A single-pixel terahertz imaging system based on compressed sensing

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Over the past several years, the wide applicability of terahertz imaging in areas such as detection of foam insulation defects, illicit drug detection, and package inspection has driven the development of high-speed terahertz imaging systems. Most existing terahertz imaging systems use a raster scan to move an object in front of a single pixel detector. This mechanical scanning significantly limits the acquisition speed. With state-of-the-art technology, it takes about 6 min to scan a 100 x 100 mm² area at 0.25 mm resolution. Real-time terahertz imaging has been demonstrated using focal-plane detector arrays. However, these systems tend to have higher complexity and operational cost. For example, available array detectors, such as microbolometer arrays, are relatively insensitive to terahertz radiation, so a bright terahertz source is needed. Single-shot electro-optic sensing also allows video-rate terahertz imaging, but this method requires a large and costly amplified femtosecond laser system. Even though interferometric or tomographic approaches have significantly reduced the number of required measurements by, for example, nonuniform sampling in the Fourier domain, the acquisition speed of such systems is still limited by raster scanning unless a full detector array is used. Our method replaces this mechanical scanning with the spatial modulation of the free-space terahertz beam, which can in principle be much faster.

The principle behind the design of CS imaging systems can be summarized in the equation $y = \Phi x$, where $y$ is a $M \times 1$ column vector of measurements, $x$ is an image with $N^2$ pixels ordered in a $N \times N$ vector, and the measurement matrix $\Phi$ is $M \times N^2$. Using CS, we acquire a much smaller number of measurements than the number of pixels in the image, i.e., $M < N^2$, and can still reconstruct the object perfectly through an optimization procedure as described in the references. Our previous work on terahertz Fourier imaging using CS and phase retrieval uses a random subset of the Fourier basis as rows of $\Phi$. Here, we choose a set of vectors, whose entries are randomly picked to be 1 or 0 with equal probability, as rows of $\Phi$. In other words, for each row in $\Phi$, only a random subset (approximately half) of the pixels are set to unity (100% transmission), while the remainder is set to zero (no transmission). Thus, the terahertz beam traveling from the object to the detector is filtered by randomly blocking a subset of the spatial wave front.

Figure 1 illustrates our imaging setup, which consists of a terahertz transmitter/receiver pair (fiber-coupled photoconductive antennas), a planar screen with a random pattern of blocked pixels, and two lenses. The terahertz beam, after passing through the object mask and the random pattern, is collected at the receiver. The positions of the screen, the focusing lens, and the receiver along the beam path are calculated according to the lens law in order to efficiently focus.
The terahertz beam is large enough to illuminate the entire object and has a high spectral amplitude. Figures 2(b) and 2(c) shows the CS reconstruction results, 32×32 images of the object in Fig. 2(a) with 1×1 mm² pixel size, using 300 and 600 measurements respectively. Our reconstruction algorithm uses minimization of the total variation (min-TV), which takes less than 10 s to compute in Matlab on a standard personal computer. Our system accurately reconstructs both the size of the object and its millimeter-scale features. Reconstruction using more measurements yields a sharper image but also adds some artifacts. Sources of noise include laser power fluctuation and alignment errors between patterns.

Figure 3 plots the normalized mean-squared error (MSE) of the reconstructed images of the object in Fig. 2 using different numbers of masks (CS measurements). Due to the reduced rate of convergence of the min-TV reconstruction algorithm for number of CS measurements below 250, we use the minimization of the l1-norm in the wavelet basis as our reconstruction method for the results in Fig. 3. The normalized MSE of each reconstructed image is computed as in \( \Sigma [X(i) - X(i)]^2 / \Sigma X(i)^2 \), where the summations are across all image pixels, \( X_i \) is the reconstructed image and \( X \) is a 32×32 grayscale reference image downsampled from a digital photograph of the object. The MSE sharply decreases from 50 to 100 CS measurements and then decays more slowly afterwards. The shape of this decay curve is dependent on the sparsity of the object in the reconstruction basis and on the system noise. In general, this decay is fast until the number of measurements reaches the sparsity level of the object. Our experimental result is consistent with this trend.

We emphasize that this reconstruction from only the amplitude measurements at a single frequency is equivalent to imaging using a continuous-wave (cw) terahertz source. If we apply this method directly to cw terahertz systems, we could use a more sensitive single-pixel detector, such as a Schottky diode, and thus reduce the source power requirement dramatically compared to imaging with existing multipixel detector arrays.

There have been very few implementations of CS systems capable of acquiring and reconstructing complex image data. Since pulsed terahertz systems are well-known for providing spectroscopic phase information, we demonstrate this capability in our single-pixel system, using CS algorithms specifically designed to reconstruct complex images. The object to be imaged consists of a simple rectangular hole, half of which is covered by a transparent plastic plate. For each random pattern, we determine both the magnitude and phase of the terahertz radiation at a single frequency (again,
100 GHz). CS reconstruction with 400 measurements using the SPGL1 algorithm (see Ref. 17) yields the image amplitude and phase shown in Fig. 4. While the amplitude image shows almost no contrast, the phase image shows a sharp contrast between the upper and lower halves of the rectangular aperture. The thickness difference ($\Delta d$) can be estimated from the measured phase difference ($\Delta \theta$) according to $\Delta \theta = \omega (n - 1) \Delta d / c$, which is valid since the plastic is essentially dispersionless. From our experimental data, when the number of CS measurements increases from 200 to 600, $\Delta d$ estimates averaged across 100–200 GHz rapidly converges to the true $\Delta d$ measured with a micrometer. To capture complex terahertz data in our system, acquisition of the entire terahertz waveform is necessary. In this case, we obtain hyperspectral and phase information at the expense of lower imaging speed due to the mechanical movements of the delay line.

To conclude, the single-pixel, pulsed terahertz camera described in this paper does not rely on raster scanning or a source/detector array, but uses random patterns for imaging. Based on the theory of CS, the system is capable of recovering a $32 \times 32$ image of a rather complicated object with only 300 measurements ($\sim 30\%$). This significant reduction in the number of measurements used for CS image reconstruction can speed up the acquisition tremendously compared to traditional raster scan systems. Unlike its optical counterpart which measures only intensity, our pulsed terahertz camera can reconstruct complex images. Currently, the major limitation of our setup is the slow translation of one random pattern to another. However, it is clear that other schemes for binary spatial modulation of a terahertz beam, driven either optically or electrically, can operate extremely rapidly and with no mechanical moving parts. This should allow the acquisition of sufficient information for image reconstruction at a rate comparable with video imaging.

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