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Analysis of Spatial Domain Multiplexing/Space Division Multiplexing (SDM) Based Hybrid Architectures Operating in Tandem with Wavelength Division Multiplexing

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ABSTRACT:

Spatial domain multiplexing (SDM) also known as space division multiplexing adds a new degree of photon freedom to existing optical fiber multiplexing techniques by allocating separate radial locations to different MIMO channels as a function of the input launch angle. These independent MIMO channels remain confined to the designated location while traversing the length of the carrier fiber, due to helical propagation of light inside the fiber core. The SDM technique can be used in tandem with other multiplexing techniques, such as time division multiplexing (TDM), and wavelength division multiplexing in hybrid optical communication schemes, to achieve higher optical fiber bandwidth by increasing the photon efficiency due to added degrees of photon freedom. This paper presents the feasibility of a novel hybrid optical fiber communications architecture and shows that SDM channels of different operating wavelengths continue to follow the input launch angle based radial distribution pattern.

Keywords: Spatial Domain Multiplexing (SDM), Optical Multiplexing, Bandwidth Enhancement, Optical Cross-talk, Wavelength Division Multiplexing (WDM), Space Division Multiplexing, Helical Propagation, Orbital angular momentum (OAM)

1. Introduction

Multi-dimensional channel capacity research indicates that the employment of multiple degrees photon of freedom such as amplitude, phase, polarization, space and orbital angular momentum of photons can improve the spectral efficiency by multiple folds, even order(s) of magnitude higher than that claimed in any fiber-optic experiment reported to date. This increase in spectral efficiency, through added degrees of photon freedom, can provide revolutionary capabilities to optical networks of the future. Increased channel capacity has always been an important area of research in electronic communications systems and improvements in this regard have been reported on a regular basis. Another such novel channel capacity improvement concept that adds a new domain to optical fiber multiplexing techniques, known as SDM was developed at the Optronics Laboratory of Florida Institute of Technology with the potential to increases the optical fiber bandwidths to T-bits/s range[1]. This method utilizes multiple pigtail laser sources of exactly the same wavelength to launch light into a single carrier fiber, in a fashion that resulting channels follow independent helical trajectories while traversing the length of the fiber. These helically propagating light beams form optical vortices inside the fiber as they carry their Orbital Angular Momentum (OAM)[2,3]; hence, the output of these beams appear as concentric donut shaped rings when projected on a screen. As a result this technique adds a new dimension, space, to the currently popular multiplexing schemes such as TDM[4] and WDM[5-7] with the potential to increase the bandwidth of existing and futuristic optical fiber systems by multiple folds.

SDM[8] allows propagation of multiple optical channels inside the core of a single fiber as a function of location. Other variants of SDM[9-13] are either akin to laying down multiple fibers or have significant cross-talk constraints rendering them

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useless for most practical purposes. For this endeavor, SDM channels follow helical paths[8,14-16] inside the core of a single fiber, where each channel is confined to a dedicated radial distance from the center of the fiber core as shown in figure 1[17,18]. The location of the individual channels is dictated by the input angle of the incident channels, where larger input angles result in larger radii of the helical paths inside the carrier fiber. The electric field at the center of these channels becomes null due to formation of optical vortices[19-21], with larger helical paths, by way of larger radii, generating a larger null regions. Consequently, signals exiting the output end of the carrier fiber form donut shaped rings whose size is determined by the launching angle of the input signal.

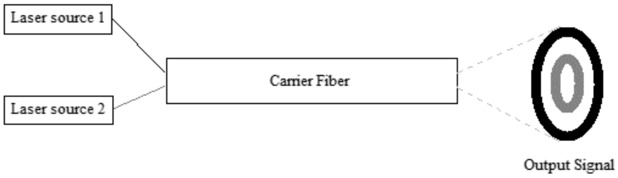

Figure 1: Minimalistic system design of two channel SDM system.

The first WDM system was introduced in the 1980s as a point to point communication system. This system worked by allowing multiple channels of data to be transmitted simultaneously by varying each channels wavelength and passing them through a single fiber. This technique has improved immensely since its first inception and has been primarily sustaining the thrust of never ending bandwidth demand in optical fiber communications and has only recently started to reach the point of diminishing returns. At the input of a WDM system, individual signals of different wavelength are combined into a single signal and coupled into a carrier fiber, while at the output end of the fiber, they are de-multiplexed back to their individual signals as a function of their independent wavelength. This basic WDM concept is graphically shown in figure 2.

