

A Sensing Demonstration of a SubTHz Radio Link Incorporating a Lens Antenna

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Abstract—We demonstrate that the future sixth generation (6G) radio links can be utilized for sub-THz frequency imaging using narrow beamwidth, high gain, lens antennas. Two different lenses, a bullet or hemispherical shape, were used in radio link setup (220–380 GHz) for an imaging application. Lenses performed with the gain of 28 dBi, 25 dBi, and the narrow beamwidths of 1° and 2.5°. Plants were used as imaging objects, and their impacts on radio beams were studied. For assessment, the radio link path loss parameter was −48.5 dB, −53.2 dB, and −57.1 dB with the frequency 220 GHz, 300 GHz, and 330 GHz, respectively. Also, the impact of the radio link distance on the imaging was studied by 50 cm and 2 m link distances. In addition, the 3D image was acquired using the phase component of the image, and it showed the leaf surface roughness and the thickness, which was similar to the measured value.

1. INTRODUCTION

Low THz frequencies have been proposed for the upcoming sixth generation (6G) wireless communication system to enable higher data rates by using the wide available signal bandwidth [1]. To meet the extreme requirements for high-speed communications, the current systems require significant development to enhance the transceiver performance in terms of gain, power, cost, and energy efficiency.

In addition to the 6G communication aspects, using the THz region enables a wide range of secondary applications such as imaging, security screening, and spectroscopy. For sustainable products and services, it is desirable that the same hardware resources can be utilized for various applications and services. This aspect should also be considered to design hardware components, such as antennas.

From a low THz receiver viewpoint, for long-distance communication, the use of high gain antennas is essential to compensate for the radio link path loss and to enable acceptable radio link distances. To overcome the challenges, antenna arrays and lens antennas are mostly used to increase the antenna gain and reduce the antenna beamwidth.

The use of lens antennas has demonstrated low loss, narrow beamwidth properties, and particularly high gain [2]. Using lenses for communication systems can also open new possibilities for the imaging applications and joint-communication sensing [3–6]. Previously, the potential of a 6G radio link has been investigated as a technology enabler for, e.g., accurate localization and high-resolution imaging [7–11].

Imaging at THz frequencies has been demonstrated before using a THz time-domain spectroscopy system [12] and 140–220 GHz system which used two horn antennas and four lenses to acquire the image [13]. There is a need to develop and test the imaging potential of the future 6G systems.

This work demonstrates the substantial potential of the 6G radio system at 220–380 GHz, which consists of a single lens antenna and horn antenna, to implement 2D and 3D imaging. The rest of

Received 9 July 2021, Accepted 29 July 2021, Scheduled 11 August 2021

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the paper is organized as follows. In Section 2, used lenses are presented and discussed. Section 3 describes the radio link setup configuration by connecting a Keysight PNA-X (67 GHz) to a VDI extender (220 GHz to 380 GHz). In Section 4, results of imaging are presented and discussed. In Section 5, we offer our conclusions.

2. LENSES FOR THE IMAGING RADIO LINK SETUP

An elliptical and extended hemispherical lens was chosen for the lens geometries as both of the lens geometries have previously been identified to result in high gains and narrow beamwidth characteristics [14–16]. Two low loss, low permittivity materials were chosen for the fabrication of the lenses. An LMO-HGMS ceramic composite that can be fabricated at room temperature and molded into a lens by a molding process (the recipe for the LMO-HGMS have been previously published [17]) and polypropylene polymer (ER182) that was hot-pressed into a lens shape [18]. The dielectrical properties of the used materials are listed in Table 1.

Table 1. Lens parameters and their performance with WR3.4 at 300 GHz.

Type	Material	Diameter (mm)	Height (mm)	ε_r	$\tan\delta$	BW (GHz)	HPBW (deg)	Waist (mm)	Gain (dBi)
Extended	polypropylene polymer	30	49.5	2.47	0.008	220 to 300	3°	3.7	25
Bullet	LMO-HGMS	30	38	1.18	0.003	220 to 300	1°	1.3	28

