Journal of Optics

PAPER

Design challenges and guidelines for free-space optical communication links using orbital-angular-momentum multiplexing of multiple beams

To cite this article: Alan E Willner *et al* 2016 *J. Opt.* **18** 074014

Design Challenges and Guidelines for Free-Space Optical Communication Links Using Orbital-Angular-Momentum Multiplexing of Multiple Beams

Alan E. Willner[*,1], Guodong Xie[1], Long Li[1], Yongxiong Ren[1], Yan Yan[1], Nisar Ahmed[1], Zhe Zhao[1], Zhe Wang[1], Cong Liu[1], Asher J. Willner[1], Nima Ashrafi[2], Solyman Ashrafi[2], Moshe Tur[3], and Andreas F. Molisch[1]
1. Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA
2. NxGen Partners, Dallas, TX 75219, USA
3. School of Electrical Engineering, Tel Aviv University, Ramat Aviv 69978, Israel
Corresponding email*: willner@usc.edu

Abstract- In this paper, recent studies on the potential challenges for an OAM multiplexing system were reviewed. The design guideline for a practical OAM multiplexing system were investigated in term of (i) the power loss due to the beam divergence and limited-size receiver, and (ii) the channel crosstalk due to the misalignment between the transmitter and receiver.

1. Introduction

Communication systems continue to strive to meet the growing demand for data capacity. Historically, the efficient multiplexing and transmission of multiple independent data streams has provided a path for significant capacity increases, in which N different beams can theoretically carry N times the capacity of a single beam. Examples include polarization division multiplexing (PDM), whereby light beams with dual polarizations, each carrying an independent data stream, are transmitted simultaneously [1], and wavelength-division-multiplexing (WDM), whereby different "colors" of data-carrying beams are propagated through the same media [2].

Another approach is space-division-multiplexing (SDM), such that multiple beams, each identified by a unique spatial pattern, are simultaneously multiplexed and transmitted [3]. A subset of SDM is mode-division-multiplexing (MDM), in which each beam is transmitted on a unique spatial mode. Each mode should be orthogonal to all other modes, enabling efficient multiplexing and de-multiplexing with little inherent crosstalk. In general, SDM is compatible with PDM and WDM, and a combination of the above could result in further increases in system capacity.

One approach to achieve MDM is the use of an orthogonal set of structured beams, such as those carrying orbital angular momentum (OAM) [4,5,6,7,8,9,10], as shown in Fig. 1. In general, OAM beam has a helical transverse phase structure of $\exp(i\ell\phi)$, where ϕ is the transverse azimuthal angle and ℓ is an unbounded integer (the OAM order). OAM beams with different orders are mutually orthogonal to each other, allowing them to be multiplexed together along the same beam axis and de-multiplexed with low inter-modal crosstalk at the receiver.

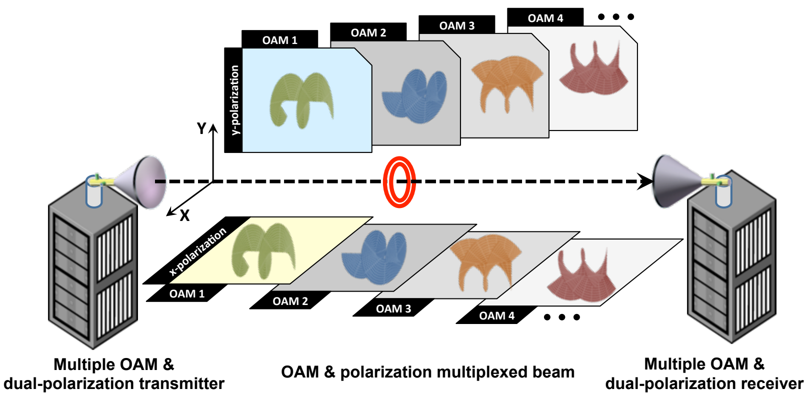

Figure 1. Concept of using beams carrying OAM for data channel multiplexing [7].

The use of beams carrying OAM for the MDM in a communication system has been demonstrated, with the following selected results: (a) a 2.5-Tbit/s free-space data link by multiplexing 32 OAM beams [4], (b) 100-Tbit/s free-space transmission using the combination of OAM multiplexing, PDM, and WDM [8], and (c) a 120-meter link by multiplexing four OAM modes with a total capacity of 400 Gbit/s [11]. OAM beam can also be employed for other communication-related researches such as encoding data bits on the spatial domain [4,12,13,14] and quantum communications [15,16,17,18,19].

In addition to free-space optical transmission, we note that results of OAM multiplexing communication systems have been achieved using special OAM-maintaining vortex fiber [6] and using radio frequencies (RF) [7,20,21,22]. However, the scope of this paper will be for free-space optical systems.

Although OAM may provide some advantages for higher-capacity free-space communications systems, OAM beams come with a unique set of systems challenges to achieve high performance. OAM beams typically have a unique azimuthal phase structure as well as a doughnut intensity profile with little power in the center, both of which give rise to problems different from single-Gaussian-beam systems. Consequently, several challenging issues should be considered when designing an OAM-based free-space link, including: (i) there would likely be higher power loss for higher-order OAM beams since beam divergence increases with OAM order, (ii) given that beam orthogonality suggests that the receiver recover the largest phase change in the beam center and yet there is less energy in this region, there is likely a trade-off between inter-channel crosstalk and received SNR, and (3) since modal purity determines the data channel, errors in beam pointing and recovery can couple light into neighboring modes thereby increasing crosstalk.

In this paper, we discuss the technical challenges and design guidelines for achieving good performance in an OAM-multiplexed free-space communication link using multiple orthogonal beams.

2. Beams carrying OAM and OAM multiplexing

2.1 Characteristics of OAM beams

The angular momentum of a light beam is related to the rotation of its electrical field. A light beam can carry spin angular momentum (SAM) if its electrical field rotates along the beam axis during propagation. This corresponds to the circular polarization property of the light. A light beam can also carry OAM if the wave vector spirals around the beam axis, leading to a helical transverse phase structure of $\exp(i\ell\phi)$ [23,24,25] (see Fig. 2). ϕ is the transverse azimuthal angle and ℓ is an integer which can therefore assume a positive, negative, or even zero value, corresponding to clockwise or counterclockwise phase helices, or a Gaussian beam (i.e., no helix which does not carry OAM). In general, an OAM beam refers to any beam that has a helical phase front of $\exp(i\ell\phi)$ where $\ell\neq0$, such as a Laguerre-Gaussian (LG) beam [26] with a non-zero azimuthal index or a Bessel-Gaussian beam [27] with a helical phase front.

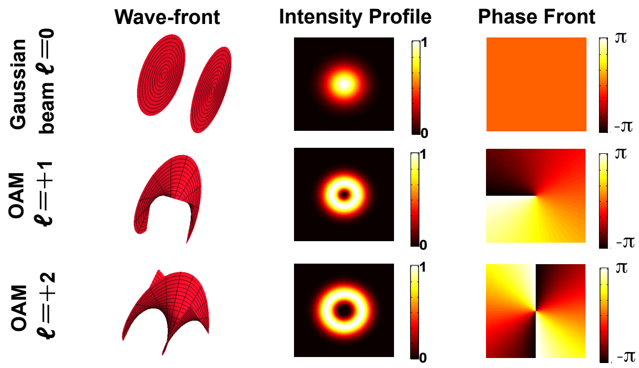

Figure 2. Wave-front, intensity profiles, and phase front of a regular Gaussian beam (ℓ=0) and OAM beams ℓ=+1, and ℓ=+2.

