Fast active THz camera with range detection by frequency modulation

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Abstract **- We report on the realization of an active fully electronic THz camera operating at 645 GHz and room temperature. It currently acquires images with about 9000 pixels in 10 seconds. Each pixel contains the amplitude as well as the phase information of the reflected THz signal. Frequency modulation allows to select a specific working distance and to suppress spurious reflections. The typical image size is in the order of hundreds of cm².**

I. Introduction

Many interesting ways of implementing THz imaging[1]–[7] have been demonstrated in the last years. Slow acquisition speeds prevent practical usage of most of them, today. On the way to a fast, room-temperature THz camera with a high reliability, we present a new system with fast scanning optics and fully electronic detection. The active illumination allows implementing several unique features like phase-sensitive detection and working-distance selection.

II. General setup

The THz camera setup mainly consists of three units: The source/detector unit, the quasi-optical telescope together with the scanner, and the data acquisition.

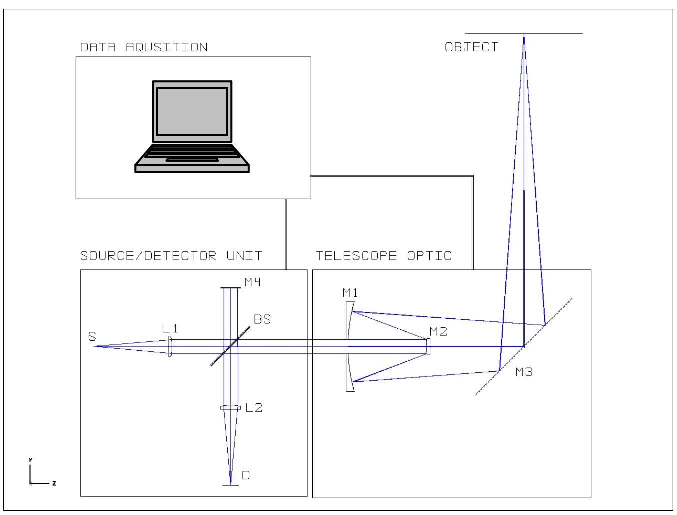

Fig. 1 Diagram of the THz camera setup.

The source/detector unit serves as an illumination source as well as a detection system with a single in- and output. This means that the illumination and the detection rays share a large part of the path between the beam splitter (BS in Fig. 1) and the object. The unit emits a collimated THz beam to the quasi-optical telescope.

The telescope optics focuses the incoming beam to the object plane, while the scanner moves the focal spot to cover the field of view (FOV). After the THz radiation is scattered or reflected by the object, the telescope optics returns it back to the input of the source/detector unit. One can imagine the source/detector unit as an interferometer, i.e., the returning wave is coherently superimposed with a part of the source radiation. Since the source frequency is swept, constructive and destructive interference are alternating within one sweep period -assuming the optical path difference is long enough- which leads to a modulation of the detected power. We can use this signal in the data acquisition unit to determine the object's reflection coefficient by detection of the modulation amplitude and the optical path difference by measuring the phase and the frequency offset of the detected signal.

III. Source/detector unit

As a source we use a frequency-swept electronic W-band source. Its radiation is first amplified, then frequency-multiplied by a factor of 6 to reach the working frequency of 645 GHz with a power of 0.5 mW. This radiation is emitted by a horn antenna (S in Fig.1), collimated by a Picarin lens (L1 in Fig.1) and split into two parts using a Mylar beam splitter (BS in Fig. 1). The signal beam is directed by the telescope optics (M1, M2 in Fig.1) and the scanning mirror M3 to the object, while the reference beam is directly reflected (M4 in Fig. 1) in the short arm of the interferometer and focused (L2 in Fig. 1) onto the Schottky detector (D in Fig.1). Hence, this detector provides the power of the coherent superposition of the two (swept) signals. Both, the source as well as detector unit are commercial products of Radiometer Physics[b].

IV. Frequency modulation

We implemented the frequency-modulated continuous wave (FMCW) approach known in the radar field. It is described in this section: The interference of the signal beam with the reference beam together with the frequency sweeping lead to a modulation of the detected power. This can be seen for the example of two frequency-swept waves with the same amplitude, but a time delay according to

$$E_n = E_0 \cdot \cos\left(\omega_0\left(t + \Delta t_n\right) + \Delta\omega \frac{\left(t + \Delta t_n\right)^2}{t_s}\right), \qquad (1)$$

where E_n is the amplitude of the n-th wave, ω_0 the base frequency, $\Delta\omega$ the frequency shift, t_s the period of sweeping, and Δt the temporal delay ($\Delta t_2 = \Delta t$, $\Delta t_1 = 0$) of wave 2 against wave 1.
The beat signal is then proportional to

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$$\cos\left(\frac{1}{2}\left(\omega_0 \cdot \Delta t + \frac{\Delta\omega}{t_s}\left(\Delta t^2 + 2\Delta t \cdot t\right)\right)\right). \quad (2)$$

Since only one term directly depends on the time, we can identify the beat frequency as

$$\omega_b = \frac{\Delta\omega}{t_s} \cdot \Delta t \quad (3)$$

The situation is illustrated in Fig. 2.