Lenses performance with the WR3.4 waveguide was simulated using a CST microwave studio. The aim of the simulation was to determine the optimal shapes for the lenses in order to achieve the highest possible gain when the lens is fed by the waveguide as a mimic of a realistic scenario. The figure of the fabricated lenses, gains at 300 GHz, and broadband gain (220–380 GHz) are shown in Figure 1. Both fabricated lenses had a diameter of 30 mm, the bullet lens had a length of 49.5 mm and the extended lens had a length of 38 mm, of which the extension part was 23 mm. Both lenses with the waveguide had better than -10.5 dB S_{11} over the broadband. Maximum gains were 28 dB and 25 dB for the bullet and the extended hemispherical lens having 1° and 3° beam width at 300 GHz, respectively. The size of the beam waist (σ) can be calculated as [19],

$$\sigma = \frac{2\lambda_0}{\pi \sin\left(\frac{D}{2f_1}\right)} \quad (1)$$

where λ_0 is the wavelength; f_1 is the focal length; and D is the lens diameter. Bullet lens had the narrowest beam waist of 1.3 mm, and extended hemispherical lens had 3.7 mm. The lens parameters are listed in Table 1.

3. RADIO LINK SETUP FOR IMAGING

To mimic a realistic continuous wave (CW) radio link, a Keysight PNA-X (operation frequency 67 GHz) was connected to a pair of Virginia Diode Inc (VDI) extender (220 GHz to 380 GHz) Transmitter (Tx) and receiver (Rx) via a pair of cables. The Tx and Rx were placed face to face with each other by specific distances (50 cm and 2 m) and height level (1.5 m from the floor). The input power of 0 dBm was adjusted to feed from the PNA-X to the Tx that attached to a standard rectangular waveguide WR3.4 with a lens in front of it. The Rx extender was connected to the WR3.4 with a 30 dBi gain horn antenna. The setup is shown in Figure 2. First, the PNA-X was calibrated to the waveguide ends, then, the distance between (as a focal point) the bullet lens and Tx was adjusted to attain the maximum antenna gain in the Rx.

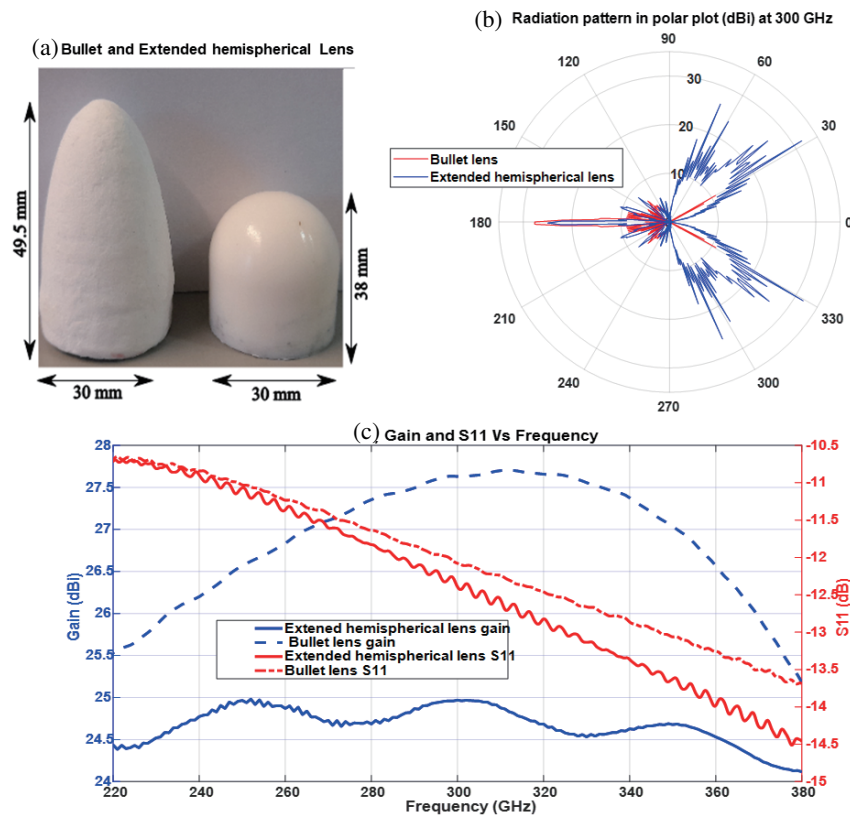


Figure 1. Simulated result of two high gain, narrow beam width lenses were fabricated for the SubTHz imaging experiment. The bullet lens was made of LMO-HGMS ceramic composite and the extended hemispherical of polypropylene polymer.

