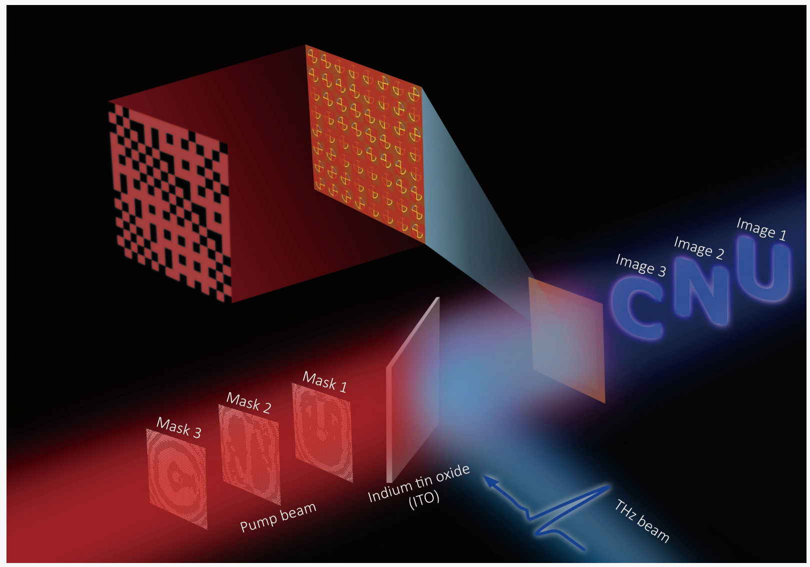
Pixel-Controlled Programmable Metasurface Enables Phase-Type Spatial Terahertz Modulation

Compact VO2-based programmable metasurface enables pixel-level 2π phase control for zoom meta-lensing, vortex beams, and dynamic terahertz holography



This schematic illustrates how a pixel-controlled programmable metasurface functions as a phase-type spatial terahertz modulator for dynamic holographic imaging. By optically addressing individual pixels with patterned pump beams, the device can encode sp

CHINA, August 3, 2026 /EINPresswire.com/ -- Spatial light modulators in the terahertz (THz) band have lagged behind their visible and near-infrared counterparts, despite growing demands for miniaturized, integrable, and multifunctional THz systems. This raises the question of how to realize optically addressed phase-type THz modulators with efficient, independent pixel-level programmability. Researchers propose a compact VO-based programmable metasurface functioning as a 2-bit phase-type spatial THz modulator, enabling full 2π phase control per pixel and zoom meta-lensing, focused vortex beams, and holographic imaging.

Spatial light modulators (SLMs), capable of conveniently loading information onto target optical fields and thereby enabling precise and flexible manipulation of the amplitude, phase, and polarization of light waves, have become indispensable components in modern optical systems. However, compared with their counterparts operating in the visible and near infrared regimes, the development of SLMs in the terahertz (THz) band has remained markedly lagging, leaving considerable room for performance enhancement and technological innovation. With the ever growing demand for multifunctional and intelligent optical systems, increasingly stringent requirements are being imposed on THz SLMs in terms of miniaturization, ease of integration, and efficient control of THz fields, and the rapid advancement of nanophotonics and metasurfaces offers a promising route to addressing these challenges.

Metasurfaces, the two dimensional metamaterials composed of subwavelength structural elements, provide compact planar platforms for tailoring electromagnetic waves, yet conventional metasurfaces are inherently passive and their functionalities are fixed upon fabrication, which severely restricts their applicability in dynamic and complex scenarios. Reconfigurable intelligent surfaces (RISs) based on tunable materials—such as phase change materials, liquid crystals, semiconductors, and graphene—have emerged as a promising route to overcoming these limitations, but existing RIS based THz SLMs still suffer from low operating efficiency, limited functionality, and difficulties in achieving truly independent pixel level programmability. Electrically addressed programmable metasurfaces intrinsically encounter high fabrication complexity, sophisticated electrode routing, and large electrode footprints that limit the number of controllable pixels, whereas optically addressed programmable metasurfaces circumvent these constraints and offer enhanced fabrication feasibility, high density integration of optical functionalities, and a significantly increased capacity for independently addressable pixels; nonetheless, optically addressed phase type THz SLMs remain largely absent.

