Commentary | Received 3 April 2026; Revised 22 July 2026; Accepted 5 August 2026; Published 31 August 2026
https://doi.org/10.55092/esp20260005

Structured-light modes for optical communications and computing: opportunities and challenges

Jing Wang and Shuqing Chen*

Institute of Microscale Optoelectronics, Shenzhen University, Shenzhen, China

* Correspondence author; E-mail: shuqingchen@szu.edu.cn.

Highlights:

- Structured-light modes are pivotal to optical communications and computing.
- Modal transformation is the crucial and common framework.
- It is the usable modal dimensionality under realistic conditions that matters.

Abstract: Structured-light modes have emerged as a promising information carrier for both optical communications and optical computing because they provide high-dimensional spatial degrees of freedom (DOFs) for multiplexing and modal transformation. Although numerous demonstrations have reported increasing transmission capacities and computational functionalities, their practical significance is often evaluated by nominal modal dimensionality rather than system-level usability. In this commentary, we argue that structured-light communications and computing share a common framework of modal transformation and should therefore be assessed using unified system-level criteria. We compare representative structured-light mode groups, discuss their roles in communications and computing, and highlight the practical challenges associated with modal fidelity, modal crosstalk, and scalability. We further propose that the key figure of merit for future structured-light systems should be the usable modal dimensionality achievable under realistic operating conditions, providing a practical perspective for the development of scalable photonic information processing.

Keywords: structured-light modes; optical communications; optical computing; mode-division multiplexing; mode transformation

1. The need for structured-light communications and computing

The rapid development of artificial intelligence has dramatically increased the demand not only for computational throughput but also for high-bandwidth data movement among processors, memories, accelerators, and communication networks. Continued scaling of electronic processing systems is therefore increasingly constrained by interconnect bandwidth, transmission latency and power dissipation. Photonics information processing has emerged as a complementary solution for addressing localized high-speed transmission and large-scale matrix computing tasks by exploiting the inherent properties of light including the broad bandwidth, low propagation latency and high parallelism. In theory, optical systems can provide parallel multiplexed channels spanning both spatial and spectral domains by layering multiple physical dimensions like wavelength, time, polarization and spatial mode. However, achieving this vision of scaling up transmission and computational throughput by relying on these resources poses stringent requirements on both components and systems, like tighter synchronization or increased hardware complexity. Structured-light modes provide a new set of spatial bases that may offer high capacity while simplifying system requirements. Their tailored amplitude, phase, and polarization distributions allow information to be encoded into high-dimensional modal states. In optical communications, these modes can serve as parallel channels for mode-division multiplexing; in optical computing, they also act as basis states for arithmetic operations, logic functions, convolution operations and matrix transformation. Hence, these two application domains share a common set of physical operations, including mode generation, multiplexing, propagation, transformation, and detection. In this commentary, we argue that the practical significance of structured-light modes should be evaluated not by their nominal modal dimensionality alone, but by the usable dimensionality that can be achieved under realistic constraints of energy loss, fidelity, channel crosstalk, and system complexity [1–5].

Although structured-light modes possess potentially unbounded basis state space and high-dimensional spatial structures, their value cannot be assessed solely from the benefits of capacity enhancement. Instead, it should be considered relative to other optical information platforms, which differ in technological maturity, hardware complexity and compatibility with existing communication and computing systems. Table 1 provides a qualitative system-level comparison [6–10].

Table 1. Qualitative comparison between structured-light systems and other optical platforms.

Information Platform	Available Dimensionality	Key Advantages	Major Limitations	Most suitable role
Wavelength Multiplexing [4,5]	Wavelength	Mature, low crosstalk, Compatible with optical fiber networks	Finite spectral resources and filter bandwidth	Long-haul and data-center communications
Time Multiplexing [4,6]	Time slots	Flexible, mature, easy for digital processing	Requires high-speed clocks, buffering and synchronization	High-speed serial transmission
Polarization Multiplexing [6,7]	Two orthogonal states	Low additional bandwidth cost	Limited dimensionality and polarization instability	Coherent optical links
Spatial Mode Multiplexing [3,8,11]	Spatial basis functions	High-dimensional, parallel, capable of executing linear transformations	Modal crosstalk, finite aperture and mode-processing complexity	Mode multiplexing and parallel modal transformation