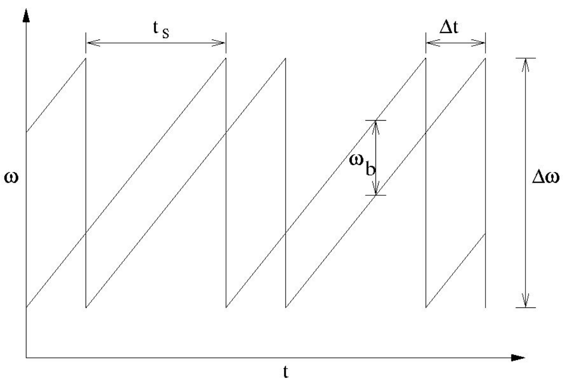

Fig. 2 Illustration of the frequency sweeping method.

One can recognize that the frequency of this modulation is directly proportional to the THz path difference which corresponds to twice the object distance. In this way, frequency selection can be used to select a specific object distance. We can estimate the achievable range selectivity from the measurement parameters: The maximum useful measuring time for frequency detection is one sweep period. This provides a limit for the accuracy of the frequency detection:

$$\Delta f = \frac{1}{t_s} \quad (4)$$

Since the frequency is our measure for the object distance, equations (3) and (4) can be combined to estimate the possible ranging performance with this method:

$$\Delta d = \frac{\Delta f}{f} \cdot c \cdot \Delta t = \frac{c}{\Delta\omega} \quad (5)$$

Its value is about 83 cm for the sweeping range of 2π•360 MHz, which we used for sweeping by frequency modulation of the synthesizer that drives the W-band source. The object distance corresponds to half the path difference, so the limit for the object ranging is about 42 cm.

In Fig. 3, experimental results to the range selectivity are shown: We varied the distance between the scanning mirror (which was not moving during these measurements) and a reflecting object (mirror). For different object positions, we measured the beat frequency using a digital oscilloscope, and acquired the modulation amplitude for different (5th-8th) harmonics of the sweep frequency using a harmonic lock-in amplifier. The squares of these amplitudes are shown as detected powers in the figure. The peak widths for the 6th and 7th harmonic agree quite well with the estimate given above.

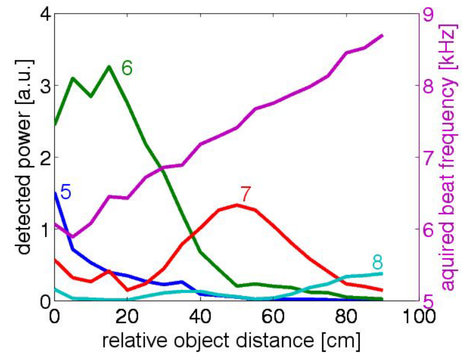

Fig. 3 Detected power for different harmonics of the sweep frequency and the detected beat frequency for various relative object distances.

The maximum sweep range of the source is limited by the frequency tripler to about 10 GHz, which provides the limit for the object distance selectivity of 1.5 cm. Additionally to the rough distance provided by the beat frequency the phase data of the detected signal provides information about the path difference with interferometric precision. The distance selection not only allows selecting specific object distances, but also avoids image artifacts by spurious reflections.

V. Scanning optics

The diffraction-limited telescope optics is shown in Fig. 4. It consists of a large primary mirror (M1 in Fig. 1), a small secondary mirror (M2 in Fig. 1) and a rotating scanning mirror (M3 in Fig. 1). The secondary mirror expands the collimated THz radiation to illuminate the whole aperture of the primary mirror. While this mirror focuses the radiation onto the object plane, the scanning mirror moves it in the object plane to cover the field of view. The diameter of the elliptically shaped primary mirror is d = 230 mm.

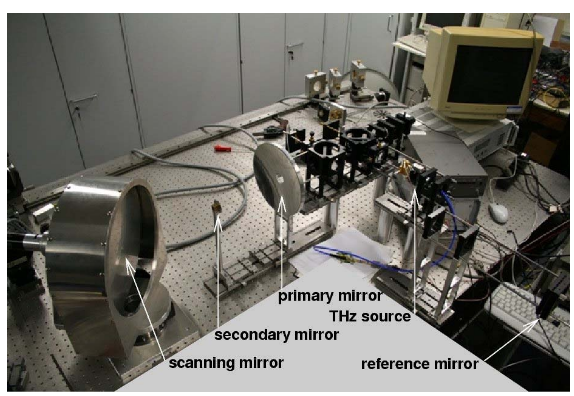

Fig. 4 Photography of the THz camera setup.

