A Superconducting Terahertz Imager

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***Abstract* - The SuperCOnducting Terahertz Imager (SCOTI) is a small Cassegrain-type telescope with a scanning secondary mirror designed for a frequency of 0.34 THz. It can map objects at a distance of 5 meter using a small array of superconducting bolometers. The resolution at the object area is about 1 cm. Purely passive images of interesting objects can be taken using SCOTI, thus opening a wide field of applications.**
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I. INTRODUCTION

Objects with a temperature different from zero are emitting electromagnetic waves corresponding to Planck's equation. In the terahertz band – usually defined as the range of frequencies between 0.1 THz and 10 THz – the continuous black body emission is interfered by spectral absorption lines corresponding to specific material properties. Consequently, in a terahertz image different materials can be discriminated although they have the same temperature. However, mapping objects at frequencies around one terahertz and from a significant distance poses a considerable challenge for any imaging device. The power emission of bodies at room temperature is very weak; therefore, a purely passive map requires an extremely sensitive sensor. Detectors operating at room temperature are only applicable for actively illuminated scenes; for a passive map a cooled detector is required.

Recently, for sub-mm wavelength, a big leap forward in the detector performance and scalability was driven by the astrophysics community. Superconducting bolometers and medium-sized bolometer arrays (up to kilopixels) have been developed and are in routine use [1, 2]. Concepts for larger devices are already projected. It is conceivable that such devices will become larger, less costly and available for a wider market. Hence, a THz imager for industrial or security applications based on superconducting detectors comes within reach.

Although devices with many pixels are foreseeable nowadays, a device with an additional scanning optic is the most straightforward approach to an imaging system having a useful resolution. The combination of a small or medium-sized detector array with an optical scanner promises to perform record of THz images with frame rates of 1 second and faster. An imager with a field of view of one meter at 10 meter distance is already attractive for security applications, even though such a prototype is only the demonstration of the concept. It can easily be expanded to larger fields of view and faster image acquisition up to video rate.

II. OPTICS

A. Optical Approach

The optical design approach is based on an on-axis telescope of the Cassegrain type with an aspheric main mirror. Manufacturing restrictions have lead to a limitation in the diameter of the main mirror, which was fixed at 410 mm. The scanning mechanism tilts the secondary mirror around its vertex. Figure 1 shows schematically the layout with ray beams (red) coming from object points with different offsets from the main axis. A second array of beams (blue) is plotted for the case of a 4° tilted secondary mirror.

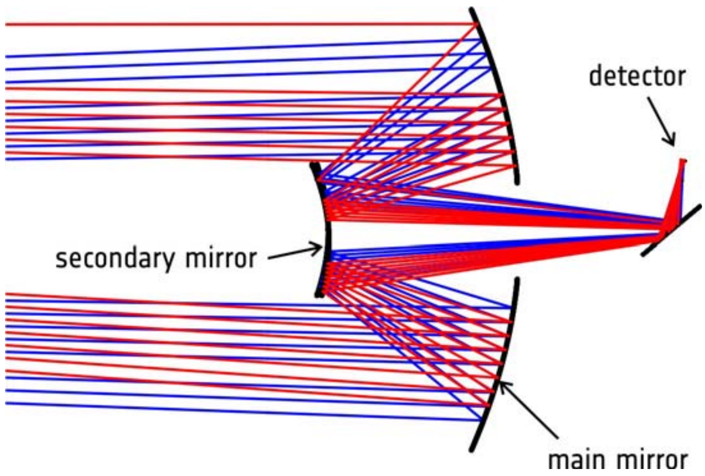

Fig. 1. Optical simulation with ZEMAX

All components of the optical layout have dimensions at least by a factor of 100 larger than the wavelength of 870 micrometer. The use of a commercial ray tracer like ZEMAX appears to be straightforward. Nevertheless, a careful treatment of the results is advisable, since ZEMAX is not designed for such long wavelengths. Later it will be shown that simulation results can be verified experimentally, suggesting that a simulation with ZEMAX is permissible.

The radiation which is collected by the telescope is coupled to the detector via a conical feed horn. The numeric aperture of the horn is 0.12. Therefore the telescope is designed to have approximately the same aperture; in that case the beam diameter is still limited by the horn.

