Architecture of an all optical de-multiplexer for spatially multiplexed channels

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ABSTRACT

Multiple channels of light can propagate through a multimode fiber without interfering with each other and can be independently detected at the output end of the fiber using spatial domain multiplexing (SDM). Each channel forms a separate concentric ring at the output. The typical single pin-diode structure cannot simultaneously detect and de-multiplex the multiple channel propagation supported by the SDM architecture. An array of concentric circular pin-diodes can be used to simultaneously detect and de-multiplex the SDM signals; however, an all optical solution is generally preferable. This paper presents simple architecture for an all optical SDM de-multiplexer.

Keywords: optical communications, fiber optics, multiplexing, spatial domain multiplexing, space division multiplexing, fiber optic communications, CAD model, spatial de-multiplexer

1. INTRODUCTION

Optical communication uses several forms of multiplexing, the most popular being frequency/wavelength and time. Both have been explored to great lengths and are rapidly approaching a point of diminishing returns in terms of bandwidth in optical fibers; whereas, the trend for increase in bandwidth demand is getting steeper. Therefore, exploration of new methods to increase fiber capacity is necessary. Lately, two methods of increasing the bandwidth have become topics of interest; spatial domain multiplexing (SDM) and orbital angular momentum multiplexing (OAM)[1,2]. SDM is a multiplexing technique that adds a new degree of photon freedom inside the fiber and allows for multifold increase in bandwidth. SDM allows co-propagation of multiple channels of same wavelength, enabling spatial reuse of optical frequencies inside a single core and it can be used for existing as well as futuristic fibers. Another deviant of SDM method allows for multiple cores inside of a single cladding[3, 4], which is akin to laying down more optical fibers, albeit with a better form factor. The rate of growth for our data usage requires that more and more fibers be laid down to cope with the growing needs. This presents an all optical de-multiplexer architecture for SDM system where multiple channels of same wavelength traverse through a single core inside the optical fiber[5, 6, 9].

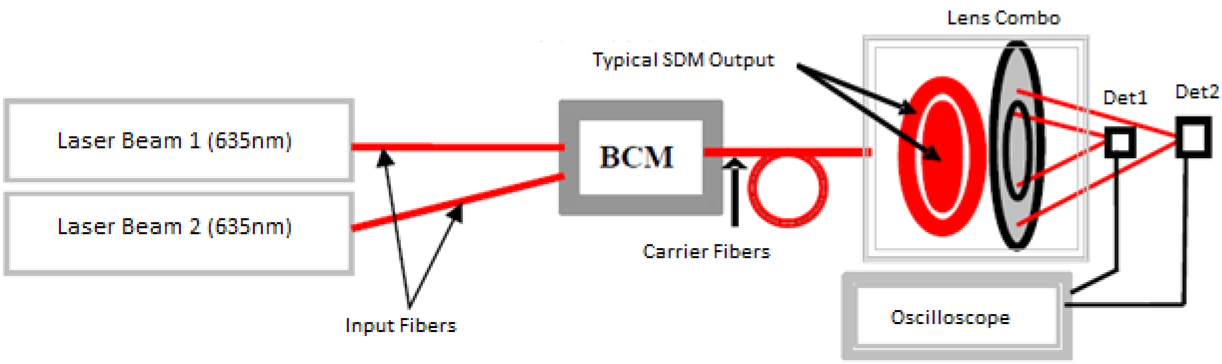

Figure 1: Block diagram of the Beam Combiner Module (BCM) or the multiplexer of the SDM system.

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In short, SDM technology is a MIMO (multiple input multiple output) approach inside a single fiber that produces spatially separated co-propagating spatial channels as a function of input angles. Each channel's input angle results in a separate helical traveling path inside the carrier fiber[6]. The architecture of the SDM system is shown in Figure 1[7]. The range of the input angles can be as large as the particular numerical aperture of the fiber, with larger angles leading to wider helical trajectories inside the fiber. The e-field at the center of these helically propagating waves becomes negligible, due to optical vector vortices[8, 9], allowing for co-propagation of same wavelength with limited interference or crosstalk. The typical output of a three channel SDM system is presented in Figure 2, where each ring presents the intensity due to an independent source/channel combination[5, 9].

