Optical communications using orbital angular momentum beams

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Orbital angular momentum (OAM), which describes the “phase twist” (helical phase pattern) of light beams, has recently gained interest due to its potential applications in many diverse areas. Particularly promising is the use of OAM for optical communications since: (i) coaxially propagating OAM beams with different azimuthal OAM states are mutually orthogonal, (ii) inter-beam crosstalk can be minimized, and (iii) the beams can be efficiently multiplexed and demultiplexed. As a result, multiple OAM states could be used as different carriers for multiplexing and transmitting multiple data streams, thereby potentially increasing the system capacity. In this paper, we review recent progress in OAM beam generation/detection, multiplexing/demultiplexing, and its potential applications in different scenarios including free-space optical communications, fiber-optic communications, and RF communications. Technical challenges and perspectives of OAM beams are also discussed. © 2015 Optical Society of America

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1. Introduction

Achieving higher data transmission capacity is one of the primary interests of the optical communications community. This has led to the investigation of using different physical properties of a lightwave for data encoding and channel addressing, including amplitude, phase, wavelength, and polarization. More recently, spatially orthogonal modes and spatial positions have been under intense investigation. A typical method of increasing the transmission capacity in optical communication systems is the multiplexing of multiple independent data channels. For example, multiple independent data channels can be located on different wavelengths, polarizations, or spatial channels, corresponding to wavelength-division multiplexing (WDM), polarization-division multiplexing (PDM), and space-division multiplexing (SDM), respectively [1,2].

A special case of SDM is the utilization of orthogonal spatially overlapping and co-propagating spatial modes, known as mode-division-multiplexing (MDM) [1]. In such a case, each mode can carry an independent data channel, and the orthogonality enables efficient (de)multiplexing and low inter-modal crosstalk among multiple modes. There are several different types of orthogonal modal basis sets that are potential candidates for such MDM systems. One such set is orbital angular momentum (OAM) [3].

It is well known that a lightwave can be interpreted quantum mechanically and thus can be viewed to carry both spin angular momentum (SAM) and OAM [4]. Contrary to SAM (e.g., circularly polarized light), which is identified by the electric field direction, OAM can be interpreted to characterize the “twist” of a helical phase front [5]. Owing to the helical phase structure, an OAM-carrying beam usually has an annular “ring” intensity profile with a phase singularity at the beam center. Depending on the discrete “twisting” rate of the helical phase, OAM beams can be quantified as different states, which are orthogonal while propagating coaxially.

This property allows OAM beams to be potentially useful in improving the performance of optical communication systems. Specifically, OAM states could be used as a different dimension to create an additional set of data carriers in an SDM/MDM system [3]. Importantly, OAM multiplexing does not rely on the wavelength or polarization, indicating that OAM could be used in addition to WDM and PDM techniques to improve system capacity. Compared to other MDM methods, OAM might have some implementation advantages stemming from the circular symmetry of the modes, which make it well-suited for many optical component technologies.
This paper will highlight recent advances in OAM-based communication systems. We will describe several proof-of-concept experimental demonstrations of OAM multiplexing for optical communications that have been reported both in free space [6] and optical fiber [7]. Additionally, technical challenges, such as the atmospheric turbulence in free-space links and mode coupling in fiber links will be discussed. We will also review progress in the device technology for OAM generation, detection, and (de)multiplexing, as well as the design of novel fibers that are possibly more suitable for OAM transmission.

2. OAM and Light Beams

It is well known that different types of movement of an object are associated with different types of momentum: an object moving in a straight line carries linear movement. Angular momentum is imparted by spinning (i.e., SAM), or orbiting around an axis (i.e., OAM), as shown in Figs. 1(a) and 1(b), respectively. A light beam may also possess these two types of angular momenta. In the paraxial approximation, a light beam carries SAM if the electrical field rotates along the beam axis (i.e., circularly polarized light) and carries OAM if the wave vector spirals around the beam axis, leading to a helical phase front, as shown in Figs. 1(c) and 1(d) [8]. In its analytic expression, this helical phase front is usually related to a phase term of $\exp(i\ell \theta)$ in the transverse plane, where $\theta$ refers to the azimuthal coordinate and $\ell$ is an integer counting the number of intertwined helices (i.e., the number of $2\pi$ phase shifts along the circle around the beam axis). $\ell$ is an integer and can therefore assume a positive, negative, or even a zero value, corresponding to clockwise or counterclockwise phase helices or a Gaussian beam (i.e., no helix), respectively [9].

Two important concepts that sometimes give rise to confusion are discussed below:

(1) **OAM and polarization:** As mentioned above, an OAM beam has a helical phase front and therefore results in a twisting wavevector. On the other
hand, SAM is connected to polarization states. A light beam carries SAM of \( \pm h/2\pi \) (\( h \) is Planck’s constant) per photon if it is left or right circularly polarized and carries no SAM if it is linearly polarized. Although the SAM and OAM of light can be coupled to each other under certain scenarios [10], they can be clearly distinguished for a paraxial light beam. Therefore, in the paraxial limit, OAM and polarization can be considered two independent properties of light [9].

(2) OAM beam and Laguerre–Gaussian (LG) beam: In general, an OAM-carrying beam could refer to any helically phased light beam, irrespective of its radial distribution. LG beams are a special subset among all OAM-carrying beams, whose radial distribution is characterized by the fact that they are paraxial eigensolutions of the wave equation in cylindrical coordinates and in homogeneous media (e.g., free space). For an LG beam, both azimuthal and radial wavefront distributions are well defined and indicated by two indices, \( l \) and \( p \), in which \( l \) has the same meaning as that of a general OAM beam (i.e., azimuthal phase dependence) and \( p \) refers to the radial nodes in the intensity distribution. LG beams form an orthogonal and complete mode in the spatial domain. In contrast, a general OAM beam may be expanded into a group of LG beams (each with the same \( l \) but a different \( p \) index) due to the absence of radial definition. Henceforth, the term “OAM beam” refers to all helically phased beams and is to be distinguished from LG beams.

3. Application of OAM to Optical Communications

Utilization of OAM for communications is based on the fact that coaxially propagating light beams with different OAM states can be efficiently separated. This is obviously true for orthogonal modes such as the LG beams. Interestingly, it also holds for general OAM beams with cylindrical symmetry by relying only on the azimuthal phase. Considering any two OAM beams having an azimuthal index of \( l_1 \) and \( l_2 \), respectively,

\[
U_1 = (r, \theta, z) = A_1(r, z) \exp(i l_1 \theta),
\]

\[
U_2 = (r, \theta, z) = A_2(r, z) \exp(i l_2 \theta),
\]

where \( r \) refers to the radial position and \( z \) is the propagation distance, one can conclude that these two beams are orthogonal in the sense that

\[
\int_0^{2\pi} U_1 U_2^* d\theta = \begin{cases} 
0 & \text{if } l_1 \neq l_2 \\
\lambda_1 \lambda_2^* & \text{if } l_1 = l_2.
\end{cases}
\]

There are two different ways to take advantage of the distinction between OAM beams with different \( l \) states in communications. In the first approach, \( N \) different OAM states can be encoded as \( N \) different data symbols representing “0”, “1”, ..., “\( N-1 \)”. A sequence of OAM states sent by the transmitter therefore represents data information. At the receiver, the data can be decoded by checking the received OAM state. This approach seems to be more favorable to the quantum communications community, since OAM could provide for the encoding of multiple bits [\( \log_2(N) \)] per photon due to the infinitely countable number of possible OAM states, and so could potentially achieve higher photon
The efficiency [11]. The encoding/decoding of OAM states could also have some potential applications for on-chip interconnection to increase data capacity [12].

