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ABSTRACT:

Spatial Domain Multiplexing/Space Division Multiplexing (SDM) can increase the bandwidth of existing and futuristic optical fibers by an order of magnitude or more. In the SDM technique, we launch multiple single mode pigtail laser sources of same wavelength into a carrier fiber at different angles. The launching angles decide the output of the carrier fiber by allocating separate spatial locations for each channel. Each channel follows a helical trajectory while traversing the length of the carrier fiber, thereby allowing spatial reuse of optical frequencies. In this endeavor we launch light from five different single mode pigtail laser sources at different angles (with respect to the axis of the carrier fiber) into the carrier fiber. Owing to helical propagation we get five distinct concentric donut shaped rings with negligible crosstalk at the output end of the fiber. These SDM channels also exhibit Orbital Angular Momentum (OAM), thereby adding an extra degree of photon freedom. We present the experimental data of five spatially multiplexed channels and compare them with simulated results to show that this technique can potentially improve the data capacity of optical fibers by an order of magnitude: A factor of five using SDM and another factor of two using OAM.

Keywords: Spatial Domain Multiplexing (SDM), Space Division Multiplexing, Orbital Angular Momentum (OAM), Optical Vortex, Helical Propagation, Bandwidth Increment

1. INTRODUCTION

The demand for bandwidth is never ending and continues to grow unabated. Scientists and engineers are continually developing solutions to address the problem. Most of these solutions are incremental in nature. Revolutionary changes that match the impact of wavelength division multiplexing (WDM) has not been introduced into the existing optical networks since the 1990s. The current push in industry continues to revolve around WDM. The continued demand for higher bandwidth has forced requirements in metropolitan networks that were once limited to long haul communications. Hence, in most current optical networks, including metropolitan networks, the need to establish lightpaths that allow optical connection between two networks, in any arbitrary directions, and then switch them on-demand has led to photonic routing devices such as reconfigurable optical add-drop multiplexers (ROADM), and photonic crossconnects (PXC) [1-6]. These devices enable optical switching and routing at or above the per-wavelength level. The optical orthogonal frequency division multiplexing (OFDM) [7,8] and Nyquist-based pulse generation [9,10] have also added new dimensions to the optical transmission discipline. Furthermore, the recent introduction of multicore and multimode optical fibers enable new venues for throughput improvement [11,12]. However it should be kept in mind that multicore fibers are akin to laying additional fibers in the cable trays, and all these technologies still result in incremental advances to the state of the art.

Thus, it is vital to add new optical fiber multiplexing concepts to allow added degrees of photon freedom to optical fiber communications. This endeavor presents a hybrid architecture that integrates five spatially multiplexed channels with opposite OAMs, over a single fiber core, to increase the fiber bandwidth by an order of magnitude. This paper briefly

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introduces the SDM and OAM concepts, and then presents a hybrid architecture integrating the two. Experimental results for two sets of five complementary SDM channels bearing opposite OAMs are also presented.

Spatial Domain Multiplexing/Space Division Multiplexing (SDM) [13] is a multiplexing technique that employs spatial reuse of optical frequencies in a MIMO [14,15] configuration to increase the data capacity of standard and futuristic optical fibers. Spatial reuse of optical bandwidths has long been a goal in optical fiber communication systems. It remained elusive due to issues associated with the very small dimensions of the optical fiber. SDM forces optical energy inside the fiber to follow helical trajectories, as helical propagation is also bound by total internal reflection and allows for multiple unique solutions that allow guided propagation of optical energy in fibers; as such, a number of channels of exactly the same wavelength can be supported as long as these channels occupy different spatial locations inside the optical fiber. Carefully controlling the location and orientation of the input beams can generate independent channels at desired spatial locations. As a result, multiple SDM channels of information with all the channels operating at exactly the same wavelength can be multiplexed over a single fiber.

