Broadband high-resolution terahertz single-pixel imaging

Adam Vallés,1,* Jiahuan He,2 Seigo Ohno,3 Takashige Omatsu1,2 and Katsuhiro Miyamoto,1,2,†

1Molecular Chirality Research Center, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
2Graduate School of Advanced Integration Science, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
3Graduate School of Science, Tohoku University, Sendai 980-8578, Japan
*adam.valles@chiba-u.jp
†k-miyamoto@faculty.chiba-u.jp

Abstract: We report a simple single-pixel imaging system with a low mean squared error in the entire terahertz frequency region (3-13 THz) that employs a thin metallic ring with a series of directly perforated random masks and a subpixel mask digitization technique. This imaging system produces high-quality reconstructed images with resolutions of up to 320 × 320 pixels. It can be extended to develop advanced imaging systems in the near-ultraviolet to terahertz region.

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1. Introduction

There has been increasing demand for imaging systems in the terahertz (THz) region, in which a variety of molecules and their aggregations exhibit stretching and vibration eigen frequencies [1]. Terahertz imaging systems allow the non-invasive identification of materials and structures in biological tissues, and thus facilitate the development of two-dimensional (2D) scanners for pathological diagnosis and illegal drug detection systems [2–4]. The aforementioned applications require a terahertz imaging system with a high signal-to-noise ratio (SNR) or a low mean squared error (MSE) [5] in the entire terahertz frequency region. 2D terahertz imaging systems based on microbolometer arrays, called THz cameras, have been developed, however, it is difficult to capture high-quality images in the entire high-frequency region above 1 THz.

Single-pixel imaging (SPI) is an imaging technique for reconstructing compressive images that employs a series of spatially resolved patterns to mask the object of interest while measuring the overall transmitted signal with a bucket detector, which lacks spatial resolution [6]. Single-pixel cameras [6, 7] allow the development of highly sensitive detection systems [8, 9] for applications such as hazardous material detection [10, 11], holography [12], polarimetry [13], microscopy [14, 15], ghost imaging [16], and three-dimensional video processing [17].

Several terahertz SPI systems have been proposed. Structured illumination based on optical-to-terahertz nonlinear conversion has been demonstrated, however, the use of a nonlinear crystal (ZnTe) strongly impacts imaging at frequencies of above 2.5 THz [18]. An optically controlled dynamic spatial light modulator also does not permit high-quality imaging at frequencies of above 2 THz [19]. A spinning disk that includes random copper patterns printed on a standard printed circuit board (PCB) substrate for terahertz compressive image acquisition has been proposed. However, it allows the reconstruction of images only at frequencies of below 0.8 THz owing to the strong absorption loss of the PCB substrate [20, 21]. Thus, it is difficult to reconstruct images with high quality while keeping the spectral information.

Here, we propose a simple terahertz SPI scheme to realize high-pixel-resolution 2D imaging in the entire terahertz frequency region (3-13 THz). A metallic ring with a series of directly perforated random masks, encoded with almost equally weighted ON:OFF pixels, is employed. We can improve the pixel resolution of the reconstructed image simply by increasing the number
of pixels encoded in the digital masks used in the reconstruction algorithm while using the same physical metallic ring. We define the pixel resolution as the pixel density used to represent a given imaging area; hence, an increase in pixel resolution enables us to distinguish smaller details in an image [22]. It is worth noting that this pixel resolution is different from the optical resolution, which is determined by the inherent diffraction effects.

