Compensation of body shake errors in terahertz beam scanning single frequency holography for standoff personnel screening*

Wei Liu(刘玮)[1], Chao Li(李超)[1,†], Zhao-Yang Sun(孙兆阳)[1], Yu Zhao(赵宇)[2], Shi-You Wu(吴世有)[1], and Guang-You Fang(方广有)[1]

[1] *Key Laboratory of Electromagnetic Radiation and Sensing Technology, Institute of Electronics, Chinese Academy of Sciences, Beijing* 100190, *China*
[2] *Electric Power Research Institute of State Grid Beijing Electric Power Company, Beijing* 100161, *China*

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In the terahertz (THz) band, the inherent shake of the human body may strongly impair the image quality of a beam scanning single frequency holography system for personnel screening. To realize accurate shake compensation in imaging processing, it is quite necessary to develop a high-precision measure system. However, in many cases, different parts of a human body may shake to different extents, resulting in greatly increasing the difficulty in conducting a reasonable measurement of body shake errors for image reconstruction. In this paper, a body shake error compensation algorithm based on the raw data is proposed. To analyze the effect of the body shake on the raw data, a model of echoed signal is rebuilt with considering both the beam scanning mode and the body shake. According to the rebuilt signal model, we derive the body shake error estimated method to compensate for the phase error. Simulation on the reconstruction of point targets with shake errors and proof-of-principle experiments on the human body in the 0.2-THz band are both performed to confirm the effectiveness of the body shake compensation algorithm proposed.

Keywords: body shake, compensation, THz imaging, single frequency holography, beam scanning

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1. Introduction

Personnel screeners with terahertz (THz) imaging technologies may have potential applications in public security because of the unique electromagnetic wave band.[1–10] Compared with microwaves and lower radio frequency waves, THz waves have short wavelength which could lead to better spatial resolutions and make objects easier to identify. Unlike optical and infrared radiation, THz waves can "see through" obscuring materials such as clothing, cardboard, plastics, and wood with relatively little loss. Unlike x-ray imaging, THz imaging is generally regarded as harmless to humans. Because of the above advantages, plenty of THz antennas and prototype imagers have been designed and developed.[10–14]

These THz prototype imagers can generally be categorized into two groups: focusing-beam scanning imaging system[10–12] and holographic imaging system.[13,14] For THz focusing-beam scanning imaging system, large focusing quasi-optics antennas are widely used to achieve narrow beam, resulting in the high azimuth resolution. However, these antennas have the disadvantages of large size, heavy weight and manufacturing difficulty. To avoid these disadvantages, a new kind of imaging scheme, the THz holographic imaging system, is developed. This kind of imaging scheme usually has relatively simple quasi-optics antennas, with coherently illuminating the target and receiving the scattered complex field. With the echoed signals, images could be reconstructed by holographic algorithms. Through the modulus and phase of the scattered field, the targets will be perfectly reconstructed without distance limitation. These advantages endow THz holography imaging with potential applications in human security.

It is quite clear that the human body shaking inherently and randomly is unavoidable. The shake will introduce phase errors into the received raw data which may significantly impair the final image quality in terms of resolution losses unless properly accounted for during the image processing. In the previous THz holographic imaging system,[13] a motionless mannequin is often imaged, ignoring the phase errors caused by body shaking. To the best of our knowledge it is the first time that body shake errors have been taken into consideration. To crack this problem, one of the solutions is to measure the real-time shake errors. However, in many cases, different parts of a body have shakes to different extents, which makes it difficult to conduct a reasonable measurement of body shake errors for the compensation in image reconstruction. Therefore the compensation algorithm with echoed raw data should be employed. There are some processing techniques to remove motion error in both optical image processing and synthetic aperture radar imaging. In this work, the blur of the reconstructed image, caused by the body shake in the terahertz holography, is different from in optical image processing and synthetic aperture radar imaging. In optical imaging processing and synthetic aperture radar imaging, the motion error can

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†Corresponding author. E-mail: cli@mail.ie.ac.cn
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be modeled by a spatial-invariant blurring process, while it is not suitable for solving the de-blurring problem of body shaking in terahertz imaging.

In this paper, a compensation algorithm with echoed raw data for terahertz human body imaging is proposed. Firstly, the echoed signal model of THz single frequency holography is rebuilt by considering the body shake and the beam scanning mode. Moreover, according to the proposed signal modal, an algorithm to resolve the shake information from the echoed signal is proposed. Numerical simulation on point targets with shakes and proof-of-principle experiments on the human body in the 0.2 THz band are both performed to confirm the effectiveness of the compensation algorithm proposed in this paper.