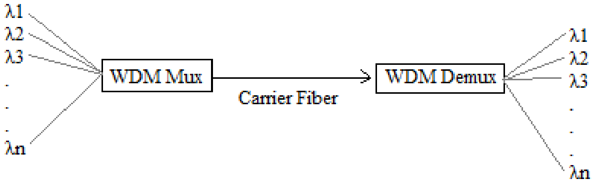

Figure 2: Schematic of typical WDM system process.

This endeavor analyzes the possibility of a hybrid architecture that combines SDM and WDM allowing for a larger system bandwidth by adding another degree of photon freedom and then experimentally proves the feasibility of such a design by showing that radial location of the output of the SDM channels depend upon the input launch angle alone and wavelength of the input channel has no bearing on the location of the output channel.

2. THEORETICAL ANALYSIS

In order for SDM to be used in conjunction with WDM, the operation of SDM must be independent of wavelength, or put simply the ring location of a typical SDM output must not vary as a function of wavelength. Otherwise, any attempts to support multiple wavelengths via spatial modulation over a single carrier fiber would cause these channels to extend into adjacent channels, creating signal collision and crosstalk; thereby, nullifying the benefits of the SDM architecture. However, if the SDM output ring pattern and location is independent of the wavelength of the input, then a simple architecture can be designed to play to SDM's properties in order to de-multiplex the signal. Such a design[22] is presented in figure 3. By allowing the typical output of an SDM system to fall over a carefully tailored concentric hollow core ring structure, one can guide the SDM signal into individual multi-mode fibers. In an SDM and WDM combined hybrid architecture scenario, the signals could be de-multiplexed using the standard WDM de-multiplexing methods. On the contrary, if the SDM signals were wavelength sensitive, the channels from different wavelengths may not be routed to the desired fiber for subsequent transmission or detection over the network.

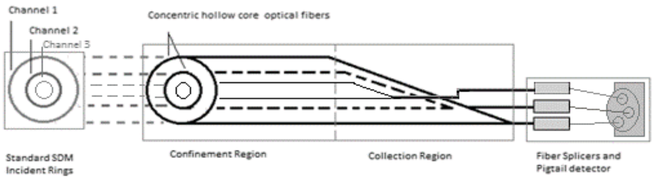

Figure 3: SDM de-multiplexer architecture routing light from multiple WDM sources could be routed in to a single carrier fiber for subsequent transmission and detection.

Therefore, it is imperative to analyze the predicted location of the SDM system output as the radial location of the SDM channel in a given fiber may change if there is a change in the numerical aperture (NA) of the carrier fiber. The index of refraction of silica is composed of a real and an imaginary part and changes as a function of wavelength. This change for silica fibers is given by the Sellmeier equation, presented by equation (1)[23,24].

$$n^2(\lambda) = 1 + \sum_{i=1}^{M} \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2} \qquad (1)$$

where each term represents absorption resonance strength Ai at a particular wavelength λi.

The NA[25] for optical fibers is governed by equation (2) which also shows the critical or acceptance angle, θ.

$$NA = \sqrt{n_1^2(\lambda) - n_2^2(\lambda)} = sin\theta \qquad (2)$$

where n_1 and n_2 are the index of refraction for the core and cladding of the fiber respectively. By expanding on Sellmeier's equation, one can find equations (3) and (4) to determine the index of refraction for n_1 and n_2 respectively.

$$n_1^2(\lambda) = 1 + \frac{A_1\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{A_2\lambda^2}{\lambda^2 - \lambda_2^2} + \frac{A_3\lambda^2}{\lambda^2 - \lambda_3^2} \qquad (3)$$

$$n_2^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - \lambda_x^2} + \frac{B_2\lambda^2}{\lambda^2 - \lambda_y^2} + \frac{B_3\lambda^2}{\lambda^2 - \lambda_Z^2} \qquad (4)$$

whereA_1, A_2, A_3, λ_1, λ_2, andλ_3 are Sellmeier Coefficients for the core and B_1, B_2, B_3, λ_x, λ_y, λ_z are Sellmeier Coefficients for the cladding.