2. Implementation

2.1. Concept and principle

As done in most SPI reconstruction methods, we aim to reduce the number of measurements required to obtain a high-pixel-resolution image when the signal intensity, which contains the spatial information, is low. Several algorithms have been proposed for reducing the total number of measurements, \( M \), to less than the total number of pixels in an image, \( N = n \times n \). Such optimization methods are beyond the scope of this manuscript (see the Appendix for more details). Thus, we simply designed a concatenation of independent and identically distributed \([0,1]\) random matrices from an uniform Bernoulli distribution [23], used in the following object (\( O \)) reconstruction algorithm:

\[
O \approx T(\Omega) \sum_{i}^{M} \frac{(x_i - \bar{x})}{\xi_i} \Phi_i,
\]

where \( T(\Omega) \) is the transmission of ON pixels that depends on the optical frequency, \( x_i \) is the transmitted optical intensity passing through each random mask \( \Phi_i \) and object \( O \) (being both \( \Phi_i \) and \( O \), an \( n \times n \) matrix), \( \bar{x} \) is the averaged \( x_i \), and \( \xi_i \) is a normalization coefficient related to the ratio of ON:OFF pixels in each mask. In the frequency range in which a supporting material exhibits large absorption, or under the cut-off frequency of a metal hole, \( T(\Omega) \) gives a low value and degrades image quality. The object \( O \) consists of a correlation of the terahertz intensity detected after traversing a given object and masked with a series of random patterns. A random mask with a spatial pattern similar to that of the object will thus be correlated to a higher transmitted intensity, and hence heavily weighted in the reconstruction algorithm. Note that the pixel resolution of the reconstructed image is directly related to the number of elements \( (n \times n) \) in the random masks \( \Phi_i \) used.

2.2. Experimental setup

Figure 1 shows a schematic diagram of the experimental setup for testing our single-pixel imaging system. A monochromatic terahertz source [24, 25], that comprises a 4-dimethylamino-N-methyl-4-stilbazolium tosylate (DAST) difference frequency generation system was used (lasing frequency: 3-13 THz; pulse repetition frequency (PRF): 1 MHz; pulse width: 8.3 ps [25]). Its output beam was collimated by a parabolic mirror (PM1) and directed towards a partially opaque object and the metallic ring (photographs shown in the Appendix). The distance between the object and the metallic ring was 20 mm.

The transmitted terahertz signal output was then focused by a second parabolic mirror (PM2) onto a bolometer, i.e., a broadband high-sensitivity terahertz point detector. It is worth noting that a lock-in amplifier was used to reduce signal output noise.

The metallic ring used in this experiment was formed from a 0.15-mm-thick stainless steel (SUS) plate directly perforated without any substrate holding the OFF pixels. It was manufactured using a solder mask for a re-flow soldering process [26] to avoid undesired absorption within the terahertz spectrum region of 3-13 THz. The 35-mm-wide ring included randomly encoded ON (white) and OFF (black) pixels with dimensions of \( 1 \times 1 \text{ mm}^2 \) and equal probabilities, as shown in Fig. 1(b). The ON pixels were formed by an aperture (hole) with dimensions of \( 0.85 \times 0.85 \text{ mm}^2 \), supported by a 0.15-mm frame. Note that the ring was supported by a metallic disk.
Fig. 1. (a) Conceptual drawing of the experimental setup used for SPI in the terahertz region. PBS: polarization beam splitter; $\lambda_1$ and $\lambda_2$: input wavelengths; FL: Fourier lens; DAST: nonlinear crystal for difference frequency generation; PM$_1$ and PM$_2$: parabolic mirrors; Bolometer: single-pixel terahertz detector. (b) Pattern encoded on the metallic ring with the measurement window example shown in the inset. (c) Transmission of the measurement windows within the metallic ring (blue diamonds) and of a standard PCB card (red circles). The orange horizontal line corresponds to the theoretical transmittance of the metallic ring, i.e., $0.5 \times 0.85^2 \approx 36\%$.

without ON pixels to improve its robustness. The red square shows an example of a possible measurement window ($32 \times 32$ mm$^2$) for a particular rotation.

The ring acted as a diffraction grating to attenuate the terahertz power by one-third for lower terahertz frequencies, as shown in Fig. 1(c). This is because the frame thickness, i.e., 0.15 mm, is on the same order of magnitude as the wavelengths in the terahertz region. However, its loss was approximately two orders of magnitude less than that of previously reported standard PCB spinning disks [1,21]. The loss in our case can be considered to be almost constant $T(\Omega)$ in Eq. (1) for the entire terahertz frequency range.