This question was addressed by a collaborative team of researchers from Capital Normal University and Beijing University of Technology, China, and Justus Liebig University, Germany, led by Professor Yan Zhang from Capital Normal University. Building on vanadium dioxide (VO_2) as a phase change material, they designed a compact, easily integrable, multifunctional, and high performance optically addressed programmable metasurface that functions as a 2 bit phase type efficiently transmissive spatial THz modulator, enabling optically addressed pixel level independent encoding within a 50 × 50 resolution array and dynamic generation and flexible manipulation of THz wavefronts through patterned pulsed optical excitation. This article was made available online in Opto Electronic Advances on June 2, 2026.

To achieve pixel-level control and full 2π phase modulation, the researchers first designed a new type of meta-atom based on C shaped split-ring resonators, into which they integrated patterned VO_2 patches on a flexible polyimide substrate. By exploiting the reversible insulator–metal transition of VO_2 under optical excitation and carefully selecting the substrate to confine heat within the VO_2 regions, the meta-atoms could switch between different phase states while maintaining comparable transmission amplitude, thus enabling a 2 bit phase-type spatial THz modulator with four discrete phase levels over the 0–2π range. These meta-atoms were then arranged into a 50 × 50 pixel array and addressed by patterned pump pulses, so that each pixel could be independently encoded according to the desired phase distribution on the metasurface.

“By combining VO_2 phase change materials with carefully engineered split-ring resonators on a flexible substrate, we were able to realize meta-atoms that not only cover the full 2π phase modulation range, but also remain reconfigurable at the pixel level,” said Prof. Zhang. “This allows us to program the phase profile across the entire metasurface simply by changing the spatial intensity pattern of the optical pump beam, thereby turning a single compact device into a versatile platform for different THz optical functionalities." In proof-of-concept experiments using an optical-pump THz imaging system, the team demonstrated that the same programmable metasurface can function as a dynamic zoom meta-lens with tunable focal lengths, a focused vortex beam generator with adjustable topological charge, and a device for dynamic holographic imaging of letters, all achieved by switching the pump-mask patterns while keeping the physical metasurface unchanged.

"As THz technologies move toward practical applications in high-speed wireless communication and high-resolution imaging, having a single metasurface that can flexibly generate, focus, and shape complex THz wavefronts is extremely valuable," Prof. Zhang added. The proposed pixel-controlled programmable metasurface, operating as a phase-type spatial THz modulator with an experimentally measured amplitude conversion efficiency of about 27%, points to a new class of miniaturized, integrated, and multifunctional THz optical devices that bridge programmable meta-optics and THz photonics. In the longer term, such reconfigurable metasurfaces may contribute to next-generation wireless communication systems, advanced THz imaging, meta-holography and AI-assisted optical architectures, opening up new avenues for controlling THz fields in compact, intelligent photonic systems.

Reference
Title of original paper: Pixel-controlled programmable metasurface as phase-type spatial terahertz modulator
Journal: Opto-Electronic Advances
DOI: https://doi.org/10.29026/oea.2026.260028

About Opto-Electronic Advances
Opto-Electronic Advances (OEA) is a premier, open-access journal dedicated to rapid, high-impact research in optics and photonics. Led by Editor-in-Chief Professor Xiangang Luo, it serves as a global platform for innovative research, boasting an Impact Factor of 22.4 and a CiteScore of 26.8. The journal's extensive scope covers fundamental and applied research in nanophotonics, plasmonics, metamaterials, and advanced optical materials. It also focuses on cutting-edge developments in light sources, sensors, optical imaging, and intelligent digital optics. Furthermore, OEA publishes significant work in biophotonics, nonlinear optics, ultrafast photonics, and photovoltaics. By publishing high-quality empirical and theoretical papers, OEA facilitates global knowledge sharing among researchers and professionals.

About Professor Yan Zhang from Capital Normal University
Yan Zhang is a professor in the Department of Physics at Capital Normal University, a doctoral supervisor, director of the Beijing Key Laboratory of Metamaterials and Devices, and a fellow of the Optical Society of America (OPTICA). His research team primarily focuses on terahertz optoelectronics, micro- and nano-optics, and optical information processing. Professor Zhang has published more than 400 SCI-indexed papers in renowned international journals, including Nature Photonics, Nature Communications, Advanced Optical Materials, and Opto-Electronic Advances. His work has been cited over 14,000 times in the SCI database, and he has delivered

more than 60 invited talks at international conferences.

Funding information
This work was supported by the National Natural Science Foundation of China (12574421, 62275175, 12174270, and 12174271) and Beijing Municipal Natural Science Foundation (2252032).

Siyi Ma
Institute of Optics and Electronics, Chinese Academy of Scie
+86 19136186296
email us here
