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Keil, Andreas; Peuser, Jörn; Loeffler, Torsten; Krozer, Viktor; Dall, Jørgen; Kusk, Anders; Zhurbenko, Vitaliy; Jensen, Thomas; de Maagt, Peter

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300 GHZ IMAGING SYSTEM WITH 8 METER STAND-OFF DISTANCE AND ONE-DIMENSIONAL SYNTHETIC IMAGE RECONSTRUCTION FOR REMOTE DETECTION OF MATERIAL DEFECTS

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Andreas Keil (1), Jörn Peuser (1), Torsten Loeffler (1), Viktor Krozer (2), Jørgen Dall (3), Anders Kusk (3), Vitaliy Zhurbenko (4), Thomas Jensen (4), Peter de Maagt (5)

(1) SynView GmbH, Hessenring 83, 61348 Bad Homburg, Germany, info@synview.com
(2) Goethe University, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany
(3)Technical University of Denmark, National Space Institute, 2800 Kgs. Lyngby, Denmark
(4)Technical University of Denmark, Dep. of Electrical Engineering, 2800 Kgs. Lyngby, Denmark
(5)ESA/ESTEC 2200 AG Noordwijk, the Netherlands

ABSTRACT

An active stand-off imaging system operating at 230–320 GHz is presented. Imaging is achieved by combining a line array consisting of 8 sources and 16 detectors with a scanning cylindrical mirror system. The stand-off distance is 8 meters and the effective aperture of the system is 0.5 meters by 0.5 meters. Range and intensity information of the object are obtained using an active FMCW (frequency modulated continuous wave) radar principle. Data acquisition time for one line is as short as 1 ms. Synthetic image reconstruction is achieved in real-time by an embedded GPU (Graphical Processing Unit). The data indicates a spatial resolution of about 2 cm and the range resolution of about 2 mm. To analyze the performance of the system, high-precision measurements employing a vector network analyzer are presented. An outlook on further developments is given.

1. INTRODUCTION

Millimeter wave imaging is a novel technique with applications in non-destructive testing (NDT) and security areas. Millimeter waves penetrate most non-conducting materials and are reflected by conducting surfaces; interfaces of different refractive index reflect the beam partially. Since millimeter waves are non-ionizing they allow for a safe and comparatively low cost technology solution to modern security challenges. A review of Terahertz imaging techniques can be found in [1]. Real time high resolution millimeter wave imaging is of great interest and different methods currently under investigation can be found e.g. [2-5]

For non-destructive testing (NDT), millimeter waves offer a wide range of applications. Non-conducting dielectric materials are generally almost transparent for millimeter waves, allowing imaging occluded surfaces. NDT of dielectric materials includes most foams and polymers. Non-destructive testing for foams is generally difficult with ultrasound and X-ray imaging due to the scattering of ultrasonic waves in the material and due to total transparency using X-rays.

Therefore, for security as well as NDT applications, millimeter waves offer a distinct advantage due to the possibility of stand-off measurements and identification of surfaces and interfaces.

In the following section we will outline the system, giving a detailed description of the electrical and optical design. In section 3 we will show experimental results for 2D and 3D measurements. 3D measurements are done on a sample for security applications. We conclude this paper with an outlook and discussion of the results in section 4.

2. SYSTEM OUTLINE

The camera outlined in this paper uses 8 transmitters and 16 receivers using frequency modulated continuous waves (FMCW) as underlying technology. The sources emit millimeter waves in the range 230-325 GHz, which are detected through mixing with a reference signal by the receivers. The FMCW technology allows for detailed information of the range data, which can be processed using synthetic aperture radar (SAR) techniques

A CAD picture of the camera is shown in Fig. 1 and the beam path of the measurement setup is shown in Fig. 2.

The optical design of the camera consists of a cylindrical optics which focuses in about 8 m distance on a horizontal slice. The height of this slice is adjusted by a planar triangular shaped rotating mirror. With a rotation of this mirror the target is vertically scanned, and a full 3D data set is created. For each slice a SAR reconstruction is performed.

The system is currently working in a different experimental mode. The original mode as described and outlined in [6] using a voltage controlled oscillator

(VCO), delay line and a distribution network. For the current mode under investigation the VCO and delay line are replaced by a vector network analyzer (VNA). Both modes will be described in detail. With both modes single horizontal line-static mirror measurements were performed. Currently full 3D datasets were only acquired with the latter design. Results are shown in the next section.

The original mode is sketched in Fig. 3. The sources operate sequentially and a full frequency sweep for each source is generated by the VCO. The VCO is swept from 12 GHz to 18 GHz, these frequencies are multiplied in the sources by a factor of 18. The receivers are operated in parallel and are driven by the same VCO sweep delayed through a fixed 50 Ohm delay line corresponding to a delay equivalent to 20 m light propagation in air. If an object is in the imaging area, which is in 8 m distance and its size about 0.5 x 0.5 m^2, reflects the signal it will create in the receivers a low intermediate frequency, typically of the order of 1-4 MHz.

