Compressed terahertz imaging system using a spin disk

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Abstract— **We report the development of a terahertz imaging system based on the concept of compressive sensing. A spin disk with random patterns was used to modulate the terahertz beam, and terahertz image was subsequently reconstructed from the measured terahertz signals. We present experimental results obtained using both a BWO source at 0.14 THz and a thermal light source (blackbody radiation) covering both infrared and visible range.**

I. INTRODUCTION AND BACKGROUND

TERAHERTZ time-domain (pulsed) imaging has found applications in areas such as medical diagnosis of human tissue, detection and chemical mapping of illicit drugs and explosives, and pharmaceutical tablet inspection. However, most existing terahertz imaging systems remain too slow for real-time applications due to their pixel-by-pixel raster scans.

Recently Chan *et al.* [1] and Shen *et al.* [2] reported fast terahertz sensing systems through a single-pixel detector. Suppose that we want to get an $I_r \times I_c$ image with $N = I_r I_c$ pixels in total and let $\mathbf{x}$ represent the vector version of the image. The imaging process in the single-pixel camera [1, 2] can be modeled through the following linear transform

$$\mathbf{y} = \Phi\mathbf{x}$$

where $\mathbf{y}$ represents an $n\times1$ measured terahertz signal ($n<<N$) and Φ is an $n\times N$ measurement matrix. In [1], Φ is a random binary matrix and in [2], Φ is optimized to maximize the sampling efficiency based on the statistical model of natural images. Since $n<<N$, nonlinear optimization is required to reconstruct $\mathbf{x}$ from $\mathbf{y}$ by exploiting the sparsity of the input image [3].

Note that in both [1] and [2], each row of Φ is implemented as an $I_r \times I_c$ binary mask and hence, n masks are required. In this paper, we propose to use ***a single rotating mask*** (a spin disk), rather than n masks, to further speed up the imaging process. In the proposed compressed terahertz imaging system, a motorized rotary stage is used. This enables the measurement to be done automatically and continuously, ideal for real-time terahertz imaging applications.

II. METHOD AND EXPERIMENT

From a signal processing point of view, the sampling operator Φ corresponding to a spin disk can be approximated as a random block toeplitz matrix with the following form:

$$\Phi \approx \begin{bmatrix} A_0 & A_1 & \cdots & A_m \\ A_{-1} & A_0 & \cdots & A_{m-1} \\ \vdots & \vdots & \ddots & \vdots \\ A_{-n} & A_{1-k} & \cdots & A_{m-n} \end{bmatrix} \qquad (1)$$

where each A_i ($-n<i<m$) corresponds to a random row vector with length of N/m whose entries are *i.i.d* Bernoulli variables. Compared with the full random matrix used in [1], Φ given above requires less storage space and yields much faster computation. More importantly, it can be easily implemented in hardware, as we will explain below. Although some theoretical results about (block) toeplitz measurement operator were investigated in literature [4, 5], their practical applications in compressive imaging applications, especially hardware implementations are still under development.

Figure.1 shows the schematic diagram of the terahertz compressed imaging system developed in this study. Like in previous studies, a single-point detector was utilized to measure terahertz signal transmitted through a sample. However, in this paper, we used a single spin disk, rather than a set of two-dimensional binary masks [1, 2], to modulate the terahertz beam pattern. This configuration allows the measurements to be done continuously. A square mask pattern with 32×32 pixels is formed at each rotation step of the spin disk. The terahertz images of the sample are then reconstructed in the same manner as reported previously [2].

III. RESULTS

In order to demonstrate the proof of the principle, we firstly performed experiments in the visible and infrared range. An infrared thermal light source was used as the source and a photodiode was used as the detector. The samples used here were copper tape with a pattern of “T”, “X” and “O”. Figure 2 shows the reconstructed images of samples using the measured and simulated signals. The dark areas (in blue) correspond to the opaque copper tape, and the bright areas (in red) correspond to the cut-through holes. In all cases, the characters of “T”, “X” and “O” can be easily recognized. Note that only 120 measurements were necessary to obtain an image of 1024 pixels. This represents a 9 times reduction in

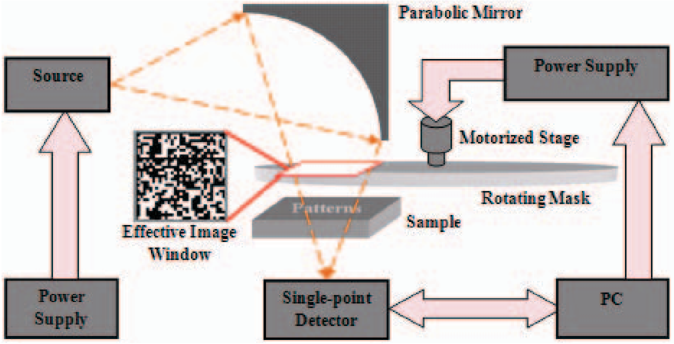

Fig.1 Schematic diagram of the compressed terahertz imaging system. A single rotating mask (a spin disk) was used to modulate the terahertz beam.