The second approach, employed in most of the recent demonstrations, is to use each OAM beam as a carrier for a different data stream [13]. A typical SDM system uses either a multicore fiber or free-space laser array so that the data channels in each core/laser beam are spatially separated [14], or a group of orthogonal modes to carry different data channels in a multimode fiber (MMF) or in free space [15]. High capacity data transmissions in a multicore fiber and in a single-core MMF have been reported [16,17]. Similar to the second SDM architecture that uses copropagating orthogonal modes, OAM beams with different states can be spatially multiplexed and demultiplexed, thereby providing independent data carriers in addition to wavelength and polarization. Ideally, the orthogonality of OAM beams can be maintained in transmission, which allows all the data channels to be separated and recovered at the receiver. A typical scheme of OAM multiplexing is conceptually depicted in Fig. 2. An obvious benefit of OAM multiplexing is the improvement in system spectral efficiency, since the same bandwidth can be reused for additional data channels [18].

4. OAM Beam Generation, Multiplexing, and Demultiplexing

4.1. OAM Beam Generation and Detection

Many approaches for creating OAM beams have been proposed and demonstrated. One could obtain a single or multiple OAM beams directly from the output of a laser cavity [19,20] or by converting a fundamental Gaussian beam into an OAM beam outside a cavity. The converter could be a spiral phase plate [5], diffractive phase holograms [21–23], metamaterials [24–27], cylindrical lens pairs [28], q-plates [29,30], fiber gratings [31], or couplers [32]. There are also different ways to detect an OAM beam, such as using a converter that creates a conjugate helical phase or using a plasmonic detector [33].

4.1a. Mode Conversion Approaches

Among all external-cavity methods, perhaps the most straightforward one is to pass a Gaussian beam through a coaxially placed spiral phase plate (SPP) [34,35] or to have it reflected by a spiral phase mirror (SPM) [36]. An SPP is an optical element with a helical surface, as shown in Fig. 3(a). To produce an OAM beam
with a state of $\ell$, the thickness profile of the plate should be machined as $\ell \lambda \theta / 2\pi (n - 1)$, with $n$ being the refractive index of the medium (note that only half of the thickness variation is required if using an SPM). Such elements can be fabricated with very high precision, and the generation of OAM beams with a charge as high as 5050 has been demonstrated [36]. As alternatives, reconfigurable diffractive optical elements, e.g., a pixelated spatial light modulator (SLM), or a digital micromirror device [23] can be programmed to function as a refractive element of choice at a given wavelength, as shown in Fig. 3(b). Importantly, the generated OAM beam can be easily changed by simply updating the hologram loaded on the SLM. To spatially separate the phase-modulated beam from the zeroth-order non-phase-modulated beam at the SLM output, a linear phase ramp is added to the helical phase mask (i.e., a “fork”-like phase pattern, as shown in Fig. 3(c)) to produce a spatially distinct first-order diffracted OAM beam, carrying the desired charge [22]. It should also be noted that the aforementioned methods produce OAM beams by only modulating the phase of the incoming beam. To generate a high quality LG$_{\ell,p}$ mode, one must jointly control both the phase and the intensity of the incoming beam. This can be achieved using a phase-only SLM with a more complex phase hologram [37].

Figure 3

Three approaches to convert a Gaussian beam into an OAM beam: (a) a spiral phase plate, (b) a phase hologram with a spiral phase pattern, or (c) a phase hologram with a “fork” pattern. In this example, the conversion to an OAM beam with $\ell = +3$ is depicted.

Figure 4

Mid-infrared metasurface phase plate that can generate OAM beams. (a) The fabricated metasurface phase plate. (b) Magnified structure of the designed metasurface. (c) Interferogram of the generated OAM beam with $\ell = +1$. Reprinted from Yu et al., Science 334, 333–337 (2011) [24] by permission from AAAS.
Some novel material structures, such as metasurfaces, can also be used for OAM generation. A compact metasurface could be made into a phase plate by manipulating the spatial phase response caused by the structure [24,25]. As shown in Figs. 4(a) and 4(b), the metasurface is created by assembling an array of subwavelength antennas, each of which is composed of two arms connected at one end. Light reflected by this plate experiences a phase change ranging from 0 to \(2\pi\), determined by the length of the arms and their relative angle [24]. To generate an OAM beam, the surface is divided into eight sectors, each of which introduces a phase shift from 0 to \(\frac{7\pi}{4}\) with a step of \(\frac{\pi}{4}\). The OAM beam with \(l = +1\) is obtained after the reflection, as shown in Fig. 4(c).

Another interesting liquid-crystal-based device called a “\(q\)-plate” is also used to convert a circularly polarized beam into an OAM beam [30]. A \(q\)-plate is essentially a liquid-crystal slab with uniform birefringent phase retardation of \(\pi\) and a spatially varying transverse optical axis pattern. Along the path circling once around the center of the plate, the optical axis of the distributed crystal elements may have a number of rotations defined by the value of \(q\). A circularly polarized beam passing through this plate would experience a helical phase change of \(\exp(i\ell \theta)\) with \(\ell = 2q\), as shown in Fig. 5 [30].

Note that almost all of the mode conversion approaches can also be used to detect an OAM beam. For example, an OAM beam can be converted back to a Gaussian-like beam if the helical phase front is removed, e.g., by passing the OAM beam through a conjugate SPP or phase hologram [5].

4.1b. Intra-cavity Approaches

OAM beams are higher order modes with respect to the Gaussian mode and can be directly generated from a laser resonator cavity. A resonator supporting higher order modes usually produces a mixture of multiple modes, including the fundamental mode. In order to avoid the resonance of the fundamental Gaussian mode, a typical approach is to place an intracavity element (e.g., an SPP or a mirror) to force the oscillator to resonate on a specific OAM mode [38]. Other reported demonstrations include the use of an annular shaped beam as

![Figure 5](image-url)

Q-plate (QP) can convert a left circularly polarized beam into a helically phased beam with right circular polarization, or vice versa. Reprinted from Marrucci et al., J. Opt. 13, 064001 (2011) [30] © IOP Publishing. Reproduced with permission. All rights reserved.
laser pump [39], the use of thermal lensing [40], or using a resonator mirror with a defect spot in the center [41].

