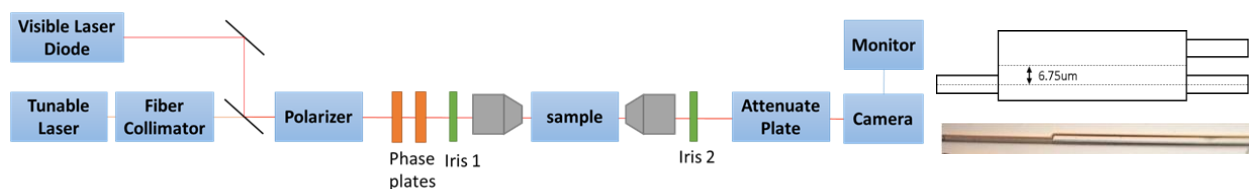


Fig. 3 Experimental set-up for testing the FM-MMI splitter. A photograph of the fabricated device and its schematic top-view is also shown. The length and width of the MMI are 886.5  $\mu\text{m}$  and 20  $\mu\text{m}$  separately. The width of input and output waveguides are 5  $\mu\text{m}$ . The input waveguide deviates 6.75  $\mu\text{m}$  from the center line of the MMI.

The experimental setup for the characterization of a 1x2 power splitter is depicted in Fig. 3. Light from a visible laser diode was used to align the setup. A collimated TE-polarized tunable laser operating near 1550 nm, was then end-fire coupled into the input waveguide through a series of phase plates and a 40x microscope. The phase plates were used to generate the desired waveguide modes. The device output facet was imaged onto an infrared camera (MicronViewer 7290A) using a 20x microscope objective. Attenuate plates were placed in front of the camera to protect the camera. A photograph of the fabricated device and its schematic top-view is also shown in Fig. 3. Figure 4 shows 1x2 splitting of all four modes of the input waveguide. The splitting of the TE<sub>11</sub> mode is not as clean as the other three modes mainly due to imperfection of exciting the pure TE<sub>11</sub> mode using the phase plates.

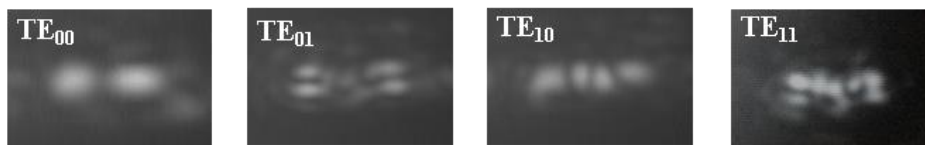


Fig. 4 Experimental results of 1x2 of the TE<sub>00</sub>, TE<sub>01</sub>, TE<sub>10</sub> and TE<sub>11</sub> modes using the device in Fig. 3.

## Conclusions

A mode-transparent power splitter, thought to be only possible with free-space implementations, was proposed and experimentally demonstrated in an integrated-optic format for the first time.

## Acknowledgements

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