Postprint

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Sub-mm Resolution Indoor THz Range and SAR Imaging of Concealed Object

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Abstract—**In radar systems, the frequency range is being extended to high frequencies such as THz for sub-mm resolution. The spectrum offers high resolution but on the contrary, propagation distance and penetration depth are limited because of smaller wavelength. It suffers from higher atmospheric absorption in comparison to sub-GHz systems. In comparison to optical technology, the radar technique majorly benefits with respect to the penetration property such as cloud/smoke cover penetration and detection of concealed objects. However, the THz range and synthetic aperture radar (SAR) imaging of concealed objects are not very well established. Therefore, this paper examines this property at THz. A testbed has been set up with a bandwidth of 110 GHz at a carrier frequency of 275 GHz. The imaging is performed of a very small metal object. Firstly, the sub-mm resolution is validated with the experiment after that the range and SAR imaging are performed in which this object is covered with different types of materials. The backscattered data is processed with the image reconstruction algorithms and the results are presented in this paper with respect to sub-mm resolution and detection.**

Keywords—radar, synthetic aperture radar, terahertz, high resolution imaging, indoor radar, hidden objects, localization and imaging

I. INTRODUCTION

Radio Detection and Ranging popularly known as Radar is a system that transmits and receives electromagnetic (EM) waves with specific polarization. The received signal is observed/processed for various applications such as target localization, detection, classification, characterization and imaging. This paper focuses on the range imaging or 1D localization and 2D imaging with the technique of Synthetic Aperture Radar. The range imaging in this paper is addressed as the 1D localization of the objects with respect to the time delay in the received signal. In this technique, the radar system is mounted at a fixed position and emits a known waveform (EM wave) towards the objects along the range directions [1]. The backscattered signal from the object is recorded at the sensor and processed to calculate the position of the object along the range. For, a sub-GHz system, the position accuracy is in the range of sub-cm or sub-m. For example, a system @2 GHz with a bandwidth B_w of 100 MHz corresponds to a resolution of 1.5 m. This resolution is directly proportional to the bandwidth. Therefore, THz range imaging is an interesting research area to achieve sub-mm resolution. Considering the system @300 GHz with B_w of 110 GHz corresponds to the resolution of 1.36 mm. This spectrum is suitable for an Indoor environment or short-range imaging.

Furthermore, the synthetic aperture radar is a remote sensing technique and basically used for 2D/3D imaging. This technique has many applications such as in meteorology,

surveillance and change detection. In this technique, addition to the range imaging, cross-range imaging is also performed and therefore results in 2D image of the object. The SAR operation can be explained as the radar sensors are mounted on a moving platform that radiates EM waves towards the target and backscattered signals are recorded at the sensor [1], [2]. Based on an altitude and moving platform, the SAR system can be characterized as space-borne, air-borne, ground based and indoor SAR [3]. This paper focuses on indoor SAR applications. The THz compact radio frontends are commercially not available therefore the imaging is performed with the Vector Network Analyzer (VNA) with the frequency range of 220 GHz to 330 GHz. However, some research prototypes of THz frontends are developed but are limited with the system bandwidth [4], [5]. Therefore, in this paper, the wide bandwidth of 110 GHz and sub-mm aperture size antenna is explored to validate the theoretical spatial resolution in the range of sub-mm [6]. Furthermore, the imaging object is a metal nut attached with two metal plates at the back as shown in Fig. 1 along with the dimensions. In experiments, this object is covered by different materials such as plastic transparent glass, plastic box, cardboard, thick white foam. The measurement results are processed and analyzed to gather information such as the positioning of the object in case of range imaging and 2D image of the object in case of SAR imaging about the object behind these materials.

The remaining paper is organized as follows, section II explains the measurement setup and imaging geometry. Section III presents the THz range imaging results. In section IV, firstly SAR signal processing is explained to gather 2D image of the object and then the 2D images of the concealed object are presented. Lastly, the conclusion is provided along with the future aspects.