2.2 OAM beams generation and detection

Several approaches for the generation of OAM beams have been demonstrated. These include OAM generation inside a laser cavity [28,29] and converting a regular Gaussian beam by passing through or reflecting by phase plates [10], diffractive phase holograms [30,31,32], meta-materials [33,34,35,36], cylindrical lens pair [37], q-plates [38,39], fiber gratings [40], or couplers [41]. Accordingly, at the receiver, in order to detect an OAM beam, a conjugate helical phase could be applied to the twisted beam to down-convert it back into a Gaussian-like beam by canceling its helical phase front.

2.3 OAM beams multiplexing and de-multiplexing

Several approaches have also been demonstrated for multiplexing and de-multiplexing OAM beams. A straightforward way to multiplex different OAM beams is by using 3 dB beam splitters (BS). One BS could combine two OAM beams; therefore, N OAM beams could be multiplexed using N-1 cascaded BSs [4,7]. Since each BS causes 3 dB loss, each beam suffers $3\lceil\log_2 N\rceil$dB loss, where $\lceil\cdot\rceil$ is on rounding. Therefore, this approach is usually used in the lab for the proof-of-concept demonstration only. To de-multiplex one of the data channels (e.g., with the OAM $\ell=\ell_i$), a spiral phase (with $\ell=-\ell_i$) could be applied to the received beams; the OAM beam $\ell=\ell_i$ would then be converted to a Gaussian-like beam. Such a beam could be separated from the others, which would remain OAM beams, using a spatial filter (e.g., a pin-hole) [4,7]. In the proof-of-concept experiment, different OAM beams are usually recovered sequentially. If the simultaneous detection of all the channels is required, cascaded BSs could be used to separate the received beam into N copies ($3\lceil\log_2 N\rceil$dB loss), and each copy is used for the recovery of an individual channel.

Other methods of OAM multiplexing/de-multiplexing include: (i) cylindrical lenses based interferometric techniques for OAM multiplexing/de-multiplexer [42], (ii) photonics-integrated circuits, wherein multiplexed OAM beams are generated from Gaussian beams in an optical waveguide [43,44,45] for OAM multiplexing, and (iii) optical geometrical transformation-based mode sorter by which several multiplexed OAM beams transferred into several spatially non-overlapped Gaussian beams [46,47] for de-multiplexing. These multiplexing/de-multiplexing approaches are usually bi-directional. A de-multiplexer could be used for the multiplexing of multiple OAM beams when they are used in reverse, and vice versa.

In terms of intrinsic loss, the multiplexing/de-multiplexing of OAM beams using mode sorter and photonics-integrated circuits are much lower than that using BS while the BS based approaches could potentially offer some flexibility for the experiment in the lab. The modal crosstalk of these approaches are usually related the alignment and resolution of the devices.

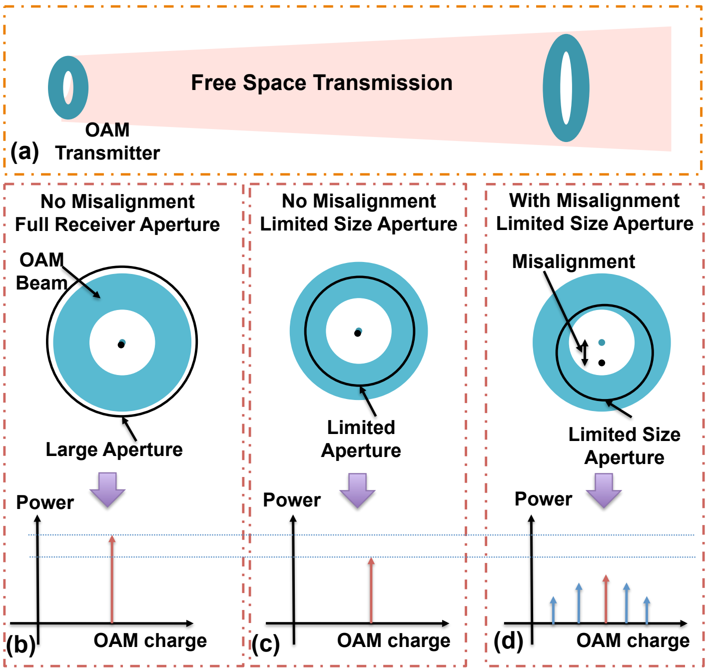

Figure 3. Potential challenges for an OAM multiplexing free-space optical communication system. (a) OAM beam divergence. (b) Receiving an OAM beam with a full receiver aperture and no misalignment. (c) Receiving an OAM beam with no misalignment but a limited size aperture. (d) Receiving an OAM beam with misalignment and a limited size aperture.

2.4 Challenges for OAM multiplexing system

OAM multiplexing can help increase the capacity and spectral efficiency of a communication system. However, challenges exist when designing such a system that is actually based on OAM multiplexing. Such challenges include:

- An OAM beam diverges when propagating in free space (Fig. 3a).
- As shown in Fig. 3c, if the receiver only has a limited size aperture, the system would suffer power loss compared to a system with a large enough receiver aperture (Fig. 3b).
- As shown in Fig. 3d, if there is misalignment between an OAM beam and its receiver, besides additional power loss compared to the case in Fig. 3c, the system would also suffer channel crosstalk.

3. Analysis of challenges for OAM multiplexing systems over free-space optical link

3.1 System model

In [48], the following simulation model was employed to analyze the potential issues to be considered for an OAM multiplexing free-space optical communication link (see Fig. 4):

- The wavelength of the laser source is 1550 nm and all channels have the same transmitted power.
- All the OAM beams are generated by passing Gaussian beams with the same beam waist through "sufficiently large" spiral phase plates (SPPs).
- Some constant losses of the link are not considered, for example, the insertion loss of the multiplexer and SPPs.
- The second moment of intensity of an OAM or a Gaussian beam is used for the calculations of spot size (beam diameter):

$$D = 2\sqrt{\frac{2\int_0^{2\pi}\int_0^{\infty} r^2 I(r,\phi) r \mathrm{d}r \mathrm{d}\phi}{\int_0^{2\pi}\int_0^{\infty} I(r,\phi) r \mathrm{d}r \mathrm{d}\phi}}, \quad (1)$$

  where $I(r,\phi)$ is the beam intensity profile and (r,ϕ) are polar coordinates [49]. Note that the spot size D shows within what size of circle the power of the beam is located, which would be helpful to determine the required aperture size. In the analysis below, if the receiver aperture is smaller than D, the received beam will be hard truncated.

- In this section, we assume that all the transmitted beams are collimated, which means all the beams have an infinity-large curvature at the transmitter plane. The case for focusing the transmitted beams will be discussed in Section 4.1.

Different parameters of an OAM multiplexing system are investigated at four different observation planes for the purpose of link parameters design, as shown in Fig. 4:

- Plane 1: The size of the beam at the transmitter is discussed. Note that the transmitter aperture size is generally larger than the transmitted beam size. Therefore, only the transmitted beam size is varied in the analysis while the transmitter aperture size is not considered.
- Plane 2: The spot sizes of an OAM beam or multiple multiplexed OAM beams are investigated, through which the divergence of the beams could be analyzed.
- Plane 3: Beams diverge during propagation. It is possible that the receiver only has a limited size aperture; therefore, only part of the beam could be captured. The power loss of the system due to a limited size aperture is investigated at Plane 3.
- Plane 4: In order to estimate the performance of a multiplexing system, one of the approaches is to study the crosstalk among different channels. In [48], the modal decomposition method is used to analyze the channel crosstalk on Plane 4. Model decomposition determines the partition of power on a specific OAM order for a received beam by calculating the projection of the received beam's electrical field over that of an ideal OAM beam with that specific order. This approach corresponds to the case where the received OAM beams are de-multiplexed without power loss and the power of a desired OAM channel is completely collected by the receiver [50].

