BUYER'S GUIDE FOR a terahertz (THz) camera

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Many academic research laboratories use terahertz cameras to characterise sources, align optical tables, study physical phenomena, *etc.* At the same time, more and more applied research teams, in R&D institutes and companies, use these cameras to investigate the applications of terahertz imaging in varied domains such as security, non-destructive testing, or environment and health issues. In response to these needs, mature uncooled terahertz cameras are now being commercialized.

The terahertz domain is not specifically defined over the electromagnetic spectrum: it extends from roughly 100-300 GHz to roughly ten terahertz (1 terahertz (THz) = 1000 gigahertz (GHz)), partially covering the millimetre and sub-millimetre bands, down to the infrared (IR) region. This corresponds to wavelengths of a few tens of micrometres up to a few millimetres.

This radiation exhibits some unique properties: it penetrates numerous non-metallic and non-polar materials (such as paper, cardboard, textiles, plastics and ceramics), many interesting molecules feature specific spectral signatures that often do not exist on other parts of the electromagnetic spectrum, such as near- and mid-infrared, and finally it does not have any ionising effects and is considered as biologically innocuous (1 THz = 4.1 meV, which is a million times weaker than X photons).

These properties open new horizons in applications like medicine, biology and pharmacy (since terahertz waves do not alter DNA), domestic security (to check what people are carrying or the content of packages) or even non-destructive testing of manufactured products (for example, to detect defects in shape, contaminants and delaminations).

THz imaging will enable applications that need to "look inside" conventionally opaque materials that are transparent in this electromagnetic range, or to determine the chemical composition of samples by **spectral analysis**. In many cases, these two approaches could even be combined: multispectral or hyperspectral THz imaging would enable to simultaneously locate and identify the chemical nature of elements in an image.

The commercial spread of THz applications is conditional on the emergence of advanced technologies combining low cost and small size. These components are becoming available commercially, in particular the uncooled video[1] 2D-array THz cameras described in this article.

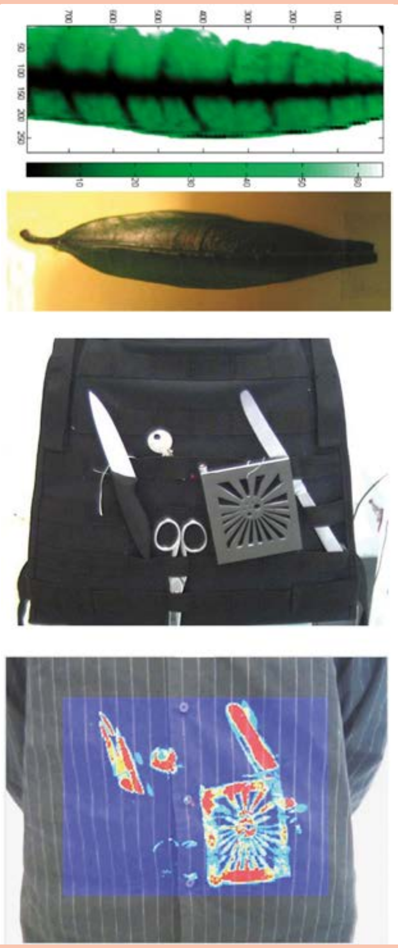


Figure 1. Examples of THz images (taken with CEA-Leti sensors). (a) Leaf in transmission. (b) Visible image of objects concealed on the chest. (c) Raw THz image of objects concealed under a shirt.

[1] '1D cameras', such as the Traycer T-Wave 1D, are also available commercially. It should also be noted that the Japanese company NEC has decided to stop manufacturing its bolometer-based THz cameras after several years of production.

Active imaging and passive imaging

There are two THz imaging methods. Passive imaging uses thermal radiation emitted by an object at non-zero temperature, whereas active imaging requires an external THz source. The low thermal power generated in the THz range requires the use of sensors with very high sensitivities (typically with a noise equivalent power (NEP) in the range of few fW/√Hz) that only cryogenic or heterodyne sensors can reach. The manufacturing and operating costs, as well as the size of these systems, limit them to applications such as defence, space and security.

