Towards industrial applications of terahertz real-time imaging

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ABSTRACT

Recent innovations in photonics and nanotechnology are now enabling terahertz (THz) research to be applied in many industrial fields such as homeland security, information and communications technology (ICT), biology and medical science, non-destructive tests or quality control of food and agricultural products. Still many challenges are to be addressed, the main one being to provide THz systems with sufficient signal to noise ratio when operated in real industrials conditions. In addition, cost is a key lock that hampers the spread of this technology but it is clear that cost-effective sources and detectors compatible with standard microelectronics will drive down the overall cost, and in particular will make THz imaging accessible for industrial use.

In order to bring THz imaging to industry, Leti has been developing over the past decade complementary CMOS-compatible uncooled imaging 2D-array technologies: antenna-coupled bolometers and Field Effect Transistor detectors. In addition, CEATech built a test platform dedicated to the development of industrial prototypes of photonics technologies. In particular, in collaboration with i2S, this platform includes the TZCAM camera equipped with Leti's 320×240 bolometric pixel array and gives access to a full industrial THz imaging chain that is essential for maturation of this emerging technology. This paper gives an overview of these developments and illustrates industrial applications with examples of uncooled THz imaging tests, e.g. opaque object 2D inspection or 3D tomography.

Keywords: antenna-coupled bolometer array, antenna-coupled Field Effect Transistor array, terahertz real-time imaging, terahertz uncooled 2D camera, THz tomography

1. INTRODUCTION

Terahertz (THz) radiation refers to the portion of the electromagnetic spectrum which lies between the microwave and infrared frequency bands, typically from 100 GHz to 30 THz. THz radiations combine quite uniquely a few remarkable properties. A wide variety of non-conducting materials (clothing, paper, cardboard, wood, masonry, plastics, ceramics…) are semitransparent. THz light interacts with materials in ways that are different than other electromagnetic radiation: it reveals many specific spectral signatures, permitting them to be imaged, identified and analyzed. In particular, THz waves are also extraordinarily sensitive to water content, and so enable the characterization of water content in materials like plants or paper. Due to its low photon energy (1 THz = 4.1 meV), which is a million times weaker than X-ray photons, it does not have any ionizing effects and is considered as biologically innocuous.

Historically, THz has long been studied in astronomy and analytical science. Recent technological progresses in photonics and nanotechnology result in a growing offer of commercial THz components, such as sources, cameras, spectrometers, and optics (lenses, mirrors, polarizers …). In addition, more and more demonstrations of applications are shown by academic and company research labs. Hence the context is now enabling THz research to be applied in many industrial fields such as homeland security, information and communications technology (ICT), biology and medical sciences, non-destructive tests or quality control of food and agricultural products.

However still many challenges are to be addressed, the major one being to provide THz systems with sufficient signal to noise ratio when operated in real industrial conditions –i.e. in uncontrolled atmosphere, screening fast moving objects or materials… Developments are needed in order to provide powerful sources, highly sensitive sensors and efficient opto-mechanical systems (including filters, mirrors, polarizers, lenses…). In addition, cost is a key lock that hampers the spread of this technology. It is clear that cost-effective sources and detectors compatible with standard microelectronics will drive down the overall cost, and in particular will make THz imaging accessible for industrial use.

Over the past decade, Leti has been developing complementary uncooled imaging array technologies: antenna-coupled silicon microbolometers and CMOS Field Effect Transistor (FET) detectors, both being compatible to standard silicon microelectronics processes. In order to make available these sensors for in-situ applications, integrations in cameras are on-going, starting with the I2S TZCAM that is equipped with Leti's 320×240 bolometric pixel array

In addition to Leti's THz lab, CEATech built a test platform dedicated to the development of industrial prototypes of photonics technologies. It gathers tools for optics design, system prototyping and integration, and a space for operational tests equipped with a wide variety of sources, cameras and optics. In particular, in collaboration with i2S this platform gives access to a full industrial THz imaging chain that is essential for maturation of this emerging technology.

This paper gives an overview of these developments and illustrates industrial applications with examples of uncooled THz imaging tests, e.g. body scanner demonstrator for security, opaque object 2D inspection or 3D tomography for non-destructive tests.

2. UNCOOLED IMAGING THZ TECHNOLOGIES DEVELOPED AT LETI

The commercial spread of THz applications is conditional on the emergence of advanced technologies combining low cost, small size and low power consumption. In particular the market awaits the availability of affordable, compact, easy-to-use and highly-sensitive cameras integrating large-format (many pixels) focal plane arrays and operating in video-mode at real-time without raster scanning. Several uncooled THz real-time imaging cameras with two-dimensional (2D) sensors are currently developed and commercialized [1].

Despite recent progresses, silicon-based uncooled detectors still lack the required sensitivity for passive imaging applications, which seek to detect the thermal radiation of objects. Hence, the low thermal radiation in the THz range of objects at room temperature requires the use of sensors with very high sensitivities (typically with a noise equivalent power (NEP) in the range of few fW) that only cryogenic or heterodyne sensors can reach. The manufacturing and operating costs, as well as the size of these systems, limit them to high-end applications such as defense, space and security.