The theoretical maximum transmission possible using our ring design is not 50%, but $0.5 \times 0.85^2 \approx 36\%$ (see orange vertical line in Fig. 1(c)). This is due to having 50% of ON pixels with hole dimensions of $0.85 \times 0.85$ mm$^2$ out of a total pixel size of $1 \times 1$ mm$^2$. Note that the diffraction losses and theoretical maximum transmission can be improved by changing the pattern design and increasing the ON:OFF pixel ratio.

Different random patterns are generated by rotating the whole ring while fixing the transverse position of the measurement window, as shown in the digitized random masks of Fig. 2. A photograph of the physical mask transmission over a simple drawing is shown for comparison in the inset of Fig. 2(a), and its digitization considering various angles ($\theta$) and pixel resolutions in Figs. 2(b-e). The object can be then reconstructed by rotating the whole disk and displacing it vertically after each full rotation to slightly improve the image quality. An animation of a reconstruction example using experimental data is given in the Supplementary Material to better explain the SPI scheme operation (see Visualization 1).
2.3. Higher pixel resolution due to subpixel digitization

The number of pixels in the digital random masks used in the object reconstruction algorithm, $\Phi_i$ in Eq. (1), determines the final pixel resolution of the output image. If we apply $32 \times 32$ pixel masks, like those in the top row of Figs. 2(b-e) and typically used in previous terahertz SPI schemes [19–21], we can quickly reconstruct any object with only a few steps.

The introduction of new random elements in $\Phi_i$ by rotating the physical metallic ring, namely the division of a physical pixel into several digital subpixels, allows us to arbitrarily increase the pixel resolution of the digital random masks. A different subpixel concept for SPI systems [22] effectively reduces the SNR by laterally displacing the encoded masks in a digital micromirror device. However, the pixel resolution is limited by the finite number of pixels in the digital micromirror device screen. The bottom row of Figs. 2(b-e) shows a digitization example considering the same angles as those in the top row but with $320 \times 320$ pixel masks. Thus, we can simulate frames and increase the similarity between a real spinning disk pattern and its digitization for all angles, as clearly shown in Fig. 2(e) for the $\theta = 20^\circ$ case.

The number of pixels per reconstructed image can be increased on demand, having to increase also the required measurements $M$ in Eq. (1). We give a more thorough description of the subpixel digitization concept and show experimental reconstruction examples demonstrating the increase of pixel resolution using the same metallic ring in the Appendix. Note that digital random masks with $320 \times 320$ pixels are considered for the proof-of-concept, manifesting that this SPI system has the potential to operate at higher pixel resolution.

3. Results

3.1. High-pixel-resolution terahertz single-pixel imaging

Figure 3 shows the reconstructed images of a $\lambda$-shaped object within a frequency region of 3-13 THz obtained by rotating the metallic ring in increments of $\theta = 0.2^\circ$. Figure 3(a) shows the intensity profile of the $\lambda$-shaped object captured with a CCD camera under visible light illumination. This is the first demonstration, to the best of our knowledge, of a terahertz SPI system operating in the whole terahertz frequency region.

Terahertz output radiation at higher frequency produced a narrower collimated beam owing to diffraction effects, as shown in the example in Fig. 3(h). Thus, we used a $\lambda$-shaped object, for which the most relevant information is concentrated in the center of the object (see the
Fig. 3. Experimental results showing the broadband high-pixel-resolution (320 × 320) imaging capabilities using our SPI scheme for different bands within the high-frequency terahertz region (3-13 THz). (a) Intensity profile of the object used for the SPI reconstruction in the (b) 3-, (c) 4-, (d) 6-, (e) 8-, (f) 11-, and (g) 13-THz regions. (h) Terahertz Gaussian beam traversing the object and metallic ring for the 11-THz case.