The SDM concept is illustrated in figure 1. The data carrying capacity of a standard multimode fibers increases as helically propagating non-meridional SDM channels allow spatial reuse of optical frequencies [16]. Helically propagating SDM channels also carry Orbital Angular Momentum (OAM) [17] while traversing the length of the fiber. Orbital Angular Momentum (OAM) causes optical vortices [18,19]; hence, donut shaped rings are achieved at the output end of SDM systems. Azimuthal phase dependence of total angular momentum contributes to the OAM [20] in the SDM technique. This endeavor describes a novel spatially multiplexed five channels SDM system in a 62.5/125 µm step index multimode fiber that preserves its OAM. Furthermore, another set of five channels can also be launched into the multimode carrier fiber at similar but complementary angles. As a result, a system architecture employing ten SDM channels with five channels bearing clockwise OAM and the other five employing counter clockwise OAM can be used to design a system where the total bandwidth of optical fibers increases by a factor of 10.

2. SPATIAL DOMAIN MULTIPLEXING

In a SDM system, light is launched from multiple single mode pigtail laser sources at different angles into a carrier fiber. Owing to helical propagation inside the fiber, distinct concentric donut shaped rings with no discernible cross talk can be seen at the output end of the fiber.

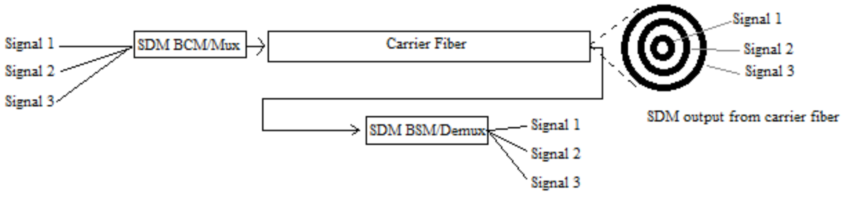

Figure 1: Schematic of an SDM model [21]

The SDM system consists of the following components as shown in figure 1:

a) Single-mode pigtail laser sources of a given wavelength
b) Beam Combiner Module (BCM) or Spatial Multiplexer
c) Standard step index multimode carrier fiber
d) Beam Separator Module (BSM) or Spatial De-multiplexer[22-24]
e) Photo-detectors to detect different channels

Figure 2 illustrates the concept of SDM by depicting a five channel output ring pattern as well as each channel individually. SDM channels propagate inside an optical fiber without interfering with each other. These channels act independent of each other and exhibit no discernable crosstalk.

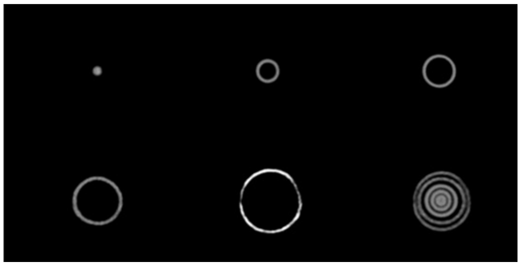

Figure 2: Depiction of a five channel SDM output signal as well as its five component channels.

2. ORBITAL ANGULAR MOMENTUM (OAM)

An optical vortex results in an electric field distribution with a place of zero field intensity at the center of the beam. It is created because of the phase singularity at the center of the optical beams, causing the fields cancel out at the center. Vortex beams can be twisted like a corkscrew, about the propagation axis where it travels helically [25].These vortex beams possess a topological charge that represents the number of times the waves twists during one wavelength. The faster the light spins, the larger the dark region at the center is. The E-field in optical fiber is given by [26]:

$$E_z = \mathrm{A}\, J_m(u\rho)\ \exp(\mathrm{j}m\varphi)\ \exp(\mathrm{j}\beta z)$$

where,

J_m represents the Bessel function of order ‘m’,
m is the azimuthal index,
φ represents the azimuthal phase angle of the fiber,
exp(i$m\varphi$) is the azimuthal phase dependence of OAM,
Core parameter, $u^2 = n_1{}^2 k_0{}^2 - \beta^2$,
n_1= refractive index of fiber core,
β= propagation constant = nk_0
k_0= free space wave number = $\frac{\omega}{c} = 2\pi/\lambda$ and
λ = wavelength

These above mentioned parameters can be used to determine the OAM per photon (mh) [27].

