THz real-time cameras

Uncooled antenna-coupled bolometer array technology for real-life applications

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The CEA et a glance

is one of the largest research organizations in Europe, focused on energy, health, information technologies, and national defense

>16,000 People (10% PhD and Post Doc)

10 Research centers
CEA DRT: Leti-List-Liten business units

- **Leti**
  - Laboratory of Electronics and Information Technologies
  - 1800 personnes - 250 M€

- **List**
  - Laboratory of Integrated Systems and Technologies
  - 800 personnes - 90 M€

- **Liten**
  - Laboratory of Innovation for new Technologies for Energy and Nanomaterials
  - 1000 personnes - 160 M€

- **Micro-nanotechnologies and their integration in systems**
- **Software-intensive systems**
- **New energy technologies and nanomaterials**
Research Technology Organisations in EU

- **IMEC**
  - 270 M€
  - 3,833 pers.

- **TNO**
  - 512 M€
  - 3,833 pers.

- **SINTEF**
  - 315 M€
  - 2,100 pers.

- **VTT**
  - 247 M€
  - 2,700 pers.

- **FhG**
  - 1,500 M€
  - 17,000 pers.

- **FZK**
  - 396 M€
  - 3,580 pers.

- **TECNALIA**
  - 140 M€
  - 1,700 pers.

- **DRT**
  - 500 M€
  - 4,500 pers.

- **CSEM**
  - 45 M€
  - 390 pers.
CEA-Leti at a glance

**Founded in 1967 as part of CEA**

**1,700 researchers**
210 PhD students + 30 post PhD with 85 foreign students (35%)

**Over 1,880 patents**
273 generated in 2011
40% under license

**250 M€ budget**
~ 30M€ CapEx

**50 start-ups**
& **365 industrial partners**

CEO
Dr. Laurent Malier
PHOTONICS DIV. : IMAGING DETECTORS

Covering a wide spectral range

Radio  Microwaves  TeraHertz  Infrared  Visible  UV  X-rays

THz arrays  Sub-mm bolometers  a-Si μbolometers  HgCdTe  InGaAs  InSb  APS

LETI Focal Plane array for ESA Herschel satellite

THz imaging at CEA-LETI – Dr F Simoens – 2012-07-27
Terahertz imaging

- Market requirements for volume applications

**Plastic card NDT**

**Antenna radome**

**NASA shuttle foam**

**Industry**

**Security**
- Body scanning
- Mail screening

**Health**
- Cancer diagnosis
  - Darmo et al., Optics Express 12 (2004)

**Pharmaceutical control**

**Art**

- Reduced acquisition time
- Simplified optics – Limited scanning
- Compactness
- Easy-to-use
- Reliable
- Low cost in fabrication & operation
THz 2D images with standard IR µbolometer FPA

room-T 2.52 THz pumping CH$_3$OH vapor with a CO$_2$ laser → $P_{out} \sim 10$ mW

160x120 µbolometer FPA (BAE)
pitch =46.25 µm
(VOx) film /SiN air bridge

Ge lens ($f = 1$ cm)
HDPE filter

→ S/N ~ 13dB for unique frame
→ Resolution ~ 1.5 mm (limited by lens)

« Real-time, continuous-wave terahertz imaging by use of a microbolometer_FPA », Lee & Hu, October 1, 2005 / Vol. 30, No. 19, Optics Letters 2005
THz 2D images with standard IR μbolometer FPA

MIT, 2006

Ex. (very) cooled real-time THz cameras (1D array)

- **4K NbN bolometers at 0.6THz (VTT-NIST)**

- **4K NbN bolometers at 0.6THz (FhG Jena, Ge)**

Fig. 5. Freeze images of a person sitting on a lab chair, with a laminar mock-up hidden underneath its clothing. The images have been taken from a movie with 4 Hz frame rate.

Fig. 7. Close-up of the cooling line made with stainless steel and mechanical emitters.

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Ex. uncooled real-time THz cameras (2D arrays only)

- **Traycer (US)** 80x64 ou 100x100, 0.6 – 1.2 THz

- **Agiltron (US)** 130x190, 1-10THz
  Heterostructure Backward Diodes hybridized on CMOS ROIC

- **INO (Canada)**
  160x120 pixels, NEP<70pW @3THz

- **Univ Wuppertal-IEMN-STm (Ge-Fr)**
  FET CMOS 32x32, 7nW / pixel @0.9THz

- **NEC (JP)**
  320x240, NEP<100pW @4THz
2 complementary technologies

Both operate at ambient temperature (no cooling system) and exhibit sensitivity in the order of few pW.

