A Near-field Millimeter-wave Dielectric Imaging Technique with Sub-wavelength Spatial Resolution

Aydin Babakhani [1], Duixian Liu, Mihai Sanduleanu, and Scott Reynolds
IBM T. J. Watson Research Center, Yorktown Heights, NY, USA

***Abstract*— A near-field millimeter-wave imaging technique is introduced which is capable of producing images with sub-wavelength resolution. A phantom made of a Teflon board containing samples of different materials with dielectric constants ranging from 1 to 48 was built, and a near-field loop antenna and a 110GHz vector network analyzer were used to capture near-field images of the Teflon board. A novel image processing method is described that is capable of achieving an image resolution of 0.5mm at 110GHz.**

I. INTRODUCTION

Far-field millimeter-wave imaging has been widely used in various applications such as security screening [1], collision avoidance radars [2], and safe landing in poor-visibility conditions [3]. These systems are usually very expensive and bulky. For example, in [3], a passive millimeter-wave video camera comprising 1024 receiver modules operating at 89GHz was reported. In this system, an 18-inch diameter plastic lens is used to collect and focus the radiation yielding a diffraction-limited 0.5° angular resolution. Although far-field imagers are able to generate images of an object located at a far distance from the antenna, due to their complexity and high cost, they have not been used in high-volume applications such as medical imaging. In addition to the high cost of these far-field imagers, the spatial resolution achieved by them does not meet the requirements of medical imaging (1mm or better). For example, the 18-inch 89GHz camera reported in [3] has an angular resolution of 0.5º which is equivalent to 8.7mm special resolution for an antenna-object distance of 1m. The limited resolution of these far-field imaging systems is due to the diffraction limit of the antenna. Fortunately, the resolution of a near-field imaging system is not set by the diffraction limit of the antenna. For an object located in the near-field of an antenna, the resolution is determined by the antenna (probe) size and it can be several orders of magnitude better than that of the far-field imager. Section II introduces a loop-based near-field probe that is capable of producing images with sub-wavelength resolution.

II. SIMULATION RESULTS

In order to demonstrate a near-field imaging system with resolution smaller than a wavelength, several simulations were performed and the results were verified by experiment. In one simulation a cylindrical dielectric object with a diameter of 2mm was inserted in a Teflon board (ε_r=2.1), as shown in Fig.1. The top surfaces of the cylindrical object and the Teflon board were located at a same Z-coordinate. A loop probe (antenna) with a diameter of 2mm was used to image the surface of the Teflon board at a distance of 100μm. To construct an image, the loop antenna was moved along the X and Y directions. At each position of the loop antenna, its reflection coefficient, S_{11}, was simulated. Fig. 2 and 3 show the amplitude and phase of S_{11} in different (x,y) positions, respectively. As can be seen in Fig. 2 and 3, a standing-wave-like pattern appears when the dielectric constant of the cylindrical object differs from that of the Teflon board. The dark red color in Fig. 2 corresponds to large amplitude of S_{11}, while dark blue corresponds to small amplitude of S_{11}. As the difference between the dielectric constants of the Teflon board and the cylindrical object increases, the variation of the amplitude of S_{11} increases in a monotonic fashion. In section III, this property of the near-field loop probe is used to estimate the dielectric constant of the surface.

III. MEASUREMENT RESULTS

In an experiment, several holes with different diameters and depths were drilled in a Teflon board, as shown in Fig. 4. The holes on the Teflon board were filled with different dielectric materials (Fig. 4).

In order to generate an image, a hand-made loop antenna and a 110GHz vector network analyzer were used. The loop antenna was connected to the 110GHz vector network analyzer using a 1mm coaxial cable. The vector network analyzer was used to measure the un-calibrated reflection coefficient S_{11}, between 65GHz and 110GHz, with linear steps of 250MHz. In this measurement, the distance between the loop antenna and the Teflon board was set to be around 80μm. Fig. 5 shows the amplitude of raw S_{11} in different (x,y) locations. In this figure, as the amplitude of S_{11} increases its color changes from blue to red. Similar to the simulation results discussed in the previous section, the difference in the dielectric constants of the hole (object) and the Teflon board (background material) generates a standing-wave-like pattern such that the amplitude of the wave depends on the dielectric constant of the material used in the hole. As the dielectric constant of the material in the hole increases, the amplitude of the wave increases, i.e. red becomes a darker red and blue becomes a darker blue. This unique characteristic of the near-field images can be used to estimate the dielectric constant of the material. In order to generate dielectric constant images, variance of amplitude or phase of S_{11} is computed.