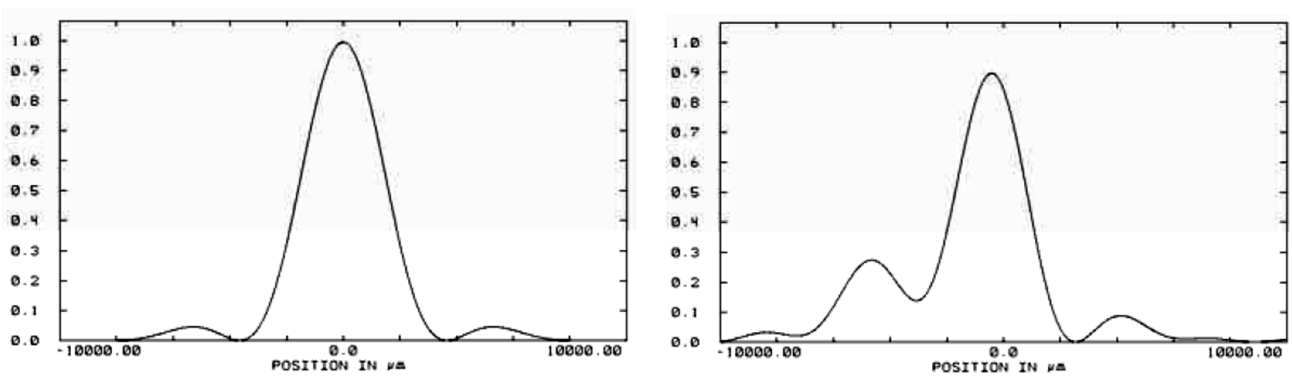

Fig. 2. Image of two point sources at 4° tilt of the secondary mirror

At 5 meter distance the calculated resolution is 1.5 cm (Rayleigh criteria) for a field of view of 40 cm by 40 cm. Figure 2 shows the simulated image of two point sources at the main axis and at an offset of 20 cm. The reproduction scale is 1 to -3.2. This means, that two point sources separated by

1.5 cm will be projected at the image plane with 5 mm distance. Thus, a detector array with a pixel spacing of 5 mm is adapted best to the capabilities of the telescope. Here we use seven detectors on a hexagonal grid, and the small sub-pictures of the array can be composed to a full image.

B. Optical scan

To raster an object we tilt the secondary mirror around its vertex. We are investigating two tilting devices. The first one uses two linear actuators to tilt the mirror around two orthogonal axes by ±4°. Control software addresses the linear motors so that the resulting scan is a meander. This scan mechanism is relatively slow, since the moving mirror has to be decelerated at every turning point. The scan of one line takes approximately 2 seconds. So a typical scan of 40 times 40 pixels can be done in 80 seconds using only one bolometer pixel. The small hexagonal array allows scanning three lines in parallel, and so the scan time can be decreased down to 25 seconds.

The second tilting mechanism currently under construction bases on a gyrating mirror. The secondary is rotated around the main axis of the complete telescope, whereas it is tilted around one orthogonal axis. So the scan figure is a circle or - in the case of a continuous tilting - a spiral. Taking into account the detector time constant of 0.2 ms a complete scan could be done in 3 seconds with one pixel or in 1 second using the array.