This comparison suggests that structured-light modes are expected to be regarded as complementary to, rather than replacements for well-established wavelength-, time-, and polarization-division multiplexing platforms. Their distinctive advantage is the ability to expand information in the same space channel while supporting parallel modal transformations within the same physical basis. This feature is particularly attractive when the spatial dimension is combined with wavelength and polarization to increase aggregate throughput or when multiple modal components are processed simultaneously. Nevertheless, the theoretical arbitrarily scalable modal dimensionality of structured-light modes does not translate into usable system capacity, whose advantages must ultimately be evaluated under realistic constraints of loss, crosstalk and system complexity [3,7,8,12,13].

2. Several typical structured-light modes and their characteristics

A practical spatial modal system must support the reliable generation, multiplexing, propagation, transformation, and detection of these states, together with adaptive calibration against environmental and hardware perturbations. These operations constitute a common modal toolbox shared by optical communications and computing. Since structured-light modes are typically tailored for specific application scenarios through combinations of traditional or novel degrees of freedom (DOFs), the concrete methods and performances within this modal toolbox are strongly dependent on the physical structure of the chosen basis. Concurrently, they exhibit different trade-offs among propagation robustness, transmission efficiency, and compatibility with free-space, fiber, or integrated platforms. In the context of structured-light, the traditional DOFs that are distinct and separable in space and time can be recast to form new forms of light with exotic properties, significantly enriching the dimensions of light-field. For instance, helical phase wavefront structure has resulted in the light carrying orbital angular momentum (OAM). Combining polarization and OAM gives rise to make vector beam, which are eigenfunctions of optical fiber. Spatial structure evolution in the path has spawned geometric-ray groups, Airy beam modes and Bessel-like beam modes while space can be mixed with polarization for optical topology. Due to their unique properties, these mode groups present distinct advantages and limitations in both transmission and processing, and comparing them is instrumental in identifying specific scenarios that match their respective characteristics. Table 2 presents a horizonal comparison of these representative structured-light modes [12–15].

Table 2. Horizonal comparison between several different structured-light modes.

Mode Group	Main Strengths	Main Limitations	Suitable Scenarios
OAM/LG Modes [2,3,8,11]	High dimensionality; Mature generation and detection	Divergence and crosstalk under misalignment of turbulence	Free-space multiplexing, high-dimensional encoding, modal logic
CVBs/Vector Modes [7,12,13]	Joint spatial-polarization encoding; Fiber-mode compatibility	Polarization-resolved detection and birefringence-induced coupling	Fiber multiplexing and vectorial processing
Bessel-like Modes [15,16]	Self-healing and quasi-nondiffracting propagation	Large aperture and sidelobe-related loss or crosstalk	Obstructed or turbulent free-space links
Airy beam Modes [17]	Curved trajectories and self-healing	Inefficient power distribution and aperture capture	Obstacle avoidance and engineered propagation paths
Optical Skyrmions [14,18,19]	Robust topological observables	Complex generation and detection; Topology does not ensure data fidelity	Robust state encoding and complex-medium transmission

The comparison above highlights that no single structured-light mode group is universally superior, with each mode group exhibiting its own trade-offs. Consequently, the choice of a structured-light mode basis should be guided by the dominant requirement of the target information-processing task rather than by the nominal number of supported modes alone [16–19].

3. Modal transformation framework in structured-light communications and computing

Both of the optical communications and computing utilizing structured-light modes can be interpreted within a common framework of modal transformation, where information is encoded, manipulated, and recovered through the evolution of optical modal states [20–24]. The process can be described as:

$$B = HA + n \tag{1}$$

where A is the input modal-state vector, H denotes the modal transformation matrix, B is the output modal-state vector, and n represents additive perturbations in two systems. Within this framework, this distinction between communications and computing lies primarily in the role of H. In optical communications, H characterizes the transmission channel together with modal coupling, and the objective is to compensate or invert this transformation for reliable information recovery. In optical computing, H is intentionally engineered as the desired operator or weight matrix to perform matrix-vector multiplication, logic operations, convolution or arithmetic operations. Consequently, mode multiplexers, mode sorters, multi-plane light conversion (MPLC), and diffractive optical networks can all be regarded as physical implementations or compensators of modal transformations [25–29].

