High capacity terahertz communication systems based on multiple orbital-angular-momentum beams

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Abstract
Structured electromagnetic waves carrying orbital angular momentum (OAM) have been explored in various frequency regimes to enhance the data capacity of communication systems by multiplexing multiple co-propagating orthogonal OAM beams (i.e. mode-division multiplexing (MDM)). Terahertz (THz) communications in free space have gained interest as THz waves tend to have: (a) larger bandwidth and lower beam divergence than millimeter-waves, and (b) lower interaction with matter conditions than optical waves. In this paper, we review recent experimental demonstrations of OAM-based THz MDM communication systems, including (a) THz MDM system with two multiplexed OAM beams; (b) THz OAM multiplexing together with frequency-division-multiplexing and polarization-division-multiplexing; (c) multiplexing a full set of two-dimensional Laguerre–Gaussian ($\text{LG}_{\ell,p}$) beams; and (d) THz integrated OAM emitter for OAM mode generation and multiplexing. System performance of THz OAM links with the effect of turbulence, divergence, and multipath is also simulated and analyzed.

Keywords: orbital-angular-momentum, multiplexing, THz communication

(Some figures may appear in colour only in the online journal)
1. Introduction

Structured electromagnetic (EM) waves have gained much interest, partially due to their unique spatial beam structures with tailored amplitude and phasefronts [1, 2]. One type of structured EM waves is a vortex beam carrying orbital angular momentum (OAM) [1, 3]. Typically, OAM beams can be characterized by (a) a helical phasefront that ‘twists’ as it propagates, (b) a mode index \( \ell \) (i.e. OAM mode values) that represents the number of \( 2\pi \) phase shifts in the azimuthal direction, and (c) a ring-like intensity profile with a central null and the size of the ring grows with \( \ell \) [3–6]. OAM beams can be considered as a subset of the two-dimensional (2D) Laguerre Gaussian (LG) modal basis [3–6].

EM beams with different OAM values are inherently orthogonal to each other. This orthogonality of OAM beams is important for communication applications. This implies that multiple independent data-carrying OAM beams with different OAM orders can be multiplexed at a transmitter aperture, spatially co-propagate, and be demultiplexed at a receiver aperture with little inherent channel crosstalk [6–8]. Therefore, the system’s data capacity can be multiplied by the number of multiplexed beams. Moreover, since all data-carrying beams are located at the same frequency band, the spectral efficiency (i.e. bits/sHz) also increases [6–8]. This data-multiplexing approach using multiple beams is a type of mode-division multiplexing (MDM), which is a subset of space-division multiplexing [6].

Such OAM-based MDM communications have been investigated and demonstrated for both free-space and fiber systems in the optical domain [6–8]. Although much work has focused on optical OAM beams, it has been shown that other EM and mechanical waves across different frequency regimes, including microwaves, millimeter waves, and acoustic waves, can be structured to carry OAM for OAM-based communications [9–16].

In terms of other frequency regimes, an area of increased recent interest is the free-space communications in the terahertz (THz) frequency regimes [17–28]. This is partially motivated by the following issues: (a) compared to millimeter waves, THz can potentially provide a more usable spectrum for communications and has lower beam divergence for longer distance transmission [27] and (b) compared to optical waves, THz generally has a lower interaction with matter and is less affected by deleterious link conditions (e.g. atmospheric turbulence, rain, and fog) [20, 29]. Therefore, there could be significant interest in utilizing OAM beams for THz data communications.

In this article, we review recent experimental demonstrations of THz communication systems based on OAM multiplexing, including (a) THz MDM system with two multiplexed OAM beams; (b) THz OAM multiplexing together with frequency-division-multiplexing (FDM) and polarization-division-multiplexing (PDM); (c) multiplexing a full set of 2D Laguerre–Gaussian (LG\( \ell_p \)) beams; and (d) THz integrated OAM emitter for OAM mode generation and multiplexing. System performance of THz OAM links with the effect of turbulence, divergence, and multipath is also simulated and analyzed.

2. Background of OAM and its applications in communications

A light wave can carry OAM when its wavevector spirals around the beam’s propagation axis and forms a ‘twisted’ helical spatial phase front, as shown in figure 1. Such a helical phase front can be described as \( \exp(i\ell \phi) \), where \( \phi \) is the azimuthal coordinate and \( \ell \) is the number of \( 2\pi \) phase shifts in the phase profile of the beam [3, 4]. In addition, the value of \( \ell \) (i.e. OAM order) represents the amount of OAM carried by the beam and the positive or negative sign of \( \ell \) corresponds to the clockwise or counterclockwise direction of the phase helices, respectively. An OAM beam with a nonzero \( \ell \) usually has a donut-shaped intensity spatial profile with a central null, which is due to the phase singularity in such a helical phase profile [3, 4]. OAM beams with different OAM orders are orthogonal to each other while propagating co-axially. Theoretically, OAM can be quantified as an infinite number of orthogonal states [3, 4].

The orthogonality of different OAM modes enables MDM communication systems using multiple OAM beams. As shown in figure 2, in an OAM-based MDM system, \( N \) OAM beams with different OAM orders are used to carry \( N \) different independent data streams. The data-carrying OAM beams are spatially multiplexed and simultaneously propagated over the same spatial medium between a single pair of transmitter/receiver aperture [6]. At the receiver, different data channels can be efficiently demultiplexed with little inherent crosstalk because of the mutual orthogonality between different data-carrying OAM beams [6]. As a result, the system’s data capacity and spectral efficiency (i.e. bit/sHz) can be multiplied by a factor of \( N \). Moreover, OAM multiplexing is generally compatible with other multiplexing techniques, e.g. PDM and wavelength/frequency division multiplexing (WDM/FDM). Therefore, in a PDM or WDM/FDM system, multiple orthogonal data-carrying OAM beams could be located at each polarization or wavelength/frequency, thus further increasing the spectral efficiency and the data capacity [30–32]. We note that OAM can also be utilized for encoding systems, where different OAM beams are transmitted as different data bits within discrete time windows. Different orthogonal OAM beams can create a large alphabet for possible data symbols [5, 33]. However, this paper will mainly discuss utilizing OAM beams for THz MDM communications.

In general, OAM beams can be considered as a subset of the 2D LG\( \ell_p \) modal basis, as shown in figure 3, which is characterized by two spatial modal indices: (a) azimuthal index \( \ell \), representing the OAM order, and (b) radial index \( p \), representing the number of concentric intensity rings in the beam [3, 4, 34]. Theoretically, 2D LG modes with different \( \ell \) and/or \( p \) values are orthogonal to each other and form a 2D spatial modal basis set. In general, a structured beam can be decomposed into...
Figure 1. The wavefront, intensity and phase profile of OAM modes with OAM order $\ell = 0, 1, 2, \text{ and } 3$. The OAM mode with a nonzero order has a helical wavefront and a ring-like intensity profile. The value of $\ell$ represents the number of $2\pi$ phase shifts in the azimuthal direction. The OAM beam with a larger $\ell$ has a larger ring-shaped intensity profile. We note that OAM modes (with $p = 0$) are a subset of 2D complete LG$_{\ell,p}$ modal basis with two mode indices $\ell$ and $p$. For LG beams, $p + 1$ represents the number of concentric amplitude rings. Reprinted with permission from [4] © The Optical Society.

Figure 2. Concept of OAM-based MDM communication systems. (a) Multiple OAM beams are coaxially transmitted between a single pair of apertures. Reproduced from [11], with permission from Springer Nature. (b) Each orthogonal OAM beam carries an independent data stream, thereby multiplying the data capacity by the number of multiplexed beams. Reproduced from [7], Copyright © 2012, Nature Publishing Group.

3. Communications and OAM beams in the THz range

In the past few decades, free-space communication systems have been investigated for different frequency regimes. As shown in figure 4, for communication systems with carrier different frequencies, there tends to be a trade-off between the beam divergence and interaction with matters: (a) lower frequencies have higher beam divergence, and (b) lower frequencies tend to have lower interaction with matter. Since the frequency of THz wave is higher than that of mm-wave but lower.
In this section, we will introduce the generation and detection approaches for the THz data signal and THz OAM beams. In addition, we will discuss system degradations for OAM-based THz communications considering beam divergence and atmospheric turbulence distortion.

3.1. Communications in the THz region

One challenge of implementing THz communications is the efficient generation and detection of high-data-rate THz beams [19]. Recently, both electronics- and/or photonics-based approaches have been demonstrated for single-beam THz free-space communications [20]. In this paper, the experimental demonstrations are mainly achieved by a system with (a) photonic-assisted signal generation and (b) electronic signal detection techniques, as shown in figure 5.