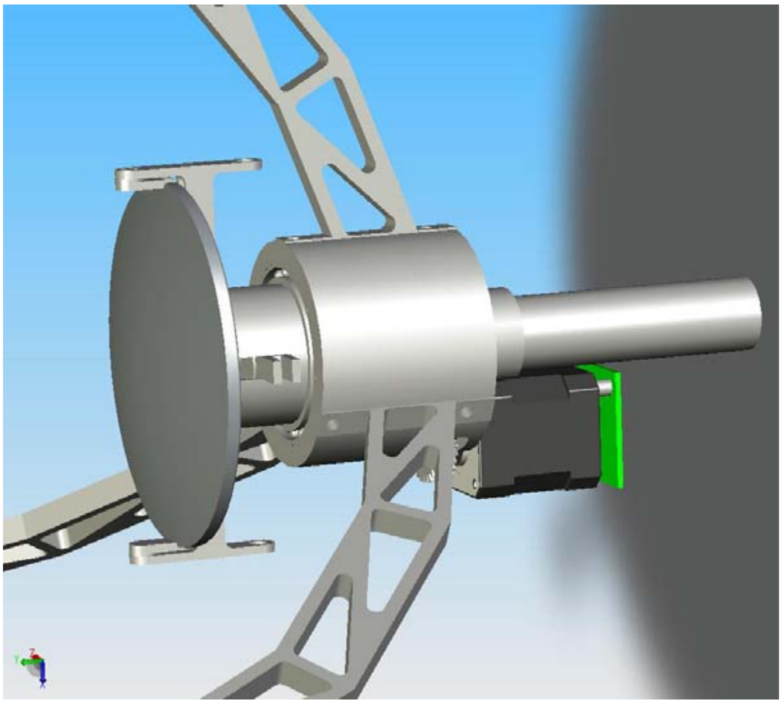

Fig. 3. Design of an optical scanner based on a gyrating mirror

III. DETECTOR

SCOTI utilizes superconducting transition edge sensors (TES) as detectors [3]. A TES is basically a bolometer which uses a superconductor operated at its transition point as a thermometer. The superconductor is voltage biased, which insures the so-called electrothermal feedback. This makes this type of bolometer by two orders of magnitude faster than the intrinsic thermal time constant would allow. In our case, the effective time constant is around 0.2 ms. As the superconductor we use a proximity bilayer of Mo and the alloy Au-Pd, with a designed transition temperature T_c of around 450 mK [4]. The wiring is made of niobium. All patterns are micro-fabricated on a silicon nitride membrane with a thickness of 1 micron. This membrane defines the thermal conductivity of the bolometer and thereby the sensitivity.

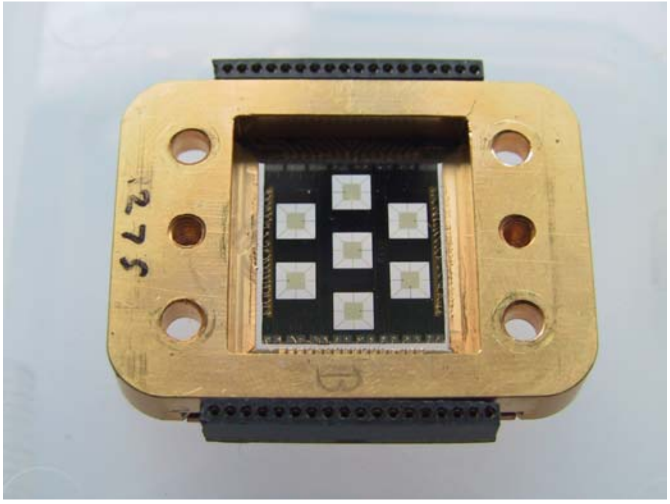

Fig. 4. Seven pixel detector array

Since TES-type bolometers saturate at a certain power load, the thermal conductivity has to be chosen so that the expected maximal power load will not overload the detector. This will ultimately limit the sensitivity. Since a TES is an energy detector which will collect all power in the incoming radiation band, for imaging systems it is advisable to operate in a narrow-band filter setup. This will allow one to use a more sensitive detector. The drawback will be to eliminate the option of spectroscopic investigations. Our filter setup is composed of cold inductive mesh filters and the horn antenna with a $\lambda/4$ back short [5]. The presented results are obtained at a wavelength of 870 µm corresponding to a frequency of 0.34 THz, with a filter band of ±5%. The filter setup can be easily replaced with filters for a different wavelength. Taking the suggested application of security scanning into account, frequencies between 0.1 THz and 1 THz are expedient. Longer wavelengths will result in a poor resolution, and for higher frequencies the atmospheric attenuation due to water absorption will be interfering.