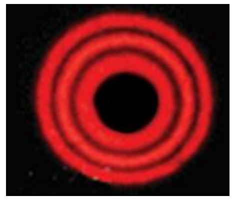
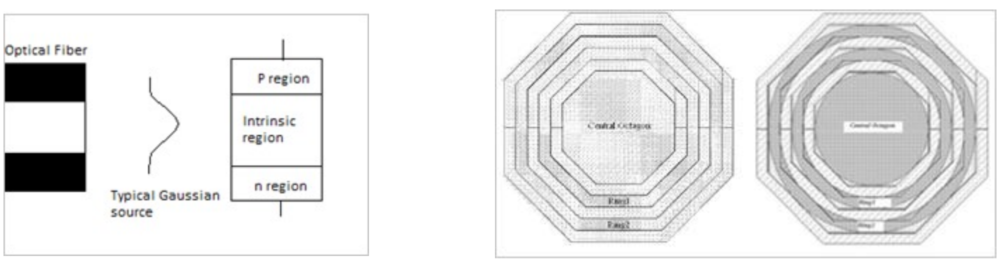


Figure 2: Output beam profile for a three channel SDM system.

In a typical fiber optic system setup, a single input through a carrier fiber is read with a PIN diode. This is shown in Figure 3(a). The data, i.e. incident light, from the optical fiber is passed to the PIN diode. From here, the light will induce electron-hole pairs, and subsequently, current will flow relative to the intensity of the incident light. The single PIN diode would not work well for SDM systems. The incident light from an optical fiber carrying multiple SDM signals would induce only a single current flow in the PIN diode, defeating the purpose of SDM. One method to read each channel of the signal is to use a PIN diode of octagonal design. One such design using an array of complementary metal oxide semiconductor (CMOS) photodiode design was recently reported and it is shown in Figure 3 (b) [10, 11]. Each region in the array design has a separate p- and n- region. Each of these regions can be connected to separate loads to read each channel of the SDM signal independently[11].



(a) (b)

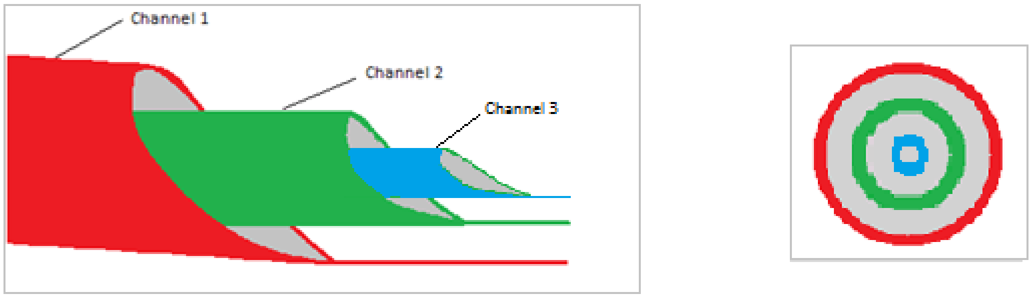
Figure 3: (a) Typical Gaussian profile from an optical fiber impinges upon a PIN diode to generate photo-current. (b) Concentric three channel CMOS photodiode structure is shown on the left while the picture on right shows the CMOS design with a typical SDM incident upon the diode.

The CMOS photodiode design de-multiplexes the SDM signal; however, this requires an optical-to-electrical (O/E) conversion. O/E conversions often increase the system complexity and typically limit the bandwidth that can be obtained from a particular signal. This limits the potential usefulness of systems using O/E conversion in communication systems. Therefore, an optical-to-optical solution is preferred, as it overcomes this bottleneck.