Instead of using bulk free-space optics, a more compact version of an OAM beam generator on the micrometer scale is reported using a modified microring resonator [42]. The idea is that whispering gallery modes can be excited and confined in a ring resonator. To change it into an OAM beam emitter, angular grating structures are embedded into the regular ring resonator to periodically vary the refractive index in the azimuthal direction, as shown in Fig. 6(a). The grating structure distributed along the ring cavity is used to create diffractions on the guided mode in the ring resonator. The principle is similar to what a linearly distributed grating does to the incoming light, as shown in Fig. 6(b). The diffracted beam from the side of the ring resonator possesses a helical phase front [Fig. 6(c)], the azimuthal state of which is determined by the difference between the azimuthal order of the mode guided in the ring and the period of grating elements in the ring. Tuning of the \( \ell \) state of the generated beam can be achieved by exciting different orders of guided modes in the ring, as discussed in [43]. Fast switching between two different OAM states at the rate of 20 \( \mu \)s is demonstrated through the use of electrically contacted thermo-optical control. Due to the miniaturized dimension, there is the potential of producing an array of such OAM beam generators on a single photonic chip. A fabricated array including three identical ring resonators and their generated output beams is shown in Figs. 6(d1)–6(d3).

4.2. OAM Beams Multiplexing and Demultiplexing

One of the benefits of OAM is that multiple coaxially propagating OAM beams with different \( \ell \) states provide additional data carriers, as they can be separated based on the twisting wavefront. Hence, one of the critical techniques is the efficient multiplexing/demultiplexing of OAM beams of different \( \ell \) states, such
that each carries an independent data channel and all beams can be transmitted and received using a single aperture pair. Several multiplexing and demultiplexing techniques have been demonstrated, including the use of an inverse helical phase hologram to convert the OAM into a Gaussian-like beam, a mode sorter \[44\], free-space interferometers \[45\], a photonic integrated circuit \[46–48\], and q-plates \[49\]. Some of these techniques are briefly described below.

4.2a. Beam Splitter and Inverse Phase Hologram

A straightforward way of multiplexing different beams is to use cascaded 3 dB beam splitters. Each beam splitter can coaxially multiplex two beams that are properly aligned, and cascaded \(N\) beam splitters can multiplex \(N + 1\) independent OAM beams at most, as shown in Fig. 7(a). Similarly, at the receiver end, the multiplexed beams are divided into four copies. To demultiplex the data channel on one of the beams (e.g., with \(l_i\)), a phase hologram with a spiral charge of \(-l_i\) is applied to all the multiplexed beams. As a result, the helical phase on the target beam is removed, and this beam will eventually evolve into a Gaussian-like beam. The Gaussian-like beam can be isolated from the other OAM beams, which still have helical phase fronts, by using a spatial mode filter, e.g., a single-mode fiber (SMF) at the focal point of a lens will couple the power only of the Gaussian mode due to the mode-matching constraints. Accordingly, each of the multiplexed beams can be demultiplexed by changing the spiral phase hologram. Although the power loss incurred by the beam splitters and the spatial mode filter makes this method quite power inefficient, it was frequently used in the initial laboratory demonstrations of OAM multiplexing/demultiplexing due to its simplicity and reconfigurability provided by the programmable SLMs.

4.2b. Optical Geometrical Transformation-Based Mode Sorter

More power-efficient multiplexing and demultiplexing of OAM beams are achieved by using an OAM mode sorter \[50,51\]. This mode sorter usually comprises three optical elements, namely, a transformer, a corrector, and a lens, as shown in Fig. 8 \[52\]. The transformer performs a geometrical transformation of the input beam from log-polar coordinates to Cartesian coordinates, such that the position \((x, y)\) in the input plane is mapped to a new position \((u, v)\) in the output plane, where \(u = -a \ln \left( \frac{\sqrt{x^2+y^2}}{b} \right)\) and \(v = \arctan(y/x)\). Here, \(a\) and \(b\) are scaling constants. The corrector compensates for phase errors and ensures that the transformed beam is collimated. Considering an input OAM beam with a ring-shaped...
beam profile, it can be unfolded and mapped into a rectangular-shaped plane wave with a tilted phase front. Similarly, multiple OAM beams having different \( \ell \) states will be transformed into a series of plane waves, each with a different phase tilt. A lens focuses these tilted plane waves into spatially separated spots in the focal plane such that all OAM beams are simultaneously demultiplexed. Since the transformation is reciprocal, the mode sorter can also be used in reverse to function as an OAM generator and multiplexer. A Gaussian beam array placed in the focal plane of the lens is converted into superimposed plane waves with different tilts. These beams then pass through the corrector and the transformer to produce properly multiplexed OAM beams \[53\].

4.2c. OAM Multiplexing/Demultiplexing Using Photonic Integrated Circuits

Integrated versions of an OAM (de)multiplexer were reported using planar photonic waveguides \[46–48\]. The concept of such a device is schematically shown in Fig. 9 \[48\]. A group of single-mode waveguides interfaced with SMFs are placed in parallel as the input ports. The beam from each input port is expanded to a plane wave with a phase tilt and is then sampled by a number of path-length-matched waveguides. The output apertures of all the waveguides are circularly arranged. The coherent combination of output beams from each aperture could evolve into an OAM beam, the state of which is determined by the position of the input port. In principle, such a device with \( N \) waveguide apertures can support at most \( N \) different OAM states ranging from \(-N/2\) to \(N/2-1\). The simulated and experimentally observed OAM beams using a circuit with nine available apertures are shown in Fig. 9(b). Note that instead of being placed perpendicularly to the chip surface, the output aperture arrays could also be arranged laterally in a 3D structure, as shown in Fig. 9(c). This device was demonstrated and used in a free-space optical communication link utilizing two multiplexed OAM states, as described by Guan et al. \[54\].

The (de)multiplexing approaches discussed above operate on the OAM beams such that OAM beams are transformed into non-OAM beams and vice versa. There also exists a scheme that performs OAM (de)multiplexing without performing mode transformation such that the OAM property is maintained even after performing the desired operation. Such a method uses free-space interferometers.

Concept of an OAM mode sorter. The log-polar geometrical-transformation-based mode sorter can be used as an OAM multiplexer (when light propagates from right to left) and a demultiplexer (when light propagates from left to right).
with Dove prisms to efficiently (de)multiplex OAM beams [45]. We note that both types of demultiplexing methods could be useful in optical communications.

5. Free-Space Optical Communications Using OAM

The first proof-of-concept experiment using OAM for free-space communications was reported by Gibson et al. in 2004 [3]. In their demonstration, eight different OAM states, each representing a data symbol, were transmitted one at a time. The azimuthal index of the transmitted OAM beam was measured at the receiver using a phase hologram modulated with a binary grating, demonstrating that information transfer can be achieved. To effectively use this approach, fast switching is required between different OAM states to achieve a high data rate. Alternatively, there has been progress in classical communications by using OAM states as data carriers, which can be multiplexed at the transmitter, copropagate through the free-space link, and be demultiplexed at the receiver [55–57]. The total data rate of a free-space communication link demonstrated in the laboratory experiments has reached 100 Tbit/s or even beyond by using OAM multiplexing [58,59]. The propagation of OAM beams through the atmosphere (e.g., across a city) is also under investigation and related discussion can be found in the experiments reported in [60,61].

