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ABSTRACT

The ability of millimeter waves (1-10 mm, or 30-300 GHz) to penetrate through dense materials, such as leather, wool, wood and gyprock, and to also transmit over long distances due to low atmospheric absorption, makes them ideal for numerous applications, such as body scanning, building inspection and seeing in degraded visual environments. Current drawbacks of millimeter wave imaging systems are they use single detector or linear arrays that require scanning or the two dimensional arrays are bulky, often consisting of rather large antenna-couple focal plane arrays (FPAs).

Previous work from INO has demonstrated the capability of its compact lightweight camera, based on a 384 x 288 microbolometer pixel FPA with custom optics for active video-rate imaging at wavelengths of 118 μm (2.54 THz), 432 μm (0.69 THz), 663 μm (0.45 THz), and 750 μm (0.4 THz). Most of the work focused on transmission imaging, as a first step, but some preliminary demonstrations of reflection imaging at these were also reported. In addition, previous work also showed that the broadband FPA remains sensitive to wavelengths at least up to 3.2 mm (94 GHz). The work presented here demonstrates the ability of the INO terahertz camera for reflection imaging at millimeter wavelengths. Snapshots taken at video rates of objects show the excellent quality of the images. In addition, a description of the imaging system that includes the terahertz camera and different millimeter sources is provided.

Keywords: terahertz, THz camera, microbolometer, millimeter-wave imaging

1. INTRODUCTION

In various fields, including security applications, there is a need for a live see-through imaging. Millimeter waves exhibit high transmissivity through various materials and for a given material show large penetration depth [1-3]. This is a strong advantage in terms of capabilities for remote security applications. Combining a video rate camera with an appropriate illumination source would be a major asset in the detection and identification of threats.

Most of millimeter-wave scanners are typically active devices in that they require some kind of illumination. For security screening for instance those devices typically require an object or a person to stand still for tens of seconds. Those units are also large in volume. As such their installation reduces the flow of people and objects to be inspected and requires large working space. Consequently their deployment is somehow confined to critical security point and high value assets. Backscatter x-ray [4] is also a see-through imaging technology but generally rises safety and privacy concerns.

Passive mm-wave units also exists [1-2]. This technology is however bulky and typically slow precluding its wide dissemination.

Other video rate cameras also exists in the THz [5], however their actual limited sensitivity in the longer THz and mm-waves precludes their used for mm-wave applications

In this paper a camera exhibiting high sensitivity at up to 3 mm is combined to very fast optics to provide video rate imaging in the millimeter wave. Preliminary experiments performed in reflective mode are very encouraging. The 384x288 pixel camera provides enough resolution to distinguish between various features. Tests with various obscurants confirm the deep penetration of the mm-wavelength band hence its ability for live remote see-through applications.

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2. MM-WAVE IMAGING SYSTEM

A representative schematic of a reflection imaging set-up is shown in Figure 1. The three main components are the THz camera, the mm-wave source and optical components, such as off-axis parabolic mirrors (OAPs) and lenses made of either high-resistivity float zone (HRFZ) silicon or high-density polyethylene (HDPE) plastic.

