# Iso-propagation vortices: a breakthrough in optical communication technology

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The rapid advance of optical communication technology requires improvements in data transmission capacity and efficiency. Conventional methods of increasing the transmission capacity such as polarization, wavelength, and spatial mode division multiplexing have shown significant promise, while spatial mode division multiplexing (SDM) offers a new approach through the use of orthogonal spatial modes as distinct communication channels. One of the pioneering advancements in this field is the utilization of orbital angular momentum (OAM) in light waves.[1] Unlike spin angular momentum (SAM), which is related to the polarization of light and is limited to only two states, OAM, defined by a helical phase front and donut-shaped intensity profiles with a null in the center,[2–4] provides an infinite number of modes and is used in applications that require high-capacity, such as optical communications and holographic imaging.[5–7] Furthermore, the orthogonality of different OAM modes increases their potential for multiplexing in communication systems to significantly increase the data capacity of communication devices. Each OAM mode can carry an independent data stream and be efficiently separated at the receiver with minimal crosstalk. The integration of OAM in optical communications holds potential for a variety of applications, including high-capacity free-space optical (FSO) links, fiber-optic systems, and even in quantum communication links. However, major challenges arise due to diffraction-induced expansion and divergence.[8,9] As OAM beams propagate, diffraction causes them to expand and diverge, which reduces the spatial coherence and causes signal interference. These issues are especially pronounced over long distances that require additional compensators to maintain the shape of the beam, while the reduction in signal strength hinders the data transmission efficiency so advanced optical design and signal processing techniques must be developed.

In an article recently published in *Advanced Photonics*, Ding, Wang, and colleagues report the significant advancement in the field of optical communications through the introduction of iso-propagation vortices (IPVs),[10] vortex beams designed to maintain an OAM independent size and divergence during propagation (Fig. 1). By configuring the radial index of Laguerre–Gaussian (LG) beams, OAM-independent propagation is achieved, a feature crucial for enhancing the efficiency and reliability of optical communication systems. This innovation is particularly impactful for applications that require stable and compact beam profiles. The enhanced transmission dynamics of IPVs, including the reduced beam size, lower divergence, and a decreased quality factor, make them exceptionally resilient to atmospheric turbulence and physical obstructions. The robustness of IPVs is further emphasized by the ability to self-restore post-damage through energy circulation from their sidelobes, which not only ensures consistent capacity performance in challenging environments, but also significantly expands the capacity of the optical communication channels. The study demonstrates that IPVs can utilize a broader spectrum of data channels compared to conventional spatial multiplexing techniques, potentially increasing subchannel availability by up to 14 times compared to conventional OAM multiplexing. This increase is critical for advancing both terrestrial and deep space communication systems to ensure faster data rates and improved signal quality.

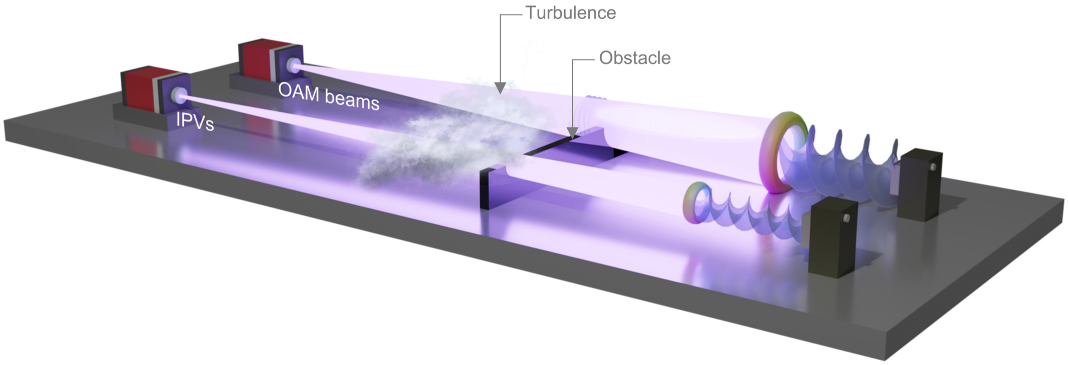

**Fig. 1** Schematic of conventional OAM beams and IPVs that maintain their structures in the presence of turbulences and obstacles.

