Beam wander relieved optical switch using Bessel beams in turbulent atmosphere

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Received April 3, 2019; accepted May 17, 2019; posted online July 26, 2019

The digital micro-mirror device (DMD)-based optical switch has the advantages of high-speed channels reallocation, miniaturization, stability, and large capacity for short reach optical communication in the datacenter. However, thermal turbulent atmosphere in the datacenter would cause perturbations and channel crosstalk for the optical switch. The self-healing optical beams such as the Bessel beams have the non-diffraction property to mitigate the turbulence issue. Here, we propose and demonstrate a Bessel beams enabled DMD-based optical switch to improve the stability and performance of optical communication in turbulent atmosphere. We statistically characterize the beam wanders of the Gaussian and Bessel beams in turbulent atmosphere at temperatures of 60° C and 80° C. We build the two-channel optical switch communication system and measure the bit error rate of the 15 Gbit/s on–off keying signals transmitted by the Gaussian and Bessel beams at temperatures of 60° C and 80° C, respectively. The optical switch using the Bessel beams shows lower bit error rates with weaker fluctuations compared with the Gaussian beams. The DMD-based optical switch using the Bessel beams has the potential for practical optical communication applications in the datacenter.

OCIS codes: 060.4510, 130.4815, 280.7060. doi: 10.3788/COL201917.090602.

Ultra-high speed, high capacity, and all-optical switching are becoming the future directions of next-generation optical networking^{[<u>1,2]</u>}. To solve the traffic problem, the elastic all-optical switching networks composing many optical switches have been proposed and demonstrated^{[<u>3-5]</sub>. By flexibly adjusting and allocating the bandwidth of the communication channels, optical switches can improve the efficiency of optical communication bandwidth resources.}</u>

An optical switch with one or more bidirectional transmission ports has the functionality of signals exchanging or processing in an optical link. Liquid crystal^[6,7] and microelectromechanical systems (MEMSs)^[8,9] are mostly adopted for optical switching devices. However, their relative low switching speed at the milliseconds level limits the applications of large-capacity optical communication. Given the fast switching frequency in several tens of kilohertz (kHz), the digital micro-mirror device (DMD) has been developed as the optical switch in recent vears $\frac{10-12}{1}$. A 7 × 7 DMDbased diffractive fiber switch at 1550 nm was implemented and tested^[10]. The DMD was also used as an optical router for 49 orbital angular momentum channels with tens of microseconds switching time^[11]. A blazed micro-grating array was designed and fabricated to improve the efficiency of the DMD-based optical switch^[12].

The key parameters of the optical switches, such as the crosstalk and efficiency, may be significantly degraded by the turbulent atmosphere in the free space communication system^[13]. In the turbulent atmosphere, the optical beams suffer from phase distortion, intensity fluctuation, and

beam wander, which have been widely investigated theoretically and experimentally^[14]. For the applications of optical switches in the datacenter, high-speed data switching will face the challenges of perturbations in the strong thermal airflow induced by the cooling facility^[15,16]. By optical beam shaping, the self-healing optical beams such as the Bessel beams can be generated with non-diffraction properties, which can efficiently reduce the perturbation in turbulent atmosphere.

The Bessel beam is referred to as an optical beam with amplitude distribution in the form of the Bessel function. The Bessel beam was first experimentally demonstrated by a ring shaped slit in 1987^[17]. The Bessel beam has the property of non-diffraction transmission in free space; therefore, its transverse intensity is independent of the propagation distance. The Bessel beam has another important property of self-healing. When the transmission path of the Bessel beam is blocked, the broken Bessel beam can be recovered after transmitting for a certain distance. Thus, the Bessel beam has the ability of resisting distortions of the amplitude and phase. Bessel beams gain much attention in fields of optical imaging^[18,19], microwave communication^[20], precise machining^[21-23], particle trapping^[24,25], and optical interconnects^[26].

In this work, we propose and demonstrate DMD-based optical switching using Bessel beams in turbulent atmosphere. The Bessel beams efficiently relieve the beam wander in the thermal airflow compared with the Gaussian beams at temperatures of 60°C and 80°C. In the twochannel optical communication system, we measure the bit error rates (BER) of the optical switch using Gaussian and Bessel beams with turbulent atmosphere, respectively. The switch using the Bessel beams shows improved performances in terms of the BER and stability.

