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A Review on Orbital Angular Momentum (OAM) Beams: Fundamental Concepts, Potential Applications, and Perspectives

Anastasios Papathanasopoulos(1), and Yahya Rahmat-Samii*(1)
(1) University of California, Los Angeles, CA, 90095, USA

Abstract

Inspired by the recent scientific interest in harnessing the unique features of orbital angular momentum (OAM) for communications applications, we review the fundamental properties of OAM, summarize the methods for the generation of OAM beams, discuss potential applications, and pinpoint technical challenges of OAM-based communications.

1 Introduction

Since the discovery that helically-phased beams carry OAM in 1992 by Allen [1], OAM has leaped to the forefront of communications research. A chronicle of milestones regarding the OAM research progress is shown in table 1. OAM-carrying beams provide a complete orthogonal modal basis set that can potentially be employed for multiplexing different signals, thus potentially greatly improving the spectral efficiency of communication systems [2–5]. However, the practical deployment of OAM communication links is still debated by many researchers; the OAM beam inherently diverges with propagating distance and the requirement to collect enough power of the divergent OAM beam with a very large aperture significantly limits the achievable distance of OAM communications [6, 7]. The OAM beam divergence may be advantageous for applications that require cone-shaped patterns, such as vehicle-to-satellite communication systems [8]. Driven by the recent scientific interest and research on OAM communications, we describe the unique properties of OAM beams and discuss several methods and devices for the generation of OAM beams. Subsequently, we review potential applications of OAM in communications and discuss technical challenges of OAM-based communications.

2 OAM Fundamental Properties

OAM-carrying beams exhibit two fundamental properties: (i) the *orthogonality* of different OAM modes and (ii) the OAM beam *divergence*. These two properties are the very reason for the recent aroused scientific interest in the potential of harnessing OAM for communications. As we will discuss in section 4, multiple orthogonal OAM modes can be used as independent data carriers for multiplexing and transmitting multiple data streams, thereby potentially

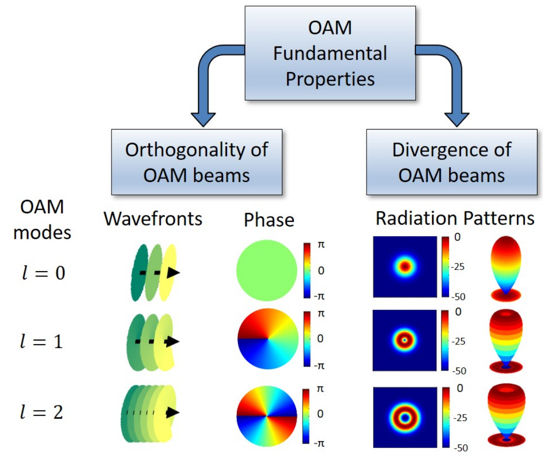

Figure 1. Two fundamental properties of OAM beams.

increasing the capacity and spectral efficiency of wireless communication links [11]. To date, experiments that employ OAM for communications have been mainly limited to near-field distances [12–14], with potential applications, for example, in short range, high-speed wireless information exchange in data centres [14]. The beam divergence, which manifests itself as a cone-shaped radiation pattern in the far-field, can be advantageous for applications such as satellite-based navigation and guidance systems that serve moving vehicles [8], but may also pose a challenge for long-distance communication links [6, 7]. OAM has also found applications outside the field of wireless communications, such as optical particle manipulation and optical and radar imaging [4].

2.1 Orthogonality

There exist several subsets of OAM-carrying beams, including Laguerre-Gaussian [1], Bessel-Gaussian [8], amongst others. In general, the electric field of an OAM-carrying beam with circular symmetry can be written as:

$$E(\rho,\phi,z) = A(\rho,z)e^{jl\phi} \tag{1}$$

where l is the OAM mode number, $j=\sqrt{-1}$ is the imaginary unit, ρ is the radial distance, ϕ is the azimuthal angle, and z is the propagation distance in the cylindrical coordinate system. $A(\rho,z)$ is a term that is different for each

Reference	Year	Main Contribution
[1]	1992	Recognized that light beams with an azimuthal phase dependence of $e^{jl\phi}$ carry OAM
[9]	2004	Conducted the first experiment on OAM free-space optical communications
[10]	2007	Numerically showed that OAM can be used in the radio frequency domain
[11]	2012	Performed the first OAM-based experiment of encoding multiple channels on the same radio frequency
[8]	2018	Suggested a potential application that takes advantage of the OAM cone-shaped pattern in the far-field