5.1. Proof-of-Principle Communications Link Demonstrations

Initial demonstrations of using OAM multiplexing for optical communications include free-space links using a Gaussian beam and an OAM beam encoded with
on–off keying data [55]. Later on, the multiplexing/demultiplexing of four different OAM beams in a free-space data link was reported by Wang et al. [56]. Four monochromatic Gaussian beams each carrying an independent 50.8 Gbit/s (4 × 12.7 Gbit/s) 16-QAM signal were prepared from an IQ modulator and free-space collimators. Then they were converted to OAM beams with \( \ell = -8, +10, +12, \) and \(-14\), using four SLMs each loaded with a helical phase hologram, as shown in Fig. 10(a). After being coaxially multiplexed using cascaded 3 dB beam splitters, the beams propagate through \( \sim 1 \) m distance in free space under laboratory conditions. The OAM beams were then detected one at a time, using an inverse helical phase hologram and a fiber collimator together with an SMF. The 16-QAM data on each channel were successfully recovered, and a spectral efficiency of 12.8 bit/s/Hz in this data link was achieved, as shown in Figs. 10(b) and 10(c).

A following experiment doubled the spectral efficiency by adding polarization multiplexing into the OAM-multiplexed free-space data link. Four different OAM beams \( (\ell = +4, +8, -8, \) and \(+16\) on each of two orthogonal polarizations (eight channels in total) were used to achieve a terabit/second transmission link. The eight OAM beams were multiplexed and demultiplexed using the same approach as mentioned above. The measured crosstalk among channels carried by the eight OAM beams is shown in Table 1, with the largest crosstalk being about \(-18.5\) dB. Each of the beams was encoded with a 42.8 Gbaud 16-QAM signal, allowing a total capacity of \( \sim 1.4(42.8 \times 4 \times 4 \times 2) \) Tbit/s [6].

![Experimental results of a free-space optical data link multiplexed with four OAM beams. (a) Intensity profile of the four OAM beams generated \( (\ell = -8, +10, +12, \) and \(-14\) and their superposition. (b) The optical spectrum of each channel after demultiplexing. (c) The recovered constellations of the 16-QAM signals carried on each OAM beam. Reprinted with permission from [56]. Copyright 2011 Optical Society of America.](image-url)
The capacity of the free-space data link was further increased to 100 Tbit/s by combining OAM multiplexing with PDM and WDM [58]. In this experiment, 24 OAM beams ($\ell = \pm 4, \pm 7, \pm 10, \pm 13, \pm 16, \pm 19$, each with two polarizations) were prepared using two SLMs, the procedures for which are shown in Figs. 11(a1)–11(a3). Specifically, one SLM generated a superposition of OAM beams with $\ell = \pm 4, \pm 7, \pm 10$, while the other SLM generated another set of three OAM beams with $\ell = \pm 13, \pm 16, \pm 19$. These two outputs were multiplexed together using a beam splitter, thereby multiplexing six OAM beams: $\ell = \pm 4, \pm 7, \pm 10, \pm 13, \pm 16, \pm 19$. Second, the six multiplexed OAM beams were split into two copies. One copy was reflected five times by three mirrors and two beam splitters, to create another six OAM beams with inverse charges. A differential delay between the two light paths decorrelated their data. These two copies were then combined again to achieve 12 multiplexed OAM beams with $\ell = \pm 4, \pm 7, \pm 10, \pm 13, \pm 16, \pm 19$. These 12 OAM beams were split again via a beam splitter. One of these was polarization rotated by 90 deg, delayed by \( \sim 33 \) symbols, and then recombined with the other copy using a polarization beam splitter (PBS), finally multiplexing 24 OAM beams (with $\ell = \pm 4, \pm 7, \pm 10, \pm 13, \pm 16, \pm 19$ on two polarizations). Each beam carried a WDM signal comprising 100 GHz spaced 42 wavelengths (1536.34–1568.5 nm), each of which was modulated with 100 Gbit/s quadrature phase-shift keying (QPSK) data. The observed optical spectrum of the WDM signal carried on one of the demultiplexed OAM beams ($\ell = +10$) is shown in Fig. 11(b).

(a) Three steps to produce 24 multiplexed OAM beams using two SLMs, mirrors, beam splitters, a half-wave plate and a PBS. (b) The optical spectrum of the WDM signal carried on an OAM beam with $\ell = +10$. Reprinted with permission from [58]. Copyright 2014 Optical Society of America.

<table>
<thead>
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<th>Transmitted</th>
<th>$\ell = +4$</th>
<th>$\ell = +8$</th>
<th>$\ell = -8$</th>
<th>$\ell = +16$</th>
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<td>NA -23.2</td>
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<td>-26.7 -30.8</td>
<td>-30.5 -27.7 -24.6 -30.1</td>
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<tr>
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<td>-25.0 NA</td>
<td>-21.6 -25.4 -23.9 -28.8</td>
<td></td>
</tr>
<tr>
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<td>-27.6 -30.8 NA</td>
<td>-26.8 NA</td>
<td>-26.5 -21.6</td>
</tr>
<tr>
<td>$\ell = +16$</td>
<td>-24.5 -31.2</td>
<td>-23.7 -23.3</td>
<td>-25.8 -26.1 NA</td>
<td>-24.0 NA</td>
</tr>
<tr>
<td>Total from other OAM beams</td>
<td>-21.8 -21.0</td>
<td>-21.2 -21.4</td>
<td>-18.5 -21.2</td>
<td>-22.2 -20.7</td>
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</table>
5.2. Atmospheric Turbulence Effects on OAM Beams

One of the critical challenges for a practical free-space optical communication system using OAM multiplexing is atmospheric turbulence [62,63]. It is known that inhomogeneities in the temperature and pressure of the atmosphere lead to random variations in the refractive index along the transmission path, and can easily distort the phase front of a light beam [64,65]. This could be particularly important for OAM communications, since the separation of multiplexed OAM beams relies on the helical phase front. As predicted by simulations in the literature, these refractive index inhomogeneities may cause intermodal crosstalk among data channels with different OAM states [66–68].

The effect of atmospheric turbulence was also experimentally evaluated. For the convenience of estimating the turbulence strength, one approach was to emulate the turbulence in the laboratory by using an SLM or a rotating phase plate [69,70]. Figure 12(a) illustrates the concept of an emulator built using a thin phase screen plate that is mounted on a rotation stage and placed in the middle of the optical path. The pseudorandom phase distribution machined on the plate obeys Kolmogorov spectrum statistics, which are usually characterized by an effective Fried coherence length $r_0$ [71,72]. The strength of the simulated turbulence can be varied either by using a plate with a different $r_0$, or by adjusting the size of the beam that is incident on the plate. The resultant turbulence effect is mainly evaluated by measuring the power of the distorted beam distributed to each OAM mode using an OAM mode sorter. It was found that, as the turbulence strength increases, the power of the transmitted OAM mode starts to leak to neighboring modes and tends to be equally distributed among modes for strong turbulence. As an example, Fig. 12(b) shows the measured average power (normalized) of $l = +3$ beam under different emulated turbulence conditions. It can be seen that the majority of the power is still in the transmitted OAM mode under weak turbulence, but it spreads to neighboring modes as the turbulence strength increases.

