Analysis of an all optical de-multiplexer architecture utilizing bevel design for spatially multiplexed optical fiber communication systems

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ABSTRACT

Spatial domain multiplexing (SDM) is a system that allows multiple channels of light to traverse a single fiber, utilizing separate spatial regions inside the carrier fiber, thereby applying a new degree of photon freedom for optical fiber communications. These channels follow a helical pattern, the screen projection of which is viewable as concentric rings at the output end of the system. The MIMO nature of the SDM system implies that a typical pin-diode or APD will be unable to distinguish between these channels, as the diode will interpret the combination of the SDM signals from all channels as a single signal. As such, spatial de-multiplexing methods must be introduced to properly detect the SDM based MIMO signals. One such method utilizes a fiber consisting of multiple, concentric, hollow core fibers to route each channel independently and thereby de-mux the signals into separate fibers or detectors. These de-mux fibers consist of hollow core cylindrical structures with beveled edges on one side that gradually taper to route the circular, ring type, output energy patterns into a spot with the highest possible efficiency. This paper analyzes the beveled edge by varying its length and analyzing the total output power for each predetermined length allowing us to simulate ideal bevel length to minimize both system losses as well as total de-mux footprint. OptiBPM simulation engine is employed for these analyses.

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

1. INTRODUCTION

With the advent of the digital age, the ability to transmit large amounts of data quickly has become a constant topic of growing interest. Research into optical fiber communication multiplexing techniques, such as wavelength division multiplexing (WDM) and polarization division multiplexing (PDM), have ebbed the growing tide of data traffic[1-3]; however, these multiplexing methods are rapidly approaching the estimated limit of their current designs[1,4]. In order to continue to improve data transmission rates, two new multiplexing methods were recently introduced, orbital angular momentum multiplexing (OAM)[5,6] and spatial domain multiplexing (SDM)[7-14]. In the field of SDM, there are currently two different methods of approaching this topic. One such method utilizes multiple cores inside a single fiber[7-9]; however, this is akin to laying down multiple fibers which, in reference to each core, is a single-input single-output (SISO) approach. Alternative methods utilize multiple sources inside a single core[10-14]. The primary method for this report achieves SDM by varying input angle of each independent source to achieve a multiple input, multiple output (MIMO) based system, which could further be used in multi-core designs later, if desired[11-14]. The design for a MIMO based SDM system is presented in figure 1.

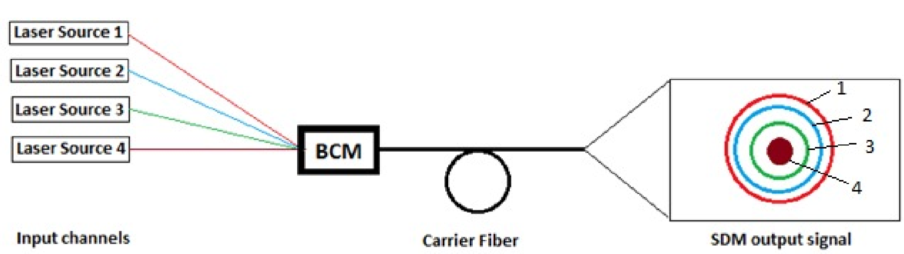

Figure 1: Four channel SDM system architecture. The four laser sources are used as input into the beam combiner module (BCM) that serves as the multiplexer. Spatial de-multiplexer is needed to properly route the independent channels.

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Each channel in an SDM system will traverse the carrier fiber in a helical trajectory based upon the angle at which each channel is guided into the carrier fiber. The steeper the input angle of the signal, the faster the helical trajectory rotates inside the fiber, and in accordance with the optical vortices theory[14-16], larger null fields at the center will result in rings with larger radii due to higher topological charge ‘m’. Consequently, each channel will travel independent of one another and little to no cross talk is observed[11,12]. As depicted in figure 2, the output of this SDM system is a series of concentric donut shaped rings that correspond to the individual inputs, with the outermost rings being those inputs with the highest input angles.

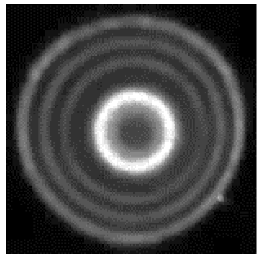


Figure 2: Typical four channel SDM output.

In a typical fiber optic system setup, a single pin diode is utilized to read the output of a carrier fiber. Because of SDM's MIMO nature, this is not a permissible detection method as the single pin diode would read all data channels as a single value, which is counter to SDM's objective. To combat this, several methods to de-multiplex the SDM output signal have been proposed. One method to read each channel of the signal is to use a PIN diode of circular/octagonal design consisting of an array of complementary metal oxide semiconductor (CMOS) photodiodes, as shown in Figure 3[17,18]. Each region in the array design has a separate p- and n- region, and each of these regions can be connected to separate loads to read each channel of the SDM signal independently. While this does de-multiplex the SDM signal, this is ultimately an optical-to-electrical solution which limits the overall bandwidth that can be achieved with the system. The design also does not fit well with current systems in place.

