Single-pixel terahertz imaging based on spatial Fourier spectrum

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Abstract

We propose and demonstrate single-pixel terahertz imaging based on spatial Fourier spectrum (SFS). The concept and the operation principle of this novel approach are introduced by comparing with the conventional compressing sensing (CS) approach, clarifying their similarities and differences. By doing this, we find that these two different approaches can share the same photo-induced coded aperture setup, facilitating their direct comparisons. Our results show that, compared with the CS approach, the SFS approach can reconstruct high-quality images with greatly reduced number of measurements, i.e., the sampling ratio, and is thus more efficient. Remarkably, the SFS-based system is capable to assemble a 64 × 64 image with signal-to-noise ratio of 6.0 for a sampling ratio of only 4.8%. We further show that deep photo-induced terahertz modulation by adopting graphene on silicon substrate and high laser power can significantly improve the image quality. We expect this work will speed up the efficiency of single-pixel THz imaging and advance THz imaging applications.

1 Introduction

Terahertz wave refers to electromagnetic radiation with a frequency of 0.1 THz – 10 THz (corresponding to wavelength of 30 µm – 3 mm). Terahertz imaging is widely used in security [1, 2], industrial inspection [3, 4], and material composition identification [5, 6] because of its unique properties such as superior spatial resolution, perspective, and spectroscopic fingerprints [7, 8, 9]. One challenge in THz imaging applications has been the amount of time it takes to form an image [10]. In most THz imaging examples, image formation relied upon a pixel-by-pixel acquisition using a single-pixel THz detector and mechanical scanning [10]. However, this process is usually slow, limiting the image acquisition speed [10]. Therefore, efforts have been put on focal-plane
array detection based on multi-pixel detectors in integrated form [11]. Despite of great progress, commercially available focal plane array detectors are still too expensive to afford for most researchers. As a result, approaches to speed up image acquisition with single-pixel THz detectors, which overcome the complexities and have a superior detection performance than a multiple-pixel detector [12], have also been attracting increasing attention over the years.

In 2008, Chan et al. [13] proposed and demonstrated single-pixel THz imaging based on a powerful approach known as compressed sensing (CS): only 500 measurements are required in order to reassemble the full image of 4096 pixels. This approach replaces the mechanical scanning with the spatial THz modulation and thus enables a much shorter image acquisition time. Chan et al. [14] further improved this approach by using a set of binary metal masks to modulate the object information, and reconstructed the full image of 1024 pixels with 300 measurements. In order to avoid the use of moving masks, which are difficult to align, Watts et al. [15] made use of metamaterial spatial modulator, Sensale-Rodriguez et al. [16] employed arrays of graphene electro-absorption modulators, and Kannegulla et al. [17] and Shams et al. [18] demonstrated photo-induced coded-aperture imaging using programmable illumination from a commercial available digital light processing projector. Recently, near-field CS-based THz imaging with subwavelength resolution [19] were also demonstrated. Although great progress has been achieved, CS-based single-pixel THz imaging still suffers from long reconstruction time especially for large images [20].

In this work, we propose and demonstrate a highly efficient single-pixel THz imaging approach based on spatial Fourier spectrum (SFS). The concept and the operation principle will be introduced by comparing with the conventional CS approach, clarifying their similarities and differences. We will implement both approaches in experiment with the same photo-induced coded aperture setup, where only the projection masks are distinct. With this common setup, we will directly compare the performance of both the CS and SFS approaches under the same experimental conditions. The influences of the photo-induced THz modulation depths on the image quality will also be discussed by comparing different laser powers that are delivered onto a monolayer graphene on silicon (GOS), and by comparing the GOS and the conventional high resistance silicon (HRS) substrates.

2 Concepts and theory

2.1 Concept for the SFS approach

Before we introduce the concept of SFS-based single-pixel THz imaging, let us first recall the conventional CS approach. For a THz image of $N \times N$ pixels to be measured, a series of random masks are projected onto the target and then the cumulative signal is measured using a single-pixel detector; a series of such measurements (with the number of $M$) lead to [13, 14]

$$Y_{\text{CS}} = P_{\text{CS}} X,$$

where $Y_{\text{CS}}$ is a $M \times 1$ vector of measurements, $X$ is the image with $N \times N$ pixels ordered in a $N^2 \times 1$ vector, and $P_{\text{CS}}$ denotes the series (with the number of $M$) of $N \times N$ projection masks $p_{CS}^{N \times N}$ ordered in a $M \times N^2$ matrix. For each measurement, the projection mask $p_{CS}^{N \times N}$ can be generated with Hadamard coding [21], which consists of “1” and “−1” elements with each row orthogonal to all other rows [22].