<table>
<thead>
<tr>
<th>1. Bolometer large array real-time camera</th>
<th>2. CMOS antenna-coupled FET array direct detection camera</th>
</tr>
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<tbody>
<tr>
<td>High level maturity on large focal plane array imaging with real-time imaging capabilities mainly in the high frequency range, i.e. the QCL operation spectrum.</td>
<td>FET CMOS detectors imaging demonstrated for smaller arrays size and with sensitivity lowered as frequency rises. Advantage of very short relaxation time and suitability for heterodyne detection.</td>
</tr>
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</table>

320x230 pixel real-time video sequence demonstrated in [1.5-3.5THz]

Imaging demonstrated between 0.3 THz & 1THz

THz imaging at CEA-LETI – Dr F Simoens – 2012-07-27
Terahertz imaging

- Bolometer array technology: relevant features
  - Resistive amorphous silicon
  - Std Si microelectronic flow chart
  - Full CMOS compatible process
  - Monolithic FPA: Retina+ROIC
    - Reduced acquisition time
    - Simplified optics – Limited scanning
    - Compactness
    - Easy-to-use
    - Reliable
    - Low cost in fabrication and operation
  - Room temperature operation
  - Mature technology
  - High yield in manufacturing
  - 2D large arrays

- Real time FPA signal acquisition
- High performance CMOS ROIC (ASIC)
- Thermal insulation
- Interconnection
- CMOS substrate
- Readout circuit pad
- Reflectors
- IR radiation

- LETI base technology patents

Spin-off 2002

R&D in IRFPA since 90’s
3rd leader in IR sensor market
Innovative antenna-coupled µ-bolometer principle

- Cross-polarized bow-tie antennas
  - Direct coupling antenna
  - Stacked capacitive coupling antenna
- Quarter wavelength resonant cavity to enhance antenna gain
- Through–silicon Oxide Vias ensure CMOS connection
- Any frequency can be addressed by proper tailoring of antenna dimension and cavity

- IR bolometer based µ-bridge
- Size of bolometer independent of pixel pitch
  - Electro-thermal performances preserved
- Antenna current dissipated in resistive loads located within the membrane
THZ BOLOMETER ARRAY AT CEA-LETI

LETI know-how: from modeling to image characterization

2D imaging sensor design at CEA-LETI

Sensor Pixel array

Modeling (EM, Optics, thermal)

Flow chart definition (+Technological R&D)

Design & simulations of ASIC ROIC

External fondry

Collective manufacturing above CMOS ASIC

Characterizations

Read-Out-Circuit

ASIC layout

8" CMOS wafer

THz imaging at CEA-LETI – Dr F Simoens – 2012-07-27
Uncooled THz imaging bolometer array

- Technological features

Innovative µbolometer pixel *(CEA-LETI patent)*

Based on mature IR techno.

Operating at ambient temperature

Broadband spectral absorption

Cost - SNR compromise

Compact

2D FPA

Std Si microelectronic processes

Monolithic 2D sensor

High speed processing (CMOS ASIC)
Uncooled THz imaging bolometer array

- Real-time imaging 2D arrays fabrication & tests

**Innovative THz pixel**

- Uncooled THz antenna-coupled microbolometers
- Standard µ-electronic processes
- Broadband spectral absorption

**320x240 pixel FPA**

- Process above IC
- Advanced image signal processing (CMOS ASIC)
  - Monolithic 2D sensor
  - 320 x 240 50µm pitch pixels
  - Sensitive surface = 16x12mm²

**Imaging lab tests**

- Transmission optical set-up
- Real-time video output
- Sensitivity in the pW range
- Room T Operation

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Uncooled THz bolometer array performance

- Performances of 1.7 THz and 2.5 THz designs

<table>
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<tr>
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<th>Design 1.7THz</th>
<th>Design 2.5THz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Responsivity</td>
<td>5.9 MV/W</td>
<td>12.6 MV/W</td>
</tr>
<tr>
<td>FPA noise $V_{noise}$</td>
<td>400 µV (rms)</td>
<td></td>
</tr>
<tr>
<td>Threshold detection power</td>
<td>68 pW</td>
<td>32 pW</td>
</tr>
</tbody>
</table>

**Measured @ 2.5 THz**

**Spectral Absorption, CC polarization**

\[ R_{THz}^{P_{opt}} = \frac{V_{out}}{P_{opt}} \]
Leti – NEC – INO THz uncooled bolometer camera

- **Published NEPs**

  - **NEC**
    - TV/4 (320x240)
    - Pitch 23.5µm
    - NEP caméra < 100pW @ 3THz
  
  - **INO**
    - "Rf modified" THz bolometer
      - (not NEP for commercial camera)
    - Pitch 23.5µm
    - NEP caméra ≈ 70pW @ 3THz