The electric field distribution of the ideal Bessel beam can be expressed as $^{\underline{[27]}}$

$$E(r,\varphi,z) = A_0 \exp(ik_z z) J_n(k_r r) \exp(\pm in\varphi), \quad (1)$$

where A_0 is the amplitude, J_n is the Bessel function of the *n*th order, k_r and k_z are the longitudinal and radial wave vectors $(k = \sqrt{k_r^2 + k_r^2} = 2\pi/\lambda)$, and r, φ , and z are, respectively, the radius, azimuth, and longitudinal components in the cylindrical coordinates. The transverse intensity distribution of the zero-order Bessel beam has a bright spot with a main maximum in the center and a series of concentric rings around the main maximum.

When the optical beam is transmitted in the atmosphere, it will wander due to turbulence. The beam wander can be expressed by the variance of the center displacement of the optical beam^[28]. Since the Bessel beam has the property of reconstruction, it has the ability to resist distortion of phase and amplitude^[29]. Therefore, the zero-order Bessel beam is expected to have smaller beam wander than the Gaussian beam.

Figure <u>1(a)</u> shows the schematic of the DMD-based optical switch using Gaussian beams. Two collimated beams (Input I and Input II) are incident on the two sub-regions (Sub-region 1 and Sub-region 2) of the DMD. By controlling the periods and orientations of the binary gratings loaded on the sub-regions, the refracted beams are steering to the desired output ports (Output I and Output II). The two binary gratings loaded on Sub-region 1 can realize the all-optical interconnect of "Input I \rightarrow Output I" and " Input I \rightarrow Output II", respectively. The two binary gratings loaded on Sub-region 2 can realize the all-optical interconnect of "Input I \rightarrow Output II", respectively. Figure 1(b) shows the schematic of the



Fig. 1. (a) Schematic of the DMD-based optical switch using Gaussian beams. The inset picture shows the image of the Gaussian beam profile. (b) The schematic of the DMD-based optical switch using Bessel beams in the turbulent atmosphere. The inset picture shows the image of the Bessel beam profile.

DMD-based optical switch using Bessel beams in turbulent atmosphere. The experiment requires several meters of non-diffraction distance. The long non-diffraction distance of the Bessel beam requires an axicon with a tiny angle of $\sim 0.2^{\circ}$. It is too difficult to fabricate an axicon with such a small angle. Therefore, we load the phase of the axicon on the spatial light modulator (SLM) to generate the Bessel beam^[30]. The two collimated Gaussian beams (Input I and Input II) are illuminated on the two subregions (Sub-region 1 and Sub-region 2) of the SLM with two identical axicon holograms and converted into two parallel Bessel beams. The two Bessel beams pass through the turbulent atmosphere and work as the channels in the DMD-based switch. A hot plate is used to heat the air and simulate the turbulent atmosphere along the Bessel beam transmission path. The distance between the beam and the hot plate is 4 cm. The temperature difference between the hot plate and the room temperature determines the strength of the turbulence. At the temperatures of 60°C and 80°C (room temperature is 25°C), the wanders of optical beams are recorded by a charge coupled device (CCD). We also measure the beam wander of the DMDbased switch using Gaussian beams as a comparison.

Figures 2(a) to 2(d), respectively, show the distributions of the beam centers when the Bessel and Gaussian beams are transmitted in the turbulent atmosphere at the temperatures of 60°C and 80°C. The coordinates represent the wander distance offset from the original central positions. The transmission distance in the turbulent atmosphere is 1 m. There are 300 points in each figure,



Fig. 2. Center displacements of the Gaussian and Bessel beams in turbulent atmospheres. (a) The light spot wander of the Bessel beam at 60°C. (b) The light spot wander of the Bessel beam at 80°C. (c) The light spot wander of the Gaussian beam at 60°C. (d) The light spot wander of the Gaussian beam at 80°C.

indicating the beam positions extracted from a 20 s video recorded by a CCD (point gray fly capture 2). For both the Gaussian and Bessel beams, the beam wanders increase with the temperature increase.

The beam wanders of the Gaussian beam and Bessel beam are statistically analyzed. Figure 3 shows the Gaussian fitting curves of the offset positions with peak positions, which also has the physical meaning of center displacement of the optical beam $(r_c)^{[28]}$. By fitting the data points using a Gaussian function, we extract the (r_c) parameter from the peak position of the fitting Gaussian curve. The Bessel beam has the smallest beam wander when the turbulent atmosphere is set at 60°C with an r_c of $5.9 \ \mu\text{m}$. The peaks of Gaussian beam wander at 60°C and the Bessel beam wander at 80°C are 7.2 and 7.7 μ m. The Gaussian beam has the largest beam wander when the turbulent atmosphere is set at 80°C with an r_c of 10.6 μ m. Since the value of r_c increases with the distance of beam wander, the beam wander of the Bessel beam is effectively relieved in the turbulent atmosphere compared with the Gaussian beam.

