Progress In Electromagnetics Research Letters, Vol. 1, 197–204, 2008

LATEST TRENDS IN MILLIMETER-WAVE IMAGING TECHNOLOGY

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Abstract—This paper overviews the latest trends of millimeter-wave (MMW) imaging technologies, focusing mainly on applications of and technical parameter variations for security surveillance and nondestructive inspections (NDI). We introduce a smart NDI tool using active W-band imaging, which is capable of detecting hidden surface cracks in concrete structures.

1. INTRODUCTION

The history of MMW technologies started in the 1890s [1], and in recent years, various applications have been developed as a result of the rapid progress in monolithic MMW integrated circuit (MMIC) technology. One of the mainstream applications is imaging for security surveillance, and products currently available on the market include active and passive security gates, the handheld passive scanners, and passive video-rate cameras. Furthermore, researchers are actively exploring other application fields of MMW imaging with much higher sensitivity and resolution.

MMWs penetrate dielectric materials, such as plastic or cloth, and are strongly reflected by metalic materials. These characteristics are very favorable for security surveillance, especially for the detection of weapons concealed under people's clothing and in baggage at airports [2–4]. Figure 1 shows a scissors that was detected hidden in a business card holder [5]. As other examples, life detection in wreckage [6] and a collision avoidance system [7] have been studied.

Nondestructive inspection is also a promising application field of MMW imaging. Figure 2 shows a MMW image of cookies in a box, which shows that the left one is split down the middle. Mizuno et al. performed experiments in which MMW imaging was used to check the maturity of fruit and white-ant-damaged in timber [8]. In this paper,

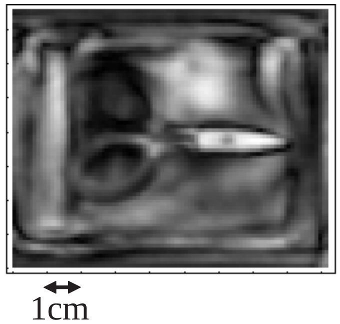

Figure 1. Detection of a scissors hidden in a business card holder (100 GHz).

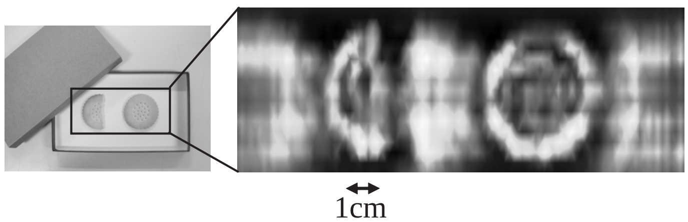

Figure 2. Inspection of cookies in a paper box (94 GHz). The left cookie is split down.

we discuss practical issues of MMW imaging and describe the technical key parameters.

2. PRACTICAL ISSUES OF MMW IMAGING

In any applications of MMW imaging, appropriate integration of key parameters shown in Table 1 is important.

Table 1. Key parameters of MMW imaging.

Choice of Frequency	30 to 110 GHz
Illumination method	Active or passive
Target distance	Far distance; close distance; near-fileld
Types of detector	Single detector with X-Y stage control; 1D/2D arrayed detectors
Image processing	Deblurring with holograppy ; deblurring with blind-deconvolution

(1) Choice of Frequency

A MMW is an electromagnetic wave with a wavelength from 10 mm to 1 mm (i.e., 30 to 300 GHz). In this region, the transmission of MMW is attenuated by atmospheric absorption caused by water vapor and oxygen [9]. However, there are some regions of low attenuation called "atmospheric windows" around 35, 94, 140, and 220 GHz. At present, 140 and 220 GHz are not normally used, because MMIC products that can work at frequencies higher than the W-band (75–110 GHz) frequency have not matured yet. Therefore, the choice of frequency is basically decided by a simple rule; use a lower frequency for deeper penetration of the dielectric materials; use a higher frequency for higher resolution. In addition, waves at lower frequencies need a wider aperture antenna for illumination and detection.

(2) Illumination Method

When a target does not emit detectable MMW signals, we have to use active illumination. A Gunn diode oscillator is commonly used for coherent active illumination. When using active illumination, the interference and multi-path problem must be carefully considered. Mizuno et al. attempted to use a household fluorescent light as an incoherent illumination [8]. On the other hand, when a target scene includes a thermal source, such as a black-body object, passive sensing is commonly used. The natural emission of MMWs from the human body has been captured by using a high-sensitivity Schottky diode detector with a low-noise amplifier [10].

(3) Target Distance

From the early stage, MMW imaging has been used at far distances ($>$ 10 wavelength) for security surveillance. Because the 10 wavelength is about 30 mm at 94 GHz, it is obvious that the normal distance of security camera (1–5 m to a target) reaches the far distance region. Serious problems in long-distance imaging are the degradation of resolution and diffusive attenuation. A focal dielectric lens is often applied to improve them. Such lenses are made of Teflon and weigh several kilograms, which makes the system large and heavy.

On the other hand, new practical applications at close distance ($<$ 10 wavelength) have been explored in recent years. Sheen et al. demonstrated the detection of concealed items in a gypsum wall with a sophisticated image reconstruction algorithm in near-field region [2], Nozokido et al. observed the evolution of photo-excited free-career distribution using a metal slit probe [11], and we has developed a concrete crack detection scanner, which is described in next section.

