Terahertz wave tomographic imaging with a Fresnel lens

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We demonstrate three-dimensional tomographic imaging using a Fresnel lens with broadband terahertz pulses. Objects at various locations along the beam propagation path are uniquely imaged on the same imaging plane using a Fresnel lens with different frequencies of the imaging beam. This procedure allows the reconstruction of an object's tomographic contrast image by assembling the frequency-dependent images.

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Terahertz (THz) radiation, or T-ray, which occupies a large portion of the electromagnetic spectrum between the infrared and microwave bands, offers innovative imaging and sensing technologies that can provide information not available through conventional methods such as microwave and X-ray techniques. Compared with the relatively well-developed science and technology in the microwave and optical frequencies, basic THz science and technology remain s relatively unexplored[1].

T-rays have several advantages over other sensing and imaging techniques. While microwave and X-ray imaging modalities produce density pictures, T-ray imaging also provides spectroscopic information within the THz frequency range. The unique rotational and vibrational responses of biological materials within the THz range provide information that is generally absent in optical, X-ray and NMR images. T-rays can also easily penetrate and image inside most dielectric materials, which are opaque to visible light and have low contrast to X-rays; this makes T-rays a useful and complementary imaging source in this context.

T-ray tomography, including computed tomography (T-ray CT), diffractive tomography, and tomography with Fresnel lenses, is a new tomographic imaging modality that allows pulsed terahertz radiation to probe the dielectric properties of three-dimensional (3D) structures. It provides sectional images of objects in an analogous manner to conventional computed tomography techniques such as X-ray CT. T-ray CT systems directly measure the transmitted amplitude and phase of broadband THz pulses at multiple projection angles. This allows a wealth of information to be extracted from the target object including both its 3D structure and its frequency-dependent far-infrared optical properties. In this letter, we report the preliminary results of THz wave tomographic imaging with a Fresnel lens.

The focal length of a Fresnel lens is linearly proportional to the frequency of the imaging beam, this allows tomographic imaging of a target using multiple frequencies. Objects at various positions along the beam propagation path are uniquely imaged on the same imaging plane using a Fresnel lens at different frequencies of the imaging beam. This procedure allows the reconstruction of an object's tomographic contrast image by assembling the frequency-dependent images, and provides a new tomographic imaging modality[2,3].

A Fresnel lens is a Fresnel zone plate with phase or amplitude patterns, formed by a series of concentric ring structures. The main focal length is defined as[4]

$$f_\nu = \frac{r_p^2}{2\lambda} = \frac{r_p^2}{2c}\nu \propto \nu, \tag{1}$$

where r_p^2 is the Fresnel zone period with a dimension of area, λ the wavelength, c the speed of light, and ν the frequency. The focal length f_ν is linearly proportional to frequency ν.

For a single-lens imaging system using the paraxial ray approximation, the relationship between object distance z, image distance z' and the focal length f_ν is governed by the imaging equation

$$\frac{1}{z} + \frac{1}{z'} = \frac{1}{f_\nu}, \tag{2}$$

with the magnification factor of $(-z'/z)$. If the image plane position is fixed, and therefore z' is fixed, for a wave with frequency ν, due to the frequency dependent focal length f_ν, the object distance z is also frequency dependent. Combining Eqs. (1) and (2), z has the form as

$$z = \frac{f_\nu z'}{z' - f_\nu} = \frac{r_p^2 z' \nu}{2cz' - r_p^2 \nu}. \tag{3}$$

At each frequency ν, there is a corresponding value of z, and a target at this position z can be well imaged at the position z' at the imaging plane. In order to keep the imaging distance $z > 0$, it requires $z' - f_\nu > 0$, therefore, $\nu < 2cz'/r_p^2$ for each fixed z'.

A broadband THz wave pulse was used to demonstrate this tomographic imaging concept. THz wave occupies a large portion of the electromagnetic spectrum between the infrared and microwave band, called *ultra-Hertz wave* in 1920s[5], is the next frontier in sciences[6]. A typical pulsed THz wave contains frequency components ranging from 100 GHz to 3 THz. The large frequency range of the THz pulse makes it an ideal candidate to testing purposes.