II. IMAGING GEOMETRY AND MEASUREMENT SETUP

The block diagram of the measurement setup is shown in Fig. 2. It consists of a VNA which operates across frequency range up to 67 GHz, and a frequency extender which operates as transceiver and up-converts the generated RF signal from the VNA into the aimed frequency range between 220-330 GHz. A horn antenna with aperture size 6×8 mm is fixed on

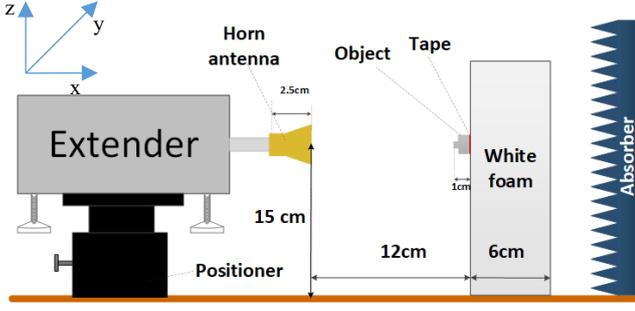Fig. 1 Optical picture of imaging object/target

Fig. 2 Block diagram of the testbed

the extender's waveguide flange, with an average gain of 25 dBi over the aimed frequency range, further parameters relating to the testbed are given in Table I. The Fig. 2 displays the imaging geometry including the imaging scene, which is composed of white foam at distance of 12 cm from the horn antenna opening, and an absorber behind the white foam. The imaging target/object and the concealing materials are fixed on the white foam, where the center point of the object is aligned with the center point of the horn at 15 cm height off the table. The SAR sensor is composed of the VNA, the extender and the implemented horn antenna, which are mounted on a y-axis positioner with a maximum 2.2 cm positioning range and a sub-µm accuracy. Furthermore, the reference slant range to the scene center from antenna opening of 12 cm is decided because of the maximum aperture length of 2.2 cm with the positioner and the beamwidth [3]. For measurements, the channel's reflection coefficient S11 is recorded for each scanning position. The maximum detectable one-way distance for each measurement sweep is 0.545 m, corresponding to the maximum two-way path distance of 1.09 m, which is determined based on the channel bandwidth (110 GHz) and the number of frequency points (401 p). One-port short calibration is implemented at the sensor to cancel the cable losses prior to the scanning process.

Table I. THz Range and SAR imaging parameters

Parameter	Value
THz Range Imaging Parameters	
Antenna Opening Horizontal Length	8 mm
Antenna Opening Vertical Length	6 mm
Antenna Length	2.5 cm
Expected Distance from Antenna Phase Centre to Antenna Opening	2 – 2.5 cm
Expected Distance from Antenna Phase Centre to Referenced White Foam	14 – 14.5 cm
Distance from Antenna Opening to Referenced White Foam, x_r	12 cm
Frequency Span	220 GHz – 330 GHz
B_w	110 GHz
r_x	1.364 mm
No. of Frequency Bins	401
Extended Parameters for THz SAR Imaging	
L_{syn}	2.2 cm
Integration Angle, $\theta(L_{syn}, x_r)$	10.34°
Azimuth Resolution, $r_y(L_{syn}, x_r)$	3.025 mm
Δu	1 mm
No. of Azimuth Sampling Points	22

III. THz Range Imaging

For range imaging, 1-port reflection coefficients are measured with VNA. This data can be captured in either frequency domain and then transformed into time domain (TD) or directly in TD from VNA. The TD response corresponding to the range distance without the target is shown in Fig. 3 (a). This response shows that the first peak from the white foam begins at 14.17 cm and the signal propagates further inside the foam. The backscattered signal is also observed from the end of the white foam at 20.16 cm and this also validates the thickness of the foam of around 6 cm. Other peaks are also observed between these two peaks and they arise because of the propagation of signal inside the white from and the multiple reflections during the return path. These results defined the time/distance gating for the target pasted on the white foam. Therefore, only the peaks before the beginning of the white foam (@ 14.17 cm) have to be observed for the target range imaging.

Range resolution is defined as the minimum resolvable distance between two scatterers and it is given by

