

La spectro-imagerie THz : bilan et perspectives

P.Mounaix

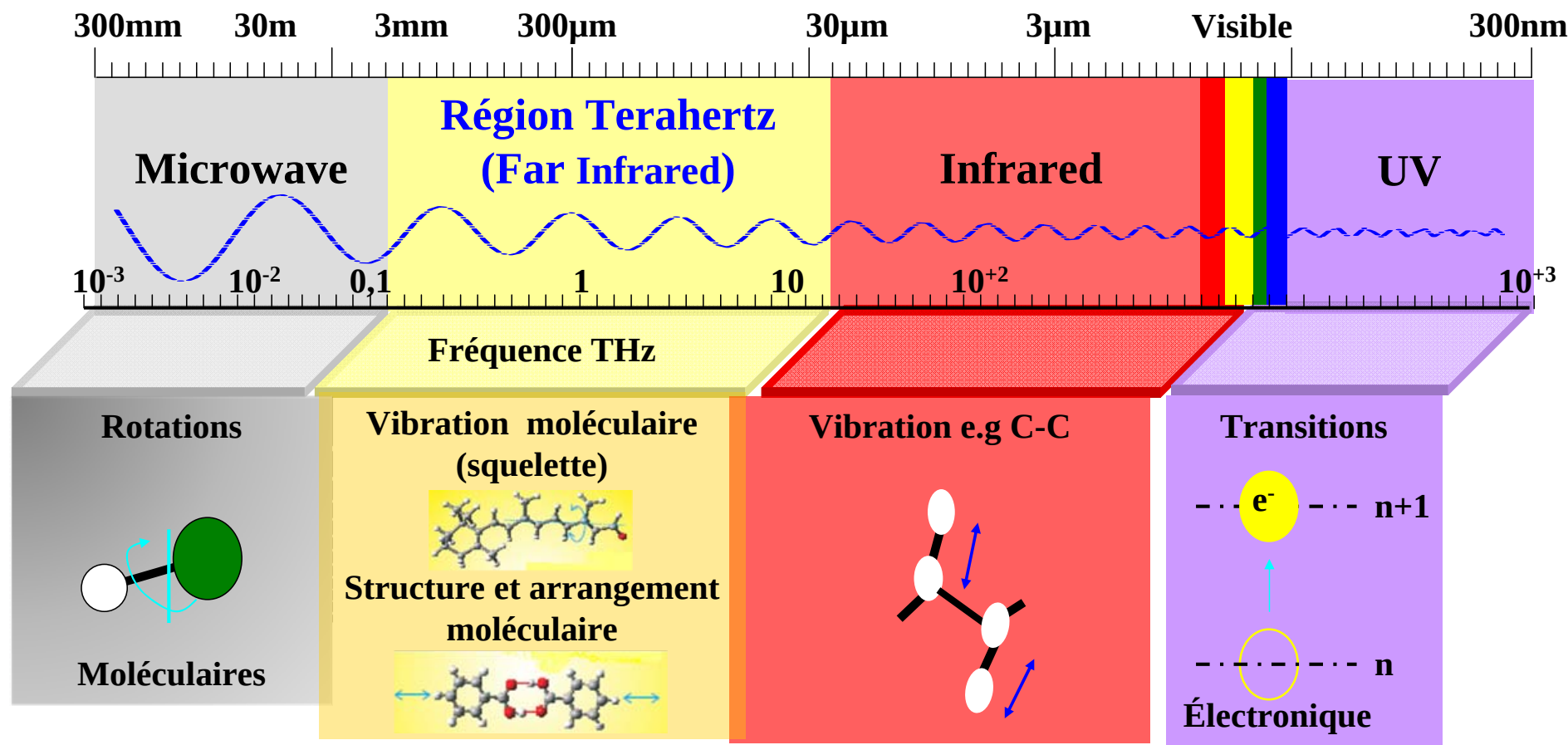
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[http://www.cpmoh.cnrs.fr/SLAM/terahertz-
spectroscopy-and-imaging/](http://www.cpmoh.cnrs.fr/SLAM/terahertz-spectroscopy-and-imaging/)

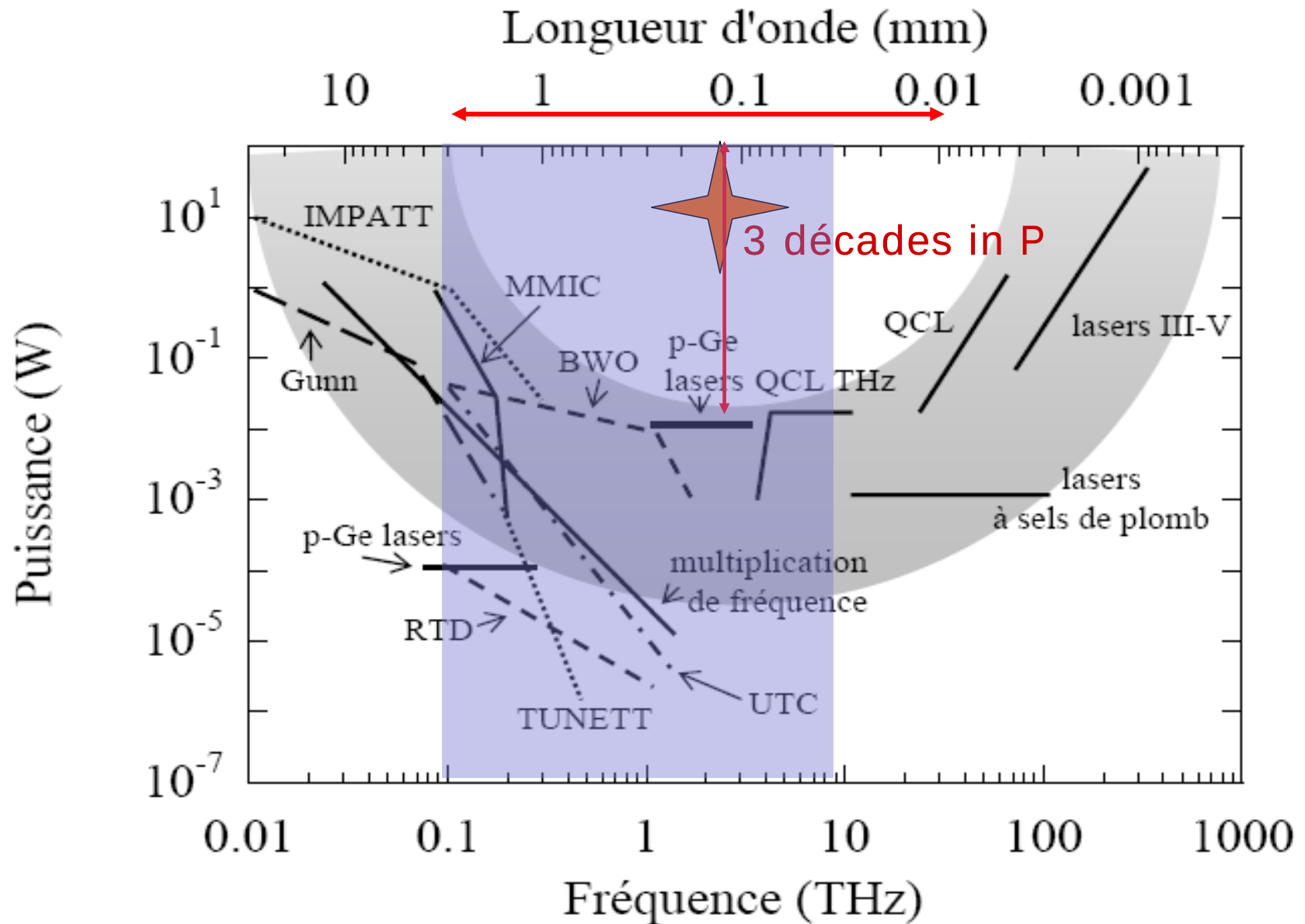
p.mounaix@cpmoh.u-bordeaux1.fr

- ✓ Contexte and Technique
- ✓ Génération & détection : Electronic versus optique
- ✓ La spectroscopie THz
- ✓ L'imagerie THz : Active et passive
- ✓ Exemples
- ✓ Conclusion

Spectre Electromagnétique



Terahertz area : 100 GHz ~ 10 THz
1 THz = 10^{12} Hz ~ 300 μm ~ 4.1 meV ~ 47.6 K
Low energy and non ionizing



