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0.14 THz imaging system for security and surveillance

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Abstract: Active terahertz-wave imaging systems play a significant role in security and surveillance applications. A 0.14 THz near-field imaging system is described, which consists of a signal generator and acquisition unit, a transceiver front end, a digital signal process unit and a motor control unit. Based on the two-dimensional synthetic aperture technique and the image reconstruction algorithm, this system is capable of producing three-dimensional images of 2 mm lateral resolution and 3 cm range resolution in concealed weapon detection experiments.

Keywords: terahertz-wave; personnel surveillance; reconstruction; wavenumber

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Conventional security inspection measures are becoming much more difficult to achieve the reliable detection under the requirements of high efficiency and high resolution. The X-ray technology is extensively applied in medical diagnostics and luggage inspection[1], however, it is restricted in personnel surveillance applications based on health considerations. The millimeter-wave and terahertz-wave imaging systems are demanded as the best solutions to the near-field personnel surveillance applications since they are competent in seeing through the common clothing materials without causing destructive ionizing radiations[2].

Much effort has been spent on developing security imaging systems[3-4]. Active mm-wave systems[5-6] working at frequencies below 80 GHz are already commercially available. The Q-band rotary scanning system[7] reduces the measurement time through the rotary scanning method, and the 0.2 THz active imaging system presented by IECAS combines the real aperture and the synthesized aperture[8]. These imaging systems show that the higher frequency obtains higher lateral resolution and provides more available bandwidth to obtain higher range resolution. On the other hand, the higher frequency results in a denser spatial sampling, which increases the difficulties in signal processing and image reconstruction[9].

In this paper, a 0.14 THz imaging system is presented based on the active radar and synthetic aperture technique. With the frequency range of 143–148 GHz, this system improves imaging resolution, at the same time, shows good performances in signal processing.

1 Signal model and imaging processing

The transmitted stepped-frequency signal can be expressed as

$$s_{\mathrm{t}}(t)=\sum_{k=0}^{N-1}\mathrm{e}^{\mathrm{j}2\pi(f_0+k\cdot\Delta f)t}\cdot rect\left(\frac{t-kT-\dfrac{T}{2}}{T}\right) \tag{1}$$

Where f_0 is the carrier frequency of the first sub-pulse, Δf is the frequency step, N is the sub-band number, and T is the pulse duration of the sub-pulse.

The echo signal is given as

$$s_{\mathrm{r}}(t)=\sum_{k=0}^{N-1}\mathrm{e}^{\mathrm{j}2\pi(f_0+k\cdot\Delta f)\left(t-\frac{2R}{c}\right)}\cdot rect\left(\frac{t-kT-\dfrac{T}{2}-\dfrac{2R}{c}}{T}\right) \tag{2}$$

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Where R is the range from the target to the antenna, and c is the speed of light.

The production of the echo signal and the conjugated reference signal can be derived

$$s_{if}(t)=\sum_{k=0}^{N-1}\mathrm{e}^{-\mathrm{j}2\pi(f_0+k\cdot\Delta f)\frac{2R}{c}}\cdot rect\left(\frac{t-kT-\frac{T}{2}-\frac{2R}{c}}{T}\right) \tag{3}$$

With the inverse Fourier Transform to the equation 3, a narrow impulse that relates to the target's range information can be obtained.

While the transmitted signal enhances the range resolution through the large bandwidth, the lateral resolution is improved by the synthetic aperture. The synthetic aperture is performed by scanning the transmitting and receiving antenna over a two-dimensional planar area.

The imaging processing method of the stepped frequency echo signal is the same as the processing method of the linear frequency modulation signal, so the conventional algorithms are still available. In this paper, the three-dimensional image reconstruction of the echo signal is based on the wavenumber domain.

In this imaging system, the transmitting antenna and the receiving antenna are separated, but they are assumed to be at the same location. The approximate location is the midpoint of the two antennas and is assumed to be at the position (x',y',z_0). The point target is assumed to be at the position (x,y,z). So the phase shift between the transmitted signal and the echo signal can be expressed as

$$\varphi=2k\sqrt{(x'-x)^2+(y'-y)^2+(z_0-z)^2} \tag{4}$$

Where k is the wavenumber that is denoted by $k=2\pi f/c$, and f is the frequency of the transmitted signal.