2. Echoed signal model of the terahertz single frequency holography with considering body shake

In this section, the echoed signal of the THz single frequency holography of fixed targets is recalled. Then the echoed signal with body shake is introduced with considering the beam scanning mode. The main part of the phase error caused by the body shake is derived and that is the reason why the reconstructed image turns blurred.

Figure 1 shows the scheme of the THz single frequency holography for personnel screening. The system scheme is similar to the one developed in our previous work.[14] The fast beam scanning in the x direction can be achieved based on the quick rotation of the sub-reflector (driven by a servo motor) with a speed of 25 cycles per second easily, and hence the scanning of the beam in the x direction can be repeated rapidly with an equivalent maximum speed of 50 rows per second due to the symmetry of the sub-reflector. Synchronously, the pan scan along the y direction is performed only once during the whole time of imaging. Such a pan scan can be readily realized based on another servo motor in the elevator. The proposed THz imaging system can finish data collection within approximately 6 s. The human target to be imaged is located at the distance z_0, with reflectivity function $f(x',y',z_0)$, and the phase center of the antenna is located at $(x,y,0)$.

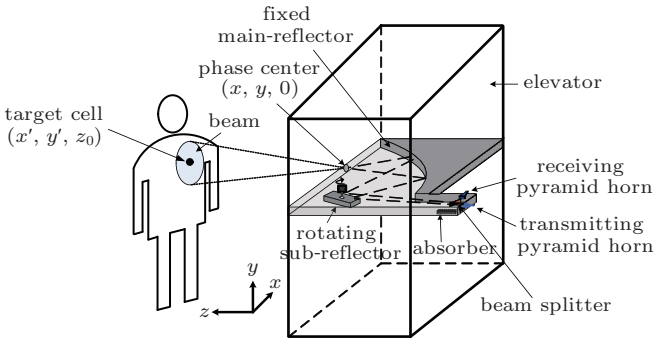


Fig. 1. Geometry of the THz single frequency holography for personnel screening.

The echoed fields scattered from the target are collected by the plane scanning of the transceiver over a two-dimensional (2D) aperture in plane $z=0$, which should take the integral form as[15]

$$s'(x,y,0) \approx \iint f(x',y',z_o)\,\alpha\left[\rho(x',y')\right] \cdot \exp\left\{-\mathrm{j}2kR\left[\rho(x',y'),z_o\right]\right\}\mathrm{d}x'\mathrm{d}y', \quad (1)$$

where $k=2\pi f/c_0$ is the usual wavenumber corresponding to the frequency and c_0 is the propagation speed of the electromagnetic wave in the free space.

$$\rho(x',y') = \sqrt{(x-x')^2+(y-y')^2}$$

is the relative polar radius, $\alpha[\rho(x',y')]$ is the radiation patterns of the antenna, and $R[\rho(x',y'),z_0]$ is the equivalent distance from target (x',y',z_0) to antenna point $(x,y,0)$.

Without the body shake, the THz images of a human body can be reconstructed based on the holographic algorithms developed in Refs. [15] and [16]. However, in a practical imaging system for personnel screening, the human body target always shakes inherently. The shake usually causes three-dimensional (3D) errors $\boldsymbol{e}=(e_x,e_y,e_z)$, which is also a function of time t. The body shake error will affect both the amplitude and the phase of the echoed data. In the holography image reconstruction, the influence of the amplitude error can usually be neglected. In this paper, only the phase error caused by the body shake is taken into consideration.

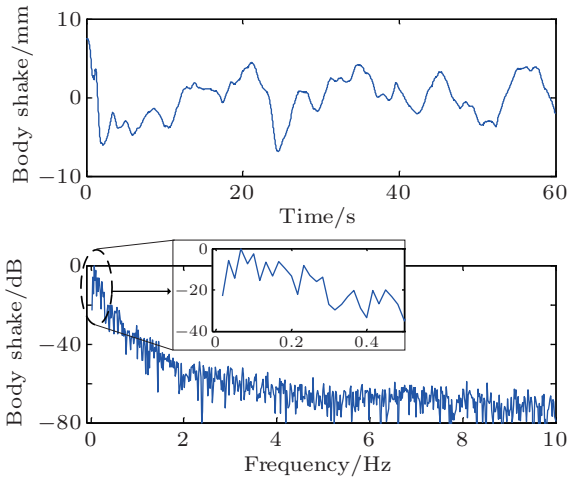


Fig. 2. Measured human body shake in the z direction.