From a system perspective, the performance of structured-light communication should be evaluated by the aggregate capacity or the maximum number of channels under the conditions of long transmission distances, low modal crosstalk, and a relatively low bit-error-rate (BER) and so on. Reliable multiplexing typically requires the modal crosstalk to be suppressed below approximately −15 ~−20 dB, alongside the BER relative to the forward-error-correction (FEC) threshold (e.g., 3.8×10^{-3} for a 7% hard-decision FEC, HD-FEC) both before and after digital signal processing (DSP). Recent demonstrations have pushed aggregate capacities exceeding 10 Tbit/s in OAM-based free-space links, supported more than one hundred multiplexed spatial modes in ring-core fibers, achieved kilometer-scale free-space transmission and tens-of-kilometer specialty-fiber transmission, while maintaining BERs below the HD-FEC threshold through adaptive multiple-input multiple-output (MIMO) equalization. However, these records are generally realized under different transmission platforms and operating conditions, highlighting that maximizing one performance metric often comes at the expense of others [30–32].

4. Mechanism of structured-light computing

The most elementary form of optical computing using structured-light modes treats discrete modal states as logic symbols rather than intensity levels, and the state-to-state mapping is described as [9,20,23–25]:

$$|l_1\rangle \to 0,\ |l_2\rangle \to 1 \tag{2}$$

where the mode with topological charge l_1 represents the “0” state while l_2 indicates the “1” state no matter for inputs or outputs. The optical logic operation is implemented by a trained sequence of phase masks, where propagation between layers supplies the linear mixing and detection assigns the output mode to a logic value. Because logical decisions are made by identifying the output mode instead of comparing an intensity threshold, the operation can be less sensitive to global amplitude fluctuations. Recent demonstrations have realized all seven basic logic operations using multi-layer diffraction architecture, with mode fidelities typically exceeding 95% for low-dimensional state spaces. The implementation of complex logic functions requires the cascading of multiple basic logic gates, whereas the practical cascadability still depends on whether the output modal basis can be directly reused as a standardized input for subsequent operations [20,24].

Modal arithmetic extends mode manipulation from discrete mapping to deterministic transformations of modal indices. Operations such as multiplication and division are commonly achieved through coordinate transformations or MPLC, enabling transformations like [21,25,29]:

$$\left|l\right\rangle \rightarrow \left|ml\right\rangle \tag{3}$$

where l is the discrete order and m refers to the multiply factor. This operation is achieved via coordinate mapping between the input and output space, thereby reshaping the spatial geometry of the mode intensity or phase profile. Recent works have reported conversion efficiencies approaching 90%~95%, mode purities above 95%, and average intermodal crosstalk below −20dB over tens of supported OAM/cylindrical vector beam (CVB) modes, while progressively reducing the number of optical elements required for a given transformation.

For matrix-vector multiplication, input vector elements can be encoded in modal amplitudes, phases, or multiplexed channels, while the programmed phase profile or interferometric transfer matrix represents the weights. Coherent superposition performs multiply-accumulate operations during propagation, followed by modal sorting or photodetection. Recent demonstrations have achieved increasingly scalable and reconfigurable unitary transformations for tens of spatial modes with low modal crosstalk and high transformation fidelity, while compact MPLC-based processors and programmable diffractive systems have substantially reduced the complexity of high-dimensional modal manipulation. More broadly, the rapid development of programmable photonic processors provides a promising hardware framework for extending these modal transformations towards general-purpose structured-light computing. Although a single optical matrix transformation is completed within the picosecond-to-nanosecond propagation time of light, the end-to-end system latency remains high for which is often dominated by electro-optic interfaces [32,33].

