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Compact continuous-wave subterahertz system for inspection applications

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We report the use of a compact continuous-wave sub-terahertz system for inspection applications, using electronic generation and detection methods. A combination of a Gunn diode emitter, a Schottky diode detector, and a polyethylene Fresnel lens provides line-scan images at 0.2 m/s with a data acquisition rate of 512 points/s. Examples of the measurement of NASA's insulating panels and applicability of the technology to other nondestructive testing applications are presented and discussed. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1856701]

Many nonconducting, dry materials that are opaque to infrared and visible light exhibit low absorption in the terahertz frequency range. Such materials are also transparent to the microwave and radio frequencies, but the shorter wavelength of terahertz radiation allows for higher spatial resolutions. The terahertz (THz) region of the electromagnetic spectrum thus represents an important intersection between spatial resolution and penetration depth for many applications.

The technique of using continuous-wave radiation in the sub-THz band for nondestructive testing has been studied for several decades,[1,2] but only recently has semiconductor technology advanced to the point where a practical system, both compact and simple to operate, is possible. Recent systems have been designed for cw imaging in the THz region, using radiation generated by a variety of methods, such as photomixing[3,4] or quantum-cascade lasers,[5] and are capable of impressive results,[6,7] but generally are of high cost and complexity. Other recent optoelectronic systems have been developed that are more compact and lower in cost.[8,9]

In this letter, we present a compact cw THz imaging system using entirely electronic generation and detection with a minimal number of components. Such a system can easily be made portable, thus opening a much wider range of possible applications. This system has been used to detect defects in space shuttle insulating panels (both foam and tile). It has been tested in many other general imaging applications, such as target screening. More noninvasive and nondestructive inspection applications in the agro-food and manufacturing industries are expected.

Figures 1(a) and 1(b) schematically illustrate two imaging geometries. The cw 0.2 THz imaging system utilizes a frequency-doubled Gunn diode oscillator with an output power of 12 mW (made by Radiometer Physics) as a source, and a Schottky diode (Pacific Millimeter Products, model GD) as the detector. After being emitted by the Gunn diode, the beam is focused by a parabolic mirror to a 4 mm spot where it is modulated by an optical chopper at 1.2 kHz. The modulated beam then passes through a silicon beam splitter, and is focused by a 5-mm-thick polyethylene Fresnel lens[9–12] with a focal length of 204 mm. The distance between the focus of the parabolic mirror and the lens is 408 mm. Accordingly, the beam reaches another focus 408 mm from the lens, after being reflected by another aluminum mirror.

In reflection geometry, shown in Fig. 1(a), the beam is reflected normal to the surface of the substrate and returns back through the Fresnel lens. The beam then is incident upon the beam splitter and is reflected towards the detector, the signal from which is read by a lock-in amplifier. The sample is moved on a pair translation stages, and an image is produced by scanning point by point, with a maximum speed of 0.2 m/s. The system may also be configured in a transmission geometry, where the mirror and beam splitter are removed and the detector is placed behind the sample, as shown in Fig. 1(b). The spot size at the focus is approximately 4 mm in the configuration presented.

The signal-to-noise ratio (calculated as the mean signal divided by its standard deviation) is between 900 and 9000, with the lock-in amplifier time constant set to 3 ms and 100 ms, respectively. In the case of reflection geometry with the silicon beam splitter, the ratio is reduced by a factor of ten.

A 0.2 THz wave source has a wavelength of 1.5 mm. A necessary condition to significantly increase the spatial resolution would be to use a shorter wavelength, as required by the Rayleigh criterion for far-field imaging. The difficulty associated with this is that in current Gunn diode technology,

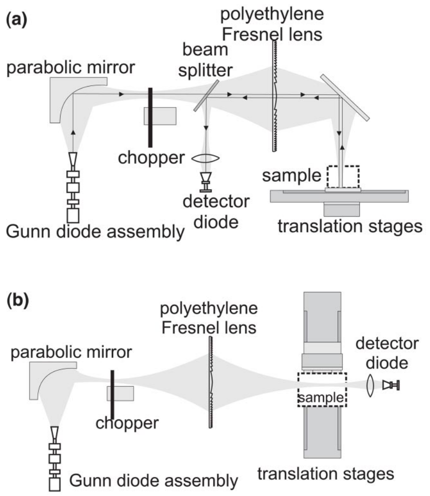

FIG. 1. Schematic diagram of the imaging system in (a) reflection, and (b) transmission geometry, respectively.

