Mode Division Multiplexing of Spiral-Phased Donut Modes in Multimode Fiber

Angela Amphawan*a,b, Yousef Fazea, Huda Ibrahim

aIntegrated Optics Group, School of Computing, Universiti Utara Malaysia, Sintok, Malaysia; bResearch Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA, USA.

ABSTRACT

Mode division multiplexing (MDM) is a promising technology for alleviating network traffic congestion in order to future proof current local area network infrastructure. In view of the capacity limits of multimode fiber in the advent of tremendous data growth, various dimensions for multiplexing and modulating data have been commercially deployed in the intensity, phase, wavelength and time domains. The eigenmode dimension, however, has been relatively untapped. This paper models the MDM of spiral-phased donut modes of different diameters in MMF for increasing the data capacity. A data rate of 40Gbit/s up for a distance of 1500 meters is achieved. Analyses of the power coupling coefficients and modal delays at the photodetectors are analyzed for different mode vortex orders.

Keywords: Mode division multiplexing, spiral phase front; donut mode, vortex lens, multimode fiber, optical communications

1. INTRODUCTION

The surge of data traffic in access networks for big data analytics and cloud computing services has fuelled innovative approaches to increase the capacity of the multimode fiber (MMF) backbones. Although modes in MMF typically induce modal dispersion and inter-symbol interference (ISI) due to differential mode delay (DMD), a remarkable bandwidth enhancement has been shown to exploit the nature the modes in MMF. Mode division multiplexing (MDM) is an emerging technology where parallel data streams are transmitted using modes of MMF [1]. MDM offers another dimension for multiplexing multiple data channels through a single optical fiber in addition to wavelength, intensity, phase, polarization and time.

In MDM, single or groups of modes are used to transmit separate data signals in MMF by precise engineering of the launch field in order to control the delay spread of propagating modes and amount of power coupled into each mode [2]. The allowed modes for each channel are adapted by the incident field at the MMF and demultiplexed by modal field matching at the receiver, thus optimizing the channel impulse response for distinct channels. The landscape of MDM has been transformed due to innovations such as spatial light modulator encoding [3-6], optical signal processing [7-9], fiber Bragg grating [10, 11], photonic crystal fibers [12] and offset launch techniques [13-15]. MDM has prospects for surpassing the bandwidth-distance product and spectral efficiency barriers [16].

Several types of modes have been explored for MDM. Laguerre-Gaussian modes have been generated using spatial light modulators [3, 5, 17] and fiber Bragg gratings [11]. In [18-20], Hermite-Gaussian (HG) modes are produced from a passive beam shaper formed on a fused silica substrate. For donut beam generation, phase plates [21], etched fiber [22], deflecting mirrors [23] and spatial light modulators [24] have been adopted.

In this paper, we report on the MDM of a novel combination of spiral-phased donut modes of different diameters from vertical-cavity surface-emitting laser (VCSEL) arrays and analyze the MDM system performance. This paper proceeds as follows. Section 2 reports on the modelling of the MDM-WDM system for spiral-phased donut modes. Section 3 presents the result and discussion and the conclusion of the paper presented in Section 4.

* angela.amphawan.dr@ieee.org; phone +60492845056; fax +604-928 5067; uumoptics.webs.com
II. SIMULATION OF SPIRAL-PHASED DONUT MODES

The MDM of four spiral-phased donut modes in MMF was modelled in Optsim 5.2 [25] and Matlab [26], as shown in Fig. 1. The model may be divided into three parts, namely the transmitter, multimode fiber, and receiver.

The transmitter constitutes of two VCSELs which operates on two wavelengths 1550.12 nm and 1551.72 nm. Each VCSEL has an array emitting two x-polarized donut modes with inner and outer radii shown in Fig 2. VCSEL 1 which transmitted on wavelength 1550.12 nm emits two donut modes - a) the first donut mode having an outer radius of 12µm and inner radius of 10 µm (Channel 1); b) the second donut mode having an outer radius of 6 µm and inner radius 2 µm (Channel 2). VCSEL 2, which transmitted on wavelength 1551.72 nm, emits two similar donut modes; a) the first donut mode has an outer radius of 12 µm, and an inner radius of 10µm (Channel 3) whereas b) the second donut mode has an outer radius = 6 µm and inner radius = 2 µm (Channel 4). Both, the first and the second donut mode of each VCSEL are radially offset from the first donut mode by 1µm. Examples of the magnitude and phase distributions of the transverse electric field profiles of the individual donut modes emitted by the two VCSELs are shown in Fig. 2(a) and Fig. 2(b). The transverse electric field of the combination of all four donut modes is shown in Fig. 2(c).

