photonic layer could be kept very small — the resonant frequency of the disks did not change when the membrane was bent to a radius of 0.8 mm. Furthermore, when the membrane was bent many thousands of times, only a small increase (0.5 dB cm^{-1}) in optical losses and a small drop (about 23%) in the resonator quality factor were observed.

Building on these results, the team went on to demonstrate devices that exploited the three-dimensional capabilities of their techniques. For example, they described vertically coupled add–drop filters employing critical coupling from an in-plane add port to a vertically coupled through port, where they achieved a useful quality factor of 2.5×10^4 and a transmission of 80% at the through port. In addition, they demonstrated a basic three-dimensional photonic crystal.

The results are further evidence that photonic devices based on chalcogenide glass have a bright future, especially for applications that are not constrained by the need to be compatible with silicon electronics. Obviously, improvements can still be made (for example, further reducing the optical losses of the waveguides), but the present results demonstrate new ways of using strain-relieving elastic layers to optimize the performance of flexible photonics even when subjected to strong bending. ❐

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TERAHERTZ IMAGING

Compressing onto a single pixel

A breakthrough in metamaterial-based spatial light modulator design makes single-pixel real-time imaging practical by using compressive sensing to dispense with slow mechanical scanning.

Withawat Withayachumnankul and Derek Abbott

Terahertz radiation spans the 0.1–10 THz frequency range[1], which lies above the microwave and below the infrared regions of the spectrum. This region accommodates a variety of microscale spectroscopic phenomena, and waves in this regime can penetrate most dry non-metallic substances. These characteristics together with the wavelength-defined resolution render terahertz waves very attractive for imaging. Using suitable hardware, submillimetre-resolution imaging can be realized and spectral information can be extracted that provides unique 'fingerprints', which can be used to identify materials. Nevertheless, accessing this frequency band has proved very challenging. Extending microwave technology into this band is largely defeated by the large time constants imposed by parasitic inductance and capacitance, whereas semiconductor-based imaging, so prevalent at optical wavelengths, is not directly applicable at terahertz frequencies owing to a mismatch in energy levels.

Reporting in *Nature Photonics*, Claire Watts and colleagues now show that it is possible to achieve practical single-pixel, real-time terahertz imaging by exploiting recent breakthroughs in terahertz metamaterials[2] and compressive sensing[3]. Achieving this in real time with no mechanical scanning and with incident powers of only a few tens of nanowatts is impressive, and it is likely to be a game changer for commercial applications. This feat was achieved by using compressive sensing, where a metamaterial-based spatial light modulator (SLM) located between the object and detector rapidly switches between a set of binary masks. The image can then be reconstructed from the resulting signals using software.

Various other well-known techniques have been used in attempts to achieve real-time terahertz imaging. Straightforward mechanical raster scanning can attain a high sensitivity but at the expense of a slow speed[4]. Faster video frame rates are achievable using two-dimensional electro-optical sampling, but this demands a coherent source and has the limitation of a slow optical delay line[5]. Although focal-plane detector arrays of microbolometers are a promising option for terahertz imaging[6], problems with pixel calibration and dead pixels add to the cost and complexity. Of these techniques, raster scanning is the only one that does not lower the dynamic range by smearing precious terahertz energy across hundreds of pixels. So is there a way to exploit the advantage of a single pixel while circumventing the need to use slow raster scanning?

The idea is to overcome the complexities and limitations of two-dimensional imaging techniques by returning to the simplicity of a single-pixel detector, which typically has a superior detection performance than a multiple-pixel detector. In single-pixel imaging, the entire scene is illuminated by a spatially modulated terahertz beam, which is then collected and integrated onto the single-pixel detector to constitute one measurement. Spatial modulation is achieved by using a set of pixelated optical masks. With no mechanical scanning, the image can be unambiguously reconstructed by repeatedly measuring the scene with different masks, whose number equals the number of image pixels. The key to simplifying this time-consuming task is to adopt compressive sensing that exploits sparsity within the scene. For a typical image scene, most of the representing coefficients can be discarded with no observable effect on the quality of reconstructed images. This principle permits the number of measurements of a scene to be significantly reduced.

The single-pixel sensing concept using a sequence of coded masks was first suggested by Golay in the 1940s[7] and was initially developed for optical imaging in the 1970s[8]. A group at Rice University in the USA reduced the number of masks by using compressive sensing[9] and extended imaging to terahertz frequencies[10]. In a proof-of-concept demonstration, the Rice University group employed a set of static random masks with binary modulation (that is, on/off) for 32 × 32 pixel imaging. Coupled with coherent terahertz time-domain spectroscopy, their system successfully reconstructed amplitude and phase-contrast images, with only one third the number of scans required by raster imaging. Achieving real-time imaging necessitated the use of reconfigurable SLMs, which were developed only subsequently. Soon afterwards, SLMs for terahertz waves were developed based on various principles, including active metamaterials[11] and carrier injection[12]. Recently, Sensale-Rodriguez *et al.* demonstrated a graphene-based spatial modulator[13], but it has a limited image resolution.