$$r_x = \frac{c}{2B_w} \qquad (1)$$

Where c is the propagation speed. From the table I, the range resolution is 1.36 mm. Therefore, based on the dimensions of the target along the range it is expected to observe the peaks from the beginning of the nut, first metal plate behind the nut, nut ending (or spacing between two metal plates) and the last metal plate. The time domain response with the target for the setup shown in Fig. 2 is presented in Fig. 3 (b) and the expected four peaks are observed. The first peak from the target is at 13.08 cm which is expected to be from the nut then the second peak is at 13.22 cm and this is expected to be from the beginning of the first metal plate. The third peak is at 13.49 cm and the fourth peak is at 13.9 cm which is expected to be from the last metal plate or ending on the target.
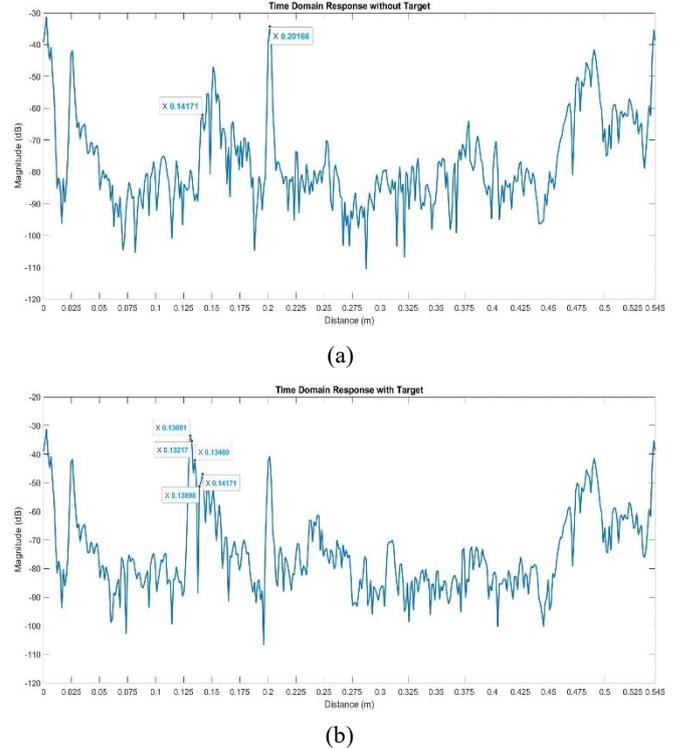

(a)

(b)

Fig. 3 (a), (b) Time domain response without and with target

For concealed object range imaging, the first material for covering the target is a plastic transparent glass with dimensions of 1.05 cm × 6.45 cm × 13.43 cm (l×b×h) as shown in Fig. 4 (a). The range imaging result is presented in Fig. 4 (d). The material has a length of 1.05 cm and therefore it is expected to localize this material 1 or 2 mm ahead of the 13.08 cm peak (beginning of the target) and the same is achieved in the imaging result. The second and third peaks are also visible at 13.35 cm and 13.62 cm but with a slight shift in range distance. The shift might be arisen because of the change in the propagation medium.

The second material that is used to cover the target is a plastic box as shown in Fig. 4 (b). The material dimensions are 2.5 cm × 6.1 cm × 13 cm. and the result of this setup is shown in Fig. 4 (e). The first peak from the material is observed around 1.6 cm ahead of the target at 11.45 cm and this validates the range imaging as per the box length. Furthermore, the other target peaks are also visible which defines the target localization or positioning but with a little shift in the accuracy. Lastly, the third material is a cardboard open from top and bottom. The target is pasted inside this material with dimensions of 3 cm × 6.5 cm × 13.5 cm and a cardboard sheet of 0.55 cm. The setup is shown in Fig. 4 (c). The results are presented in Fig. 4 (f). In this case, the object in the range imaging must be positioned around 2 cm after the first peak from the material. The results represent the material positioning at 10.9 cm and target first peak at 12.94 cm and other peaks from the target at 13.35 cm and 13.76 cm which goes well as per the dimensions of the object. Moreover, the side lobes can be suppressed with range compression or match filtering technique.

IV. THz Synthetic Aperture Radar Imaging

A. SAR Imaging Signal Processing

The SAR signal processing includes the collection of raw data and processing this raw data with an image reconstruction algorithm. In this paper, the SAR movement is stop-and-go approximations. The sensors positioned at u_0 radiates towards the target and the backscattered signal is recorded at this position. Further, the sensors are moved along the y-axis with a step size of 1 mm and data is recorded at each aperture position. This data matrix is known as raw data. All the relevant parameters are listed in Table I and the detailed theoretical explanation is provided in [6]. With an aperture length of 2.2 cm, the raw data matrix is of 22×801 form. The data is captured in the frequency domain. Firstly, this data is zero padded by the factor of 8 and afterward transformed into the time domain to be processed with *Backprojection (BP) Algorithm* [1], [6]. It is a time domain algorithm however the raw data can also be processed with the frequency domain algorithms such as Range Migration or Range Doppler. With BP image reconstruction algorithm, the range distance and associated time delays for the image pixels locations are calculated. Based on these indexed pixel locations, the pixel value is taken from the zero padded time domain data and the values are superpositioned for each azimuth position.