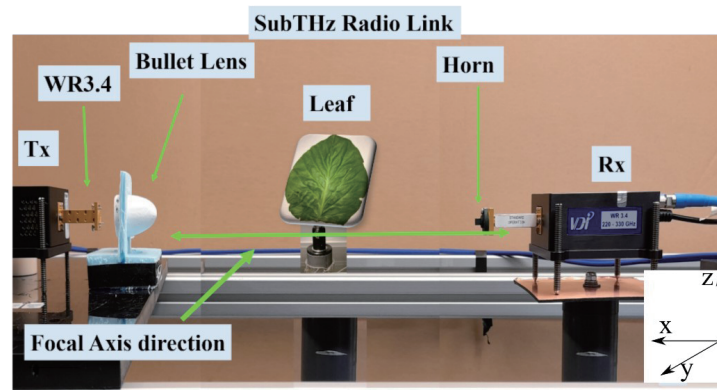


Figure 2. Photograph of sub-THz radio link Set Up for 220–380 GHz sub-THz frequency including Tx and Rx units, waveguides, horn antenna and fabricated bullet lens.

4. RESULT AND DISCUSSION OF IMAGING

This section describes and discusses image acquisition for Tx-Rx link distances (50 cm and 2 m). Short-range imaging also focused on how the roughness of the imaged object can be determined through the measured phase. For the imaging objects, the leaves from two different plants were used (Bergenia and Ficus Elastica).

4.1. Short Range Imaging

The *Bergenia* leaf (Figure 3(a)) was used as the image object having a substantial thickness of 100 μm in general and 2 mm wide water veins. Then the previous measurement setup was used to acquire the radio image by measuring the path loss (S_{21}) at three frequencies (220, 300, and 330 GHz) when the leaf was placed in the middle of the beam path. The leaf was mounted on a plate, which was mounted on a three-dimensional (3D) positioner that could move in the X -, Y -, and Z -dimensions using stepping motors. To acquire the image of the object, the plate movement area of 100 mm $\times$ 100 mm in Z -, Y -directions having a step of 5 mm was used. The imaging was performed separately for each frequency (220, 300, and 330 GHz), and acquired images are shown in Figures 3(b)–3(d).