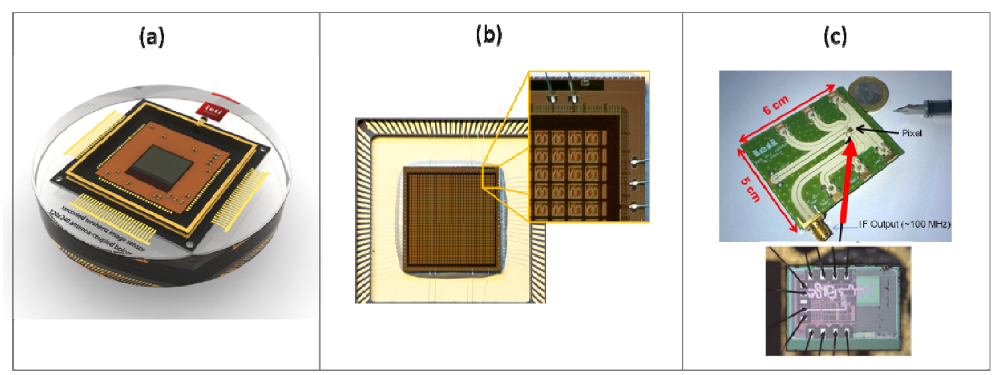

Figure 1. 320x240 antenna-coupled bolometer array (a); 31x31 FET 130 nm CMOS synchronous detection array (b); CMOS 65 nm 278 GHz heterodyne receiver (c).

Instead, silicon-based uncooled detectors require external THz sources of illumination to reach an adequate image quality. Such configuration is referred as an active imaging system where an artificial radiation source –or several sources- is used to illuminate the scene and the image is formed by detecting the back-scattered, reflected or transmitted radiation.

Leti has developed three complementary uncooled imaging array technologies, all being compatible to standard silicon microelectronics processes: antenna-coupled silicon micro-bolometers, CMOS Field Effect Transistor (FET) detectors and CMOS heterodyne receivers.

A proprietary architecture of antenna-coupled micro-bolometer array for THz sensing has been built upon a 20-year old know-how in thermal infrared sensors (Fig. 1, a). High technological maturity has been achieved as illustrated by the demonstration of fast scanning of large field of view and the recent development of a commercial camera in collaboration with the French SME i2S.

In parallel, two FET-based detection technologies are developed at Leti using direct and heterodyne detection, respectively, to address low-cost applications in the sub-THz frequency range (Fig. 1, b & c). The former has reached the most advanced demonstration level with 31x31-pixel arrays and real-time 2D imaging, while the latter has demonstrated very promising sensitivity performances with single-point heterodyne detectors in raster scanning mode.

2.1 Bolometer-based THz arrays

Each pixel is based on a two-storey cross-antenna architecture (Fig. 2, left) that enables absorption in the THz range in dual polarization and over a wide frequency band [2]. The longer bowtie antenna located on the suspended membrane, named 'DC' for direct coupling, is excited by the incident THz wave whose polarization is aligned along the axis of this antenna. In order to couple the orthogonal polarization, a large antenna is located below the microbridge and coupled via a capacitive mechanism to metallic planes deposited on the suspended membrane. This membrane is suspended 1-2 µm above a thick (~11 µm) oxide layer and a metal reflector implementing a quarter-wavelength optical cavity.

Thermal dissipation (Joule effect) of the incident waves in the resistive loads heats up the thermo-resistive amorphous silicon layer, whose resistance is measured by the read-out circuit. Copper through-oxide vias connect the microbolometer to the read-out circuit through the oxide layer. This device is fabricated in Leti's clean room facilities on top of CMOS 8-inch wafers (read-out circuits) provided by a third-party foundry.

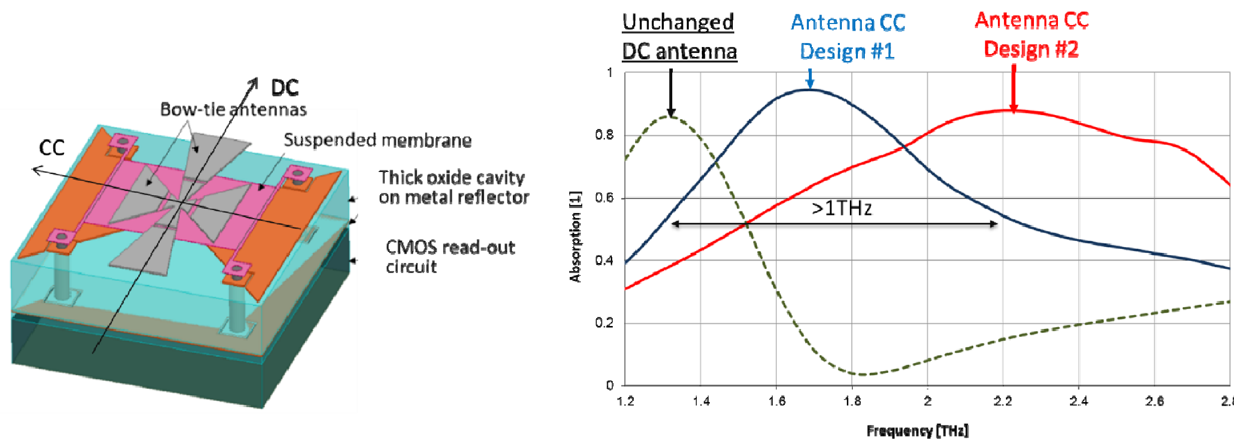

Figure 2. THz two-storey cross-antenna pixel (left) and spectral absorption of different prototyped designs (right)