Appendix for an example of a larger object), thereby enabling the rapid recognition of the image shape with high pixel resolution. We were able to further increase image quality by repeating the whole rotation for five vertical positions 1 mm apart. The total number of measurements was $M = 5 \times 1800 = 9000$; this value is still below the $N = 320 \times 320 \approx 10^5$ measurements ($M < N/10$) needed for a pixel-by-pixel raster scanning SPI scheme. The whole reconstruction process took around $T = 210$ minutes, mostly due to the slow rotation of the disk. The integration time was 400 $\mu$s and the time needed to complete each 0.2° rotation was approximately 1 s ($T = 1.4 \times 9000$ s). As shown in Fig. 4, the $\lambda$-shaped object can be reconstructed after only $M = 300$ measurements ($M \approx N/300$), corresponding to $T < 8$ minutes. A further improvement in image quality, without increasing the number of measurements, can be achieved by implementing the reconstruction optimizations described in the Appendix.

It is worth noting that it was difficult to image these objects using a THz camera with a low sensitivity [27], even for the simplest example of the terahertz beam shown in Fig. 3(h).

There are several ways to quantify reconstructed image quality or the level of noise with respect to the signal. Here, we use the mean squared error (MSE) [5] obtained from a pixel-by-pixel comparison of the true object ($O'$) and its reconstructed image ($O$) from Eq. (1). The MSE decreases as the object and its image converge.

$$\text{MSE} = \frac{\sum_{i,j}^{n} \left[ O'_{i,j} - O_{i,j} \right]^2}{\sum_{i,j}^{n} O_{i,j}^2},$$  \hspace{1cm} (2)

where $O'_{i,j}$ and $O_{i,j}$ are the measured output of the reconstructed image and its object reference at pixel $(i, j)$, respectively, and $n$ is the number of pixels along the x and y axes.

As shown in Fig. 4, the MSE sharply decreases from $\sim 0.06$ to $\sim 0.006$ after the first revolution is completed in increments of $\theta = 0.2°$ ($M = 1800$). A further increase in $M$ produced higher-quality images without any background noise, with minimum MSE = 0.0034 for $M = 9000$. 
The slight MSE saturation after the first revolution ($M = 1800$), shown in Fig. 4(h), suggests that longer vertical displacements notably improve the convergence between $O'$ and $O$. Note that all the SPI results shown in Fig. 3 have MSE values of below 0.004.

### 3.2. Spectral imaging

Figure 5 shows an example of how we can perform a 2D spectral analysis of a particular sample. We used three molecules, namely A-glucose, B-glucose, and polypropylene (PP), which have different transmission spectra in the terahertz region. A-glucose, B-glucose, and PP were respectively purchased from Kanto Chemical Co. Inc. (CAS No. 50-99-7), Tokyo Chemical Industry Co., Ltd. (CAS No. 921-60-8), and Spectra Design Co., Ltd. (CAS No. SD-PPW5).

Fig. 5. Experimental results showing the broadband high-pixel-resolution imaging capabilities using our SPI scheme in the terahertz region for A-glucose, B-glucose, and PP. (a) Transmittance and (b) photograph of the sample. 2D spectral imaging results obtained at (c) 4 and (d) 8 THz.
The powders of these materials were placed inside the bottom-right, top-most, and bottom-left sections of the plate, respectively. The plate was then pressed by a compression molding machine. Its thickness was measured to be approximately 0.3 mm. PP exhibits high transmission in the frequency region of 3-13 THz, whereas A-glucose and B-glucose show relatively low transmittance in the 4-THz region (∼0.3 and ∼0.4, respectively), and even lower transmittance in the 8-THz region (∼0.007 and ∼0.02, respectively), as shown in Fig. 5(a). A plate made from these molecules looks uniformly transparent (i.e., without any domains in the visible spectrum), as shown in Fig. 5(b). Figures 5(c) and (d) show the reconstructed images at 4 and 8 THz, respectively, enabling the assignment of the exact allocation of individual molecule domains.