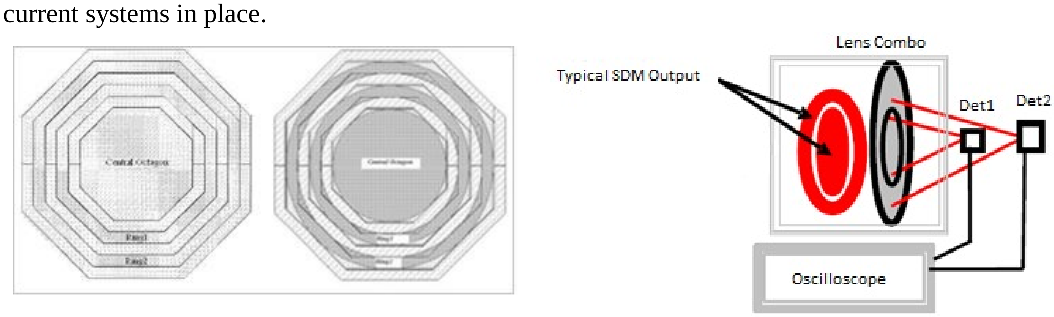


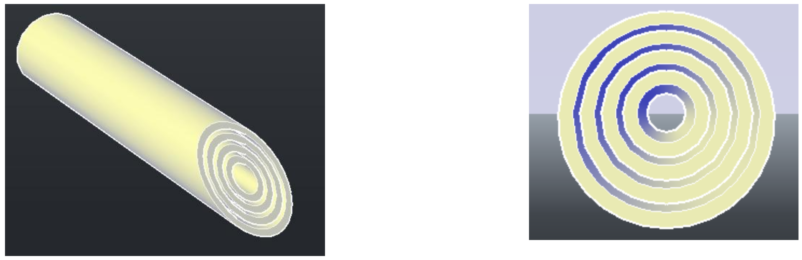
Figure 3: CMOS photodetector SDM de-multiplexer on the left. Bulk optic based lens combo design to rout de-multiplexed signals into corresponding photodetectors is presented on the right.

Another alternative de-multiplexer design utilizes an array of lenses whose radii correspond to each ring. These lenses focus each channel's intensity down to a single point where it can be read by individual detectors[18], as depicted on the right side of figure 3. This design offers an optical-to-optical solution that can be retrofit to current systems; however, it is an expensive solution that is subject to errors due to vibrations and other environmental effects. Endeavors into minimizing this lens model are being studied for future reference. A third model consists of an inline fiber architecture that is devised of concentric hollow core fibers[19] and is the subject of study of this endeavor.

2. HOLLOW CORE DE-MULTIPLEXER MODEL

2.1 Architecture and CAD Model

As shown in figure 2, the experimental output intensity of an SDM system consists of independent concentric circular rings. In order to utilize an optical-to-optical solution, we must condense these rings onto separate photodetectors or pin diodes. As previously mentioned earlier, one way to accomplish this would be through an array of concentric hollow core fiber waveguides. The output of the SDM system from figure 1 can be easily coupled to this hollow core waveguide architecture, and by gradually tapering the output end of the architecture, we can guide each channel from our SDM system into individual fibers. This architecture is presented in figure 4.



(a) (b)

Figure 4: De-multiplexer architecture CAD representation. (a): 3d view (b): top view.

The architecture shown in figure 4 utilizes a beveled edge which employs total internal reflection to guide optical energy from each ring onto a single point such that it can be efficiently coupled into other optical fibers. These other fibers could then be either spliced to additional lengths of optical fibers or coupled onto typical photodetectors, allowing them to conform to conventional fiber optic communication systems. Figure 5 depicts the fiber architecture highlighting the nature of the beveled fibers edges that can be easily coupled to additional fibers or photodetectors, while figure 6 summarizes the entirety of the design.

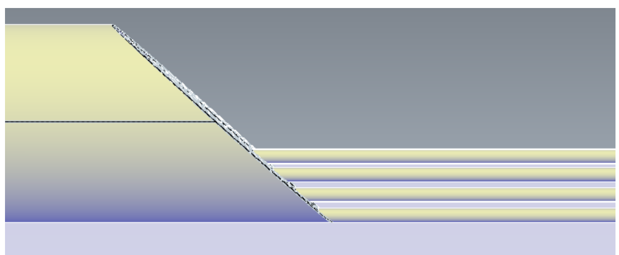


Figure 5: Close up of the hollow core fiber architecture with beveled edges and integrated multimode fibers.

