Orbital-angular-momentum-based reconfigurable optical switching and routing

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Orbital angular momentum (OAM) has gained interest due to its potential to increase capacity in optical communication systems as well as an additional domain for reconfigurable networks. This is due to the following: (i) coaxially propagated OAM beams with different charges are mutually orthogonal, (ii) OAM beams can be efficiently multiplexed and demultiplexed, and (iii) OAM charges can be efficiently manipulated. Therefore, multiple data-carrying OAM beams could have the potential capability for reconfigurable optical switching and routing. In this paper, we discuss work involving reconfigurable OAM-based optical add/drop multiplexing, space switching, polarization switching, channel hopping, and multicasting.

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1. INTRODUCTION

Multiplexing multiple data channels has been widely used to significantly increase the data capacity in optical networks [1,2]. Examples include wavelength-division multiplexing (WDM) and polarization-division multiplexing (PDM), for which multiple unique light beams of different wavelengths or polarizations simultaneously carry independent data streams [3,4]. Another multiplexing approach using spatial degree of freedom, known as space-division multiplexing (SDM), has gained recent interest [5–8]. Note that SDM is compatible with PDM and WDM, such that a combination of the techniques has the potential to further increase the total capacity in optical networks [9].

In addition to multiplexing for raw capacity increase, optical networking using a property of the light to determine the channel routing has been deployed to great benefit and efficiency. This is true for wavelength-dependent routing and switching, such that data paths can be reconfigurably set up in a network based on the wavelength of the channel. Such routing allows for highly efficient and granular manipulation of data channels. Moreover, the channel can be passively routed to a destination or actively switched to another wavelength for subsequent routing [3].

Another property of light is the spatial domain, for which each light beam would occupy a unique orthogonal mode. In this case, the specific mode could be used as a routing and switching identifier in an optical network [10–12].

As a potential SDM approach, the use of orbital angular momentum (OAM) light beams as an orthogonal set of beams has been explored [13–17]. An OAM beam has a helical phase front of $\exp(i\ell\phi)$, where ϕ is the azimuthal angle and ℓ is an unbounded positive or negative integer corresponding to the OAM charge [12]. OAM beams with different charges are mutually orthogonal to each other, allowing them to be efficiently (de)multiplexed with low crosstalk [13].

Similar to WDM networking, we could enable OAM-based reconfigurable optical networks by manipulating different OAM charges for switching and routing, as shown in Fig. 1(a). OAM has the capability for different base functionalities in a multiuser environment, including (i) charge shift, i.e., shifting all the OAM beams with the same charge step, (ii) charge exchange, i.e., reversing the orders of all the OAM beams, and (iii) charge-selective manipulation, i.e., manipulating the charge of one OAM beam while not affecting the others' charges, as shown in Figs. 1(b)–1(d) [18].

In this paper, we review various OAM-based networking techniques, including OAM-based reconfigurable (1) add/drop multiplexing, (2) space switching, (3) polarization switching, (4) channel hopping, and (5) multicasting.

2. OAM-BASED ROADM

In optical networks, reconfigurable optical add/drop multiplexers (ROADMs) are useful in selectively adding or dropping data traffic at a given network node. An OAM-based ROADM would selectively add or drop a data channel by identifying and manipulating the OAM charge of a given beam. As shown in Fig. 2, the OAM-based ROADM comprises three steps: (i) downconvert the OAM beam to be dropped into a Gaussian-like beam, while other beams remain OAM beams with different charges, (ii) drop the central Gaussian-like beam and add in another one carrying a new data stream,

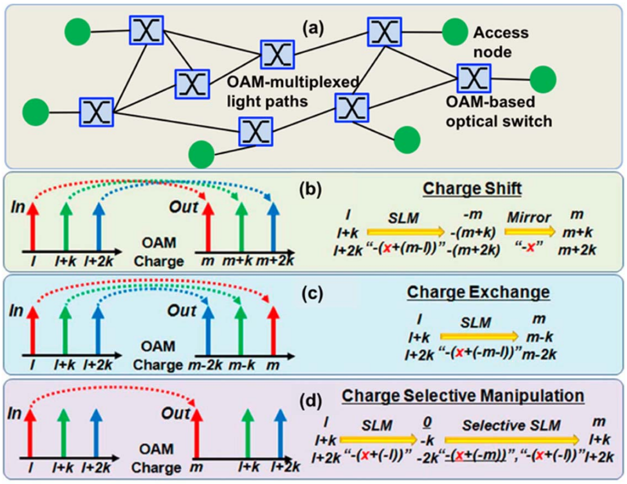

Fig. 1. Concept of (a) an OAM-multiplexed optical network with OAM-multiplexed optical connections and OAM-based reconfigurable optical networking functions: (b) charge shift, (c) charge exchange, and (d) charge-selective manipulation [3,18].

