

# Metasurfaces for full-parameter optical wavefront engineering

Zhipeng Yu<sup>1,2</sup> and Xiangping Li<sup>1,\*</sup>

## Abstract

Multidimensional light-field control is opening new frontiers in photonics. Recent breakthroughs in metasurface design and the integration of Dammann optimisation with spin-decoupled phase modulation enable the simultaneous manipulation of phase, amplitude, polarisation, and orbital angular momentum to project information into three-dimensional space. This paradigm shift towards full-parameter control in stereoscopic volumes is promising for revolutionising applications from high-capacity optical communications to secure encryption and parallel computing, marking a significant advancement in integrated photonic systems.

**Keywords:** Metasurface, Light field manipulation, Vortex beam

Comprehensive control of the multiple dimensions of a light beam, such as phase, amplitude, polarisation, and orbital angular momentum (OAM), represents one of the most compelling frontiers in modern photonics. Mastering the full suite of dimensions is key to unlocking transformative advances in high-capacity communications, secure encryption, and optical computing systems. In this context, the emergence of metasurfaces, which are engineered two-dimensional materials composed of subwavelength nanostructures, provides a paradigm-shifting solution. By offering local control over the wavefront of light, these ultrathin platforms can modulate various parameters of light, such as phase, amplitude, and polarisation, enabling imaging<sup>1–5</sup>, holography<sup>6–10</sup>, and structured beams<sup>11–13</sup>. However, the integration of these independent controls into a unified, single-element device capable of projecting complex, information-rich, and spatially variant light fields into a three-dimensional

volume remains a critical challenge. Previous results have largely been limited to two-dimensional systems or have involved significant trade-offs among different parameters. Consequently, the broader possibilities of volumetric optical landscapes with multiple parameters remain largely unknown.

In a recently published paper on *Light: Science & Applications*, Zhang et al. conceived and realised a novel metasurface platform that generates a full-parameter-modulated three-dimensional vectorial generalised vortex beam (GVB) array<sup>14</sup>. This work represents a paradigm shift towards holistic light-field synthesis, pushing the frontiers of multidimensional optical control. The recent concept of GVBs has added a new layer of flexibility by allowing custom-designed non-linear azimuthal phase gradients. This breaks the rigid doughnut intensity profile of traditional vortex beams, enabling intuitive graphical representations of mathematical operations and other novel functionalities<sup>15,16</sup>. The current work elevates this concept by creating not only a single GVB but also an entire 3D array, each with independently tailored properties.

This study aims to promote Dammann vortex optimisation, as shown in Fig. 1. The principle of

Correspondence: Xiangping Li (xiangpingli@jnu.edu.cn)

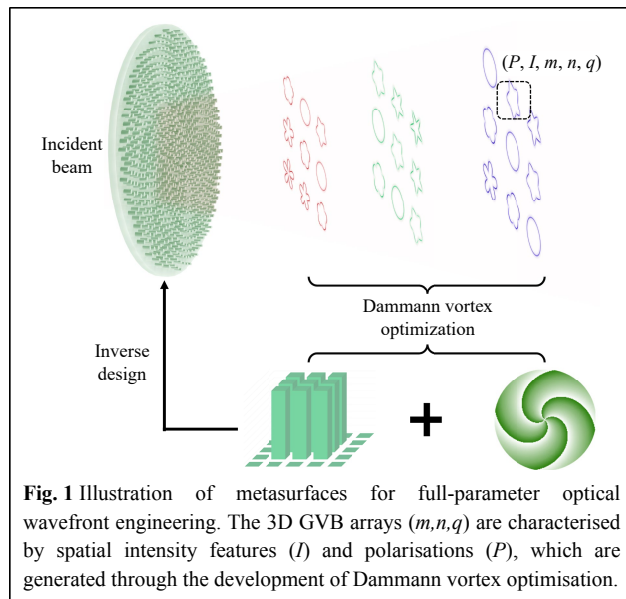
<sup>1</sup>Guangdong Provincial Key Laboratory of Optical Fiber Sensing and Communications, Institute of Photonics Technology, Jinan University, Guangzhou 510632, China

<sup>2</sup>Department of Biomedical Engineering, Hong Kong Polytechnic University, Hong Kong SAR 999077, China