Using the CS approach, the number of measurements for assembling the image can be much smaller than the number of image pixels, that is $M \ll N^2$. The sampling ratio can be defined as

$$S_R \equiv M/N^2,$$

Even with highly undersampled measurement sets, the image can still be accurately reconstructed [23]. This is usually done through a minimization of the L1-norm [13, 14]. Quite recently, a more complicated algorithm that performs total variation minimization has been developed to obtain an image with a significantly better signal-to-noise ratio [19, 24]

$$\min \sum_i \sqrt{(D_h X)_i^2 + (D_v X)_i^2} \text{ s.t. } ||P_{\text{CS}} X - Y_{\text{CS}}||_2 < \gamma$$

where $\gamma$ is a relaxation variable that determines the smoothness of the reconstructed image, and $D_h$ and $D_v$ are the discretized gradient operators along the horizontal and vertical directions, respectively.
With the knowledge of the CS approach, we now introduce the concept of the SFS-based THz single-pixel imaging. Similar to the single-pixel optical imaging based on Fourier spectrum [25], the 2D discrete Fourier transform of a THz image of \( N \times N \) pixels can be expressed as

\[
F_{kl} = \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} x_{mn} \exp \left[-j2\pi(mk + nl)/N\right], \tag{4}
\]

where \( k, l = 0, \ldots, N - 1 \). Since \( \exp(-j\Theta) = \cos \Theta + j\cos(\Theta + \pi/2) \) with \( \Theta = 2\pi(mk + nl)/N \), we can introduce a series of projection masks \( p_{SFS}^{N \times N}(k, l, \varphi) \) with elements defined as

\[
p_{SFS}^{N \times N}(k, l, \varphi) \equiv \cos(\Theta + \varphi), \tag{5}
\]

where \( m, n = 0, \ldots, N - 1 \), and \( \varphi \) is the initial phase. Thus Eq. (4) can be written as

\[
F_{kl} = Y_{SFS}^{N \times N}(k, l, 0) + jY_{SFS}^{N \times N}(k, l, \pi/2). \tag{6}
\]

Similar to the CS approach, here \( Y_{SFS}^{N \times N}(k, l, \varphi) \) is a \( M \times 1 \) vector of measurements,

\[
Y_{SFS}^{N \times N}(k, l, \varphi) = p_{SFS}^{N \times N}(k, l, \varphi)X, \tag{7}
\]

where \( X \) is the image with \( N \times N \) pixels ordered in a \( N^2 \times 1 \) vector, and \( p_{SFS}^{N \times N}(k, l, \varphi) \) denotes the series (with a number of \( M \)) of projection masks \( p_{SFS}^{N \times N}(k, l, \varphi) \) ordered in a \( M \times N^2 \) matrix.

With Eqs. (4) and (6), the image can be reconstructed from \( Y_{SFS}^{N \times N}(k, l, 0) \) and \( Y_{SFS}^{N \times N}(k, l, \pi/2) \) through the inverse discrete Fourier transform (IDFT), which is expressed as

\[
x_{mn} = \frac{1}{N^2} \sum_{k=0}^{N-1} \sum_{l=0}^{N-1} F_{kl} \exp \left[j2\pi(mk + nl)/N\right]. \tag{8}
\]

Here the undersampling is achieved by truncating the spatial Fourier spectrum with a low-pass filter, i.e.,

\[
F_{kl} = \begin{cases} 
\text{Eq. (6)} & \text{for } 0 \leq k, l \leq \sqrt{M} - 1, \\
0 & \text{otherwise}.
\end{cases} \tag{9}
\]

The sampling ratio \( S_R \) can also be defined by Eq. (2).