Uncooled THz cameras can overcome these ‘market’ barriers, but in return, they require the use of external sources of illumination. Currently, at the same time as an increase in commercial sources, a dozen or so uncooled cameras are now available commercially (cf. table at the end of the article).

Main technologies used in uncooled cameras

Two main transduction phenomena are used in existing cameras.

(1) Thermal sensors convert optical radiation into heat at the level of each pixel. This local temperature change is in turn results in the variation of a physical property of the pixel, its electrical resistance (resistive bolometer) or its surface charge (pyroelectric effect).

The bolometric sensors of INO cameras have a micro-bridge structure very similar to that of standard IR sensors; absorption in the THz range is optimised by modifying the equivalent impedance of the absorber, either by coating it in extremely porous black gold or adding frequency selective surfaces (FSS) on the membrane.

In comparison to standard bolometers, the ones developed at Leti (integrated as detectors of the i2S TZCAM camera) are groundbreaking insofar as they separate the optical collection and thermometry functions. These two functions can therefore be optimised independently. Optical absorption is provided by the antennae located under and on the micro-bridge in conjunction with a resonant cavity between the antennae plane and the CMOS readout circuit. The heating of the antennae loads generated by the surface currents is then converted by a thermo-resistive layer placed on the micro-bridge.

Figure 2. i2S TZCAM camera integrating the technology of CEA-Leti bolometric 320×240 matrix sensors and an *f*/0.8 lens.

The Ophir Pyrocam camera features a matrix of 160×160 $LiTaO_3$ pyroelectric pixels connected by an indium ball to a multiplexing readout circuit. This camera also includes a mechanical chopper, required in this type of thermal sensor due to its sensitivity to current variations.

Another THz thermal camera (NeTHIS OpenView) firstly uses a membrane to convert THz photons into heat and then images the infrared (IR) emissions of this membrane using a commercial IR camera.

(2) Sensors based on electro-optical rectification in the channel of a **field effect transistor** (FET). In order to optimise the optical coupling of THz radiation, antennas are connected to two FET ports (*e.g.* gate and source) and a truncated hemispheric lens is placed above the antenna plane.

Main shared features of these cameras

Being quadratic, these sensors only provide information on the amplitude of the THz signal[2].

[2] Consistent THz sensors do exist but not, to date, in the matrix format used in commercial cameras.

With the exception of OpenView, Pyrocam III and Terasense, all of these cameras are based on direct detection by a monolithic sensor incorporating both the pixel matrix and the CMOS ASIC circuit[3]; this circuit provides the functions of multiplexing, filtering, amplification and video formatting of signals detected by each pixel.

The FET-based sensors of the Tic-Wave camera are processed directly in the CMOS silicon (Si) wafers, whereas the bolometer matrices of the INO and i2S-Leti cameras are produced collectively above the CMOS substrates according to standard microelectronic Si processes. This specificity provides miniature sensors and electronic processing in ASIC CMOS as close as possible to the pixels. It also offers opportunities for significant reductions in production costs if the volume of cameras sold were to increase.

Finally, it should be noted that only the two bolometric cameras mentioned are equipped with lenses with numerical apertures between 0.7 and 0.9 and focal lengths of a few tens of millimetres.

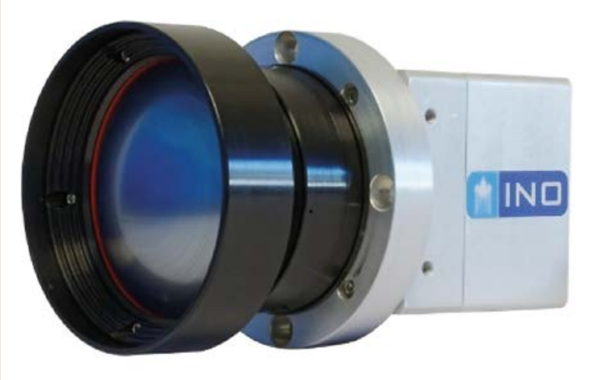


Figure 3. The INO MICROXCAM-384i-THz camera with integrated bolometric matrix sensor and equipped with its lens.