5. Outlook

Despite the remarkable progress achieved in structured-light modes communications and computing, translating laboratory demonstrations into deployable systems requires overcoming a series of practical constraints that become increasingly severe as the modal dimensionality grows. In realistic free-space links, atmospheric turbulence and scattering distort modal orthogonality, while fabrication imperfections, alignment errors and phase drift introduce additional transformation errors in integrated and free-space processors. Thus, maintaining low modal crosstalk (typically below −20dB), high mode purity and transformation fidelity (generally exceeding 95%), low BER or high classification accuracy across the entire supported modal basis remains a fundamental challenge. Moreover, as more modes multiplexed or processed simultaneously, the available optical power is distributed over an increasing number of channels, while finite apertures, sidelobes and insertion losses further reduce the received power of each mode. Recent advances in low-loss mode converters, MPLC, adaptive optics and turbulence compensation have substantially improved conversion efficiency and modal fidelity, yet maintaining a high signal-to-noise ratio and sufficient detector dynamic range for large-scale modal systems remains difficult. Therefore, the practical significance of structured-light modes should be evaluated not by their nominal modal dimensionality alone, but by the usable dimensionality that can be sustained under realistic constraints of multiple kinds of metrics. Continued advances in modal engineering, programmable photonic hardware and AI-assisted signal processing are expected to further increase the usable dimensionality of structured-light systems, paving the way for practical high-capacity communications and scalable optical computing [25,31–34].

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools in the writing of this manuscript. Specifically, the authors used ChatGPT for idea development in limited sections and for language polishing in substantial portions. The authors take full responsibility for the content of the manuscript.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (62271322); Shenzhen Science and Technology Program (JCYJ20240813143018024); Shenzhen Key Industry Research and Development Program (ZDCY20250901100033003).

Authors' contribution

Writing—original draft preparation, J.W.; writing—review and editing, S.C.; funding acquisition, S.C. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Shuqing Chen holds the position of Associate Editor for *Electronics and Signal Processing* and has not peer reviewed or made any editorial decisions for this paper. The authors declare no other conflicts of interest associated with this manuscript.

References

[1] Forbes A, de Oliveira M, Dennis MR. Structured light. *Nat. Photon.* 2021, 15(4):253−262.
[2] Wang J, Liu J, Li S, Zhao Y, Du J, *et al.* Orbital angular momentum and beyond in free-space optical communications. *Nanophotonics* 2022, 11(4):645–680.
[3] He C, Shen Y, Forbes A. Towards higher-dimensional structured light. *Light Sci. Appl.* 2022, 11(1):160.
[4] Essiambre RJ, Tkach RW. Capacity trends and limits of optical communication networks. *Proc. IEEE* 2012, 100(5):1035–1055.
[5] Han J, Yan G, Li K, Shen B, Shu H, *et al.* Exploiting a centrally powered coherent microcomb for lightweight optical transmission. *Nat. Commun.* 2025, 16(1):10588.
[6] Lu HH, Li CY, Tsai WS, Chang PS, Lin YY, *et al.* A two-way 224-Gbit/s PAM4-based fibre–FSO converged system. *Sci. Rep.* 2022, 12(1):360.
[7] Chen S, Xie Z, Ye H, Wang X, Guo Z, *et al.* Cylindrical vector beam multiplexer/demultiplexer using off-axis polarization control. *Light Sci. Appl.* 2021, 10(1):222.