3. EXPERIMENTAL SETUP

The experimental setup to determine the presence of OAM in SDM consists of spatial multiplexer or a beam combiner module (BCM) and spatial de-multiplexer or a beam separator module (BSM) [28]. In order to verify the presence of OAM in SDM channels and quantify it, a method elaborated by Savchenkov et al. [29] can be used. The presence of OAM in SDM channels can be easily determined by using a setup similar to the one shown in figure 3.

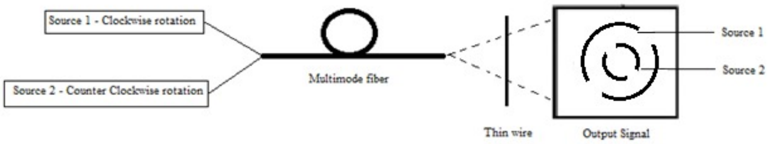

Figure 3: Experimental setup of OAM

This setup consists of multiple single mode input signals of same wavelength. The signals from the single mode fibers are launched into a 62.5/125µm step index multimode fiber. The input signals are launched within the acceptance angle or numerical aperture. The ouput is projected on a white screen and the intensity distribution is analysed. It is noted that distinct concentric donut shaped rings of similar thickness, intensity and spatial separation are projected on the screen. The rings do not interfere each other, which implied that SDM channles are propagting with no discernible amount of crosstalk.

In accordance with the method shown by Savchenkov, a thin wire is placed in front the output end of the multiple mode fiber. A certain amount of shadow is present in the output side. The shadows varies as the incident angles or distance from the fiber to the varies. Two inputs having the same azimuthal or incident angle, but different topological charge can be launched simulatneously into the carrier fiber, and this will create two shadow distortions at the output, as shown in figure 4 (left). The outer ring exhibits clockwise momentum and the inner ring exhibits counter clockwise momentum [30].

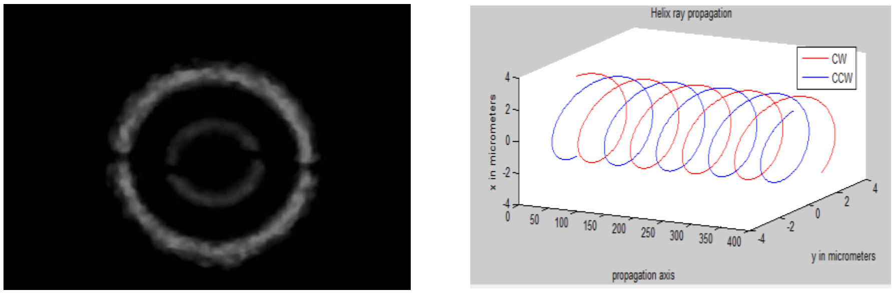

Figure 4: OAM causes shadow twis for two different inputs (left) and simulated plot of CW & CCW propagations at same spatial location with the inputs launched at same though complimentary angles (right)

Figure 5 shows an SDM system composed of five MIMO channels. All of them can propagate the length of the fiber using either clockwise or counter clockwise helical trajectories [31]. The simulated plot of these counter propagating helical channels is presented in figure 4. The figure on the left progressively shows the shadow distortion for a SDM system bearing clockwise OAM when the thin wire is gradually moved away from the fiber, while the figure on the right shows similar effect for a five channels SDM system bearing counter clockwise OAM. It should be noted that the positions of the fiber and the screen remain unaltered during this experiment.