The delay line uses amplifiers to compensate for signal loss, due to its length. In Fig. 4 and Fig. 5 the electrical characteristics of the simulated and actual delay line are shown. The attenuation is approximately constant and around 0 dB magnitude over a frequency range of 12-19 GHz which is show in Fig. 4. In Fig. 5 the actual delay is simulated and measured. The measured delay is 72.5 ns and corresponds to 21.75 m delay in air. The theoretical predictions for the delay line are in good agreement with experiment.

To improve our understanding of the system an alternative electrical design employing a VNA is implemented. This design is shown in Fig. 6. Each transmitter-receiver combination is separately measured. For the measurements a Rohde & Schwarz ZVT 20 network analyzer is used. The VNA is operating at 12-18 GHz stepping through in 201 steps. Two signals are generated by the VNA, the local oscillator (LO) and the radio frequency (RF) signal. These signals are slightly detuned, with a frequency difference of 10 MHz. The RF signal is sent to each transmitter and the LO signal is used for the receiver arrays to mix the received signal, generating an intermediate frequency (IF) of about 180 MHz. The IF is 18 times higher than the detune due to the frequency multiplier in the transmitter. This IF signal is measured by the VNA. To measure a stable phase in the IF signal, an external reference is needed. The external reference is generated by mixing the RF and LO signal the intermediary 10 MHz signal is electronically multiplied it by 18 to generate a 180 MHz reference signal.

After data for a full line is acquired the signals are reconstructed by using a backprojection algorithm implemented on a general purpose graphics processing unit (GPGPU). These algorithms are generally numerically expensive but due to this special optical design the algorithm has only to consider 2D slices, leading to a significant reduction of computation time. Real time reconstruction is achieved in the current system.

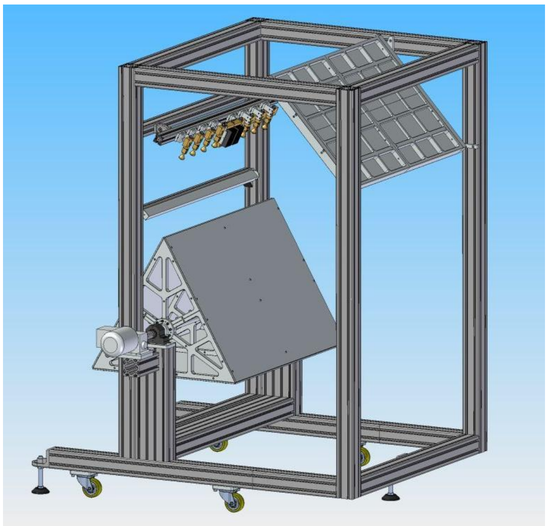

Figure 1 CAD Image of the camera

Figure 2 Measurement range. The beam is in the vertical direction focussed to a thin slice in the imaging area