5.3. Turbulence Effects Mitigation Techniques

One possible approach to mitigate the effects of atmospheric turbulence on OAM beams is to use an adaptive optical (AO) system. The general idea of an AO system is to measure the phase front of the distorted beam first, based on which an error correction pattern is produced and applied onto the beam to undo the distortion. As

![Figure 12](image-url)

(a) A rotating phase plate is used as an atmospheric turbulence emulator. An ideal OAM beam emerges as a distorted OAM after passing through the phase plate. (b) Measured power distribution of an OAM beam after passing through the turbulence emulator with different strengths. Reprinted with permission from [70]. Copyright 2013 Optical Society of America.
for OAM beams with helical phase fronts, it is challenging to directly measure the phase front using typical wavefront sensors due to the phase singularity. A modified AO system can overcome this problem by sending a Gaussian beam as a probe beam to sense the distortion [73], as shown in Fig. 13(a). Due to the fact that turbulence effects are almost independent of the light polarization [64], the probe beam is orthogonally polarized as compared to all of the other beams so that it is convenient to separate it at the receiver end. The correction phase pattern can be derived based on the probe beam distortion, which is directly measured by a wavefront sensor. It is noted that this phase correction pattern can be used to simultaneously compensate multiple coaxially propagating OAM beams. Figures 13(b1)–13(b3) and 13(b4)–13(b6) illustrate the intensity profiles of OAM beams with \( \ell = +1, +5, \) and \( +9, \) respectively, for a random turbulence realization with and without mitigation. From the far-field images, one can see that the distorted OAM beams (upper), up to \( \ell = +9, \) were partially corrected, and the measured power distribution also indicates that the channel crosstalk can be reduced.

As an alternative approach for combating turbulence effects, one could partially move the complexity of the optical setup into the electrical domain, and use digital signal processing (DSP) to mitigate the channel crosstalk. A typical DSP method is blind multiple-input–multiple-output (MIMO) equalization, which is able to blindly estimate the channel crosstalk and cancel the interference [74]. The implementation of a \( 4 \times 4 \) adaptive MIMO equalizer in a four-channel OAM multiplexed free-space optical link using heterodyne detection was described in [75]. Four OAM beams \( (\ell = +2, +4, +6, \) and \( +8, \) each carrying 20 Gbit/s QPSK data, are collinearly multiplexed and propagated through weak turbulence emulated by the rotating phase plate under laboratory conditions. After demultiplexing, four channels are coherently detected and recorded simultaneously. The standard constant modulus algorithm [76] is employed in addition to the standard procedures of coherent detection to equalize the channel interference. Results indicate that MIMO equalization could be helpful to mitigate the crosstalk caused by either turbulence or imperfect mode generation/detection, and to improve both

![Figure 13](image)

A feedback loop including a wavefront sensor and a wavefront corrector can be used to partially compensate the turbulence-induced distortions. (a) Concept of feedback loop of the wavefront compensator. (b) Experimental results of the wavefront compensation. (b1)–(b3) Distorted OAM beams with \( \ell = +1, +5, \) and \( +9. \) (b4)–(b6) Distortion mitigation using adaptive optics. Reprinted with permission from [73]. Copyright 2014 Optical Society of America.
the error vector magnitude (EVM) and the bit-error rate (BER) of the signal in an OAM-multiplexed communication link. It should be noted that MIMO DSP is not universally useful, as outage could happen in some scenarios involving free-space data links. For example, most of the power of the transmitted OAM beams may be transferred to other OAM states under strong turbulence without being detected, in which case MIMO would not help to improve system performance.\[77\].

5.4. OAM Free-Space Link Design Considerations

To date, many of the experimental demonstrations of optical communication links using OAM beams have taken place under laboratory conditions. Due to the unique beam profile of OAM beams, challenges exist for designing a free-space optical communication link with a longer distance. Several important issues, such as beam divergence, aperture size, and misalignment of transmitter and receiver, need to be carefully considered. To study how those parameters affect the performance of an OAM multiplexed system, a simulation model was described by Xie et al.\[78\], the schematic setup of which is shown in Fig. 14. Different collimated data-carrying Gaussian beams having the same wavelength are followed by SPPs with a unique order to convert the Gaussian beam into a data-carrying OAM beam. Different orders of OAM beams are then multiplexed to form concentric rings and coaxially propagate through free space to the receiver aperture located at a certain propagation distance. Propagation of multiplexed OAM beams is numerically calculated using the Kirchhoff–Fresnel diffraction integral.\[79\]. To investigate the signal power and crosstalk effects on neighboring OAM channels, power distribution among different OAM modes is analyzed through a modal decomposition approach, which corresponds to the case where the received OAM beams are demultiplexed without power loss and the power of a desired OAM channel is completely collected by its receiver.\[80\].

5.4a. Beam Divergence

For a communication link, it is generally preferred to collect as much signal power as possible at the receiver to ensure a sufficient signal-to-noise ratio (SNR). Based on diffraction theory, it is known that a collimated OAM beam diverges while propagating in free space. Given the same spot size of 3 cm at the transmitter (here the spot size of the OAM beam is defined based on the intensity profile), an OAM beam with a higher azimuthal index diverges even faster, as shown in Fig. 15(a). Besides the index \( \ell \), the received beam size is also related to the beam waist size at the
transmitter, wavelength $\lambda$, and propagation distance $z$ [82]. Figure 15(b) shows the spot size of different OAM beams at the receiver as a function of the transmitted beam sizes over a 100 m link. Clearly, the received beam size is not a monotonic function of the beam size at the transmitter. For each OAM beam, there is a transmitter beam size that corresponds to a minimum value of diffraction-limited radius after propagating for 100 m. On the other hand, the receiving optical element usually has a limited aperture size and may not be able to collect all of the beam power. Note that for each individual OAM mode, there is a minimum requirement of the received power, which is mainly related to two factors. (a) The sensitivity of the receiver: the receiver needs to receive enough power to guarantee a sufficient SNR. (b) The crosstalk from all of the other modes: the receiver needs to receive enough power in the desired mode to guarantee a sufficient signal-to-interference ratio [83]. The calculated link power loss as a function of receiver aperture size is shown in Fig. 15(c), with different transmission distances and various transmitted beam sizes. As expected, the power loss of a 1 km link is higher than that of a 100 m link for the same transmitted beam size due to the larger beam divergence. It is interesting to note that a system with a transmitted beam size of 3 cm suffers less power loss than that of 1 and 10 cm over a 100 m link. The 1 cm transmitted beam diverges faster than the 3 cm due to its larger diffraction. However, when the transmitted beam size is 10 cm, the geometrical characteristics of the beam dominate over the diffraction, thus leading to a spot size at the receiver larger than that of the 3 cm transmitted beam. A trade-off between the diffraction and geometrical characteristics of the beam therefore needs to be carefully considered in order to achieve a proper size received beam when designing a link.

5.4b. Misalignment Tolerance

Besides the power loss due to a limited size aperture and beam divergence, another issue that needs further discussion is the potential misalignment between the transmitter and the receiver, which can lead to both power loss and modal crosstalk. In an ideal OAM multiplexed communication link, the transmitter and receiver are perfectly aligned.