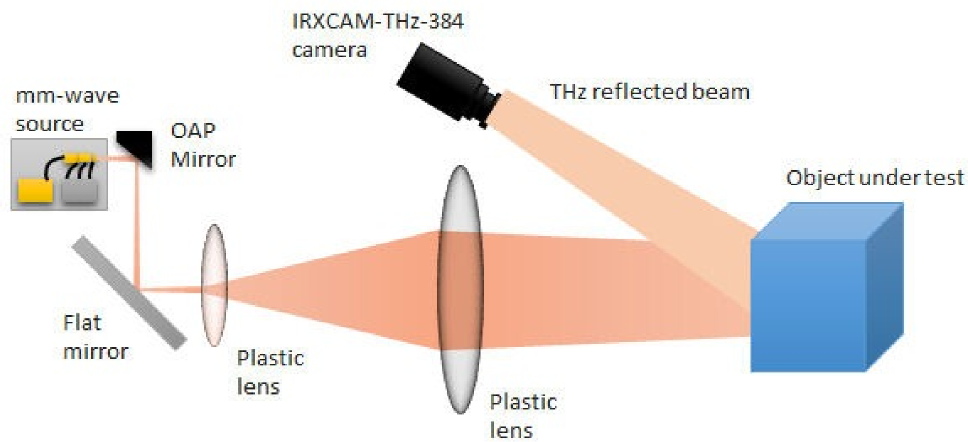

Figure 1. Example mm-wave reflection imaging experimental set-up, including a mm-wave source, a combination of off-axis parabolic mirrors and plastic lenses and the THz camera.

The THz imager used for these mm-wave reflection imaging tests was the INO IRXCAM-384-THz, shown in Figure 2 [6-7]. The camera's focal plane array (FPA) consists of 388 x 284 uncooled mircobolometric pixels with 35 µm pixel pitch. The camera core can be adapted to various detectors through by changing only the proximity board. It can be equipped with a sealed detector or a dynamically pumped detector. A dynamically pumped detector provides the opportunity to change the front window of the detector and thus test various materials and anti-reflection coatings over the wide response bandwidth of the detector. The camera is connected through a gigabit Ethernet link to a computer where the 16-bit raw data can be further processed.

One of the challenges of using mm-wave illumination is the large point-spread function that comes with the longer wavelengths. To overcome this difficulty, ultrafast optics exhibiting an F-number of 0.7 were developed [8]. Uniform illumination is also a key factor to produce an image of good interpretability. Various optical elements were specifically designed to improve the uniformity of the illuminating beam. While refractive materials in the millimeter wave range usually show reduced chromatic dispersion, mirrors offer uniform athermalized and aspectral optical properties.

Another element to consider in the design of a mm-wave set-up is the source. Monochromatic GUNN diodes and IMPATT diodes are both compact sources emitting around 94 GHz (3.2 mm) and may be equipped with frequency multipliers to produce output wavelengths closer to 1 mm (at the expense of output power). Variable frequency backward wave oscillators (BWOs) are more bulky but offer a range of base frequencies (33 – 90 GHz) and may also be coupled with frequency multipliers to extend their range. Such sources are especially useful to determine absorption properties of various materials as a function of wavelength.

Figure 2. Photograph of the IRXCAM-THz-384 THz camera with a dynamically pumped test detector package used for real-time mm-wave reflection imaging.

3. IMAGING RESULTS

3.1 Initial mm-wave reflection imaging tests

As a first step, a close-range reflection set-up similar to that shown in Figure 1 was realized and is shown in part in Figure 3, where the distance between the object under test (metallic housing of a digital camera) and the THz camera was 0.75 m. The source (not shown) was a GUNN diode with a frequency tripler with output wavelength of about 1 mm and an output power of less than 2 mW. The resulting mm-wave image (shown on the screen in the left side of the two photos of Figure 3) is the specular reflection from the metallic case of a digital camera. In the left panel, the digital camera is in direct line-of-sight of the THz camera, and in the right panel a 2 cm thick piece of foam insulation was placed in front of the digital camera. Although the foam does absorb some of the mm-wave radiation, the THz camera is still able to produce a clear image of the reflected radiation off of the object.

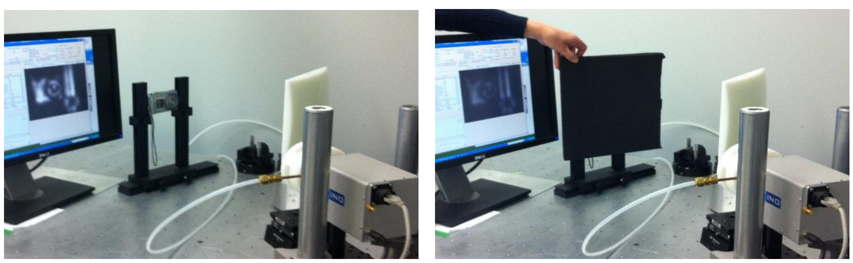

Figure 3. A mm-wave reflection set-up showing the mm-wave image of the metallic housing of a digital camera in plain sight (left) and behind a 2 cm thick piece of foam insulation (right).