Fig. 6 shows the processed image that was generated using the variance function. In Fig. 6, a block of 16×16 pixels was used to calculate the variance at each point. The holes on the Teflon board were filled with materials having dielectric constants of 1, 3, 6, 8, 30, and 48. Based on the plots in Fig. 6, as the dielectric constant of the surface increases, the image

[1] Aydin Babakhani was with IBM T. J. Watson Research Center, now with Rice University ECE Dept., Houston, TX, USA

color gets closer to dark-red. In Fig. 6, the blue color corresponds to the dielectric constant of the Teflon.

To illustrate the resolution of these images, a zoomed-in picture is shown in Fig. 7. Based on this figure, a resolution of better than 0.5mm is achieved at 110GHz (λ=2.7mm).

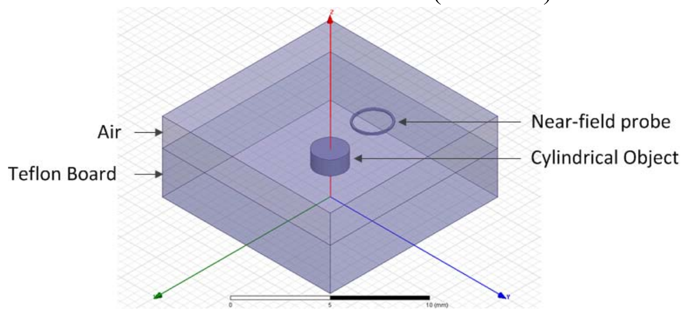

Fig. (1) A near-field loop probe and a cylindrical object

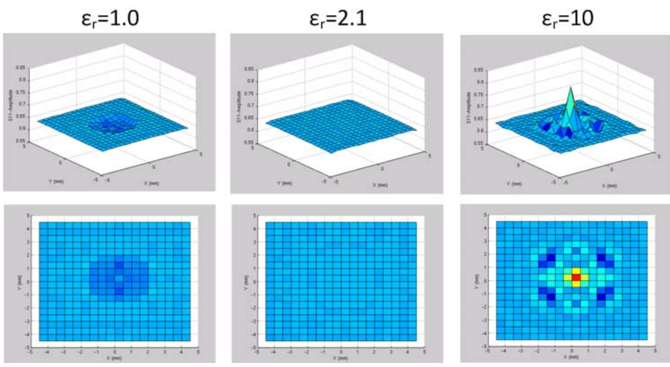

Fig. (2) Amplitude of S_{11} in a linear scale.