The body shake in three directions has different contributions to keeping the human body standing still. According to the imaging scheme and the topology of the human body shown in Fig. 2, the shake in the y direction is smaller than those in x and z directions. The two feet of a human make the body stand in the x direction easier than that in the z direction and the body needs less adjustment in the x direction. So the shake in the x direction is assumed to be smaller than in the z

direction. Therefore, the maximum body shake errors in the three directions naturally satisfy the following inequality:

$$\max\left(\left|e_y\right|\right) < \max\left(\left|e_x\right|\right) < \max\left(\left|e_z\right|\right) \ll z_0. \tag{2}$$

Figure 2 shows the measured body shake error in the z-direction with the Panasonic HL-G1-series compact laser displacement sensor. The inherent body shake is found to be usually random and have low frequency.

In addition, in the face-looking mode shown in Fig. 1, the main phase error contributing to the degradation of image reconstruction results from the body shake in the range direction (z direction). This can be demonstrated based on the simulation of a point target with shakes from different directions. In the simulation, the transmitted signal of the transceiver is from the Gaussian beam. The beam waist radius w_0 of the transmitted Gaussian beam is set to be 4.7 mm and located at the scanning plane $z = 0$. The frequency is set to be 0.2 THz. The size of the scanning aperture is set to be 0.4 m $\times$ 0.4 m and the total scanning time is assumed to be 4 s. The sampling intervals in both the x and y directions are both set to be 2 mm which satisfies the anti-aliasing requirement in cross range. The point target is located at position $(0, 0, 0.5\ \text{m})$.

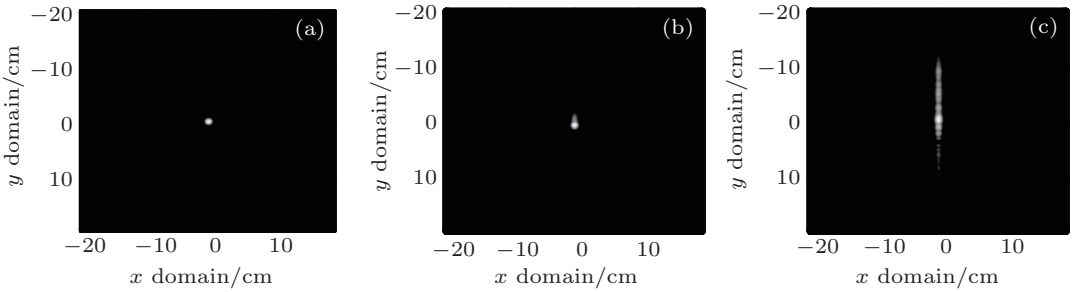


Fig. 3. (a) Reconstructed result without any shake error. Panels (b) and (c) are the reconstructed results where the shake errors e_y and e_z are considered respectively.

Figure 3(a) shows the reconstructed image without any shake error. Figures 3(b) and 3(c) show the reconstructed images where the shake errors e_y and e_z are considered respectively. Both the shake errors e_y and e_z are assumed to be equal to that measured in Fig. 2. The result in Fig. 3(b) is focused with some resolution loss, while the result in Fig. 3(c) is defocused. By neglecting the cross-direction shake errors, the phase error can be derived as

$$e_\varphi \approx -2ke_z. \tag{3}$$

In a practical system, the phase error is also relative to the scanning mode which determines the mapping from time t to the scanning position (x, y). In this paper, we consider the scanning mode in Fig. 1 which is suitable for fast personal screening. The beam is assumed to linearly scan in two vertical directions shown in Fig. 4(a), and the scanning track is shown in Fig. 4(b). The whole scanning time is assumed to be about 5 s–10 s: the beam scans fast in the x direction and slowly in the y direction.

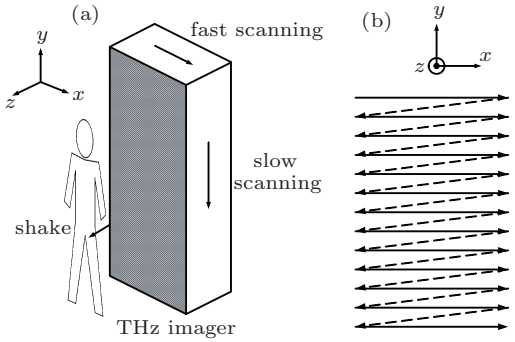


Fig. 4. (a) THz imaging of human body with shake, and (b) the scanning track of THz beam.

