OEA | Opto-Electronic Advances

News & Views

March 2026, Vol. 9, No. 3

Open Access

Optical addressing enables a new architecture for spatial light modulators

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Abstract: Rapidly developing augmented/virtual reality (AR/VR), light detection and ranging (LiDAR), and holographic display technologies require spatial light modulators (SLMs) with high pixel resolution and fast refresh rates to meet increasing application demands. However, existing modulators are limited by large pixel sizes and low spatiotemporal product density. A recent work reports an optically addressed metasurface spatial light modulator (OA-MSLM) that achieves sub-micron pixel pitch with optical addressing of independently tunable meta-atom supercells. The device enables real-time complex-amplitude holography, three-dimensional focusing, and wide-angle beam steering in the visible spectrum. This approach represents a revolutionary paradigm in wavefront control, promising scalable platforms for three-dimensional display, additive manufacturing, and adaptive optics.

Keywords: spatial light modulator; optically addressing; metasurface; holography; beam steering

DOI: 10.29026/oea.2026.260049 | CSTR: 32247.14.oea.2026.260049

Citation: Huang XY, Liu N. Optical addressing enables a new architecture for spatial light modulators. *Opto-Electron Adv* **9**, 260049 (2026).

Spatial light modulators (SLMs) are core components in advanced optical systems ranging from three-dimensional holographic displays[1] and additive manufacturing[2] to quantum optics[3] and adaptive imaging[4]. A key metric for evaluating SLM performance is the spatiotemporal product density (STPD), defined as the number of independently addressable pixels per unit area multiplied by the modulation rate[5]. Therefore, reducing pixel size while increasing refresh rate is critical for enhancing performance and meeting the requirements of emerging applications. For example, practical real-time 3D holography requires an STPD on the order of 10^{12} pixels/(s·cm^2), a benchmark that remains far beyond the capabilities of existing commercial and research SLM technologies.

Over the past few decades, liquid crystal on silicon (LCoS) and digital micromirror device (DMD) technologies have advanced steadily, driven by improvements in fabrication and driving electronics. However, commercial LCoS and DMD systems still employ pixel sizes on the order of several micrometers, which are much larger than visible wavelengths. In LCoS devices, the thickness of the liquid crystal layer and fringing-field effects limit the number of scalable pixels without inducing crosstalk or degrading phase modulation[6]. In DMDs, mechanical constraints such as hinge stiffness restrict both mirror miniaturization and switching speed[7]. As a result, achieving true wavelength-scale pixelated modulation in the visible range remains a formidable challenge, motivating exploration beyond conventional electro-optic and microelectromechanical systems.

With metasurfaces emerging as a versatile platform for subwavelength wavefront engineering[8–10], the integration of commercial SLMs with passive metasurface layers has improved certain system functions, such as spot-count scaling[11], dimensional conversion[12], and field-of-view expansion[13]. Furthermore, active metadevices based on phase-change materials[14,15] and electrochemical actuation[16,17] have demonstrated some dynamic tuning capability, but these approaches are typically limited to single-parameter modulation and millisecond-scale responses. Electrically addressed schemes, including liquid crystal-integrated metasurfaces[18,19] and indium tin oxide (ITO)-based devices[20,21], present promising alternatives for achieving pixel miniaturization,

Received: 13 February 2026

Accepted: 2 March 2026

Published online: 6 March 2026

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yet most implementations support only one-dimensional beam steering and still rely on micrometer-scale pixels.

In a recent paper published in *Nature Nanotechnology*, Prof. Gao H, Prof. Xiong W, Prof. Qiu CW, and collaborators report a conceptually distinct strategy that achieved previously unattainable indicators: an optically addressed metasurface architecture that sidesteps the electrical wiring bottleneck[22]. As shown in Fig. 1, the authors employ a pre-discretized metasurface platform in which each meta-atom supercell is pre-encoded with a static modulation function and selectively activated by structured optical addressing patterns. This "light controlling light" scheme eliminates the need for dense electrical interconnects and enables independent pixel control. The resulting system achieves a pixel pitch of 756 nm and operates at high refresh rates with a frame interval of 77 μs, corresponding to an STPD of 2.3×10^{12} pixels/(s·cm^2). This performance surpasses previous technologies and reaches the threshold required for practical high-speed 3D holography.

