Hybrid WDM and Optical-CDMA over Multi-Mode Fiber Transmission System based on Optical Vortex

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Abstract: The optical vortex has recently attracted scholars to implement it in optical tweezers, microscopy, optical communications, quantum information processing, optical trapping, and laser machining. Optical vortex beam applied classically that can be transferred to the transverse amplitude of a heralded single-photon, and optical vortex possesses a helical wavefront and carries orbital angular momentum. In this study, Optical vortex is applied in optical-CDMA (optical code-division multiple-access) in conjunction with WDM (wavelength division multiplexing). This mechanism aims to increase the capacity and security in optical communication significantly. The implementation of Laguerre-Gaussian (LG) modes with optical vortex based on one dimension zero cross-correlation (ZCC) code shows that mode coupling reduces effectively. Consequently, a positive increase in channel performance and response. Accordingly, the LG modes based on the 1D-ZCC code are investigated and propagated over multi-mode fiber (MMF) based on an optical vortex, which also substantially reduces channel effects. Consequently, all these attributes combined will result in a hybrid WDM-Optical-CDMA with an optical vortex system over MMF.

1. INTRODUCTION

Recently, there has been a tendency to miniaturize sensors, computers, and cellular phones as well as increased attention of smart cities toward communication technologies to enable error-free connectivity.

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Additionally, the network connection is the backbone of smart cities. The connection does not only require availability, high reliability, and high speed but needs features that are necessary for today’s networks as well. Furthermore, other devices with new requirements must demand to be connected effectively [1]. According to the Cisco report, vast numbers of IP traffic are expected to create in 2022 than in the 32 years after starting internet services. Additionally, the report stated that more than half of the global population would become Internet users. Furthermore, the multimedia (e.g., video) will make up 82 percent of all IP traffic with more than 28 billing devices, and connections will be online [2]. Therefore, technology companies pay more attention to provide a wide variety of connectivity services in smart cities. WDM-optical-CDMA is one of the emerging multiplexing technique that attracts the researchers, which can provide high security by using different types of code. This kind of code can be multiplexed and in which each mode is spatially overlapping. Additionally, each mode can be propagated at different wavelength carriers, which can transmit a different kind of data stream. Therefore, this method was an attempt to increase the spectral efficiency and capacity linearly with increasing the number of used modes [3]. With well multiplexed (separated) at the transmitter (receiver), in the system, different optical vortex can acknowledge each of multiple data channels. Therefore, achieving spectrum efficiency and maximum transmission capacity can be performed by focusing on optical vortex [4].

It is well known that the optical communication capacity can be determined by three main factors, namely: modulation order, multiplexing order and transmission bandwidth. It is worth mentioning that increasing each of these factors leads to a higher capacity. Furthermore, out of these increases, the order of the modulation has attained the practical limit in actual systems. Accordingly, no dramatic improvement can be seen in capacity and spectrum efficiency. Moreover, it is not easy to expand the bandwidth in the wavelength. Consequently, the best solution to meet the current and future demands for the internet capacity hybrid multiplexing is the best solution to get the required growth on spectrum efficiency and capacity.

A spiral phase plate is an optical device where its optical thickness may be increased according to the changes of the azimuthal angle. The increase can be done by emerging of the incident beam with a helical phase front as its phase alters continuously and smoothly [5]. Very recently, an increasing interest in an optical vortex is noted in different parts, such as optical tweezers, microscopy, optical communications, quantum information processing, optical trapping, and laser machining [6]. Briefly, studying a variety of fields of the optical vortex has attracted increasing interest over the last two decades [6-8]. Potential uses of phase vortex beams have been made in the following technologies:

1. Optical tweezers [9].
2. Optical manipulation [10].
3. Optical trapping [11].
4. Optical spanner [12].
5. Optical vortex knots [13].
6. Microscopy [14].
7. Quantum information processing [13, 15].

As a complex beam shape, an optical vortex beam is utilized in light waves on the physical space dimension, particularly (i.e., spatial polarization/amplitude/phase structures [6]). Nowadays, optical vortex beams have shown possible applications in optical interconnects and optical communications. By using optical vortices, a large number of proof-of-concept experimental demonstrations were performed in free space and optical fiber [16, 17]. Furthermore, very recently, much attention has been paid on light beams having a spiral phase front. Moreover, it can be defined as a phase vortex that has a null intensity at the beam center. Specifically, at the beam center, the phase can be seen to be undefined (i.e., screw dislocation or phase singularity) [6].

Phase vortex with a spiral phase front has implemented in orbital angular momentum (OAM). In 1992, the scholar Allen demonstrated that azimuthal phase is the shape of the light beams with a spiral phase front. Phase vortices and polarization vortices (Optical vortices) similar to other mode sets that could be
candidates for optical communications. Similarly, phase vortex multiplexing or phase vortex modulation can be exploited in the implementing optical vortices like different physical dimensions (e.g., frequency, time, complex amplitude and polarization) [6]. To generate vortex beams, there are various techniques, such as spatial light modulator (SLM), computer-generated spiral phase and controllable all-fiber OAM mode converter. It is worth mentioning that the optical vortex can not be implemented in conventional SMF.

Multimode fiber, FMF and any special fibers can be utilized for the guiding and transmission of an optical vortex in a fiber optics [18, 19]. In the literature, much attention has been paid to the optical vortex (phase vortex) in fiber optical and free-space communications and interconnects. An optical vortex is an alternative mode set that can be a consequence of improving transmission capacity and spectral efficiency. Although using optical vortices presents significant progress in developing optical communications, several challenges are still open research issues. Additionally, optical processing is another important theme of optical communications. This paper proposes applying Optical vortex in hybrid optical-CDMA-WDM to increase the capacity and security in optical communication significantly. This paper is structured as follows. Section 2 presents the Hybrid Optical-CDMA-WDM system based on optical vortex are presented. Section 3 explains the results and discussion of hybrid multiplexing. Finally, the conclusions of this work are drawn in Section 4.