(a) Optoelectronic transmitter (Tx) using photonic techniques: Photonic-assisted techniques with telecommunication devices can be used to generate high-baud-rate data-carrying THz waves with a flexible tuning range [18–23, 26–28]. At the Tx, Laser 1 can be modulated with a high-speed data stream of different modulation formats (e.g. quadrature-phase-shift-keying (QPSK) or quadrature amplitude modulation (QAM)) using an in-phase and quadrature modulator. The data channel is thus combined with a continuous-wave (CW) light generated by Laser 0 with a frequency difference of $\Delta f$. After being amplified by an optical amplifier, the optical waves are mixed in an optical heterodyne photomixer. This mixer functions as a THz emitter. It converts the mixed optical signal to a THz data-carrying wave with a carrier frequency of $\Delta f$ and emits the THz Gaussian waveform into free space through an antenna.

(b) Electronic receiver (Rx): At the Rx, a common practice of using electronic devices can help detect THz signal with a high data rate [18–20, 22, 23, 26–28]. Using a horn antenna to collect the THz waveform, the received THz signal can be amplified through a low-noise THz amplifier. Subsequently, the THz signal will be down-converted to the intermediate frequency (IF) domain using a sub-harmonic down-converter. The IF data signal will be recorded with a real-time digital oscilloscope, and the signal will be processed for data information recovery and analysis.

3.2. OAM generation and detection in the THz region

Because the THz frequency lies between the mm-wave and the optical frequencies, similar concepts for the generation/detection of mm-wave/optical OAM beams could be applied to THz regimes. However, they also require some unique features in the THz region. In recent years, there have been experimental demonstrations for free-space THz OAM generation and detection [41]. These techniques could potentially be utilized in OAM-based THz MDM communication systems. Examples are shown in figure 6.

As shown in figure 6(a), the spiral phase plate (SPP) is one of the simple and straightforward structures for OAM
A typical SPP could be fabricated using dielectric materials with its thickness corresponding to the azimuthal spatial phase of the OAM beams $H = \ell \varphi \lambda / 2\pi (n - 1)$, where $\varphi$ is the azimuthal angle and $n$ is the refractive index of the dielectric material [15, 16, 43–45]. A THz Gaussian beam transmitting through the SPP will be converted to a THz OAM beam. In order to detect a THz OAM beam, a reverse SPP with the thickness proportional to $-\ell \varphi$ could be used to convert the OAM beam back to a Gaussian beam. SPPs could be easily fabricated by 3D printing or computer numerical control machining. However, since a single SPP can usually generate one OAM beam with a single input Gaussian beam, it requires the use of beam splitters (BSs) to multiplex and demultiplex OAM beams. This will induce combining loss proportional to the number of the modes used for multiplexing.

The metasurface could be another approach for THz OAM generation and detection with reduced size and thickness [14, 46–48], as shown in figure 6(b). A metasurface is typically composed of a 2D array of diffractive elements with variant sub-wavelength structures, each inducing a different phase shift, along the azimuthal direction. By engineering the metasurface, the thickness and size of different types of metasurface-based OAM converters could be greatly reduced. Moreover, OAM beams with different orders can be generated independently for input beams with different polarizations or different incident angles [49, 50]. Similar to the SPPs, as passive reciprocal devices, THz metasurfaces could also be used reversely to demultiplex and detect OAM beams.

Other than spatially converting input beams for generating OAM beams, a structure of uniform circular array (UCA) with multiple phased array antennas can directly generate OAM beams with tunable orders. UCAs have been previously widely demonstrated in the mm-wave regimes. A typical UCA has multiple circularly symmetric antennas. To generate OAM beams, the input signal will be firstly split into different copies, each adding a different phase delay, and then different copies of the signal will be fed into the corresponding antennas. Similarly, the phase delay of each antenna also follows the relationship of $\ell \varphi$. To generate and multiplex different signals each on a different OAM mode, specially designed couplers with multiple input ports (e.g. star coupler [52] and Butler matrix [53, 54]) can be used to combine different signal channels and provide different phase delays for different OAM modes. The same scheme can also be reversely used to demultiplex and detect OAM modes [52–54]. The signals carried by different OAM modes can be received by the UCAs and sorted to the corresponding coupler ports as outputs.

Recently, such a structure was used for THz OAM generation in a THz OAM-encoding system. Figure 6(c) shows a prototype of the complementary metal-oxide-semiconductor (CMOS) THz UCA. This high-frequency chip can directly generate and detect THz OAM beams with tunable OAM states [51]. By encoding different OAM states with different bits, an OAM-encoded link can be achieved with $\sim$Mbit s$^{-1}$. Since the THz wave from different antennas is coherently combined with the carrier frequency of hundreds of GHz, accurate phase different control between different antennas is
required. Future exploration might be required for using THz UCA for high-speed multiplexing systems.

Laudable goals for future OAM converter design might include: (a) increasing the conversion efficiency of the mode generation and detection; (b) generating and multiplexing multiple OAM modes with different inputs using a single device; (c) achieving tunable and reconfigurable generation and detection of different OAM modes; and (d) reducing the size and weight of the mode converter.

4. System performance analysis in OAM-based THz links

In general, OAM-based free-space communications have been investigated in various frequency regimes. There tend to be different key challenges for OAM-based communications implemented in different frequency regimes. These challenges could potentially induce system degradations, such as power loss and channel crosstalk.

One challenge is atmospheric turbulence, as shown in figure 7(a), which can induce amplitude and phase distortion on the OAM beams. This kind of random turbulence can cause distortions on the intensity and phase profiles of OAM beams along both azimuthal and radial directions. Therefore, it would induce modal power coupling from the transmitted mode to other modes with different azimuthal ($\ell$) and radial ($p$) indices [55]. This power coupling could induce channel crosstalk, which degrades the performance of an OAM-based MDM system [55].

Another challenge is beam divergence. The divergence of OAM beams increases with the OAM orders [56]. Therefore, when the receiver aperture size is limited, it becomes more difficult to capture the whole higher-order OAM beams due to the beam truncation. Such beam truncation can induce significant power loss. Moreover, the beam truncation by a circular limited-size receiver aperture could further cause modal power coupling from the transmitted mode to some LG modes with different $p$ values [57], as shown in figure 7(b). In addition, if the limited-size receiver aperture is misaligned with the incoming OAM beam, the receiver will not be able to ‘distinguish’ the transmitted modes, thereby inducing power coupling to other undesired LG modes (both $\ell$ and $p$ modes) [57].

Importantly, for different frequencies, there tends to be a trade-off between the beam divergence and turbulence-induced degradation, as shown in figure 8. The wavelength of THz waves is located between that of mm-wave waves and optical waves. This can cause divergence and turbulence degrading the performance of THz OAM links that are not similar to optical and mm-wave frequencies [57–59]. In this section, we discuss turbulence-induced degradations and beam divergence-induced multipath and receiver aperture effects in OAM-based THz links.

4.1. Turbulence-induced degrading effects for THz-OAM communications

Turbulence can induce degrading effects for THz communications based on OAM beams. These effects have been numerically simulated in [59]. As shown in figure 9, at higher frequencies, atmospheric turbulence can induce greater distortion and power coupling for THz OAM beams. For instance, at 10 THz frequency, the OAM beam experiences
losses are simulated when varying the OAM order. To
in the case of considering the same atmospheric structure con-
vergence; however, the
for instance, at higher frequencies, the beam has lower diver-
ence, thereby resulting in higher values of
beams at different frequencies have the same value of
beams at different frequencies. OAM

Figure 9. Simulation results: OAM spectra and beam profiles for
different THz OAM beams under (a) weaker and (b) stronger
turbulence effects. (Transmitted OAM order of \( \ell = +4 \), beam waist
of \( w_0 = 1 \) m, and link distance = 1 km for all the cases. Weaker
turbulence: \( C_n^2 = 1 \times 10^{-13} \text{ m}^{-2/3} \); stronger turbulence:
\( C_n^2 = 1 \times 10^{-11} \text{ m}^{-2/3} \)). Reproduced from [59]. CC BY 4.0.

Figure 10. The normalized power distribution of different OAM
modes at different frequencies. OAM +4 with beam waist \( w_0 \) of
0.1 m is transmitted over a 200 m link when (a) \( D/r_0 \) = 0.224, and
(b) \( C_n^2 = 1 \times 10^{-11} \text{ m}^{-2/3} \) XT1: modal crosstalk to the
right-(higher)-nearest mode. XT2: modal crosstalk to the
second-nearest mode. Reproduced from [59]. CC BY 4.0.

distortion for both cases of weaker (\( C_n^2 = 1 \times 10^{-13} \text{ m}^{-2/3} \))
and stronger turbulence (\( C_n^2 = 1 \times 10^{-11} \text{ m}^{-2/3} \)). However, at
a frequency of 0.1 THz, an OAM beam is much less distorted
and experiences lower modal power coupling under stronger
turbulence.