2. ARCHITECTURE & CAD MODEL

2.1 Architecture

The typical output intensity of SDM Channels is shown in Figure 2. The challenge in an all optical detector design involves capturing photons from the SDM intensity profile and efficiently guiding those into subsequent fibers or pigtailed detectors. An array of concentric hollow core fiber waveguides can be used to efficiently couple optical energy from the individual SDM channels into separate waveguides. The other end of the hollow core fiber waveguide array can be gradually tapered down to efficiently confine light from these SDM channels into a typical fiber type geometry to allow efficient coupling between other fibers using mechanical or fusion splices. This concept is presented in figure 4.



(a) (b)

Figure 4: Core architecture for SDM output for three channels. This figure shows the general layout of the design with figure ‘a’ showing three dimensional side view of the presented architecture while figure ‘b’ shows two dimensional the top view.

Once efficient coupling is achieved between the SDM output and the hollow core fiber array, the next task is to again efficiently couple the optical energy from the individual hollow core waveguides to independent fibers or pigtail detectors. Gradual tapering of the of the output end of the hollow core fibers into standard fiber geometry can achieve this task. This is accomplished in the architecture by a simple beveled edge that conforms to total internal reflection and Snell's law, as shown in Figure 5.

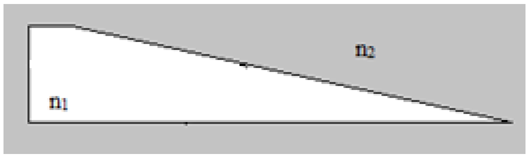


Figure 5: Bevel edged fiber with n_1 being the index of the core material while n_2 is free space.

The beveled edge eases out into a standard fiber geometry that can be easily spliced to another fiber or pigtail detector. Figure 6 summarizes this design concept.

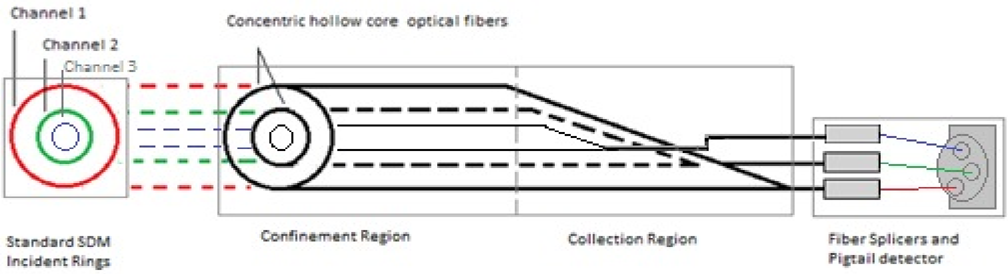


Figure 6: Architecture of the all optical De-Multiplexer. Data channels from carrier fiber are coupled into an array of concentric hollow core fibers that tapers down to guide optical energy into independent fibers or pigtail photo-detectors.

2.2 CAD Model

OptiBPM[12] is a commercially available fiber optic simulation engine that is commonly used for beam propagation modeling in optical fiber systems. We also used OptiBPM to simulate our architecture by employing two index values, the core index, n_1=1.5, and the free space index, n_2=1.0. The core index is given to the rings inside our carrier fiber to mimic hollow core silica fiber wave guides. The fibers presented in this paper are all contained in a one meter space. This space contains three key regions for the carrier fiber, ring formation region to generate the rings, bevel region to guide the rings in a single fiber, and output fiber region to couple optical energy from SDM channels into independent fibers or detectors. These regions are similar to those depicted in Figure 7.

