Reconfigurable switching of orbital-angular-momentum-based free-space data channels

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Abstract

Light beams can carry orbital angular momentum (OAM) such that a helical phase front twists along the direction of propagation. OAM beams have been demonstrated in a wide variety of applications and have been found to offer a new orthogonal degree of freedom for multiplexing independent data streams for high-capacity point-to-point optical communications. However, to enable their efficient use in reconfigurable networks, approaches must be developed to manipulate OAM beams. We demonstrate OAM-based reconfigurable optical switching functions among multiple OAM beams. Selective data switching among three 100 Gb/s quadrature phase-shift keying OAM channels was achieved with a 2.1 dB optical signal-to-noise ratio penalty. The scheme of selective OAM-beam manipulation can be potentially cascaded to realize an arbitrary $n \times n$ switching function. © 2013 Optical Society of America

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The photon has been proven to be a more effective particle over the electron for carrying information, due to its inherent broad bandwidth and high speed. A few degrees of freedom of photons (amplitude, phase, time, wavelength, and polarization) have been successfully explored to boost the information capacity of optical communications systems over the past few decades [1]. However, the everlasting challenge is to meet the needs of the exponential growth in data transmission capacity. Moreover, fueled by emerging bandwidth-hungry applications, much work has been focused on increasing the spectral efficiency of the communications system. Multilevel/multidimensional modulation and polarization-division multiplexing have been utilized to meet this goal. Another prosperous approach that has gained much attention recently is spatial mode-division multiplexing. Separable spatial modes can carry independent data streams to increase the system capacity and the spectral efficiency simultaneously. Currently, linearly-polarized (LP) modes are widely investigated in a few mode fiber systems [2].

Recently, orbital angular momentum (OAM) has emerged as a potential multiplexing technique to increase system capacity as well as spectral efficiency [2–5]. In general, photons can carry OAM, which is associated with an azimuthal phase dependence (i.e., helical phase front) of the complex electric field. Light beams carrying OAM can be described in the spatial phase form of $\exp(i\ell \phi)$ ($l = 0, \pm 1, \pm 2, \ldots$), where $l$ is the topological charge and $\phi$ is the azimuthal angle [6]. Since OAM-based systems can be designed to have an infinite number of orthogonal eigenstates (l), OAM provides another degree of freedom for multiplexing, as well as manipulating, the optical field. Both free-space and fiber OAM communication systems have been demonstrated for spectral and high-capacity communication links [5–8]. For example, multiplexing Laguerre–Gaussian (LG) beams carrying OAM has been demonstrated in free-space optical communication links at Tbit/s capacities and 90 bits/s/Hz efficiencies [5].

In general, research published in OAM-based free-space communications systems involves relatively static point-to-point links [5–7]. However, similar to the historical advancements made in wavelength-division-multiplexed (WDM) systems, reconfigurable networking functions for a multiuser environment might bring advantages for OAM systems. Potentially desirable functions include switching and manipulation of data channels.

Recently, data exchange between two different OAM beams has been demonstrated using a spatial light modulator (SLM) [5], but it was only for two channels and was not readily scalable to selective multichannel environments. A laudable goal would be to reconfigurably manipulate multiple OAM channels, thereby potentially enabling a dynamic and efficient communications network for multiuser applications.

In this Letter, we experimentally demonstrate reconfigurable optical switching functions when multiple OAM beams are used. Selective OAM manipulation is realized by spatially separating the OAM beams and implementing the desired phase patterns at different regions of the SLM. As the scheme manipulates the phase information at bright regions in the field, the switching function is applied to higher-order OAM beams [10]. We demonstrate selective data switching among OAM$_5$, OAM$_{+2}$, and OAM$_{+8}$ channels, and the average optical signal-to-noise ratio (OSNR) penalties for the channels without and with switching are 1.3 dB and 2.1 dB, respectively. The scheme of selective OAM-beam manipulation can be potentially cascaded to realize arbitrary $n \times n$ switching functions.

Figure 1 is the schematic diagram of an $n \times n$ OAM switch, which shows the architecture to switch $n$ input beams with arbitrary OAM charges to $n$ OAM beams with desired charges. By using the OAM-based reconfigurable optical networking functions, as shown in Fig. 2, this building block can be realized with 2$n + 2$ SLMs. "Charge shift" can shift all the OAM beams with the same charge...
Fig. 1. Schematic diagram of $n \times n$ OAM switch.