For experimental validation, the authors demonstrate a range of wavefront control capabilities. The device supports full complex-amplitude modulation, enabling simultaneous phase and amplitude control that suppresses speckle noise, improves reconstruction fidelity, and reduces computational load compared with phase-only holography. With a sub-micron pixel pitch and kilohertz refresh rates, the high STPD supports real-time dynamic holographic video at visible wavelengths with a wide field of view. The team presents both far-field and near-field reconstructions and multi-plane 3D holography, showing accurate intensity and phase reproduction across propagation regimes. The modulator also enables large-angle beam steering and high-speed patterned scanning while maintaining beam quality, supporting continuous scanning and random-access directional switching across hundreds of output directions.

Moreover, the authors performed experimental demonstrations of multifunctional beam control. With dynamic phase encoding, the OA-MSLM achieves large-angle beam deflection and high-speed patterned scanning while maintaining excellent far-field beam quality. Benefiting from its subwavelength pixel architecture and microsecond-scale response time, the platform supports continuous high-speed scanning as well as random-access directional switching. The researchers demonstrate rapid reconstruction of predefined patterns across hundreds of output beam directions.

This work demonstrates an optically addressed metasurface spatial light modulator capable of sub-micron pixel control and high-speed dynamic operation, achieving a record spatiotemporal product density. The device supports real-time complex-amplitude holography, three-dimensional focusing, and wide-angle beam steering in the visible spectrum, addressing key limitations of conventional electrically addressed SLMs. Future research may investigate integration with compact photonic drive systems, expanding the spectral bandwidth, and implementing tiled optical addressing schemes to further improve scalability and functionality. The study establishes a scalable platform for advanced wavefront control, offering insights that could guide the development of next-generation optical systems for displays, computing, communications, manufacturing, and sensing applications.

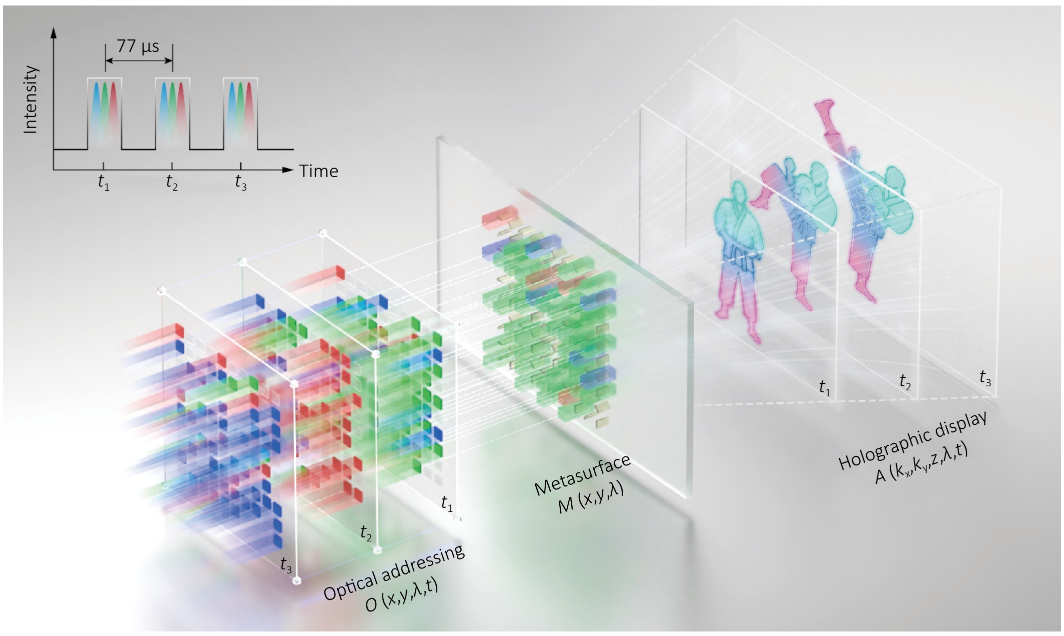

Fig. 1 | Optically addressed metasurface spatial light modulator. OA-MSLM employs time-varying structured optical beams to illuminate a metasurface carrying pre-encoded static modulation functions. By sequentially activating different spatial modulation channels, the device enables independently controllable subwavelength wavefront modulation without electrical wiring constraints. Figure reproduced with permission from: ref.[22], Springer Nature.

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Acknowledgements

We acknowledge support from the Max Planck Society (Max Planck Fellow).

Published by Editorial Office of *Opto-Electronic Advance*, Institute of Optics and Electronics, Chinese Academy of Sciences.

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