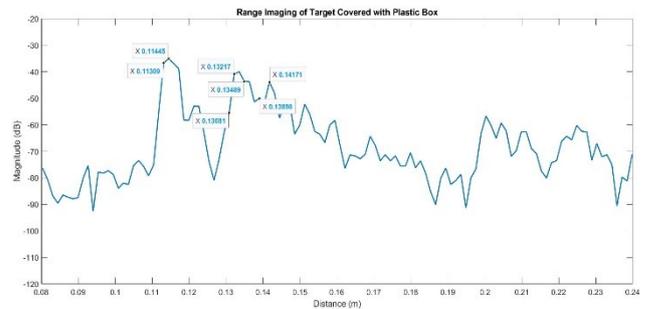### B. SAR Imaging Results

2D SAR image of the target without any cover or blocking as shown in Fig. 2 is presented in Fig. 5. This result is
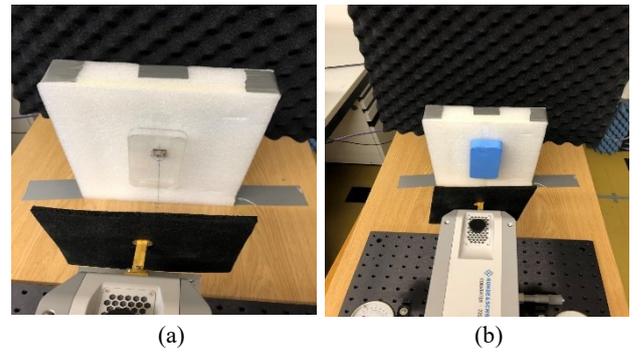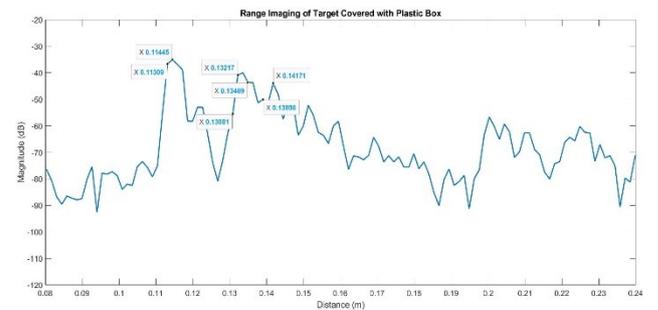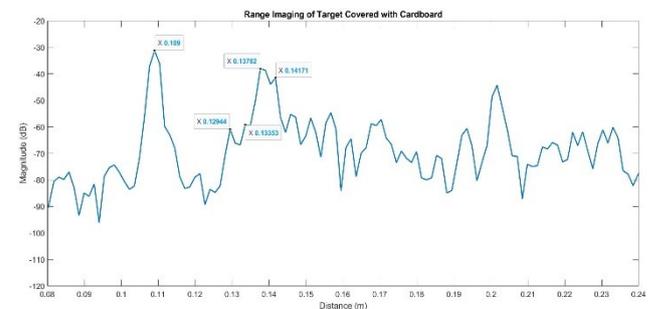

(a)   (b)
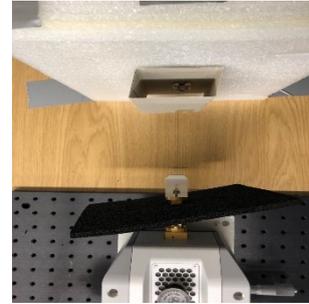
(c)

(d)

(e)

(f)

Fig. 4 (a), (b), (c) Optical picture of object covered with plastic glass, box and cardboard, (d), (e), (f) Range imaging results of objects covered with plastic glass, box and cardboard
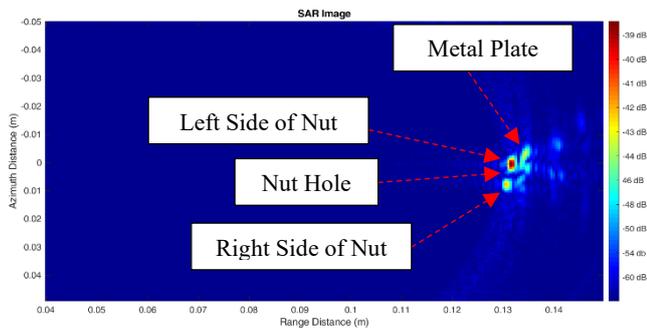
Fig. 5 SAR image of nut