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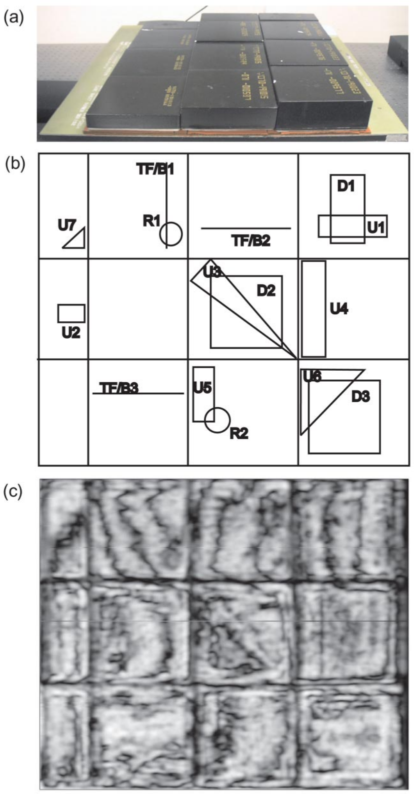

FIG. 2. (a) Photograph of the tile sample. (b) Defect map of the sample. The defects are labeled as follows: U: Debond; TF/B: Varyingly poor bond; R: Back-filled tile; D: 0.025 pocket. (c) 0.2 THz image of the sample.

output power is a rapidly decreasing function of frequency above 100 GHz, with about 10% conversion efficiency during frequency doubling. This relationship may change with future devices, however.[13] Additional difficulties associated with decreasing the wavelength are the availability of Schottky diode detectors further into the THz region of the spectrum, and that the absorption or scattering coefficients of the sample will likely increase with frequency, in the case of foam insulation.[14] Other detectors in this range that would be more sensitive, such as the photo-acoustic Golay cell, have a much slower response than the diode detectors and so scanning speed decreases significantly if they are employed at the same step size.

The first application of this imaging system presented in this letter is the detection of defects in a molded ceramic tile composed of compressed silica fibers. The material exhibits low absorption at 0.2 THz and thus can be inspected by the system described herein. The sample, provided by NASA Marshall Flight Center, contains numerous built-in defects designed to test the performance of potential nondestructive testing mechanisms. The panel contains 12 plates. A photo of a 60 cm × 60 cm panel, a partial pre-build defect map, and an image of the panel are shown in Fig. 2. The image, Fig. 2(c), has a step size of 1 mm and the lock-in time constant was set to 10 ms.

A defect with vertical extent, such as a pocket or void, will be more visible than a flat defect such as a debond, since in the former there will be volumetric features to scatter and absorb the radiation, while a debond will only affect the beam via the qualities of the reflection.

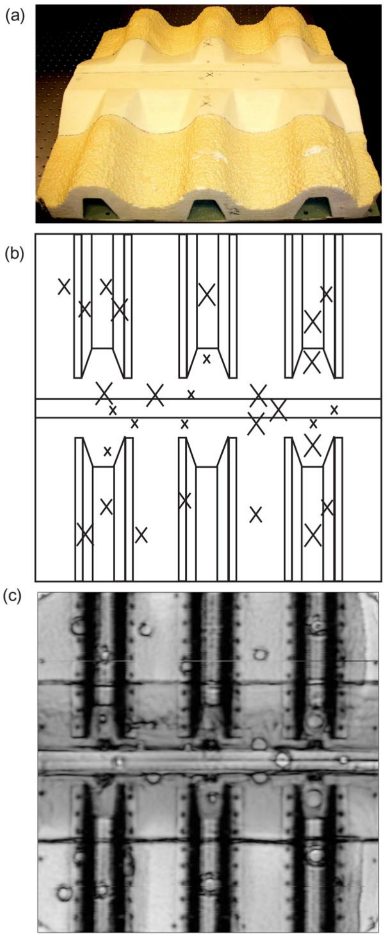

FIG. 3. (a) Photograph of the foam sample. (b) Defect map of the sample. Each void defect is marked with an “X”. (c) cw 0.2 THz image of the sample in reflection geometry using a silicon beam splitter.