According to the measured body shake error shown in Fig. 2, the body shake error varies little in once x direction fast scanning. The human body can be seen to be fixed and the phase error can be neglected when the image is reconstructed in the x direction. In this paper, the phase error is assumed to be changed only in the y direction scanning and expressed as follows:

$$e_\varphi \approx -\varphi\left(y\right), \tag{4}$$

where $\varphi\left(y\right) = 2ke\left(y\right)$. The echoed signal of human body with phase shake error (Eq. (4)) can be reshaped into

$$s\left(x, y, 0\right) = s'\left(x, y, 0\right)\exp\left[-\mathrm{j}\varphi\left(y\right)\right], \tag{5}$$

where $s'\left(x, y, 0\right)$ is the corresponding idea echoed signal without body shake as shown in Eq. (1).

3. Body shake compensation with echoed data

For a practical THz single frequency holography system for personnel screening, after measuring the returned signal in I–Q channels, an M–N 2D complex data matrix can be obtained, where $m = 0, 1, \ldots, M-1$ and $n = 0, 1, \ldots, N-1$. M is the number of the sample points in the y direction and N is the number of the sample points in the x direction. Matrix $s'_{m,n}$ is assumed to be the corresponding idea echoed data without human body shake. According to Eq. (5), the matrix $s_{m,n}$ can be written as

$$s_{m,n} = s'_{m,n}\exp\left(-\mathrm{j}\varphi_m\right), \tag{6}$$

where φ_m is the discrete form of $\varphi\left(y\right)$.

To compensate for the body shake errors in the original echoed data $s_{m,n}$, φ_m needs to be estimated. However, it is difficult to estimate the φ_m without any priori information about the idea echoed data $s'_{m,n}$. In most imaging systems, the THz beam usually scans fast in one direction. This leads to a correlation of the adjacent data in another direction. In this paper, the sample interval in the y direction is assumed to be small enough so that the adjacent data bins of $s'_{m,n}$ in the y direction are almost the same. The optimized φ_m should minimize the quadratic sum of the error between the adjacent data bins:

$$J_m = \sum_n \left| s'_{m,n} - s'_{m-1,n} \right|^2, \tag{7}$$

where $m = 1, 2, \ldots, M-1$.

Combining Eq. (6) with Eq. (7), the minimizing of evaluation function J_m is the same as the maximizing of evaluation function J'_m:

$$J'_m = Re\left[\exp\left(\mathrm{j}\varphi'_m\right) \sum_n s_{m,n} s^*_{m-1,n} \right], \tag{8}$$

where $Re(\cdot)$ is the real part of a complex variable, and $(\cdot)^*$ is the conjugate of a complex variable. $\varphi'_m = \varphi_m - \varphi_{m-1}$ is the numerical gradient of φ_m. J'_m can reach its maximum when the imaginary part of $\exp\left(\mathrm{j}\varphi'_m\right) \sum_n s_{m,n} s^*_{m-1,n}$ is equal to 0. Therefore the optimized φ'_m can be calculated from

$$\exp\left(-\mathrm{j}\varphi'_m\right) = \frac{\sum_n s_{m,n} s^*_{m-1,n}}{\left| \sum_n s_{m,n} s^*_{m-1,n} \right|}. \tag{9}$$

The optimized φ_m can be calculated by the numerical integration of φ'_m, with assuming $\varphi_0 = 0$. After obtaining the φ_m, the body shake errors can be compensated for by

$$s'_{m,n} = s_{m,n} / \exp\left(-\mathrm{j}\varphi_m\right). \tag{10}$$

The whole procedure of the algorithm consists of three main steps as follows.

1) Compute the gradient phase items $\exp\left(-\mathrm{j}\varphi'_m\right)$ according to Eq. (9).

2) Calculate phase items $\exp\left(-\mathrm{j}\varphi_m\right)$ by numerical integration:

$$\exp\left(-\mathrm{j}\varphi_m\right) = \begin{cases} 1, & m = 0, \\ \prod_1^m \exp\left(-\mathrm{j}\varphi'_m\right), & m \geq 1, \end{cases} \tag{11}$$

3) Compensate for the body shake errors with the estimated phase items $\exp\left(-\mathrm{j}\varphi_m\right)$ according to Eq. (10) and obtain the compensated data $s'_{m,n}$.