4. Conclusion

We demonstrated a terahertz single pixel imaging (SPI) technique that allows the reconstruction of an object within an entire terahertz frequency range (3-13 THz) by employing a metallic ring with a random mask. This technique can potentially be extended to develop ultra-broadband terahertz imaging systems that produce lower-noise higher-resolution images compared to those obtained using commercial THz cameras. The imaging system itself has, in principle, no spectral limits for imaging if the correct materials for the ring are used. It is worth noting that the metallic ring, which includes holes, does not inherently constrain the frequency range of light sources, and thus this system enables the reconstruction of high-quality images in more spectral regions than those for previously proposed SPI schemes [19–21], even when also considering visible (532 nm) and near-infrared (1510 nm) regions (see characterization results in the Appendix).

Although the proposed SPI scheme would benefit from further improvement, such as increasing the scanning velocity, it can already be applied to advanced technology, such as broadband terahertz spectroscopic imaging beyond current SPI schemes. Commercially available spatial light modulators (SLMs) and digital micromirror devices (DMDs) do not cover all spectral regions and exhibit high diffraction losses in long-wavelength regions. Furthermore, we can improve the pixel resolution for a rotating random mask configuration without changing the intensity coefficients. The reconstruction algorithm can use any pixel resolution in $n \times n$ format for masks $\Phi_i$ in Eq. (1), as long as it is correlated with the correct angular position of the physical metallic ring.

Such directly perforated random mask allow the development of ultra broadband 2D SPI systems that have applications such as the detection of harmful gas or pedestrians in imaging systems for self-driving cars. Furthermore, the ability to use such simple and inexpensive spatial projection for the visible and infrared regions may allow 2D imaging applications for which reducing costs while maintaining high pixel resolution is an important commercial goal. The light traversing the metallic ring can be frequency-multiplexed and detected using fast and inexpensive point detectors. Real-time images could thus be obtained using any band of the optical spectrum, from near ultraviolet to terahertz (see Fig. 8 in the Appendix).

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Disclosures

The authors declare no conflicts of interest related to this article.
Appendix

**Single-pixel camera reconstruction optimization**

The simplest image reconstruction method using highly efficient single-point detectors is to perform a single-pixel raster scan [28]. This involves transversely displacing a transmitting window (surrounded by a non-transmitting material) while recording the transmitted signal for each transverse position. The problem is that the transmitting window should be displaced as many times as the number of pixels in the image, e.g., \( N = 320 \times 320 \approx 10^5 \). Thus, depending on the desired resolution, this method can be extremely time-consuming. Furthermore, a higher resolution leads to smaller pixels, i.e., a lower transmitted signal, making it difficult to detect the signal even with high-sensitivity detection systems.

Single-pixel camera configurations reduce complexity by considering only a single detector, which can be any fast broadband high-sensitivity detector. The proportion of transmitting and blocking pixels (ON:OFF) in the spatially resolved random patterns is expected to be 50:50, meaning that the detected power, on average, is independent of the selected resolution (pixel size). In other words, to increase the resolution of the final image, more measurements are required but without paying the price of reducing the signal to noise ratio.

There are many methods for generating patterns for masking an object (with ON and OFF pixels that transmit and block the optical signal, respectively), including the Hadamard [29], Fourier [30], and Toeplitz [31] methods. There are also several ways to optimize the reconstruction algorithm, including by reducing the total number of measurements needed \((M < N)\), e.g., by minimizing the \( \ell_1 \)-norm [32] or the total variation and curvature in an image [33,34]. With an optimized reconstruction algorithm, reconstructed \(32 \times 32\) pixel images can be obtained with much fewer measurements \((M \approx 200)\), as shown in previous work [7,21]. Such algorithms for SPI optimization slightly increase computation times.