IV. READOUT

The TES will transform the detected radiation signal into a change in the electrical current flowing through the thermometer due to the voltage bias. We use a superconducting quantum interference device (SQUID) as an amperemeter to measure this current signal. The use of a SQUID is a natural choice for a superconducting bolometer, since the intrinsic noise of a SQUID is at least two orders of magnitude lower than the bolometer noise. Thereby the detected radiation signal will not be affected by the readout. Additionally, such a low noise amplifier allows us to use a multiplexed readout, which is essential for the construction of larger arrays of bolometers.

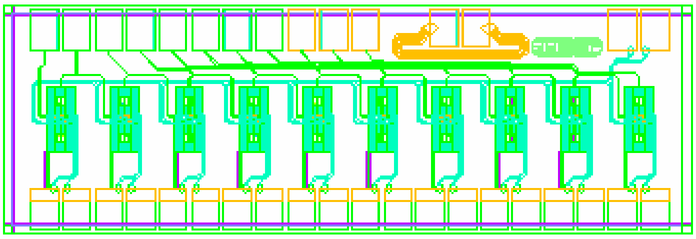

Fig. 5. Layout of the multiplexer

Our approach is adapted to the TES we are using. Since the time constant of the bolometer is around 1 ms, we can switch one readout channel between several bolometers, if the switching is much faster than the detector's time constant. Such a scheme is called time-domain multiplexing (TDM) [6]; all bolometers are switched on permanently and a serial connection of attendant first-stage SQUIDS is read out by one amplifier SQUID. From the first-stage SQUIDs only one is switched at a time, the others are in the superconducting state. Thus, the amplifier will read only the signal from a single SQUID and the attendant bolometer pixel. Digital electronics are used to switch the first-stage SQUIDs on and off, in our case with a frequency of 20 kHz.

Using this scheme, one room-temperature electronics set is enough to read out some tens of bolometer. Our prototype needs only one such set to read all seven bolometers from the used small array. The multiplexed signal is transferred to a microprocessor-controlled demultiplexer, which separates the individual signals and allocates them to a bolometer channel. Then the separated signals are transferred to a computer, where the synchronizing with a trigger signal from the optical scanner is done resulting in the image formation.

V. COOLING

The operation temperature of the bolometer is 450 mK, achieved by a ^{3}He sorption cooler with a base temperature of 300 mK. The ^{3}He system is self contained; at room temperature a connected bottle stores about 3 liters of ^{3}He gas. Because this gas is liquefied at a temperature below 1.5 K a pre-cooling is needed. There are two options available. In our laboratory demonstrator we used a pumped ^{4}He cryostat with a temperature of about 1.5 K. However, we plan to replace the ^{4}He cryostat with a pulse tube cooler (PTC), since it is desired to employ the camera in a public environment and without the need of operation by cryogenic specialists. The PTC, manufactured by Vericold [7], is currently being tested. Major concerns are microphonics and temperature fluctuations at the pulse frequency of about 1 Hz, which have to be cancelled out.

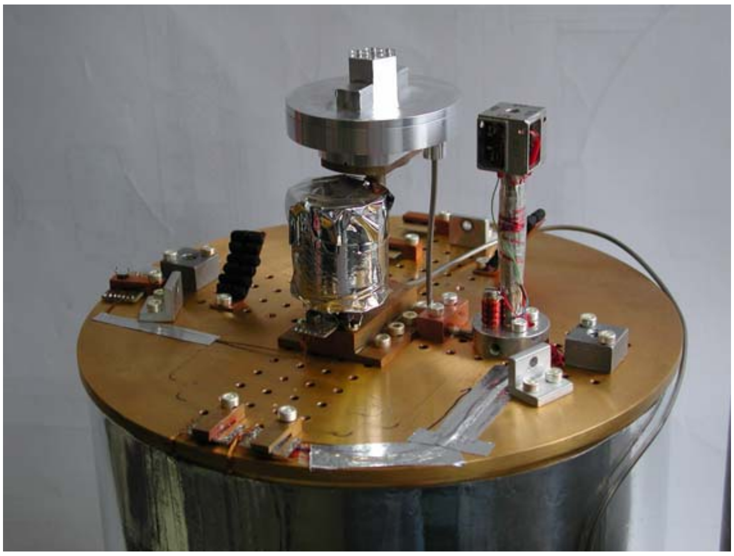

Fig. 6. Upside-down view on the cold plate of the cryostat, with the aluminium bolometer chamber atop.

