Electrically tunable metasurface unlocks real-time THz holography

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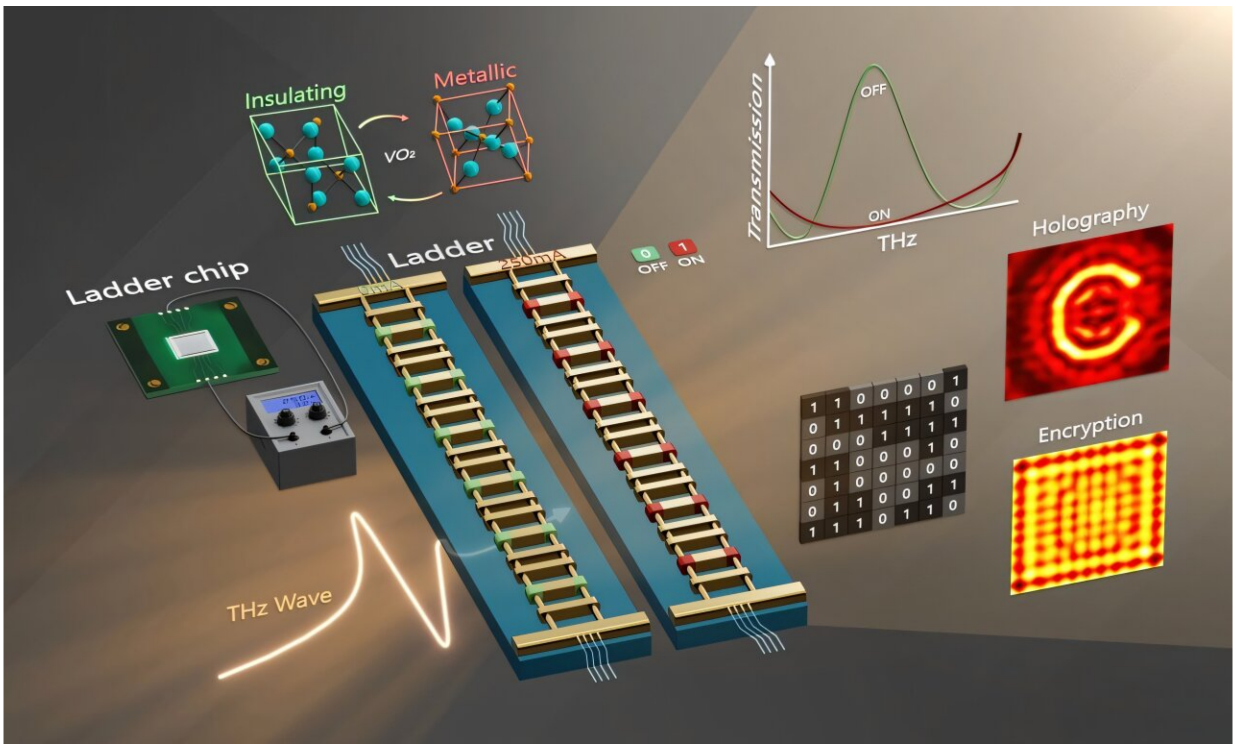

The proposed 'microladder' metasurface has a THz response that can be electrically controlled, making it ideal for holographic imaging and encryption in real time. Credit: Ma, Fan, et al., DOI: 10.1117/1.AP.7.6.066003.

The terahertz (THz) band of the electromagnetic spectrum holds immense promise for next-generation technologies, including high-speed wireless communication, advanced encryption, and medical imaging.

However, manipulating THz waves has long been a technical challenge, since these frequencies interact weakly with most natural materials.

Over the past two decades, researchers have increasingly turned to metasurfaces to tackle this problem. These are ultrathin materials carefully engineered to exhibit specialized properties, providing unprecedented control over THz waves.

Ideally, metasurfaces for THz applications in encryption and holography should be easily configurable, featuring an adjustable response that can be controlled externally. Despite this, tunable metasurface systems often rely on cumbersome or energy-inefficient methods, such as external thermal control.

Furthermore, the holographic information contained in metasurfaces is typically captured using slow near-field scanning systems, which hinders true real-time operation. These limitations have made it difficult to develop practical THz holographic devices for dynamic displays and reversible encryption.

Against this backdrop, a research team, including Dr. Lin Chen and Prof. Dangyuan Lei from the University of Shanghai for Science and Technology and City University of Hong Kong, developed a novel electrically tunable metasurface for THz holographic devices.

Their work, published in *Advanced Photonics*, used an innovative design by leveraging the unique properties of vanadium dioxide (VO_2) in a way that minimizes energy consumption and response time.

Unlike most transition metal oxides, VO_2 exhibits a reversible transition from insulator-to-metal at a low temperature of 68 °C. This transition makes it possible to dynamically modulate the "transparency" of the material to THz waves.

To achieve this, the researchers employed a microladder design, where the handrails of the ladder are conducting gold wires and the ladder steps contain small VO_2 gaps.

When an external current is run through the wires of a given ladder unit, local changes in temperature caused by resistive heating result in a quick insulator-to-metal transition in VO_2, providing a fast, energy-efficient way to modulate the ladder unit's THz response.

After experimentally validating the design and tunability of their microladder metasurface, the researchers demonstrated its use in holography and encryption.

Using a combination of dynamic pixels (with VO_2) and static pixels (without VO_2), they showed how a character can be holographically encoded into the metasurface.

The only way to read out the encoded character is to apply the necessary current to the metasurface while also observing how it transmits THz waves. To read out these THz images at high speed, the researchers used a THz focal-plane imaging system.

The research team highlighted the robustness of their metasurface in terms of its durability and replicability. Image quality remained stable after dozens of hours of operation, and performance was largely unaffected by small changes in distance within the imaging setup.

Speed was also a key strength. "With our microladder metasurface, the dynamic response time for switching holographic images is just about 4.5 seconds in experiment—and for all-dynamic-pixel configurations, it's even faster, sometimes as low as two seconds," explained Chen.

"This level of speed and robustness opens the door to practical, next-generation applications like real-time optical encryption, anticounterfeiting, and next-generation wireless communications."

Thermodynamic analysis revealed that the proposed metasurface can fully change phase in less than three seconds, with experimental switching times matching this rapid performance.

Overall, this study offers valuable design insights that could advance the development of tunable terahertz (THz) metasurfaces. The microladder structure, paired with a THz focal-plane imaging system, provides several advantages: it integrates easily with electronic systems, consumes very little power (about 0.8 watts), supports active modulation, and enables real-time operation.

Additionally, the team at City University of Hong Kong and Creator Electronic Limited plans to continue research and development on electrically controlled THz technologies.

Future work will focus on improving thermal performance and enabling control at the individual pixel level—key steps toward unlocking the full potential of tunable THz metasurfaces.

More information: Shuxiang Ma et al, Electrically controlled real-time terahertz "microladder" integrated with VO2 patches for broadband holographic encryption, *Advanced Photonics* (2025). DOI: 10.1117/1.ap.7.6.066003

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