4. Experimental results

4.1. Shake compensation based on simulated data

To demonstrate the effectiveness of the algorithm proposed in Section 3, a simulation is performed with point targets illuminated by a THz Gaussian beam, scanned in a raster fashion over a square aperture. In the simulation, the transmitted Gaussian beam is set to propagate in the $+z$ direction. The frequency of the transmitted signal is set to be

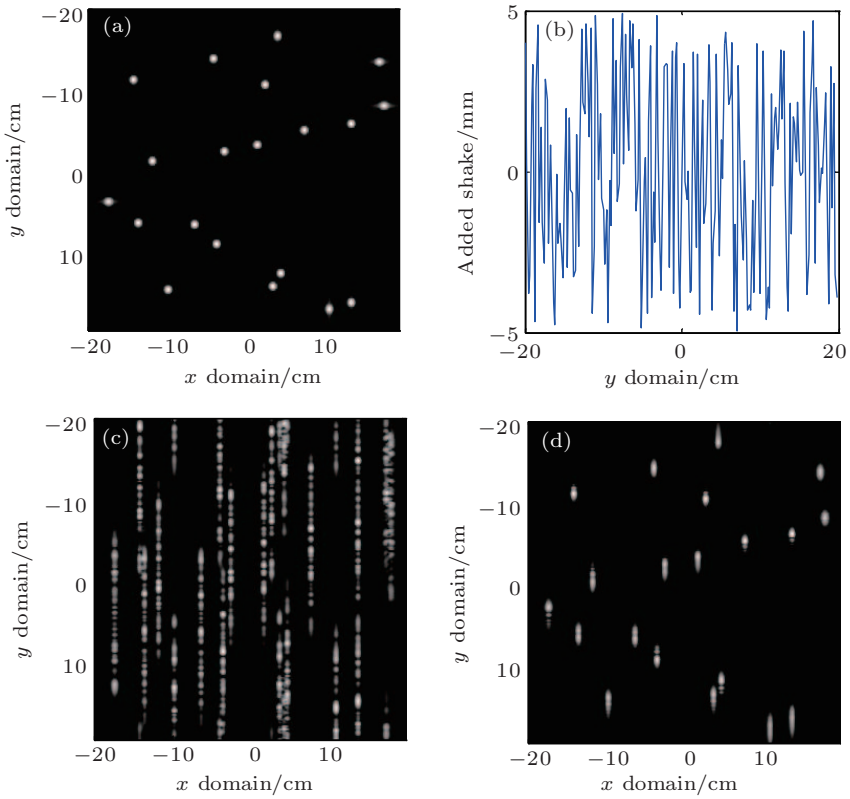


Fig. 5. (color online) (a) Reconstructed image of the echoed data without shake errors, (b) added body shake errors, (c) reconstructed image of the echoed data with shake errors, (d) reconstructed image after body shake compensation proposed in this paper.

0.2 THz. The beam waist radius w_0 of the transmitted Gaussian beam is set to be 4.7 mm and located at the scanning plane $z = 0$. The size of the scanning aperture is set to be 0.4 m × 0.4 m. The sampling intervals in both the x and y directions are both set to be 2 mm, satisfying the anti-aliasing requirement in cross range.

In the simulation, twenty point targets are set randomly at (x_i, y_i, z_0), where $|x_i| \leq 0.2$ m, $|y_i| \leq 0.2$ m, and $z_0 = 0.5$ m. Firstly, the echoed data are created without shake errors according to Eq. (1) and figure 5(a) shows the reconstructed image. Then the echoed data are created with considering random y direction body shake errors and the reconstructed image is shown in Fig. 5(b). The echoed data with shake errors are reconstructed without compensation and the resulting image is out of focus in the y direction as shown in Fig. 5(c).

To estimate the body shake error phase, the echoed data are processed with steps proposed in Section 3. Figure 5(d) shows the reconstructed image after error compensation which is in focus with some resolution loss in the y direction.