(4) Types of Detector

In experimental studies in laboratories, the basic approach for image capturing is to sweep a single detector with an X-Y motorcontrolled stage. For practical use, arrayed detectors are preferable in order to shorten the scanning time. Brijot Inc. has achieved fast video-rate capturing (0.5 seconds per frame) for the security surveillance cameras. They used a 1D array of 16 detectors and a mirror reflector that periodically moves to sweep a whole area in a scene. The integration of a fixed 1D/2D array of detectors and a movable mirror reflector is common for video-rate MMW cameras [10, 12, 13]. Another approach of image capturing is to use a leaky wave antenna as 1D array detector, which can capture the MMW reflections arriving from 60 directions simultaneously (20 seconds per frame).

(5) Image Processing

In imaging systems, the diffusive scattering and the speckle of electromagnetic waves makes an observed image blurry. To improve resolution, several image-processing techniques have been proposed [14, 15]. Sheen et al. employed a holographic approach using both magnitude and phase information at 10–30 GHz, and performed image reconstruction with sub-wavelength resolution using a 2D/3D Fourier transform algorithm [2, 3]. Another deblurring technique is blind deconvolution, which works when phase information is not available. A demonstration of this technique used for deblurring an evanescent microwave image has been reported [16].

3. AN APPLICATION TO CIVIL STRUCTURES AND MATERIALS

In this section, we introduce a new our application of MMW imaging, which aims at a nondestructive inspection of civil structures [17].

Alarm to the hazards of old decrepit concrete structures is spreading, and the possibility of unscrupulous developers falsifying construction data, as seen in the recent faked earthquake-proof certification scandal in Japan, is becoming a serious social concern [18]. The integrity of concrete structures is commonly evaluated through crack inspection. However, cracks are often hidden by wallpaper, paint, and tile. To solve this problem, we developed an NDI MMW-imaging tool called "Crack Scan", which is used as shown in Figure 3.

The target in this case does not include black-body radiation. Therefore, we chose a Gunn oscillator with W-band frequency (75–110 GHz) for active illumination. In addition, considering the need for portability and working efficiency, the tool must be compact, about the size of a handhold imager. To meet this requirement, we chose close-distance sensing without a focal lens, but with a 1D detector array. Figure 4 shows the system layout. Scanning this device over a wall surface makes it possible to display hidden surface cracks as 2D

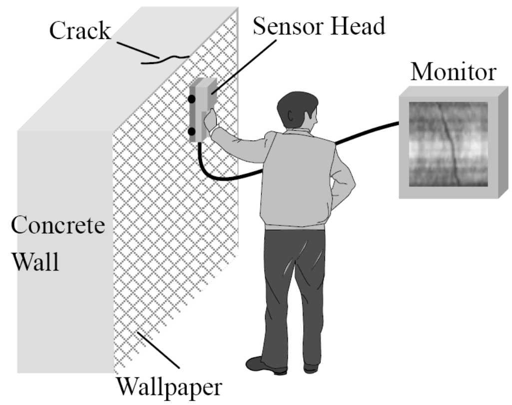

Figure 3. Practical scene of Crack Scan.

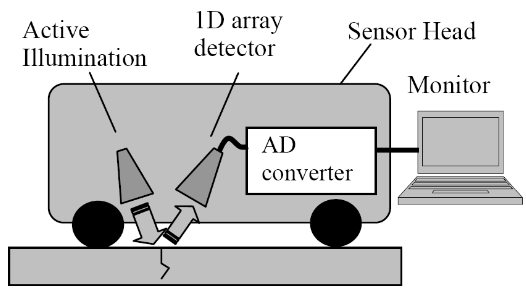

Figure 4. System layout of Crack Scan.

images on a monitor. The MMWs pass through wallpaper and lining paint but are scattered on impact with fine cracks.

Figure 5 shows a photograph of Crack Scan and an experimental result of crack detection under wallpaper. Generally, the spatial resolution of imaging in the far-distance region is limited to the radiowave wavelength. However, by detecting the dispersion of MMWs scattered by cracks in at close distance, crack-inspection accuracy covering sub-millimeter widths (specified in civil engineering standards) is obtained.

We are aiming to deploy the Crack Scan technology in the repair and maintenance departments of facilities as a non-destructive inspection method for concrete structures. Moreover, we are pushing ahead with research and development on applications of Crack Scan in areas other than concrete-structure inspection, such as security surveillance and food inspection.

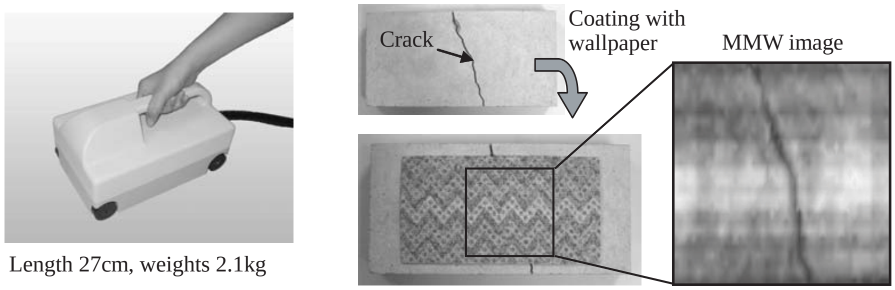

Figure 5. Photograph of Crack Scan and a result of crack detection under wallpaper.

4. CONCLUSION

To achieve a MMW imaging system, we have to carefully select targets on the basis of the transmission and reflection principals in this frequency region, and consider the best integration of frequency, illumination, distance, detector type, and image processing. As major price decline of MMIC products, the millimeter-wave imaging will prevail among our daily life in the near future.

ACKNOWLEDGMENT

The development of Crack Scan was supported by AIREC Engineering Corporation.

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