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The consistent size of IPVs is in contrast with conventional LG beams. The authors describe how the complex amplitudes of LG beams are distributed and show that, when configured correctly, the innermost rings exhibit minimal size and divergence that remain constant during propagation. LG beams exhibit consistent propagation dynamic when they share the same beam quality factor. Specifically, LG beams of different modes but identical beam quality factor maintain the same size and divergence upon propagation. For IPVs, this quality factor is engineered to stay constant, ensuring that the beams do not degrade in quality as their OAM varies. The most critical part of the IPV structure is the innermost ring, which is the brightest part of the beam. By configuring the radial index appropriately, the size and divergence of this innermost ring are kept independent of the OAM, ensuring it remains robust and consistent. In contrast, conventional vortices maintain an OAM-independent radius near a specific plane but fail to achieve OAM-independent propagation. The IPV mode parameters, including the beam quality factor, size of the LG beam, and divergence angle, increase with the absolute value of the topological charge but decrease with the radial index. Therefore, IPVs exhibit superior transmission characteristics with significantly lower size, divergence, and beam quality factor compared to conventional LG beams. Furthermore, the self-restoration ability of the IPVs is demonstrated. After interacting with obstacles, the vortices tend to regenerate their original form with help from the sidelobes due to the radial energy component which draws energy from the outer sidelobes. Additionally, modal scattering due to atmospheric turbulence[11] that generally disrupts the optical link over long distances is reduced for IPVs. This scattering reduction is crucial for maintaining signal integrity in FSO systems, emphasizing the practical benefits of IPVs in real-world communications.

However, conventional SDM faces inherent challenges due to diffraction, which causes an inevitable increase in beam size and divergence with rising topological charge. Therefore, larger receivers are required to accommodate higher capacity that includes more modes. This often conflicts with physical size constraints, limiting the capacity potential. These limitations can be overcome with IPVs, which provide broad access to subchannels. This increase in information capacity is validated by determining the number of IPVs suitable for line-of-sight FSO systems, characterized by the spatial bandwidth product. By utilizing IPVs, more subchannels can be efficiently utilized, significantly increasing the overall capacity of the system. Moreover, the number of IPV channels can be further increased by adopting metasurface platforms with larger panel sizes and ultra-high resolution. Metasurfaces composed of sub-wavelength-sized nanoantennas can manipulate electromagnetic waves with high precision, enabling small, lightweight, and dynamically reconfigurable optical components.[12–14] The integration of metasurfaces and IPVs enhances the precise control of beam parameters to create highly customized, efficient beam profiles that optimize transmission over a various media, facilitating the use of more subchannels within the same receiver size, and therefore resulting in a significant increase in capacity. This synergy improves beam control, reducing the size and divergence of IPVs and enabling advanced multiplexing techniques, adaptive optics for deep space communications, high-resolution imaging, and quantum communications.

In summary, a significant advance in the field of optical communications is introduced to overcome the limitations of conventional vortex beams. IPVs are designed to maintain a constant size and spread regardless of the OAM mode, which greatly improves their efficiency and practicality in FSO. Through theoretical descriptions and experimental results, the superior transmission dynamics, obstacle recovery ability, and reduced mode scattering in atmospheric turbulence of IPVs is demonstrated. These characteristics make IPVs a promising solution for the future of high-capacity optical communication networks. In the future, IPVs are likely to be utilized in a variety of fields, including image processing, microscopy, metrology, quantum information processing, and light–matter interaction research.

## Disclosures

The authors declare no competing interests.

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