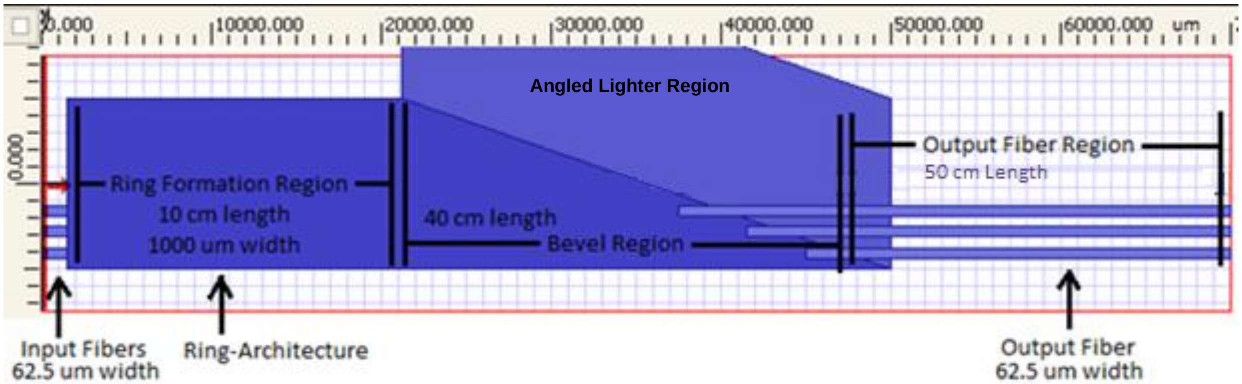


Figure 7: OptiBPM design showing the three key regions (not to scale). The darker region in the first half of the figure shows the hollow core fibers with the input fibers to the left of it. The angled lighter region indicates cladding with refractive index of 1 and the output fibers are to the right of it.

The ring formation region excites helical propagation inside the fiber to establish co-propagating SDM channels in the carrier fiber. The second region is the bevel region, which is 40 cm from the beginning of the bevel to its end. A strip of free space is placed over the architecture. Since the surrounding region of the fiber is free space, the strip will blend well with free space and simulate the beveled edge in Figure 6. A better view of the bevel region coupled with the output fibers, as seen by the simulator, is shown in Figure 8. The final region of interest is the output fiber region. This region spans 50 centimeters in the simulation and consists of the three output fibers, as shown in Figure 7.

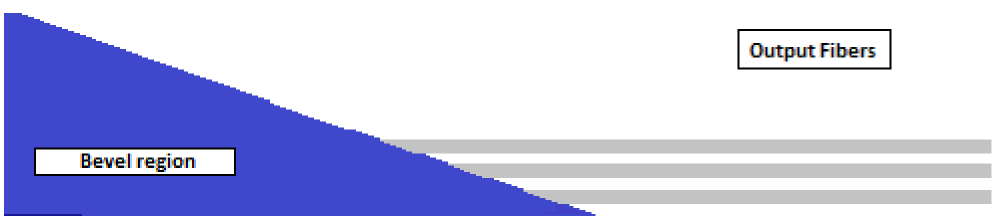
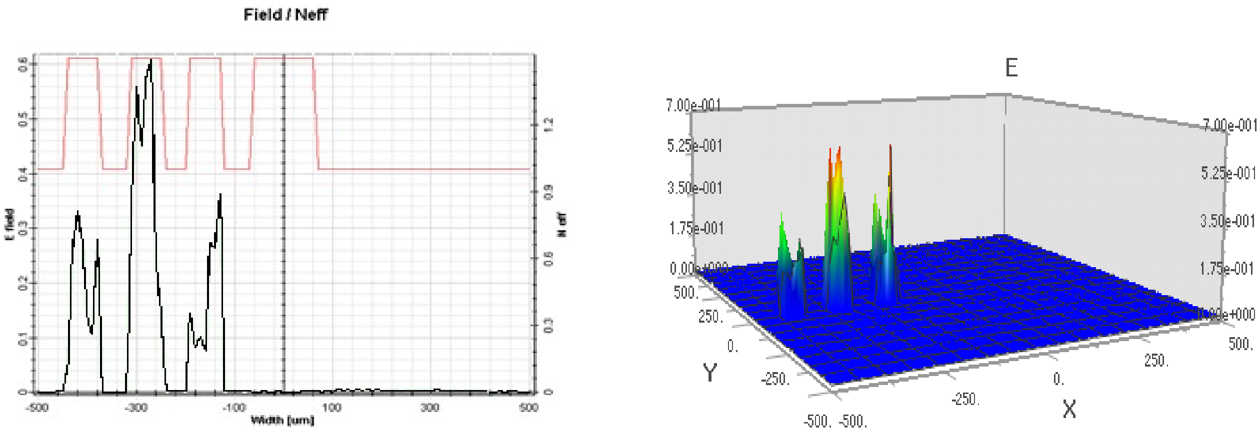