Furthermore, the turbulence effects on signal power and
crosstalk of OAM beams for THz communications over \( \sim 0.1-10 \) THz were simulated and analyzed. First, as shown in
figure 10(a), the case in which different frequencies have the
same transmitted beam size \( D \) and a fixed value for the Fried
parameter \( r_0 \) is considered. As a result, the phase distortion
is similar for different frequencies. Here, XT1 and XT2 are
referred to as the power coupling to the right-(higher)-nearest
and second-nearest modes, respectively. Note that the power
coupling values are normalized by the received power on the
transmitted OAM mode (\( \ell = +4 \)). In this case, the transmitted
beams at different frequencies have the same value of \( D/r_0 \),
where the XT1 and XT2 values decrease at higher frequencies.
This could be due to the faster divergence of OAM beams at
lower frequencies, thereby resulting in higher values of \( D/r_0 \)
for OAM beams at low frequencies and, consequently stronger
phasefront distortion as well as larger modal power coupling
[49, 50].

Subsequently, the XT values are analyzed over the fre-
quency range of \( \sim 0.1-10 \) THz when considering the same
atmospheric structure constant \( C_n^2 \). Here, both the beam size
\( D \) and the Fried parameter \( r_0 \) are frequency dependent. Con-
sequently, the \( r_0 \) value increases at lower frequencies [49].
This can be explained by the dependency of the phase distor-
tion \( D/r_0 \) to both \( D \) and \( r_0 \) values. As shown in figure 10(b),
for instance, at higher frequencies, the beam has lower diver-
gence; however, the \( r_0 \) value also decreases further. Therefore,
in the case of considering the same atmospheric structure con-
stant, the values of \( D/r_0 \) increase with frequency, thereby lead-
ing to higher phase distortion and modal coupling.

Moreover, the cases considering the atmospheric absorp-
tion losses are simulated when varying the OAM order. To
analyze the power of different OAM modes: (a) a multiple-
phase plate model is considered; and (b) the power values
are subtracted by the molecule absorption loss [61]. The total
absorption loss follows the expression of \( \text{Loss} = \alpha_L L \)
in which the \( \alpha_L \) is the frequency-related coefficient (e.g. \( \sim 0.11 \text{ B m}^{-1} \) at
0.5 THz), and \( L \) is the free-space propagation distance [61].
In figure 11, the signal power and XT1 values for OAM +1, + 4,
and + 9 modes are obtained: (a) with and without considering
atmospheric absorption, and (b) when free-space propagation
is from 100 m to 1 km. The results indicate that: (a) at a given
propagation distance, higher-order OAM modes experience
lower signal power and higher XT1; and (b) as the propaga-
tion distance increases, higher-order OAM modes tend to have
a faster reduction of the signal power; nevertheless, a faster
increase of XT1. This might be because higher-order OAM
modes, compared with lower-order modes having the same
beam waist, (a) have larger beam diameters and consequently
higher values of \( D/r_0 \) at the transmitter side, thereby having
larger distortion, and (b) diverge faster, resulting in higher
beam sizes after propagation. This results in a higher \( D/r_0 \) and
leads to a stronger distortion. As can be seen from figures 11(c)
and (d), the signal power decreases by \( >100 \text{ dB} \) compared
with the case without considering the atmospheric absorption.
However, considering the effect for different OAM modes, the
signal powers follow the same trend and the XT1 tends to be
unchanged.

In conclusion, the atmospheric turbulence would have
a stronger effect on the THz waves at higher frequencies.
In addition, considering a similar phase distortion \( D/r_0 \),
faster divergence results in higher modal power coupling
from the transmitted mode to neighboring modes. How-
ever, when concerning the same atmospheric structure con-
stant \( C_n^2 \), the divergence tends to have less effect, and the
power leakage is proportional to \( D/r_0 \) (Note that \( D/r_0 \) increases with frequency, beam waist, and OAM order). Thus,
considering the same turbulent atmosphere, there might be a
trade-off between the crosstalk performance and carrier wave
frequency. Furthermore, the turbulent atmosphere might limit the number of OAM modes that can be multiplexed for THz OAM communications. The channel capacity could be potentially increased by multiplexing more OAM modes with higher OAM orders. Nevertheless, the channels carrying higher-order modes could have higher crosstalk and power loss, thereby degrading the system performance.

Atmospheric turbulence can induce power loss and channel crosstalk to OAM-based THz communication systems. To mitigate the influence of atmospheric turbulence, different approaches might be inspired by recent advances in the optical ranges. For example, the turbulence effect might be potentially compensated by (a) compensating the phase distortion of the received beam using THz wavefront shaper with the sensing of turbulence-induced distortions [62–66]; (b) channel equalization using digital signal processing to reduce the channel crosstalk caused by the turbulence effects [67]; and (c) retrieval of the scattering matrix caused by the distortion medium, and then performing the pre- or post-compensation on the OAM beams [68–72].

4.2. Multipath and receiver aperture effects in THz-OAM links

For THz wireless communications, due to the beam divergence, the surrounding objects could partially reflect the beam during the propagation. At the receiver, the directly propagating beam and the reflected beam would interfere with each other and cause multipath effects and degrade the system performance. OAM beams generally have larger divergence as compared to Gaussian beams and are more likely to suffer from multipath effects. Figure 12 illustrates a simplified case of multipath effects on THz communication links using OAM beams with limited-size-aperture transmitters and receivers [57]. As shown in figure 12(a), an OAM beam of order \( \ell \) is transmitted from the Tx. A reflector (with a planar reflection of 100% reflectivity) is placed in parallel to the propagating beam. In this case, due to divergence, some of the OAM beam will be reflected by the reflector (i.e. reflected field), while the rest propagates directly to the receiver (i.e. direct field). The coherent sum of the direct fields and reflected fields refers to the total field. At the receiver, it will be cropped by the receiver aperture. The beam profiles of the direct, reflected, and total field (OAM +3 is transmitted as an example) are shown in figure 12(b). In this investigation, the propagation of the OAM beams is simulated by Fresnel diffraction. Furthermore, the wavefront of the reflected beam is regarded as a laterally truncated OAM beam with an opposite order \(-\ell\) transmitted from an image transmitter (Tx‘) [57, 73]. As presented in figure 12, the wavefront of the directly propagated beam is laterally truncated and reflected by the reflector during its propagation. Due to the divergence of the beam, an increasing portion of the beam will be reflected along the propagation distance. The direct and reflected fields interfere, resulting in interference fringes in the total field. The received beam profile along the radial direction is also truncated if the Rx has a limited aperture size. As a result, the interference and intensity/phase distortion will cause the modal coupling to neighboring

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Figure 11. (a) The received signal power and (b) XT1 for different OAM modes. Figures (c) and (d) are the corresponding signal power and XT1 when considering the atmospheric absorption loss. (Link distance = 1 km, \( C_n^2 = 1 \times 10^{-11} \) m\(^{-2/3}\), \( f = 0.5 \) THz, and \( w_0 = 0.1 \) m at the transmitter side). Reproduced from [59]. CC BY 4.0.

Figure 12. (a) Schematic of multipath effects in a THz OAM link. The transmitted OAM beam can get reflected by a reflector placed in parallel with the propagation direction. (b) Intensity and phase profiles of the direct, reflected, and total fields in the multipath effect when OAM +3 is transmitted. The reflector is assumed to be perfect metal and can purely reflect the beam. Reproduced from [57]. CC BY 4.0.
modes and induce both intra- and inter-channel crosstalk for a THz OAM multiplexing system.

We note that our approach is an approximation of the propagation and reflection of the OAM beam. In this case, we adopt that there might be some inaccuracy in the simulation results, for example, the phase and intensity shift of OAM beams caused by the reflection is not considered [74]. In the mm-wave range, an experimental multipath investigation was performed with a similar system configuration [73]. This might provide some evidence to indicate that the simulation model is a reasonable approximation at a large physical scale.

