Spiral-Phased Laguerre-Gaussian Modes Generation in SWDM over Few Mode Fiber based on Electrical Equalization

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Abstract. Space division multiplexing, in conjunction with wavelength division multiplexing, is a powerful mechanism that increases spatial channels significantly in a single optical fiber. Spiral Phased- Laguerre-Gaussian (SP-LG) modes indicate that they effectively reduce mode coupling, thereby increasing the channel response and performance positively. However, mode-coupling influence optical fiber system leads to inter-symbol interference (ISI) between the channels and reduces both capacity and distance. In this paper, we apply the SP-LG modes in a space wavelength division multiplexing over a few-mode fiber system. The results demonstrate significant improvements in reducing channels effects and ISI. The performance evaluations are based on the bit-error-rate (BER), eye diagram and spectrum analyzer.

1. Introduction

Internet communication supports our daily life, and its demand increases exponentially towards the future. Currently, the growth rate is 1.5 times/year, which means that it is expected to increase by 60 times after ten years. In consequence, the demanding requires higher capacity in the optical communication systems [1]. In this respect, Space division multiplexing (SDM) is a promising multiplexing technique and considered as a hot topic[2]. Specifically, each mode can be spatially overlapping and coaxially propagating at the same wavelength carrier (which can transfer any data stream). The authors in [3] were attempted to increase the capacity as well as the spectral efficiency linearly with increasing the number of modes. In such a system, multiple data channels should be acknowledged by a different
spatial mode where can be well multiplexed at the transmitter and well separated at the receiver. Therefore, SP-LG mode enables of achieving maximum transmission capacity and spectrum efficiency [4]. It is well known that the capacity of optical communication comprises of three essential factors: 1) Transmission bandwidth; 2) Modulation order; and 3) spatial multiplexing order. An increasing of any factor may lead to a higher capacity. However, in the systems, the modulation order has already reached the practical limit, and therefore, will not increase the capacity dramatically. Furthermore, it is hard to expand the bandwidth in the wavelength. Accordingly, spatial multiplexing is the best solution to achieve the desired expansion on capacity and spectrum efficiency [5]. Therefore, SP-LG mode enables the spatial multiplexing, and the light property can describe the helical phase pattern of the wave front in which indicates the degree of twists of a beam [6]. The degree of twisting can generate different modes received in the receiver without being interfering with other modes. This multiplexing technology benefits from the advantage of light characteristics. In this paper, the concept of SWDM describes the orthogonal polarization [7] of transverse modes spatially. It can be achieved within one fiber using different VCSELs [8] operating at different wavelengths [9] ranging from 1550.12 nm and 1551.72 nm. The spatial separation facilitates the generation of individual data streams [10], which are then multiplexed onto a single few-mode fiber (FMF). On the receiver side, the wavelengths are de-multiplexed and then the signals converted to parallel electrical signals, which then undergo electrical equalization [11-14]. The process of combining the SWDM with SDM [15] as well as wavelength division multiplexing (WDM) [16] is more superior than other previous multiplexing schemes. The reason of this process is because of including of WDM, orthogonal frequency division multiplexing (OFDM) [17], time-division multiplexing (TDM) [18, 19] and polarization division multiplexing (PDM) [20]. Nevertheless, the abovementioned schemes have proven to be insufficient for future bandwidth demands. Therefore, SDM is the best solution which can be juxtaposed as mode division multiplexing (MDM) [21, 22] to complement the current multiplexing schemes (where WDM is famed as the workhorse [23] of major telecommunications companies). Previously, Laguerre-Gaussian (LG) modes were generated in [24] using a multilevel spiral phase plate to carry an orbital angular momentum (OAM) with a doughnut-shaped orientation, where a Gaussian beam was reverse-engineered to come up with a generated LG beam. A spiral phase plate [25] is an optical device that has an optical thickness increases with the azimuthal angle. Additionally, this increase can be made in such a way that an incident beam emerges with a helical phase front as its phase changes smoothly and continuously. In [26], 1008 data channels were multiplexed and de-multiplexed using OAM mode division multiplexing (MDM) combined with WDM and quadrature phase-shift keying (QPSK) modulation of the signal to achieve BER of $10^{-4}$ and $10^{-6}$, respectively. In this respect and to achieve the desired BER, we apply an SDM and a non-return-to-zero (NRZ) modulation to the signal. Furthermore, this paper incorporates electrical equalization in the form of decision feedback equalizer (DFE) for further refining the received signal. In the literature, DEF has been used for dispersion compensation in a WDM system [27]. Whereas, the dispersion describes signal distortion as the modes propagate in the fiber. This can be occurred due to signal spreading in the time since the propagation velocity of the optical signal is not the same for all modes. Consequently, this creates irregularities in the received signal, hence needing rectification using filters. In the literature, DEF has also been significantly implemented to improve the eye diagrams and BER (e.g., in [15, 28, 29]), and compensation of the ISI [30]. Besides, its interior comprises of a feed-forward filter and feedback filter. More specifically, a linear filter
is the feed-forward filter, and the other part of DFE is a nonlinear filter (i.e., feedback filter) with minimum mean square error (MMSE) optimization [31]. It is worth mentioning that the optimization of MMSE can be applied between the actual data and the target data. Additionally, the error of MMSE may update the weight of the tap filter to get a better result. Lastly, the performance of the eye diagram and BER have been significantly improved after applying this equalization scheme. The main reason is to prove that the main objective of decision feedback equalization is able to enhance the signal received from the transmitted signals and can reduce ISI. The remainder of the paper is structured as follows. Section 2 presents the SWDM system of SP-LG modes. Result and discussion of SDM simulation are explained in Section 3. Finally, Section 4 concludes this paper.