In contrast to thermal infrared micro-bolometers proposed by other laboratories, Leti's patented pixel architecture separates the THz radiation absorption (antennas with resistive loads) and the thermal sensing (amorphous silicon film) functions. This architecture benefits from a higher design flexibility to optimize electromagnetic and thermal properties, in particular the frequency and the polarization sensitivity. As shown by the measured spectral absorption (Fig. 2, right) [3], the 320×240 prototyped arrays (Fig. 1, left) were optimized to cover the 1-3 THz band with 50×50 µm pixel size. A very wide absorption bandwidth is observed (Full Width Half Maximum in the order of 1 THz), that makes them suitable for a very large range of operation frequency that can be chosen with respect to the targeted application.

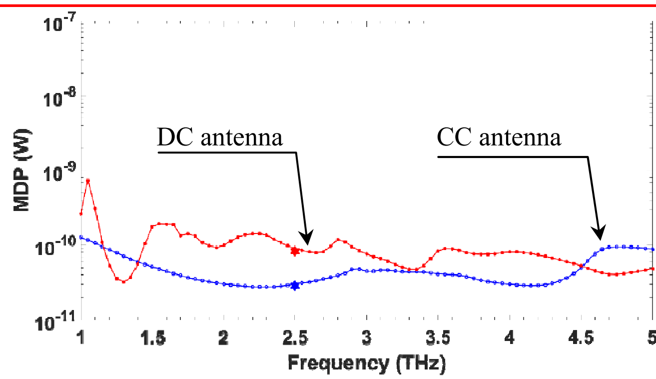

Figure 3. Spectral minimal detectable power (MDP) of the 320x240 THz array –Design 2- for the 2 crossed bow-ties 'CC' & 'DC' antennas (symbol : measurement / plain lines: simulated).

The noise of the imagers $Noise_{array}$ is evaluated by the mean standard deviation of the pixels over a sequence of consecutive frames during a period of 1s. As the frame rate varies between the imagers, the number of frame is set accordingly. From the measurement of the spectral responsivity R and from the temporal noise evaluation of the imager in video mode, which is close to 350µV RMS, we can assess the spectral minimal detectable power (MDP) of the array (Fig. 3). MDP, which represents the incident power per pixel to get a unit signal-to-noise ratio at the array output, is defined as:

$$MDP = \frac{Noise_{array}}{R} \text{ (W)} \qquad \text{Eq. 1}$$

State-of-the-art MDP of 32 pW was measured at 2.5 THz with the array integrated in a camera operating at a 25 Hz frame rate (Fig. 3).

The current detector sensitivity below 1 THz is limited by the antenna dimensions (50µm long bow ties) and by the thickness of the quarter wavelength dielectric cavity (11 µm). However, this camera still offers competitive sensitivity levels that have been estimated below 1THz [4]: MDP of the sensor is in the nW range at 300 GHz and reaches its lowest value around 850 GHz with a MDP of a few hundreds of pW.

It is important to point out that micro-bolometer arrays can reach very-large-scale integration (VLSI) thanks to silicon process technologies. As illustrated by the growing commercial offer of IR bolometer array for consumer applications – for example some low cost IR imagers can now be connected to smartphones – this technology applied to THz will benefit from silicon microelectronics assets in terms of yield and cost when applications will emerge.

2.2 FET-based THz arrays

In addition to high-sensitivity micro-bolometer detectors, Leti is studying and developing THz detector arrays based on CMOS Field Effect Transistors (FET), either in direct or heterodyne detection [5].

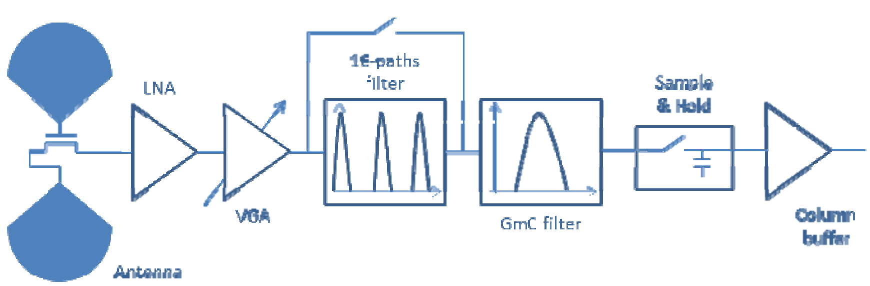

Figure 4. Block diagram of the in-pixel signal processing architecture for the direct CMOS FET detection.

THz transistor-based direct detection received a lot of attention for the last 10-15 years with many studies and demonstrations of antenna-coupled detectors implemented on CMOS or III-V technologies. Leti's researches in this field [6] are currently focused on innovative CMOS read-out-integrated circuit designs: proposed architectures (Fig. 4) take advantage of the large pixel pitch to enhance the flexibility and sensitivity through an embedded in-pixel configurable signal processing chain that reduces thermal and 1/f noises. A 31×31-pixels array has been demonstrated at 200-375 GHz in CMOS 130 nm technology (Fig. 1, b). The pixel size is 240×240 μm^2 and the total chip size is 8.5×8.5 mm^2. The power consumption is 210 µW per pixel. Video sequences at a rate of 100 frames per second have been achieved with a responsivity of 5-39 kV/W and a MDP of 128-1000 nW.