### 2.2 Modified theory for experiments

In photo-induced coded aperture setup, the projection masks in both the CS and the SFS approaches can be implemented by optically modulating the terahertz wave with semiconductors, such as GOS or HRS. The laser beam can be coded with a digital micromirror device (DMD) with “0” (dark) and “1” (bright), corresponding to strong (“1”) and weak (“0”) terahertz wave transmission, respectively. Since it is difficult to describe “-1” in THz transmission, the above theories for both the CS and the SFS approaches, of which the projection masks consist of “-1” and “1”, should be properly modified so as to be consistent with the experiments.

For the CS approach, the Hadamard projection mask \( p_{CS}^{N \times N} \) composed of “1” and “-1” elements is replaced by the substation of two masks \( p_{CS, I}^{N \times N} \) and \( p_{CS, II}^{N \times N} \), both of which consist of “1” and “0” elements, that is,

\[
p_{CS} = p_{CS, I}^{N \times N} - p_{CS, II}^{N \times N}, \tag{10}
\]

as illustrated by Fig. 1(a). Thus \( Y_{CS} \) in Eqs. (1) and (3) should be replaced by \( Y_{CS} = Y_{CS, I}^{N \times N} - Y_{CS, II}^{N \times N} \) with \( Y_{CS, I}^{N \times N} = p_{CS, I}^{N \times N}X \).

Similarly, the projection mask for the SFS approach \( p_{SFS}^{N \times N}(k, l, \varphi) \) should also be properly scaled to the range of \([0, 1] \),

\[
p_{mn}^{SFS}(k, l, \varphi) = a + b\cos(\Theta + \varphi), \tag{11}
\]

where \( a = b = 1/2 \). According to Eq. (7), we find

\[
Y_{SFS}^{N \times N}(k, l, 0) + jY_{SFS}^{N \times N}(k, l, \pi/2) = (1 + j)a \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} x_{mn} + bF_{kl}. \tag{12}
\]
Figure 1: (a) A typical $4 \times 4$ projection mask using Hadamard coding, which is composed of “$-1$” and “1”, is replaced by two matrices composed of “1” and “0” for the CS approach. (b) Typical $32 \times 32$ projection masks for the SFS approach, which have been scaled properly to be within the limit of $[0, 1]$. 

Table 1: Similarities and differences between CS- and SFS-based THz single-pixel imaging.

| Approach | Projection masks | Reconstruction methods |
|----------|------------------|------------------------|
| CS       | $p_{CS}^{4 \times 4}$ and $p_{CS}^{4 \times 4}$ | Optimization procedure such as Eq. (3) |
| SFS      | $p_{SFS}^{32 \times 32}(k,l,\varphi)$ with $\varphi = 0, 2\pi/3, 4\pi/3$ | IDFT in Eqs. (8) and (13) |

Thus the terahertz image can no longer be reconstructed with IDFT using $Y_{SFS}^{\prime}(k,l,0)$ and $Y_{SFS}^{\prime}(k,l,2\pi/3)$.

In order to solve this problem, we introduce three-step projections with three matrices $p_{SFS}^{3 \times 3}(k,l,0)$, $p_{SFS}^{3 \times 3}(k,l,2\pi/3)$ and $p_{SFS}^{3 \times 3}(k,l,4\pi/3)$, which are illustrated in Fig. 1(b) with $N = 32$, $k = 1$ and $l = 2$. Because

$$p_{SFS}^{3 \times 3}(k,l,2\pi/3) + p_{SFS}^{3 \times 3}(k,l,4\pi/3) = 2a - b \cos \Theta, \quad p_{SFS}^{3 \times 3}(k,l,2\pi/3) - p_{SFS}^{3 \times 3}(k,l,4\pi/3) = -\sqrt{3}b \sin \Theta, \quad \cos(\Theta + 2\pi/3) + \cos(\Theta + 4\pi/3) = 2\cos(\Theta + \pi) \cos(-\pi/3) = -\cos \Theta, \quad \cos(\Theta + 2\pi/3) - \cos(\Theta + 4\pi/3) = -2\sin(\Theta + \pi) \sin(-\pi/3) = -\sqrt{3}\sin \Theta$$

have been included, we have

$$F_{kl} = \frac{1}{3b} \left[ (2Y_{SFS}^{\prime}(k,l,0) - Y_{SFS}^{\prime}(k,l,2\pi/3) - Y_{SFS}^{\prime}(k,l,4\pi/3)) + \sqrt{3}j \left( Y_{SFS}^{\prime}(k,l,2\pi/3) - Y_{SFS}^{\prime}(k,l,4\pi/3) \right) \right].$$  \hspace{1cm} (13)

