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40Gbit/s MDM-WDM Laguerre-Gaussian Mode with Equalization for Multimode Fiber in Access Networks

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Abstract: Modal dispersion is seen as the primary impairment for multimode fiber. Mode division multiplexing (MDM) is a promising technology that has been realized as a favorable technology for considerably upsurges the capacity and distance of multimode fiber in conjunction with Wavelength Division Multiplexing (WDM) for fiber-to-the-home. This paper reveals the importance of an equalization technique in conjunction with controlling the modes spacing of mode division multiplexing-wave-length division multiplexing of Laguerre-Gaussian modes to alleviate modal dispersion for multimode fiber. The effects of channel spacing of 20 channels MDM-WDM were examined through controlling the azimuthal mode number and the radial mode number of Laguerre-Gaussian modes. A data rate of 40Gbit/s was achieved for a distance of 1,500 m for MDM-WDM.

Keywords: MDM, WDM, multimode fiber, modal dispersion, equalization

1 Introduction

Optical fiber is a promising candidate for providing substantially more bandwidth for triple play services, extending the transmission distance and ensuring the reliability of network services [1, 2]. Around the world, government and private enterprises are realizing the value of fiber-to-the-home (FTTH) and as a result, millions of homes and business are connected over optical fiber each year [3]. Multimode fiber (MMF) supports a finite number of optical modes which can be analyzed by solving Maxwell’s equations [4]. However, modal dispersion in MMF considered as the main limitation along with mode coupling for bandwidth increases [5]. In addition, however, the tremendous increase of heavy bandwidth applications along with the user’s continuous demand for more bandwidth, stimulate researchers around the globe to look for more effective approaches to increase the transmission capacity of MMF. Mode division multiplexing is a promising technology [6–9] for exploiting the capacity of MMF to increase the bandwidth-distance product, whereby several transverse modes are transmitted orthogonally in MMF, then de-multiplexed into separate channels in an attempt to break through current capacity barriers [10–13]. Modes in MMF with the ability of multiplexing [14, 15] can be exploited through the use of mode division multiplexing (MDM) whereby diverse transverse modes are transmitted in parallel through a single optical fiber [16]. To optimize the propagation differences between modes, MDM recently employed different selective mode excitation approaches including – spatial light modulators [17], fiber gratings [18, 19], digital signal processing algorithms, modal decomposition algorithms [20, 21], photonic crystal fiber [22], adaptive optics [21–25], modes propagation using few mode fiber (FMF) [26–32], multi-core fibers (MCF) [33, 34] or multi-ring fibers [35, 36], and modal de-multiplexing methods [20, 21, 37]. Moreover, several launching schemes were explored such as HG modes [38, 39] and spiral-phased donut mode [40–42]. Furthermore, in order to make MDM more feasible in respect to high capacity performance photonic and electronic equalization schemes need to be integrated and explored which will make MDM better scale than through being simple hardware duplication. Therefore, coupling matrix can be inverted either in the optical domain [43, 44] or in the electrical domain which categories into two approaches: time domain [45, 46] and frequency domain [47, 48]. Generally, for long haul systems, frequency domain approach reduces the computational complexity significantly compared to the time domain approach [48]. In addition, FMF is utilized for a
huge distance, which means high modal dispersion whereby multi-input-multi-output (MIMO) equalization was introduced to alleviate this computational complexity. However, these approaches are out of this paper’s scope whereby this paper only concentrates on short distance optical fiber communication. This paper demonstrating the ability of electric time domain equalization to accurately reshape and correct the transmitted pulse by conforming the time-delay weights to the impulse response amplitude of MMF. There are significant works that have been presented in Refs [45, 49] taking the advantage of electric time domain equalization attractiveness either technically in respect of being adaptable and robustness over optical fiber or economically [50] in respect to lower cost. Recently in Ref. [46] 6-taps decision feedback equalizer was demonstrated using adaptive algorithm Least Mean Square (LMS) algorithm to minimize the error comparing to the ideal signals, achieving a data rate of 10Gbit/s up to a distance of 300 m. Improvement was presented in Ref. [45], introducing 3 to 11 taps feed-forward equalizer along and feedback equalizer using LMS algorithm, achieving a data rate of 10Gbit/s over a maximum distance of 1 km.