Heterodyne THz detection is an alternative development leveraging on Leti's strong experience in millimeter-wave transceiver developments for high data-rate wireless communications. Heterodyne terahertz receivers are equipped with mixers, usually pumped sub-harmonically, to convert the terahertz signal down to a low-frequency intermediate frequency (IF) with highly sensitive amplitude and phase detection capabilities.

In contrast to direct detectors which can be easily integrated in large arrays thanks to their small pixel size and low power consumption, heterodyne receivers are limited today to single-pixel or small array chips but they exhibit better sensitivities by several orders of magnitude. Single-pixel heterodyne source and detector circuits have been designed and prototyped (Fig. 1, c). Highly sensitive raster-scanning THz imaging at 278 GHz has been demonstrated with an equivalent NEP of 0.2 fW/Hz and a power consumption of 47 mW [7]. Such sensitivity that can be achieved at high frame rate makes this heterodyne sensor suitable for industrial in-line fast detection by a 1D-linear sensor, for example imaging objects carried by a conveyor.

3. A THZ PLATFORM TO TEST INDUSTRIAL APPLICATIONS

The investigation of THz imaging applications for industrial use-cases requires to combine state-of-the-art detectors, sources and optical components with rigorous experimental methodologies. CEA and i2S developed a THz experimental platform to address industrial needs in THz imaging and spectro-imaging for a variety of applications including, but not limited to, non-destructive control, material characterization or detection, THZ beam characterization, security, etc.

3.1 Uncooled THz bolometric camera for active imaging

CEA and i2S jointly developed a THz camera, named TZCAM, based on Leti's micro-bolometer array sensor presented in section 2.1 and fabricated in Leti's facilities (Fig. 1a). The camera system is developed by i2S and includes a dedicated electronics to supply and control the THz imager, an optics and the camera software. The supply chain includes also several subcontractors implementing standard industrial activities such as packaging, PCB manufacturing, mechanical machining.

Great efforts were carried out in order to achieve a cost-effective and high-performance vacuum sealed package that is compulsory for high performance sensitivity. Some of the challenges involved in the package design are to minimize the package size as well as processing/assembly operations; such developments were aiming at reducing the cost and embedding passive devices close to the FPA chip to minimize parasitics (capacitances, losses) that may increase the response time and noise.

Specifically, studies were conducted to optimize the radiometric budget of the optical path that encompasses the lenses and the vacuum packaging window. A 0.75-mm thick High-Resistivity Float-Zone Silicon (HRFZ-Si) plate is used as the package window with double-sided anti-reflection (AR) processing. Such AR coating minimizes reflection losses and in-band transmission ripples due to the optical index contrast between silicon and air or vacuum. Two main solutions were demonstrated for this purpose. The first one consists in coating the silicon window with a material such as Kapton having an optical index close to the square-root of the silicon index (i.e. $n \sim 1.8$) and a thickness of a quarter wavelength at the targeted frequency band. The second solution is to structure the silicon surface with sub-wavelength apertures of quarter-wavelength depth in order to obtain an equivalent optical index material close to the optimal value. Such micro-structuration can be done by sawing or deep etching, the latter being preferred at THz and above frequencies where a high aperture resolution and moderate depths are needed.

Figure 5. TZCAM i2S THz camera integrating the 320×240 bolometer array with a specific terahertz objective lens.

Table I: optical characteristics of the TZCAM camera optics.

Focal length	50mm
F/number	F/0.8
Useful bandwidth	100GHz-5 THz
Magnification	x-0.25 @196mm
Optical distortion	<1%
MTF10% frequency	> 7.6 cy/mm
Transmission	> 83% @120µm

The camera (Fig. 5) is equipped with silicon optics optimized for the 120µm (2.5THz) wavelength in order to give priority to high spatial resolution imaging. The pixel size of 50µm is well adapted for this wavelength, assuming possible F/number lower than 0.9. According to the preferred identified applications, the lens was designed to have 0.2-mm pixel resolution on objects, which leads to a ×0.25 (1/4) magnification (50µm pixel size). At F/0.8, the objective lens has a theoretical cut-off frequency of 10cy/mm (for 120 µm wavelength), which is exactly equal to the Nyquist frequency of the focal plane array. This condition leads to well sampled imaging systems, i.e. imaging systems that give higher possible resolution without aliasing.

The optical design work showed that the F/0.8 objective was achievable with two HRFZ Silicon lenses leading to good imaging quality at a distance of 196 mm. Lenses are coated with parylene as an antireflection layer. The pupil was chosen to be placed on the front lens to minimize the size and cost of the lenses. Since more than one aspherical surface leads to high alignment sensitive objective lenses, only one surface is aspherical. The image quality was optimized using a MTF criteria at 5 cy/mm (half cut-off frequency) better than 90% of the diffraction limit at 120µm wavelength for all field positions of the focal plane array, even when taking into account manufacturing and misalignment tolerances (Monte-Carlo analysis for more than 80/100 systems). The distortion is lower than 1% over the whole field of view.

Due to the wide transmission range and the constant refractive index of materials, this objective lens exhibits a very wide spectral bandwidth of 100 GHz – 5THz. If high transmission is needed, antireflection coatings of the lenses and the image sensor should be optimized for the selected frequency. Although optically optimized for 120µm (2.5THz), this objective lens is still very good for wavelengths down to 60µm (5 THz). The table I summarizes the optical characteristics of the lens.