The experimental setup of an imaging system with a CCD camera is similar to the one used for the characterization of a THz wave reported elsewhere[7]. A 30-mm diameter silicon Fresnel lens with a focal length of 2.6 cm at 1 THz was used as the THz wave Fresnel lens. The Fresnel lens focused the THz wave scattered by the targets onto a 4 mm thick ZnTn EO sensor. When an optical probe beam and a THz wave collinearly propagated through the EO sensor, the probe beam was modulated
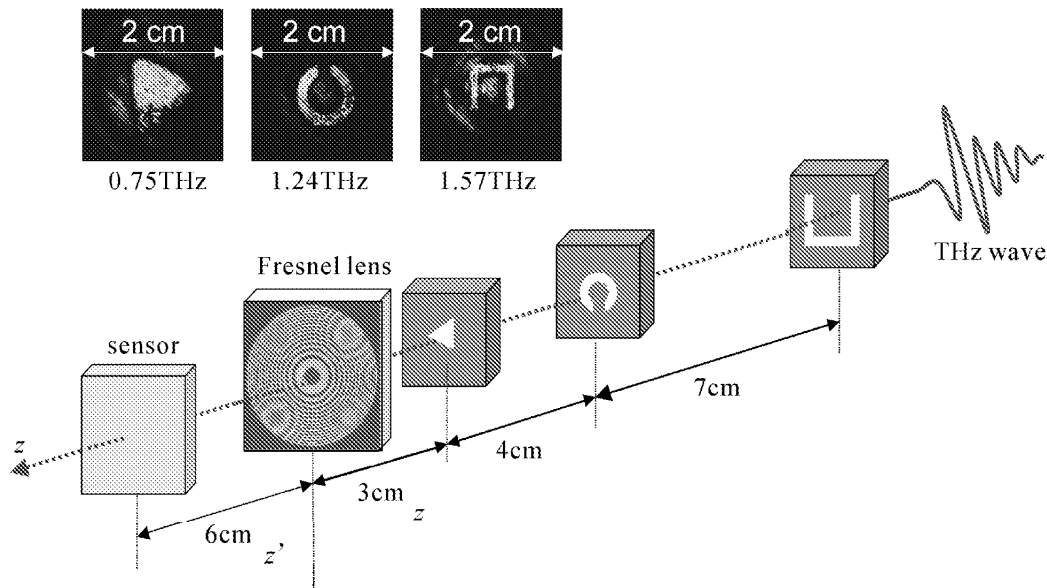
Fig. 1. Schematic illustration of tomographic imaging with a Fresnel lens. Targets at various locations along the beam propagation path are uniquely imaged on the same imaging sensor plane with different frequencies of the imaging beam. Three plastic sheets were cut with different patterns placed 3, 7, and 14 cm away from the Fresnel lens. The multiple patterns are imaged on the sensor at a distance of 6 cm from the Fresnel lens, with inverted tomography images of the patterns at the frequencies of 0.75, 1.24 and 1.57 THz, respectively. The measured image size is determined by the frequency dependent magnification factor, which is defined as z'/z.
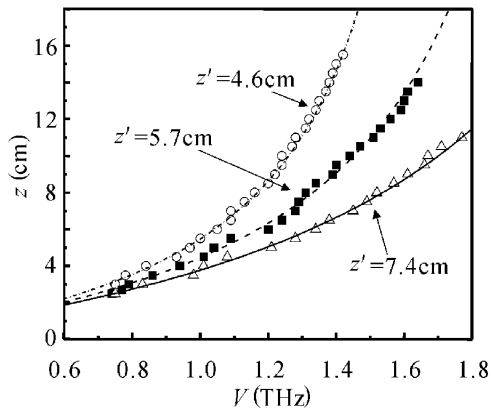

Fig. 2. Measured data and calculated curves of the object distance z versus the imaging beam frequency ν with the imaging distance z' at 4.6, 5.7, and 7.4 cm, respectively. The focal length f of the Fresnel lens is 2.6 cm at 1 THz.

by the THz wave due to Pockels effect; the THz two-dimensional (2D) distribution pattern on the EO sensor was therefore transferred upon the probe beam. Then a lens was used to image the modulated probe beam onto the CCD camera. As a result, the CCD camera was able to take the THz 2D distribution image. By scanning the time delay between the THz wave and the optical probe beam, a temporal waveform of the THz wave at each pixel on the image plane was measured. Fourier transformation of the temporal waveforms provides the THz field amplitude (or intensity) distribution on the image plane at each frequency. The measured 2D THz field distribution at each frequency provides images of the THz field

transmission of a target at each corresponding position along the z-axis.