2. HYBRID OPTICAL-CDMA-WDM SYSTEM BASED ON OPTICAL VORTEX

In this section, optical vortex in hybrid optical-CDM based on one dimension zero cross-correlation (ZCC) code with WDM based on Laguerre-Gaussian (LG) modes over MMF is designed. It is a powerful mechanism that aims to increase the capacity and security in optical communication significantly. As illustrated in Figure 1, the system has been simulated and designed using opti-system [20-25] and MATLAB [12, 26-28] software. Basically, an optical communication system consists of three components: transmitter, MMF (which are the medium), and the receiver. The transmitter part consists of five items:
1. An Optical-CDMA multiplexer.
2. Data generator, which is a pseudo-random binary sequence (PRBS) modulated.
3. Non-return-to-zero (NRZ) modulation, which converts the binary to electrical. The code sequence of this multiplexer is based on one dimension zero cross-correlation (ZCC) code.
4. Four encoders.
5. Four modulators.

![Figure 1 Hybrid optical-CDMA-WDM over MMF](image)
As shown in Figure 2, the other multiplexer is WDM, which consists of four spatial lasers (continuous-wave laser) with 0 dBm of input power is used for generating four LG modes (LG 01, LG 02, LG 03, and LG 04) magnitude distribution with four spiral-phase (SP-LG 0 1, SP-LG 0 2, SP-LG 0 3, and SP-LG 0 4). The system operates over four wavelengths; 1548 nm, 1549 nm, 1550 nm, and 1551 nm, and the multiplexing that multiplexes four WDM signal channels. The second part of the hybrid system section is MMF, and the optical vortex sets the maximum distance link as 8 km. Besides, the parameters of MMF are an attenuation of 0.25 dB-Km, and the core radius is selected to be 50 nm. The final part is the receivers where the received signal is demultiplexed into four channels pass through and four decoders. Additionally, at the receiver, we put Photo-detector PIN to perform the conversion from optical to electrical domain. Furthermore, Electrical Filter (EF) and analyzer are used at the receiver.

3. RESULTS AND DISCUSSION

The performance evaluation of our system is conducted by calculating Q-Factor, Bit error rate and eye diagram in three different experiments. The first simulation illustrates the BER and Q-factor results of a hybrid system using optical vortex over different distances, which are (10 Km, 8 Km, 6 Km, 4 Km, and 2 Km). Over these distances, the BER and Q-Factor results of four channels (User1-LG 0 1, User2-LG 0 2, User3-LG 0 3, User4-LG 0 4) are evaluated and drawn in Figures 3 and 4, respectively. The experiment demonstrates that the results over different distances are acceptable until reaching a 10 Km distance, which shows unacceptable results.

Figure 2 Laguerre-Gaussian modes (magnitude distribution), spiral-phase (Phase distribution), ZCC (Code Sequence)

Figure .3 BER results of four channels of hybrid optical-CDMA and WDM system over different distances of MMF based on optical vortex.
Figure .4 Q-Factor results of four channels for hybrid optical-CDMA and WDM system over different distances of MMF based on optical vortex.

The second experiment calculates the BER and Q-factor results of a hybrid system without optical vortex over different distances, which are (10 Km, 8 Km, 6 Km, 4 Km, and 2 Km). Over these distances, the BER and Q-Factor results of four channels (User1-LG 0 1, User2-LG 0 2, User3-LG 0 3, User4-LG 0 4) are calculated and depicted in Figures 5 and 6, respectively. Similar to the first experiment, the results over different distances are acceptable until reaching a 10 Km distance, which shows unacceptable results. In the third part of our analysis, we compare BER, Q-Factor and eye diagram results of hybrid WDM-Optical-CDMA system with and without optical vortex. The performance results of the hybrid system are analyzed after distance 8 Km, which is the maximum distance of MMF. As illustrated in Figure 9, the hybrid system has improved BER by E-5 point and E-3 point at the distances 8 km and 10 km, respectively. Similarly, Q-Factor has enhanced by 3 points and 1 point based on optical vortex at the distances 8 km and 10 km, respectively. Lastly, eye diagram visualizer is drawn to measure eye pattern for four channels (User1-LG 0 1, User2-LG 0 2, User3-LG 0 3, User4-LG 0 4) with an optical vortex. Similarly, however without optical vortex, the results of the hybrid system of (SP-LG 0 1: User 1, SP-LG 0 2: User 2, SP-LG 0 3: User 3, and SP-LG 0 4: User 4). All the patterns in Figure 9 show an acceptable range.
Figure .6 Q-Factor results of four channels for hybrid optical-CDMA and WDM system over different distances of MMF without optical vortex.

Figure .7 Minimum BER results of four channels for hybrid optical-CDMA and WDM system over different distances of MMF with and without optical vortex.

Figure .8 Minimum Q-Factor results of four channels for hybrid optical-CDMA and WDM system over different distances of MMF with and without optical vortex.
Figure 9 Eye diagram results of four channels for hybrid optical-CDMA and WDM system with and without optical vortex.

4. CONCLUSION

In this paper, Optical vortex has been applied in optical-CDMA in conjunction with WDM over MMF based on LG modes with one dimension ZCC code. This work aimed to improve the capacity and security in optical communication. Over different wavelengths, the data rate of the hybrid system based on optical vortex is 2,488 Gbps up for a distance of 8 Km. The results were analyzed in terms of BER over different distances, eye diagrams, and spectrum analyzers.

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