Edge detection by spiral phase contrast imaging at terahertz frequencies

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This paper proposes the spiral phase contrast (SPC) imaging at terahertz (THz) frequencies to achieve the target edge detection. The THz SPC imaging is built based on a classical 4f imaging system, and a spiral phase plate is placed in the Fourier plane to generate the spiral phase. Owing to the unique nature of the spiral phase, edge detection can be achieved. The THz SPC imaging mechanism is analysed by the scalar diffraction theory, and its corresponding analytical expression is derived. A circle target is simulated and the resultant image shows a remarkable edge detection. A proof-of-principle experiment is carried out using our designed THz SPC imaging system and the effectiveness of target edge extraction on the THz images is validated. A circle same as the simulation is imaged firstly, which is consistent with the simulated result. And the letter “Z” with more edges is imaged later. All edges in experiments are extracted perfectly, which are extremely consistent with the THz SPC imaging theory.

Introduction: Terahertz (THz) wave is referred to the spectrum from 0.1 to 10 THz, which lies between the microwave and infrared of the electromagnetic spectrum. THz imaging has great potential in applications such as security screening, non-destructive testing, and biological detection [1–4], where the high requirement of image quality is indispensable. Obviously, the edge detection is important for high-frequency information of the image. Furthermore, the edge detection can enhance the contrast of the image. Especially, the THz images obtained from the targets with low scattering coefficient and low contrast are urgent to be recognised effectively [5, 6]. In order to meet this demand, as an effective method for edge detection in the visible and infrared bands, the spiral phase contrast (SPC) imaging method can be used for low-quality THz images. The SPC imaging originated from the radial Hilbert transform was demonstrated by Davis et al. [7]. The corresponding theories and experiments are further developed by Fürhapter et al. [8]. They applied the SPC imaging method to light microscopy and demonstrated that the spiral phase can detect the image edges and reveal the good image quality by improving the imaging contrast in the experiments. Therefore, the SPC imaging method is considered to play an important role in the field of target edges detection [9–12].

This paper proposes a THz SPC imaging mechanism. By inheriting the advantages of the THz imaging and the SPC imaging simultaneously, the THz SPC imaging mechanism can achieve the excellent performance of target edge detection at THz frequencies. In our work, the theory of THz SPC imaging is first analysed by scalar diffraction theory. The simulation is then carried out based on the theory, and an experimental setup is developed to carry out the THz SPC imaging. The experiments and simulation are in a good agreement, verifying the potential of the proposed imaging method for target edge detection.

Theory of THz SPC Imaging: The schematic of the THz SPC imaging mechanism is shown in Figure 1. First, the imaging object is illuminated by a collimated THz beam, and the THz image of the object can be described as \( u_1(x_1, y_1) \), where \( (x_1, y_1) \) is the Cartesian coordinate of the target plane. Then, the \( u_1(x_1, y_1) \) is handled by a 4f imaging system, which is composed of two lenses with the same focal length of \( f \). The distance between the imaging object and the first lens is \( f \) so that the \( u_1(x_1, y_1) \) can be described as \( u_2(x_2, y_2) \) after propagating the distance \( f \), which satisfies the following equation according to the scalar diffraction theory:

\[
F \{ u_2(x_2, y_2) \} = F \{ u_1(x_1, y_1) \} \exp \left[ -j \pi f \left( f_x^2 + f_y^2 \right) \right] \tag{1}
\]

where \( F \{ \} \) is the Fourier transform, \( (x_2, y_2) \) is the Cartesian coordinate of the first lens plane, \( f \) is the wavelength of the THz beam, and \( f_x \) and \( f_y \) are the spatial frequencies of \( f_x = \frac{x_2}{f}, f_y = \frac{y_2}{f} \).