The VCSEL is driven by independent pseudo-random binary sequence (PRBS) electrical signals and optically modulated to non-return-to-zero (NRZ) pulses. The generated transverse electrical field profile of the donut mode from the VCSEL array is described as [25]:

\[
\psi(r, \phi) = \begin{cases} 
\kappa, & r_{\text{min}} \leq r \leq r_{\text{max}} \\
0, & r > r_{\text{max}} 
\end{cases} 
\]

(1)

where \(\kappa\) is normalization constant, \(r_{\text{min}}\) is the minimum radius and \(r_{\text{max}}\) is the maximum radius of the donut. Within the minimum and maximum radii, the electric field is constant, whereas outside of these bounds, the transverse electric field is zero. The VCSELs are connected to a vortex lenses used to transform the flat phase front to a helical phase front as shown in Fig 3. The applied phase transformation is expressed as [25]:

\[
t(x, y) = \exp \left[ -j \left( \frac{n\pi r^2}{2\lambda f} + m\theta \right) \right] 
\]

(2)

\[
r = x^2 + y^2 
\]

(3)

\[
\theta = \tan^{-1}(y/x) 
\]

(4)
where $x$ and $y$ are transverse coordinates in the $x$-$y$ plane, $\lambda = 1550.12$ nm or 1551.72 nm is the signal wavelength depending on whether the donut mode is generated from VCSEL 1 or VCSEL 2, $m$ is the vortex order, $n$ is the material index and $f = 8.0$ mm is the lens focal length. The influence of the vortex order of the spiral-phased donut modes on the system performance is analyzed each run for $m = 1, m = 2, m = 3, m = 4$.

The MDM signals are then propagated through a 1500m-long manufactured MMF. The assumed value for attenuation is 1.5 dB/km with consideration of power modal coupling. Two photodetectors are used to retrieve the signals. The modes are then retrieved at the photodetector based on a noninterferometric modal decomposition [3]. The transverse electric field distributions, power coupling coefficients, degenerate mode group delays and bit error rates are analyzed for different HG modes and radial offsets. The results and analysis are presented in Section III.

### III. RESULTS AND DISCUSSIONS

Fig. 3 shows the transverse electric field distributions of the four donut modes after propagating through the MMF. From the output transverse electric field distributions, it is evident that the donut modes are composed of many higher-order linearly polarized modes. For a quantitative analysis of the modal decomposition, the power coupling coefficients in linearly polarized MMF modes versus modal delay after the photodetector are analyzed for different vortex orders, $m$. The total power into the five VCSELS is normalized to 1. The total power per channel received at each photodetector is 0.2.

Fig. 4 shows the power coupling coefficients versus modal delay for Channel 2. In Fig. 4(a) the power is coupled more in higher-ordered modes with a lower percentage coupled into medium-ordered modes and low-ordered modes. In Fig. 4(b) the power is coupled dominantly in higher-ordered mode. Therefore, the effective time delay between modes is minimized leading to an ideal narrow width pulse. In Fig. 4(c) as observed, power is mostly coupled in higher ordered mode and relatively little power is coupled in low-ordered modes. However, a moderate amount of power is present in one of the lower-ordered mode groups, hence differential time delay is high. In Fig. 4(d) modes are scrambled due a high amount of power distributed over higher-ordered and medium-ordered mode, in effect leading to a relatively wide pulse.
Fig. 3 Transverse spatial electric field for Photodetector 1 after propagating through the MMF for vortex orders: (a) \( m = 1 \) (b) \( m = 2 \)

Fig. 4 Power coupling coefficient versus modal delay for Channel 2 on 1550.12 nm after propagating through the MMF for different vortex orders: (a) \( m=1 \) (b) \( m=2 \) (c) \( m=3 \) and (d) \( m=4 \)
Fig. 5 shows the power coupling coefficients versus degenerate mode group (DMG) and the differential mode delay for Channel 2. From the curves, it is observed that the best DMD is achieved when the vortex order \( m = 2 \) with monotonically decreasing peaks with time. Other cases \((m=1, m=3\) and \(m=4))\) have fluctuating peak values. This agrees with the power coupling coefficient plots in Fig. 4. Symmetric and anti-symmetric modes are observed in the power coupling coefficients of degenerate modes due to opposing propagation constants.

The average system BER values in ascending vortex order are \(6.56 \times 10^{-5} (m=1), 3.11 \times 10^{-20} (m=2), 1.76 \times 10^{-4} (m=3)\) and \(7.32 \times 10^{-3} (m=4))\). The BER values elucidate that a high BER is achieved when the power is significantly distributed in higher-order modes and the peak values of the DMG pulse is monotonically decreasing. Lower BER performance is inevitable when the pulse shape is wide and the peaks values from DMG pulse are erratic.

In local area networks, MMF lengths are mostly shorter than 500 meters [27]. The MMF link yield for the proposed MDM model is 1500m, thus satisfying the length requirement for local area networks.

**IV. CONCLUSION**

Four spiral-phased donut modes operates on two different wavelengths 1550.12 nm and 1551.72 nm, carrying independent data streams were launched in a MMF to achieve 40Gbit/s data transmission with acceptable BER for a vortex order of 2.
V. REFERENCES