The image can then be reconstructed through the IDFT expressed in Eq. (8) from $Y_{SFS}^{\prime}(k,l,0)$, $Y_{SFS}^{\prime}(k,l,2\pi/3)$ and $Y_{SFS}^{\prime}(k,l,4\pi/3)$, where the undersampling is implemented by replacing Eq. (6) in Eq. (9) with Eq. (13).

2.3 Similarities and differences between CS and SFS approaches

By comparing the CS and SFS approaches for THz single-pixel imaging, we find that there exist similarities and differences between these two approaches, as summarized in Table 1.

Both approaches rely on collecting the cumulative signal with a single-pixel detector when a photo-induced coded aperture (i.e., a mask) is projected onto the image, as shown by Eqs. (1) and (7). The difference lies on the projection masks (column 2 in Table 1), which are two modified Hadamard matrices, $p_{CS}^{4 \times 4}$ and $p_{CS}^{4 \times 4}$ for the CS approach, or three matrices in Eq. (11) for the SFS approach. Fig. 1 shows that these projection masks corresponding to randomly “0” and “1” elements or sinusoidal stripes with elements varying between 0 and 1, respectively.
Since the projection masks for both approaches can be implemented by coding the laser beam with a DMD, both approaches can share the same experimental setup. The use of a common setup will greatly facilitate the direct comparison of these two approaches for THz single-pixel imaging under the same conditions.

Another major difference between these two approaches is the distinct reconstruction processes (column 3, Table 1). The CS approach relies on an optimization procedure, which is slow and computationally extensive; whereas the SFS adopts the inverse discrete Fourier transform, which should be very fast and computationally efficient. We thus expect that the proposed SFS-based THz single-pixel imaging would be more efficient than the CS approach.

3 Experiment setup

We implement both the CS- and the SFS-based THz single-pixel imaging systems with a common experiment setup, as illustrated in Fig. 2. It is based on a typical home-built THz time-domain spectroscopy (THz-TDS) system [26]. A pair of biased low-temperature-grown GaAs (LT-GaAs) photoconductive antennas illuminated by femtosecond laser pulses ($\lambda = 800 \text{ nm}, < 100 \text{ fs}, 80 \text{ MHz}; \text{Coherent Vitesse 800-5}$) are used to generate and detect THz radiations. Figures 2(b) and 2(c) show the THz pulse and its spectrum between $0.1 \sim 2 \text{ THz}$, respectively. We recorded the measurements at the peak of the THz field, which was achieved by properly setting the delay-line for femtosecond laser pulses. The central frequency of our THz pulse is approximately 0.22 THz, corresponding to a central wavelength of 1.363 mm.

![Figure 2: (a) Schematic of the experiment setup for both the CS- and the SFS-based THz single-pixel imaging systems. The target is a three-arm cartwheel hollow-carved in the gold film. (b) E-field and (c) normalized Fourier transform of the generated THz radiations.](image)

The terahertz beam with a diameter of 3.82 mm is delivered onto a monolayer graphene on a high-resistant silicon (2000 $\Omega \cdot \text{cm}, 100 \mu\text{m}$ thick). The graphene was grown on a copper substrate using chemical vapor deposition, and then transferred onto the silicon substrate using PMMA and wet etching. A layer of 100 mm thick gold film with a three-arm cartwheel pattern was fabricated on the other side of the silicon using photolithography and thermal evaporation.