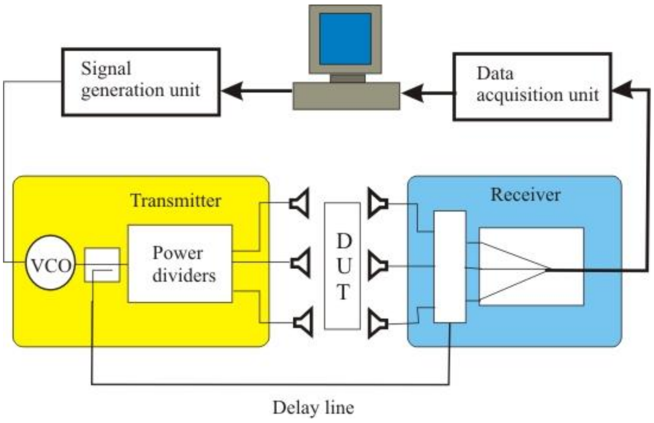

Figure 3 Outline of the electrical part of the system using the VCO design

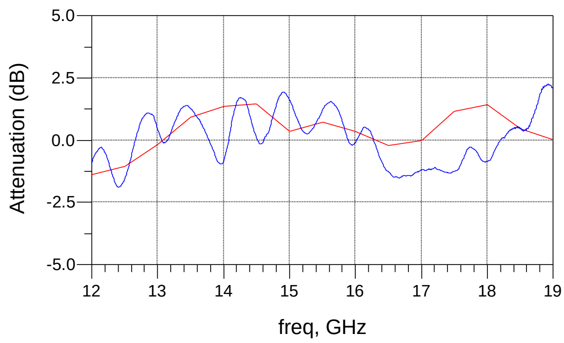

Figure 4 Delay line attenuation: simulated (red) and measured (blue) results

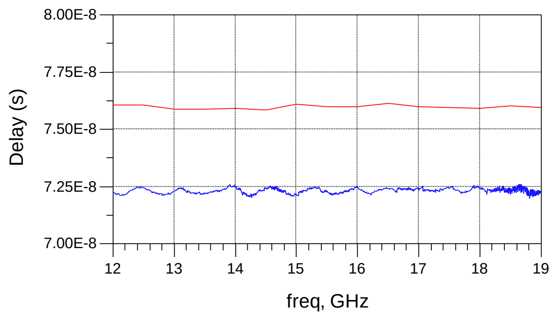

Figure 5 Delay in seconds of the delay line: simulated (red) and measured (blue) results. Measured delay is 72.5 ns corresponding to 21.75 m delay in air

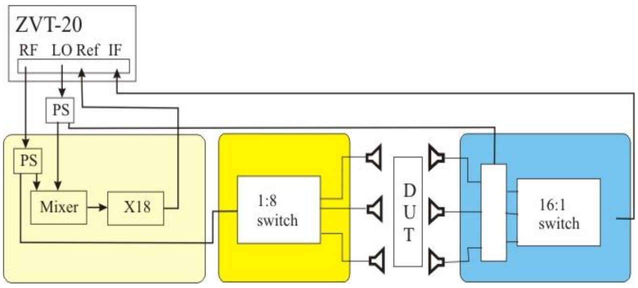

Figure 6 Electronic design utilizing a NVA, two power-splitter (PS) are used to

3. EXPERIMENTAL RESULTS

In this section we present experimental results of the camera. We start with 2D measurements for which the triangular mirror is kept at a fixed position. These measurements are performed in both electrical configurations, i.e. using the VCO and using the NVA. Afterwards the triangular mirror is rotated step-wise and a full 3D image is acquired using the NVA.

For each position of the triangular mirror, the beam is almost horizontal or slightly tilted upwards. The optics focuses the beam on a thin horizontal slice in the target range of about 8m. The direction vector connecting the camera and the target area defines the 'range' direction. The horizontal direction perpendicular to the range direction defines the 'cross-range' direction.

For the reconstructed images, range resolution is essentially determined by the frequency bandwidth and cross-range resolution by the transmitter-receiver array spacing.

After setting the optics to the correct height for the target area, the system has to be calibrated. The calibration consists of two steps. One 'matched' calibration which records the background with an empty target area and is subtracted from the data; and a 'short' calibration with a fully reflecting mirror allowing for a phase calibration.

In Fig. 7 we see the reconstructed results of a single slice-2D measurement for a) two 25 mm wide metal blocks and b) a r=25 mm metal column. The right column of Fig. 7 shows an eagle eye view sketch of the individual scene. Each slice in Fig. 7 had the data recording time of approx 1 ms using the VCO design. Reconstruction of the images was performed on a NVIDIA GTX 580 general purpose graphics processing unit (GPGPU). Currently a 100x100 pixel slice representing a 1x1 m² horizontal slice is reconstructed in less than 1ms. Currently real time performance is only bottle-necked by the data transfer from the ADC to the computer. This will be improved in the future.

The measurements with the vector network analyzer (VNA) are more time consuming. Typically 201 data points per transmitter receiver combination with a resolution bandwidth of 2 kHz are acquired and transmitted to the computer in 2 min for all transmitter receiver combination. For higher precision the resolution bandwidth is switched to 200 Hz extending the measurement time. These rather long acquisition times poses new challenges to the thermal stability of the total system.

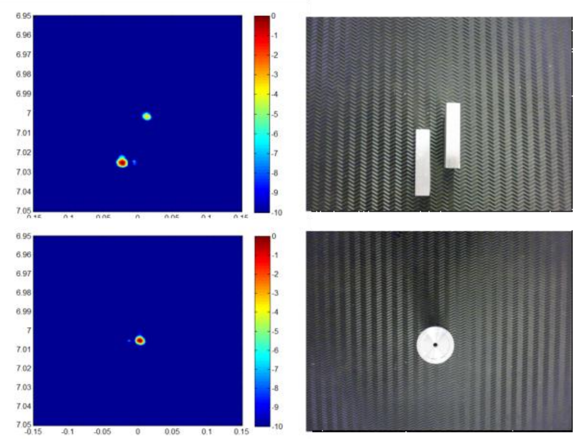

Figure 7 Left column shows reconstructed results measured with the VCO design; right column sketches the measured scene, the first row shows two 2.5 cm wide metal-blocks, the second row a r=2.5 cm metal column. The pictures represent an eagle's eye view, so the millimetre wave camera is measuring from the 'above'-direction

In the upper part Fig. 8 we show measured data with the NVA and a resolution bandwidth of 200 Hz. The lower part of Fig. 8 shows a simulated signal. The measured signal agrees in terms of range and cross-range resolution and in the appearance of side lobes quite well with the simulated signal.