Watts and colleagues from Boston College in Massachusetts, USA, have now demonstrated a complete single-pixel terahertz imaging system[3] (Fig. 1). A key enabling component is an SLM based on the principle of terahertz perfect absorbers. To achieve spatial modulation, the absorber is divided into 8 × 8 square areas, each independently controlled via electronics to reflect or absorb terahertz waves. In the measurement process, terahertz radiation from an incoherent mercury-arc lamp is guided and collimated by reflective optics to illuminate the object. The object's shadow is then projected onto the SLM, which modifies the amplitude of the reflected terahertz beam in accordance with the mask pattern. A liquid-helium-cooled silicon bolometer collects the entire beam via focusing optics. To enhance the sensitivity, the SLM is biased with the reference a.c. signal and the encoded bolometer signal is demodulated by a lock-in amplifier. The collected data are processed to reconstruct the original image, based on the principle of compressive sensing.

This imaging system incorporates significant improvements compared to that of the Rice University group[10]. A major milestone is that the active SLM enables real-time imaging. The 12 MHz modulation speed of the SLM sets an upper bound on the video frame rate. Additionally, instead of employing random masks, a Hadamard encoding scheme is adopted to create uncorrelated masks that eliminate redundancy in the collected data. The Hadamard masks are shown to yield reasonable image quality with only one third of the scans. Another major leap is the use of positive and negative mask values, available through in-phase and out-of-phase lock-in modulation, to lower the noise level. Overall, these techniques, in combination with compressive sensing, lead to impressive terahertz video with a 1 Hz frame rate, which is limited by the lock-in time constant. Remarkably, the entire scene can be imaged using a power of only 67 nW. In addition, the researchers demonstrated that the system is highly tolerant to dead pixels in the SLM.

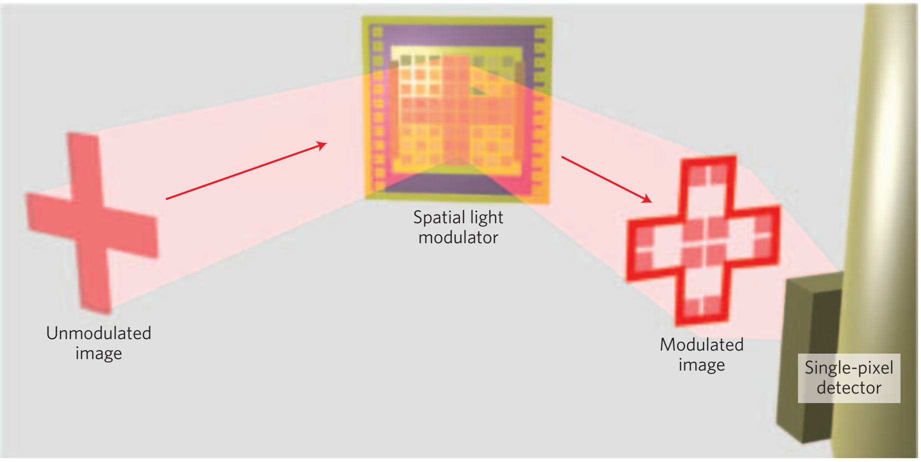

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Figure 1 | Schematic of single-pixel terahertz imaging with an active SLM. In this scheme, the SLM masks parts of the image. When a series of different mask patterns is rapidly cycled through, the sequence of data from the detector contains enough information that the complete scene can be reconstructed using software. This is a form of compressive sensing. Using a Hadamard coding scheme for the masks turns out to be considerably more efficient than employing random mask patterns.

Some drawbacks include the use of binary images, a limited image resolution and a relatively low modulation speed. In addition, a relatively high 26 V supply is required to power the device. Nevertheless, these disadvantages are not fundamental limitations, and should be considered as challenges for further improvement. Passive imaging is possibly ruled out, as the SLM will radiate black-body radiation — although a cooled SLM may circumvent this. It will be interesting to see if future work will lead to a pixel size comparable to the diffraction limit. Beyond that, if the mask has subwavelength pixels and is positioned within a wavelength from the object, it might be possible to resolve near-field terahertz images using existing far-field systems. Moreover, the technique can be readily extended to real-time multispectral or hyperspectral imaging at terahertz frequencies. The design flexibility afforded by metamaterials allows the pixel count and SLM area of this imaging system to be increased. Metamaterials also allow for the possibility of colour measurements as well as sensitivity to phase and polarization, for example.

Traditionally, imaging in the long-wavelength regime has been difficult because of both the lack of commercial focal plane arrays and the large physical size of such arrays. By rethinking how imaging is performed, this groundbreaking work has avoided the need to use large arrays of individual detectors, and it has moved us towards single-pixel terahertz imaging. Rather than developing expensive detector technology, exploring creative and innovative techniques may improve this simple, low-power, low-cost metamaterial SLM.

Watts and co-workers have created a high-frame rate, high-fidelity terahertz imager utilizing only a single-pixel detector, which is capable of capturing terahertz images using a low-power source. It has the potential to revolutionize imaging in the long-wavelength regime. In particular, its much improved performance and compact size promise to open up a wide range of applications in both industry and biomedical research for which non-invasive substance detection is highly desired. ❐

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