A cw 808 nm laser beam (size $4 \text{mm} \times 4 \text{mm}$) patterned by a DMD (DLP3000, Texas Instruments) is projected onto the graphene on silicon, resulting a photo-induced coded aperture through optically modulated terahertz transmission. We employ percentages to define the laser intensity, which is expressed as an 8-bit grayscale (256 gray levels): 100% intensity denotes white (255 grayscale),
and 0% denotes black (0 grayscale). When the laser spot reflected by the DMD increases from black to white, the terahertz transmission decreases from high to low. Therefore, black and white laser intensities correspond to the “1” and “0” elements in the two modified Hadamard matrices for the CS masks, respectively, whereas grayscale laser intensities correspond to the discrete numbers between 0 and 1 for the SFS masks.

In this work, we consider \( N = 64 \) and focus on the acquisition of the \( 64 \times 64 \) THz image of the three-arm cartwheel target. We adopt GOS as the optically controlled THz modulator. This is because GOS has superior modulation performance than conventional semiconductors [27, 28, 29, 30], including high resistance silicon (HRS) [18, 19, 24] and germanium [31]. Unless otherwise specified, the measurements were performed with a high laser power of 350 mW. The influences of modulation depth will be discussed later by imposing different laser powers and comparing the GOS and HRS substrates.

### 4 Results and discussion

#### 4.1 Results

![Figure 3: Reconstructed images of \( N = 64 \) for (a) the CS and (b) the SFS approaches under full sampling, i.e., \( M = N^2 \). The scalar bar denotes 500 μm.](image)

Figure 3 shows that the \( 64 \times 64 \) images can be successfully reconstructed for both the CS- and SFS-based THz single pixel imaging systems with full sampling ratio \( M = N^2 \). These two reconstructed images are almost identical except that there exist periodic noises for the SFS approach. In order to quantify the image quality, we adopt signal-to-noise ratio (SNR) as the figure of merit. It is defined as the average value of the signal in the region of the three-arm cartwheel, \( \mu(\text{signal}) \), divided by the standard deviation of the noise in the signal-free area of the image, \( \sigma(\text{background}) \), that is [32]

\[
\text{SNR} = \frac{\mu(\text{signal})}{\sigma(\text{background})}.
\]  

(14)

Figure 4 shows that the SNR of the reconstructed images for the CS system increases with the sampling ratio in general. The image can be reconstructed only when the sampling ratio is larger than 28.2%, at which there still exist pronounced background noises and the SNR is only 3.20, as shown in Fig. 5(e). Note that the undersampling is achieved through truncating the Hadamard projection matrix with a small number of rows \( M \), as illustrated in Fig. 5(a)–(d). As the sampling ratio increases, the image quality improves with reduced noises and increased SNR: the SNR reaches 4.30 for \( S_R = 56.2\% \), and increases to 4.59 for \( S_R = 76.6\% \); for both cases, background noises become weak, as shown in Fig. 5(f)-(g). For full sampling, i.e., \( S_R = 100\% \) or \( M = N^2 \), the SNR reaches the maximum value of 5.1 [Fig. 5(h)].

As a comparison, the SFS system has distinct performance. The image can be reconstructed even for a very small sampling ratio down to 1.6%, as shown by Figs. 4 and 6(e). In this case, the reconstructed image is very bright compared with the clean and dark background, corresponding to a large SNR of 5.11. A problem is that the edge of the reconstructed image is not very clear, because the low-spatial-frequency information only contains the large area variations, which determines the global image contrast. In other words, the object’s global outline can be accurately reconstructed even for a very small sampling ratio. Note that the undersampling for the SFS system is performed by truncating the spatial Fourier spectrum with a low-pass filter, as illustrated in Fig. 6(a)–(d). As the sampling ratio increases to \( S_R = 4.8\% \), Fig. 4 shows that the SNR dramatically increases to
Figure 4: Signal-to-noise ratio (SNR) versus sampling ratio for the CS- (symbols ◦) and the SFS-based (symbols ×) THz sing-pixel imaging systems.

Figure 5: (a)–(d) Truncated (in row) Hadamard projection matrices $P_{\text{CS}}$ composed of “−1” (in black) and “1” (in yellow) used in the CS-based single-pixel THz imaging system. The size of the matrices is $M \times N^2$ with $M$ the number of rows and $N^2$ the number of columns, and the different sampling ratio is $S_R \equiv M/N^2$. (e)-(h) The reconstructed images with SNRs labeled. Each column has the same sampling ratio. Scalar bars in (e)–(h) denote 500 µm.
6.00. The SNR further slowly increases to the maximum value of 6.20 for $S_R = 11.8\%$. Meanwhile, the edges of the reconstructed images become clearer, as shown by Fig. 6(f). This is because an increased sampling ratio includes more high-spatial-frequency information, which contains the small area variations and determines the sharpness and local image contrast. However, as the sampling ratio further increases, the SNR gradually decreases to 4.97 at full sampling, since periodic noises of high spatial frequency are included for larger sampling ratios, as shown in Fig. 6(g)–(h).