Figure 13 shows the frequency dependence of the received power and intra-channel coupling caused by the multipath and receiver aperture effects. Figures 13(a) and (b) show the received power at different frequencies for the Gaussian and OAM +3 beams. For the direct path, the received power of Gaussian and OAM +3 beams increases by \( \sim 28 \) dB and \( \sim 110 \) dB, respectively, when the frequency increases from 100 GHz to 1000 GHz. This could be because the coupling power of the direct field mainly depends on the beam divergence, and a higher frequency or lower OAM mode tends to have a smaller divergence and, thus, a larger portion of the beam is detected without truncation. The received power of the Gaussian beam for the reflected path decreases with a higher frequency. However, for OAM +3, the received reflected power first increases with the increase of \( f \) from 100 GHz to 200 GHz. When \( f \) further increases to 1000 GHz, the received reflected power decreases. This phenomenon could be due to the ring-shaped intensity profile of OAM beams in combination with the offset of the aperture from the center of the ring shape. The insets of figures 13(a) and (b) show the intensity profiles of the reflected field for Gaussian and OAM +3 beams at frequencies of 100 GHz, 200 GHz, and 400 GHz. The overlap between the receiver aperture and the reflected OAM beam (i.e. receiver reflected power) first increases and then decreases with an increase in frequency since there is little power at the center of the OAM beam. Therefore, for the intra-channel, a combination of the frequency and the system configuration needs to be taken into consideration for an OAM-based THz link.

5. Experimental demonstration of OAM-based MDM THz communication systems

In this section, we review several recent experimental demonstrations of OAM-based THz communication systems. First, we show the basic concept and schematic diagrams of these systems. Subsequently, we provide a detailed description and discussion of different experiments, including (a) THz MDM communications with two multiplexed OAM beams; (b) demonstration of the compatibility of OAM-based MDM with FDM and PDM; (c) multiplexing a full set of 2D LG beams varying two different modal indices (i.e. both \( \ell \) and \( p \)); and (d) THz integrated OAM emitter to potentially reduce cost, size, weight, and power consumption.

5.1. Concept and schematic diagrams of photonics-assisted OAM-based MDM THz communications

Figure 14(a) shows the conceptual diagram for the generation, transmission, and detection of a THz data channel carried by a single OAM beam [30]. At Tx, a data modulated light and a CW light are photomixed in a photodiode (PD) to generate a THz data channel. The carrier frequency \( f_{THz} \) of the generated data channel is equal to the frequency spacing \( \Delta f \) of the two laser light. The generated data channel is transmitted to free space using an antenna and carried by a THz Gaussian beam (\( \ell = 0 \)). After propagating through a specific SPP, the THz Gaussian beam is converted to a THz-OAM beam with a specific OAM order (\( \ell = \ell_1 \)).

At the receiver (Rx), an inverse SPP with a specific state (\( -\ell_1 \)) is used to convert the OAM beam back to a Gaussian-like beam (\( \ell = 0 \)) with a planar phasefront [11]. The converted

![Figure 13. Simulated received power with (a) the Gaussian (\( \ell = 0 \)) and (b) OAM +3 beams transmitted. The reflector distance \( h = 30 \) cm, transmitted beam waist \( w_0 = 5 \) cm, aperture radius \( r = 10 \) cm, and the propagation distance \( L = 40 \) m. Inset figures show the reflected field at the frequency of 100, 200, and 400 GHz for transmitted (a) Gaussian and (b) OAM +3 beam. Reproduced from [57]. CC BY 4.0.](image-url)
Figure 14. A schematic overview of THz communication links using OAM multiplexing. (a) The generation, transmission, and detection of a data-carrying THz OAM beam, including (i) data channel generation in the optical domain, (ii) OAM generation/detection, (de)multiplexing, and transmission in the THz domain, and (iii) data channel detection and recovery in the intermediate frequency (IF) domain. (b) A THz OAM-multiplexed communication link with multiplexing of two OAM beams each carrying an independent data channel. Two THz OAM beams with different OAM orders ($\ell_1$ and $\ell_2$) are generated by SPPs, spatially multiplexed using a THz BS, and coaxially propagate simultaneously. (c) A THz link combining PDM, FDM, and OAM multiplexing. THz FDM channels are generated by mixing WDM channels with a CW laser. PDM is achieved by combining two beams with different polarizations using a polarization beam splitter (PBS). Reproduced from [30]. CC BY 4.0.

Gaussian-like beam is highly mode-matched to the receiver’s antenna and thus can be efficiently coupled into the receiver. A THz low-noise amplifier is used to amplify the captured THz data channel and, subsequently, the data channel is down-converted to the IF using a sub-harmonic down-converter. The IF data signal is recorded with a real-time digital oscilloscope and processed using an off-line digital signal processing (DSP) for data information recovery and analysis.

Figure 14(b) shows a system-type diagram for a THz OAM-multiplexed link using two different OAM beams [30]. At the Tx, two positive-intrinsic-negative (PIN)-PD-based THz emitters are used to generate two THz Gaussian beams with each beam carrying an independent data channel (Ch1 or Ch2). The two THz data channels are located at the same THz carrier frequency $f_{\text{THz}} = 0.3$ THz and on the same polarization [75, 76]. Two THz OAM beams with different OAM orders ($\ell_1$ and $\ell_2$) are generated by different SPPs, and then spatially multiplexed using a THz BS, and coaxially propagate simultaneously toward the Rx. At the Rx, the received OAM beams are split into two copies, where each copy is mode-wise demultiplexed and converted into a Gaussian-like beam by an SPP that has a design inverse to that of the SPP used at Tx. Then, the two Gaussian-like data-carrying beams are coupled into the antenna for signal detection.

Additionally, a system diagram that combines PDM, FDM, and OAM multiplexing in a THz link is shown in figure 14(c) [30]. At the Tx, THz FDM channels located at the spectral vicinity of 0.3 THz are first generated by mixing optical WDM data channels with a frequency-offset CW laser in the PIN-PD-based THz emitter. Since the frequency spacing between each
WDM channel and the CW laser is different, each channel is independently converted to a different THz carrier frequency [20, 30]. Subsequently, PDM is achieved by combining two FDM-modulated THz beams with different linear polarizations using two THz polarization BSs (PBSs). After FDM and PDM, two different SPPs designed for 0.3 THz are used to convert the two multiple frequencies, doubly polarized outputs to OAM beams. Finally, OAM multiplexing is again achieved by a THz BS. At the Rx, the received OAM beams are mode-demultiplexed using conjugated SPPs and each converted Gaussian-like beam is polarization demultiplexed using a PBS. After down-conversion to the IF domain, the FDM channels are separated by digital filtering using DSP.

5.2. Demonstration of a THz link using two multiplexed OAM beams

5.2.1. Characterization of generated THz OAM beams. The normalized beam intensity profiles and interferograms for a Gaussian beam (\( \ell = 0 \)) and OAM beams with \( \ell = +1, -2, \) and +3 are shown in figures 15(a) and (b). For the generated beams with a non-zero OAM order (\( \ell \neq 0 \)), ring-shaped spatial power distributions are observed in the measured normalized intensity profiles. The undesired pattern can be observed on the bottom of the Gaussian beam and generated OAM beams’ profiles, which might be caused by the imperfect Gaussian beam emitted from the PIN-PD-based THz emitter [75]. Interferograms are generated by interfering the OAM beams with a coaxial Gaussian beam using BSs [11]. In the interferograms, the number of rotating arms and the rotating direction (clockwise or counterclockwise direction) corresponds to the OAM mode order and their signs.

To characterize the modal purities of the generated OAM beams, the OAM spectra (the power contents of different OAM components in the examined beam) are measured by recording the received IF power after propagating the beam through different SPPs. As shown in figure 15(c), there is power coupling to other undesired modes, and the maximum power leaked to undesired modes is \( \sim 10 \) dB lower than that of the desired mode, which is probably because the imperfect Gaussian beam emitted from the THz emitter is not being converted to a ‘pure’ OAM beam. Compared to the Gaussian beam (without SPPs at both Tx and Rx), an increase in the Gaussian-to-OAM conversion power with the mode order value of \( |\ell| \) is observed (e.g. \( \sim 7 \) dB loss for OAM \( \ell = +3 \)). This might be due to the following reasons: (a) the generated beam through an SPP is a superposition of LG modes with the same azimuthal index \( \ell \) but a range of radial indices \( p \) [4, 77], and (b) the beams with a larger \( |\ell| \) have larger beam divergence and might experience more severe beam truncation induced by the Rx aperture [56], also contributing to larger power loss and power coupling to other \( p \) modes [57].

5.2.2. Data transmission performance of the THz link using two multiplexed OAM beams. The crosstalk between the two multiplexed beams (OAM +1 and +3) is first measured, as shown in figure 16. The values shown in the crosstalk matrix are normalized received IF power when transmitting different OAM beams and receiving them using different SPPs. The results show a \( \sim 19.6 \) dB modal crosstalk between OAM +1 and OAM +3.

Figure 15. Characterization of generated OAM beams at 0.3 THz. Experimentally measured and simulated (a) normalized intensity profiles and (b) interferograms. (c) Experimentally measured OAM spectra for the generated beams. All power values are normalized to the received power without SPPs at both Tx and Rx. Reproduced from [30]. CC BY 4.0.