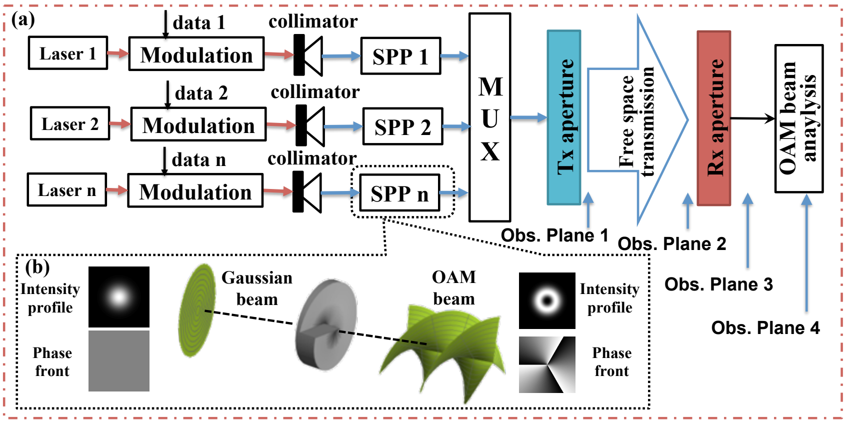

Figure 4. Models for the investigation of the potential challenges for free-space optical communication links using OAM multiplexing. SPP: spiral phase plate, Obs: observation [48].

3.2 Beam divergence and power loss

As shown in Fig. 5, OAM beam diverges more rapidly than a regular fundamental Gaussian beam and as the OAM order increases, the beam diverges even faster. According to [51], the divergence rate of an OAM beam is proportional to $\ell+1$ if it is generated from a diffraction grating, while it is proportional to square root of $\ell+1$ if generated using a cylindrical lens mode converter [51]. Such beam divergence gives rise to increased power loss for a limited-size receiver aperture. To recover data from the multiplexed beams, one needs to recover both their phase information and signal power simultaneously. The phase information enables the efficient separation of the multiplexed beams [10] while the signal power guarantees a sufficient signal-to-noise ratio (SNR) for data recovery [52]. Unfortunately, the amount of phase change per unit area for an OAM beam is greatest at the beam center, where there is also lower signal power [10,24]. Therefore, the design trade-off between capturing the beams' phase information and intensity information should be carefully considered to ensure a high SNR and low modal crosstalk.

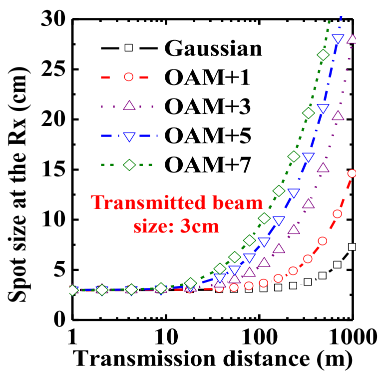

Figure 5. Beam divergence of different orders of OAM beams as a function of transmission distance [48].

The divergence of different orders of OAM beams as a function of the transmitted beam size over a 100-m link is shown in Fig. 6a. When the transmitted beam size is too small (e.g., 1 cm), the beam size at the receiver site is large due to the significant diffraction limit of a small beam. However, if the transmitted beam size is too large (e.g., 20 cm), the beam size at the receiver is also large due to its geometric properties. Therefore, for a specific order of OAM beam, there exists a proper transmitted beam size, which produces the smallest spot size at the receiver site. For OAM beams with a larger order, the minimum spot size at the receiver and the corresponding transmitted beam size are also larger. Figure 6b shows the minimum spot size of different orders of OAM beams for link distances of 100 m, 1 km, and 10 km. The minimum spot size goes up as the OAM order and link distance increase. Figure 6c shows the corresponding transmitted beam size to achieve the minimum spot size at the receiver in Figure 6b.

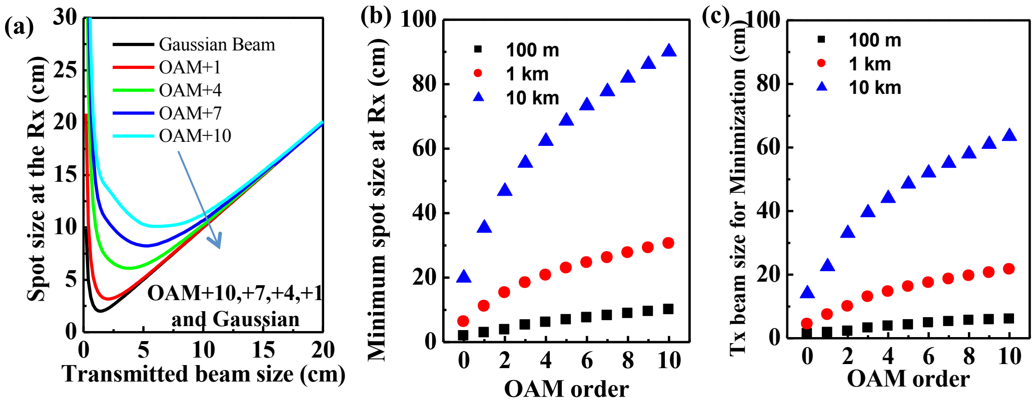

Figure 6. (a) Simulated spot size of different orders of OAM beams as a function of transmitted beam size over a 100-m link. (b) Minimum spot sizes for different orders of OAM beams that could be achieved at different link distances. (c) Relative transmitted beam size to achieve the minimum spot size at the receiver [48].

Note that the transmitted beam size to achieve a minimum spot size at the receiver varies for different orders of OAM beams. Therefore, to implement a practical system, two approaches could be considered: (i) Design different transmitted beam sizes for the channels using different OAM orders, or (ii) choose a tradeoff value as the transmitted beam size for all channels so that all orders of OAM beams used for data multiplexing have reasonable spot sizes at the receiver, although they will not have the theoretically minimum spot size. For example, in a 100-m link with OAM $\ell=\pm1$, ±3 multiplexed, a transmitter beam size of ~3 cm could be a good value to achieve reasonable sizes for all OAM beams at the receiver. For such an OAM multiplexing system over 1 km and 10 km links, a ~10 cm and ~30 cm transmitted beam size may be needed, respectively.

In a free-space optical communication system, the beam at the receiver could be too large to be fully captured. Figure 7 shows the power loss of a specific OAM beam (i.e., OAM+3) as a function of the receiver aperture size for different transmitted beam sizes and different link distances. For the 100-m link, the 3-cm transmitter beam size shows lower power loss than those of the 10-cm and 30-cm ones while the 10-cm and 30-cm transmitted beam sizes show lower power loss than the others for 1-km and 10-km, respectively. In [48] it assumes that 3-cm, 10-cm and 30-cm transmitted beam sizes are used over 100-m, 1-km and 10-km link, respectively. According to Fig. 7, in order to capture most of the transmitted power at the receiver, the receiver sizes for the 100 m, 1 km, and 10 km links are suggested as 4.5 cm, 15 cm, and 45 cm, respectively.