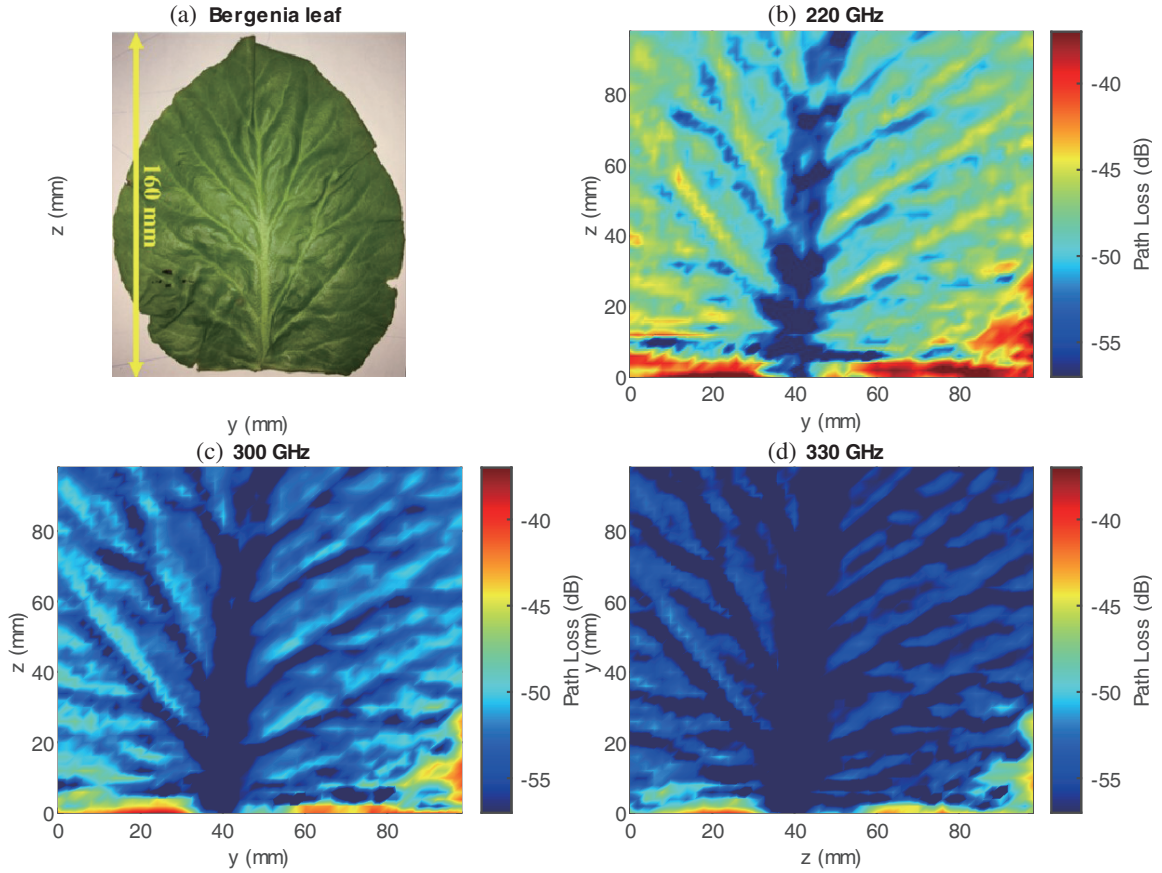


Figure 3. *Bergenia* leaf and measured path loss images through the leaf. Due the different structures in the leaf the measured path loss is different which leads to a radio image of the leaf.

As the leaf is not uniform in thickness and water composition, the different parts of the leaf could be distinguished from the path loss images where the water veins were shown as most lossy. It was observed that at 220 GHz most of the signal passed easily through the leaf, and by increasing the frequency path loss increased as expected even though the gain of antenna increased. The measured loss increased from -50 dB (220 GHz) to -60 dB (330 GHz). In addition, average path loss through the leaf was assessed, and it was found to increase from -48.5 dB (220 GHz) to -57.1 dB (330 GHz) which is illustrated in Figure 4. Also, it was noted that when the frequency was increased from 220 GHz to 300 GHz lateral resolution increased from 2 to 1 mm.

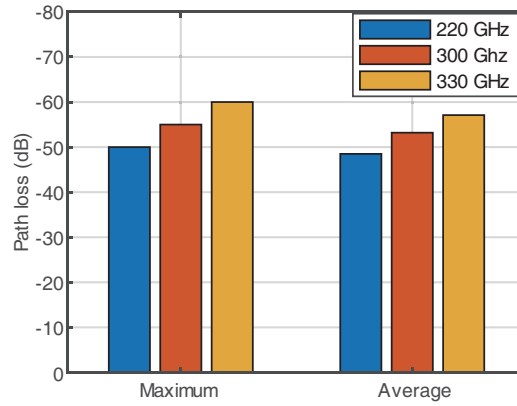


Figure 4. Measured Path loss vs maximum and average for different frequencies.

4.1.1. Constructing 3D Image

To construct the 3D image I_{3D} , the phase component of image $\phi_{(x,y)}$ is essential based on the equation [20, 21]

$$3D = \frac{\lambda}{2\pi(n_{sample} - n_{air})} \phi_{(x,y)} \quad (2)$$

where n_{sample} and n_{air} are the refractive indices of air and sample and are assumed to be (1.5 and 1) [22], and λ is the wavelength. The phase component, $\phi_{(x,y)}$, from the previously acquired image, Figure 3(c), was used, and the figure of the phase change from the leaf is shown in Figure 5. As expected, the water veins had the biggest impact on the phase, which rotated the phase a full 180 degrees.

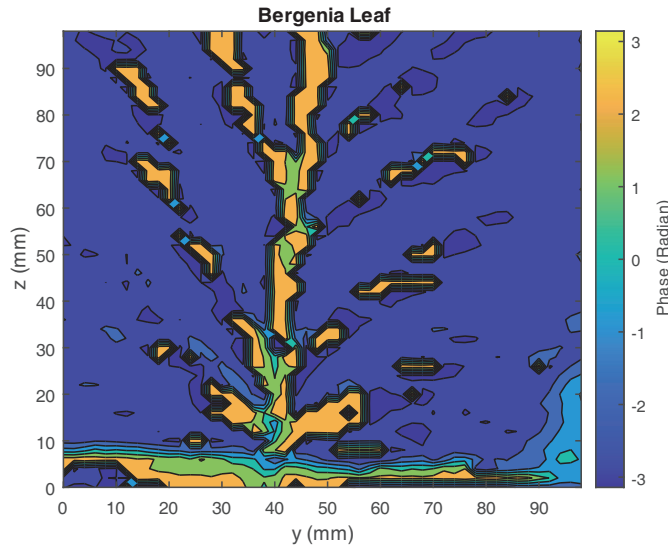


Figure 5. Measured phase change in Bergenia leaf at 300 GHz. Water veins shift the phase full 180 degrees.