Système Semiconducteur déclenchés optiquement:

Photoswitch ultrarapide

Emetteur de surface

Diode p-i-n, RTD

Méthodes fondées sur l'optique non linéaire:

Rectification optique

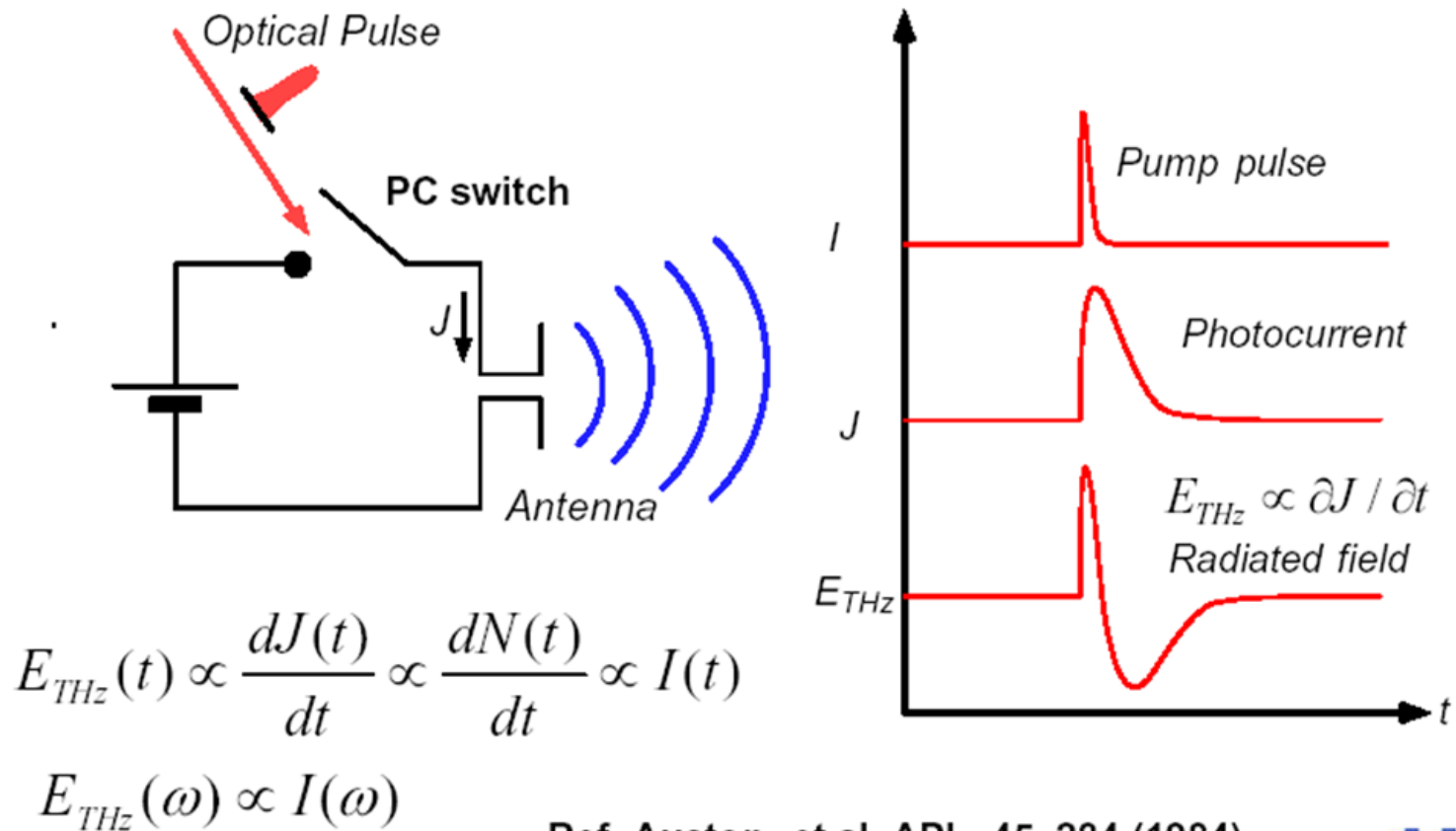
PPLN

Plasma

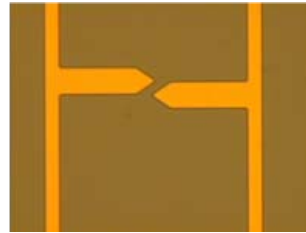
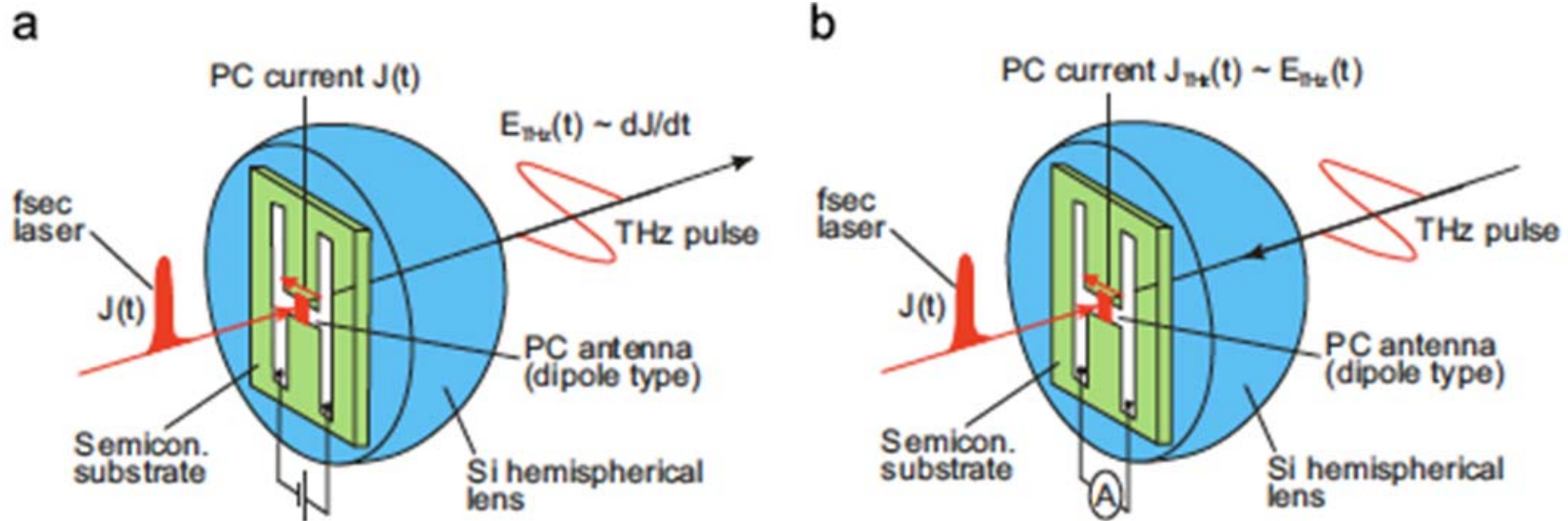
LASERS Ultracourts



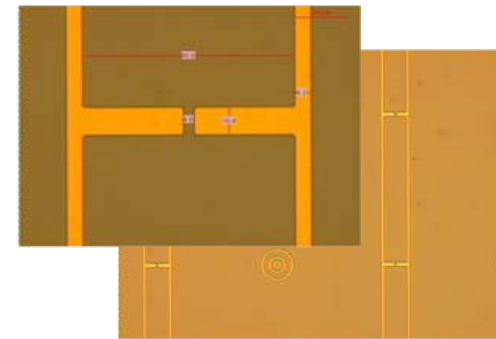
Generation of THz radiation by photoconductive (PC) switching