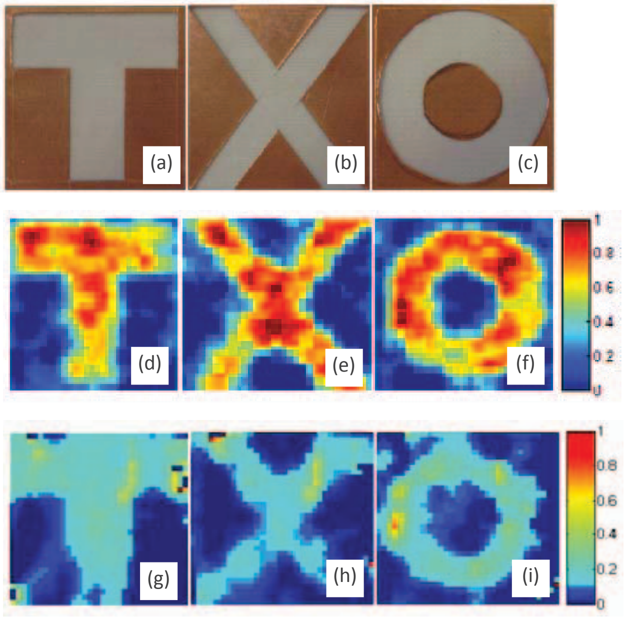

Fig. 2 Photograph of the sample ((a)-(c)), infrared images reconstructed using simulated signals ((d)—(f)), and measured signals ((g)—(i)). The samples used are copper tape with a cut-through pattern of “T”, “X” and “O”. A rotating mask was used in the measurements, and the images were reconstructed from 120 measurements. Each image has 32×32 pixels with a pixel size of 1.2 mm x 1.2 mm. A thermal light was used as the source and a photodiode was utilized as a single-point detector.

measurement number and thus measurement time.

As a further demonstration that the developed compressed imaging system is also applicable to terahertz imaging, Figure.3 shows the images of the copper tape samples concealed in fiber reinforced epoxy resin. Here we used a BWO source (Insight Product Company, USA) which provides electromagnetic radiation at 0.14 THz. The detector used was SPH-49 (Spectrum Detector Inc. USA). A DSP Lock-in Amplifier (SR830, Stanford Research System, USA) was used to amplify the signal in the measurements. Again all sample patterns can be identified. Note that the images were reconstructed from 100 measurements in about 200 seconds, which represents a significant reduction in both the measurement number and the measurement time. We anticipate that better image quality could be obtained by improving the signal-to-noise ratio, and shorter image acquisition time could be achieved by using a fast terahertz detector.

IV. CONCLUSION

In conclusion, we demonstrated here that a spin disk based compressed terahertz imaging system is well suitable for automatic and continuous measurement, thus could have great potential in real-time imaging applications. For the further research, we will focus on improving the signal noise ratio of the system, aiming for biological imaging applications.

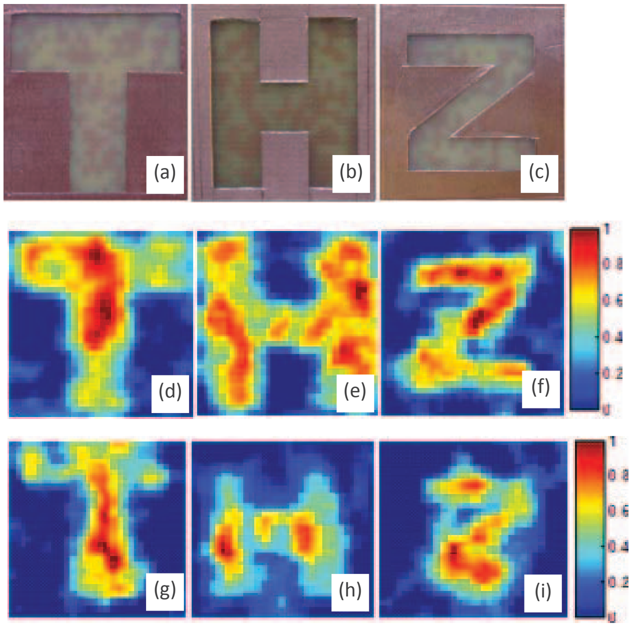

Fig.3 Photograph of the sample ((a)-(c)), THz images reconstructed using simulated signals ((d)—(f)), and measured signals ((g)—(i)). The samples used are copper tape with a cut-through pattern of “T”, “H” and “z”, which is concealed in fiber reinforced epoxy resin. A rotating mask was used, and the images were reconstructed from 100 measurements. Each image has 32×32 pixels with a pixel size of 1.0 mm x 1.0 mm. A BWO source at 0.14 THz was used to illuminate the sample and the transmitted terahertz radiation was measured using a single-element pyroelectric sensor.

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