Terahertz multiplex imaging with reconfigurable masks

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Terahertz spatial light modulators composed of metamaterial arrays enable novel imaging techniques, offering the potential for improved image resolution, acquisition time, and spectral information.

Through the use of spatial light modulators (SLMs), a scene may be imaged with sparse detector arrays and even single-pixel cameras. This is especially useful in longer-wavelength regimes such as the terahertz (THz) gap, the region of the electromagnetic spectrum falling between microwave and IR frequencies where conventional electronics and semiconductor devices no longer function. The creation of high-resolution detector arrays is often unfeasible at these wavelengths. Imaging and sensing at THz frequencies has significant advantages due to the safe interaction of THz radiation with human tissue, and has shown promise in chemical fingerprinting, skin cancer detection, and imaging of hidden weapons.

Modern implementations of single-pixel cameras at optical and near-IR wavelengths use commercially available digital micromirror devices (DMDs) and liquid-crystal-based displays as SLMs. However, researchers have not yet realized the design and implementation of efficient masks at lower frequencies. Initial THz studies explored multiplex techniques and relied on mechanical binary masks being physically interchanged, resulting in extremely slow acquisition rates unsuitable for realistic applications. Metamaterials are engineered electromagnetic materials, typically fashioned from arrays of shaped conducting patterns, that exhibit great control over electromagnetic waves. They can be designed to yield highly efficient absorption by carefully tailoring their electric and magnetic responses. Dynamic control of pixelated THz metamaterial absorbers (MMAs) then permits the formation of a SLM that enables THz single-pixel imaging.

In typical single-pixel cameras, an object is imaged onto a SLM where some spatial portions of the image are blocked and others are passed to the detector: see Figure 1(a). The device can display a combination of known masks in sequence, with a single measurement obtained for each mask, and the image is then reconstructed from these individual mask measurements. For example, it is possible to raster scan using masks that display only one pixel at a time. However, we can increase the signal-to-noise ratio significantly by sampling a combination of spatial pixels using random masks, Hadamard masks, and other types of binary masks.

![Figure 1](image)

Figure 1. Single-pixel multiplex imaging using a spatial light modulator (SLM) encodes spatial information onto a single pixel. (a) Schematic depicting an image modulated with a SLM. (b) Experimentally measured maximum differential absorption for each pixel in the terahertz (THz) multi-color metamaterial absorber–spatial light modulator (MMA-SLM) system. Inset: Photograph of the MMA-SLM sample. (c) Optical image of a commercial digital micromirror device with a Hadamard mask frame displayed for a 31 × 33 pixel array, with 328 μm pixel size.

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We developed technology demonstration systems using this technique at THz frequencies. One imaging setup consists of a doped semiconducting metamaterial as the SLM, with multicolor super pixels composed of arrays of electronically controlled MMAs. The $8 \times 8$ pixels of the MMA-SLM system are arranged in a Bayer-type pattern and form a multi-color super pixel, with each pixel independently modulated at a unique THz frequency. We measured the modulated absorption spectrum for each pixel: Figure 1(b) shows the maximum differential absorption obtained. Our device demonstrated modulation of THz radiation at frequencies up to 12MHz with modulation depths of up to 50%. By using a flip-chip bonded n-doped gallium arsenide epitaxial layer in the MMA, we were able to attain high pixel density while achieving minimal device capacitance, thus allowing for high-speed modulation. Our design is scalable and can accommodate large active areas for much larger pixel count, which permits higher-resolution applications.

We implemented a different system enabling high-resolution, high-fidelity, multiplex single-pixel THz imaging. Our apparatus relies on the fact that optical photoexcitation of semiconductors can lead to an increase in the free-carrier density and hence an attenuation of THz transmission, which can also be used to dynamically tune the electromagnetic properties of metamaterials. By co-propagating a THz and collimated optical laser beams through a high-resistivity silicon (Si) wafer (with or without a metamaterial patterned on the surface), we can control the THz transmission in real time by modifying the optical power. By further encoding a spatial pattern on the optical beam with a DMD, we can write masks for THz radiation in the Si. Figure 1(c) shows an example Hadamard mask in which the black and white areas denote spatial portions where light is respectively blocked and passed to the detector. Photodoping in pure Si permits broadband THz imaging, whereas metamaterial/Si substrates offer greater modulation depths for design frequencies that can offer improvements in resolution and acquisition time. Additionally, metamaterials enable acquisition of multi-color spectral information in a similar fashion to the THz MMA-SLM system in Figure 1.

Figure 2 shows results from our single-pixel THz imaging experiment. We acquired images of a cross pattern—a binary aperture mask—using both a bare and metamaterial-patterned Si wafer. We encoded images using a set of 1023 Hadamard masks (31 $\times$ 33 pixels) for the bare Si and 255 Hadamard masks (15 $\times$ 17 pixels) for the metamaterial patterned Si wafer. Our imaging system magnified our object down to an image size of approximately 10mm in diameter with a linewidth for the cross of approximately 2.5mm: see Figure 2(a). We reconstructed images using the inverse Hadamard transform: Figure 2(b, c) shows the results obtained.

In summary, we have presented effective methods for single-pixel THz imaging. The combination of metamaterials and semiconducting device technology provides significant advantages over traditional masks due to the benefit of spectral sensitivity and real-time control. The study of THz imaging using a DMD to project a spatially modulated optical beam onto a metamaterial-patterned high-resistivity Si wafer shows high-fidelity imaging is possible. Future work will expand the size of the MMA-SLM array to image more complex scenes.

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