Figure 16. Measured channel crosstalk between OAM +1 and OAM +3. The values are received IF power when transmitting and receiving different OAM modes. The measured power is normalized to the maximum value in the crosstalk matrix. Reproduced from [30]. CC BY 4.0.
Figure 17. Measured optical spectrum at the THz transmitter and electrical spectrum after down conversion at the receiver for (a) the 15-Gbaud QPSK signal and (b) the 3-Gbaud 16-QAM signal. The error vector magnitudes (EVMs) and constellation diagrams of the received (c) 15-Gbaud QPSK signal under an signal-to-noise ratio (SNR) of $\sim 13.5$ dB and (d) 3-Gbaud 16-QAM signal under an SNR of $\sim 16.5$ dB. The bit error rate (BER) performance of each data channel for the (e) 15-Gbaud QPSK signal and (f) 3-Gbaud 16-QAM signal. Reproduced from [30]. CC BY 4.0.

The data transmission performance is subsequently evaluated in a THz OAM-multiplexed link using two OAM beams (OAM $+1$ and $+3$). Two cases with different modulation formats and baud rates are considered. Case 1 is a 15-Gbaud QPSK signal per channel, and Case 2 is a 3-Gbaud 16-QAM signal per channel. Figures 17(a) and (b) show the optical spectra at the Tx as well as the electrical spectra at the IF band after the down-conversion at the Rx for Case 1 and Case 2, respectively. Figures 17(c) and (d) show the error vector magnitudes (EVMs) and data constellation diagrams of received QPSK and 16-QAM signals when multiplexing OAM $+1$ and $+3$. Larger EVMs and more blurred constellations can be observed when the two OAM channels are multiplexed, which are induced by the crosstalk. The bit error rate (BER) performance of each data channel is shown in figures 17(e) and (f) for Case 1 and Case 2, respectively. For different signal modulation formats and baud rates, the BER performance for all channels could reach below the 7% hard decision-forward error correction (HD-FEC) limit [79]. Figures 17(e) and (f) show the BER performance of each data channel carried by (a) a single Gaussian beam, (b) a single OAM beam without multiplexing, and (c) such a beam with multiplexing. Specifically, compared to the single Gaussian channel, the case of the single OAM channel (without multiplexing and crosstalk) shows a similar BER performance. When multiplexing OAM $+1$ and $+3$, the signal-to-noise ratio (SNR) penalty induced by the channel crosstalk is $\sim 1.5$ dB for 15-Gbaud QPSK channels and $\sim 2$ dB for 3-Gbaud 16 QAM data channels.

5.3. Demonstration of a THz link combining PDM, FDM, and OAM multiplexing

To show the compatibility of the PDM, FDM, and MDM for THz communications [30], combines two polarizations (X and Y pol.), two frequencies (0.3 and 0.310 THz), and two OAM modes (OAM $+1$ and OAM $+3$) in an eight-channel-multiplexed THz link. Each data channel carries a 5-Gbaud QPSK signal. Figure 18(a) shows the normalized crosstalk between the eight channels. The results indicate that the crosstalk between different polarizations and OAM modes is lower than $-18$ dB. In addition, there is $\sim -30$ dB crosstalk between different frequencies. Figure 18(b) shows the input optical spectrum of the WDM data channels and the received electrical spectrum of the down-converted FDM channels. Figure 18(c) shows the EVMs and data constellations of the received channel on the Y pol., 0.3 THz carrier frequency, and OAM mode of $\ell = +3$ with a received SNR of 12.5 dB. Compared to the case of transmitting a single OAM channel, the data constellation becomes more blurred, and EVMs increase from 27.9% to 33.7% with OAM multiplexing, PDM, and FDM, which is due to the crosstalk between different channels. Figure 18(d1) shows the measured BER...
for the data channel on Y pol., 0.3 THz carrier frequency, and OAM mode of \( \ell = +3 \). In a link transmitting a single data-carrying beam (without crosstalk), the data channel carried by OAM \( \ell = +3 \) has a performance similar to that carried by a Gaussian beam. When multiplexing two OAM beams, the crosstalk from the other OAM modes \( \ell = +1 \) would induce a \( \sim 1 \) dB SNR penalty at the FEC limit. In addition, an additional \( \sim 0.5 \) dB and a negligible SNR penalty is observed, which are caused by the crosstalk between two polarizations (PDM) and two frequencies (FDM), respectively. Figure 18(d2) shows that the measured BERs for all 8-multiplexed channels could reach the 7% HD-FEC limit and a total data capacity of \( 80 \) Gbit s\(^{-1} \) (8 channels \( \times 5 \) Gbaud/channel \( \times 2 \) bits/symbol = 80 Gbit s\(^{-1} \)) is demonstrated.

5.4. Demonstration of a THz link using two multiplexed LG beams

In [32], a THz communication system using multiplexing of orthogonal THz LG beams having two different modal indices (i.e. \( \ell \) and \( p \)) can be both varied instead of only changing \( \ell \) was demonstrated. Comparing THz communications based on multiplexing LG modes rather than OAM modes as a 1D OAM modal basis set, a larger set of channels and beams could be potentially used for MDM for such THz communication systems [36].

5.4.1. The approach for generating and down-converting LG modes at the THz frequency range. In figure 19, the approaches used to generate and down-convert LG modes at the THz frequency range are illustrated. In figure 19(a1), an incident Gaussian beam is diffracted to a tilted direction compared to its original propagation direction using a grating pattern [80, 81]. The grating pattern has a grating period, which relates to the periodic phase along the \( x \) axis. To redirect the incident beam in different directions, the grating period can be tailored. Moreover, to attenuate the beam, the grating efficiency can be manipulated. In addition, in figure 19(a2), a Gaussian beam can be modulated to an OAM beam using an SPPs with a helical phased pattern.

Figure 19(a3)–(a4) shows how to modulate a Gaussian beam to an LG beam using the complex-amplitude modulation approach. In this approach, a phase pattern (PP) is created by (a) combining an SPP and a diffraction grating, and (b) subsequently, multiplying the resultant by the function of desired LG mode intensity [80, 81]. Consequently, by jointly modulating the phase and amplitude of the input Gaussian beam, the desired LG mode will be generated at a specific diffraction angle and at a given distance.

To down-convert THz LG modes to a Gaussian-like beam, a spatial phase modulation approach is used, as shown in figure 19(b). This approach is used as compared with the inverse of complex-amplitude modulation since spatial phase modulation: (a) does not require a separation distance for detection as well and also detecting the received beam at an angle, (b) can result in higher conversion efficiencies. However, it also has lower mode purities [82]. The photos of generation and down-conversion PPs for LG\(_{1,1}\) and LG\(_{2,0}\) modes are shown in figure 19(c).

5.4.2. Intensity profiles and interferograms of THz LG modes. The intensity profiles of the LG modes with \( \ell \) and \( p \) of \((0,0), (1,0), (2,0), (0,1), (3,0), (1,1), (2,1),\) and \((1,2)\) are obtained in figure 20, both through simulation and experiment at 0.3 THz.
**Figure 19.** (a) The approach to generate THz LG modes. (a1) A Gaussian beam will propagate in a tilted direction after passing through a diffraction grating, $\theta$: diffraction angle. (a2) To generate OAM beams, using an SPP. (a3) To generate LG modes, using complex-amplitude modulation. The PP is created by combining the diffraction grating and SPP and consequently multiplying by a function of the intensity of the desired LG mode. (a4) An incident Gaussian beam will be modulated to an LG mode, using a PP. The modulated portion of the beam at the diffraction angle is the desired LG mode. (b) To down-convert the generated LG mode into the Gaussian-like beam, that is used for recovering data, using a down-conversion PP. (c) The photos of generation and down-conversion PPs of LG $-2,0$ and LG $1,1$ mode. PP: phase pattern. © [2022] IEEE. Reprinted, with permission, from [32].

**Figure 20.** Captured intensity profiles of THz LG modes when $(\ell, p)$ values are from {(0,0), (1,0), (2,0), (0,1), (3,0), (1,1), (2,1), and (1,2)} both through (a) simulation and (b) experiment, respectively. Here, the results are analyzed considering that: (i) the beam propagates 40 cm after the generation PP; (ii) the Gaussian beam has a beam waist of 20 mm; and (iii) the designed beam waist of LG beams is 10 mm. The beamwidth of LG modes is shown in the table, using the experiment. © [2022] IEEE. Reprinted, with permission, from [32].

The results indicate that: (a) the incident Gaussian beam has a width of $\sim$20 mm; (b) the beamwidth of different LG modes equals $\sim$10 mm after the PPs; and (c) only the desired LG mode is considered when the beam is propagated through $\sim$40 cm free-space after the generation PP. Note that the beam profiles of LG modes are sorted based on the value of $|\ell| + 2p$. 