This paper develops half-duplex link mode division multiplexing-wavelength division multiplexing (MDM-WDM) model in conjunction with electronic dispersion compensation equalization, to investigate the importance of controlling the azimuthal and radial mode number of MDM-WDM model. The model performance is evaluated using spatial electric field, eye diagram and numerically bit-error-rate (BER). The paper is organized as follows. Section 2 describes the simulation of the MDM-WDM model and Section 4 presents the results of the simulation.

2 Methodology and simulation

The proposed MDM-WDM of Laguerre-Gaussian (LG) model is illustrated in Figure 1, which was simulated using Synopsis Optsim 5.2 [51] and Matlab [52]. The MDM-WDM LG model consists of three distinct parts, each differs in its azimuthal and radial mode number of operations as input phase (the transmitter), processing phase (medium of the traverse), and the output phase.
The transverse electrical field profile of the launched \( LG_{ml} \) mode in the first VCSEL is expressed as:

\[
\psi_{ml}(r, \phi) = \alpha \left( \frac{2n^2}{w_0^2} \right)^{1/2} I_{ml} \left( \frac{2r^2}{w_0^2} \right) \exp \left[ -\frac{r^2}{w_0^2} \right] \cdot \begin{cases} \cos(L\phi), & l \geq 0 \\ \sin(L\phi), & l < 0 \end{cases}
\] (1)

where \( \alpha \) is normalization constant, \( L = | l | \), \( \lambda \) is the field wavelength, and \( I_{ml} \) is generalized Laguerre polynomial. At the beam waist, the inverse of \( R_0 \) is zero, indicating a flat phase front. At any distance to the left or right of the waist, the beam begins to diverge and \( R_0 \) become finite.

The VCSEL is connected to a vortex lens used to transform the flat phase front to a LG phase front. The focal length of lens, \( f = 8.0 \text{ mm} \) and the vortex order, \( m = 4 \).

The applied phase transformation is expressed as [51]:

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

\[
r = x^2 + y^2
\] (3)

\[
\theta = \tan^{-1}(y/x)
\] (4)

where \( x \) and \( y \) is the transverse coordinate for the \( x, y \) plane and \( f \) is the lens focal length, \( \lambda \) is the wavelength and \( n \) is the material index, \( m \) is the vortex order. Figure 2 shows the transverse electric field for different mode number spacing after the vortex lens whereby in each run the azimuthal mode number \( l \) is maintained to 0 while the radial mode number \( m \) is varied each run to \( (\Delta m = 1, \Delta m = 2, \Delta m = 3 \text{ and } \Delta m = 4) \). Figure 3 shows the transverse electric field for different mode number spacing after the vortex lens whereby in each run the radial mode number \( m \) is maintained to 0 while the azimuthal mode number \( l \) is varied each run to \( (\Delta l = 1, \Delta l = 2, \Delta l = 3 \text{ and } \Delta l = 4) \).

The MDM signals are then propagated through a 1,500 m-long MMF with a dip refractive index profile described by [53]:

\[
n(R) = n_{co} (1 - \Delta R^{1/2})
\] (5)

where \( n_{co} \) is the maximum refractive index of the core, \( R \) is the normalized radial distance from the center of the core, \( \Delta = (n_{co}^2 - n_{cl}^2) / (2n_{co}^2) \) is the profile height parameter where \( n_{cl} \) is the refractive index of the cladding at \( R = 1 \) and \( \alpha = 1.81 \) in a purpose to mimic the real environment as shown in Figure 4. The core diameter of the MMF is 50.0 ± 2.5 \( \mu \text{m} \) while the cladding diameter is 125 ± 1 \( \mu \text{m} \). The assumed value for attenuation is 1.5 dB/km with consideration to the power-coupling coefficient. The special electric field (Phase and amplitude) of the excited modes was measured before and after the launch. The power coupling efficiency into the desired mode at the input of the MMF is expressed in [54] as:

\[
C_{lim\ in} = \left( \int \int_{A_{core}} |E_{in}(x, y)E_{im}^*(x, y) dx dy |^2 \right) / \left( \int \int_{A_{core}} |E_{in}(x, y) |^2 dx dy \right)
\] (6)
where the desired generated electric field at the input is represented by \( E_{lm} \), \( E_{lm} \) is the polarized transverse electric field for LG mode of a weakly-guiding infinite MMF. The signals are then retrieved at four photodetectors at wavelength 1,550.12 nm. The performance matrices of spatial transverse electric field, power coupling coefficient, eye diagram and BER were used to analyze the model performance.