2. System model
As shown in Figure 1, the schematic configuration of the SWDM system simulation of 12 SP-LG modes over FMF. The system has simulated using OptSim [32] and MATLAB [33]. Specifically, the SWDM modal of 12 SP-LG modes consists of three parts: 1) the transmitter part; 2) FMF part; and 3) the receiver part. The transmitter part consists of four components as follows:-

1. Generating a signal based on a pseudo-random binary sequence (PRBS) modulated.
2. NRZ modulation to convert the binary to electrical.
3. Vertical-cavity surface emitting lasers (VCSELs).
4. Vortex lens.

Each VCSEL is modulated at a bit rate of 3 Gbps, and thus, the generated data rate of the 12 VCSELs is 36 Gbps. As shown in Figures 2 and 3, the transmitter comprises of two groups that operate on two wavelengths 1550.12 nm and 1551.72 nm.

1. The first group emits six SP-LG modes operate on the wavelength 1550.12 nm. The modes are symbolized as follows: SP-LG 0 0, SP-LG 0 1, SP-LG 0 2, SP-LG 1 0, SP-LG 1 1 and SP-LG 1 2. The vortex lens is used for applying phase to LG modes. The following equation describes the applied phase [34]:

\[ T(x, y) = \exp \left[ -j \frac{\pi n(x^2 + y^2)}{2\lambda f} + ma \tan \left( \frac{x}{y} \right) \right] \]  \hspace{1cm} (1)

Where \( j \) is the focal length, \( m \) is the vortex parameter, and \( n \) is the refractive index.

2. In the other group, six SP-LG modes are emitting and operate on the wavelength 1551.72 nm. Similar to the first group, the modes are symbolized as follows: SP-LG 0 0, SP-LG 0 1, SP-LG 0 2, SP-LG 1 0, SP-LG 1 1, and SP-LG 1 2).

Each mode is then coupled to the 6 Km FMF with a core diameter 18 µm, and attenuation is 0.25. On the other hand, the receiving part consists of two components: receiver and equalizer. Very briefly, 12 receivers and equalizers are used to retrieve the arrived signals and electrical equalization, respectively.
Figure 1. SWDM system simulation of 12 SP-LG modes over FMF.

Figure 2. First group of SP-LG modes operates on wavelength 1550.12 nm.
3. Result and Discussion

We evaluated the performance of our system with three metrics: the eye diagram, BER and spectrum analyzer. The outcomes of the evaluation are illustrated in Figures 4-7. In the beginning, as shown in Figure 4, we measured the BER of SDWM system of 12 SP-LG modes over three distances: 5 Km, 6 Km and 7 Km, respectively. It is clear that the BER results are acceptable in the distances 5 Km and 6 Km BER; while BER presents low results in the 7 Km distance.

![Figure 4](image-url)

**Figure 4.** BER Result of 12 channels in the SWDM system over a different distance of FMF.
In the second experiments, we evaluated the eye diagram of the SWDM system of SP-LG modes over 6 Km distance (Figures 5 and 6). Specifically, the tests are carried out to show the eye diagram with and without equalizer (i.e., DEF). Figure 5 and 6 present the eye diagram of the modes (SP-LG 0 0, SP-LG 0 1, SP-LG 0 2, SP-LG 1 0, SP-LG 1 1, and SP-LG 1 2) based on 1550.12 nm and 1550.72 nm, respectively. According to the results, it is clear that all channels have clean and open eyes observed with the equalizer.

![Eye Diagrams](image)

**Figure 5.** The first six channels (SP-LG modes) based on 1550.12 nm over 6 Km FMF.

![Eye Diagrams](image)

**Figure 6.** The first six channels (SP-LG modes) based on 1550.72 nm over 6 Km FMF.

Finally, we measured in Figure 7 the spectrum analyzer diagrams of the system before and after FMF. The results show that the spectrum analyzer diagrams for the transmitter and receiver side (i.e., before and after FMF) is 10 dBm. Additionally, the lowest noise levels were found makes the system highly efficient in terms of signal loss.
4. Conclusion
In this paper, we applied 12 SP-LG modes in an SWDM over FMF for increasing the data capacity based on electrical equalization. The performance evaluations were based on the bit-error-rate (BER), eye diagram and spectrum analyzer. Based on two wavelengths 1550.12 nm and 1551.72 nm, a data rate of 36 Gbps for 6 Km has been achieved.

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