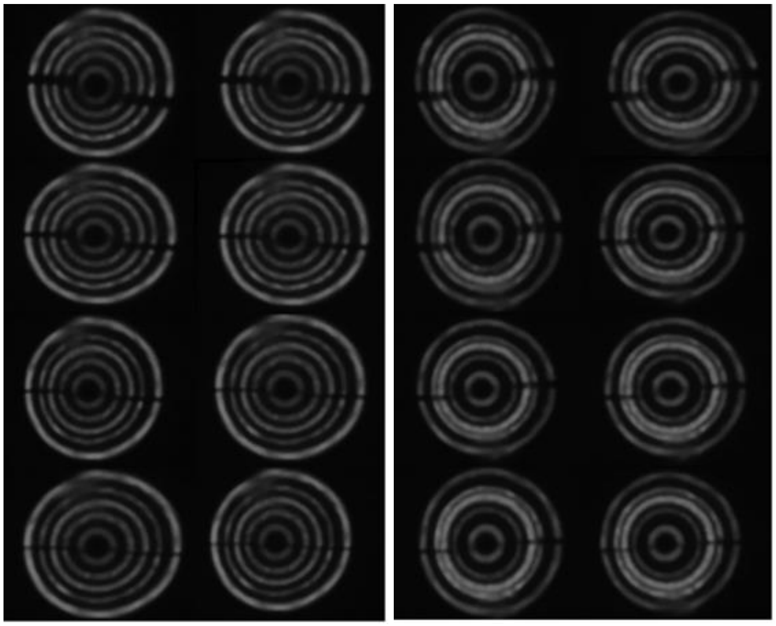

Figure 5: Effects of moving the wire away from the fiber in clockwise direction (left) and effects of moving the wire away from the fiber in counter clockwise direction (right).

4. SDM, WDM & OAM

Since SDM channels carry OAM [32,33], complementary input launch conditions could be used to launch two sets of SDM channels at the same location but with opposing OAMs. Hence, it is possible to utilize the same five channel SDM system presented earlier and launch ten sets of WDM channels; five with clockwise (CW) OAM and another five with counter clockwise (CCW) OAM. It should be noted that this hybrid system is possible as the numerical aperture of a fiber does not vary with wavelength. Hence, according to the fiber geometry, light propagating inside optical fiber will exit at an angle equal to the incident angle, provided the medium at the input and output ends of the fiber is same. The block diagram of such a system is presented in figure 6. Indeed the screen projection will only have five SDM rings for the two sets of the five channels each. However, it will be possible to separate them using the opposite OAMs. As a result, the data capacity of such a system will increase by an order of magnitude.

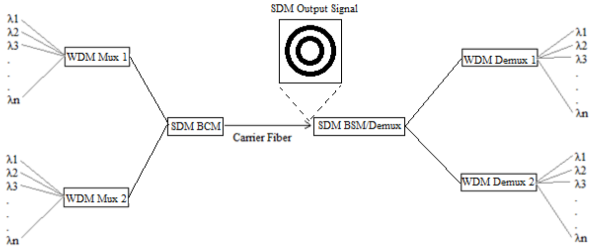

Figure 6: SDM hybrid architecture with WDM

A special purpose dedicated detector would be required to detect and de-multiplex these channels. The five SDM channels with clock wise OAM will occupy exactly the same location as the five SDM channels with counter clockwise OAM. A simple optical detector, designed to detect and process optical output from such a hybrid architecture carrying OAM with opposite topological charges, can be constructed using a ridge based segmented detector, presented in reference [34].

5. CONCLUSION

This paper offers the experimental validation of counter rotating OAMs. A five channel SDM architecture is also presented showing that each of them can be launched from two complementary input launch angles. These complementary angles support opposite topological charges, giving rise to clockwise and counter clockwise OAMs inside the optical fiber [35]. Hence, a system can be designed where the SDM channels occupy the same spatial location but they carry opposite OAMs. Proper signal processing arrangements utilizing the output intensity in conjunction with OAM can be used to de-multiplex the SDM channels with clockwise and counter clockwise OAMs. Hence, a set of two five channel SDM systems, launched using complementary angles, coupled with counter rotating OAMs can increase the fiber channel capacity by an order of magnitude. The fiber channel capacity can be increased even more, if more than five spatial channels are packed into the same fiber.

6. ACKNOWLEDGEMENTS

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