Criteria for choosing a terahertz camera

When an imaging system is designed, an initial sizing of the system can provide an assessment of the incident optical flux on the image plane, of the optimum operating frequency range, of the maximum possible video rate and of the spatial coverage.

In light of this system analysis, the first criterion to consider when choosing a camera is its detection threshold in the chosen spectral operating range. This is often the critical feasibility milestone to overcome, given the low level of optical power delivered by commercial THz sources (a few hundred mW at most in continuous mode with gas or quantum cascade lasers) and the heavy attenuation of radiation that occurs during propagation in atmosphere and through various obstacles and optical dioptres.

In order to compare cameras, this per-pixel sensitivity threshold should be calculated using the measurement of signals delivered by the matrix camera in video mode. It should be acknowledged that this setting is often unknown or misleading[4]. In particular, spectral absorption curves are

BRAND	PRODUCTS	INFO	CONTACT
i2S Vision	TZCAM camera with an f/0.8 20 mm lens, incorporating a 320×240 microbolometer matrix sensor (50 µm pitch, 25 Hz, CEA-Leti technology)	http://www.i2s.fr/project/camera-terahertz-tzcam/	Alexandre Besson Tel. +33(0)6 71 22 14 53 a.besson@i2s.fr
INO	MICROXCAM-384i-THz camera with 2 possible lenses (44 mm f #0.7 & f #0.95) and a 384×288-pixel bolometric sensor (35 µm pitch, 50 Hz)	http://www.ino.ca/en/products/terahertz-camera-microxca-384i-thz/	Pierre Talbot Tel. +1 (418) 657-70-06 pierre.talbot@ino.ca
NeTHIS	OpenView conversion membrane-based THz-IR camera combined with a commercial IR camera (256×320, 170 µm pitch / 512×640, 80 µm pitch)	http://nethis-thz.com/index.php/openview/	Jean-Pascal Caumes Tel. +33(0)6 47 16 93 22 / +33(0)5 47 74 62 10 jean-pascal.caumes@nethis-thz.com
TeraSense	GaAs FET IMPATT-based Tera camera (3 models: 16×16 / 32×32 / 64×64, pitch = 1.5 mm)	http://terasense.com/products/sub-thz-imaging-cameras/	Tel. +1 (408) 600-14-59 info@terasense.com
Tic-Wave	TicMOS-1px FET CMOS-based camera (up to 500 fps, 100×100 pixels)	http://ticwave.com/products.html	contact@ticwave.com
Newport/Ophir	Pyrocam IV camera based on a 320×240 pyroelectric sensor (pitch = 80 µm)	http://www.ophiropt.com	Nicolas Chaise, OPHIR Spiricon Tel. +33(0)1 60 91 68 23 / +33(0)6 01 01 27 32 nicolas.chaise@eu.ophiropt.com Ariane Billard, Newport Corporation Tel. +33(0)1.60.91.68.68 ariane.billard@newport.com

[3] ASIC: application-specific integrated circuit.

[4] For example, it is often difficult to know whether one of the settings has been calculated rather than measured, whether averaging has been used, the level of response from which pixels are considered functional, etc.

rarely given for the displayed frequency range, which is often very broad.

The sensitivity criteria can be defined by the minimum detected power (MDP, expressed in watts) at a given image frequency. The MDP is defined as the relationship between the RMS noise measured at the output of the camera (in Vrms) and the average pixel response (expressed in V/W)[5].

Bolometric cameras are the most sensitive, with MDPs in the range of a few dozen pW on peak absorption frequencies (a few THz), whereas the MDPs of FET-based cameras come close to dozens of nW (9 nW measured at 0.9 THz by the University of Wuppertal, which developed the Tic-Wave camera). The NeTHIS thermo-conversion membrane-based camera and the Pyrocam III camera have an MDP of around ten µW, but in return boast a very broad IR to THz response spectrum.