Fig. 2. Concept of OAM-based reconfigurable optical networking functions: (a) charge shift, (b) charge exchange, and (c) charge selective manipulation.

step $m-l$, and it can be realized by using a SLM with topological charge $m-l$ and a mirror. “Charge exchange” can reverse the order of the OAM beams. The physical implementation of this function is simply accomplished by a single SLM. A function that can be realized is the exchange of information between two OAM beams [5], and can be potentially extended to information exchange among symmetrically distributed multipair OAM beams on the OAM spectrum. “Charge shift” and “charge exchange” operate on all the OAM beams simultaneously. To realize a fully functional OAM-based reconfigurable optical network, more advanced functions to manipulate individual OAM beams are in great demand. “Charge selective manipulation” functions can potentially be implemented to meet this goal. We can manipulate the charge of one OAM beam, while not affecting the others’, by simply using 2 SLMs. If the target OAM charge (to be switched to for one channel) is already occupied by an OAM beam, we need to first switch this beam to another unoccupied OAM charge with an additional 2 SLMs. Consequently, by effectively cascading the above function, we can relocate any input $n$ OAM beams to any desired output state with a maximum of $2n+2$ SLMs.

Figure 3 depicts the concept and principle of selective manipulation among spatially overlapping OAM beams. As shown in Fig. 3, for a set of multiplexed OAM beams (e.g., $l-k, l+k$), we would like to manipulate one OAM beam (within the dotted red region) differently from the others. The OAM$_{m-k}$ beam is first converted down to the center as a Gaussian beam by reflecting from a SLM with a topological charge of $-l+k$ spiral phase pattern, while the other beams maintain the ring-shape intensity profile. Consequently, the intensity distribution of the selected OAM beam is spatially separated from the other OAM beams. Then, the pixel array of another SLM is spatially separated into center circular region 1 and outer region 2.

By implementing desired patterns to different regions of the SLM, selective manipulation of the OAM beams can be realized. By using 2 SLMs, we can realize three different cases: (A) only one OAM beam is changed, (B) all OAM beams besides one are changed, and (C) all OAM beams are changed.

As an example, Fig. 4 depicts the conceptual diagram of selective switching of two data channels among three OAM beams. Three OAM beams, each carrying its own data stream: OAM$_{5}$ (Data 1), OAM$_{2}$ (Data 2), and OAM$_{8}$ (Data 3). Here, the two information-carrying beams, OAM$_{5}$ and OAM$_{8}$, are selectively switched to produce OAM$_{5}$ (Data 3) and OAM$_{8}$ (Data 1) without affecting the third OAM beam [OAM$_{2}$ (Data 2)]. The steps involved are as follows. At the input, OAM$_{5}$ (Data 1), OAM$_{2}$ (Data 2) and OAM$_{8}$ (Data 3) are spatially multiplexed. The OAM$_{5}$ (Data 2) beam is first converted to a Gaussian beam, i.e., OAM$_{0}$ (Data 2), by launching the multiple OAM beams into the SLM4 with a topological charge of $-2$, while OAM$_{5}$ (Data 1) and OAM$_{8}$ (Data 3) are converted to OAM$_{5}$ (Data 1) and OAM$_{6}$ (Data 3). SLM5 is spatially separated into two regions. The central region has a uniform phase, while the outer region has a topological charge of $-1$. After reflecting from SLM5, OAM$_{7}$ (Data 1) and OAM$_{6}$ (Data 3) are converted to OAM$_{6}$ (Data 1) and OAM$_{7}$ (Data 3), while OAM$_{0}$ (Data 2) maintains its Gaussian profile. After the up-conversion from SLM6 with topological charge of $-2$, channels OAM$_{6}$ (Data 1), OAM$_{0}$ (Data 2), and OAM$_{7}$ (Data 3) become OAM$_{8}$ (Data 1), OAM$_{2}$ (Data 2), and OAM$_{5}$ (Data 3), thereby accomplishing the selective switching of data between OAM$_{5}$ and OAM$_{8}$.

Figure 5 illustrates the experimental setup for reconfigurable switching among channels carried by OAM beams. To generate a 100 Gbit/s quadrature phase-shift keying (QPSK) signal, a continuous-wave (CW) laser is modulated by an inphase/quadrature (I/Q) modulator at $2 \times 50$ Gbit/s. The signal is then split into three paths, decorrelated by fiber with different length, and coupled out for free-space Gaussian beams after the collimators.