Figure 15

Simulation results. (a) Simulated spot size (diameter) of different orders of OAM beams as a function of transmission distance when the spot size of the transmitted beam is 3 cm. (b) Simulated spot size of different orders of OAM beams as a function of the transmitted beam size for a 100 m link. (c) Simulated power loss as a function of aperture size when only $\ell = +3$ beam is transmitted; $D_t$, transmitted beam size. © 2014 IEEE. Reprinted, with permission, from Xie et al., IEEE Globecom 2014, Optical Wireless Communication Workshop (2014) [78].
and receiver would be perfectly aligned (i.e., the center of the receiver would overlap with the center of the transmitted beam, and the receiver plane would be perpendicular to the line connecting their centers, as shown in Fig. 16(a)). However, due to jitter and vibration of the transmitter/receiver platform, the transmitter and receiver may have relative lateral shift (i.e., lateral displacement) or angular shift (i.e., receiver angular error), as depicted in Figs. 16(b) and 16(c), respectively [84]. Both types of misalignment may lead to degradation of system performance.

For a link distance of 100 m, Figs. 17(a) and 17(b) show the power distribution among different OAM modes due to lateral displacement and receiver angular error when only $\ell = +3$ is transmitted with a transmitted beam size of 3 cm. In order to investigate the effect of misalignment, the receiver aperture size is chosen to be 4.5 cm, which could cover the whole OAM beam at the receiver. As the lateral displacement or receiver angular error increases, power leakage to other modes (i.e., channel crosstalk) increases while the power on $\ell = +3$ state decreases. This is because larger lateral displacement or receiver angular error causes a larger phase profile mismatch between the received OAM beams and receiver. The power leakage to $\ell = +1$ and $\ell = +5$ is smaller than that of $\ell = +2$ and $\ell = +4$ due to their larger mode spacing with respect to $\ell = +3$. Therefore, a system with larger mode spacing (which also uses higher order OAM states) has less crosstalk. However, such a system may also have a larger power loss due to the fast divergence of higher order OAM beams, as discussed above. Clearly, this trade-off between channel crosstalk and power loss shall be considered when choosing the mode spacing in a specific OAM multiplexed link.

To show the angular error lateral shift effects under different propagation distances, the ratio of the received power on OAM+4 to the received power on OAM+3 when only OAM+3 is transmitted is analyzed as an example [78]. For simplicity, such a ratio is named XT-1. Figures 17(c) and 17(d) show XT-1 as functions of lateral displacement and receiver angular error for various transmission distances and transmitted beam sizes. As can be seen from the figure, a larger beam size at the receiver will result in two opposing effects: (i) a smaller lateral-displacement-induced crosstalk (because the differential phase-change per unit area is smaller) and (ii) a larger tilt-phase-error-induced crosstalk (because the phase error scales with a larger optical path delay).

**Figure 16**

Three different cases of alignment between the transmitter and receiver: (a) a perfectly aligned system, (b) a system with lateral displacement, and (c) a system with receiver angular error. Tx, transmitter; Rx, receiver; $z$, transmission distance; $d$, displacement; $\phi$, angular error. © 2014 IEEE. Reprinted, with permission, from Xie et al., IEEE Globecom 2014, Optical Wireless Communication Workshop (2014) [78].
5.5. Longer Distance OAM Beam Propagation in Free Space

In addition to simulation studies, experimental demonstrations of OAM beams propagating over longer distances has also been reported [60]. In this experiment, multiplexed OAM beams were used to transfer information over a 3 km intracity link in Vienna under a strong turbulence condition. As shown in Fig. 18, from the top of widely spaced buildings in Vienna, the Austrian group transmitted data bits representing a gray-scale image of Mozart such that each image pixel was sequentially transmitted on one of 16 different OAM modes ($\ell = 0, \pm 1, \ldots, \pm 15$). Each OAM mode is carried by a light beam at a wavelength of 532 nm. An incoherent detection scheme is used by directly observing the unambiguous mode-intensity patterns on a screen with the help of a standard adaptive pattern recognition algorithm, and indeed, the image of the treasured composer was successfully recovered, with an average error rate of $\sim 1.7\%$.

6. Optical Fiber Communications Using OAM Multiplexing

Optical fiber forms the worldwide backbone of high-capacity wired communications. Therefore, it is valuable to determine the feasibility and practicality of employing OAM in fiber [85]. OAM modes are essentially a group of higher order modes defined on a different basis as compared to the other forms of modes in fiber, such as linearly polarized (LP) modes and fiber vector modes. In principle, each of the modal sets forms an orthogonal mode basis spanning the spatial domain, and could be used to transmit different data channels. Both LP modes and OAM modes face challenges of mode coupling when propagating in a fiber, and may also cause channel crosstalk problems.

In general, two approaches could be utilized in fiber transmission using OAM multiplexing. The first such approach is to implement OAM transmission in a regular few-mode fiber (FMF). As is the case of SDM using LP modes, MIMO...
DSP is generally required to equalize the modal crosstalk. The second approach is to utilize a specially designed vortex fiber that has less mode coupling, and DSP equalization can therefore be avoided for a relatively short transmission distance.

### 6.1. OAM Transmission in Regular Few-Mode Fiber

In light of MDM in FMFs, LP modes have been used to achieve impressive results [1,2]. However, it might be valuable to explore different forms of mode basis that could exist in FMFs. In a regular FMF, each OAM mode represents approximately a linear combination of the true fiber modes (the eigensolutions to the wave equation in the fiber). For example, an LP OAM beam with \( \ell = \pm 1 \) comprises the components of eigenmodes including \( \text{TE}_{01}, \text{TM}_{01} \), and the two \( \text{HE}_{21} \) modes. Due to perturbations or other nonidealities, the OAM modes that are launched into a FMF may quickly couple to each other, and this mutual mode coupling may lead to interchannel crosstalk and eventually failure of the transmission. One possible solution for the mode coupling effects is to use MIMO DSP in combination with coherent detection.

A recent experiment demonstrated the transmission of four OAM beams (\( \ell = +1 \) and \( -1 \), each with two orthogonal polarization states), each carrying 20 Gbit/s QPSK data, in an \( \sim 5 \) km regular FMF [53]. As shown in Fig. 19(a), four data channels (two with \( x \) polarization and two with \( y \) polarization) were converted to polarization multiplexed OAM beams with \( \ell = +1 \) and \( -1 \) using a mode sorter (discussed in Section 4.2b) in the reverse direction. The two polarization multiplexed OAM beams (four in total) were coupled into the FMF for propagation. At the fiber output, the received modes were decomposed into an
Data transmission experiment using OAM multiplexing over a 5 km FMF. MIMO DSP was used to mitigate the mode coupling effects. (a) Schematic setup of the data transmission experiment. (b1)–(b8) Recovered constellations of a 20 Gbit/s QPSK signal carried on each OAM beam (top, without MIMO DSP; bottom, with MIMO DSP). (c) Measured BER curves. Reprinted with permission from [53]. Copyright 2014 Optical Society of America.

OAM mode basis ($\ell = +1$ and $-1$) using another mode sorter. Then each of the two OAM components of light was coupled into a fiber-based PBS for polarization demultiplexing. Each output was detected by a photodiode, followed by an analog-to-digital converter and offline processing. To mitigate the interchannel interference, the constant modulus algorithm was used to blindly estimate the channel crosstalk and compensate for it using linear equalization. Eventually, the QPSK data carried on each OAM beam was recovered with the assistance of MIMO DSP, as shown in Figs. 19(b) and 19(c).