3.2 THz test platform

In partnerships with academics and industrial companies, a comprehensive ecosystem was established to provide industrials with full development capabilities going from feasibility studies, proof-of-concepts up to prototype fabrication and tests. Addressing the industrial needs with THz imaging solutions requires not only a high performance camera but also high power and compact sources capable to deliver mW-range power levels with good temporal stability. Moreover, a THz beam engineering is frequently required to optimize the illumination of the scene. CEA Tech has set up a THz platform on its Bordeaux (France) site to address actual industrial use cases and provide industrials with a unique site to evaluate this new imaging technology.

The platform is equipped with two TZCAM THz cameras from i2S, both having broad detection range between 300GHz and 5THz. Several THz sources are available from 300 GHz up to 4.66 THz: solid-state sources (Virginia Diodes Inc) cover between 750 and 1mW between 300 GHz and 1THz, while quantum cascade lasers (QCLs) from Lytid deliver beams at 2.5, 3.36 and 4.66 THz with power from 1 to 3mW power depending on the operation mode (multi-mode or single mode). The three QCL chips are integrated in a single equipment giving the possibility to easily shift between frequencies and then perform multicolor spectro-imaging for material identification.

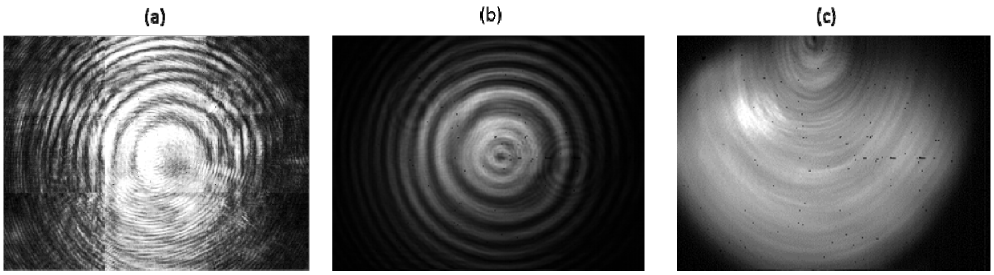

Figure 6. Native THz QCL beam (a), spatial filtering through 600µm hole (b), spatial filtering + mechanical mixing using a rotating THz diffuser (c).

Providing a uniform illumination of the object is generally a challenge in THz imaging systems. First, most of the THz sources like QCLs deliver a coherent light that generates interference patterns overlapping with the image (Fig. 6a). This phenomenon is often worsened by interferences in the optical components (mirrors, lenses) of the system. In addition, the far-field pattern of the sources is generally not uniform, and is rarely corresponding to a pure single-mode Gaussian beam and presents side-lobes.

Newly developed illumination methods can dramatically reduce the interference patterns and several strategies can be considered to mitigate non-uniformity issues of THz illumination. They include the fast (i.e. compared to detectors' response time) frequency modulation of the source, mechanical beam mixing using a high-speed rotating THz diffuser, and spatial filtering. Fig.6a shows a typical THz beam of the 2.5 THz QCL source with strong ring patterns. The same beam shows a better uniformity after spatial filtering through a 600µm hole placed at the focal plane of a secondary source created by a doublet of conjugated lenses (Fig. 6b). The projection of the beam on a THz diffusing rotating disk breaks the ring pattern (Fig. 6c).

The currently available experimental set-up exhibits satisfactory illumination uniformity for industrial applications as illustrated in the following section.

4. INVESTIGATING INDUSTRIAL APPLICATIONS

Terahertz imaging covers a large number of applications taking advantage of the unique properties of this radiation. A THz system can provide:

- See-through real-time imaging on a large field of view thanks to its high penetration property;
- Non-contact material characterization thanks to the specific spectral response measured when THz radiation interacts with matter that differs upon the chemical composition, relative content of water, or excitation frequency;
- Localization and identification of hidden materials when the previously functions are combined, i.e. penetrating imaging and spectroscopic analysis.

Such functions pave the way to a wide variety of industrial applications that the authors investigate with end-users in the test platforms. This chapter illustrates some of these opportunities.

4.1 Example of body scanner demonstrator for security applications

One market, which did already take off, is security applications. Body scanners, which work with sub-THz waves, are already routinely used at airports to screen passengers for weapons or explosives.

A THz body scanner has been designed and prototyped with a high operating frequency, bringing higher resolution than millimeter-wave portals. This scanner is based on an active imaging architecture combining reflective optics, a 2.5-THz QCL source and the bolometric 320×240 pixel array. A specific optical set-up has been designed in order to scan the beam towards the scene, here the chest of a person. A metallic horn ensures beam mixing to provide better illumination uniformity on the imaging plane located at 1 m from the demonstrator housing. A large plane mirror is used to illuminate an area size of 40×60 mm² in the scene and to collect the reflected and backscattered radiation from the imaged objects. Then a folded Newton telescope focuses the beam onto the camera FPA.