© The Author(s) 2026



**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.



Dammann gratings, which efficiently split a beam into an array of uniform-intensity spots, was combined with the phase manipulation ability of vortex metasurfaces and a zone plate for longitudinal control. Through an analytical model and joint optimisation, a metasurface was designed that projects a 3D lattice of diffraction orders. Each order  $(m, n, q)$  in this lattice acts as an independent channel carrying a unique GVB with a predefined intensity profile and polarisation state. Researchers developed two distinct implementations to showcase their concepts. In the first study, a geometric phase metasurface with rotating silicon nanofins was used to create a scalar 3D GVB array. In this array, the intensity profile of each beam, forming a five-pointed star or classic doughnut, can be spatially varied and controlled based on the sum of its diffraction indices  $m + n + q$ . A more advanced implementation employs a birefringent metasurface composed of rectangular nanopillars. This design allows for independent phase modulation of two orthogonal linear polarisation channels. Through a "vectorial Dammann optimisation" process, the team endowed each of the 27 diffraction orders in a  $3 \times 3 \times 3$  array not only with a distinct intensity profile but also with an arbitrary polarisation, including horizontal, vertical, diagonal, anti-diagonal, left and right handedness circular polarisations.

In summary, this technology demonstrates the potential of metasurfaces to replace complex multicomponent optical systems with single compact devices. The integration of full-parameter control into compact

metasurface platforms represents a significant advancement towards the practical implementation of complex optical systems. As fabrication techniques continue to improve, we anticipate that these devices will be implemented in practical systems for communication, sensing, and computing applications.

#### Data availability

All data are available from the corresponding authors upon reasonable request.

#### Conflict of interest

The authors declare that they have no competing interests.

Received: 04 December 2025 Revised: 13 December 2025 Accepted: 15 December 2025

Published online: 20 January 2026

#### References

1. Khorasaninejad, M. & Capasso, F. Metalenses: Versatile multifunctional photonic components. *Science* **358**, eaam8100 (2017).
2. Lin, R. J. et al. Achromatic metalens array for full-colour light-field imaging. *Nature Nanotechnology* **14**, 227-231 (2019).
3. Wang, S. et al. A broadband achromatic metalens in the visible. *Nature Nanotechnology* **13**, 227-232 (2018).
4. Chen, W. T. et al. A broadband achromatic metalens for focusing and imaging in the visible. *Nature Nanotechnology* **13**, 220-226 (2018).
5. Li, F. J. et al. Meta-grating-lens-based monolithic polarization camera. *Science Advances* **11**, eadx9886 (2025).
6. Yu, Z. et al. Spin-orbit-locking vectorial metasurface holography. *Advanced Materials* **37**, 2415142 (2025).
7. Song, Q. et al. Vectorial metasurface holography. *Applied Physics Reviews* **9**, 011311 (2022).
8. Song, Q. et al. Broadband decoupling of intensity and polarization with vectorial Fourier metasurfaces. *Nature Communications* **12**, 3631 (2021).
9. Deng, Z. L. et al. Multi-freedom metasurface empowered vectorial holography. *Nanophotonics* **11**, 1725-1739 (2022).
10. Deng, Z. L. et al. Vectorial compound metapixels for arbitrary nonorthogonal polarization steganography. *Advanced Materials* **33**, 2103472 (2021).
11. Yu, Z. et al. A spatial-frequency patching metasurface enabling super-capacity perfect vector vortex beams. *eLight* **4**, 21 (2024).
12. Yang, Q. et al. Ultra-secure optical encryption based on tightly focused perfect optical vortex beams. *Nanophotonics* **11**, 1063-1070 (2022).
13. Liu, M. et al. Broadband generation of perfect Poincaré beams via dielectric spin-multiplexed metasurface. *Nature Communications* **12**, 2230 (2021).
14. Zhang, X. et al. Full-parameter-modulated three-dimensional vectorial generalized vortex array. *Light: Science & Applications* **15**, 7 (2025).
15. Zhang, X. et al. Multiplexed generation of generalized vortex beams with on-demand intensity profiles based on metasurfaces. *Laser & Photonics Reviews* **16**, 2100451 (2022).
16. Zhang, X. et al. Basis function approach for diffractive pattern generation with Dammann vortex metasurfaces. *Science Advances* **8**, eabp8073 (2022).