3 Equalization structure

Electronic Dispersion Compensation (EDC) is another approach to enhance the modal bandwidth of MMF. DFE is a combination between linear and nonlinear filter however it is considered as a non-linear equalizer that consists of a forward filter and feedback filter. The forward filter is working as symbol spaced equalizer while
feedback filter consists of a tapped delay line whose inputs are the decision made on the equalized signal. The main objective of DFE is to cancel Intersymbol Interference while minimizing noise enhancement. EDC architecture is shown in Figure 5. The output of the DFE can be expressed as:

\[
s(t) = \sum_{i=1}^{n} u_i x(t - [i\Delta t]) - \sum_{i=1}^{m} d_m s(t - [i\Delta t])
\]  

(7)

where \(u_i\) is variable tap weight, \(n\) is the number of FFE taps while the \(x(t)\) is the input signal. Then \(m\) is the time delay between two adjacent equalizer taps. The second item is corresponding to the feedback taps; \(M\) is the time delay between two adjacent equalizer taps. In this paper 14 FFE taps and 5 DFE taps were used with LMS algorithm to optimize the tap weights of the equalizer.

4 Results and discussion

For qualitative evaluation of the effects of different radial offset of the LG mode. Figure 6 illustrates an example of
the output transverse electric field for LG modes after propagating through the MMF for Channel 1 whereby, the azimuthal mode number maintained to 0, while the radial mode number is varied each run.

As observed in Figure 6, the intensity of the spatial field still can be determined after a distance of 1,500 m for the case (d) while the rest not. Figure 7 shows the transverse electric field for LG modes after the modes are propagated through the MMF. As BER were examined in three parts (after the MMF, after feed-forward equalizer and after decision feedback equalizer). Table 3 shows the comparison between different modes spacing once the azimuthal mode number is fixed, while Table 4 shows the comparison between different mode spacing once the radial mode number is fixed. Eye diagram comparisons without equalizer and with equalizer were illustrated in Figures 8 and 9. Generally, significant results have been obtained once the azimuthal mode number fixed, whereas the radial mode number varied in each run due to the similarity of the spatial electric field. Figure 8 outperform Figure 9 due to the clearance and widely open of the eye.

Table 3: The effects of different mode spacing once the azimuthal mode number are maintained to 0 while the radial mode number is varied each run.

<table>
<thead>
<tr>
<th>VCSEL array</th>
<th>No equalization</th>
<th>Feed-forward equalizer</th>
<th>Decision feedback equalizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.62 \times 10^{-03}</td>
<td>1.24 \times 10^{-08}</td>
<td>1.58 \times 10^{-10}</td>
</tr>
<tr>
<td>2</td>
<td>1.21 \times 10^{-03}</td>
<td>5.97 \times 10^{-28}</td>
<td>3.51 \times 10^{-09}</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>1.00</td>
<td>3.86 \times 10^{-04}</td>
</tr>
<tr>
<td>4</td>
<td>5.71 \times 10^{-07}</td>
<td>4.75 \times 10^{-17}</td>
<td>4.19 \times 10^{-22}</td>
</tr>
</tbody>
</table>

Table 4: Effects of different mode spacing whereby the radial mode number is maintained to 0 and the azimuthal mode number is varied each run.

<table>
<thead>
<tr>
<th>VCSEL array</th>
<th>No equalization</th>
<th>Feed-forward equalizer</th>
<th>Decision feedback equalizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>3.83 \times 10^{-03}</td>
<td>9.90 \times 10^{-05}</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>5.24 \times 10^{-04}</td>
<td>4.98 \times 10^{-05}</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>8.68 \times 10^{-05}</td>
<td>1.15 \times 10^{-05}</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
<td>5.45 \times 10^{-05}</td>
<td>7.77 \times 10^{-06}</td>
</tr>
</tbody>
</table>
5 Conclusion

Data transmission of 40Gbit/s is achieved for a $4 \times 10$ MDM-WDM model. The novel optimization approach of controlling the modes spacing was examined through controlling the azimuthal mode number and the radial mode number. Electronic dispersion compensation was integrated to the model with five feed-forward tap delays and 14th decision feedback tap delays. A significant result was achieved either before or after integrating the equalizer part. 40Gbit/s over a distance of 1,500 m was achieved for WDM-MDM.
Figure 9: Eye diagram effects once the radial mode number is maintained to 0 and the azimuthal mode number is varied each run for MMF for a distance of 1,500 m.

References


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