The polarization states of the Gaussian beams are optimized with half-wave plates (HWP$s$) before the SLMs. Three SLMs (SLM1–3) are loaded with different phase patterns, and convert the Gaussian beams into three OAM beams (OAM$_{5}$, OAM$_{2}$, OAM$_{8}$). Three 100 Gbit/s QPSK-carrying OAM beams are combined using three
nonpolarizing beam splitters (BS). Three SLMs (SLM4, SLM5, and SLM6) are used to perform the functions of baseband conversion, selective manipulation, and back conversion, respectively. SLM4 and SLM6 are programmed with a spiral phase pattern of topological charge \(-l\) and function as the down-converter and up-converter, respectively \((l = -5, +2, +8\) for without switching OAM \(-5\), OAM \(+2\) and OAM \(+8\)). To perform selective switching function, SLM5 is loaded with a designed phase pattern including two regions, as shown in Fig. 6(b2). The central region has uniform phase and maintains the information on the Gaussian beam, while the outer region has a specified phase pattern and switches the information between the desired two beams. Moreover, differential quadrature phase-shift keying (DQPSK) signal is used and demodulated through a 50 GHz delay line interferometer (DLI). The output is sent to the receiver (Rx) for direct detection. The demodulated temporal waveforms are obtained to confirm the success of selective switching. Another SLM (SLM7) loaded with a specified phase pattern is used to demultiplex one of the superposed OAM beams back to a Gaussian beam and coupled into the fiber for coherent detection and offline digital signal processing (DSP). A flip mirror is used to reflect the OAM beams into the camera for monitoring the intensity and phase information.

Figures 6(a) and 6(b) depict the intensity profile of multiplexed OAM beams and the patterns on SLM4–SLM6 in different manipulation stages. For the SLM patterns, a forked diffraction grating is used to avoid cross talk induced by the zero-order diffraction of the other OAM beams, which is associated with imperfect diffraction efficiency. As shown in Fig. 6(b2), the pattern on SLM5 has a circular buffer region between the central \((r < r_1)\) and outer \((r > r_2)\) regions, with a different diffraction grating period that reduces interbeam cross talk. As shown in Fig. 6(c), interferograms of the switched OAM beams (OAM \(-5\) and OAM \(+8\)) and reference Gaussian beam clearly indicate the switching of their topological charges. The temporal waveforms, as...
shown in Fig. 7, further verify the successful switching of 100 Gbit/s QPSK signals carried by OAM_{-5} and OAM_{+8}.

Figure 8(b) shows the measured bit error rate (BER) curves of selective data switching between 100 Gbit/s QPSK channels carried by OAM_{-5} and OAM_{+8}. Furthermore, the reconfigurability of the proposed scheme is demonstrated by selectively switching between OAM_{+2} and OAM_{+8}, and between OAM_{-5} and OAM_{+2}. Figures 8(a) and 8(c) depict the measured BER curves of selective data switching for OAM_{-5} and OAM_{+8} and for OAM_{-5} and OAM_{+2}. The average OSNR penalties for the channels without and with switching are 1.3 dB and 2.1 dB, respectively.

Our demonstrated schemes have potential scalability to accommodate a system with additional OAM beams and more advanced switching functions. In order to implement these functions, several aspects should be considered and improved. First, operational speed is mainly limited by the SLM, which has a switching time on the scale of milliseconds. This switching time is close to the one used in the network nowadays. Alternative solutions, such as a high-speed electrically or optically controlled OAM generator, might be able to further improve the functional speed. Second, by reducing intermodal cross talk, additional channels could be used with smaller OAM charge interval, which would also boost the functional scalability. Using SLMS with smaller pixel size or larger diffraction efficiency might be one potential solution. Furthermore, although OAM is theoretically orthogonal to other degrees of freedom for the photon, in practice, optical components used in the functional block could introduce some dependence (e.g., the SLMS we used are effective only in one polarization direction, and are wavelength dependent). SLM can function across the C band with low penalty [6], and one potential solution to the polarization dependence is to introduce a polarization diversity scheme [11]. Moreover, replacing SLMS with integrated OAM generators can potentially realize complex switching function at a low cost [7,12].

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References