VI. RESULTS

A. Optical resolution

As mentioned above, the simulation of the optical parameters with ZEMAX requires a careful verification. The ideal way is to map a point source and to evaluate the size of the image. It is more straightforward to map a grating, which gives in addition some information about first-order aberrations. Therefore, we have built a grating from small Eccosorb stripes which are heated by manganin wires to a temperature approximately 10 K above room temperature. The distance between the stripes was set from 5 cm decreasing down to 4, 3, 2 and 1 cm.

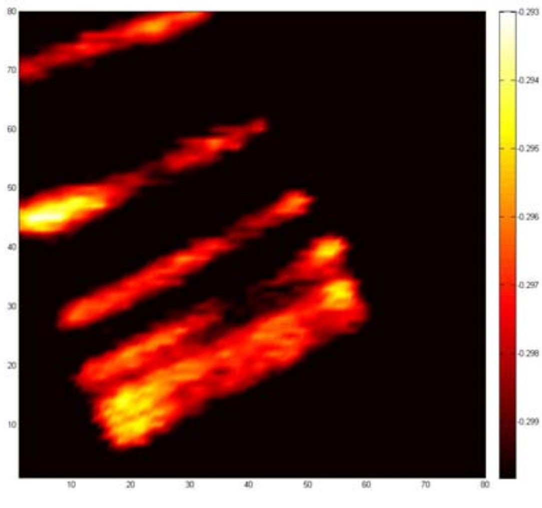

Fig. 7. THz image of a grating from Eccosorb stripes, recorded from 5 meter distance

Figure 7 shows, that the last two stripes separated by 1 cm are not discriminated, although there is a slight indication of a separation. There next strip at a distance of 2 cm is clearly resolved, indicating that the optical resolution is between 1 and 2 cm, as predicted by the simulation with ZEMAX. Further, no distortions can be seen at the map. The variation in the thickness of the stripes results from an inhomogeneous temperature due to a non-uniform heating. Figure 8 is a line scan, which shows the scanned profile of two of the Eccosorb stripes, which are separated by 5 cm.

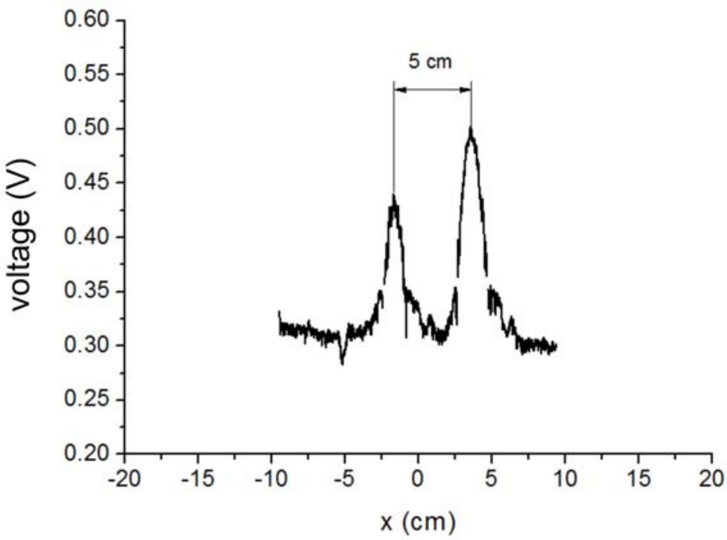

Fig. 8. Line scan of the grating imaged in Fig. 7.

B. Proof of concept

Typical application scenarios for a THz camera are security areas at airports or public buildings. Two main properties of THz radiation can be exploited. First, in contrast to the human body which is an almost perfect black body, metals and ceramics are close to 100% reflective. This is apparent in Figure 9, where the wrist of a human hand is masked by a metallic watch.