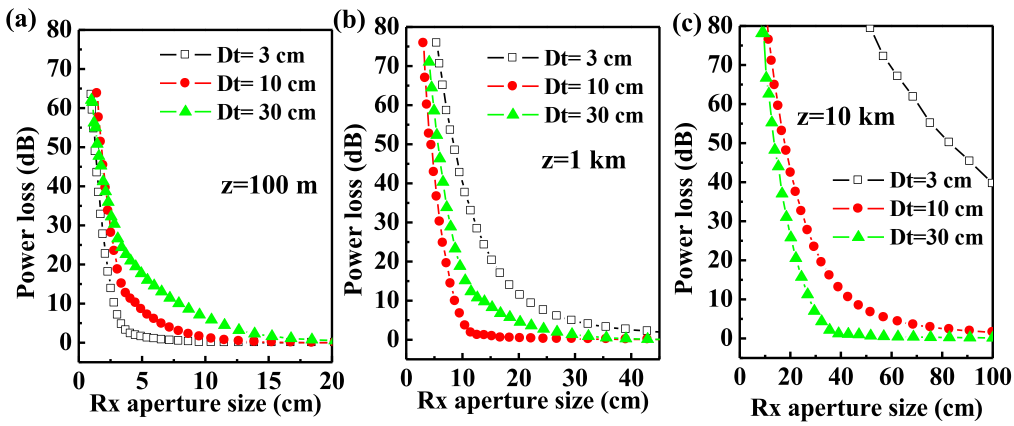

Figure 7. Simulated power loss as a function of receiver aperture size when only OAM+3 is transmitted for (a) z=100 m, (b) z=1 km, and (c) z=10 km. Dt: transmitted beam size; z: transmission distance [48].

Considering the power loss due to the beam divergence and possible limited size of the aperture, compared to a regular system using only a single Gaussian beam, an OAM multiplexing system usually: (1) requires a relatively larger aperture size and a more limited total transmission distance; (2) requires a more detailed design in terms of transmitted beam size, receiver aperture size, or even orders of OAM modes used for data multiplexing.

3.3 Pointing accuracy

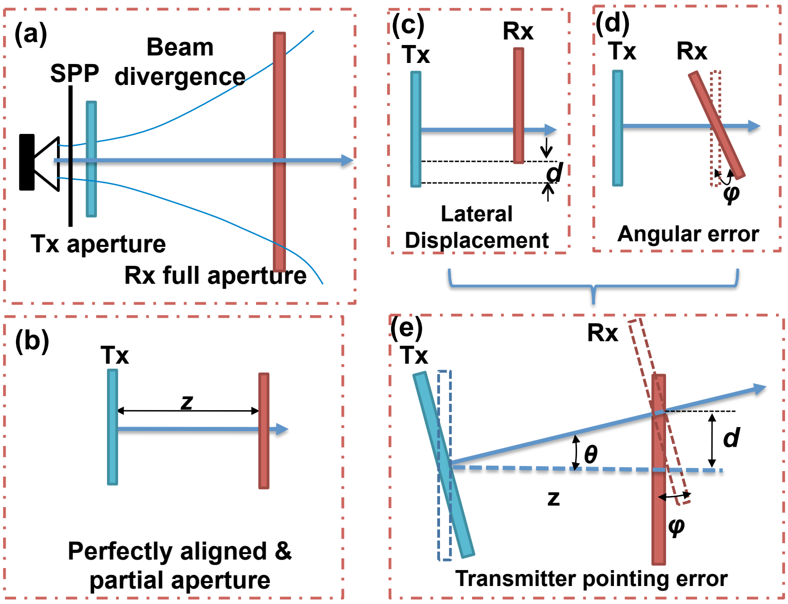

Figure 8. Alignment between the transmitter and receiver for (a) a perfectly aligned system with a large enough receiver, (b) a perfectly aligned system with a limited size receiver, (c) a system with lateral displacement and a limited size receiver, (d) a system with receiver angular error and a limited size receiver, and (e) a system with transmitter pointing error and a limited size receiver. Tx: transmitter; Rx: receiver; z: transmission distance; d: lateral displacement; φ: receiver angular error; θ: pointing error [48].

Orthogonality among OAM beams is ensured when all beams are co-axially propagated and the receiver is perfectly aligned on-axis with the beams [6]. However, any misalignment among the beams, or between the beams and receiver, may degrade the orthogonality due to a phase mismatch and cause power to be coupled into other modes, i.e., severe intermodal crosstalk. Figure 8b shows an ideal case where the receiver is perfectly aligned with the beam. In this case, the center of the receiver would overlap with the center of the transmitted beam, and the receiver would be perpendicular to the line connecting their centers. However, in a practical system, due to jitter and vibration of the transmitter/receiver platform, there might exists lateral shift (Fig. 8c) or angular shift (Fig. 8d) between the beams and the receiver [53]. Moreover, the lateral displacement and receiver angular error could happen simultaneously, a specific example of which is a pointing error at the transmitter, as depicted in Fig. 8e.

The effect of lateral displacement, receiver angular error and transmitter pointing error on the power distribution of the received beam is shown in Fig. 9a, 9b, and 9c, respectively, when OAM+3 is transmitted through a 100-m link [48]. The transmitted beam size and receiver size are assumed to be 3 cm and 4.5 cm, respectively. The simulation results indicate that: (i) the power leaked from the desired mode (OAM+3) to the neighboring modes increases as the misalignment increases; (ii) the power leaked to the modes with smaller order difference to the desired mode is higher. To mitigate the effect of the power leakage from one mode to the neighboring modes (channel crosstalk), the system may either employ a pointing-tracking system with higher resolution to reduce the misalignment, or use a larger OAM mode spacing (e.g., using every other OAM modes instead of using adjacent ones) for channel multiplexing.

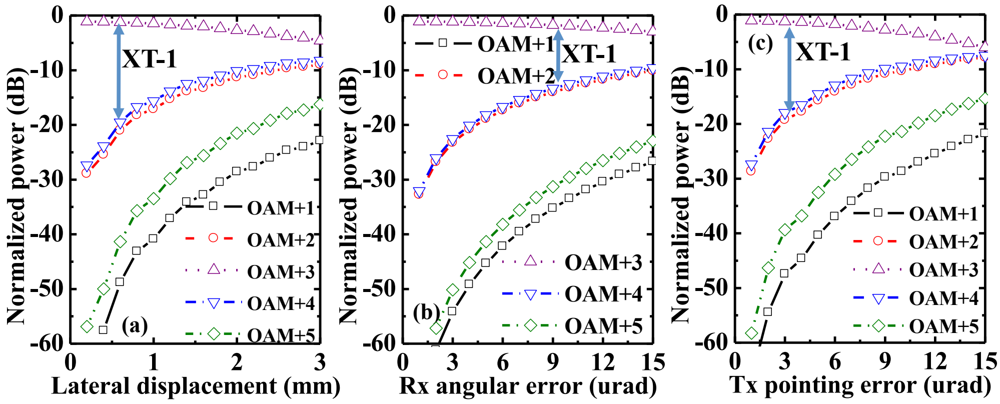

Figure 9. Simulated power distribution among different OAM modes as a function of (a) lateral displacement, (b) receiver angular error, and (c) transmitter pointing error over a 100-m link for which only the OAM+3 mode is transmitted; the transmitted beam size Dt=3 cm and the receiver aperture size is 4.5 cm. XT-1: relative crosstalk to the nearest-neighboring mode (OAM+4) [48].

One of the most important concerns for an OAM multiplexing system could be the power leaked to the nearest modes. The relative crosstalk to the nearest neighboring mode XT-1 is defined as the ratio of the power leaked to the nearest neighboring mode (i.e., OAM+4) to the power on the desired mode (i.e., OAM+3). Figure 10 shows the relative crosstalk of XT-1 as a function of lateral displacement and receiver angular error, respectively, for different link distances with various transmitted beam sizes. Larger transmitted beam sizes and longer transmission distances result in smaller XT-1 for a specific lateral displacement, but larger XT-1 for a specific receiver angular error. This is because: (i) In terms of a given lateral displacement, a larger beam has less phase change on a unit area, thus suffers less phase mismatch. (2) In terms of a given receiver angular error φ, the incoming phase front hitting the receiver has an additional tilt-related term $\varphi D/2$, where D is the spot size at the receiver; therefore larger beam size suffers larger phase deviations.