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known as mode order [56, 83, 84]. To calculate the conversion efficiency of LG modes, the power values of the generated beam are normalized by the power values of the incident Gaussian beams. Furthermore, from the intensity profiles, the beam diameters of LG modes are calculated and shown in the table. The results indicate that the number of intensity rings for LG modes equals \( p + 1 \). Moreover, higher-order LG modes may experience: (a) lower conversion efficiency, (b) higher divergence after propagation, and (c) higher power loss [56, 83, 84]. For instance, observing the outer rings of the LG\(_{1,2}\) mode is more difficult as compared to the LG\(_{1,1}\) mode.

### 5.4.3. Experimental results of multiplexing two LG modes for THz communications

The modal crosstalk is evaluated when LG\(_{-2,0}\) and LG\(_{1,1}\) are multiplexed. The crosstalk matrix is shown in figure 21(a). The modal coupling/crosstalk is \( \sim 12 \) dB. Higher-order LG modes (e.g. LG\(_{1,1}\)) experience higher power loss and crosstalk compared to lower-order modes (e.g. LG\(_{-2,0}\)). This can be due to (a) the misalignments in the experimental setup and (b) an increase in beam width for higher-order modes, which results in beam truncation by the limited-sized receiver aperture [56, 83, 84].

In figure 21(b), the data transmission performance when varying SNR is shown when transmitting a 4 Gbit s\(^{-1}\) QPSK signal on each channel. In each of the two paths of the experimental setup, three possibilities for multiplexing are considered as follows: (a) Gaussian beam, (b) single LG beam, and (c) multiplexed LG modes. In all considered cases of multiplexing, BER values below the FEC limit could be reached. The constellation diagrams and EVM of channels when (a) transmitting/receiving Gaussian as well as (b) multiplexing LG\(_{1,1}\) and LG\(_{-2,0}\) modes and receiving LG\(_{1,1}\) mode are shown as an example in figure 21(c). At 10.7 dBm as the input optical power of PIN-PDs, when multiplexing LG modes compared with the transmission of Gaussian modes: (a) the EVM value is higher, and (b) the SNR penalty is \( \sim 0.5 \) dB higher. These higher power penalty and EVM values when multiplexing LG modes might be due to that: (a) the conversion efficiency in the process of generating and down-conversion LG modes is low [85]; (b) the PIN-PD emits an imperfect Gaussian beam; and (c) the divergence and power coupling increases when multiplexing higher-order LG modes [51, 63, 64].

In summary, by multiplexing LG modes instead of OAM modes, a larger set of channels could potentially be used for multiplexing in THz communications. However, when comparing MDM using LG modes with OAM modes, some issues should be considered: (a) as the order of LG modes increases, the divergence and beam size increases, and the conversion efficiency decreases, thereby resulting in an increase in power loss; and (b) the system is more sensitive to the transmitter and receiver misalignments and the beam truncation by the limited receiver aperture size can, which leads to experiencing higher crosstalk and power coupling for the LG channels.

### 5.5. THz integrated circuit for OAM MDM systems

Optical systems have taken advances of using photonic integrated circuits to reduce the cost, size, weight, and power consumption [39, 86]. THz integrated circuits could similarly bring benefits to THz communication systems. For an OAM-based THz MDM system, a laudable goal would be to design a THz integrated circuit that can generate multiple high-speed-data-carrying OAM beams and multiplex them with co-axial propagation direction for transmission. In [87], a silicon THz integrated circuit with a pixel array to multiplex two 10 Gbit s\(^{-1}\) QPSK channels each on a different OAM beam for MDM is demonstrated.

Figure 22 shows the function of the THz integrated OAM emitter. The device has two inputs on the left and right, which can couple THz signals. At the center of the chip, the OAM mode converter can emit two co-axially propagated OAM modes with two different OAM orders vertically to the free space with the two different input ports, respectively. The schematic diagram of the device is shown in figure 23.
There are three regions in the device: (a) two input ports consist of coupling spikes. These inputs can be inserted into WR3.4 hollow metallic waveguides to couple THz signal power from the metallic waveguides. The coupling loss can be achieved relatively low [88]. (b) Two adiabatic tapering structures expand the mode profile with a waveguide size from 280 µm to 3.6 mm. The modal structure inside the taper maintains a single TE00 mode. (c) A pixel-array-based OAM mode converter designed with partial etching can vertically multiplex two data-carrying OAM channels with signals from two different ports [89]. The OAM mode converter has a size of 3.6 × 3.6 mm. The experimental results of the far-field intensity of the generated OAM +1/−1 and interferogram with a Gaussian beam are shown in figure 23.

The normalized received power of two OAM channels is first measured as the crosstalk matrix. The results in figure 24(a) show a ∼−16 dB modal crosstalk between two modes at the center frequency of ∼317 GHz. Figure 24(b) shows the BER performance at different SNRs with a single OAM channel or OAM-multiplexed channels transmitted. Each THz OAM beam carries a 5-Gbaud QPSK signal at ∼317 GHz. For the THz multiplexed OAM link, there are ∼1 dB SNR penalties at the FEC limit caused by the crosstalk between different OAM channels. In total, a 20 Gbit s⁻¹ data rate is achieved for a THz multiplexed free-space OAM link.

6. Summary and discussion

This paper reviews the recent experimental demonstration of OAM-based THz MDM communication systems. We discussed different THz MDM systems, including (a) multiplexing different OAM modes; (b) combining OAM multiplexing and FDM and PDM; (c) multiplexing different 2D LG modes; and (d) using an integrated THz OAM emitter for OAM modes generation and multiplexing. System performance of THz OAM links with the effect of turbulence, divergence, and multipath is also simulated and analyzed.

Similar to potential benefits of OAM-based communication systems in the optical and mm-wave ranges, one might consider that OAM beams would also gain interest in THz communications. We note that the demonstrations of OAM-based MDM communications in this paper are proof-of-concept experiments mainly conducted under laboratory conditions with relatively short link distances and a small number of MDM channels. Outlook about the future directions for OAM-based THz communications may include the following issues:

Divergence: The beam divergence could be a key factor affecting the link distance. In general, beam divergence tends to require larger receiver apertures as link distance increases in order to capture sufficient signal power [56, 90]. Moreover, since the divergence of an OAM beam grows with |ℓ|, higher-order OAM beams tend to require even larger receiver apertures. Wavefront structuring of the transmitted beam might mitigate the limited-size receiver aperture effect [91, 92]. To save size and weight for larger apertures, alternatives to SPPs for THz OAM generation/detection can be considered, such as using antenna-array structures with multiple smaller antenna elements and thinner metasurface structures [12].

Integration: Furthermore, a potential goal for THz OAM communications would be to multiplex more modes and reduce the SWaP. To potentially increase the number of multiplexed OAM beams in the THz MDM systems, designing and utilizing a single compact device that can generate/detect and (de)multiplex multiple data-carrying OAM beams can be considered. Various structures and devices have been demonstrated in optical and mm-wave regimes for multiple OAM channels generation and multiplexing [12, 89, 93, 94], which might potentially inspire the designs for the THz region.
Hybrid system: Moreover, OAM-based communication systems might be benefited from a hybrid system adopting multiple frequency bands. The performance of OAM free-space systems in different frequencies tends to follow a trade-off between beam divergence and wave–matter interaction. Therefore, OAM-based systems might benefit from hybrid technologies over different frequency domains to accommodate different link requirements and conditions [95–97]. In such a system, one of the challenges is to dynamically select and switch the frequency bands for different link conditions. Tunable and broadband components may also need to be further investigated to support such heterogeneous OAM-multiplexed systems, including but not limited to signal emitters/detectors and frequency converters covering a large frequency range.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