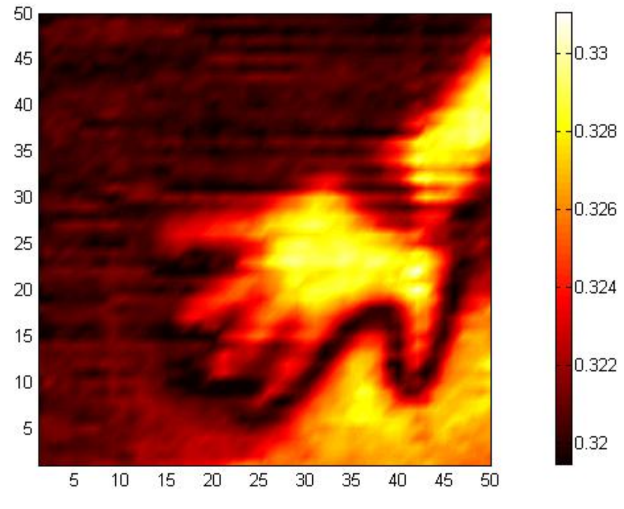

Fig. 9. Human hand at 0.34 THz, from 5 meter distance

Second, dielectric materials in general and specifically human clothing are almost transparent. Combining these two properties, a THz camera could possibly find potentially hazardous objects hidden underneath the clothing of suspects.

We have simulated such a scenario. A test person placed a handgun mock-up in front of his body. The THz portrait clearly shows the contrast between the black body at 310 K and the reflection of the background at 295 K coming from the metal surface. If the test person hides the handgun mock-up underneath his clothes the contrast is maintained. Standard clothing like shirts or sweater are more or less completely transparent. Figure 10 shows such a scenario: the scan at 0.34 THz reveals the handgun mock-up underneath the shirt of the test person.

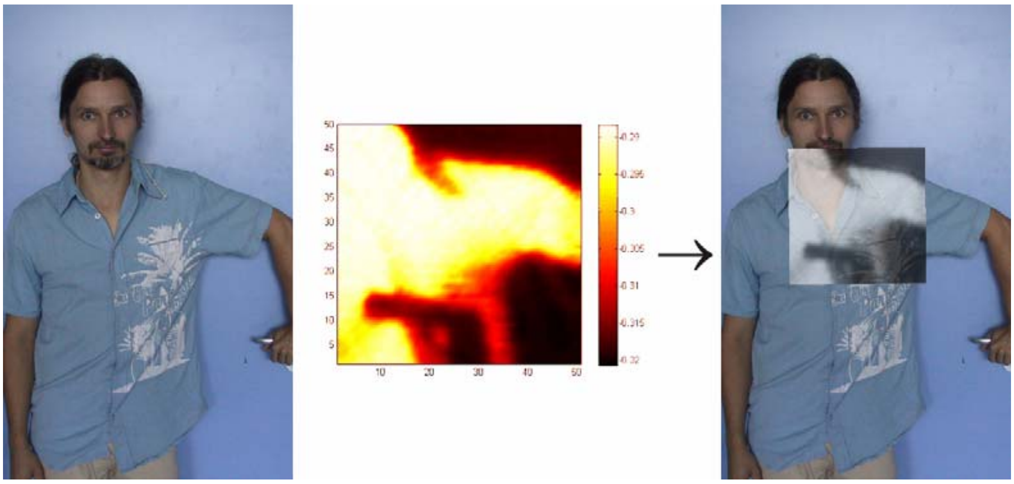

Fig. 10. Test scenario: a test person hides a handgun mock-up underneath his shirt, and the THz scan reveals the threat from 5 meter distance.

VII. CONCLUSION AND OUTLOOK

We demonstrated passive imaging at a frequency of 0.34 THz. It is important to point out that all images shown above can be taken without any additional illumination or an artificial increase of the contrast by a cold background. The imaging is entirely passive at a stand-off distance of 5 meters, with a speed which is already useful in an airport check-in scenario. Future developments are projected: the spiral scanner will decrease the frame rate to approximately 1 Hz, and concepts for video frame rate are under development. The next generation of cameras will have a larger field of view, higher resolution and maybe a zoom optic.

For an industrial product it is indispensable to get away with liquid cooling. The availability of commercial cryocoolers at reasonable prices and with long maintenance cycles promises a user-friendly and affordable camera at a price below 100k€. Once demonstrated, it may stimulate a sizable market.

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