MDM of Hybrid Modes in Multimode Fiber

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Abstract—This paper reports on MDM of a combination of helical-phased modes comprising ring modes and HG modes. 44Gbps data transmission is achieved by a wavelength division multiplexing (WDM) - MDM system of two center-launched helical-phased ring modes and two 3µm radially offset HG mode on wavelengths 1550.12nm and 1551.72nm for a 1500m-long multimode fiber. The power coupling coefficients, degenerate mode group delays and bit error rates are analyzed for different HG modes and radial offsets.

Keywords—Mode division multiplexing; spiral phase front; ring mode; Hermite-Gaussian modes; HG modes; vortex lens; multimode fiber; big data; cloud computing; optical communications

Introduction

Cloud computing trends from interactive multimedia services are thrusting changes towards enhancing scalability, agility, and reliability of data centers and access networks. Multimedia applications such as voice-over-internet-protocols (VoIP), television streaming, and security surveillance are flooding optical backbones, predominantly multimode fiber (MMF) [1]. In the quest to future-proof data centers, it is imperative to tap into new multiplexing technologies as the surge of network traffic will soon overwhelm the capacity of MMF backbones in data centers and access networks [2, 3].

Mode division multiplexing (MDM) is a remarkable bandwidth enhancement technique whereby information is transmitted via propagating modes in MMF. This emerging technology exploits modal dispersion and offers another dimension for multiplexing several data channels in data centers through a single optical fiber in addition to wavelength, polarization, and time. In MDM, single or groups of modes are used to transmit disparate data streams in MMF by precise engineering of the launch field to optimize the differential mode delay and power coupling coefficients. Only a subset of selected modes are excited by matching the incident wave front at the input facet to the intrinsic fiber mode profile. MDM is realized by various mechanisms such as spatial light modulators [4-7] optical signal processing [8-10], few mode fiber [11-16], photonic crystal fibers [17] and modal decomposition methods [18-20].

Beams with helical phase fronts have attracted significant attention as data carriers in MMF [21]. OAM modes have helical phase fronts with azimuthal phase variations corresponding to the OAM mode order and a ring-shaped intensity profile with a null in intensity at the center [22]. MDM of OAM modes have been demonstrated using spatial light modulators, equalizers and specially designed optical fiber [21, 23-25]. Apart from harnessing the capacity of MMF by providing additional data channels, ring-shaped OAM beams also circumvents central core regions where refractive index imperfections in manufactured MMF are most prevalent [26].

In this paper, MDM of a new combination of helical-phased modes comprising ring modes and radially offset Hermite-Gaussian (HG) modes is modeled using a vertical-cavity surface-emitting laser (VCSEL) array and a vortex lens and coupled into a MMF. The spatial electric fields, mode group delays and power-coupling coefficients into individual modes and degenerate mode groups are analyzed for various HG mode indices.

This paper proceeds as follows. Section II reports on the modeling of a new MDM scheme for helical-phased ring modes and radially offset HG modes. Section III analyzes the power coupling coefficients, degenerate mode group delays, and bit error rates for different HG modes. The paper is concluded in Section IV.
Simulation of spiral-phased ring Modes

MDM of helical-phased ring modes and HG modes in MMF was modeled in Optsim 5.2 [27] and Matlab, as shown in Fig. 1. The model may be divided into three parts, namely the transmitter, multimode fiber, and receiver.

The transmitter constitutes two VCSEL on 1550.12nm and 1551.72nm and four vortex lenses. Each VCSEL has an array emitting x-polarized ring modes with inner and outer radii of 10µm and 12µm respectively and a radially offset HG mode. The VCSEL is driven by pseudo-random binary sequence (PRBS) electrical signals and modulated to non-return-to-zero (NRZ) pulses. The generated transverse electrical field profile of the ring mode from the VCSEL array is described as [27]:

$$\psi_{lm}(x,y) = \alpha.H_l\left(\frac{\sqrt{2}(x-b)}{w_{0x}}\right).exp\left(-\frac{(x-b)^2}{w_{0x}^2}\right).$$

$$\exp\left(-\frac{y^2}{w_{0y}^2}\right).H_m\left(\frac{\sqrt{2}y}{w_{0y}}\right)$$

where $w_{0x}= 2\mu$m and $w_{0y} = 2\mu$m are the x and y spot sizes respectively, $b$ is the radial offset from the core center; $R_{0x}= 0$ and $R_{0y} = 0$ are the x and y radii of curvature respectively; $H_l$ and $H_m$ are Hermite polynomials. The radial offset, $b$, is varied on the interval $b = 1\mu$m to $10\mu$m for performance analysis. The VCSEL is connected to a vortex lens used to transform the flat phase front to a helical phase front. The focal length of lens, $f=8$. 0mm and the vortex order, $m = 4$. The applied phase transformation is expressed as [27]:

$$ \psi_{lm}(x,y) = \alpha.H_l\left(\frac{\sqrt{2}(x-b)}{w_{0x}}\right).exp\left(-\frac{(x-b)^2}{w_{0x}^2}\right)\exp\left(-\frac{y^2}{w_{0y}^2}\right).H_m\left(\frac{\sqrt{2}y}{w_{0y}}\right)$$