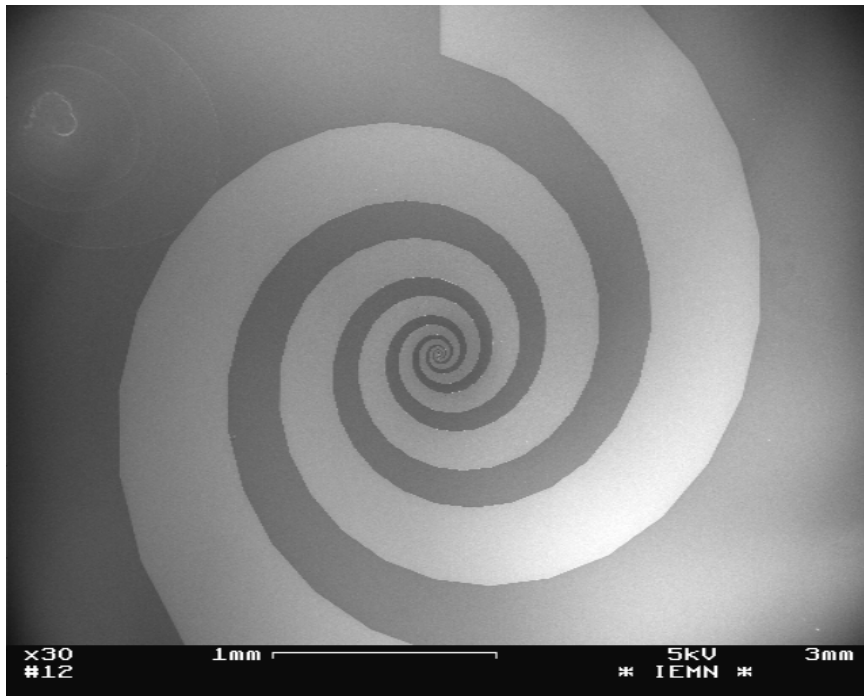


Photoswitch

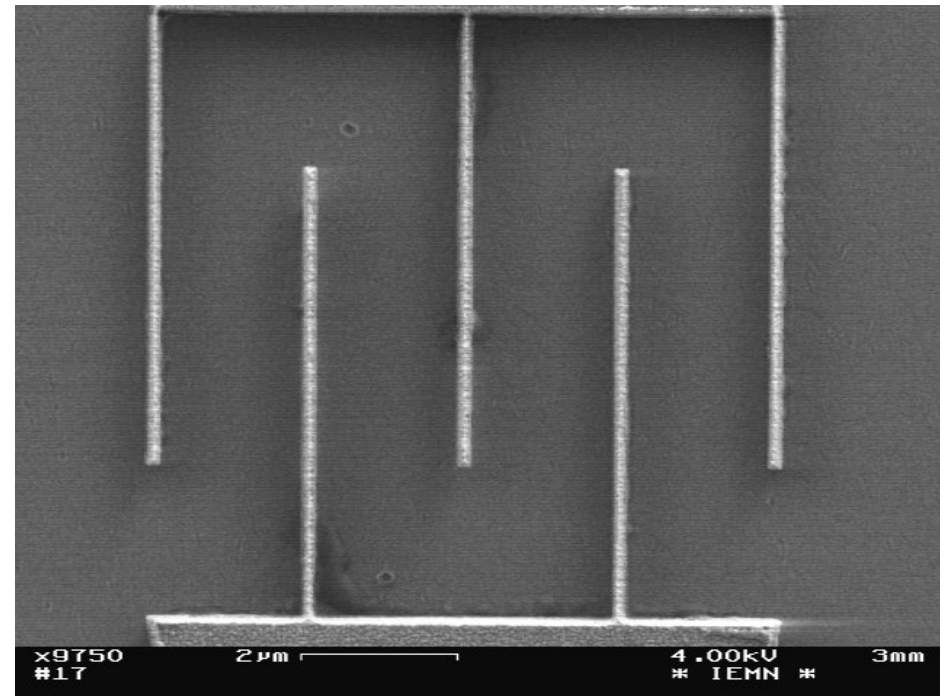


IEMN





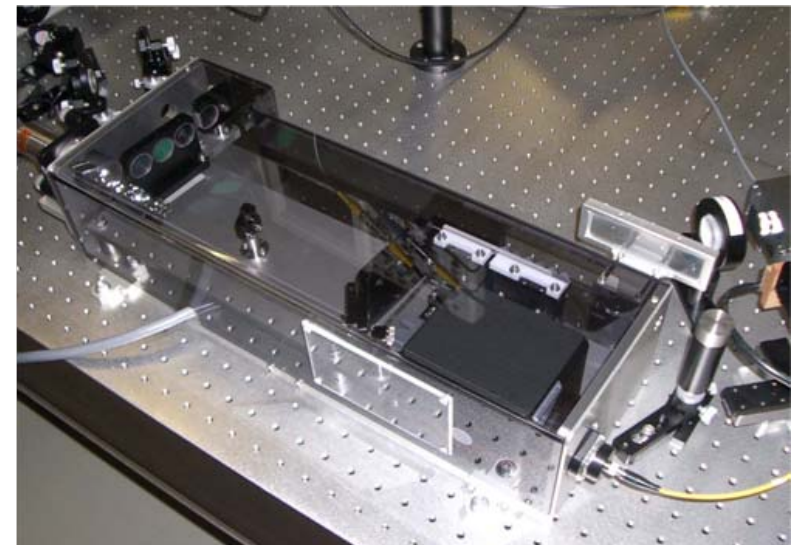
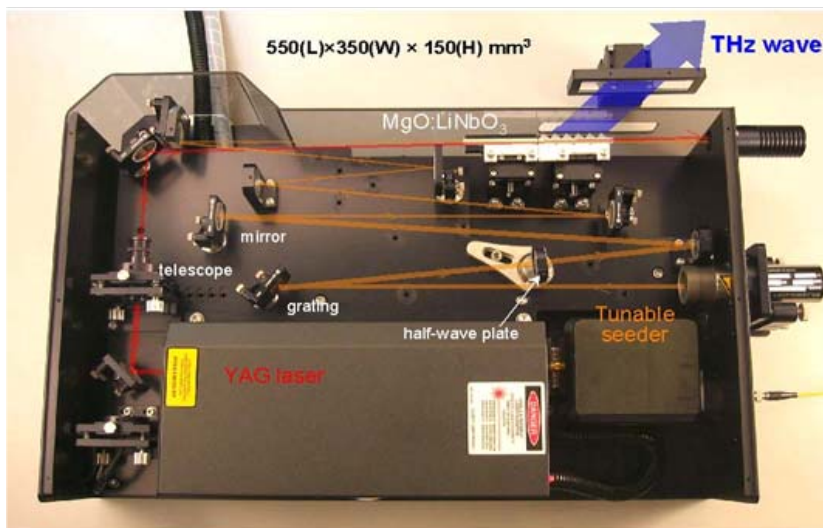
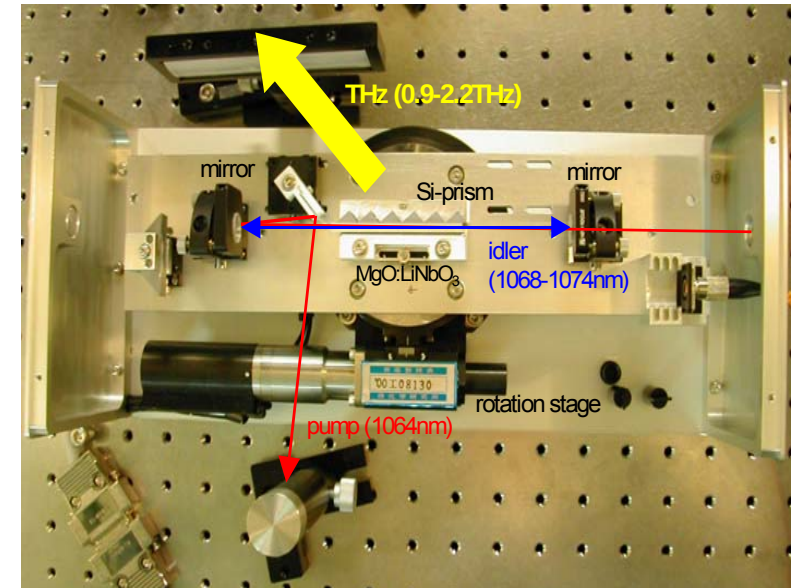
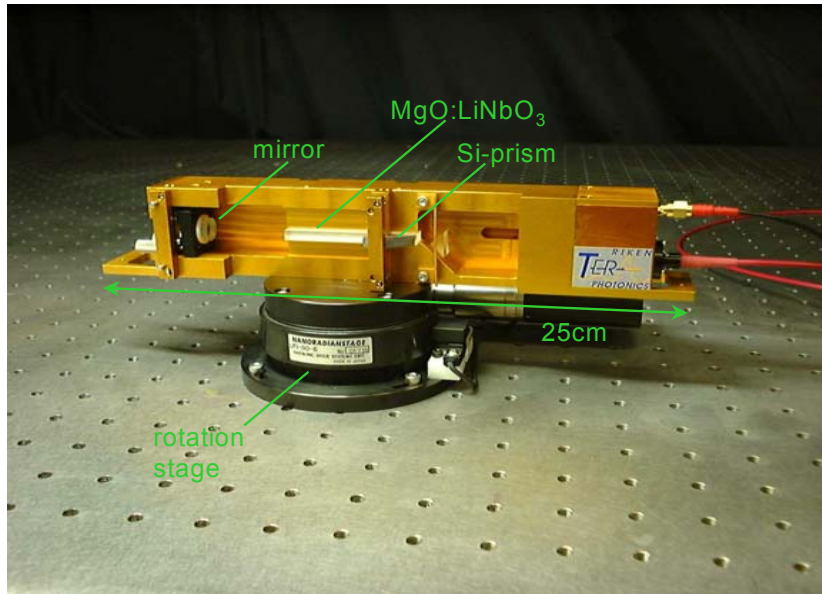
Logarithmic Spiral