From Fig. 4 we find that for most sampling ratios, the SFS system has much larger SNRs than the CS system; the only exception occurs at the full sampling ratio, at which the SNR for the SFS (SNR = 4.97) is slightly smaller than that for the CS (SNR = 5.14). Remarkably, the SNR of the SFS system is larger than 6.0 for $4.8\% \leq S_R \leq 31.6\%$. These striking performances, i.e., much better image quality and much smaller sampling ratio, indicate that the SFS approach is more efficient than the conventional CS approach for single-pixel THz imaging.

4.2 Influences of the modulation depth

Previously, we adopted the GOS under illumination of a high laser power of 350 mW as the THz modulator. We now show that the depth of the photo-induced THz modulation plays a key role in the image quality. This is done by comparing the performance of the SFS approach for different laser powers and different substrates.

Figure 7 show that, the SNR of the reconstructed images increases with the laser power. The SNR is only 3.06 for 50 mW and 3.19 for 150 mW, increases to 5.79 for 250 mW, and further increases to 6.20 for 350 mW. This is because as the laser power increases, higher carrier density is generated in the GOS, resulting in deeper THz modulation. On the other hand, a larger contrast between “1” (high THz transmission) and “0” (low THz transmission) will enhance the spatial frequency information of the target compared with the noises.

Figure 8 compares the reconstructed image quality using two different substrates, the conventional HRS and the GOS. The comparison is performed under the same other conditions: the laser power is 350 mW and the sampling ratio is 11.8%. Results show that for the HRS substrate, the reconstructed image has very poor quality with a small SNR of only 1.91; whereas for the GOS substrate, the reconstructed image is very clean and clear, and the SNR is as high as 6.20, more than three times of that for the HRS substrate. By comparing Figs. 7(a) and 8(a), we notice that the GOS substrate under a laser power of 50 mW has much better image quality than the HRS substrate under a laser power of 350 mW. This great improvement is due to the much deeper photo-induced THz modulation by using the GOS, as demonstrated in [27, 28, 29, 30].
Figure 7: Reconstructed images for the SFS approach at different laser powers: (a) 50 mW, (b) 150 mW, (c) 250 mW, and (d) 350 mW. The sampling ratio is $S_R = 11.8\%$ and the substrate is GOS. Scalar bars denote 500 $\mu$m.

Figure 8: Reconstructed images for the SFS approach using (a) HRS and (b) GOS substrates. The laser power is 350 mW and the sampling ratio is 11.8%. Scalar bars denote 500 $\mu$m.

5 Conclusions

In conclusion, we have proposed and demonstrated an efficient approach for single-pixel THz imaging based on spatial Fourier spectrum. We have developed the operation principle for the novel SFS approach by comparing with the conventional CS approach side by side. We have thus found similarities and differences between these two approaches, and managed to implement them with the same photo-induced coded aperture setup, where only the projection masks are different. Direct comparison in experiments has shown that, for the CS system, the image can be reconstructed only when the sampling ratio is larger than 28.2%, at which the image has a relatively low SNR of 3.20; whereas for the SFS system, the reconstruction can be done even when the sampling ratio is as low as 1.6%, and the image has a large SNR of 5.11. More strikingly, the SNR of the SFS system can be larger than 6.0 when the sampling ratio is between 4.8% and 31.6%, and can reach a maximum of 6.20 for a sampling ratio of 11.8%. By comparing different laser powers and compared the GOS and the HRS substrates, we have shown that large photo-induced THz modulation depth greatly improves the quality of the reconstructed images. This points to strategies for further improvement. We expect our work will greatly improve the efficiency and the image quality of single-pixel THz imaging, and will advance THz imaging system in practical applications.

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