Various objected were imaged in reflection with such a set-up and the results are presented in Figure 4. The objects imaged were the digital camera (left), an aluminum plate with one 5 cm diameter hole and two 1 cm diameter holes drilled into it (center) and a plastic toy truck covered with a metallic spray paint (right). The mm-wave images are shown in the top row and visible images of the objects are shown for reference in the bottom row. Figure 4 demonstrates the high image quality of the THz camera in the mm-wave range.

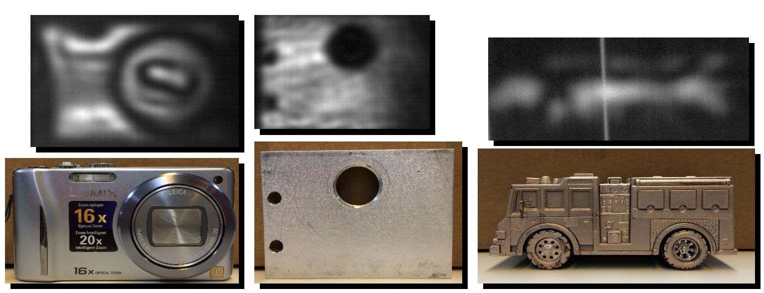

Figure 4. Example mm-wave images taken in reflection with the THz camera (top row) and visible images (bottom row): digital camera’s metallic case (left), aluminum block (center) and spray-painted plastic toy truck (right).

Preliminary tests at a longer distance were performed, using the same source, thus output wavelength 1 mm and power less than 2 mW. The set-up is shown in Figure 5, where the distance between the camera and the object was 2.5 m. Images were taken in reflection of the spray painted toy truck (left) and of a cinderblock (center and right). These images demonstrate that long-distance reflection imaging is possible on objects with the THz camera since at 1 mm there is little atmospheric absorption. This is demonstrated by comparing the mm-wave image of the toy truck in Figure 5 with that shown in Figure 4. The brightness of the two images is at the same level. The center (complete set-up) and right (zoom-in on the mm-wave image next to actual cinderblock) photographs show that even a rough porous surface can be imaged using the THz camera at longer distances.