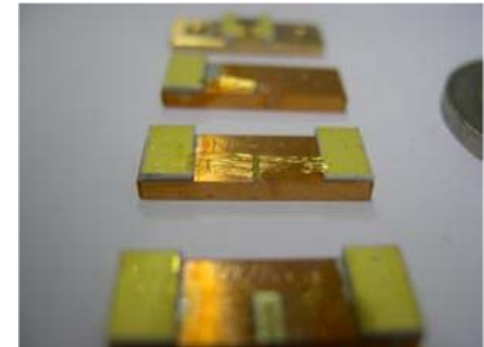
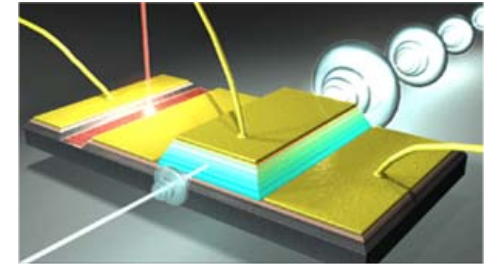
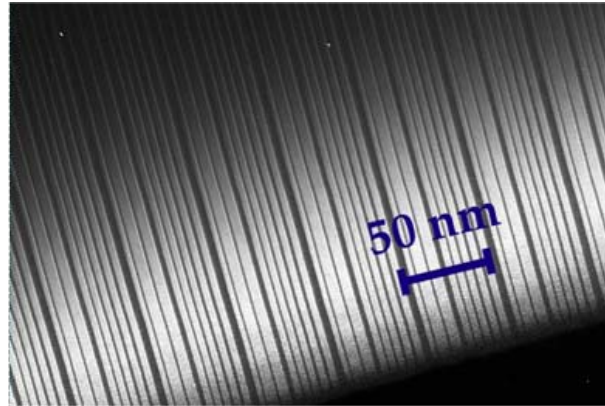