### 6.2. OAM Transmission in a Vortex Fiber

The major reason for power exchange (i.e., coupling) between two modes during transmission through a conventional fiber is the relatively small difference between their effective refractive indices ($\Delta n_{\text{eff}}$) [86]. By modifying the fiber refractive index profile, mode coupling can be reduced, thereby simplifying the receiver by avoiding MIMO DSP [87]. Recently, a specially designed FMF was demonstrated (i.e., a vortex fiber), with an additional high index ring around the fiber core, as shown in Figs. 20(a) and 20(b) [7]. This design leads to an increase in the effective index differences among the modes and, therefore, reduces the mutual mode coupling. Using this vortex fiber, two OAM modes with $\ell = +1$ and $-1$, and two polarization multiplexed fundamental modes were coupled into the vortex fiber with an insertion loss of $<2$ dB. Each of the four distinct modes carried a 50 Gbaud QPSK signal at the same wavelength and simultaneously propagated in the vortex fiber. After simultaneous propagation through a 1.1 km vortex fiber, the measured mode crosstalk between two OAM modes was approximately $-20$ dB, and all of the data could be recovered, with a power
penalty of $\sim 4.1$ dB. The power penalty could be attributed to the multipath effects and mode crosstalk. In another experiment, WDM was added to further extend the capacity of the vortex fiber transmission system. A 20-channel fiber link using two OAM modes and 10 WDM channels (from 1546.64 to 1553.88 nm), each channel carrying a 80 Gbit/s 16-QAM signal, was demonstrated, resulting in a total transmission capacity of 1.6 Tbit/s.

6.3. Other Novel Fibers for OAM

Innovative efforts are also being made to design and fabricate fibers that are more suitable for OAM multiplexing. A recently reported air-core fiber has been demonstrated to further increase the refractive index difference of eigenmodes such that the fiber is able to stably transmit 12 OAM states ($\ell = \pm 5, \pm 6$, and $\pm 7$, each with two orthogonal polarizations) over 10 m, of which eight of these states remained low loss enough to enable km-length propagation with greater than 98% purity [88]. Ung et al. [89] designed a FMF with an inverse parabolic graded index profile, in which the transmission of eight OAM orders ($\ell = \pm 1$ and $\pm 2$, each with two orthogonal polarizations) over 1 m was demonstrated. The same group recently presented a newer design of an air-core fiber, whereby the supported OAM states could potentially be increased to 16 [90]. One possible design that can further increase the supported OAM modes in a fiber is to use multiple-ring structure, as predicted by numerical simulations [91,92]. All of these reports indicate good prospects for OAM multiplexing for fiber communications, and further details on the prospects of scalability of OAM in fibers is discussed in [93].

7. OAM-Based Networking Functions

In general, networking functions (e.g., data switching and add/drop multiplexing) are quite useful in multi-channel, high-performance communication networks for...
which a user at an intermediate point may want to switch, reroute, or access an individual orthogonal channel without disturbing/detecting the nonselected channels. This is common in efficient time-multiplexed and wavelength-multiplexed networks that share the same transmission medium. For example, any channel may be selectively rerouted or dropped without affecting the other channels. Such an all-optical routing or add/drop function has been demonstrated in the wavelength domain to great advantage. Given the present interest in OAM-based transmission channels, it might be desirable to individually route/switch/drop channels in the spatial domain by taking advantage of the beam structure and orthogonality among different OAM modes. The above functionality might increase the use of OAM beyond static point-to-point links. For example, by using reconfigurable SLMs to manipulate the phase of the OAM beams, the unique wavefront structure of an OAM beams could be dynamically modified to enable some networking functions. In this section, we describe some networking functions that were implemented with the aid of OAM beams.

7.1. Data Swapping

Data exchange could be a useful function in an OAM-based communications system. A pair of data channels carried on different OAM states can exchange their data in a simple way with the assistance of a reflective phase hologram, as shown in Fig. 21. If two OAM beams, e.g., OAM beams with $\ell = +\ell_1$ and $+\ell_2$, which carry two independent data streams, are launched onto a reflective SLM loaded with a spiral phase pattern with an order of $-(\ell_1 + \ell_2)$, the data streams will swap between the two OAM channels. Obviously, the phase profile of the SLM will change these two OAM beams to $\ell = -\ell_2$ and $\ell = -\ell_1$, respectively. In addition, each OAM beam will be changed to its opposite charge under the reflection effect. As a result, the channel on $\ell = +\ell_1$ is switched to $\ell = +\ell_2$, and vice versa, which indicates that the data on the two OAM channels are exchanged. As an example, Fig. 21 shows the data exchange between $\ell = +6$ and $\ell = +8$ using a phase pattern in the order of $\ell = -14$ on a reflective SLM. A power penalty of $\sim 0.9$ dB is observed when demonstrating this in the experiment [6,94].

A recent experiment further demonstrated that the selective data swapping function can handle more than two channels [95]. Among multiple multiplexed OAM beams, any two OAM beams can be selected to swap their data without affecting the other channels.

Figure 21

Concept of data exchanging between two channels carried on different OAM states. Reprinted with permission from [94]. Copyright 2013 Optical Society of America.
7.2. Reconfigurable Optical Add/Drop Multiplexer

In general, reconfigurable optical add/drop multiplexers (ROADMs) are important function blocks in WDM networks [96]. A WDM ROADM is able to selectively drop a given wavelength channel and add in a different data channel at the same wavelength, without having to detect all pass-through channels. A similar scheme can be implemented in an OAM-multiplexed system to selectively drop and add a data channel carried on a given OAM beam. One approach to achieve this function is based on the fact that OAM beams generally have a distinct intensity profile when compared to a fundamental Gaussian beam. A proof-of-concept experiment using SLMs and spatial filters is shown in Fig. 22(a) [97]. The principle of an OAM-based ROADM could be explained in three steps: downconversion, add/drop, and upconversion. The downconversion refers to transforming an OAM beam (a doughnut-like transverse intensity profile) into a Gaussian-like beam with $\ell = 0$ (a spot-like transverse intensity profile). After the downconversion, only the selected OAM beam becomes a Gaussian beam, while the other beams remain OAM but have a different $\ell$ state. The downconverted beams are then reflected by a specially designed phase pattern that has different gratings in the center and in the outer ring region. The central and outer regions are used to redirect the Gaussian beam in the center (containing the drop channel) and the OAM beams with ring shapes (containing the pass-through channels) in different directions. Meanwhile, another Gaussian beam carrying a new data stream can be added to the pass-through OAM beams (i.e., add channel). Following this selective manipulation, an upconversion process (the inverse of the downconversion) is applied to recover the $\ell$ states of all the beams. Figures 22(b1)–22(b6) show the images of each step in the add/drop of a channel carried by an OAM beam with $\ell = +2$.

Some other networking functions in OAM-based systems have also been demonstrated. These include multicasting [98], $2 \times 2$ switching [99], polarization switching [100], and mode filtering [52].