We also demonstrate the DMD-based optical switch using Bessel beams in an optical communication system in turbulent atmosphere. Figure 4 shows the optical switching communication system for the BER testing. In the transmitter, as shown in Fig. 4(a), the 1550 nm laser is amplified by an erbium-doped fiber amplifier after modulation by a Mach–Zehnder modulator with 15 Gbit/s on-off keying (OOK) signals. Figures 4(b1) and 4(b2)show the DMD-based optical switch using Gaussian and Bessel beams. The amplified light beam is divided into two paths by a 3 dB coupler. The two beams are emitted through the collimators, respectively. For the Gaussian beam case, the collimated two beams from a 1550 nm laser with 15 Gbit/s OOK signals are incident in parallel directions on the DMD to switch through thermal turbulent atmosphere. For the Bessel beam case, the two collimated lights are incident in parallel directions on the SLM to generate the Bessel beams. Then, the Bessel beams pass through the thermal turbulent atmosphere and are



Fig. 3. Gaussian fitting curves of the distributions of the beam centers.



Fig. 4. Optical switching communication system for the BER measurements. (a) The transmitter of the optical switch communication system. (b1) The schematic diagram of the DMD-based optical switch using Gaussian beams. (b2) The schematic diagram of the DMD-based optical switch using Bessel beams. (c) The receiver of the optical switch communication system.

incident parallel on the DMD. A CCD camera is placed on the focal plane of the focusing lens for real-time monitoring of the coupling surface state of the output light. As shown in Fig. 4(c), at the receiver end, the beams of Output I and Output II are coupled into single mode fibers by a lens, respectively. The received signals are amplified by a small signal amplifier. The optical signals are converted to electrical signals by a photodiode after noise filtering. After using the oscilloscope (Keysight DCA-X 86100D) to observe the eye diagrams, the BERs are measured by a pattern error detector (Tektronix PED3200).

Figure 5(a) shows the measured BER curves of the Gaussian and Bessel beams after the DMD-based optical switch with turbulent atmosphere at 60°C. The black curves show the BER measured at room temperature as a reference. In order to estimate the performance with random perturbations, the BER values are measured three times, as labeled in different symbols. The average BER values are fitted in solid curves to indicate the trends. In general, the BER values of the Bessel beam are lower than those of the Gaussian beam, and all satisfy the threshold of the enhanced forward error correction (EFEC). In addition, the BER fluctuations in the multiple measurements of the Bessel beams are smaller than those of the Gaussian beams. By further increasing the temperature to 80° C, as shown in Fig. 5(b), the BER curves of the Bessel beam show similar values and fluctuations, while the Gaussian beam shows serious bit error with the increased temperature. Therefore, we can claim that the



Fig. 5. BER curve of Gaussian and Bessel beams at the temperatures of 60° C and 80° C. The 25°C Gaussian is measured at the temperature of 25°C from the Gaussian beam as a comparison. G1, G2, and G3 refer to the BERs measured three times from the Gaussian beams. B1, B2, and B3 refer to the BERs measured three times from the Bessel beams.

Bessel beams are less influenced by the thermal atmosphere compared with the Gaussian beams.

We propose and demonstrate a DMD-based optical switch using Bessel beams to relieve the beam wanders in turbulent atmosphere. The beam wanders of the Gaussian and Bessel beams are characterized by the central position displacements at the temperatures of 60°C and 80°C. By fitting the distributions of the position offsets, the Bessel beams have the central position displacements of 5.9 μ m (60°C) and 7.7 μ m (80°C), which are smaller than the Gaussian beams of 7.2 μ m (60°C) and 10.6 μm (80°C). We also experimentally measure the BERs of the DMD-based optical switch using both the Gaussian and Bessel beams in turbulent atmosphere. From multiple times measurements, the Bessel beams enable lower BERs with better stability compared with the Gaussian beams at the temperatures of 60°C and 80°C. According to the theory^[31], the higher-order Bessel beams</sup> should have better performance for resisting distortions than the zero-order Bessel beams. DMD-based optical

switches using Bessel beams may apply to datacenters to solve the problem of turbulence caused by cooling devices in the future.

This work was supported by the National Natural Science Foundation of China (Nos. U1701661, 61427819, 11774240, and 11604218) and the Science and Technology Innovation Commission of Shenzhen (Nos. KQTD2015071016560101 and KQJSCX20170727100838364). X. Yuan appreciates the support given by the Leading Talents of Guangdong Province Program (No. 00201505) and the Natural Science Foundation of Guangdong Province (Nos. 2016A030312010 and 2017A030313351). The authors wish to thank the anonymous reviewers for their valuable suggestions.

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