Table 1. Chronicle of milestones regarding OAM

subset of OAM beams. The azimuthal phase term $e^{jl\phi}$ gives rise to a spiral wavefront, as shown in Fig. 1. The phase twists around the beam axis and changes $2\pi l$ after a full turn. If we consider the electric fields $E_1(\rho,\phi,z)$, $E_2(\rho,\phi,z)$ of two OAM beams with modes l_1, l_2, and terms $A_1(\rho,z)$, $A_2(\rho,z)$, the following orthogonality relation is satisfied [2]:

$$\int_0^{2\pi} E_1(\rho,\phi,z)E_2^*(\rho,\phi,z)d\phi = \begin{cases} 0 & \text{, if } l_1 \neq l_2 \\ A_1(\rho,z)A_2^*(\rho,z), & \text{if } l_1 = l_2 \end{cases} \tag{2}$$

where the asterisk (*) denotes the complex conjugate. That is, OAM beams form an infinitely countable set of orthogonal modes.

2.2 Divergence

The far-field signature of the vortex phase is a cone-shaped pattern with an amplitude null at the vortex center. The null size can be described in terms of a divergence angle, which represents the angle from the null to the maximum gain. The radiation patterns of the Laguerre-Gaussian modes $l = 0,1,2$ are shown in Fig. 1. Laguerre-Gaussian beams are shown because they are one of the most popular example of OAM-carrying beams (see, for example, [1, 8, 9]), and a general OAM-carrying beam can be expanded in a complete basis of Laguerre-Gaussian modes [2, 15]. The null size of increases for larger modes and higher-order modes diverge more rapidly with propagating distance.

3 Generation

The generation of OAM-carrying beams necessitates the design of antennas that can generate the vortex aperture phase and spiral wavefront that are associated with OAM beams. Various designs have been developed for this purpose that operate in the radio frequency domain, including helicoidal parabolic antennas [11], reflectarrays [8], transmitarrays [16], stepped spiral reflecting surfaces [17], circular phased arrays [18], and spiral phase plates (SPPs) [19], as shown in Fig. 2. The previous designs can generate single-mode OAM beams [11, 17, 19], superposition of OAM modes, i.e. mixed-mode OAM beams [8, 16], and mode-reconfigurable OAM beams [18]. Several techniques

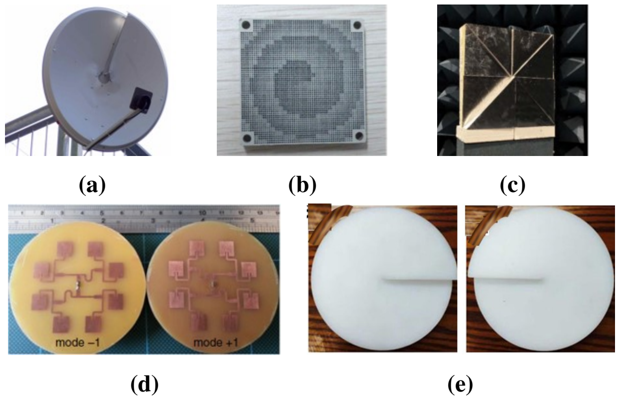

Figure 2. Devices for the generation of OAM beams: (a) Helicoidal parabolic antenna [11]. (b) Planar-spiral phase plate (SPP)/transmit-array [16]. (c) Stepped spiral reflecting surface [17]. (d) Circular phased array [18]. (e) Spiral phase plates (SPPs) [19].

have also been developed to generate OAM beams at optical frequencies, such as holographic gratings, spatial light modulators, plasmonic metasurfaces, and holograms (see, for example, [4, 8], and the references therein).

4 Emerging Applications

4.1 Vehicle-to-Satellite Communications

Inspired by the two unique features of OAM beams, namely the orthogonality and divergence, recent works have discussed potential applications of OAM beams in communication systems. The first application that may take advantage of the OAM cone-shaped pattern is the local satellite-based navigation and guidance system that serves moving vehicles. For such an application, the satellite is usually placed in a geostationary orbit. For uninterrupted vehicle-to-satellite communication, a circularly-polarized antenna with a beam that scans a cone in space is mounted on the moving vehicle to maintain the same directivity level in the direction of the satellite regardless of the orientation of the vehicle [8]. This approach requires the knowledge of the satellite's location and increases the antenna cost and complexity. An alternative approach is an antenna with a cone-shaped pattern, with the peak of the cone pointing towards the satellite, as shown in Fig. 3. An OAM antenna is a powerful apparatus that can systematically generate a cone-shaped pattern [8]. To maintain the desired communication link, attention needs to be given to the frequency of oper-