Interdigitated Comb

IEMN

Exemples de sources paramétriques





Conventional SC Laser

A single high energy photon is emitted per electron-hole pair recombination

Laser QC

A electron gradually loses its energy by emitting several low energy photons

Single-pixel THz detectors



He-cooled bolometer

Pyroelectric detectors



Schottky diodes

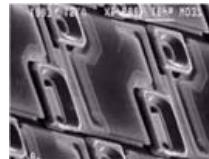


Golay cell

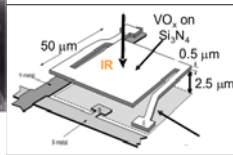


THz detector arrays

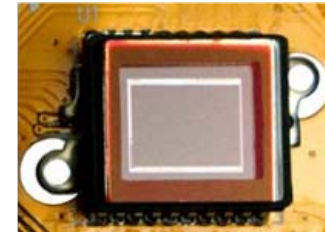
Spiricon Pyrocam



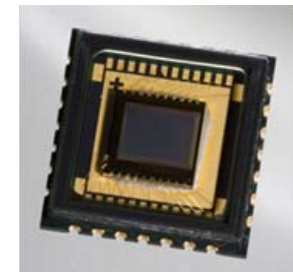
Microbolometer array



IR and visual imaging sensors



CCD chip



CMOS chip

Devices are typically

- Bulky
- High maintenance costs
- Expensive fabrication

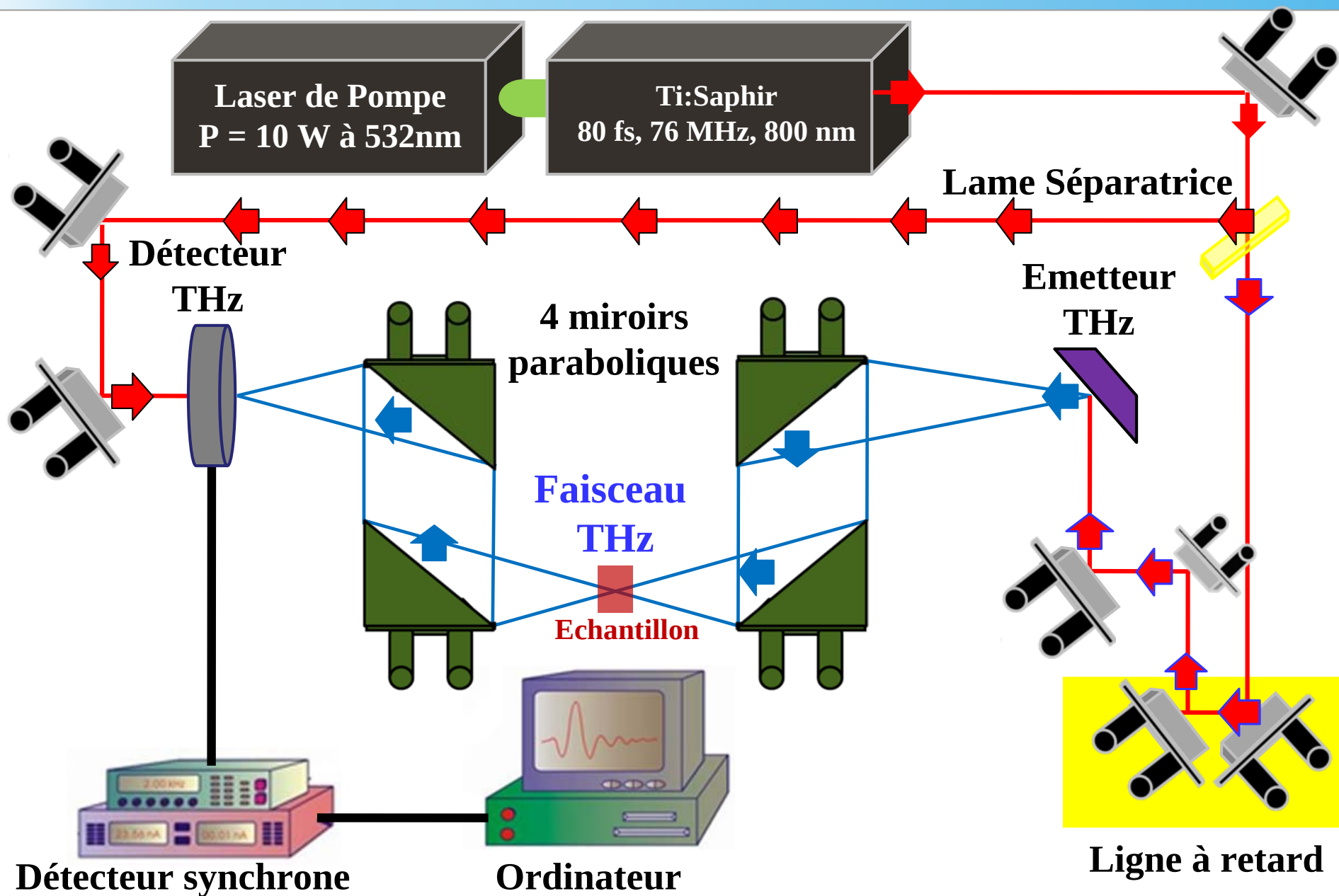
Specialized process technology

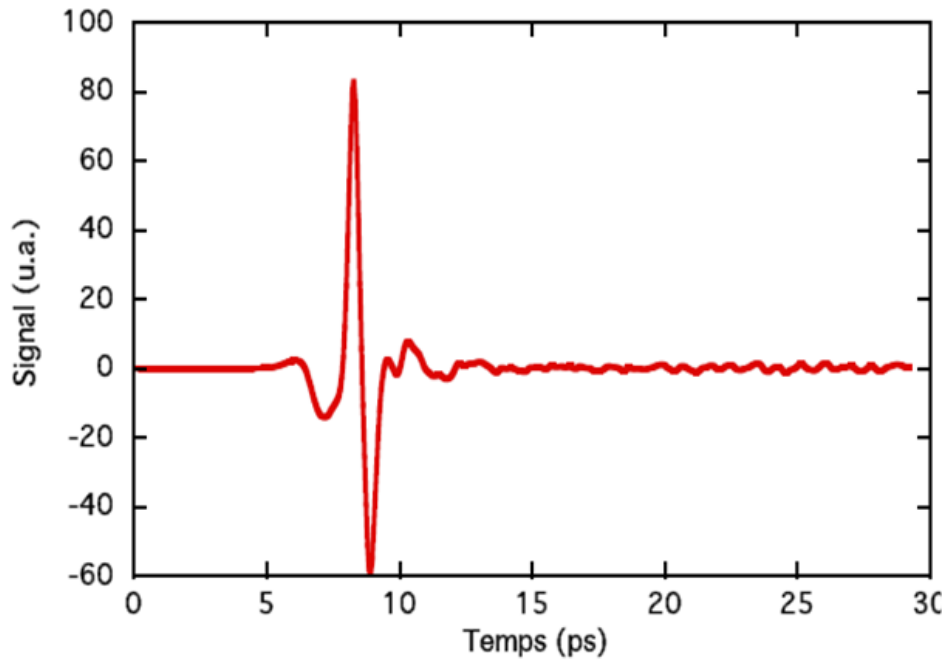
- Expensive
- Low volume
- Low integration levels

Based on silicon technology

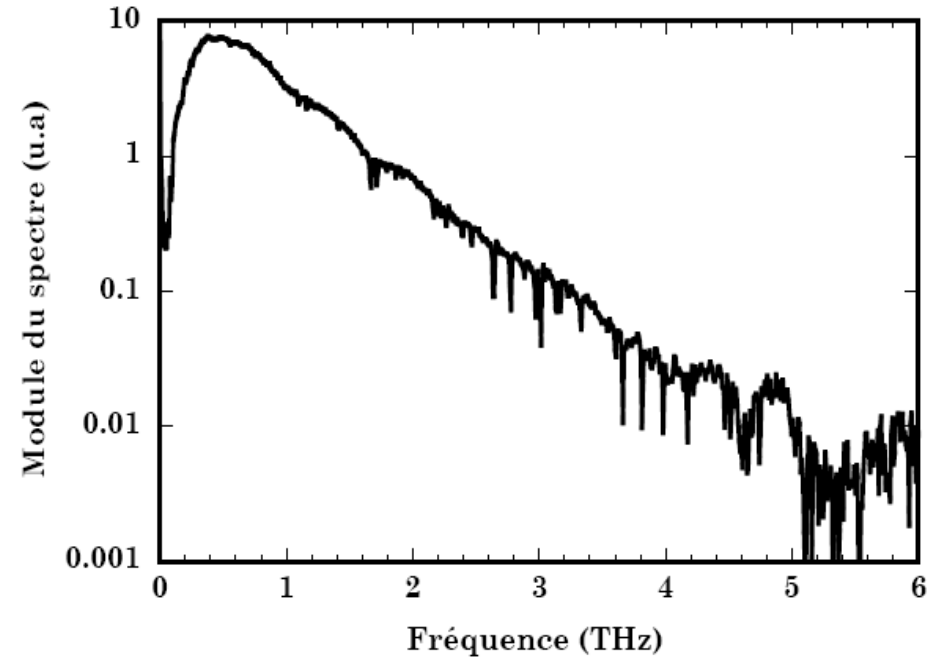
- Low costs at high volumes
- High level of integration
- Applicability to THz electronics?

Spectrometre terahertz





Typical THz Pulse. Nearly Monocycle Electric Pulse



FFT Spectrum of the THz pulse

Measuring the electric field in the time domain

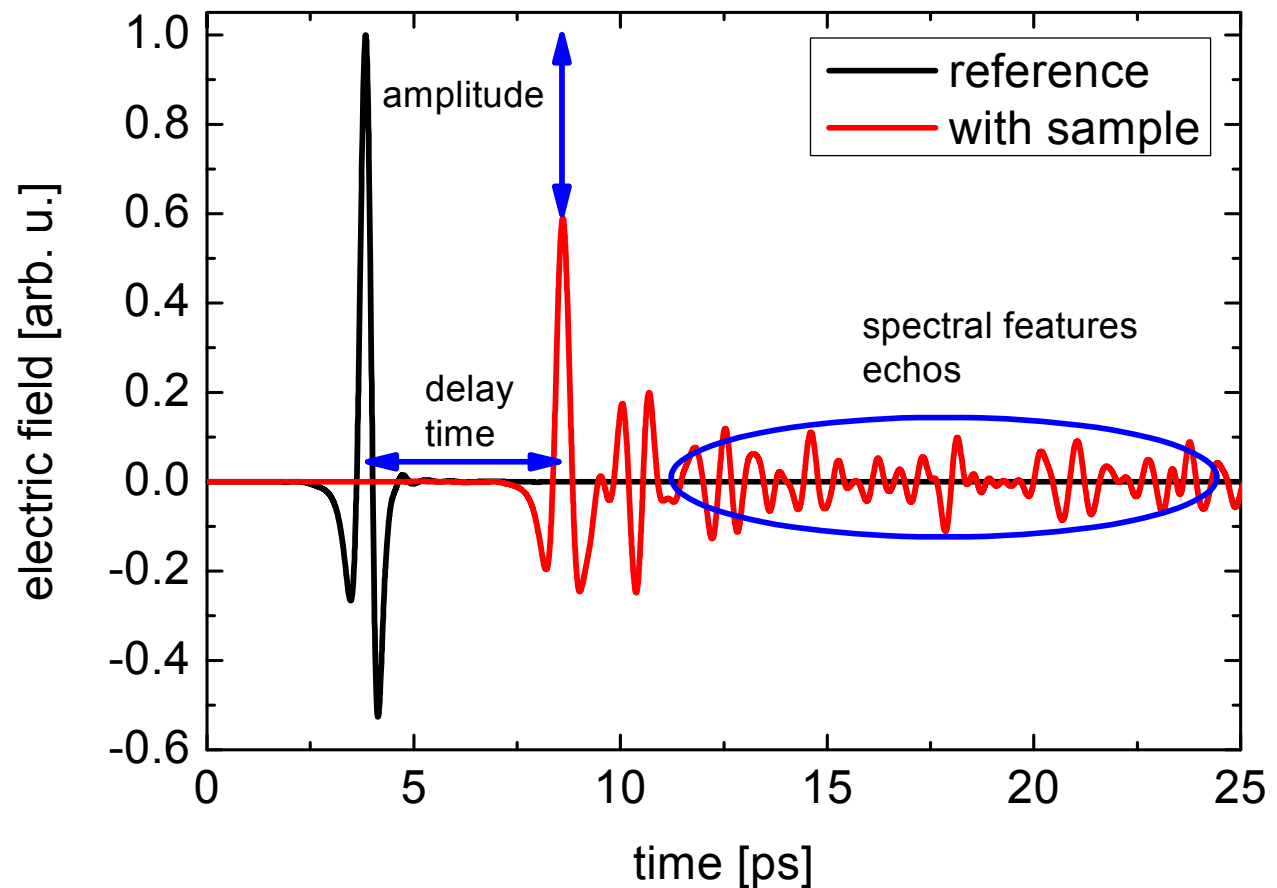
Coherent detection with high S/N ratio

Information about:

Amplitude/Intensity

Time delay

Spectral content



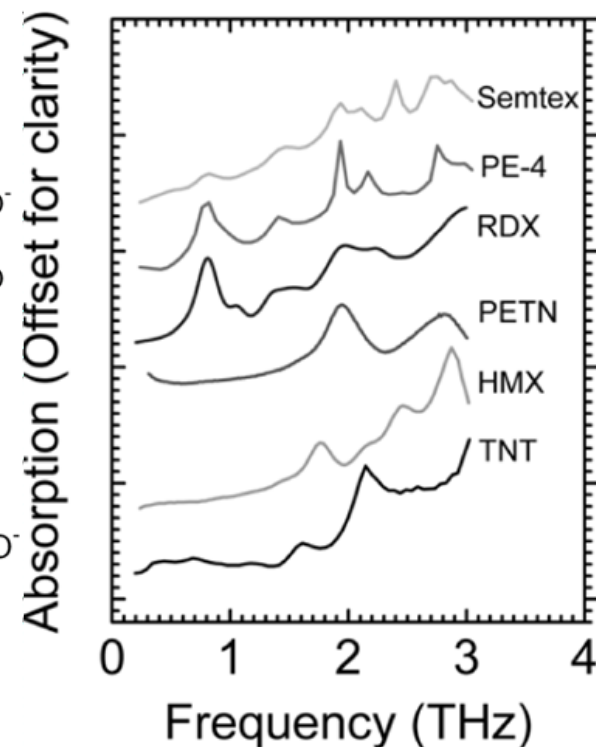
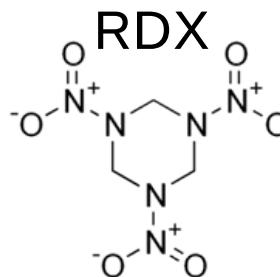
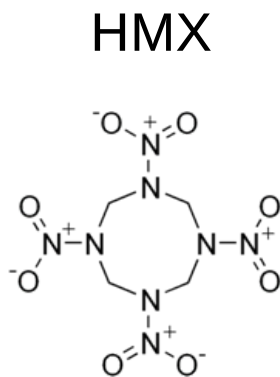
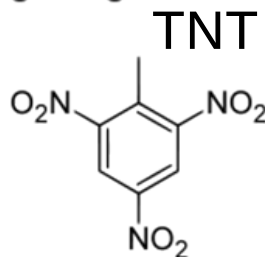
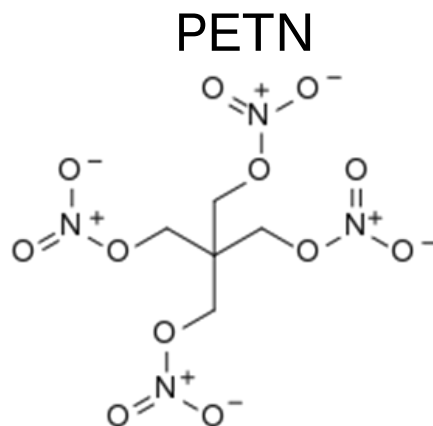
FTIR (Fourier Transform IR Spectro.)

Gases, Liquids, Solids, Polymers, SC

Inorganic/Organic Crystals, Ferroelectric (Phonon, Polaron, ...)

Explosives

Flame



+Radiation très peu énergétique

→ Non ionisante(T-Ray vs. X-Ray)

+Transparence (vs. Opaque dans le domaine visible)

+/- Absorption de la vapeur d'eau

- Resolution l_{THz}

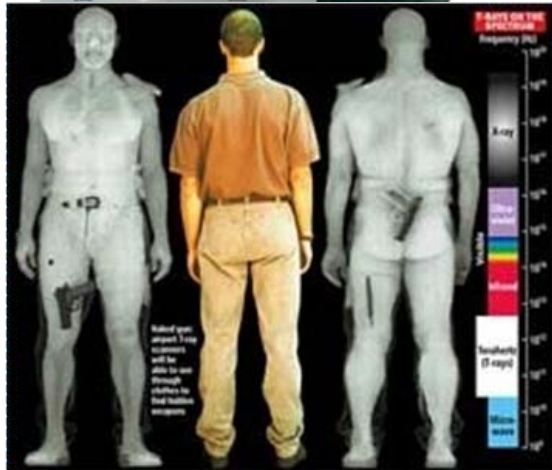
- Brillance des sources

Portiques:



Détection de :

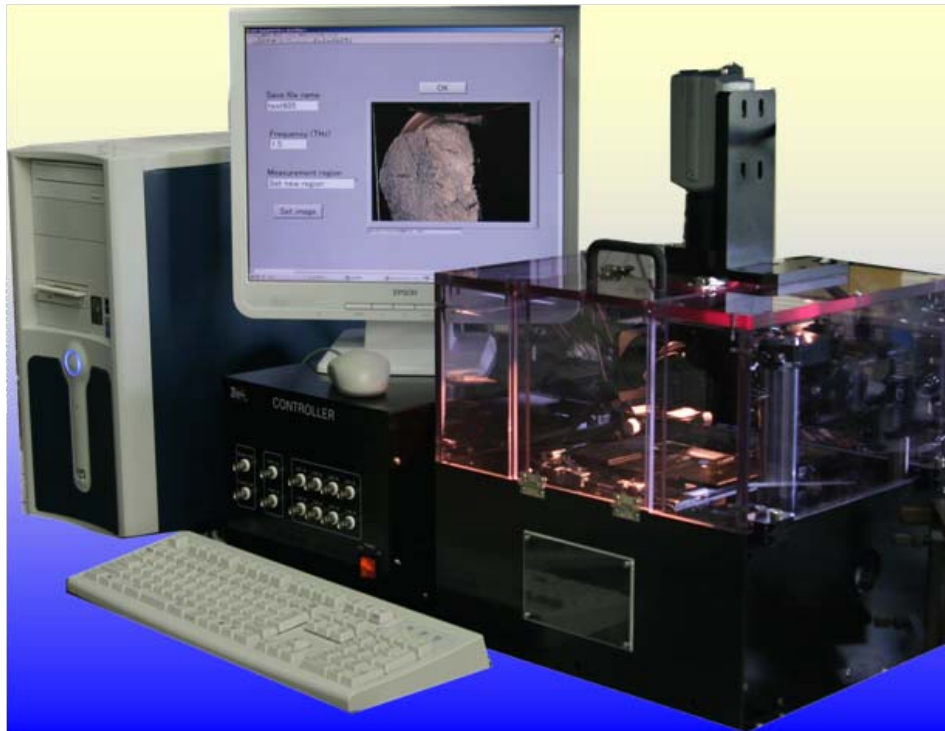
- *Metal and non-metal*
- *Armes*
- *Drogues*
- *Liquides dont alcool*
- *Ceramiques, Plastiques etc.*



SMITHS TADAR



- Imagerie „ temps réel“
- Rapport signal-à bruit
- Faible ouverture numérique
- Résolution limitée par la longueur d'onde



Domaines applicatifs :



- ✓ Biologie
- ✓ Défense et sécurité
- ✓ Environnement : détection de gaz : cov

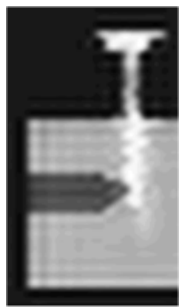
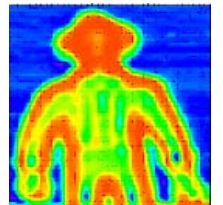
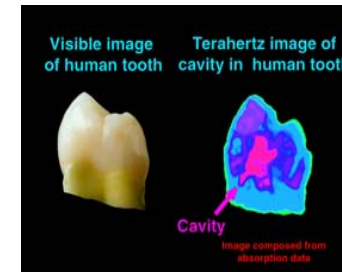


Applications:

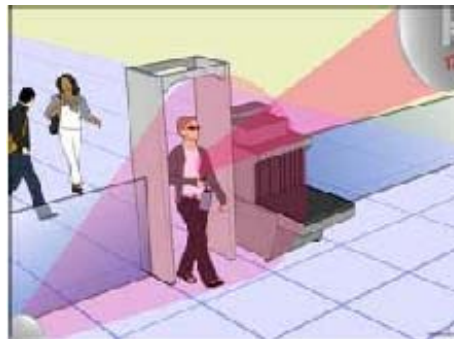
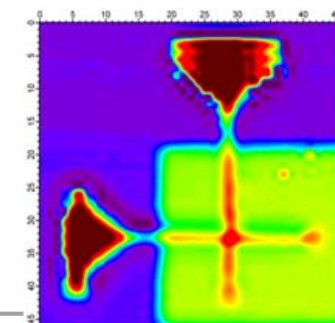
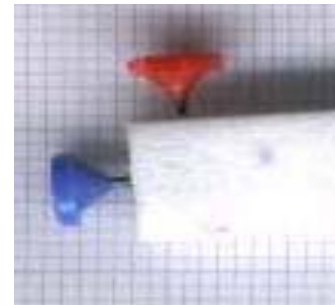
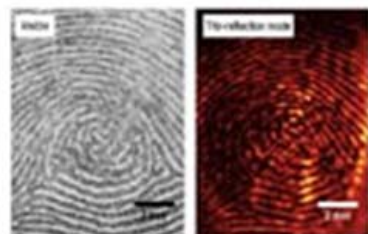
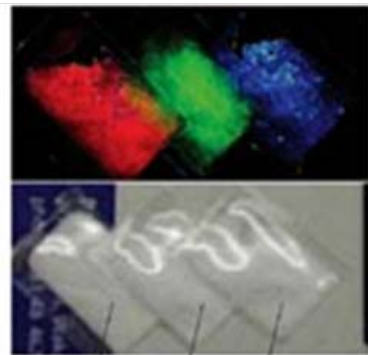
Sécurité