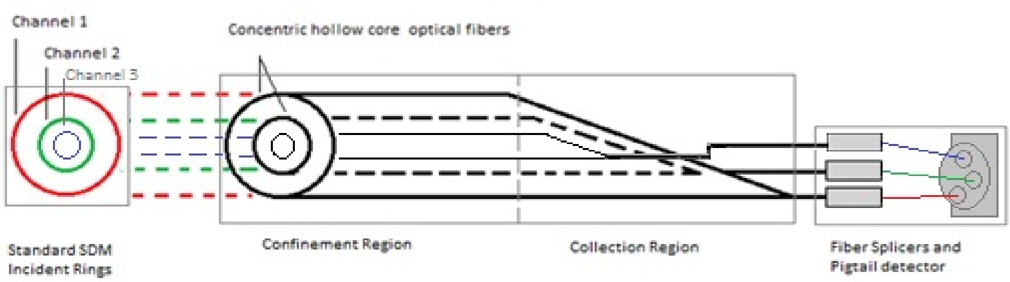


Figure 6: Architecture of the all optical De-Multiplexer. Data channels from carrier fiber are coupled into an array of concentric hollow core fibers that tapers down to guide optical energy into independent fibers or photo-detectors[19].

2.2 CAD Model

In order to analyze this system, a commercially available optical fiber analysis program, OptiBPM[20] simulation engine, was employed. A four fiber hollow core architecture, as devised in OptiBPM, can be seen in figure 7. This figure is similar to the architecture shown in figure 5. The notable differences are as follows: The darker slanted region is a piece of free space material. In order to achieve a bevel in OptiBPM, this free space region overlaps the hollow core architecture shown by the lighter region on the left. Since the surrounding media is also composed of free space material, the program will blend the free space region into the background and create a slanted, or beveled, region at the end of the hollow core architecture. The four objects extending from the hollow core architecture are output multimode fibers. These fibers extend inside the de-multiplexer architecture to regions defined as the separate hollow core structures, in order to improve the coupling between the structure and the output fibers.

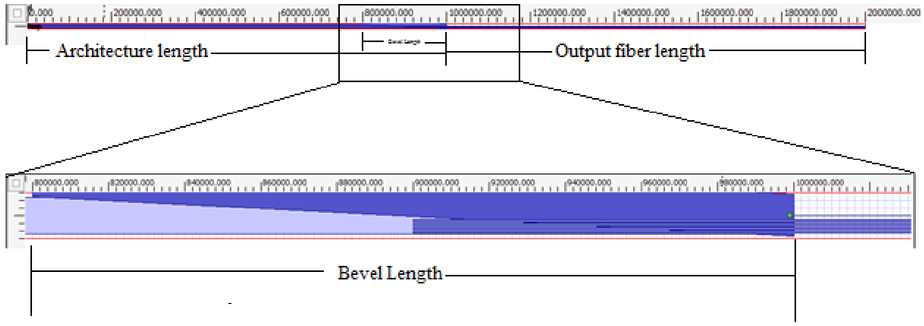


Figure 7: OptiBPM simulation setup for hollow core fiber de-multiplexer architecture. The blown up portion is a close up of the bevel region. It should be noted that the length of the bevel extends into the architecture length.

The OptiBPM design utilizes a core index of 1.5 for both the hollow core structures and the output fibers. The coating between each hollow core is a material resembling free space, with refractive index of 1, for simplicity. The radius of the hollow core structure is 500 μm, and each of the output fibers has a radius of 62.5 μm. Previous analysis[19] of the design utilized a half meter long three ring hollow core structure and showed total losses in the range of -7 dB, with a bevel length of 40 cm. While the losses have since been reduced greatly, further analysis into the architecture would determine key loss points. One such point is along the bevel's edge.

During the course of this study, multiple simulations were conducted by varying the length of the bevel in an attempt to determine any key points where increasing the length of the beveled region provides little decrease in power loss. Such a point is necessary to reduce total design footprint while increasing design robustness. For these simulations, the hollow core region is held fixed at one meter in length while varying the bevel region backwards into this region, as shown by the blown up region in figure 7. The output fibers extend another one meter beyond the end of the bevel. The losses in the system are determined based upon total power in the system at the final two meter distance.

3. SIMULATED RESULTS

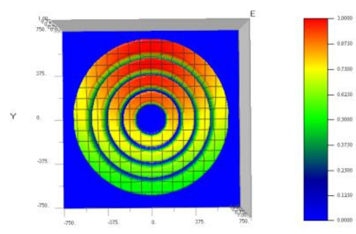


Figure 8: Input fields coupling into the hollow core de-multiplexer architecture.