8. Quantum Information Distribution Using OAM

Although the focus of this paper pertains to OAM applications in classical communications, it should be briefly noted that OAM can be carried by an individual photon and has a potential role in the development of secure quantum communications [101,102]. One of the examples is high-dimensional quantum key...
distribution (QKD) \[103,104\]. QKD involves encoding information in quantum states and sharing them between two parties. QKD systems have conventionally utilized the polarization or phase of light for encoding. The original proposal for QKD (i.e., the BB84 protocol of Bennet and Brassard) encodes information on the polarization states and so can allow only one bit of information to be encoded onto each photon \[105,106\]. There may be benefits to OAM-based QKD systems given that OAM states reside in an infinite dimensional Hilbert space, and there is a possibility of encoding multiple bits of information on an individual photon. Similar to the use of OAM multiplexing in classical optical communications, the secure key rate may be further increased if simultaneous encoding of information in different domains is implemented by using high-dimensional entanglement.

Previous investigations of the QKD system using OAM states can be found in both theoretical analysis and experimental demonstration, including (a) the secure information capacity as well as security analysis of a high-dimensional OAM-based QKD system \[104,106,107\], (b) high-dimensional OAM entanglement of photon pairs \[101,108,109\], (c) a 210 m QKD link using rotation-invariant OAM vector modes \[110\], and (d) principle-of-concept demonstration of a seven-dimensional QKD link based on OAM encoding \[111\], the concept of which is illustrated in Fig. 23(a). Figure 23(b) shows the two complementary seven-dimensional bases used for information encoding.

Achieving OAM-based QKD systems with a high secure key rate still faces technical challenges. It is beyond the scope of this paper to discuss those, and we refer the reader to the following references for more detail \[11,44,50,112–114\].

9. RF Communications Using OAM

OAM is a fundamental property of electromagnetic waves – not just light – and thus can be employed for OAM multiplexing in all frequency ranges.
Specifically, OAM can also be carried by waves with either short wavelengths (e.g., x rays \([115]\)), or long wavelengths (millimeter waves \([116]\) and terahertz waves \([117]\)). In the RF regime, OAM beams at 90 GHz were initially generated using a SPP made of Teflon \([116]\). Different approaches, such as a phase array antenna \([118]\) and a helicoidal parabolic antenna \([119]\) were proposed later. RF OAM beams were also used as data carriers for RF communications, as reported by Tamburini et al. \([120]\). A Gaussian beam and an OAM beam with \(\ell = +1\) at \(\sim 2.4\) GHz were each transmitted by a Yagi–Uda antenna and a spiral parabolic antenna, respectively, which were placed in parallel. These two beams were distinguished by the differential output of a pair of antennas at the receiver side. In a later experiment, the number of channels was increased to three (carried on OAM beams with \(\ell = -1, 0,\) and \(+1\)) using a similar apparatus to send an \(\sim 11\) Mbit/s signal on an \(\sim 17\) GHz carrier \([120]\). Note that, in these two demonstrations, different OAM beams propagated along different spatial routes.

In a recent demonstration as described by Yan et al. \([121]\), eight polarization multiplexed RF OAM beams (four OAM beams on each of two orthogonal polarizations) were coaxially propagated through a 2.5 m free-space link. The four different OAM beams with \(\ell = -3, -1, +1,\) and \(+3\) on each of two orthogonal polarizations were generated using SPPs. The observed intensity profile for each of the beams and their interferograms are shown in Fig. 24(a). Then these OAM beams were coaxially multiplexed using specially designed beam splitters. After propagation, the OAM channels were demultiplexed using an inverse SPP and a spatial filter (the receiver antenna). The measured crosstalk at 28 GHz for each of the demultiplexed channels is shown in Fig. 24(b). It can be seen that the crosstalk is low enough for 16-QAM data transmission without the assistance of extra DSP to reduce the intermodal interference.

Considering that each beam carries a 1 Gbaud 16-QAM signal, a total link capacity of 32 Gbit/s at a carrier frequency of 28 GHz and a spectral efficiency of 16 Gbit/s/Hz was achieved. As an example, the recovered signal constellations of the data carried on two polarizations of the \(\ell = +3\) beam are shown in Fig. 24(c).

### 10. Perspectives

The concept that beams with helical phase dependence carry OAM has been discovered relatively recently, and applications of OAM in communication systems still represent a young subfield that has a rich set of issues to explore, including potential opportunities and technical challenges. It is worth making note of a few key issues.

First, in its fundamental form, a beam carrying OAM has a helical phase front with a twisting speed that depends on the mode number, such that beams with different mode numbers are orthogonal and, hence, distinguishable from other OAM states. Although other mode groups (e.g., Hermite–Gaussian modes) also have orthogonality and can be used for mode multiplexing, OAM has the possible advantage of its circular symmetry. Indeed, many free-space data link demonstrations attempt to use OAM-carrying modes since such modes have circular symmetry and tend to be compatible with commercially available optical components. Therefore, one can consider that OAM is used more as a technical convenience for efficient multiplexing than as a necessarily “better” type of modal set.
Second, many of the demonstrated communication systems with OAM multiplexing use bulky and expensive components that are not necessarily optimized for OAM operation. As was the case for many previous advances in optical communications, the future of OAM deployment would greatly benefit from advances in the enabling devices and subsystems (e.g., transmitters, (de)multiplexers, and receivers). Particularly with regard to integration, this represents significant opportunity to reduce cost and size and to also increase performance.

Finally, it should be noted that OAM has other applications besides communications, including micromanipulation and imaging [122, 123]. Although the field of OAM is young and challenges remain, the general prospects are indeed exciting.

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References


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Solyman Ashrafi is a technology entrepreneur with over 25 years of technology/product development expertise. He was previously leading the social, messaging, digital media (music and video), financial services, advertising, and Rich Communications Services (RCS) product teams at metroPCS (a multibillion dollar Fortune 500 public wireless company in Richardson, Texas). He was responsible for all product partnerships with telecom operators, internet companies, advertising agencies, video/music content providers, search companies, app developers, and OTTs. He was also the lead to combine social and telephony graphs to achieve improved User Experience (UX) and advertising. At metroPCS, Dr. Ashrafi was also driving a coherent portfolio of more than 50 products/services with optimal distribution of investments in each. He was responsible for launching the first 4G LTE service in 2010 and in late 2012 made metroPCS to be the first carrier in the world to offer Rich Communication Services (RCS) and VOLTE with a 4G LTE smart phone. After the merger of metroPCS and T-Mobile, he was responsible for integrating the two product management groups for the combined companies. Prior to metroPCS, he designed and built telecom networks for major operators in the U.S. and Europe and held executive positions at Nortel, Ericsson, LCC, and CSC. During his career, Dr. Ashrafi raised money from multiple funds and launched a number of venture-backed companies in software, technology, and cloud-based applications. He was the stakeholder Board member of a Richardson-based incubator for Nortel in 1997 and a Richardson-based accelerator for Ericsson in 1999 for their investment in new technology companies. He initiated a new program called Quantum Layer Multiplexing (QLM) in 2013 for next generation broadband to disrupt access in telecom and achieve much higher spectral efficiencies using higher order modulation, as well as new photon orbital angular momentum modes for multiplexing. He received a Ph.D. in Applied Physics, a MEE in Communications Engineering, a M.SC. in Wave Propagation, and a BEE degree in Electrical Engineering.