4.2. Laboratory compensation results

In order to illustrate the effectiveness of the compensation algorithm, a proof-of-principle experiment with THz beam transceiver in 0.2-THz band is performed on a human body wearing the clothes with a hidden metal knife at the position of the left breast. The simplified THz transceiver is shown in Fig. 6. The signal of the transceiver is a continuous wave of frequency 0.2 THz with coherent demodulation to obtain the amplitude and the phase of the return wave. By the advanced scanning mechanism shown in Fig. 1, the echoed data are collected quickly within about 10 s over an aperture of 0.6 m × 1 m with 4-mm spatial sampling intervals. The distance of the target to the scan plane $z = 0$ is about 0.5 m. Figure 7(a) shows the reconstructed image on dB scale without body shake error compensation. The contour of the human body with a hidden metal knife is out of focus in the y direction. Figure 7(b) shows the resulting image on dB scale obtained by utilizing the proposed compensation algorithm. It is seen that the defocus of the reconstructed image from the body shake can be greatly reduced based on the proposed algorithms.

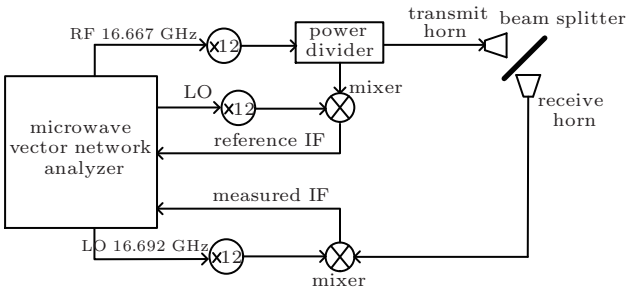


Fig. 6. Simplified THz transceiver scheme.

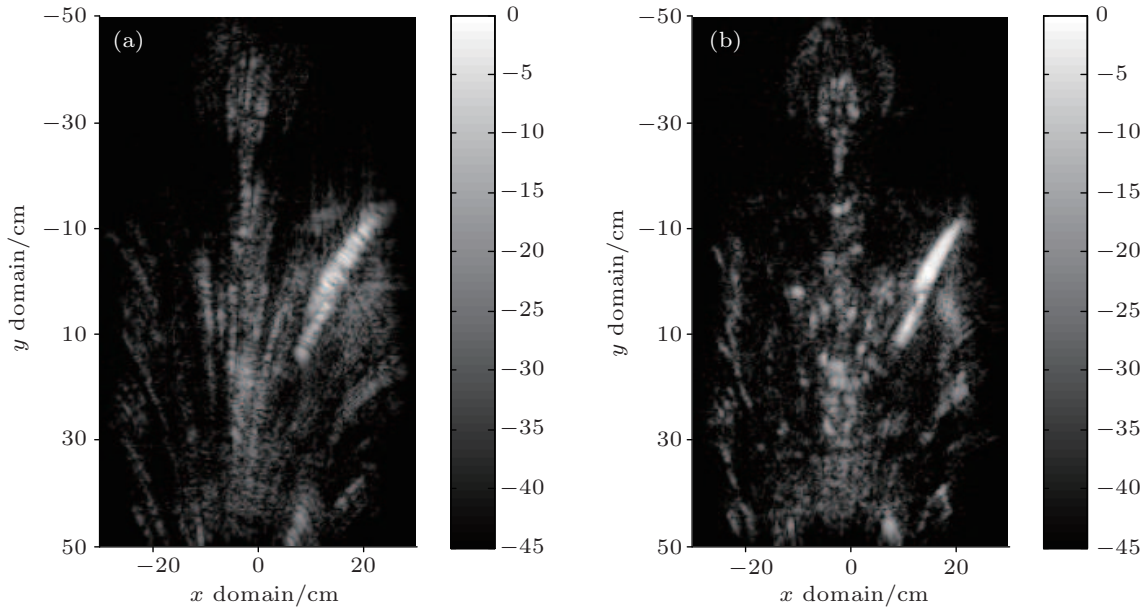


Fig. 7. (a) Reconstructed image without body shake error compensation, and (b) resulting image obtained by utilizing the proposed compensation.

5. Conclusions

In this paper, the echoed signal model of the beam scanning THz single frequency holography of a human body with body shake is studied. The method to extract the phase errors resulting from the body shake and the corresponding compensation algorithm to improve the quality of the image reconstruction are proposed. The algorithm consists of just a few steps which take little time as compared with the reconstruction algorithm. Simulations on random point targets are performed, and the results are in fairly good agreement with the experimental results, which verifies the proposed algo-

rithm. Proof-of-principle experiments in the 0.2-THz band are also performed based on a monostatic prototype imager with a Gaussian beam transceiver. The experimental result of the human body confirms the effectiveness of the body shake compensation algorithm proposed in this paper.

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