The phase image was plugged into Eqn. (2) and resulted in 3D and contour images which are shown in Figures 6(a) and 6(b). As from the 3D image, the leaf roughness is clearly visible. The average roughness of the leaf was determined (0.11 mm) from the 3D image which was close to the measured value by a micrometer.

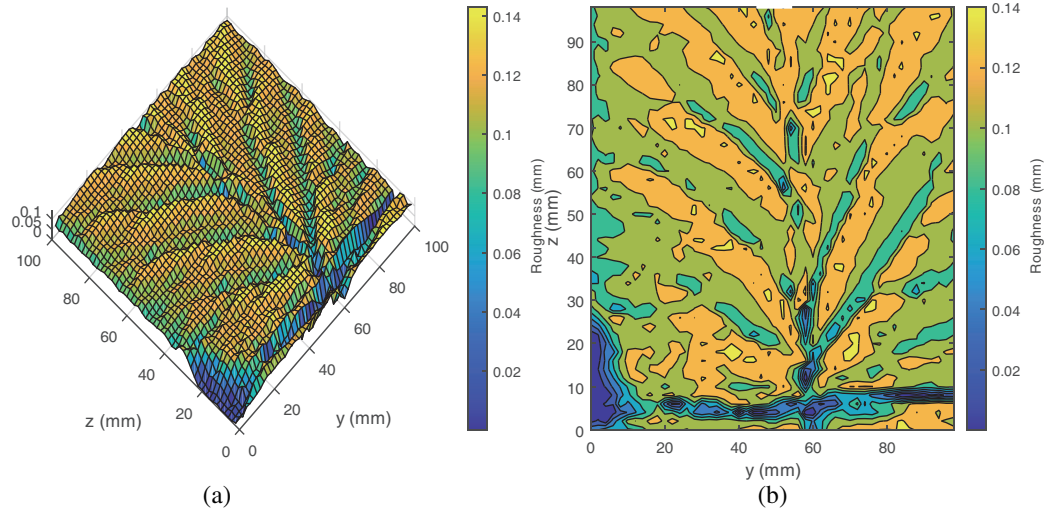


Figure 6. Roughness of the Bergenia leaf at 300 GHz, (a) 3D image, (b) contour plot.