  - **CEA-Léti**
    - TV/4 (320x240)
    - Pitch 50µm
    - NEP caméra < 30pW @ 2.5THz
Imaging demonstrations

- Raster scanning image: tree leaf

→ Humidity content imaging
Imaging demonstrations

- Real-time 2D imaging in transmission geometry: video of scissors concealed in an envelop
Imaging demonstrations

- Real-time imaging of THz TDS photoconductive emitter

15 fs Laser

THz Emitter

Optical shutter

Parabolic mirrors

PTFE lens

Flat mirror

Optical delay line

Detectors

THz power spectrum of the source

Spectral overlap ≈ 10% of overall signal is absorbed

Good SNR imaging is achieved

- Peak Voltage 332.5mV
- Background level noise 0.43mV
- SNR 29dB

Accepted for Optics Express + OTST2013 oral presentation
Imaging demonstrations

- Real-time imaging of THz TDS photoconductive emitter

2D images of a focused beam using a $f=50$ mm optics

Parabolic mirrors correctly adjusted

Misaligned parabolic mirrors

PTFE doublet (strong absorption)

Accepted for Optics Express + OTST2013 oral presentation

All images correspond to the same surface of $70 \times 75$ pixels.
THz spectro-imaging demonstrator

- THz frequency-sensitive imaging: 2 combined functions
  - THz 2D real time active imaging
    - THz 2D real time active imaging
  - THz spectroscopy
    - THz spectroscopy

QCL-based multicolor THz source → optical system → 2D bolometer imaging sensor

Broadband absorption 2D sensor

THz spectral fingerprints database

Multicolor 2D THz images

Location of hidden objects

Chemical nature identification

Design #1 with max. absorption at 1.7THz for one polarization

Design #2 with max. absorption at 2.4THz for the same polarization

η ~ 90%

η ~ 45%
THz spectro-imaging demonstrator

- **Principle**
  - Confocal illumination
  - Folded Newton telescope for collection

- Illumination
- Collection

- Uncooled bolometer FPA camera
- QCL-based THz source

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THz spectro-imaging demonstrator

- Camera integration
- 320x240 pixel FPA
- Specific vacuum packaging
- FPGA front-end electronics
- Camera housing
THz spectro-imaging demonstrator

Complete system

THz source (QCLs)

Uncooled bolometer camera
THz spectro-imaging demonstrator

- Real-time imaging of a concealed object

  - 4.8 x 6.4 cm² area imaged by the real-time camera in reflection optical configuration

  - Leti pattern covered by a nylon clean room coat
Real-time imaging of a concealed object

Resolution of the order of 2mm
THz spectro-imaging demonstrator

- Localization and identification of sugar pellets

- THz 2D real time active imaging

  - f1 = 2.5THz
  - f2 = 2.7THz

- THz spectroscopy

  - Broadband absorption 2D sensor
    - η ~ 90%
    - η ~ 45%
  - Design #1 with max. absorption at 1.7THz for one polarization
  - Design #2 with max. absorption at 2.4THz for the same polarization

- THz spectral fingerprints database
  - f1 = 2.5THz
  - f2 = 2.7THz
  - Maltose
  - Glucose
  - Fructose
  - Maltose 9%
  - Glucose 1%
  - Fructose 1%
Integration agility: Multispectral FPA

- **MUTIVIS FP7** → imaging in multiple spectral band for security applications
  - VIS, IR for surveillance
  - THz for spectroscopic analysis of threats

- **Monolithic detector** → FPA bolometers
  - Fully compatible with CMOS standard technology
  - Similar process flow for IR and THz antenna coupled bolometer
  - Low-cost both in fabrication and operation
Integration agility: Multispectral FPA

- Real-time VIS / THz simultaneous imaging
  - Very simple optical system → Tsurupica lens doublet
  - 2.5THz QCL modulated at 1.25Hz imaged through paper sheet
  - "CEA" test pattern imaged with VIS photo-diode
Perspectives

- 2009: 1st raster scanning imaging with single pixel
- 2010: Extraction of transmission coefficient of materials
- 2011: POP with single pixel
- 2012: High technological yield on 200mm (8'') wafer
- 2013: POP with single pixel
- 2013: 1st 2D video sequences
- 2013: Extraction of reflection coefficient of materials
- 2013: 2D array POP
- 2013: 2D video sequences in system configuration
- 2013: 2D sensor for 2D imaging
- 2013: Validation of spectro-imaging in reflection mode
- 2013: Spectro-imaging demonstrator

Technology ready for integration in real-life applications
Thanks for your attention