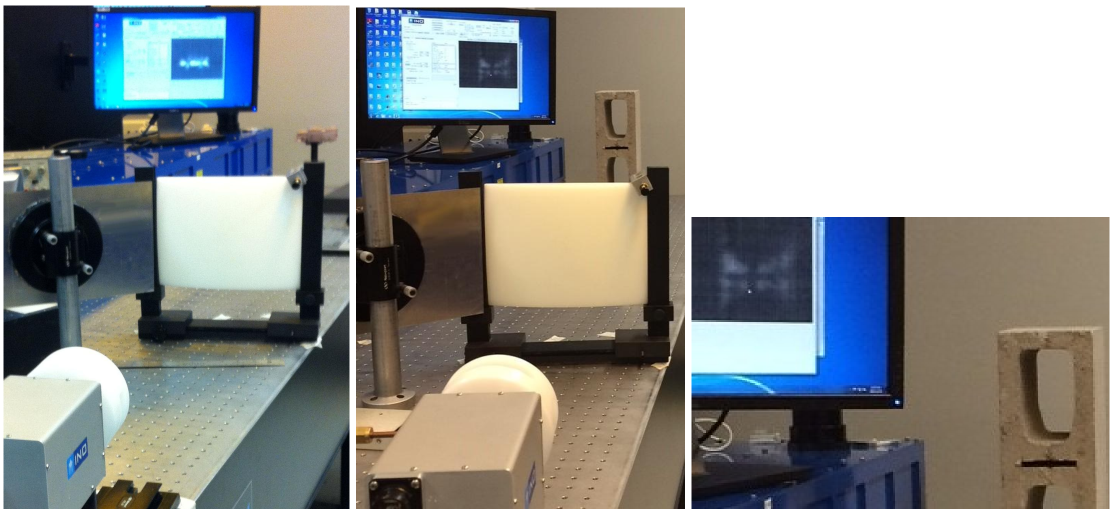

Figure 5. Examples of mm-wave reflection images taken at a distance of 2 meters: painted toy truck (left) and cinderblock (center) with zoomed section of the mm-wave image next to the cinderblock (right).

The results presented in Figure 5 above demonstrate that there is not a significant decrease in signal power at a wavelength of 1 mm for a distance of a few meters. Figure 6 below is a graph of the atmospheric transmission (through water and oxygen) calculated over a wavelength range of 0.9 mm to 3 mm (333 GHz to 100 GHz) and distance traveled of 100 meter for various atmospheric models. The influence of humidity and temperature on the transmission is seen and is greater for wavelength under 2 mm, but even over very long distances there is still good over 75% transmission in the worst case of the Tropical model, with 1013 mb pressure, 26.55C temperature and 75.51% humidity.

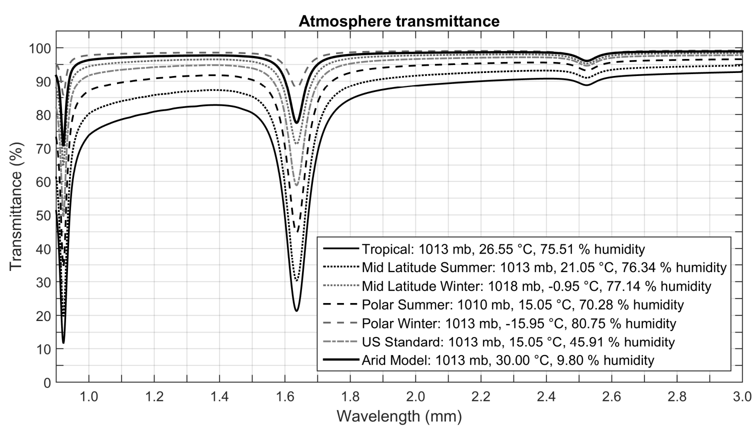

Figure 6. Atmospheric transmission as a function of wavelength for a wavelength range of 0.9 mm to 3 mm using various atmospheric models for a distance of 100 meters.

3.2 Degraded Visual Environment

A direct test of the capability of the THz camera to image through low visibility conditions such as fog was performed. The imaging set-up is shown in Figure 7, where front (top) and back (bottom) views are shown for clarity. In this set-up, a plastic box was built around the object to be imaged, in this case the digital camera. A small hole was drilled on its back side to allow the entrance of fog from a fog machine. The THz camera and mm-wave source are side-by-side facing the object in the plastic box. The screen showing the mm-wave image is also seen in the figure on the opposite side of the plastic box (for space reasons). The configuration used for these tests is more compact than the previous design. In addition, the focal lengths of the lenses were different and allowed for a zoom in of the camera shutter, seen clearly in the mm-wave image.