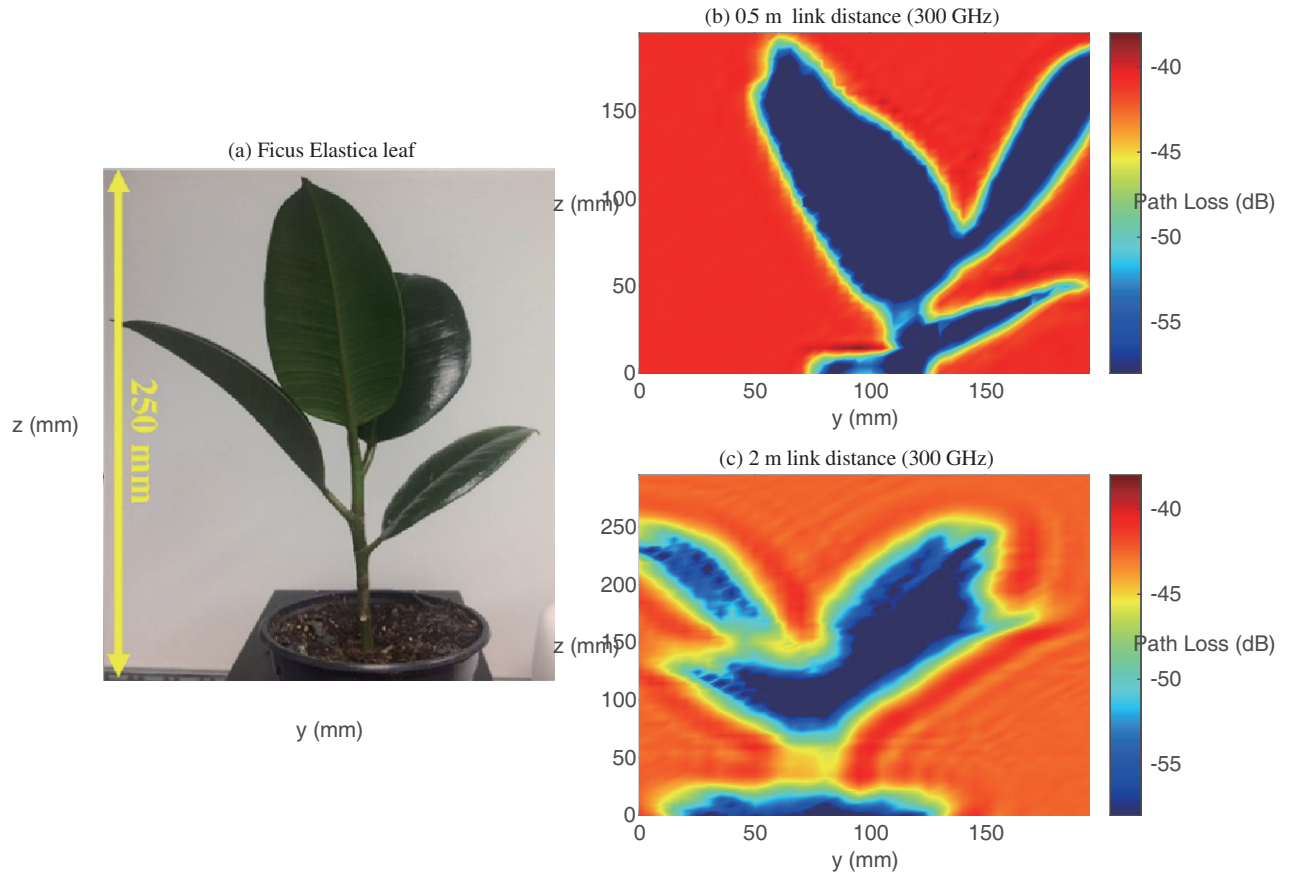


Figure 7. (a) Ficus Elastica leaf and radio images of it at distances, (b) 0.5 m and (c) 2 m link distances at 300 GHz. 2 m measurement show a shadow around the leaf which comes from the scattered THz waves from the environment (also, plant has been rotated between the 0.5 m and 2 m measurements).

4.2. Long-Range Imaging

In the second experiment, the same measurement setup was used, but instead of the bullet, an extended hemispherical lens was applied to acquire the image of the Ficus Elastica leaf (Figure 7(a)) at 300 GHz. The link distance was either 0.5 or 2 m, and the object was in the middle of the radio link. The Ficus Elastica leaf was on a plate with the same positioner, movement area (100 mm $\times$ 100 mm), and the step of 5 mm, as in previous short-range imaging. The 2D radio images are shown in Figures 7(b) and 7(c). The image at 2 m distance showed a shadow area that included scattered THz waves from the environment. (Also, the plant has been rotated between the 0.5 m and 2 m measurements).

5. CONCLUSION

This work demonstrated the substantial potential of the 6G radio system for 2D and 3D imaging. A fabricated bullet lens achieved the gain (28 dBi) with a narrow beamwidth (1°). 2D images were taken for different frequencies (220, 300, and 330 GHz), and the impact of the frequency on the image was analyzed. The maximum measured path losses were -50 dB, -55 dB, and -60 dB at 220, 300, and 330 GHz, respectively. It was noted that when the frequency was increased from 220 to 300 GHz, the lateral resolution at 50 cm distance was improved from 2 to 1 mm. Based on the 3D image taken, a roughness of 0.11 mm was calculated for the leaf, which was close to the measured value by a micrometer. These 2D and 3D images confirmed the SubTHz radio link imaging capability with the help of higher gain and narrow beamwidth, thanks to the lens antenna. In addition, it should be noted that parameters such as operation frequency, beamwidth, antenna gain, and image resolution (the size of the step when the plant was moved) impact on the accuracy of the acquired images and their derivatives such as determining the surface roughness of the object through the 3D image.

ACKNOWLEDGMENT

This study was supported partly by Microelectronic Research Unit, Faculty of Information Technology and Electrical Engineering, University of Oulu, Finland and partly by Academy of Finland 6genesis Flagship (grant No. 318927).

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