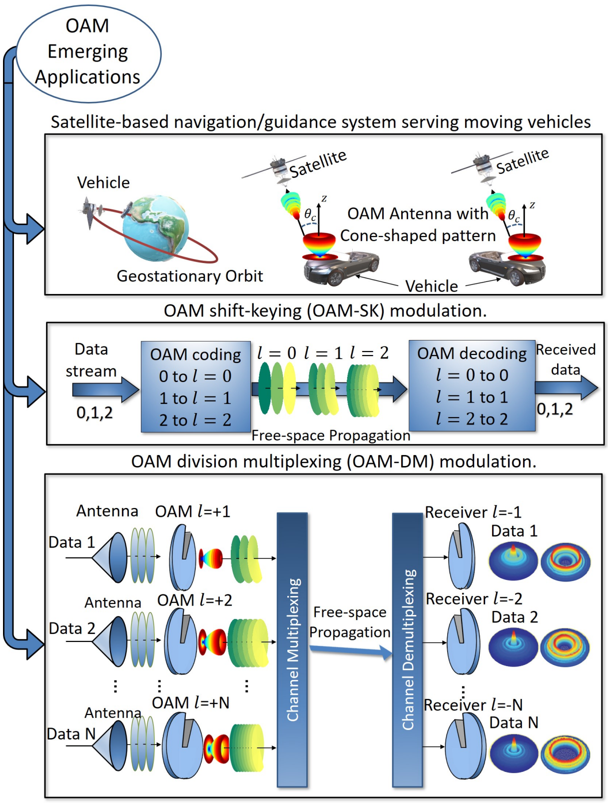

Figure 3. OAM emerging applications.

ation and required physical size in order to achieve proper gain and communication link budget.

4.2 OAM Shift-Keying (OAM-SK)

The second fundamental property of OAM beams, namely the orthogonality, can be employed to transfer information. OAM shift-keying (OAM-SK) uses distinct OAM modes as a communication alphabet and takes advantage of the distinction of different OAM modes. In this communication technology, the information transfer is achieved by encoding the data symbols in the OAM mode number l of OAM states, as shown in Fig. 3. The first experiment to use OAM-SK for free space information transfer was carried out by Gibson et al. in 2004 [9]. In Gibson's seminal work, eight different OAM modes in the set $\ell = \{-16, -12, -8, -4, +4, +8, +12, +16\}$, each representing a data symbol, were used as communication alphabet up to a transmission range of 15 m using a HeNe laser transmitter at a wavelength of 632.8 nm. Since the pioneering work of Gibson, several experiments followed (see, for example, [20]).

4.3 OAM Division Multiplexing (OAM-DM)

Another communication technology that employs the orthogonality of OAM beams is the OAM division multiplexing (OAM-DM) [5]. An independent data stream is encoded in the OAM mode number, as shown in 3. The multiple OAM beams are multiplexed at the transmitter, co-propagate in free space, and are de-multiplexed at the receiver, as shown in Fig. 3. Finally, the data information carried by each OAM mode can be retrieved. OAM-DM modulation technique allows the simultaneous transmission of different data streams through the same channel. Consequently, the spectral efficiency is increased by a factor N equal to the number of the carrier OAM modes. OAM-DM can be combined with other multiplexing schemes, such as polarization multiplexing [12] and wavelength multiplexing [13]. Several recent experiments have demonstrated the potential of OAM-DM to increase the spectral efficiency of wireless communication systems in optical frequencies [12, 13], as well as in radio frequencies [11, 14].

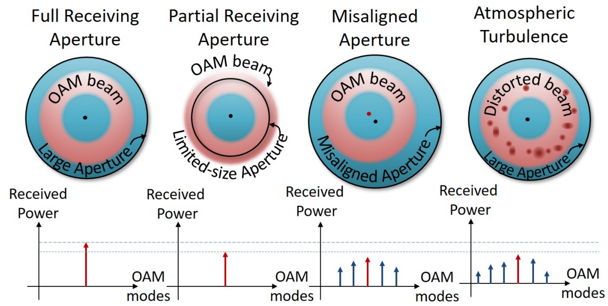

Figure 4. OAM challenges.

5 Challenges and Discussion

An OAM-based communication link presents challenges that are related to the OAM beams' inherent characteristics, such as the beam divergence. Ideally, A large receiving aperture would capture the OAM beam. Capturing part of the OAM beam with a limited-size aperture would cause power loss of the received mode, and any misalignment would cause power leakage to neighboring modes [3, 21], as shown in Fig. 4. Atmospheric turbulence in the path of the OAM beam can cause wavefront distortion and significant system degradation [4]. As the turbulence strength increases, the power of the transmitted OAM mode starts to leak to neighbouring modes and tends to be equally distributed among modes for strong turbulence [3, 5]. The requirement to collect enough power of the divergent OAM beam with a very large aperture (compared to wavelength) greatly limits the achievable distance of OAM communication links [4]. References [6, 7] question the possibility of using OAM antennas in long-distance communication links. So far, apart from the applications suggested in [8], the experiments that employ OAM for communications are mainly limited to the radiating near-field links rather than the far-field. The adoption of OAM in far-field wireless communications is still an open problem.

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