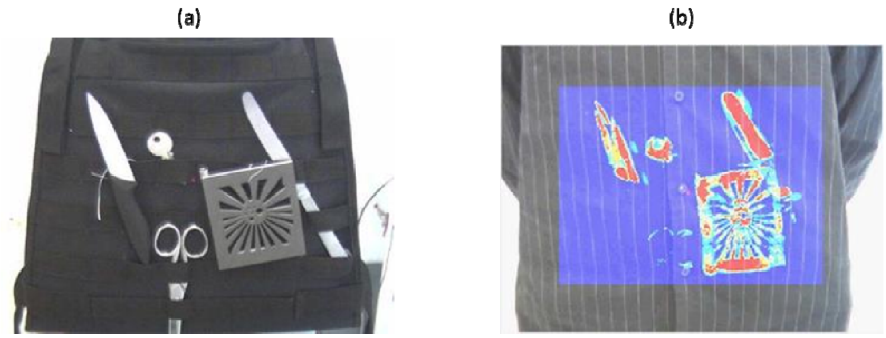

Figure 7: Visible image of hidden objects under a textile shirt (a), and raw tiled THz image (b)

As shown by the raw tiled THz image of Fig. 7, a human trunk of a typical 20×30cm^2 surface – where metallic and ceramic objects can be identified – has been successfully scanned in less than 10 seconds. This study demonstrates the opportunity of THz imaging for fast scanning on a large field-of-view, even with a long optical path (4 m long from the QCL source to the camera, of which 2 meters are in air) that is often considered as a major barrier in the THz range.

4.2 Non-Destructive Testing: transmission 2D-imaging.

Non-destructive testing (NDT) of industrial goods is very likely expected to be the most promising market. Of course, industrial NDT is already a wide field with a plethora of different existing sensors. The adoption of THz techniques is contingent upon the offer of advantages over existing sensors, i.e. they have to measure a crucial parameter which is not accessible up to now, or measure a parameter with a greater precision or at a lower cost. Hurdles are often the speed with which industrial items can be controlled and the price of THz systems.

Terahertz spectroscopy and imaging constitute promising non-destructive and contactless techniques that may be especially interesting in plastics industry and aeronautics. Quality control can be applied to reveal, for example, defects, bubbles inclusion or polymer composition deviation.
Detection below 1THz is of particular interest for many applications where moderate spatial resolution is needed while absorption in atmosphere and in objects is acceptable. On the other hand, the spatial resolution at higher frequencies is more accurate and can reveal very small defects.

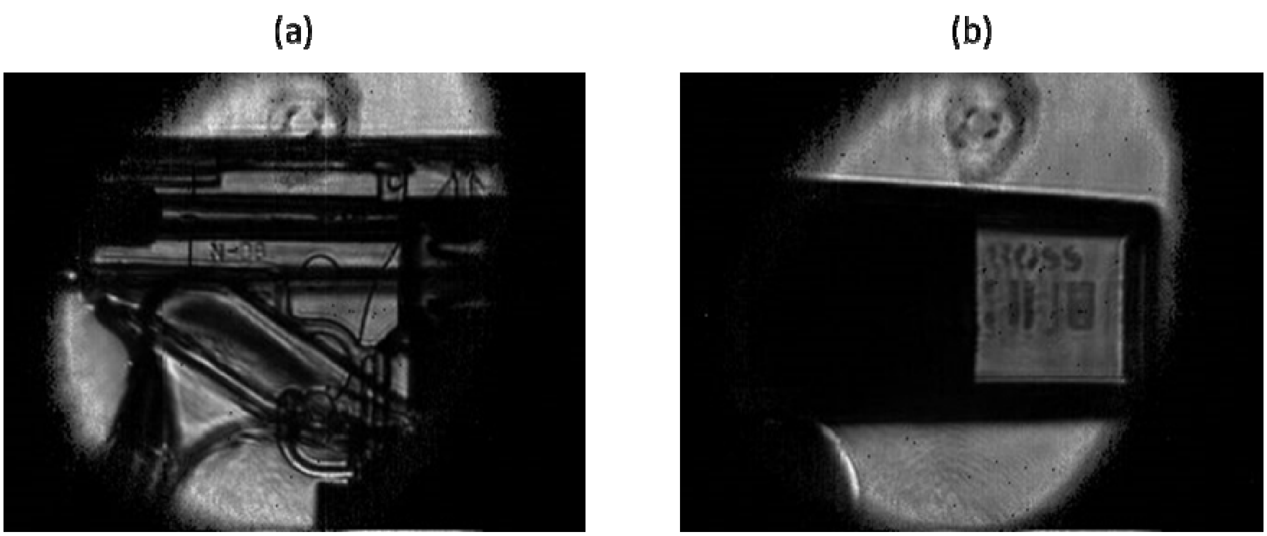

Figure 8: THz transmission image of a plastic household gun (a) and of the tip of a highlighter pen (b).

Real time acquisitions performed at 2.5 THz with a QCL as illumination source are illustrated in Fig. 8. The left image is a transmission image of a plastic household gun: it clearly shows the inner details of the mechanism and a reference hidden inside the parts. This picture illustrates the quality of the image and the resolution achievable at such frequency (about 120µm). The next example (Fig. 8b) corresponds to the transmission image of the tip of a highlighter pen showing the ink level and revealing the inscriptions on the opposite side of the marker.