[8] Liu J, Zhang J, Liu J, Lin Z, Li Z, *et al.* 1-Pbps orbital angular momentum fibre-optic transmission. *Light Sci. Appl.* 2022, 11(1):202.
[9] Hu J, Mengu D, Tzarouchis DC, Edwards B, Engheta N, *et al*. Diffractive optical computing in free space. *Nat. Commun.* 2024, 15(1):1525.
[10] Nikkhah V, Pirmoradi A, Ashtiani F, Edwards B, Aflatouni F, *et al*. Inverse-designed low-index-contrast structures on a silicon photonics platform for vector–matrix multiplication. *Nat. Photon.* 2024, 18(5):501–508.
[11] Trichili A, Rosales-Guzmán C, Dudley A, Ndagano B, Ben Salem A, *et al.* Optical communication beyond orbital angular momentum. *Sci. Rep.* 2016, 6(1):27674.
[12] Liu J, Wu Z, Zeng Q, Zhang B, Chen J, *et al.* Efficient dynamic free-space-to-fiber coupling of cylindrical vector beams via twisted moiré meta-devices. *Commun. Phys.* 2025, 8(1):394.
[13] Zhu Z, Janasik M, Fyffe A, Hay D, Zhou Y, *et al.* Compensation-free high-dimensional free-space optical communication using turbulence-resilient vector beams. *Nat. Commun.* 2021, 12(1):1666.
[14] Shen Y, Zhang Q, Shi P, Du L, Yuan X, *et al*. Optical skyrmions and other topological quasiparticles of light. *Nat. Photon.* 2024, 18(1):15–25.
[15] Li S, Wang J. Adaptive free-space optical communications through turbulence using self-healing Bessel beams. *Sci. Rep.* 2017, 7(1):43233.
[16] Reddy IVAK, Bodet D, Singh A, Petrov V, Liberale C, *et al.* Ultrabroadband terahertz-band communications with self-healing Bessel beams. *Commun. Eng.* 2023, 2(1):70.
[17] Hu J, Guo Z, Shi J, Jiang X, Chen Q, *et al.* A metasurface-based full-color circular auto-focusing Airy beam transmitter for stable high-speed underwater wireless optical communications. *Nat. Commun.* 2024, 15(1):2944.
[18] Wang AA, Zhao Z, Ma Y, Cai Y, Zhang R, *et al.* Topological protection of optical skyrmions through complex media. *Light Sci. Appl.* 2024, 13(1):314.
[19] Fan X, Wu X, Ren K, Zhou L, Guo X, *et al.* Topological state and number transitions of optical skyrmions upon free-space beam propagation. *Commun. Phys.* 2025, 8(1):500.
[20] Wang P, Xiong W, Huang Z, He Y, Xie Z, *et al.* Orbital angular momentum mode logical operation using optical diffractive neural network. *Photon. Res.* 2021, 9(10):2116–2124.
[21] Wang J, Zeng Q, Wu H, Xie C, Ye H, *et al.* Mode multiplication of cylindrical vector beam using raytracing control. *Chin. Phys. Lett.* 2024, 41(9):094202.
[22] Ling Q, Dong P, Chu Y, Dong X, Chen J, *et al.* On-chip optical matrix-vector multiplier based on mode division multiplexing. *Chip* 2023, 2(4):100061.
[23] Cheng J, Huang C, Zhang J, Wu B, Zhang W, *et al.* Multimodal deep learning using on-chip diffractive optics with *in situ* training capability. *Nat. Commun.* 2024, 15(1):6189.
[24] Wang Q, Liu J, Lyu D, Wang J. Ultrahigh-fidelity spatial mode quantum gates in high-dimensional space by diffractive deep neural networks. *Light Sci. Appl.* 2024, 13(1):10.
[25] Rocha JCA, Būtaitė UG, Carpenter J, Phillips DB. Self-configuring high-speed multi-plane light conversion. *Nat. Commun.* 2026, 17(1):73.
[26] Yao Q, Sun Y, Ke X, Xie Y, Liu S, *et al.* Parallel matrix–vector multiplication using a scalable multiport interferometer. *Laser Photon. Rev.* 2026, 20(6): e01876.
[27] Zhang Y, Liu X, Yang C, Xiang J, Yan H, *et al.* Direct tensor processing with coherent light. *Nat. Photon.* 2026, 20(1):102–108.

[28] Sharma V, Brandmüller D, Bütow J, Eismann JS, Banzer P. Universal photonic processor for spatial mode decomposition. *Nat. Commun.* 2025, 16(1):8010.
[29] Wang J, Li K, Quan Z. Integrated structured light manipulation. *Photonics Insights* 2024, 3(3):R05.
[30] Martinez AI, Cavicchioli G, Seyedinnavadeh S, Zanetto F, Sampietro M, *et al.* Self-adaptive integrated photonic receiver for turbulence compensation in free-space optical links. *Sci. Rep.* 2024, 14(1):20178.
[31] Zhang Z, Kong L, Zhang L, Pan X, Das T, *et al.* Structured light meets machine intelligence. *eLight* 2025, 5(1):26.
[32] Kong A, Ren J, Wang K, Yu Y, Lin R, *et al.* Ultra-wideband optical diffractive network for mode multiplexing across the entire telecommunication range. *Nat. Commun.* 2026, 17(1):233.
[33] Cao Z, Du H, Yuan X, Wu B, Zhang J, *et al.* Programmable three-dimensional photonic neural network chip. *Nat. Commun.* 2026, 17(1):5476.
[34] Na Y, Ko DK. Deep-learning-based high-resolution recognition of fractional-spatial-mode-encoded data for free-space optical communications. *Sci. Rep.* 2021, 11(1):2678.