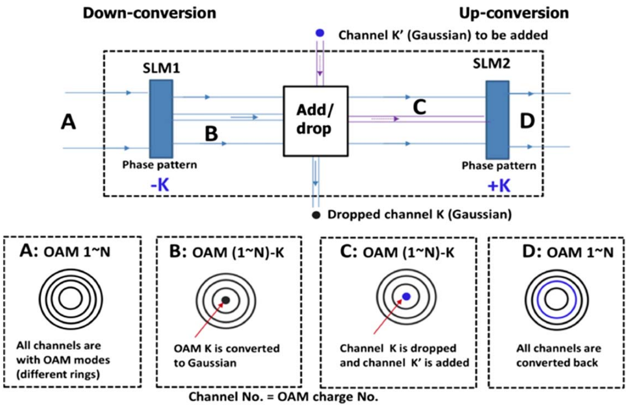

Fig. 2. Concept of OAM channel add/drop multiplexing [19].

and (iii) upconvert the newly aligned beams back to their original OAM charges. Tunable spatial light modulators (SLMs) can be used for down- and up-conversions [19].

In [19], an OAM-based ROADM with three OAM beams (OAM −5, +2, and +8), each carrying a 100 Gbit/s quadrature phase-shift keying (QPSK) signal, is demonstrated. The images of three multiplexed OAM beams before and after downconversion, the add/drop of the OAM +2 channel, and the newly aligned beams before and after upconversion are shown in Figs. 3(a1)–3(a6). Figures 3(b1) and 3(b2) show the bit error rate (BER) curves for the added/dropped channels on OAM +2 and the pass-through channels on OAM-5 and OAM +8, respectively. The optical signal-to-noise ratio (OSNR) penalties at a BER of 2×10^{-3} for all channels are below 2 dB, which could be reduced using higher resolution SLMs [19].

3. OAM-BASED RECONFIGURABLE SWITCHING

Beyond an ROADM, the next higher-level switching function would be a full $n \times n$ space switch. Through manipulations of OAM channels, a reconfigurable $n \times n$ OAM-based space switch could switch n OAM beams with arbitrary charges to n OAM beams with the desired charges, enabling dynamic and efficient data exchange [18].

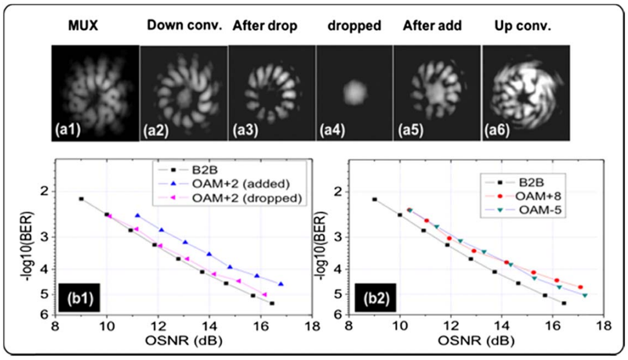

Fig. 3. Experimental results: (a1)–(a6) intensity profiles of multiplexed OAM beams for each step of adding/dropping the OAM +2 channel; BER curves for (b1) added/dropped channels and (b2) pass-through channels. B2B, back-to-back; BER, bit error rate; conv., conversion; MUX, multiplex; OSNR, optical signal-to-noise ratio [19].

In [20], a reconfigurable 2×2 OAM-based switching of 100 Gbit/s QPSK channels is achieved. Such a switch is analogous to a 2×2 WDM switch, which either allows a channel to pass through without being redirected, i.e., the "bar" state or redirects it to appear at the opposite output port, i.e., the "cross" state [20]. In each port, multiplexed OAM beams are first downconverted, transforming one beam into a Gaussian-like beam while others remain OAM beams with different charges. Afterward, all beams are spatially separated by a programmable mode-dependent beam-steering element, redirecting the Gaussian-like beam and OAM beams in different directions, such that the Gaussian-like beam from one path is aligned with the OAM beams from the other path, and vice versa. The newly aligned beams are upconverted to their original charges, as shown in Fig. 4 [20]. For example, two multiplexed OAM beams with $\ell = +4, -4$ and $\ell = +2, -6$ are used for the input ports A and B, respectively. Each channel carries a 100 Gbit/s QPSK signal. BERs are shown in Fig. 5 with OSNR penalties <2.5 dB [20].