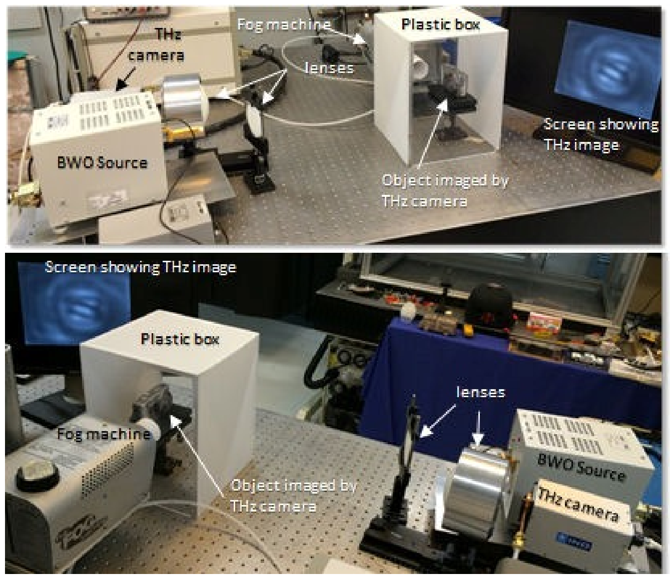

Figure 7. Two views of the mm-wave reflection imaging set-up for degraded visual environment simulation

Figure 8 compares two mm-wave images, one where there is no fog in the plastic box (left) and one where the plastic box is filled with the fog (right). It is clearly demonstrated that there is no noticeable difference between the two images. This indicates that the THz camera would be ideal for use in degraded visual environments such a fog.

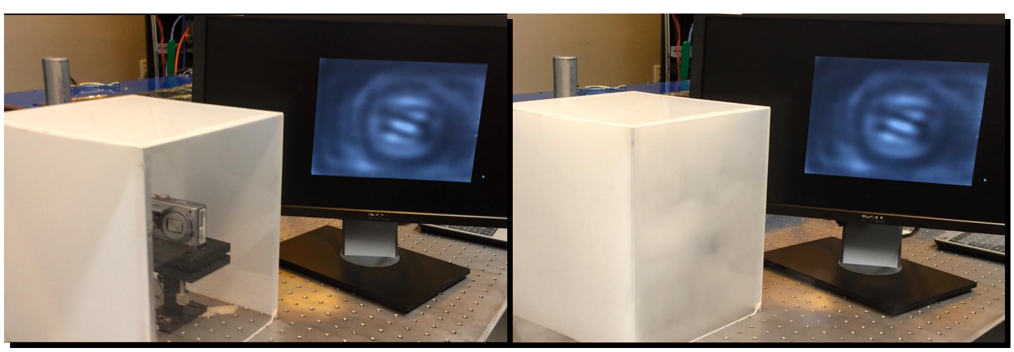

Figure 8. MM-wave image comparison of a digital camera metallic housing within a plastic box before (left) and after (right) filling the box with (glycerine-based) fog.

3.3 Through the wall application

Another possible application for the THz camera would be through-the-wall detection. A set-up was designed using a 94 GHz source and output power of 100 mW for greater penetration through a manufactured wall cutout. The compact set-up is shown in Figure 9 where the wall section was made from gypsum board and held together by an aluminum frame. This set-up allowed for detection of objects through the wall rather than imagery.

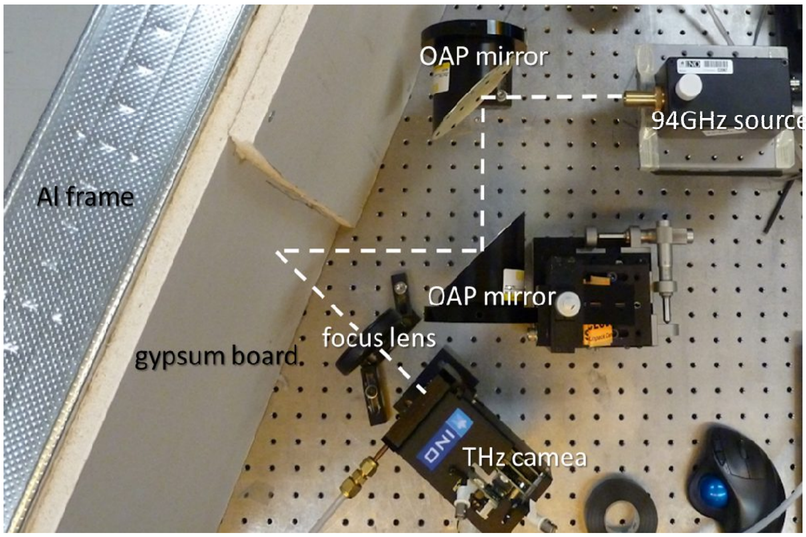

Figure 9. Imaging set-up for through-the-wall application.