Figure 8: Representation of bevel region and output fibers by the simulation engine.

3. SIMULATED RESULTS

Three simulated signals, each with a normalized power of 0dB, were coupled into an array of concentric hollow core fibers as shown in Figure 6. Transmission from the ring formation region to the bevel region was nearly lossless and at the beginning of the fiber bevel, the intensity of the signal was close to the original strength. The signal undergoes attenuation while traversing through the bevel region and by the time the signals reach the individual output fibers, the total losses in the system were approximately 3.8dB. By the end of the meter long simulation region, the losses were approximately 7.0dB. The results from each of the individual output fibers are shown in Figure 9. The signal at the beginning of a given channel read a normalized value of 1, or 0dB. This leaves us with loss in each channel, respective to Figure 9(a), of 9.8dB, 4.4dB, and 4.3dB. The total normalized power in the system as a function of distance, z in micrometers, is shown in Figure 10. Though the bevel region provides better coupling efficiencies, however the signal undergoes losses. These losses can be attributed to the way the OptiBPM simulation engine handles curved surfaces. We are currently investigating alternate strategies to improve the performance of the system.



(a) (b)

Figure 9: (a) Normalized E-field intensities confined within the core regions of the three fibers. The core region of the 4th fiber that is located at the origin is not illuminated.
(b) 3-D representation of the E-fields inside the three output fibers.

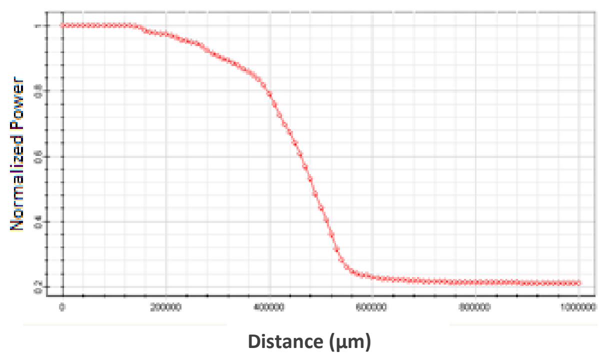


Figure 10: The normalized power decreases with increasing distance.

A series of simulations were run for each channel individually, in order to analyze cross talk between each output channel. The values obtained show an average cross talk of approximately -14dB, with a variance of 3dB. These values have since been improved by another 3dB by tweaking different model parameters. This includes decreasing the slope of the bevel region, changing the indices of refraction, increasing the mesh density, etc. Other improvements to the design involve incorporating conditioning of the SDM signal prior to coupling into the hollow core array. It should also be noted that OptiBPM is not optimized for helical propagation of light inside optical fibers. Hence, we are currently evaluating alternate simulation engines.

4. CONCLUSION

The architecture presented in this paper is a simple design that plays to the features present in SDM signals. The results for the simulation show that the signal is being guided onto the output fibers as expected, and acts as a proof of principle. Refinements of the design as well as proper implementation of the input should further improve the results and allow for a practical optical-to-optical solution for SDM channel detection and processing. Future work on the architecture will include design modifications as well as the use of additional simulation tools such as OptiSystem, which has the potential to simulate the entire communications network rather than the de-multiplexer unit alone. This could provide a better insight to the operation of the individual components of the SDM system including the de-multiplexer unit.

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