The generated masks should be orthogonal to each other and equally ON:OFF pixel weighted for faster reconstruction. However, pseudo-random pattern reconstruction methods, i.e., non-orthogonal patterns with a small number of new pixels per mask, have been proven to be as effective as those using fully random patterns [35,36]. Taking advantage of this principle, we make use of a circular random mask ring, where the introduction of new randomly situated pixels in the measurement window is due to the rotation of the whole ring-shaped structure. We considered a wide ring \((r = 112 \text{ mm in Fig. 2(a)})\) for this proof-of-concept experiment because a large \(r\) value leads to a large number of newly introduced elements per angle when rotating the whole disk while keeping the measurement window static.

**Subpixel digitization analysis**

The experimental examples in Fig. 6 show the different reconstructed image resolutions that we can obtain by selecting the number of pixels in the digitization mask \(\Phi_i\) in Eq. (1). We use the same SPI system given in Fig. 1 but with an 'L'-shaped object and laser light at 1510 nm to illuminate the whole object (see Fig. 6(a) and photograph below).

If we consider lower-pixel-resolution digital masks \(\Phi_i\), i.e., \(32 \times 32\) pixel masks, as typically used in previous terahertz SPI schemes [19–21], we can quickly reconstruct any object with only a few steps. In other words, the physical composition of holes and frames in the metallic ring for the ON pixels can be digitally approximated by different binary masks of '0's and '1's. For example, we can consider that each physical pixel corresponds to one digital pixel, thus ignoring the frame holding the holes. In this case, we can reconstruct a \(32 \times 32\) pixel image by rotating the metallic ring in increments of \(\theta = 2^\circ\) for five vertical positions \(1\) mm apart \((M = 5 \times 180 = 900\) measurements\). Figures 6(a) and (b) respectively show the transmitted intensity profile captured with a CCD camera and its reconstruction results when using several random \(32 \times 32\) pixel masks, as the ones in the examples in the top row of Figs. 2(b-e).
We can digitally simulate the frames holding the holes ('1' pixels), for example, by dividing each physical pixel by 10 when encoding the digital masks to mimic the frame. With this composition, smaller rotations can be made while keeping fairly new random pixels in each new mask $\Phi_i$. Figure 6(c) shows how we can reconstruct the same object with higher resolution by simply changing the digital masks $\Phi_i$ in the reconstruction algorithm (see bottom row in Figs. 2(b-e)). Similarly, we rotated the whole disk in increments of $\theta = 0.2^\circ$ for five different vertical positions, i.e., $M = 5 \times 1800 = 9000$ measurements, obtaining a $320 \times 320$ pixel resolution image. Note that the resolution can be changed to obtain even higher resolution images, which have the same detected signal on average. Figure 6(d) shows an experimental example of a $1200 \times 1200$ reconstructed image obtained using the same measurements as those in (c) but with a smaller measurement window ($12 \times 12 \text{ mm}^2$) and each physical pixel divided by 100.

Although an experimental example of extremely high pixel resolution is given to show the full capability of our scheme, i.e., $1200 \times 1200$, digital random masks with $320 \times 320$ pixels were used in all terahertz SPI results shown in this manuscript.

**Masks and objects**

Figure 7 shows photographs of the metallic ring and 'L'- and $\lambda$-shaped objects. The hand-crafted 'L' object was too large to be used in the terahertz SPI experiments due to the small terahertz beam size (see Fig. 3(h)). We thus decided to assemble a smaller $\lambda$-shaped object from some
SUS plates. Most of the important spatial information is in the center of the object. The diameter of the whole metallic ring was 256 mm. The ‘L’-shaped object was 12 mm high and 8.5 mm wide and the ‘λ’-shaped object was 7 mm high and 5 mm wide.

**Broadband SPI characterization**

To characterize our broadband SPI scheme, Figure 8 shows the λ-shaped object reconstruction using laser light at 532 and 1510 nm. Here, we rotated the metallic ring in increments of 0.2° for five vertical positions, as done for the reconstruction results in the main text. Note that when using visible and infrared light, we did not encounter the terahertz small size problem, and could thus distinguish the whole λ shape.

Fig. 8. Characterization measurements for the (a) λ-shaped object using (b) 532-nm and (c) 1510-nm laser light.

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