Considering the power loss and pointing accuracy, several tradeoffs need to be carefully designed for the OAM multiplexing free-space optical communication system: (i) According to the transmission distance, a proper transmitted beam size need to be selected so that all the transmitted beams could have a reasonable beam size at the receiver. (ii) When the received beam is larger, it is more tolerant to the lateral displacement but less tolerant to the angular error. (iii) Larger mode spacing usually gives less crosstalk among modes; however, system using larger mode spacing usually employs larger OAM modes, which suffers more power loss.

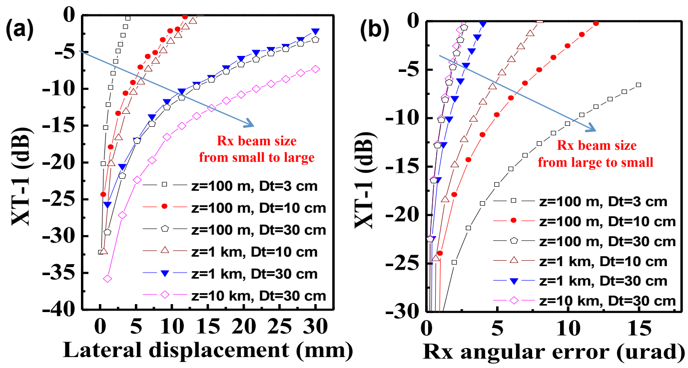

Figure 10. XT-1 as a function of lateral displacement and receiver angular error for different transmission distances and transmitted beam sizes. XT-1: relative crosstalk to the nearest-neighboring mode (OAM+4) [48].

4. Potential approaches to improving the OAM multiplexing system performance

According to the above analysis, since an OAM beam diverges when it propagates in free space, its spot size might be larger than the hard truncation receiver aperture, resulting in a power loss that grows with the propagation distance and OAM order. To correctly recover an OAM beam, the rapid phase change that occurs in the center needs to be collected in order to ensure orthogonality among the OAM beams, while sufficient optical power should also be received to satisfy the system requirement. Therefore, sufficient capture of an OAM beam is critical and will limit the transmission distance and the number of modes that can be supported. There are several potential approaches to overcome this design issue, including using transmitter lenses, and using OAM modes with non-zero radial indices.

4.1 Transmitter lenses

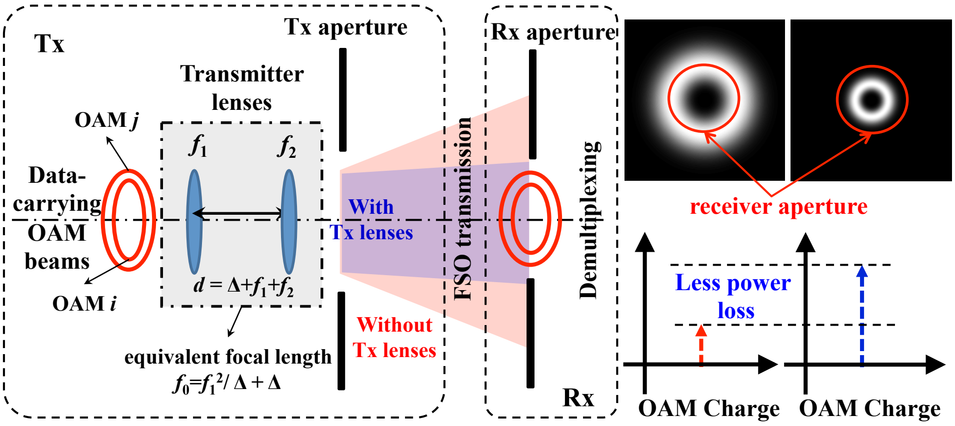

Figure 11. Concept of an OAM-multiplexed free-space optical communication link using a pair of transmitter lenses. Tx: transmitter; Rx: receiver; f_0: equivalent focal length; d: center-to-center spacing between the two transmitter lenses; Δ: spacing offset between two transmitter lenses [54].

One approach to achieving sufficient capture could be to use lenses at the transmitter to focus the OAM beams, thereby achieving smaller beam sizes at the receiver and perhaps helping to reduce power loss caused by beam divergence and limited size apertures (Fig. 11) [54]. Figure 12a shows the simulated power loss as functions of transmission distance for different orders of OAM beams with and without the use of transmitter lenses, indicating that power loss decreases when the equivalent focal length of the transmitter lenses is adjusted to be around the same as the transmission distance. Both Fig. 12b and Fig. 12c show that higher-order OAM beams (e.g., OAM+7) would produce a greater benefit, which might result from their large divergence characteristics. Here, the spacing offset $\Delta = f_1 + f_2 - d$ determines the equivalent focal length of transmitter lenses, where f_1 and f_2 are the focal length of each transmitter lens and d is the spacing between them.

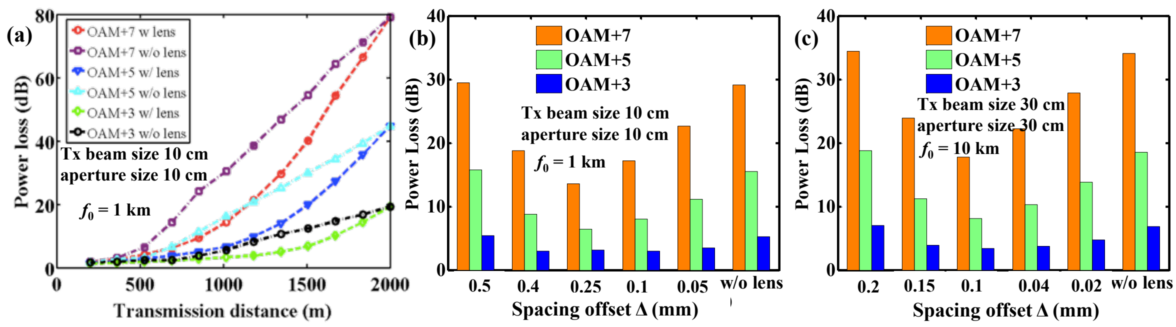

Figure 12. (a) Simulated power loss as a function of transmission distance of different orders of OAM beams. (b) and (c): Simulated power loss as a function of spacing offset between two transmitter lenses in 1 km and 10 km links, respectively. In (a), both the transmitted beam size and aperture size are 10 cm, and the equivalent focal length of the transmitter lenses is 1 km. The transmitted beam sizes and aperture sizes are 10 cm in (b) and 30 cm in (c); focal lengths of the transmitter lenses are 0.5 m in (b) and 1 m in (c). Tx: transmitter; f_0: equivalent focal length of transmitter lenses; OAM ℓ: beam carrying OAM of ℓ; z: transmission distance [54].