Figure 10 presents the captured reflected radiation captured by the THz camera in four different cases. In the first case (a) there was nothing placed behind the wall. Next, three different objects were placed behind the wall: a flat metal plate (b), a plastic PVC pipe (c) and a thin metal rod (d). In these three cases the presence of the object was clearly detected. These results demonstrate that the THz camera used in the mm-wave band is ideally suited for construction applications where detection of pipes and electrical wiring is possible.

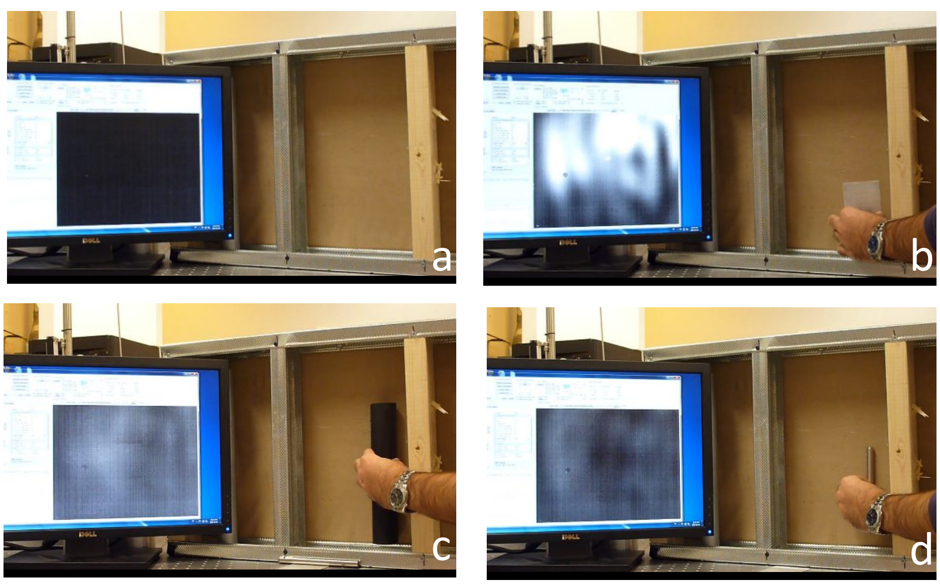

Figure 10. Images of various objects taken at 94 GHz in reflection from behind a gypsum board shown with object: no object (a), small metallic plate (b), PVC pipe (c), metallic rod (d).

4. CONCLUSIONS

This paper reviewed different mm-wave reflection imaging results taken with the IRXCAM-THz-384 camera. All the images presented here were taken at a rate of 50 Hz without any further processing performed on them. The compact sensitive camera, its excellent image quality and video-rate capture allows for various applications of see-through imaging, such as live wall scanning that are not possible with single element detectors.

In addition, the transmission of millimeter wavelength radiation is less affected by the atmosphere than far infrared wavelengths. On the initials tests performed, it was shown that the THz camera provides excellent image through fog-like conditions. Thus, it is ideally suited for use in degraded visual environments such a heavy fog. Given that it can provide large field of view images at a rate of 50 Hz, it is ideally suited to provide a visual aid for such applications as air, land and maritime transport where real-time imaging capability is a necessity. According to a National Oceanic and Atmospheric Administration report [9], in 2010 in US, more than 210 million people where living directly on the shoreline. These locations are often submitted to fog events, and a see-through-fog system would be a key element for a safer transportation systems.

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