Figure 1 schematically illustrates the tomographic imaging arrangement. Three plastic sheets with different patterns are placed along the THz beam path, and their distances to the lens, corresponding to z in Eq.(3), are 3, 7 and 14 cm, respectively. Images of patterns on the sensor plane at distance $z'=6$ cm are measured at frequencies of 0.74, 1.24, and 1.57 THz, respectively. At each frequency, a Fresnel lens images a different plane section of a target object while images from other depths remain blurred. Each point in the different object planes along the z-axis is mapped onto a corresponding point on the z' plane (sensor plane) with the magnification factor $-z'/z$ at their corresponding frequencies. The calculated frequency-dependent magnification factor is defined as $-z'/z$. The ratio of the measured image size to the actual size of the pattern agrees well with the calculated magnification factor.

Figure 2 plots the measured and calculated z versus the imaging beam frequency ν with three different imaging distance z' at 4.6, 5.7, and 7.4 cm, respectively. The image frequency was determined by finding the peak amplitude of the THz distribution, which is a function of frequency and spatial position. The focal length f of the Fresnel lens is 2.6 cm at 1 THz.

The depth of focus of the THz wave introduces the depth uncertainty. Since the depth uncertainty of the target position is equal to the depth of focus divided by the square of the magnification factor[8], the uncertainty of the target position is also a function of z. The measured depth of focus in the imaging system is 3 mm. For a large value of $z (z \gg z')$, the depth resolution decreases.

Although this demonstration uses broadband THz ra-

diation as the imaging beam, such a tomographic imaging concept is also applicable to a tunable narrowband imaging beam, and can be applied to other frequency ranges, including the visible. Unlike other transmitted THz tomography techniques, which require the rotation of the target[9,10], this tomography image is obtained without rotating or moving the target.

Several factors might limit the depth resolution. The first one is the depth uncertainty Δz along the z-axis induced by the frequency uncertainty can be estimated by differentiating Eq.(3) to obtain

$$\Delta z = \frac{2c(r_p z')^2}{(2cz' - r_p^2 \nu)^2} \Delta \nu. \qquad (4)$$

For a broadband THz system with a frequency resolution of $\Delta \nu = 1$ GHz and $\nu = 1$ THz, from Eq. (4), the depth uncertainty $\Delta z = 0.6$ mm, whereas for a narrowband THz source with $\Delta \nu < 1$ MHz, the depth resolution $\Delta z = 0.6$ μm. The second factor is the depth uncertainty along z-direction induced by the depth of focus. The measured depth of focus at 1 THz is 3 mm. Since the depth uncertainty of the target position is equal to the depth of focus divided by the square of the magnification factor, the uncertainty of the target position is a function of z. It is clear that for a large value of z, the depth resolution decreases. The third limitation is the caustic curve that is induced by the non-paraxial ray. Among all these limitations, the depth uncertainty generated by the depth of focus is the most primary one. One possible way to improve the depth resolution is to use longer imaging distance z', with the expense of the spatial resolution in the x-y plane.

In conclusion, we demonstrated the use of a Fresnel lens to perform tomographic imaging. From 0.5 to 2 THz, 1 $\times 1$ cm^2 2D targets with a z-depth greater than 10 cm has been resolved. In principle, the same concept for 3D imaging also applies to other frequency ranges[11], such as the visible frequency range. However, it requires a large frequency range in order to obtain large imaging depth. Due to the diffractive nature of the Fresnel imaging lens, it is also worth noting that tomographic imaging using a Fresnel lens is more sensitive to the imaginary part (absorption) of the dielectric constant distribution than to the real part (refractive index) of the dielectric constant.

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