The simulated input field intensity in the four ring hollow core fiber architecture is shown in figure 8, which is similar to the typical SDM output as depicted seen in figure 2. The simulated fields do not carry OAM, which is typically present in SDM output signals[5,6]; however, it offers many similarities and can be used to test the present architecture. Upon reaching the bevel, some of the intensity leaks out and the rest is guided along the bevel's edge toward the fused output fibers.

The total transmittance of our input signal is analyzed using the total power function available in OptiBPM. The function analyses total power at any given point along the architecture and records it as a value normalized to the initial input power. Figure 9 displays what is observed on the power analysis for a bevel length of 40 cm as well as a 3D depiction of the E-field intensities at the two meter point in the simulation.

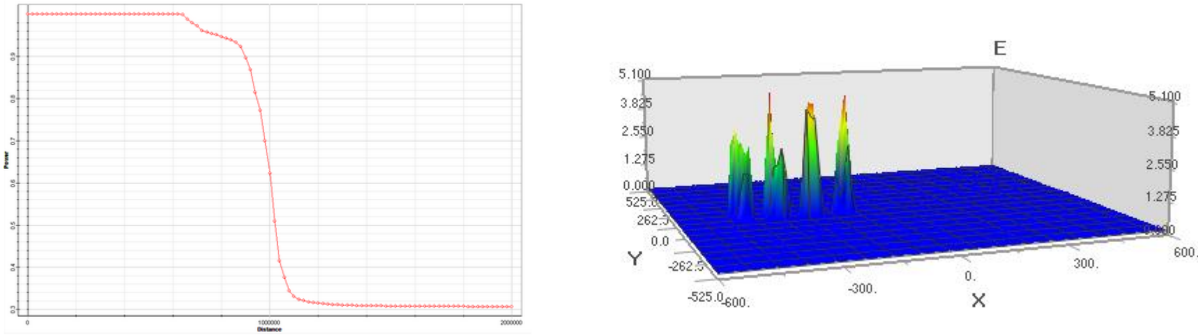


Figure 9: Power versus distance plot given by OptiBPM on the left. The image on right shows the 3-d representation of the e-fields at the output of our architecture design.

Simulations for the bevel length were performed for lengths ranging from 1 – 75 cm in increments of 1 cm. The total power at the two meter point was taken and converted to decibels for analysis. The results can be seen in figure 10.

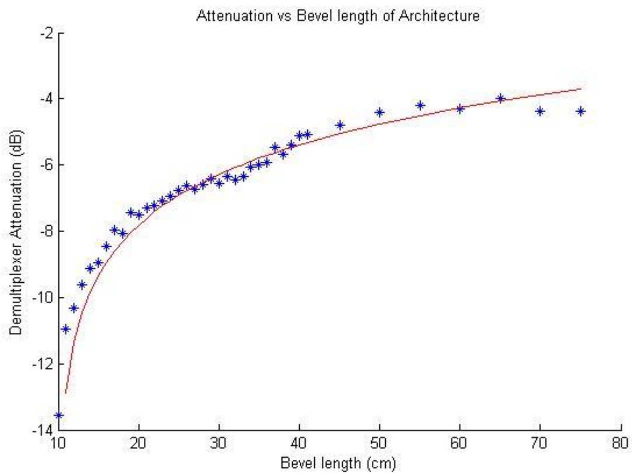


Figure 10: Output power gain as a function of bevel length. The best fit line has a mean squared error of $R^2 = 0.9875$.

It can be noted from figure 10 follows a logarithmic response as the length of the bevel is extended. It is also observed that the losses approach a limit of approximately - 4 dB. The initial jump is attributed the critical angle of the fiber along the bevel. As the bevel length increases, the angle at which our signals encounter the bevel decreases. As this angle drops below the critical angle, the signal is better confined along the edge of the bevel. Losses at this point are a function of boundary conditions. The best fit to the simulated data can be presented using equation 1 with a mean squared error of 0.9875,

$$Power\ (dB) = 2.2 * \ln(x - 10) - 12.881 \qquad [1]$$

4. CONCLUSION

A simple architecture is presented in this paper that adapts well to the features of the SDM signals. An analysis into the proposed all optical de-multiplexer architecture's bevel length was performed and total losses attributed to different bevel lengths are presented. Further research into the design will be focused to minimalize the losses incurred as well as to minimize overall de-multiplexer footprint. Current losses range upwards of roughly -4 dB; however, better values with losses approaching -1 dB may be obtained by applying minor refinements to different aspects of the current architecture. These refinements are currently under investigation and will be presented in the near future.

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