Typically, optical fibers use silica as the base material for their construction. To bring the refractive indices of the core and the cladding to desired levels, various dopants are added to modify the refractive index. The effect of different operating wavelength on the NA[25] of two common dopants, GeO_2 and P_2O_5 are analyzed using the Sellmeier equation and plotted in figure 4 showing that the NA of standard optical fibers is independent of the wavelength of the signals

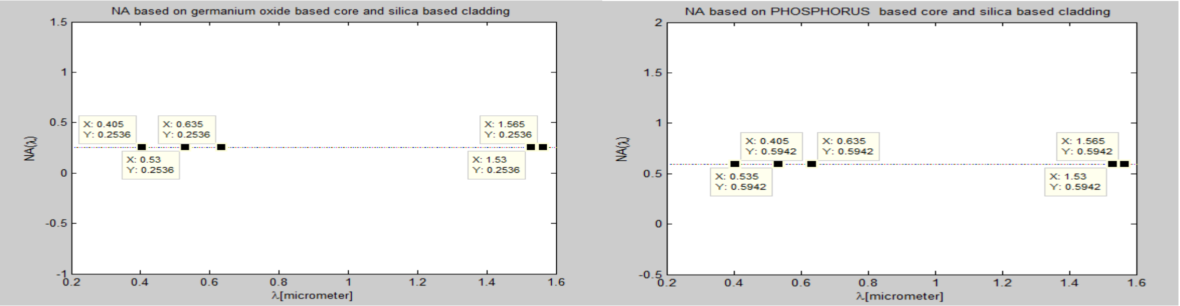

Figure 4: Numerical aperture plot for both GeO_2, left, and P_2O_5, right[27].

This is further reinforced by Snell's law which supports that the output angle of the traversing signal will be equivalent to its input angle (within the numerical aperture of the fiber), irrespective of the operating wavelength of light. This relationship is graphically shown in figure 5.

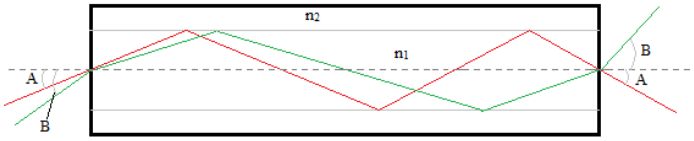

Figure 5: Relationship between input angle and output angle for an optical fiber. The input angle is the same as the output angle as long as the angles are within the critical angle of the fiber.

Since the numerical aperture of the fiber does not vary with wavelength, the output angle is equivalent to the input angle. Consequently, the SDM signal is independent of the operating wavelength and the location of the output rings will not change as the wavelength is varied; hence, SDM lends itself to be used in conjunction with WDM based systems and a hybrid architecture combining SDM and WDM is feasible.

3. EXPERIMENTALVERIFICATION

It has been repeatedly shown that a 635 nm source follows almost a one-to-one linear relationship between input and output angles[8,26] within the numerical aperture of the fiber. However, for SDM to work with WDM, it is important to establish that this relationship holds true for all wavelengths; therefore, an experimental SDM system was set up with three different wavelengths: blue at 405 nm, green at 532 nm, and red at 635 nm. These signals were launched into a single carrier fiber at various angles and the output projected onto a graduated screen. The screen projections for the three wavelengths spanning 230 nm are shown in figure 7 for angles of 4^o, 7^o, 11 ^{o}, and 13^o and then results are carefully analyzed. Figure 6 sketches the experimental setup.

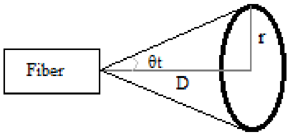

Figure 6: Relationship between transmitted angle, θ_t, and the radius of the output ring, r, which follows a simple inverse tangent relationship.

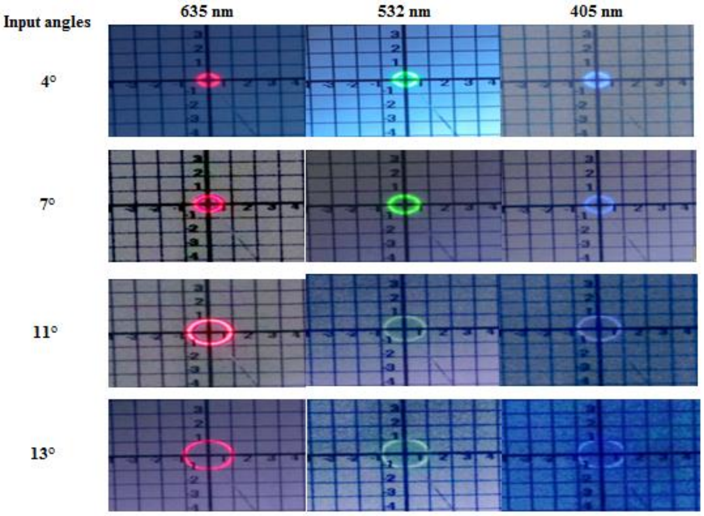

Figure 7: Output ring patterns for wavelengths of 405 nm, 532 nm, and 635 nm for input angles ranging from 4^o to 13^o [27].