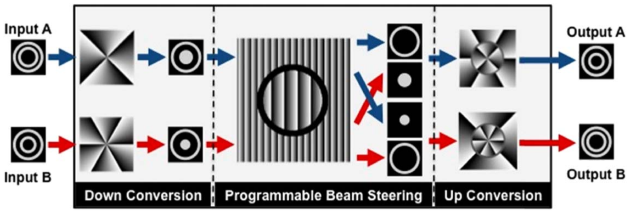

Fig. 4. Functional block diagram of the 2×2 OAM-based switch. Switching is performed with the help of mode downconversion, programmable beam steering, and mode upconversion stages [20].

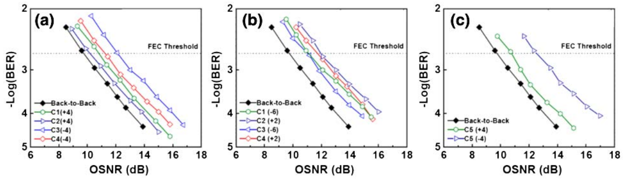

Fig. 5. BERs for modes appearing at output port A for different switch configurations: (a) channels from input port A, (b) channels from input port B, (c) channels from input port A while switch was in "bar" state. FEC: forward error correction [20].

4. OAM- AND POLARIZATION-BASED SWITCHING

Since OAM multiplexing and PDM are compatible with each other, reconfigurable manipulations of data channels residing on both the OAM charge and the polarization state could further increase the capacity and flexibility of optical networks [21]. As shown in Fig. 6, polarization-multiplexed beams could be separated by a polarization beam splitter (PBS). One beam is downconverted to a Gaussian-like beam, and the other beam is polarization rotated by 90°, such that the two beams are on the same polarization. After shifting OAM charges and multiplexing, these beams are converted to OAM-multiplexed beams. Inversely, OAM-multiplexed beams could be downconverted, with one beam being a Gaussian-like beam and the other one remaining an OAM beam. After separation, the OAM charges are shifted to the desired ones, and the polarization state of one beam is rotated by 90°. After combining using a PBS, these beams are converted to polarization-multiplexed beams [21].

For example, in [21], two OAM +2 beams on two orthogonal polarizations was transformed to OAM +3 and +6 on the same polarization; and OAM +1 and +6 beams on the same polarization was transformed to two OAM +1 beams on two orthogonal polarizations, as Fig. 7 shows.

5. OAM-BASED CHANNEL HOPPING

In reconfigurable multi-access networks, OAM-based channel hopping can route data streams based on the specific OAM charge that a channel occupies [22]. Data channels are input to a high-speed optical switch, each output of which is sent to a different phase hologram of a specific OAM charge. A hopping controller is used to select the data signal for a specific user by controlling the optical switch, such that in a certain time slot, the signal is output from a specific output port and imposed on a corresponding OAM mode from a chosen OAM mode set, as shown in Fig. 8(a). The OAM charge and time duration depend on the bit information and frequency of the controller signal, with a guard time required to ensure the recovery of the entire data stream [22].

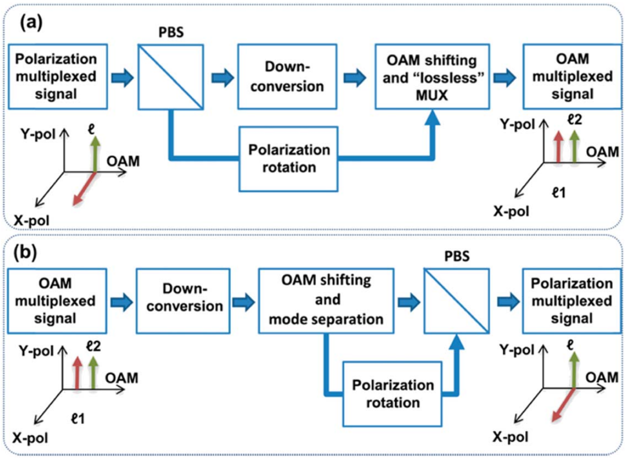

Fig. 6. Procedures of the conversion (a) from a polarization-multiplexed signal to an OAM-multiplexed signal, (b) from an OAM-multiplexed signal to a polarization-multiplexed signal. MUX, multiplexing [21].