The reflectivity function of the point target is described by $f(x,y,z)$, so the echo signal received by the transceiver (x',y',z_0) is

$$s(x',y',k)=\iiint f(x,y,z)\mathrm{e}^{-\mathrm{j}2k\sqrt{(x'-x)^2+(y'-y)^2+(z_0-z)^2}}\mathrm{d}x\mathrm{d}y\mathrm{d}z \tag{5}$$

The Fourier Transform of the equation 5 is given by

$$S(k_x,k_y,k)=\iiint f(x,y,z)\cdot S_1(k_x,k_y,k)\mathrm{d}x\mathrm{d}y\mathrm{d}z \tag{6}$$

Where $S_1(k_x,k_y,k)=\iint \mathrm{e}^{-\mathrm{j}2kR}\mathrm{e}^{-\mathrm{j}k_x x'-\mathrm{j}k_y y'}\mathrm{d}x'\mathrm{d}y'$, and R is the range from the target to the antenna which is described by $R=\sqrt{(x'-x)^2+(y'-y)^2+(z_0-z)^2}$. Based on the principle of stationary phase, the simplification of $S_1(k_x,k_y,k)$ is

$$S_1(k_x,k_y,k)\approx \mathrm{e}^{-\mathrm{j}\sqrt{4k^2-k_x^2-k_y^2}(z_0+z)}\mathrm{e}^{-\mathrm{j}k_x x-\mathrm{j}k_y y} \tag{7}$$

Then the Fourier Transform of the echo signal is

$$S(k_x,k_y,k)=\mathrm{e}^{-\mathrm{j}\sqrt{4k^2-k_x^2-k_y^2}z_0}\cdot\iiint \mathrm{e}^{-\mathrm{j}k_x x-\mathrm{j}k_y y-\mathrm{j}k_z z}f(x,y,z)\mathrm{d}x\mathrm{d}y\mathrm{d}z \tag{8}$$

Where $k_z=\sqrt{4k^2-k_x^2-k_y^2}$.

Combining above relations, the reconstruction of the echo signal is

$$s(x,y,z)=IFFT_{(k_x,k_y,k_z)}\left[S(k_x,k_y,k)\cdot \mathrm{e}^{\mathrm{j}\sqrt{4k^2-k_x^2-k_y^2}z_0}\right] \tag{9}$$

2 System architecture design

The configuration of the 0.14 THz imaging system is shown in Fig.1. This system consists of a signal generator and acquisition unit, a transceiver front end, a digital signal processing unit, and a motor control unit. The signal generator and acquisition unit is utilized to generate a 143–148 GHz stepped-frequency signal and acquire the reflected signal. In this imaging system, the Vector Network Analyzer is adopted to accomplish the signal generator and acquisition. The transceiver front end consists of a power amplifier, a low noise amplifier, and the transceiver antenna. The 143–148 GHz stepped-frequency signal is launched using a wide-beam width antenna, and the reflected signal is received by the receiving antenna. The digital signal processing unit reconstructs the received signal to get a three-dimensional image contains the target information. The motor control unit is employed to control the position of the transceiver antenna.

The base spacing d between the antennas must satisfy the Nyquist criteria in order to obtain a successful discretization. Specifically, the phase shift from one spatial sampling point to the next must be less than π rad. The transmitting antenna beam width and the receiving antenna beam width in this system are both 60°. Therefore, d is equal to $\lambda/2$ at 143 GHz (i.e. d=1 mm), where λ is the wavelength that is derived by $\lambda=c/f$.

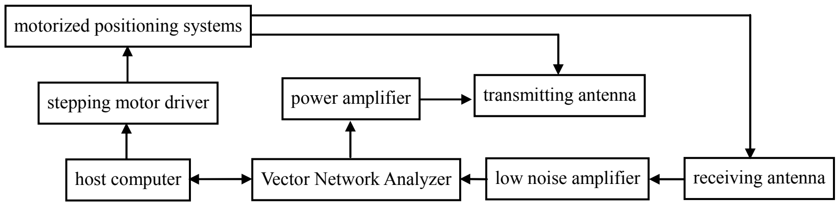

Fig.1 Configuration of the 0.14 THz imaging system

3　Results

The 0.14 THz imaging system described in the previous sections is tested in experiments. The transmitted stepped-frequency signal is from 143 GHz to 148 GHz with 201 frequency steps, in which the frequency sampling Δf is 25 MHz. The transmitted power is 1 mW. The spatial separation d is 1 mm. The reflected signal acquired by the Vector Network Analyzer is reconstructed through the equation 5, and the procedure of the reconstruction is shown in Fig.2.

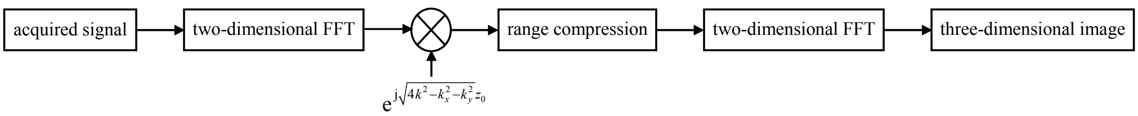

Fig.2 Procedure of the three-dimensional reconstruction

Fig.3 shows an example image of the high quality imaging system. The left side is a photograph of a metal gun at a distance about 0.5 m from the transceiver antennas, while the right side is the reconstruction image. The aperture is 20 cm×20 cm in this experiment. The scanning time now is about 2 h under the restriction of the stepping motor driver, and it can be minimized to several seconds with replacing the mechanical scanning by linear arrays in the further work.


Fig.3 Reconstructed image of a gun

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