NDT (Non Destructive Testing)

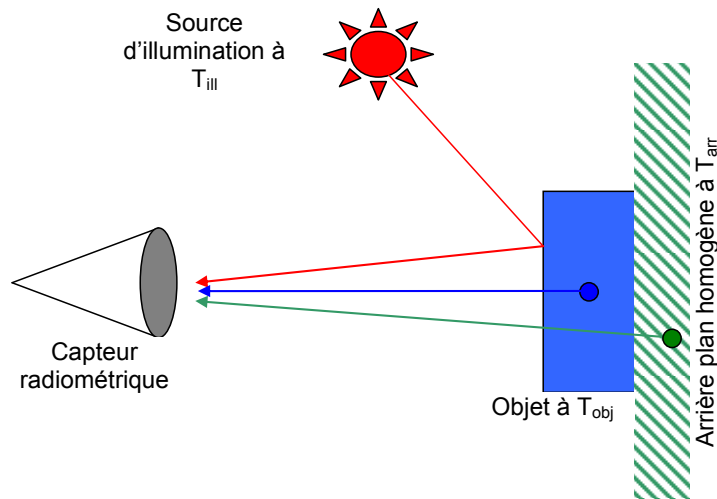
Medical (Not 100% Sure)



Spot the knife? Millimeter waves, close to terahertz, show their ability to see through clothes and paper.



- Radiométrie = mesure de l'intensité du rayonnement électromagnétique
- Tout corps dont $T > 0K$ émet un rayonnement électromagnétique (auto-émission)
- L'intensité du rayonnement d'un corps est également liée à la réflexion des ondes générées par les sources d'illumination externes ainsi qu'à la transmission des ondes émises par la scène située en arrière plan.
- Ces trois contributions peuvent être décrites par les composantes « réflectivité » (R), « émissivité » (ϵ) et transmissivité



Ces composantes dépendent des caractéristiques physiques et géométriques des matériaux tels que la permittivité (ϵ) et la perméabilité complexes (μ), l'angle d'incidence (θ_i), l'angle formé entre le champ électrique et le plan d'incidence (α) ainsi que la polarisation de l'onde (p).

Température équivalente reçue par le capteur radiométrique:

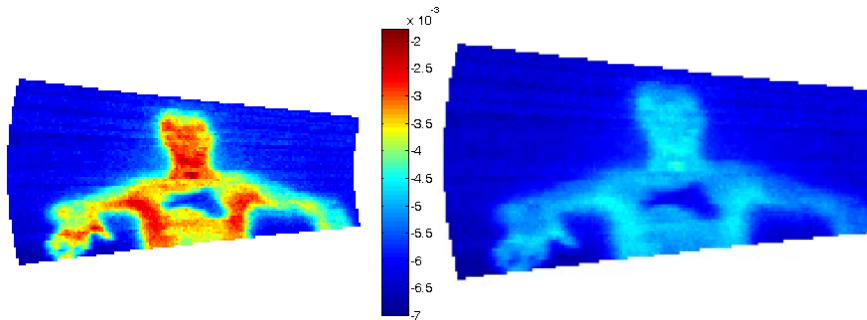


Image radiométrique passive à 90GHz d'une personne située à 2 m de l'objectif et portant sous sa veste un revolver

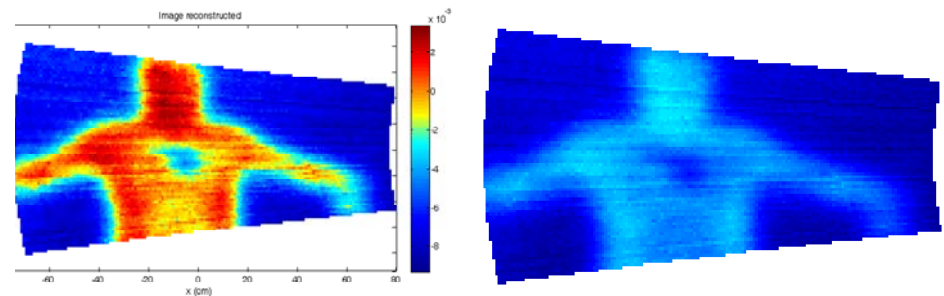


Image radiométrique passive à 30 GHz d'une personne située à 2 m de l'objectif et portant sous sa veste un revolver

- Le revolver est parfaitement visible sous la veste à 90 GHz
 - Levée de doute réussie, résolution spatiale suffisante
- Le revolver est visible sous la veste à 30 GHz mais le forme est mal définie
 - Résolution spatiale insuffisante

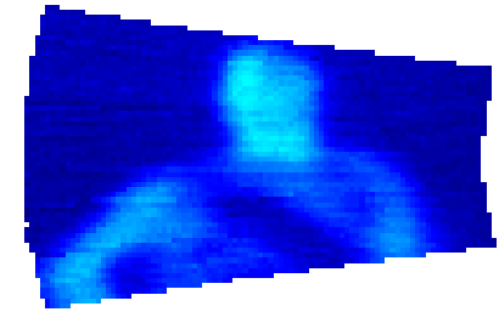
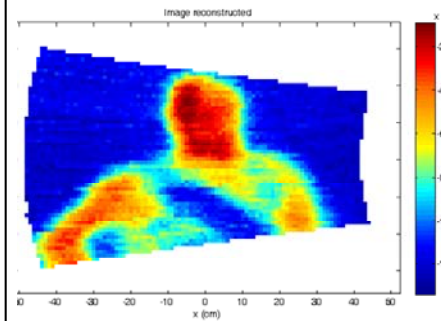
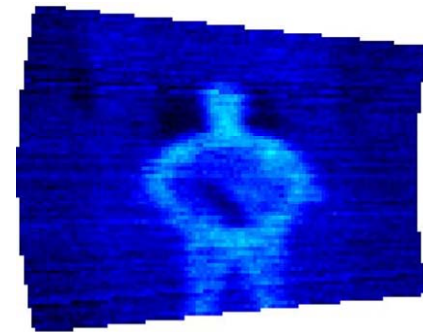
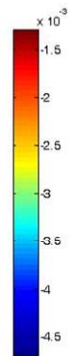
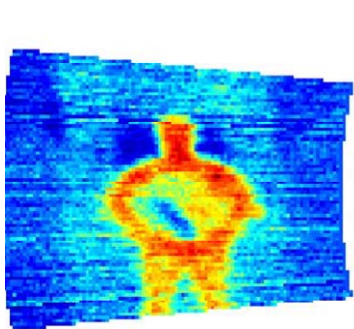


Image radiométrique passive à 90GHz d'une personne située à 6 m de l'objectif et portant dans son sac à dos une bouteille d'eau en plastique à Tamb

Image radiométrique passive à 30GHz d'une personne située à 2 m de l'objectif et portant dans son sac à dos une bouteille d'eau en plastique à Tamb

- La bouteille d'eau est visible à travers le sac à 90 GHz à 6m et 30GHz à 2m
 - Levée de doute non réussi, résolution spatiale insuffisante
 - Signal d'alarme donné