[1] Forbes A, de Oliveira M and Dennis M R 2021 Structured light Nat. Photon. 15 253–62
[2] Rubinsztein-Dunlop H et al 2016 Roadmap on structured light J. Opt. 19 013001
[3] Allen L, Beijersbergen M W, Spreeuw R J C and Woerdman J P 1992 Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes Phys. Rev. A 45 8185–9
[4] Yao A M and Padgett M J 2011 Orbital angular momentum: origins, behavior and applications Adv. Opt. Photonics 3 161–204
[5] Gibson G, Courtil J, Padgett M J, Vasnetsov M, Pas’ko V, Barnett S M and Franke-Arnold S 2004 Free-space information transfer using light beams carrying orbital angular momentum Opt. Express 12 5448–56
[6] Willner A E et al 2015 Optical communications using orbital angular momentum beams Adv. Opt. Photonics 7 66–106
[7] Wang J et al 2012 Terabit free-space data transmission employing orbital angular momentum multiplexing Nat. Photon. 6 488–96
[8] Bozovic N, Yue Y, Ren Y, Tur M, Kristensen P, Huang H, Willner A E and Ramachandran S 2013 Terabit-scale orbital angular momentum mode division multiplexing in fibers Science 340 1545–8
[9] Tamburini F, Mari E, Sponselli A, Thiid B, Bianchini A and Romanato F 2012 Encoding many channels on the same frequency through radio vorticity: first experimental test New J. Phys. 14 033001
[10] Spinello F, Someida C G, Ravanelli R A, Mari E, Parisi G, Tamburini F, Romanato F, Coassini P and Oldoni M 2016 Radio channel multiplexing with superpositions of opposite-sign OAM modes AEU—Int. J. Electron. Commun. 70 990–7
[11] Yan Y et al 2014 High-capacity millimetre-wave communications with orbital angular momentum multiplexing Nat. Commun. 5 4876
[12] Sasaki H, Yagi Y, Yamada T, Semoto T and Lee D 2020 Hybrid OAM multiplexing using Butler matrices toward over 100 Gbit/s wireless transmission 2020 IEEE Globecom Workshops (GC Wkshps) (GC Wkshps) pp 1–5
[13] Shi C, Dubois M, Wang Y and Zhang X 2017 High-speed acoustic communication by multiplexing orbital angular momentum Proc. Natl Acad. Sci. USA 114 7250–3
[14] He J, Wang X, Hu D, Ye J, Feng S, Kan Q and Zhang Y 2013 Generation and evolution of the terahertz vortex beam Opt. Express 21 20230–9
[15] Schemmel P, Pisano G and Maffei B 2014 Modular spiral antennas for 0.1-THz orbital angular momentum (OAM) communications OFC 2014 OFC 2014 pp 1–3
[16] Elayan H, Amin O, Shihada B, Shubaik M A and Alouini M-S 2020 Terahertz band: the last piece of RF spectrum puzzle for communication systems IEEE Open J. Commun. Soc. 1 1–32
[17] Nagatsuma T, Horiguchi S, Minamikata Y, Yoshimizu Y, Hisatake S, Kuwano S, Yoshimoto N, Terada J and Takahashi H 2013 Terahertz wireless communications based on photonics technologies Opt. Express 21 23736–47
[18] Koenig S et al 2013 Wireless sub–THz communication system with high data rate Nat. Photon. 7 977–81
[19] Nagatsuma T, Ducournau G and Renaud C C 2016 Advances in terahertz communications accelerated by photonics Nat. Photon. 10 371–9
[20] Hartter T et al 2020 Generalized Kramers–Kronig receiver for coherent terahertz communications Nat. Photon. 14 601–6
[21] Jia S et al 2018 0.4 THz photonic-wireless link with 106 Gb/s single channel bit rate J. Lightwave Technol. 36 610–6
[22] Peng X et al 2016 260 Gbit/s photonic-wireless link in the THz band 2016 IEEE Photonics Conf. (IPC) 2016 IEEE Photonics Conf. (IPC) pp 1–2
[23] Peng X et al 2022 Bridging the terahertz gap: photonics-assisted free-space communications from the submillimeter-wave to the mid-infrared J. Lightwave Technol. 1
[24] Zhang L, Pang X, Jia S, Wang S and Yu X 2020 Beyond 100 Gb/s optoelectronic terahertz communications: key technologies and directions IEEE Commun. Mag. 58 34–40
[25] Jia S et al 2022 Integrated dual-laser photonic chip for high-purity carrier generation enabling ultrafast terahertz wireless communications Nat. Commun. 13 1388
[27] Jia S, Yu X, Hu H, Yu J, Guan P, Ros F D, Galili M, Morikata T and Oxnolsw K L 2016 THz photonic wireless links with 16-QAM modulation in the 375–450 GHz band Opt. Express 24 23777–83
[28] Yu X, Jia S, Hu H, Galili M, Morikata T, Jepsen P U and Oxnolsw L K 2016 160 Gbit/s photonic wireless transmissions in the 500–500 GHz band APL. Photonics 1 081301
[29] Su K, Moeller L, Barat R B and Federici J F 2012 Experimental comparison of terahertz and infrared data signal attenuation in dust clouds J. Opt. Soc. Am. A 29 2360–6
[30] Zhou H et al 2022 Utilizing multiplexing of structured THz beams carrying orbital-angular-momentum for high-capacity communications Opt. Express 30 25418–32
[31] Huang H et al 2014 100 Thbit/s free-space data link enabled by three-dimensional multiplexing of orbital angular momentum, polarization, and wavelength Opt. Lett. 39 197
[32] Minoofar A et al 2022 Experimental demonstration of sub-THz wireless communications using multiplexing of Laguerre-Gaussian beams when varying two different modal indices J. Lightwave Technol. 40 3285–92
[33] Krenn M, Handsteiner J, Fink M, Fickler R, Ursin R, Malik M and Zeilinger A 2016 Twisted light transmission over 143 km Proc. Natl Acad. Sci. USA 113 13648–53
[34] Kim H-C and Lee Y H 1999 Hermite–Gaussian and Laguerre–Gaussian beams beyond the paraxial approximation Opt. Commun. 169 9–16
[35] Xie G et al 2017 Spatial light structuring using a combination of multiple orthogonal orbital angular momentum beams with complex coefficients Opt. Lett. 42 901–4
[36] Pang K et al 2018 400-Gbit/s QPSK free-space optical communication link based on four-fold multiplexing of Hermite-Gaussian or Laguerre-Gaussian modes by varying both modal indices Opt. Lett. 43 3889–92
[37] Li L et al 2017 Power loss mitigation of orbital-angular-momentum-multiplexed free-space optical links using nonzero radial index Laguerre–Gaussian beams J. Opt. Soc. Am. B 34 1–6
[38] Willner A E 2021 OAM light for communications Opt. Photonics News 32 34–41
[39] Sengupta K, Nagatsuma T and Mittleman D M 2018 Terahertz integrated electronic and hybrid electronic–photon systems Nat. Electron. 1 622–35
[40] Molisch A F 2012 Wireless Communications 2nd edn (Hoboken, NJ: Wiley)
[41] Yang H, Zheng S, He W, Yu X and Zhang X 2021 Terahertz orbital angular momentum: generation, detection and communication China Commun. 18 131–52
[42] Beijersbergen M W, Coerwinkel R P C, Kristensen M and Woerdman J P 1994 Helical-wavefront laser beams produced with a spiral phaseplate Opt. Commun. 112 321–7
[43] Schenkel P, Maccalli S, Pisanu G, Maffei B and Ng M W R 2014 Three-dimensional measurements of a millimeter wave orbital angular momentum vortex Opt. Lett. 39 626–9
[44] Miyamoto K, Suizu K, Akiba T and Omatu T 2014 Direct observation of the topological charge of a terahertz vortex beam generated by a Tsurupica spiral phase plate Appl. Phys. Lett. 104 261104
[45] Wang X, Shi J, Sun W, Feng S, Han P, Ye J and Zhang Y 2016 Longitudinal field characterization of converging terahertz vortices with linear and circular polarizations Opt. Express 24 7178–90
[46] Zhang H et al 2018 Polarization-independent all-silicon dielectric metasurfaces in the terahertz regime Photon. Res. 6 24–29