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

$$r = x^2 + y^2$$

$$\theta = \tan^{-1}\left(\frac{y}{x}\right)$$

where $x$ and $y$ are transverse coordinates in the x-y plane, $\lambda$ is the signal wavelength, $m$ is the vortex order, $n$ is the material index and $f$ is the lens focal length. Fig. 2 shows the amplitude and phase distributions of the transverse electric field of the
generated ring mode after the vortex lens. Fig. 3 shows the magnitude and phase distributions of the transverse electric field of helical-phased HG mode of different $x$-indices and $y$-indices from the VCSEL array. Fig. 4 shows the magnitude and phase distributions of the transverse electric fields of both helical-phased ring mode and various HG mode from the VCSEL array after the vortex lens, incident at the MMF input facet.

The four independent 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. The measured refractive index profile of the manufactured MMF is shown in Fig. 5.

Two photodetectors are used to retrieve the de-WDM-ed signals. The modes are then demultiplexed at the photodetectors based on a noninterferometric modal decomposition [4] to retrieve the four channels.

The power coupling coefficients, modal delays and BER performances are analyzed for different HG modes. The results and analyses are presented in Section III.

Results and Discussion

Fig. 6 shows the power coupling coefficients into MMF linearly polarized (LP) modes versus modal delay after the Channel 2 output. The impulse responses obtained from the new mode combination are narrower with the excitation of predominantly higher-ordered modes compared to the impulse pulses for the excitation of pure helical-phased HG modes [29]. For the investigation of radial offsets, it is observed that a radial offset, $b$ of $3\mu m$ achieves the best impulse response. This is consistent with experimental results from MDM of HG modes [30, 31] where the optimal radial launch for alleviating modal dispersion and increasing bandwidth capacity in MMF is less than $3\mu m$.

Fig. 7 illustrate the degenerate mode groups (DMG) and the relative group delays of the DMGs. From the curves, it is evident that the lowest DMD is achieved when for HG$_{20}$. Also, HG$_{20}$ exhibits the best suppression of power into odd mode.
Fig. 5 Measured refractive index profile of manufactured MMF in MDM model.

Fig. 6 Power coupling coefficients into LP modes versus modal delay at Channel 3 output for different HG modes at 1500 m: (a) HG\(_{02}\) (b) HG\(_{04}\) (c) HG\(_{20}\) and (d) HG\(_{40}\).

Fig. 7 Relative group delay versus DMG (green) and power coupling coefficient versus DMG (red) for Channel 3 output for different HG mode: (a) HG\(_{02}\) (b) HG\(_{04}\) (c) HG\(_{20}\) (d) HG\(_{40}\)
Fig. 7 shows the power coupling coefficients versus groups, resulting in a large contrast ratio between more dominant mode groups. This ensures that destructive interference between the propagating mode groups is constrained. Thus, HG_{20} is the most robust compared to HG_{02}, HG_{04} and HG_{40} although radial offset of twin anti-phase spots demonstrate better suppression of symmetric modes [32].

For a comparison of the different HG modes, the BER at Channel 3 were examined, as shown in Table 1. Consistent with the power coupling coefficients and modal delays in Fig. 6 and Fig. 7, the lowest BER is attained for HG_{20}, followed by HG_{04}, HG_{40}, and HG_{02}. The BER performance implies that the y-index change affects the channel more profoundly than the x-index of the Hermite polynomial.

In a typical data center, MMF lengths are mostly shorter than 500 meters [33]. The MMF link yield for the proposed MDM model is 1500m, thus satisfying the length requirement for data centers.

**Conclusion**

A four-channel 44Gbps data transmission is achieved for MDM of a set of helical-phased center-launched ring modes and radially offset helical-phased HG modes on wavelengths 1550.12nm and 1551.72nm. The lowest BER is attained for HG_{20}, followed by HG_{04}, HG_{40}, and HG_{02} at a radial offset of 3µm. The MDM model could be viable for parallel optical interconnects in data centers.

**References**