There are other features shown in the block that do not correspond to features marked in the defect map. They may be artifacts of the manufacturing process, additional intentional or unintentional defects, strong density fluctuations within the sample, but may also be the result of a standing wave due to the fact that the radiation is coherent.

The measured defects locations match well with the position on the map: the backfilled tile and 0.025 in. pocket defects, which extend through three dimensions, are visible in the image. There is some contrast in the expected area of the variable poor bond defect, which may or may not be caused by the defect itself, and the pure debonds show no readily visible effect.

The space shuttle insulating foam, sprayed-on foam insulation (SOFI), shown in Fig. 3(a), is another good subject for THz techniques because it has a low absorption coefficient and index of refraction in this region of the electromagnetic spectrum.[14,15] The samples measured are sprayed layer-by-layer onto an aluminum substrate. As in the tile sample, there are various intentional defects inside to test the systems’ abilities to find them. This sample has only void defects, which appear in the cw image as dark circles with light interiors, corresponding to scattering and interference at the edge of the feature and enhanced transmission due to the lack of material in the interior. Figure 3(b) is a defect map with the positions of 29 defects.

The 0.2 THz wave image of this sample is shown in Fig. 3(c). Of the defects shown on the measurement, all but two are visible in the images. One of the missing defect is located

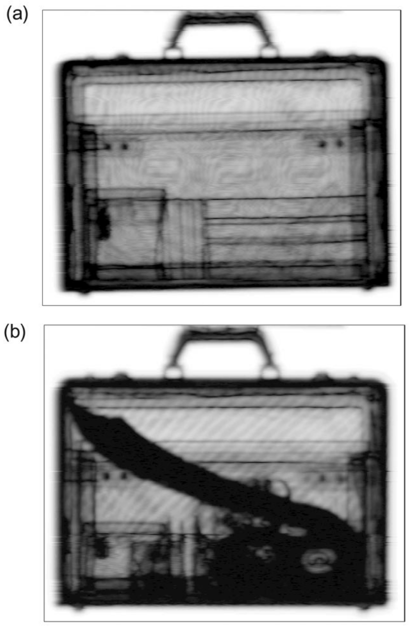

FIG. 4. (a) Transmission geometry 0.2 THz cw image of an empty leather briefcase. (b) Image of the same briefcase holding a large knife and various harmless contents such as a compact disc, a video cassette, and audio cassette and pens

on a tilted surface, so that the radiation is not reflected in the direction of the detector. It can be seen in the image that SOFI makes an ideal subject for this imaging system as the foam absorbs very little radiation and defects show a high contrast with their surroundings.

Outside of nondestructive testing, a field which may hold applications for cw THz imaging is security. The method of millimeter-wave security inspection was proposed in the 1970s.[16] While it has many of the same strengths and limitations today, the miniaturization of generation and detection technology now allows for a portable system, which may make it more desirable.

Figure 4 shows a 0.2 THz cw scan of a standard size leather briefcase, both empty and containing benign and suspicious items. The strengths of the system can be immediately seen: objects can be recognized fairly easily, and since the radiation involved is nonionizing, it poses little threat to human beings. The primary limitations are also clear. Metal objects are shown only as silhouettes since, unlike the case of x-ray radiography, the THz radiation does not penetrate macroscopic conductive materials. As a result, a lone metallic object can be fairly easily identified, but multiple overlapping conductive objects become indistinct. This can be partially resolved by using multiple detectors to measure reflected, scattered, and transmitted radiation from the subject. Additionally, while the images are clear, the system's resolution is fundamentally limited to the THz wavelength. Finally, the system shown here utilizes only one detector with point scanning, systems utilizing a matrix or linear array of detectors would be more suitable for real-time imaging applications.

In conclusion, we presented a compact and inexpensive method for non-destructive testing utilizing a Gunn diode source, a Schottky diode detector, and a Fresnel lens. The system is limited to relatively simple structures, as it lacks depth and phase information, yielding only two-dimensional images of transmitted energy. In general, such a system provides useful information in an application where the subject meets the following requirements: there must be no conductive material in front of the desired area of inspection; the features to be identified must be larger than the scale of the wavelength and have some extent in the dimension parallel to the incoming beam; and the features to be identified should be distinguishable when superimposed over one another.

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