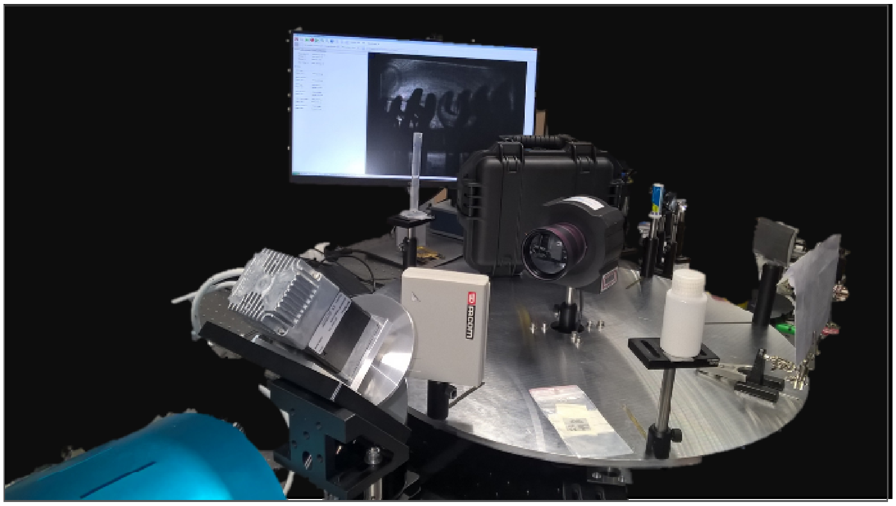

Figure 9: set-up demonstrating THz imaging for NDT applications of diverse materials and objects.

Recently, a specific set-up (Fig. 9) was built to demonstrate real-time transmission imaging through several objects and illustrate potential NDT applications. The illumination uniformity has been optimized as illustrated by the images in Fig. 10 & 11.

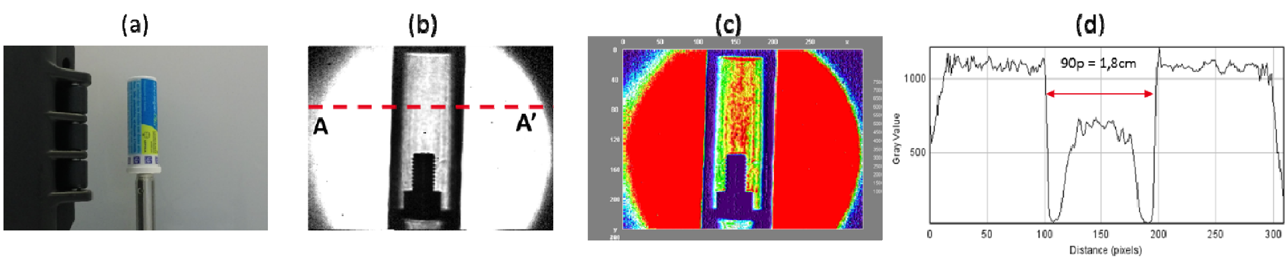

Figure 10: Visible (a), THz (b & c), images of a plastic aspirin tube with an inserted metallic screw. Inner dimensions extracted from the THz image on the A-A' line section (d).

For example, a metallic screw has been inserted in a plastic tube (Fig. 10a) and is revealed in the THz images (Fig. 10b and 10c). Inner dimensions can be extracted accurately from these THz images (Fig. 10d).

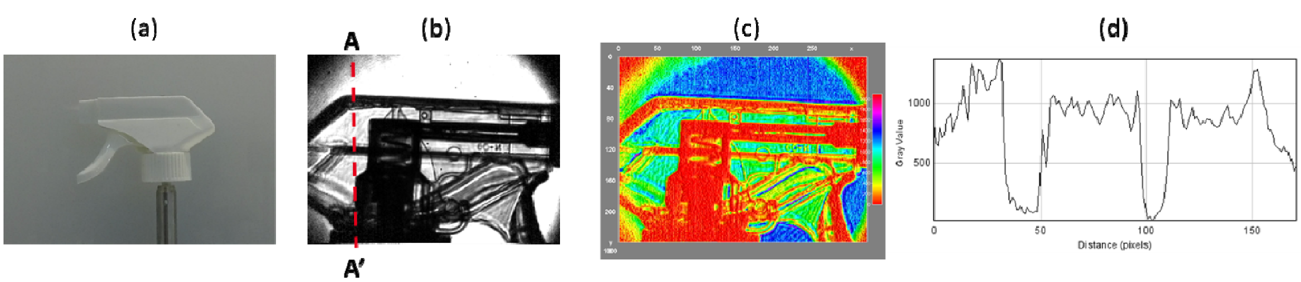

Figure 11: Visible (a), THz (b & c), images of a plastic water gun. Inner dimensions extracted from the THz image on the A-A' line section (d).

A second example is provided in Fig. 11 with the visible and THz images of a plastic water gun (Fig. 11a). THz images show the inner parts of the object, as well as the metallic spring. Again inner dimensions can be extracted from these THz images (Fig. 10d).

4.3 Non Destructive Testing: THz tomography

The penetrating property of THz radiations makes them very relevant for Computed Tomography (CT). Such technique requires multiple-angle image acquisition in order to reconstruct the 3D structure of the device under test. Unlike X-ray CT that is now a well-established technique, feasibility experiments of THz CT have to be carried out with real samples in order to assess the optimal wavelength to combine transparency, resolution, and ability to fairly image the sample.
In particular the acquisition time can be a barrier for industrial applications. The use of a large-format array sensor with real-time operation can potentially help in the reduction of the imaging time in comparison to CT set-up using single-point detectors.
First set of projections coming from the exterior of the sample have been acquired with the camera described in section 3.1. The 3D structures have been reconstructed with unoptimized inverse mathematical models as shown in the following images in Fig. 12 and 13.