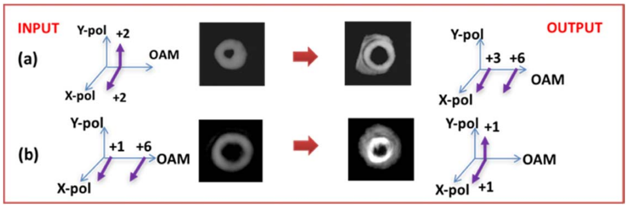

Fig. 7. Schematic view of conversion (a) from OAM +2 on x-pol and y-pol to OAM +3 and OAM +6 on x-pol, and (b) from OAM +1 and OAM +6 on x-pol to OAM +1 on x-pol and y-pol [21].

OAM-based channel hopping is demonstrated in [22], in which a 100 Gbit/s QPSK signal hops between four different OAM modes with a 2 ns switching guard time. Figures 8(b1) and 8(b2) show received one-period waveforms for an OAM of $\ell = +1$ at hopping rates of 10 and 50 MHz when using a mode set of $\ell = -3, -1, +1$, and $+3$. Figures 8(b3) and 8(b4) depict the recovered signal constellations during the effective data period and the switch transition time at a 50 MHz hopping rate, respectively. It is observed that the QPSK constellation during the switch transition time becomes blurred, which may due to the crosstalk when hopping to another mode [22].

6. OAM-BASED MULTICASTING

Multicasting is a useful routing function in multiuser networks, in which data on one channel can be duplicated on multiple channels, such that it can be routed to multiple destinations simultaneously. Previously, multicasting based on time slots and wavelength channels has been demonstrated, and extending this concept to OAM has potential benefits [23]. Sliced phase patterns are designed to achieve the OAM multicasting function. It has been shown that an angular amplitude aperture with an N-fold rotational symmetry can spatially distribute energy from the input OAM beam to multiple OAM beams having equally spaced OAM charges. The generated OAM power spectrum has a sinc^2-like profile. To equalize the power of the multicast channels, a complementary sliced phase pattern is designed, as shown in Fig. 9(a) [23]. As shown in Fig. 9(b), the OAM channel $\ell = +15$ is multicast onto $\ell = +6, +9, +12, +15$, and $+18$, and little power is achieved on the nonmulticasting channels [23].

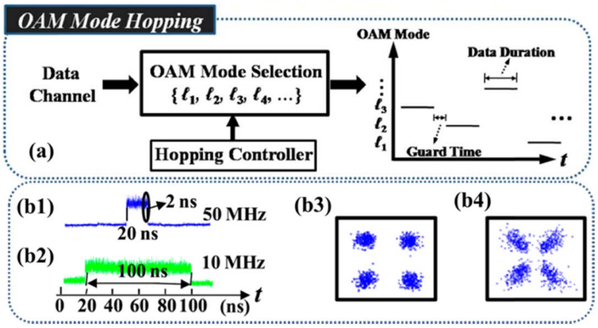

Fig. 8. (a) Concept of channel hopping in the spatial domain using OAM modes; one period of the received waveforms for channel $\ell = +1$ at hopping rates of (b1) 10 and (b2) 50 MHz; recovered 100 Gbit/s QPSK constellations for channel $\ell = +1$ during the (b3) data period and (b4) hopping transition time at 50 MHz hopping rate (2 ns guard time). Mode set $\ell = -3, -1, +1, +3$ is used [22].

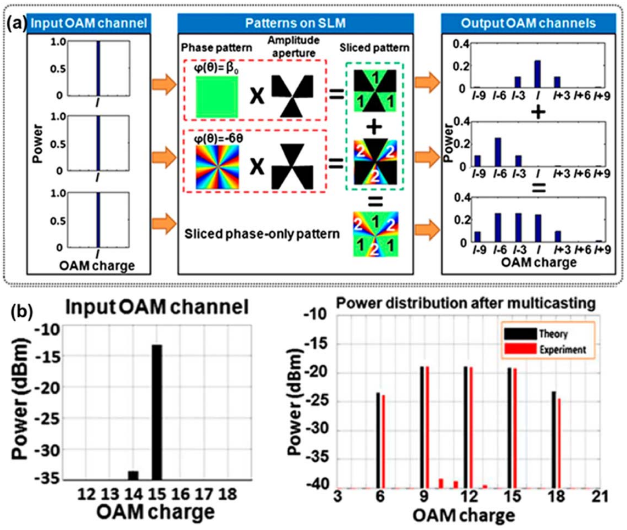

Fig. 9. (a) Concept of the multicasting function in an OAM multiplexing system, (b) the OAM power spectrum before and after multicasting [23].

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