After passing through the first lens and arriving at its Fourier plane where the spiral phase plate (SPP) is located, the THz field distribution is described as \( u_3(x_3, y_3) \):

\[
u_3(x_3, y_3) = \frac{\exp(\frac{j k f}{f_x} \cdot \frac{x_2}{x_3} + x_3^2 + y_3^2)}{\pi f_x f_y} \cdot \exp \left( \frac{j k}{f_x} \frac{x_3^2 + y_3^2}{(x_3^2 + y_3^2) \cdot f_x^2} \right) dx_3 dy_3 \tag{2}
\]

where \( k \) is the wavenumber, \( (x_3, y_3) \) is the Cartesian coordinate of the Fourier plane, and \( \exp(-j k x_3^2 + y_3^2)/2 \) is the modulation function of the first lens.

After being modulated by the SPP, the corresponding THz field distribution can be written as

\[
u_4(x_3, y_3) = u_3(x_3, y_3) T(\rho, \phi) \tag{3}
\]

where \( T(\rho, \phi) \) is the modulation function of the SPP and can be expressed as \( T(\rho, \phi) = \text{circ}(\rho/R) \text{exp}(\phi) \). The \( \text{circ}(\rho/R) \) describes a circular function with the radius of \( R \), \( \rho \) is the polar radius in the Fourier plane and \( \phi \) is the azimuth in the Fourier plane.

According to Equations (1) and (2), the THz beam arrived at the THz detector can be written as

\[
u_5(x_5, y_5) = \frac{\exp(\frac{j k f}{f_x} \cdot \frac{x_3}{x_5} + x_5^2 + y_5^2)}{\pi f_x f_y} \cdot \exp \left( \frac{j k}{f_x} \frac{x_5^2 + y_5^2}{(x_5^2 + y_5^2) \cdot f_x^2} \right) dx_3 \cdot dy_3 \tag{4}
\]

where \( (x_5, y_5) \) is the Cartesian coordinate of the detector plane, and \( \exp(-j k x_5^2 + y_5^2)/2 \) is the modulation function of the first lens.

Here, \( \exp(\phi) \) represents the point spread function (PSF) of the SPP, which can be written as Equation (5) [13]:

\[
h(\rho) = \text{PSF}(H(\rho)) = \frac{\pi R}{2 \rho} \left( H_0 \left( \frac{k R \rho}{f_x} \right) - H_1 \left( \frac{k R \rho}{f_x} \right) \right) \exp(\phi) \tag{5}
\]

where \( J_m(\cdot) \) is the \( m \)-th order Bessel function of the first kind, \( H_m(\cdot) \) is the \( m \)-th order Struve function, and \( (\rho, \phi) \) is the polar coordinate of the detector plane.
point is uniform, the convolution with \( \exp(j \theta) \) makes the image point equal to zero. Therefore, the boundary in image would be highlighted.

According to the theory of THz SPC imaging mechanism, as shown in Figure 2, a simulation is given out to demonstrate the effectiveness for the target edge detection. Figure 2a is the simulated circle target with 100% transmittance for the circle and 0 transmittance for the background. In Figure 2b, the resultant THz SPC image of the circle is only a ring, which reveals a successful edge detection. To further compare the simulated results, the intensity curves corresponding to the red dashed lines across the upper images is shown in Figure 3c. The peaks of the SPC imaging are located on the edges of the circles precisely, which illustrates that the SPC images respect the edges of the circles.

**Experimental Results:** To verify the THz SPC imaging mechanism, a proof-of-principle experimental setup is developed in Figure 3. Taken as the source in the experiment, we adopt a THz quantum cascade laser (THz-QCL) with the working frequency of 3.7 THz. Its transmitting power is about 0.3 mW, and the pulse repeat frequency is 5 kHz. For the reception of THz beam using Golay cell, the 10 Hz modulation is still applied to THz-QCL. The transmitted THz beam from the THz-QCL is first reshaped by a small hole with 2 mm diameter and then collimated by a lens. The collimated THz beam is elliptical, and the diameters of the beam in the horizontal and vertical directions are 7.5 mm and 5.7 mm, respectively. After passing the target, the THz beam enters the 4f imaging system and is modulated by a SPP in the system later. The SPP is composed of high-density polyethylene with an azimuthally varying thickness, the maximum spiral thickness is 158 \( \mu \)m. The diameter of the SPP is 50.8 mm, which is much larger than the size of the THz beam. After that, the THz field distribution is received by a Golay cell installed in the two-dimensional lifting platform. Note that a diaphragm is installed at the entrance cone of the Golay cell, which is used to restrict the size of the receiving aperture.