The focal lengths of M1 are f_1 = 250 mm and f_2 = 1250 mm, respectively. The spherical secondary mirror has a diameter of d = 50 mm and a radius of curvature of r = 51 mm. The latter as well as the distance between the secondary and primary

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mirror are adjusted in such a way that the telescope optics works in a diffraction-limited way over the FOV. To scan a specific object, the planar scanning mirror (diameter D = 320 mm) is tilted by an angle of 5 deg. against its fast rotation axis. This leads to an ellipse-shaped scanning path in the object plane. The fast axis is slowly turned by a rotation stage in a perpendicular direction, which leads to a horizontal translation of the ellipse-shaped path which ultimately covers the FOV.

VI. Data acquisition and processing

The data acquisition of our system takes 500 samples per revolution of the fast axis. While the rotational stage moves by 10 deg. in 10 seconds, the scanning mirror typically performs 100 revolutions. We hence acquire about 50,000 data points with the corresponding angular positions. For an adequate display on a pixel-based computer screen, some data processing is necessary. We mainly transform the angle pairs into Cartesian coordinates in the object plane and connect the points with triangles (Fig. 5), using the Delaunay algorithm[9]. Some binning and averaging of data points avoids triangles with extremely short sides. Depending on the processing parameters, we obtain about 10,000 effective points, connected with triangles. The area of each triangle is then filled by interpolating the intensity values of each triangle's corners. This leads to an image output like the example shown in Fig 6.

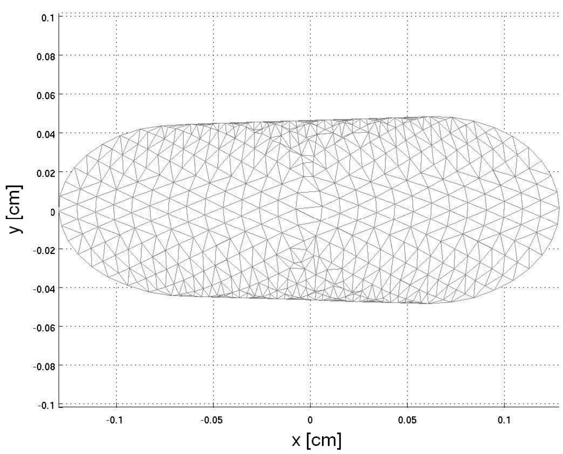

Fig. 5 Triangulated mesh in the object plane, generated with the Delaunay algorithm to cover the scan field of view.

VII. Results and outlook

With the scanning mirror rotating at 600 rpm about the fast axis, which was slowly rotated with 1 deg. per second with the rotation stage, we are able to acquire a picture within 10 seconds. In Fig. 6, a THz image of a weapon covered with a cotton shirt is shown. The image consists of approximately 9000 pixel. The distance from the center of the scanning mirror to the weapon is about 450 mm.

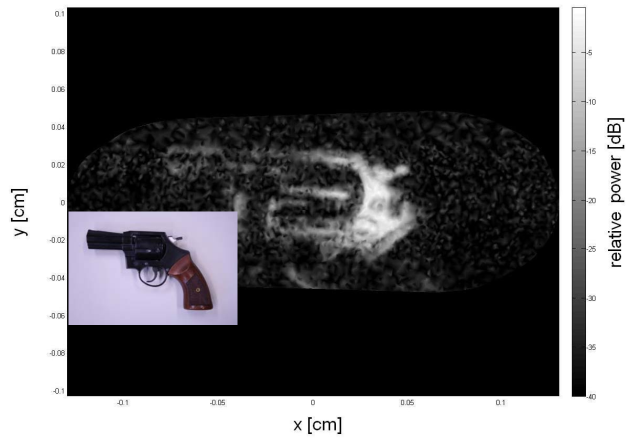

Fig. 6 THz picture of a weapon covered with a cotton shirt (the inset shows a photography of the weapon).

The dynamic range of the picture exceeds 35 dB. The phase data (not shown) could be used to evaluate the object's topography with a depth resolution in the order of tens of microns[8]. We target a near-video rate of 10 frames per second by using a scanner with a detector array and an improved range selection by increasing the sweep frequency with a voltage-controlled oscillator (VCO) and enhanced data acquisition and processing. Additionally, in order to achieve a larger object distance with the same imaging performance, we target the use of a larger primary mirror.

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