published in [6] and shown here only for the reference. It can be seen that the nut and hole of the nut are clearly visible and even though the metal plate behind the nut is also observed. This is the sub-mm high resolution image. The THz SAR imaging of a concealed object is performed with two materials covering the target. The first one is the same plastic box and setup as shown in Fig.4 (b). The processed SAR image of this setup is presented in Fig. 6. The result shows that the target is visible and the shape of the target can also be identified. However, it is being found that the position of the target has been shifted with respect to the results in Fig. 5 and this could be because of the change of propagation medium.

Furthermore, the second experiment is performed with the target inside the cardboard box as shown in Fig.7 (a). The target is pasted on the inside back sheet of the cardboard. Also, inside the box a solid thick white foam that is shown in Fig. 7 (b) is placed in front of the target that makes imaging much more complex. The result of this setup is presented in Fig. 7 (c). It can be seen the shape-oriented image of the target is not any more achievable. In the SAR image, only the cardboard front sheet is visible. It is expected that the solid thick white foam act as an absorber and not much information about the foam is available in the image.

V. CONCLUSION

The paper analyzed the radar and SAR imaging of the concealed or covered target with the plastic materials and carboards. The THz radar imaging results validate the range resolution of 1.4 mm. Moreover, the results prove the detection of the target in three different concealed scenarios. In the case of plastic glass, all the four peaks of the target are observed but with the other materials target is still visible but not all the peaks are very well defined and at correct positions because of multi-path environment and change of propagation medium. Furthermore, the SAR imaging results
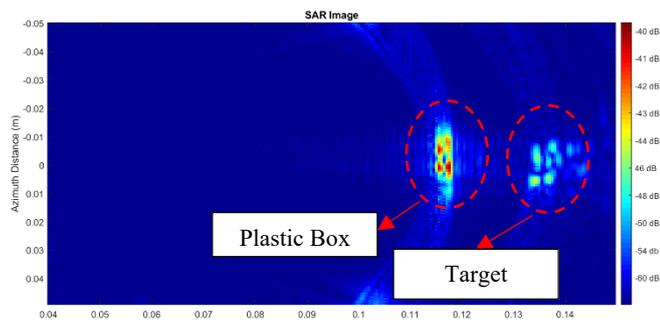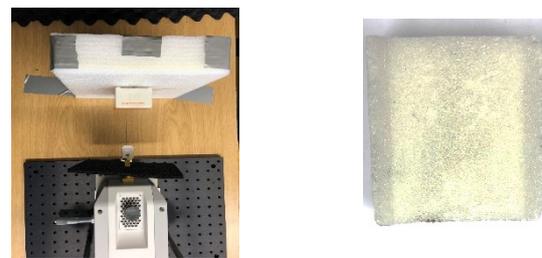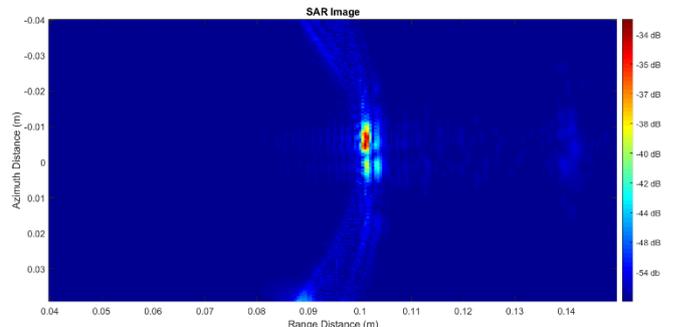

Fig. 6 SAR image of nut covered with plastic box

(a)   (b)

(c)

Fig. 7 (a) Picture of nut covered inside carboard, (b) thick white foam that is in front of the nut inside cardboard, (c) SAR image

with plastic box represent the achievement of shape-oriented sub-mm spatial resolution image of the target whereas in the second case, the object is not visible in the image anymore, Still, artifacts behind the image of the front sheet of the cardboard box represent that there will definitely be some backscattered signals received from the foam and the target but the signal strength is too less or in the range of the noise floor of the VNA. Therefore, the detection and imaging of the target are difficult in this scenario at THz with the noise floor of around -105 dB. In the future publication, the results will be analyzed for imaging of the objects at sub-m distances.

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