Fig. 9 and Fig. 10 show first 3D results. Fig. 9 shows the scan of a small hand weapon with 200 Hz resolution bandwidth. The sample is clearly visible in the 3D reconstructed dataset.

In Fig. 10 a full, life-size 3D image was taken. The resolution bandwidth is 2 kHz and the total measurement time is 5 h. The lower part of Fig. 10 shows the mannequin without (on the left) and with (on the right) hidden object. The difference is clearly visible. Currently image quality is still limited by some slight aberrations in the optics. This make the calibration procedure less than perfect, leading unfortunately to unexpected side lobes.

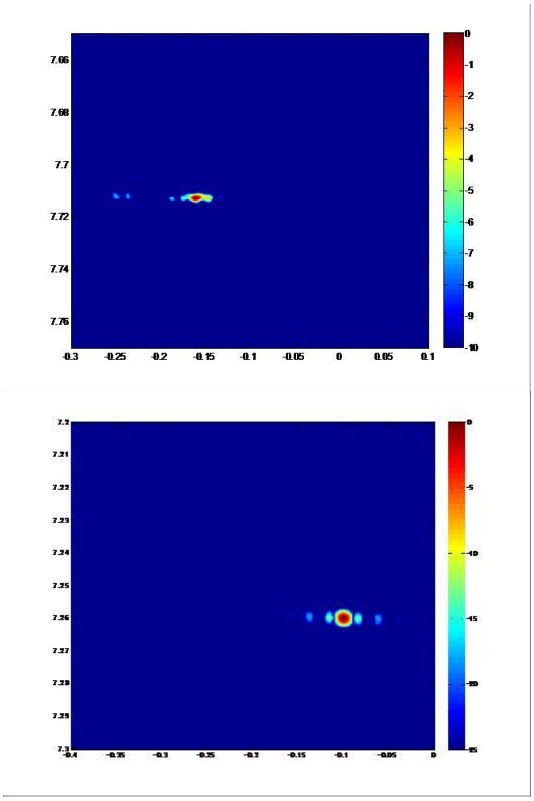

Figure 8 Upper figure shows measured data of r=2.5 cm column using the NVA. Lower figure shows simulated results. All scales are in meter, the view is as in Fig. 7.

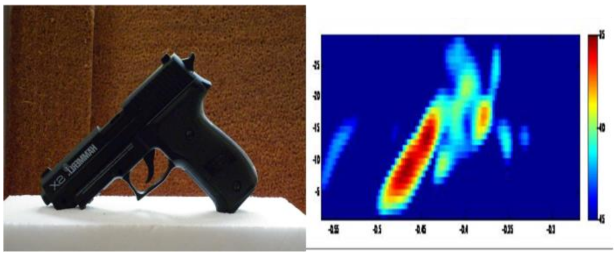

Figure 9 Measured object and maximum intensity of the reconstructed result using the NVA design

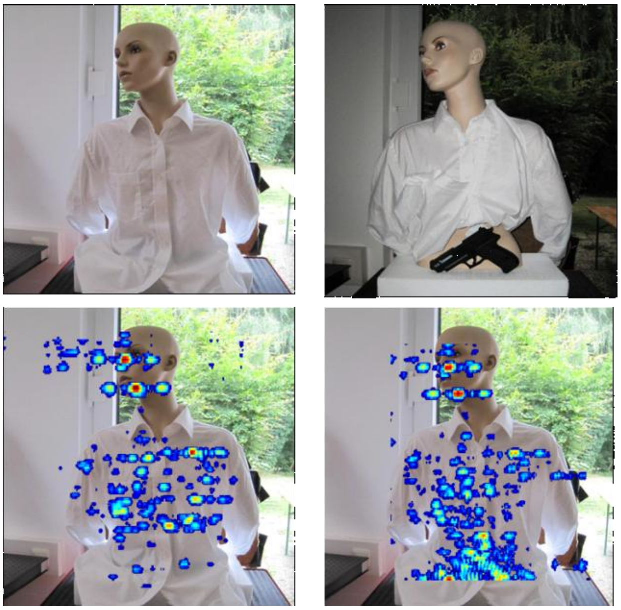

Figure 10 Upper row shows the measured sample and the hidden object. Lower row left inset show the measured data without hidden object, right inset shows with hidden object measured with the NVA design

4. OUTLOOK & SUMMARY

In this paper we presented the current status of the 300 GHz millimeter-wave imaging system. Full 3D images were measured in 8 m stand-off distance.

The current image quality has been shown to be promising for security applications. Material defects have not been evaluated so far. Since it is known that most foams are transparent to millimeter-waves and glue interfaces reflect millimeter-waves, such composite materials are considered to be promising. These material defects will be considered in future work.

5. ACKNOWLEDGEMENTS

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