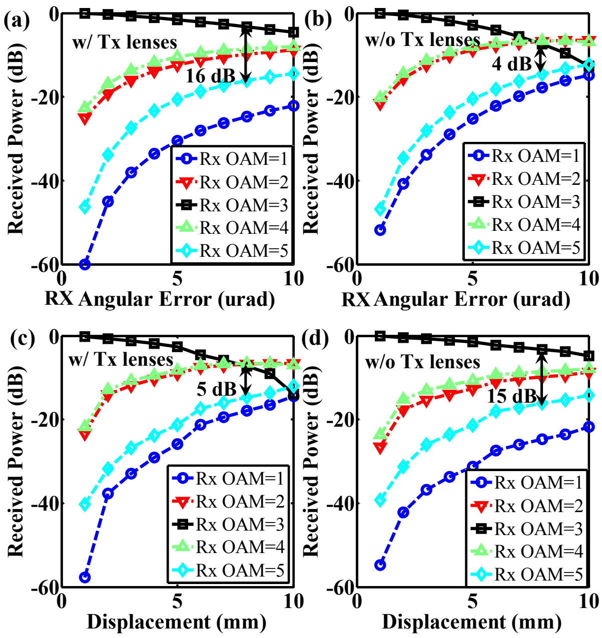

Figure 13. Simulated OAM power distribution of 1-km free-space optical link: (a) with angular error and transmitter lenses; (b) with angular error but without transmitter lenses; (c) with displacement and transmitter lenses; and (d) with displacement but without transmitter lenses. Transmitted beam size is 10 cm, and only OAM+3 beam is transmitted. Rx OAM= ℓ: power coupled into the receiver for mode OAM= ℓ [54].

[54] also studied the effect of transmitter lenses on the robustness of OAM multiplexing communication links, especially in terms of angular error and lateral displacement between the transmitter and the receiver. Figure 13 shows simulated power distributions of an OAM beam as a function of angular error and lateral displacement, with and without transmitter lenses. This work shows that because angular error would introduce phase mismatch between the incoming OAM beam and the receiver plane due to different additional phase-shift that increases linearly in the radial direction, using transmitter lenses might reduce phase mismatch and, consequently, channel crosstalk. Conversely, under the same displacement, beams with larger spot size would experience a smaller mismatch; therefore, using transmitter lenses may increase channel crosstalk due to lateral displacement.

4.2. OAM modes with non-zero radial indices

Another potential approach for sufficient beam capturing would be using OAM modes with non-zero radial indices. In addition to the phase change in the azimuthal direction, beams carrying OAM may also have unique radial structures, described by its OAM order ℓ and radial index p (i.e., $LG_{p,\ell}$) as shown in Fig. 14a. In general, an OAM beam with p > 0 diverges faster as compared to an OAM beam with the same ℓ value but with p = 0. However, under certain transmission distances, the size of the innermost ring of a p > 0 beam could be smaller than that of the only ring of the p = 0 beam with the same ℓ value (Fig. 14b). This indicates that p > 0 beams may have more signal power near the beam center in such cases [55]. Figure 15 shows the simulated power loss for OAM beams of different ℓ and p values as functions of transmission distance, which indicates that (i) the power loss of $LG_{0,1}$ is lower than $LG_{1,1}$ at most transmission distances, and it is worth noting that at very near distances $LG_{1,1}$ may have less power loss than $LG_{0,1}$; (ii) for transmission distance from 650 m to 1 km, $LG_{1,5}$ and $LG_{1,9}$ shows lower power loss than $LG_{0,5}$ and $LG_{0,9}$, respectively. When ℓ = 9, these p > 0 beams show no significant difference between each other in terms of power loss under various aperture sizes.

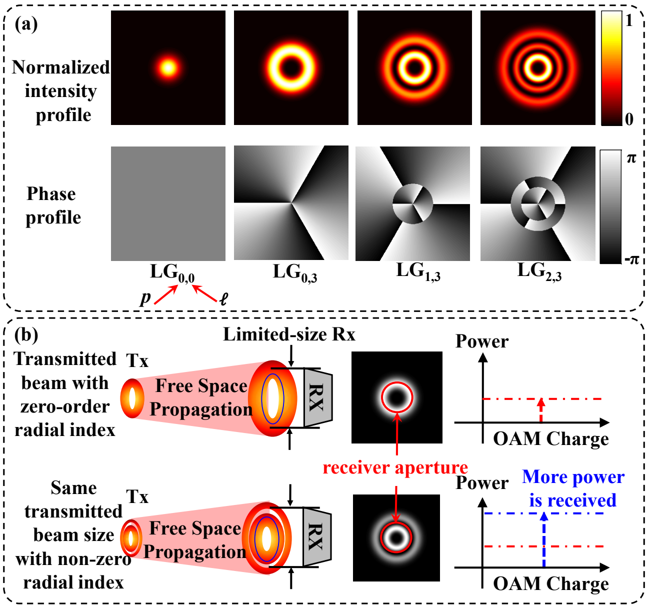

Figure 14. (a) Normalized intensity and phase profile of Gaussian, $LG_{0,3}$, $LG_{1,3}$, and $LG_{2,3}$ beams. (b) Concept and simulation model of power efficient OAM-multiplexed free-space optical link transmitting LG beams with non-zero radial indices. Tx: transmitter; Rx: receiver [55].

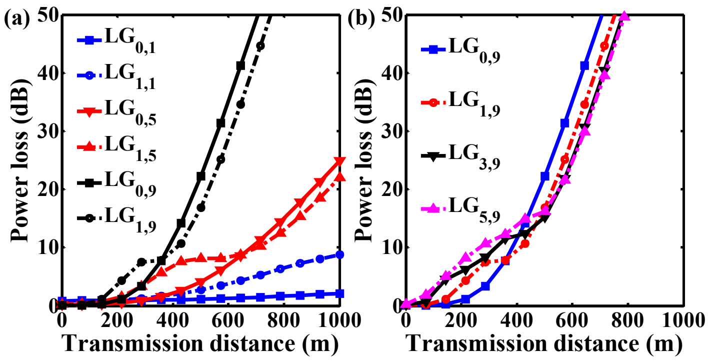

Figure. 15. Simulated power of (a) OAM beams with radial indices of p=0 and p=1, and (b) OAM beams with azimuthal index of ℓ =9 but different radial indices as functions of transmission distance, with transmitted beam sizes as well as transmitter/receiver aperture diameters being 8 cm [55].

Other potential approaches: besides the above-mentioned approaches to enhance the performance of an OAM multiplexing system, some other methods have been investigated. In [56] and [57], the pros and cons of putting limited size receivers at the annulus, where their intensity is high, was discussed. In [58], the use of the sector-shape receiver for the simultaneous de-multiplexing of multiple OAM beams was examined while in [59], the use of discrete antenna array to sample the multiplexed OAM beam was investigated. All these approaches could help to provide potential solutions to mitigate the issues of beams divergence and channel crosstalk for OAM multiplexing systems.

5. Discussion

We note that, from the perspective of SDM, there are other orthogonal modal basis sets, such as Hermite-Gaussian (HG) modes [60], that could also be used for multiplexing data channels, especially in free space. Although it is not straightforward to say which of these modal sets is necessarily "better", OAM modes do offer the potential advantage of being conveniently matched to many optical subsystems due to their circular symmetry.

The analysis reviewed in this paper was based on a static link. However, in practical systems, lateral displacement and receiver angular error are generally time-varying random processes that are typically described as beam jitter and beam wandering [61]. The reviewed work could be helpful in terms of providing an analysis of the upper and lower bounds of the system performance, given a specific dynamic range of beam jitter and beam wandering. The research discussed also focused on improving the system performance through the optical design. Digital signal processing approaches to the electrical domain, such as multiple-input-multiple-output (MIMO) equalization could also be considered for OAM multiplexing systems; in this way, the effects of the lateral displacement and receiver angular error could be reduced [62].