[47] Dharmavarapu R, Izumi K, Katayama I, Ng S H, Vongsivit J, Tobin M J, Kuchmizhak A, Nishijima Y, Bhattacharya S and Juodkazis S 2019 Dielectric cross-shaped-resonator-based metasurface for vortex beam generation at mid-IR and THz wavelengths Nanophotonics 8 1263–70
[48] G-b W, Chan K F, Shum K M and Chan C H 2022 Millimeter-wave and terahertz OAM discrete-lens antennas for 5G and beyond IEEE Commun. Mag. 60 34–39
[49] Zhao H, Quan B, Wang X, Gu C, Li J and Zhang Y 2018 Demonstration of orbital angular momentum multiplexing and demultiplexing based on a metasurface in the terahertz band ACS Photonics 5 1726–32
[50] Zheng C et al 2021 All-dielectric metasurface for manipulating the superpositions of orbital angular momentum via spin-decoupling Adv. Opt. Mater. 9 2002007
[51] Khan M I W, Woo J, Yi X, Ibrahim M I, Yazicigil R T, Chandrakasan A P and Han R 2022 A 0.31-THz orbital-angular-momentum (OAM) wave transceiver in CMOS with bits-to-OAM mode mapping IEEE J. Solid-State Circuits 57 1544–57
[52] Guan B et al 2014 Free-space coherent optical communication with orbital angular momentum multiplexing/ demultiplexing using a hybrid 3D photonic integrated circuit Opt. Express 22 145–56
[53] Sasaki H, Yagi Y, Kageyama T and Lee D 2022 Implementation and evaluation of sub-THz OAM multiplexing transmission 2022 IEEE Int. Conf. on Communications Workshops (ICC Workshops) pp 175–9
[54] Yagi Y, Sasaki H, Yamada T and Lee D 2021 200 Gb/s wireless transmission using dual-polarized OAM-MIMO multiplexing with uniform circular array on 28 GHz band IEEE Antennas Wirel. Propag. Lett. 20 833–7
[55] Ren Y et al 2013 Atmospheric turbulence effects on the performance of a free space optical link employing orbital angular momentum multiplexing Opt. Lett. 38 4062
[56] Phillips R L and Andrews L C 1983 Spot size and divergence for Laguerre Gaussian beams of any order Appl. Opt. 22 643–4
[57] Su X et al 2022 Receiver aperture and multipath effects on power loss and modal crosstalk in a THz wireless link using orbital-angular-momentum multiplexing Sci. Rep. 12 14053
[58] Su X et al 2021 Modal purity and LG coupling of an OAM beam reflected by a rough surface for NLoS THz links 2021 IEEE Int. Conf. on Communications Workshops (ICC Workshops) pp 1–6
[59] Zhao Z et al 2021 Modal coupling and crosstalk due to turbulence and divergence on free space THZ links using multiple orbital angular momentum beams Sci. Rep. 11 2110
[60] Willner A E, Pang K, Song H, Zou K and Zhou H 2021 Orbital angular momentum of light for communications Appl. Phys. Rev. 8 041312
[61] Akkas M A 2019 Terahertz wireless data communication Wirel. Netw. 25 145–55
[62] Li S, Chen S, Gao C, Willner A E and Wang J 2018 Atmospheric turbulence compensation in orbital angular momentum communications: advances and perspectives Opt. Commun. 408 68–81
[63] Li W et al 2022 Dual-color terahertz spatial light modulator for single-pixel imaging Light Sci. Appl. 11 191
[64] Watts C M, Shrekenhamer D, Montoya J, Lipworth G, Hunt J, Sleasman T, Krishna S, Smith D R and Padilla W J 2014 Terahertz compressive imaging with metamaterial spatial light modulators Nat. Photonics 8 605–9
[65] Venkatesh S, Lu X, Saiedi H and Sengupta K 2020 A high-speed programmable and scalable terahertz holographic metasurface based on tiled CMOS chips Nat. Electron. 3 785–93
[66] Cui T J, Qi M Q, Wan X, Zhao J and Cheng Q 2014 Coding metamaterials, digital metamaterials and programmable metamaterials Light Sci. Appl. 3 e218

[67] Ren Y et al 2016 Atmospheric turbulence mitigation in an OAM-based MIMO free-space optical link using spatial diversity combined with MIMO equalization Opt. Lett. 41 2406–9

[68] Gong L, Zhao Q, Zhang H, Hu X-Y, Huang K, Yang J-M and Li Y-M 2019 Optical orbital-angular-momentum -multiplexed data transmission under high scattering Light Sci. Appl. 8 27

[69] Hu N et al 2022 Demonstration of turbulence mitigation in a 200-Gbit/s orbital-angular-momentum multiplexed free-space optical link using simple power measurements for determining the modal crossstalk matrix Opt. Lett. 47 3539–42

[70] Nape I et al 2022 Revealing the invariance of vectorial structured light in complex media Nat. Photon. 16 538–46

[71] Gong C, Pan Z, Dedo M I, Sun J, Wang L and Guo Z 2021 Improving the demultiplexing performances of the multiple Bessel Gaussian beams (mBGBs) Results Phys. 30 104829

[72] Dedo M I, Wang Z, Guo K, Sun Y, Shen F, Zhou H, Gao J, Sun R, Ding Z and Guo Z 2019 Retrieving performances of vortex beams with GS algorithm after transmitting in different types of turbulence Appl. Opt. 58 2269

[73] Yan Y et al 2016 Multipath effects in millimetre-wave wireless communication using orbital angular momentum multiplexing Proc. IEEE 6 33482

[74] Merano M, Hermosa N, Woerdman J P and Aiello A 2010 How orbital angular momentum affects beam shifts in optical reflection Phys. Rev. A 82 023817

[75] Smith J, Naftaly M, Nellen S and Globisch B 2021 Beam profile characterisation of an optoelectronic silicon lens-integrated PIN-PD emitter between 100 GHz and 1 THz Appl. Opt. Sci. 11 465

[76] Nellen S, Lauck S, Peytavit E, Szriftigiser P, Schell M, Ducournau G and Globisch B 2022 Coherent wireless link at 300 GHz with 160 Gbit/s enabled by a photonic transmitter J. Lightwave Technol. 4178–85

[77] Dennis M R, O’holleran K and Padgett M J 2009 Chapter 5 Singular optics: optical vortices and polarization singularities Prog. Opt. 53 293–363

[78] Schmogrov R et al 2012 Error vector magnitude as a performance measure for advanced modulation formats IEEE Photonics Technol. Lett. 24 61–63

[79] Alvarado A, Ives D J, Savory S J and Bayvel P 2016 On the impact of optimal modulation and PEC overhead on future optical networks J. Lightwave Technol. 34 2339–52

[80] Ando T, Ohtake Y, Matsumoto N, Inoue T and Fukuchi N 2009 Mode purities of Laguerre–Gaussian beams generated via complex-amplitude modulation using phase-only spatial light modulators Opt. Lett. 34 34–36

[81] Bolduc E, Bent N, Santamato E, Kariim E and Boyd R W 2013 Exact solution to simultaneous intensity and phase encoding with a single phase-only hologram Opt. Lett. 38 3546–9

[82] Xie G et al 2016 Experimental demonstration of a 200-Gbit/s free-space optical link by multiplexing Laguerre–Gaussian beams with different radial indices Opt. Lett. 41 3447–50

[83] Siegman A E 1998 How to (maybe) measure laser beam quality DPSS (Diode Pumped Solid State) Lasers: Applications and Issues (1998), paper MQ1 Diode Pumped Solid State Lasers: Applications and Issues (Optica Publishing Group) p MQ1

[84] Schulze C, Flamm D, Duprè M and Forbes A 2012 Beam-quality measurements using a spatial light modulator Opt. Lett. 37 4687–9

[85] Tyler G A and Boyd R W 2009 Influence of atmospheric turbulence on the propagation of quantum states of light carrying orbital angular momentum Opt. Lett. 34 142–4

[86] Smit M, van der Tol J and Hill M 2012 Moore’s law in photonics Laser Photon. Rev. 6 1–13

[87] Su X et al 2022 A THz Integrated Circuit based on a pixel array to mode multiplex two 10-Gbit/s QPSK channels each on a different OAM beam J. Light. Technol. 1–9

[88] Headland D, Withayachumnankul W, Yu X, Fujita M and Nagatsuma T 2020 Unclad microphonics for terahertz waveguides and systems J. Lightwave Technol. 38 6583–62

[89] Xie Z, Lei T, Li F, Qiu H, Zhang Z, Han M, Du L, Li Z and Yuan X 2018 Ultra-broadband on-chip twisted light emitter for optical communications Light Sci. Appl. 7 18001

[90] Xie G et al 2015 Performance metrics and design considerations for a free-space optical orbital-angular-momentum-multiplexed communication link Optica 2 357–65

[91] Pang K et al 2020 Experimental mitigation of the effects of the limited size aperture or misalignment by singular-value-decomposition-based beam orthogonalization in a free-space optical link using Laguerre–Gaussian modes Opt. Lett. 45 6310–3

[92] Wan Z, Shen Y, Wang Z, Shi Z, Liu Q and Fu X 2022 Divergence-degenerate spatial multiplexing towards future ultrahigh capacity, low error-rate optical communications Light Sci. Appl. 11 144

[93] Su T, Scott R P, Djordjevic S S, Fontaine N K, Geisler D J, Cai X and Yoo S J 2012 Demonstration of free space coherent optical communication using integrated silicon photonic orbital angular momentum devices Opt. Express 20 9396–402

[94] Li S et al 2018 Orbital angular momentum vector modes (de)multiplexer based on multimode micro-ring Opt. Express 26 29995–9005

[95] Trichili A, Cox M A, Cox M A, Ooi B S and Alouini M-S 2020 Roadmap to free space optics J. Opt. Soc. Am. B 37 A184–201

[96] Khalid H, Muhammad S S, Nistazakis H E and Tombras G S 2019 Performance analysis of hard-switching based hybrid FSO/RF system over turbulence channels Computation 7 28

[97] Ahdi F and Subramanian S 2011 Optimal placement of FSO links in hybrid wireless optical networks 2011 IEEE Global Telecommunications Conf.—GLOBECOM 2011 pp 1–6