Applying the inverse tangent law on the output signals, the output angle of the resultant rings spanning 230nm were determined.

$$\theta_t = \tan^{-1}\frac{r}{D} \qquad (5)$$

Equation (5) provides the relationship between the radius of the output rings and the transmission angle. Using results presented in figure 7 and the inverse tangent law, the transmitted versus the incident angle for the three wavelengths spanning 230nm in the visible range is presented in figure 8 which reiterates that the output angle of light is independent of the wavelength. Furthermore, the broad range of wavelength used in this experiment implies that the SDM system could be applied to the entire range 1550nm, 1310nm, or any other optical transmission window.

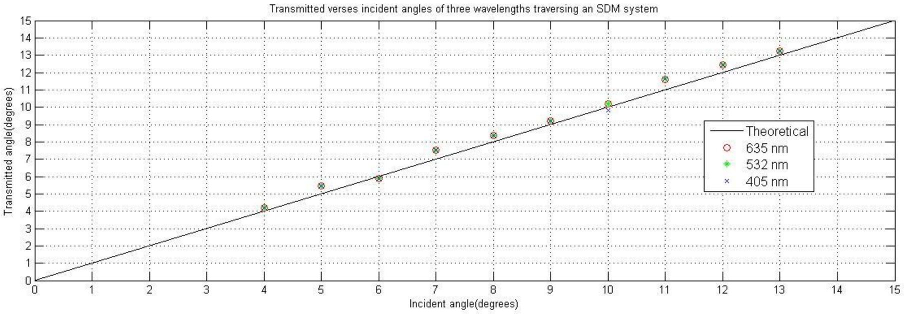

Figure 8: Transmitted angle verses incident angle for the SDM system over the visible spectrum

In short, figures 7 and 8 show that the transmission angles follow a linear relationship to incident angles for wavelengths in the visible spectrum. Therefore, the SDM system is compatible with WDM within the visible spectrum; however, current fiber optical communication systems utilize lower infrared spectrum to minimize attenuation and dispersion in silica fibers during transmission. In order to establish the feasibility of the SDM/WDM hybrid architecture at standard telecom wavelengths used by standard optical communications systems, simulated results generated by OptiBPM optical simulation engine were used. An SDM model was designed, simulated and tested[28] using wavelengths of 1530 nm and 1565 nm. The 3-D e-field profiles for these two wavelengths are presented in figure 9 which shows remarkable similarity between the two profiles

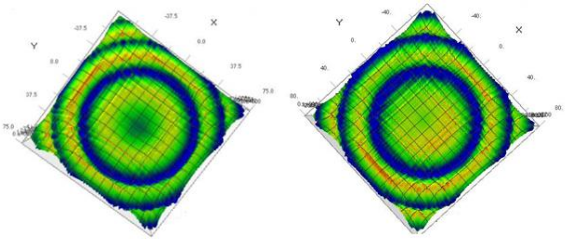

Figure 9: E-field patterns for 1530 nm and 1565 nm wavelengths after passing through the SDM system[27].

The two E-Field profiles for 1530 nm and 1560nm indicate that even at spectrum of communications interest, the output rings are incident at almost the same location ensuring compatibility of WDM and SDM hybrid architectures at a very broad range of wavelengths including the Telecom wavelengths.

3. CONCLUSION

The SDM systems is compatible to WDM systems as the SDM signal output profile is independent of the wavelength. The Sellmeier equation model as well as experimental results confirm that the SDM output signal only depends upon the input angle for a broad range of wavelengths including wavelengths at both visible as well as lower infrared spectra. Hence, SDM systems can be employed in hybrid architectures to work in conjunction with WDM based architectures allowing a new degree of photon freedom to enable significantly higher optical communication data rates.

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