Atmospheric turbulence might also result in beam distortions in an OAM multiplexed link [63,64,65]. Of all the effects caused by turbulence, beam wandering and arrival angle fluctuation could be considered as lateral displacement and receiver angular error, as discussed above. However, the intensity and phase fluctuation of the received beam, caused by atmospheric turbulence, might lead to severe signal fading at the receiver. Such effects are not considered in this review, but may warrant further exploration.

6. Summary

In this paper, recent studies on the potential challenges for an OAM multiplexing system were reviewed. The design guideline for a practical OAM multiplexing system were investigated in term of (i) the power loss due to the beam divergence and limited-size aperture, and (ii) the channel crosstalk due to the misalignment between the transmitter and receiver. Moreover, approaches, such as applying a lens pair at the transmitter and using OAM mode with non-zero radial order, may potentially help to improve the system performance under certain scenarios. To summarize, optical communication systems that use the multiplexing of structured light represent a fresh sub-field that has a rich set of issues to explore, including technical challenges and potential application opportunities.

References

[1] P. M. Hill, R. Olshansky, and W. K. Burns, “Optical polarization division multiplexing at 4 Gb/s,” IEEE Photonics Technology Letters **4**, 500-502 (1992).

[2] H. Ishio, J. Minowa, and K. Nosu, “Review and status of wavelength-division-multiplexing technology and its application,” Journal of Lightwave Technology **2**, 448-463 (1984).

[3] D. J. Richardson, J. M. Fini, and L. E. Nelson, “Space-division multiplexing in optical fibres,” Nature Photonics **7**, 354-362 (2013).

[4] G. Gibson, J. Courtial, M. Padgett, M. Vasnetsov, V. Pas'ko, S. Barnett, and S. Franke-Arnold, “Free-space information transfer using light beams carrying orbital angular momentum,” Optics Express **12**, 5448-5456 (2004).

[5] J. Wang, J.-Y. Yang, I. M. Fazal, N. Ahmed, Y. Yan, et al., “Terabit free-space data transmission employing orbital angular momentum multiplexing,” Nature Photonics **6**, 488-496 (2012).

[6] N. Bozinovic, Y. Yue, Y. Ren, M. Tur, P. Kristensen, et al., “Terabit-scale orbital angular momentum mode division multiplexing in fibers,” Science **340**, 1545-1548 (2013).

[7] Yan. Yan, G. Xie, M. P. J. Lavery, H. Huang, N. Ahmed, et al., “High-capacity millimetre-wave communications with orbital angular momentum multiplexing,” Nature Communications **5** (2014).

[8] H. Hao, G. Xie, Y. Yan, N. Ahmed, Y. Ren, et al., “100 Tbit/s free-space data link enabled by three-dimensional multiplexing of orbital angular momentum, polarization, and wavelength,” Optics Letters **39**, 197-200 (2014).

[9] A. E. Willner, H. Huang, Y. Yan, Y. Ren, N. Ahmed, et al., “Optical communications using orbital angular momentum beams,” Advances in Optics and Photonics **7**, 66-106 (2015).

[10] A. M. Yao and M. J. Padgett, “Orbital angular momentum: origins, behavior and applications,” Advances in Optics and Photonics **3**, 161-204 (2011).

[11] Y. Ren, Z. Wang, P. Liao, L. Li, G. Xie, et al., “400-Gbit/s free space optical communications link over 120-meter using multiplexing of 4 collocated orbital-angular-momentum beams,” In *Optical Fiber Communication Conference*, (Optical Society of America, 2015), paper M2F-1.

[12] A. J. Willner, Y. Ren, G. Xie, Z. Zhao, Y. Cao, et al., “Experimental demonstration of 20 Gbit/s data encoding and 2 ns channel hopping using orbital angular momentum modes,” Optics Letters **40**, 5810-5813 (2015).

[13] M. Krenn, R. Fickler, M. Fink, J. Handsteiner, M. Malik, et al., “Twisted light communication through turbulent air across Vienna,” New Journal Physics **16**, 113028 (2014).

[14] J. Du, and J. Wang, “High-dimensional structured light coding/decoding for free-space optical communications free of obstructions,” Optics Letters **40**, 4827-4830 (2015).

[15] J. Leach, E. Bolduc, D. J. Gauthier, and R. W. Boyd, “Secure information capacity of photons entangled in many dimensions,” Physical Review A **85**, 060304 (2012).

[16] M. Bourennane, A. Karlsson, G. Bjork, N. Gisin, and N. Cerf, “Quantum key distribution using multilevel encoding: security analysis,” Journal of Physics A **35**, 10065-10076 (2002).

[17] J. Leach, B. Jack, J. Romero, A. K. Jha, A. M. Yao, et al., “Quantum correlations in optical angle-orbital angular momentum variables,” Science **329**, 662-665 (2010).

[18] G. Vallone, V. D’Ambrosio, A. Sponselli, S. Slussarenko, L. Marrucci, et al., “Free-space quantum key distribution by rotation-invariant twisted photons,” Physical Review Letters **113**, 060503 (2014).

[19] M. Mirhosseini, O. S. Magana-Loaiza, M. N. O’Sullivan, B. Rodenburg, M. Malik, et al., “High-dimensional quantum cryptography with twisted light,” arXiv:1402.7113v11 (2014).

[20] B. Thidé, H. Then, and J. Sjöholm, et. al, “Utilization of photon orbital angular momentum in the low-frequency radio domain,” Physical Review Letters **99**, pp. 087701 (2007).

[21] F. Tamburini, E. Mari, and A. Sponselli, et. al, “Encoding many channels on the same frequency through radio vorticity: first experimental test,” New Journal of Physics **14**, pp. 033001, (2012).

[22] F. E. Mahmouli, and S. D. Walker, “4-Gbps uncompressed video transmission over a 60-GHz orbital angular momentum wireless channel,” IEEE Wireless Communications Letters **2**, pp. 223-226 (2013).

[23] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, “Orbital angular-momentum of light and the transformation of Laguerre-Gaussian laser modes,” Physical Review A **45**, 8185-8189 (1992).

[24] L. Allen, M. Padgett, and M. Babiker, “The orbital angular momentum of light,” Progress in Optics **39**, 291-372 (1999).

[25] S. Barnett and L. Allen, "Orbital angular momentum and non paraxial light beams," Optical Communications **110**, 670-678 (1994).

[26] J. Courtial, K. Dholakia, L. Allen, and M. J. Padgett, "Gaussian beams with very high orbital angular momentum," Optics Communications **144**, 210-213 (1997).

[27] K. Volke-Sepulveda, V. Garcés-Chávez, S. Chávez-Cerda, J. Arlt, and K. Dholakia, "Orbital angular momentum of a high-order Bessel light beam," Journal of Optics B: Quantum and Semiclassical Optics **4**, S82 (2002).

[28] J. M. Vaughan and D. V. Willetts, "Temporal and interference fringe analysis of TEM01 laser modes," Journal of Optical Society of America **73**, 1018-1021 (1983).

[29] A. J. Lee, C. Zhang, T. Omatsu, and H. M. Pask, "An intracavity, frequency- doubled self-Raman vortex laser," Optics Express **22**, 5400-5409 (2014).

[30] V. Bazhenov, M. V. Vasnetsov, and M. S. Soskin, "Laser-beams with screw dislocations in their wave-fronts," Optical Angular Momentum, 152 (2003).

[31] N. R. Heckenberg, R. McDuff, C. P. Smith, and A. White, "Generation of optical phase singularities by computer-generated holograms," Optics Letters **17**, 221-223 (1992).

[32] M. Mirhosseini, O. S. Magaña-Loaiza, C. Chen, B. Rodenburg, M. Malik, and R. W. Boyd, "Rapid generation of light beams carrying orbital angular momentum," Optics Express **21**, 30196-30203 (2013).