The optical images of experimental targets are shown in Figure 4. A practical circle consistent with the simulated circle is shown in Figure 4a, which is produced by punching a metal plate, the diameter of the circle is 8 mm. The transmittance of the circle is 100% and the transmittance of other metal areas is 0. The cardboard wrapped in copper foil is used to make a letter “Z” with more edges as shown in Figure 4b, the width and height of the letter are 7 mm and 9 mm, respectively. Similarly, the transmittance of the letter is 100% and the transmittance of other metal areas is 0.

The experimental results of the circle are shown in Figure 5. Figure 5a is the normalised bright-field (BF) image, which is acquired by the THz SPC imaging system without the SPP. The energy is concentrated in the circle, and there is nearly no energy in other areas. The resultant ring in Figure 5b represents the edge of the practical circle, indicating the clear circle edge detection. Compared with the simulation, the energy in the circle in Figure 5a is non-uniform, which is caused by the uneven THz beam. The even THz beam also leads to the non-uniform edge shown in Figure 5b. The experimental result agrees well with the simulation in general, which confirms the feasible target edge detection. The intensity distributions at \( y = 0 \) are plotted in Figure 5c, corresponding to the dashed line shown in Figure 5a and 5b. It is clearly shown that the energy...
at the boundary is enhanced and the energy in the middle of the hole is suppressed.

Further, the letter is imaged in the experimental system, and the experimental results are shown in Figure 6. The BF image (Figure 6a) shows the original THz image of the letter, which is consistent with the target. The medium of the letter is brighter than the upper and the lower area, which is also caused by the uneven distribution of the THz beam. In the SPC image (Figure 6b), the edges of the letter “Z” are well extracted. The intensity distributions of the edges are proportional to the intensity gradient of the original THz image of target, which causes the non-uniform edges in Figure 6b.

**Discussion:** The THz SPC imaging can acquire the edges of the objects perfectly, and the spatial resolution should also be considered. Note that the spatial resolution in calculations and experiments would be limited due to the different receiving schemes. Generally, one kind of receiving scheme is the hypersensitized THz camera, the other is the Golay cell. The pixel size of THz camera is always less than the wavelength of 81 μm, and the THz spiral phase contrast imaging system could not break the diffraction limit. Therefore, the THz camera is satisfied with the sampling requirement for reconstructing the image spatial resolution in our imaging system. For the Golay cell, the receiving aperture can be controlled with a size-adjustable diaphragm aperture. Due to the system cost, the THz camera is not an affordable way for us to implement our proposed THz spiral phase contrast imaging. In our experiments, a Golay cell with a diaphragm aperture is taken as the receiver to collect the THz signal. Compared to the wavelength of 81 μm for the THz working frequency, the size of the diaphragm aperture is much larger, leading to the inaccurate image resolution in the measurements. However, the smaller diaphragm will directly cause the weaker reception of THz signal at Golay cell. To overcome this problem, the long integration time is required. We believe that the image spatial resolution will be improved when the hypersensitized THz camera is applied in our imaging system.

**Conclusion:** This paper proposes a THz SPC imaging mechanism to achieve target edge detection. The related imaging theory is analysed first and then analytic expression is derived according to the scalar diffraction theory. The simulation is carried out based on the theory, and the simulated image shows a successful edge detection. The experiments are conducted at 3.7 THz. The target of the first experiment is consistent with the simulation, and the experimental result agrees well with the simulation, which could verify the correctness of our method. A letter “Z” with more edges is chosen to be imaged later, and the edges are extracted perfectly after the THz SPC imaging. Therefore, the THz SPC imaging mechanism shows great potential for target edge detection, which could be a good tool for improving the THz imaging contrast.

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