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140-GHz subwavelength transmission imaging for foreign body inspection in food products

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A B S T R A C T

Non-diffractive beam scanning in the millimeter and terahertz wave ranges can provide extended depths of focus and high spatial resolutions for foreign body imaging inspection in food products. Here, an axicon lens was utilized to focus a 140-GHz Bessel–Gauss beam carrying a finite energy and realizing such a beam. An axicon lens array was employed to acquire transmission images using this beam. Even a 1.1 mm-linewidth element could be discriminated at 140 GHz ($\lambda = 2.14$ mm), where the focused beam spot diameter (0.84λ) was almost identical to its theoretical value (0.79λ). A 1 mm-linewidth foreign body (in this case, a paper clip) in a food product was successfully identified using the subwavelength imaging system.

1. Introduction

At present, despite efforts to ensure food safety and quality in the global supply chain, no reduction in the number of foreign body incidents has been noted; thus, consumer complaints are increasing (White, 2016; Wright and Friedrichs, 2017). Among these incidents, those involving hard foreign bodies like metal, glass, and stone could easily by prevented, by filtering these materials using conventional food inspection tools including X-ray imaging and metal detection. In contrast, soft foreign bodies like insects, mold, and polymers cannot easily be detected using conventional inspection methods. Hence, soft foreign bodies are the dominant sources of incidents, and development of a higher-sensitivity method for detecting soft foreign bodies in food products is necessary.

Millimeter (MM) and terahertz (THz) wave imaging techniques are advantageous because of their usability for nondestructive testing of biomaterials and food products, which results from the nonionizing properties of such waves (Gowen et al., 2012; Hu and Nuss, 1995; Jördens and Koch, 2008; Lee et al., 2012; Ok et al., 2012, 2014a, b, 2015; Tonouchi, 2007; Wang et al., 2017). Unlike X-ray transmission imaging, these methods have also been reported to be employed for detecting soft foreign bodies, such as pieces of plastic and insects, in dry food products (Ok et al., 2012, 2014a, b, 2015). More specifically, among the MM and THz wave imaging techniques, terahertz spectroscopic imaging (terahertz time-domain-spectroscopic (TDS) imaging) and monochromatic imaging (continuous-wave (CW) imaging) are well-known techniques for nondestructive food inspection (Gowen et al., 2012; Wang et al., 2017). In particular, the raster-scanning CW imaging technique, which is similar to confocal laser scanning imaging, has many merits for transmission-type inspection, because of its high transmission power, low cost, and fast detection (Karpowicz et al., 2005). As a result, the raster-scanning CW imaging modality can be considered as an effective candidate for foreign body detection in food products. These benefits merit further improvement of the performance of raster-scanning MM and THz CW imaging techniques (e.g., their imaging resolution, speed, and area) to meet industrial requirements and to accelerate the commercial application of these methods for nondestructive inspection in the food industry (Ok et al., 2015).

In raster-scanning CW imaging, the image spatial resolution is generally dependent on the diffraction-limited focused beam size and source frequency. However, increasing the source frequency can also increase the cost and power attenuation because of water absorption (Ok et al., 2014b, 2015). Moreover, because of the diffraction-limited nature of the focused beam, the image spatial resolution is confined to near the source wavelength size. Hence, subwavelength beam focusing techniques beyond diffraction should be employed in raster-scanning imaging to obtain higher-

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quality images using low-cost sources with low frequency.

A previous study on subwavelength beam focusing using MM and THz waves mainly focused on near-field techniques (Adam, 2011). Non-diffracting beams were recently primarily employed in these bands because Bessel beams can simultaneously provide fine lateral resolutions and long depths of focus (DOFs) (Bitman et al., 2012, 2014; Brzobohatý et al., 2008; Busch et al., 2015; Durnin et al., 1987; Liu et al., 2010; McLeod, 1954; Wang et al., 2008; Wei et al., 2013; Yu et al., 2016; Zhang and Buma, 2011). However, most investigations on Bessel beam imaging in these bands focused on increasing the DOF, while the use of Bessel beams for subwavelength MM and THz wave imaging has rarely been reported (Bitman et al., 2012, 2014; Busch et al., 2015; Liu et al., 2010; Zhang and Buma, 2011).