Spatial resolution and total acquisition period are often key specifications for the intended application. Preference should be given to the most sensitive sensors, but also the largest formats and fastest frame rates. Microbolometer-based cameras are the largest, typically a quarter of VGA, but they also have reduced pixel footprints (a few dozen micrometres). FET-based cameras are smaller, but have larger pixel footprints and are therefore more suitable for the spectral range, around 100 GHz. The frame rates of commercial cameras are all close to standard usual video frequencies.

Finally, cost is obviously a decision-making determinant, as well as the choice of THz sources and opto-mechanical systems that may be required. But in light of often very critical radiometric reports, this selection criterion is of secondary importance compared to those described above. We have yet to find the 'killer application' for this type of camera to take off and bring about more affordable prices, which the currently used technological approaches should allow. ■

FURTHER READING

[1] N. Oda *et al.*, *J. Infrared Milli. Terahz. Waves* **35**, 671 (2014)

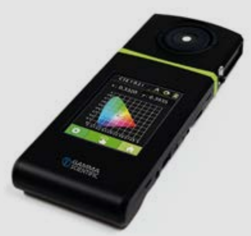
[2] H. Sherry *et al.*, in ISSCC 2012 (IEEE), https/doi.org/10.1109/ISSCC.2012.6176997

[3] M. Bolduc *et al.*, *Proc. SPIE* 8023, 80230C (2011)

[4] F. Simoens and J. Meilhan, *Phil. Trans. R. Soc. A* (2014)

[5] Four organisations developing these cameras, NEC [1], Tic-Wave [2], INO [3] and Leti [4], have determined the sensitivity of their matrix sensors based on this setting, allowing for comparisons with minimal assumptions and uncertainties.

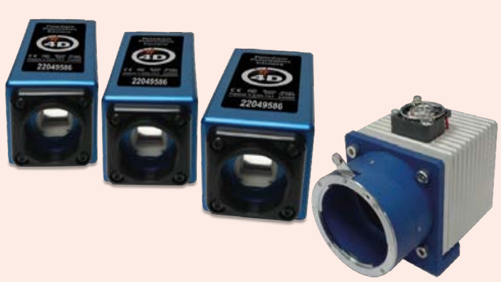
OUR SELECTION OF NEW PRODUCTS



Handheld spectrometers

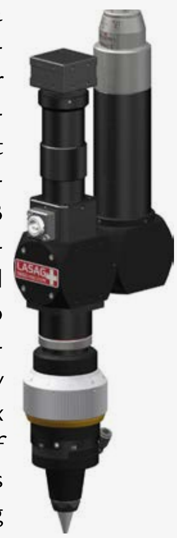
The PG100N allows light measurement with fully NIST-traceable performance. Through an integrated, high resolution color display, parameters such as LUX, CCT, chromaticity, CRI and SPD can be viewed instantaneously or monitored over time. The CMOS linear image sensor is effective from 380 nm in the UVA to 780 nm in the near-infrared. In addition to internal data logging, downloads via SD card, USB port or Wi-Fi mode allow data tracking and analysis with download capability in Excel and JPG formats.
www.gamma-sci.com

Micropolarizer cameras



The PolarCam snapshot micropolarizer camera simultaneously captures four polarization states in each video frame, enabling a range of image enhancement techniques and polarimetric measurements. CMOS technology sensors enable up to 164 frames/second imaging rate at 1700×1200 pixel resolution. A high resolution model captures 3.8 MP frames for detailed analysis of polarization even in fast-changing scenes. Customizable regions of interest make it possible to process a subset of the acquired pixels, resulting in frame rates in the kilohertz range.
www.4dtechnology.com/polarcam

Fiber laser processing head



The FLBK40 is a light weight, compact modular beam delivery system. Four different focal length collimators with QB connectors, to ensure that the head can be matched to the output characteristics of virtually any fiber laser. Six different sets of focusing optics (four for welding and two for cutting) enable focusing at a number of different spot size and working distance combinations. The integrated IR illumination and camera options guarantee good visibility of the work surface.
www.coherent.com