[33] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J. P. Tetienne, F. Capasso, and Z. Gaburro, "Light propagation with phase discontinuities: generalized laws of reflection and refraction," Science **334**, 333-337 (2011).

[34] E. Karimi, S. A. Schulz, I. D. Leon, V. Qassim, J. Upham, and R. W. Boyd, "Generating optical orbital angular momentum at visible wavelengths using a plasmonic metasurface," Light: Science & Applications **3**, e167 (2014).

[35] Z. Zhao, J. Wang, S. Li, and A. E. Willner, "Metamaterials-based broadband generation of orbital angular momentum carrying vector beams," Optics Letters **38**, 932-934 (2013).

[36] J. Zeng, X. Wang, J. Sun, A. Pandey, A. N. Cartwright, and N. M. Litchinitser, "Manipulating complex light with metamaterials," Scientific Report **3**, 2826 (2013).

[37] M. W. Beijersbergen, L. Allen, H. van der Veen, and J. P. Woerdman, "Astigmatic laser mode converters and transfer of orbital angular momentum," Optical Communications **96**, 123-132 (1993).

[38] S. Oemrawsingh, J. van Houwelingen, E. Eliel, J. P. Woerdman, E. Verstegen, et al., "Production and characterization of spiral phase plates for optical wavelengths," Apply Optcs **43**, 688-694 (2004).

[39] L. Marrucci, E. Karimi, S. Slussarenko, B. Piccirillo, E. Santamato, E. Nagali, and F. Sciarrino, "Spin-to-orbital conversion of the angular momentum of light and its classical and quantum applications," Journal of Optics **13**, 064001 (2011).

[40] N. Bozinovic, S. Golowich, P. Kristensen, and S. Ramachandran, "Control of orbital angular momentum of light with optical fibers," Optics Letters **37**, 2451-2453 (2012).

[41] Y. Yan, J. Wang, L. Zhang, J.-Y. Yang, I. M. Fazal, N. Ahmed, B. Shamee, A. E. Willner, K. Birnbaum, and S. J. Dolinar, "Fiber coupler for generating orbital angular momentum modes," Optics Letters **36**, 4269-4271 (2011).

[42] P. Martelli, P. Boffi, A. Fasiello and M. Martinelli, "Interferometric orbital angular momentum mode multiplexer/demultiplexer based on pairs of cylindrical lenses," Electronics Letters **51**, pp. 278-280 (2015).

[43] C. R. Doerr and L. L. Buhl, "Circular grating coupler for creating focused azimuthally and radially polarized beams," Optics Letters **36**, 1209-1211 (2011).

[44] T. Su, R. P. Scott, S. S. Djordjevic, N. K. Fontaine, D. J. Geisler, X. Cai, and S. J. B. Yoo, "Demonstration of free space coherent optical communication using integrated silicon photonic orbital angular momentum devices," Optics Express **20**, 9396-9402 (2012).

[45] N. K. Fontaine, C. R. Doerr, and L. Buhl, "Efficient multiplexing and demultiplexing of free-space orbital angular momentum using photonic integrated circuits," in Optical Fiber Communication Conference (Optical Society of America, 2012), paper OTu1I.2.

[46] J. Leach, M. Padgett, S. Barnett, S. Franke-Arnold, and J. Courtial, "Measuring the orbital angular momentum of a single photon," Physical Review Letters **88**, 257901 (2002).

[47] M. P. J. Lavery, D. J. Robertson, G. C. G. Berkhout, G. D. Love, M. J. Padgett, and J. Courtial, "Refractive elements for the measurement of the orbital angular momentum of a single photon," Optics Express **20**, 2110-2115 (2012).

[48] G. Xie, L. Li, Y. Ren, H. Huang, Y. Yan, N. Ahmed, Z. Zhao et al., "Performance metrics and design considerations for a free-space optical orbital-angular-momentum–multiplexed communication link," Optica **2**, 357-365 (2015).

[49] R. Phillips, and L. Andrews, "Spot size and divergence for Laguerre Gaussian beams of any order," Applied Optics **22**, 643-644 (1983).

[50] H. Qassim, F. M. Miatto, J. P. Torres, M. J. Padgett, E. Karimi, and R. W. Boyd, "Limitations to the determination of a Laguerre–Gauss spectrum via projective, phase-flattening measurement," Journal of the Optical Society of American B **31**, 20-23 (2014).

[51] M. J. Padgett, F. M. Miatto, M. P. J. Lavery, A. Zeilinger, and R. W. Boyd, "Divergence of an orbital-angular-momentum-carrying beam upon propagation," New Journal of Physics **17**, 023011 (2015).

[52] B. Sklar, Digital Communications. NJ: Prentice Hall, 2001.

[53] A. Farid, and S. Hranilovic, "Outage capacity optimization for free space optical links with pointing errors," Journal of Lightwave Technology **25**, 1702-1710 (2007).

[54] L. Li, G. Xie, Y. Ren, N. Ahmed, H. Huang, et al., "Performance enhancement of an orbital-angular-momentum-based free-space optical communication link through beam divergence controlling," In Optical Fiber Communication Conference (Optical Society of America, 2015), paper. M2F-6.

[55] L. Li, G. Xie, Y. Yan, Y. Ren, N. Ahmed, et al., "Experimental demonstration of a 400-Gbit/s free space optical link using multiple orbital-angular-momentum beams with higher order radial indices," In CLEO: Science and Innovations, (Optical Society of America, 2015), paper. SW4M-5.

[56] G. Xie, Y. Ren, H. Huang, Y. Yan, C. Bao, et al., "Analysis of aperture size for partially receiving and de-multiplexing 100-Gbit/s optical orbital angular momentum channels over free-space link," In Globecom Workshops, 1116-1120 (2013).

[57] G. Xie, Y. Ren, H. Huang, N. Ahmed, L. Li, et al., "Experimental comparison of single and double partial receiver apertures for recovering signals transmitted using orbital-angular-momentum," In CLEO: Science and Innovations (Optical Society of America, 2014), paper. SM3J-2.

[58] S. Zheng, X. Hui, J. Zhu, H. Chi, X. Jin, S. Yu, and X. Zhang, "Orbital angular momentum mode-demultiplexing scheme with partial angular receiving aperture," Optics Express **23**, 12251-12257 (2015).

[59] D. K. Nguyen, O. Pascal, J. Sokoloff, A. Chabory, et al., "Antenna gain and link budget for waves carrying orbital angular momentum," Radio Science **50**, 1165-1175 (2015).

[60] S. Saghafi, C. J. R. Sheppard, and J. A. Piper, "Characterising elegant and standard Hermite–Gaussian beam modes," Optics Communications **191**, 173-179 (2001).

[61] L. Andrews, and R. Phillips, Laser Beam Propagation Through Random Media, Bellingham: SPIE press (2005).

[62] Q. Spencer, A. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," IEEE Transactions on Signal Processing **52**, 461-471 (2004).

[63] X. Zhu, and J. Kahn, "Free-space optical communication through atmospheric turbulence channels," IEEE Transactions on Communication **50**, 1293-1300 (2002).

[64] N. Chandrasekaran, and J. Shapiro, "Photon Information Efficient Communication Through Atmospheric Turbulence–Part I: Channel Model and Propagation Statistics," Journal of Lightwave Technology **32**, 1075-1087 (2014).

[65] Y. Ren, H. Huang, G. Xie, N. Ahmed, Y. Yan, et al., "Atmospheric turbulence effects on the performance of a free space optical link employing orbital angular momentum multiplexing," Optics Letters **38**, 4062-4065 (2013).