Consequently, in this work, we report subwavelength raster-scanning transmission imaging with Bessel–Gauss beam focusing based on a low-cost 140-GHz source for detecting even 1-mm foreign bodies in food products. A Bessel beam model (Brzobohatý et al., 2008) and a Bessel–Gauss beam model (Gori et al., 1987) are used to theoretically estimate the subwavelength beam spot diameter. The two theoretical estimates are compared with those obtained using a finite-difference time-domain (FDTD) model. These estimates are also experimentally compared by employing a point-scanning method (Karpowicz et al., 2005) to ensure the subwavelength focusing and beam propagation properties. Lastly, the imaging performance is investigated using the transmission-mode imaging setup with a USAF 1951 resolution chart and foreign bodies embedded in a food product.

2. Materials and methods

2.1. Materials

The positive USAF 1951 resolution chart (chromium coating on a glass plate; 76.2 mm × 76.2 mm × 1.5 mm; Edmund Optics, Barrington, NJ, USA) was used as a test pattern to evaluate the imaging performance (Ok et al., 2014a). The chart was mounted on a sample holder with a rectangular hole (74 mm × 74 mm). Foreign bodies embedded in a food product were also used to demonstrate the applicability of the subwavelength imaging technique. A paper clip (8 mm × 34 mm; 1-mm thick) was attached with tape to the back side of a chocolate bar (65 mm × 26 mm × 8 mm). In addition, a 16-mm-long and 2-mm-thick mealworm was buried in the chocolate bar, and a 9-mm-long and 1.4-mm-thick dried maggot was attached to the front side of the chocolate bar (Fig. 1). The chocolate bar with these various foreign bodies was then carefully rewrapped in its original polyethylene wrapper and mounted on a sample holder with a 60-mm-diameter hole (Fig. 1).

2.2. Theoretical beam size calculation

Subwavelength resolution can be realized in raster-scanning imaging by reducing the focused beam spot diameter to less than the beam wavelength. If an axicon lens is used to generate the subwavelength focused beam, the spot size can be controlled simply by adjusting the apex angle of the lens (Liu et al., 2010). The field intensity distribution $I(\rho,z)$ behind the axicon lens should be calculated to precisely estimate the focused beam diameter. Among the various approaches to this calculation, in this study, two different analytical models based on scalar diffraction theory were used to obtain $I(\rho,z)$, namely, the Bessel and Bessel–Gauss beam models (Brzobohatý et al., 2008; Gori et al., 1987). The beam propagation results generated using these models were also compared with those obtained from an FDTD simulation.

The Bessel beam intensity distribution $I_0(\rho,z)$ behind an axicon lens illuminated by a Gaussian beam can be expressed as follows (Brzobohatý et al., 2008):

$$I_0(\rho,z)=\frac{4Pk\sin\alpha_0}{w_0}\frac{z}{z_{max}}\exp\left(-\frac{2z^2}{z_{max}^2}\right)J_0^2(k\rho\sin\alpha_0)\equiv I_0(z)I_0(\rho), \tag{1}$$

where ρ is the radial distance from the optical z-axis; P is the total power of the incident Gaussian beam; $k=2\pi/\lambda$ is the wavenumber; w_0 is the waist of the incident Gaussian beam; α_0 is the angle between the wavevectors of the refracted plane waves and the z-axis; z_{max} is the DOF in the non-diffracting region ($=w_0/\tan\alpha_0$); and J_0 is the zeroth-order Bessel function (Fig. 2). Here, α_0 is related to the design parameters of the axicon lens and expressed as

$$\alpha_0=\arcsin\left(\frac{n}{n_0}\cos\left(\frac{\tau}{2}\right)\right)+\frac{\tau-\pi}{2},\quad \left(0<\alpha_0<\frac{\tau}{2}\right), \tag{2}$$

where n and n_0 are the refractive indices of the axicon lens ($n=1.54$) and the surrounding medium ($n_0=1.0$), respectively, and τ is the apex angle of the axicon lens (Brzobohatý et al., 2008).

The full-width at half maximum (FWHM) of the Bessel beam ρ_{FWHM} can be expressed as $2\times1.1264/(k\sin\alpha_0)$ using the fact that $J_0^2(1.1264)=0.5$. This term is expressed as follows:

$$\rho_{FWHM}=\frac{1.1264}{\frac{\pi}{\lambda}\sin\left[\arcsin\left(\frac{n}{n_0}\cos\left(\frac{\tau}{2}\right)\right)+\frac{\tau-\pi}{2}\right]}. \tag{3}$$

Fig. 1. Left: Wrapped chocolate bar with the foreign bodies on the circular sample holder. Right: Foreign bodies embedded in the chocolate bar, where the dried maggot was attached to its front side, the paper clip was on its back side, and the mealworm was buried inside it. The image of the chocolate bar is reproduced with the permission of the Hershey Company.