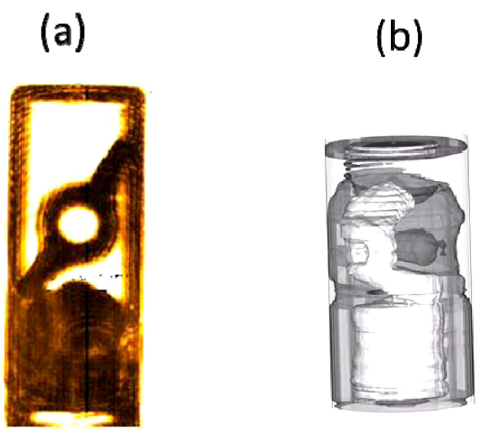

Figure 12: 2D THz image of a metallic thumb nub placed inside a plastic tube (a), THz 3D reconstructed image of the interior of the tube (b).

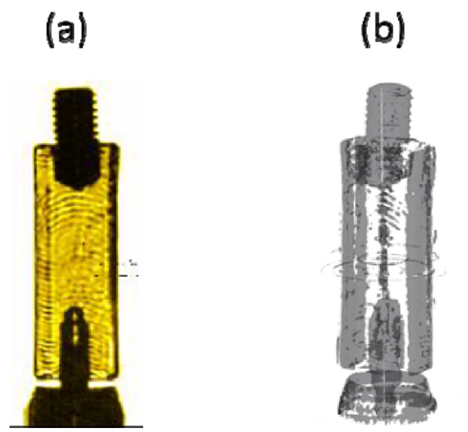

Figure 13: 2D THz image of metallic screws inserted in a teflon cylinder (a), THz 3D reconstructed image of the interior of the object (b).

Thanks to the recent improvements of the illumination uniformity, these preliminary 3D reconstructed images exhibit good resolution and enable non-contact inspection of the tested devices. This technique allows, for example, the detection and accurate measurement of defaults shape and dimensions.

5. CONCLUSION

As for other imaging sensor markets, the spread of terahertz (THz) techniques for industrial applications depends on the availability of components – sources, cameras, optics – that meet the criteria of high sensitivity, low cost and SWAP (size, weight and power). Monolithic silicon-based 2D sensors integrated in uncooled THz real-time cameras are good candidates to meet these requirements. Leti is currently developing such real-time imaging cameras based on 2 complementary technologies, i.e. bolometers and field-effect transistors. A CEA Tech industrial test platform is equipped with these cameras in combination with THz sources in order to test potential industrial applications from 300 GHz to 5 THz. Specific efforts have been carried out in order to improve the image quality, in particular the uniformity of illumination. Experimental tests have shown opportunities in fast see-through imaging on a large field-of-view, as well as in Non Destructive Testing of opaque objects. Preliminary tests of THz computed tomography have shown promising 3D reconstructed images with good resolution that enable non-contact inspection of the tested devices.

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REFERENCES

[1] Simoens, F., “THz cameras”, in “Handbook of Terahertz Technologies: Devices and Applications”, Ed. H-J. Song and T. Nagatsuma, Pan Stanford, April 2015, ISBN 9789814613088

[2] Simoens F., Meilhan J., “Terahertz real-time imaging uncooled array based on antenna- and cavity-coupled bolometers,” Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 372(2012), 20130111 (2014).

[3] Nguyen D.T., Simoens F., Ouvrier-Buffet J.-L., Meilhan J., Coutaz J.-L., “Simulations and Measurements of the Electromagnetic Response of Broadband THz Uncooled Antenna-coupled Microbolometer Array,” IEEE Transactions on Terahertz Science and Technology 2(3), 299 – 305 (2012).

[4] Meilhan, J., Delplanqu, B., Dussopt, L., Hamelin, A., Oden, O., Simoens, F., Monnier, N., Nicolas, J.A., Sicard, G., Ceolato, R., Guerineau, N., Hespel, L., Rommeluère, S., “Performance evaluation of state-of-the-art uncooled focal plane detectors for sub-millimeter imaging,” OPTRO 2018, to be presented (2018)

[5] Simoens F., Meilhan J., Nicolas J-A., “Terahertz Real-Time Imaging Uncooled Arrays Based on Antenna-Coupled Bolometers or FET Developed at CEA-LETI,” J. Infrared Millimeter Terahertz Waves 36, 961–985 (2015).

[6] A. Boukhayma, J-P. Rostaing, A. Mollard, F. Guellec, M. Benetti, G. Ducournau, J-F. Lampin, A. Dupret, C. Enz, M. Tchagaspanian, J-A. Nicolas, “A 533pW NEP 31×31 pixel THz image sensor based on in-pixel demodulation,” IEEE European Solid State Circuits Conference (ESSCIRC), 303-306 (2014).

[7] A. Siligaris et al., “A 278 GHz heterodyne receiver with on-chip antenna for THz imaging in 65 nm CMOS process,” in ESSCIRC Conference 2015 - 41st European Solid-State Circuits Conference (ESSCIRC), 2015, pp. 307–310.