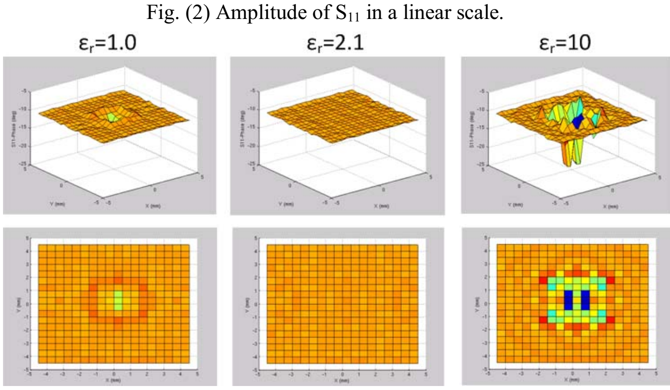

Fig. (3) Phase of S_{11} in a linear scale

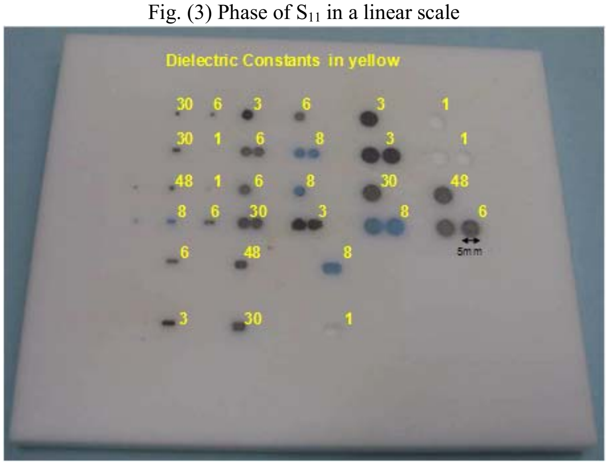

Fig. (4) A photograph of the Teflon phantom

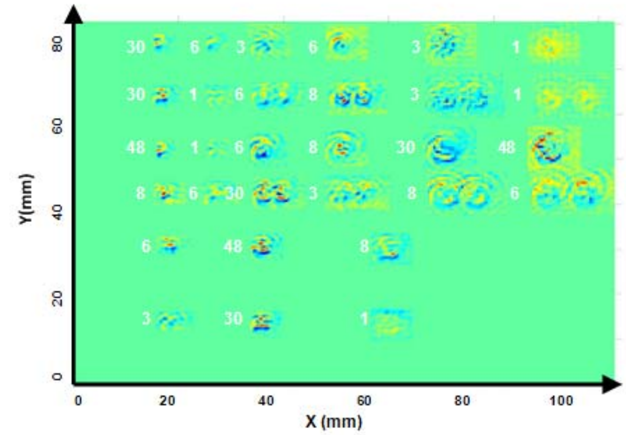

Fig. (5) Amplitude of raw S_{11} at 110GHz

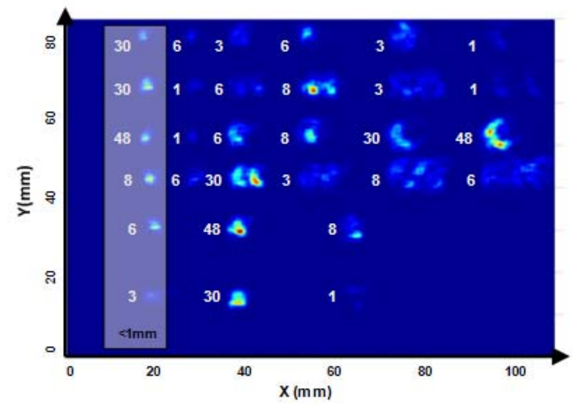

Fig. (6) Processed S_{11} amplitude at 110GHz

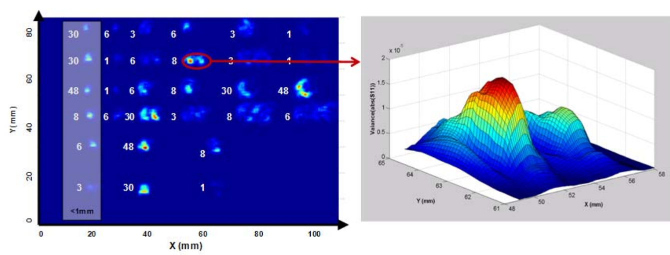

Fig. (7) A zoomed image of two adjacent holes (ε_r=8)

IV. CONCLUSIONS

A novel near-field technique for generating sub-wavelength-resolution images in the millimeter-wave frequency region is introduced. This technique is capable of generating images with resolution of 0.5mm at 110GHz. This opens a great opportunity for implementing a new generation of low-cost medical imaging systems that operate in the millimeter-wave region.

REFERENCES

[1] S. F. Hallowell, "Screening people for illicit substances: A survey of current portal technology", Talanta, vol. 54, p.447 , 2001.

[2] A. Babakhani, *et. al.*, "A 77-GHz Phased-array transceiver with on-chip antennas in silicon: Receiver and antennas," IEEE J. Solid-State Circuits, vol. 41, no. 12, pp. 2795–2806, Dec. 2006.

[3] L. Yujiri, *et. al.* "Passive millimeter-wave imaging", IEEE Microwave Magazine, pp.39 - 50 , 2003.