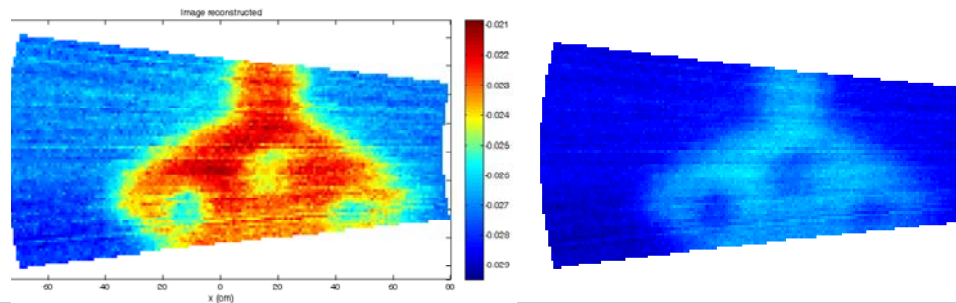
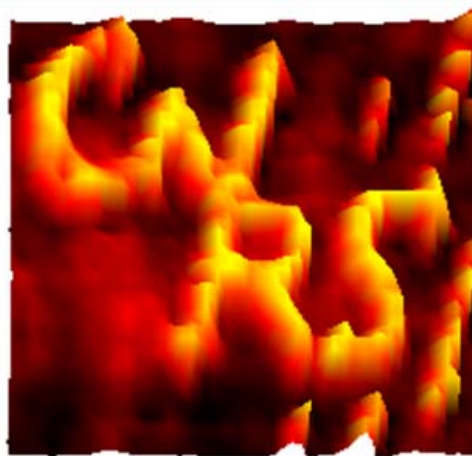
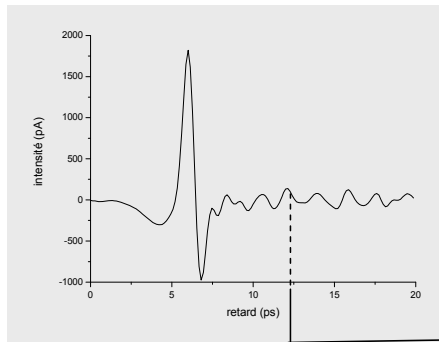
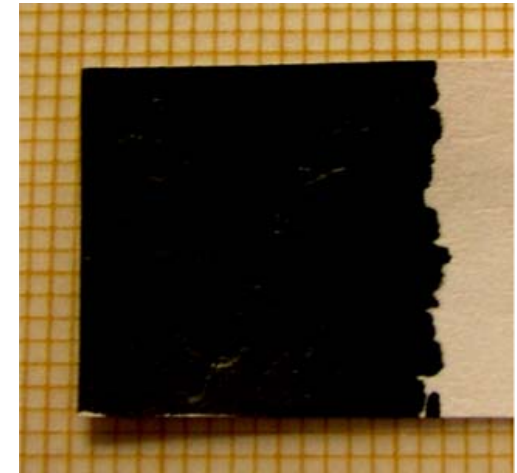
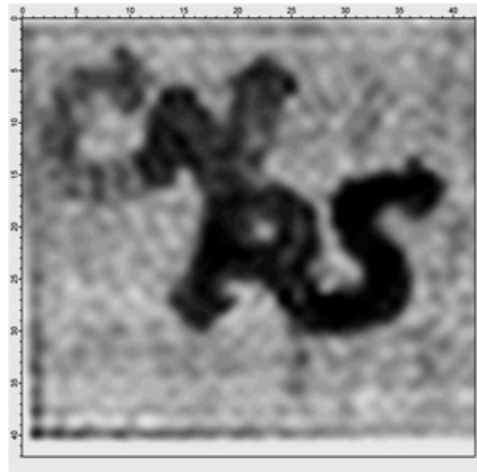


Image radiométrique passive à 30GHz d'une personne située à 2 m de l'objectif dans une pièce différente et portant dans son dos un revolver

- La silhouette de la personne est parfaitement visible et on distingue l'arme à 30GHz
- Silhouette et arme non détectée à 90GHz à travers la cloison

Imagerie THz active exemple



Phase

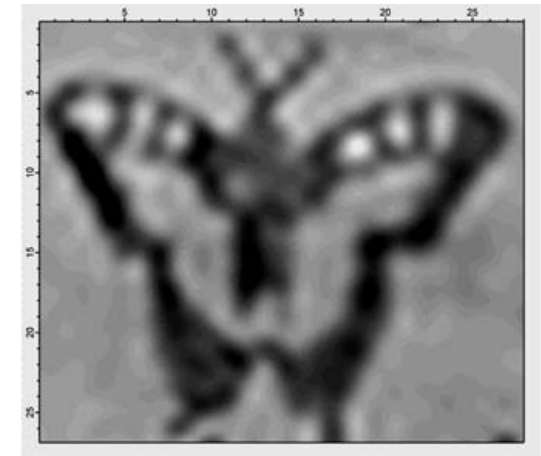


Image at 2 THz

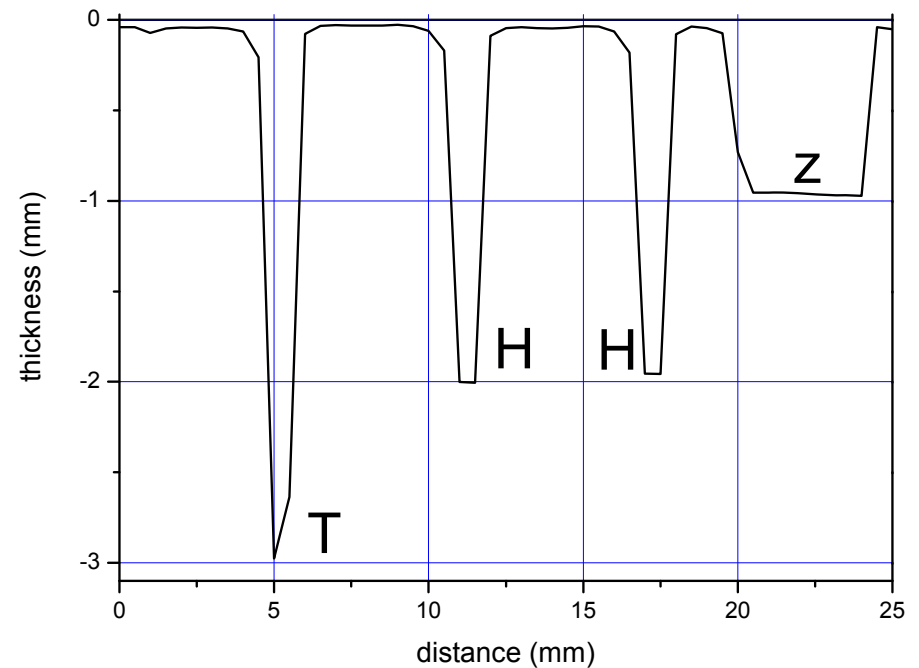
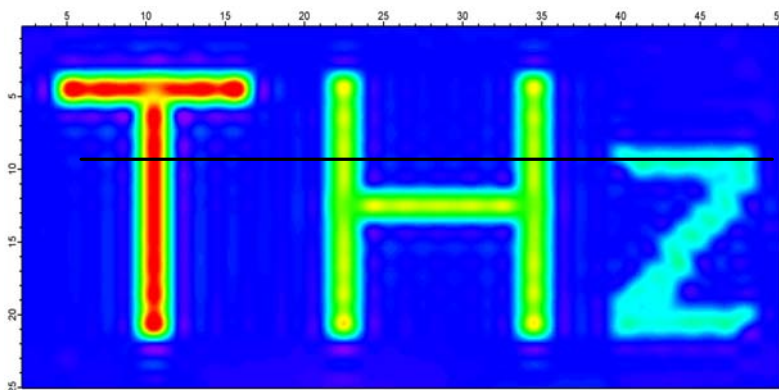
“Broadband terahertz imaging of documents written with lead pencils, Optics Communications (2009)

Mot THz gravé à differente profondeur

(groove depth: T: 3mm, H: 2mm, z: 1mm,
1mm wide).

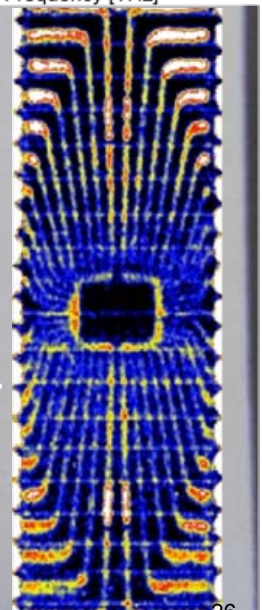
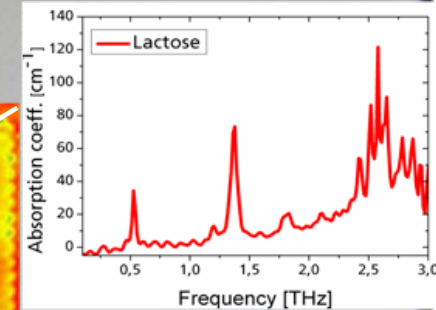
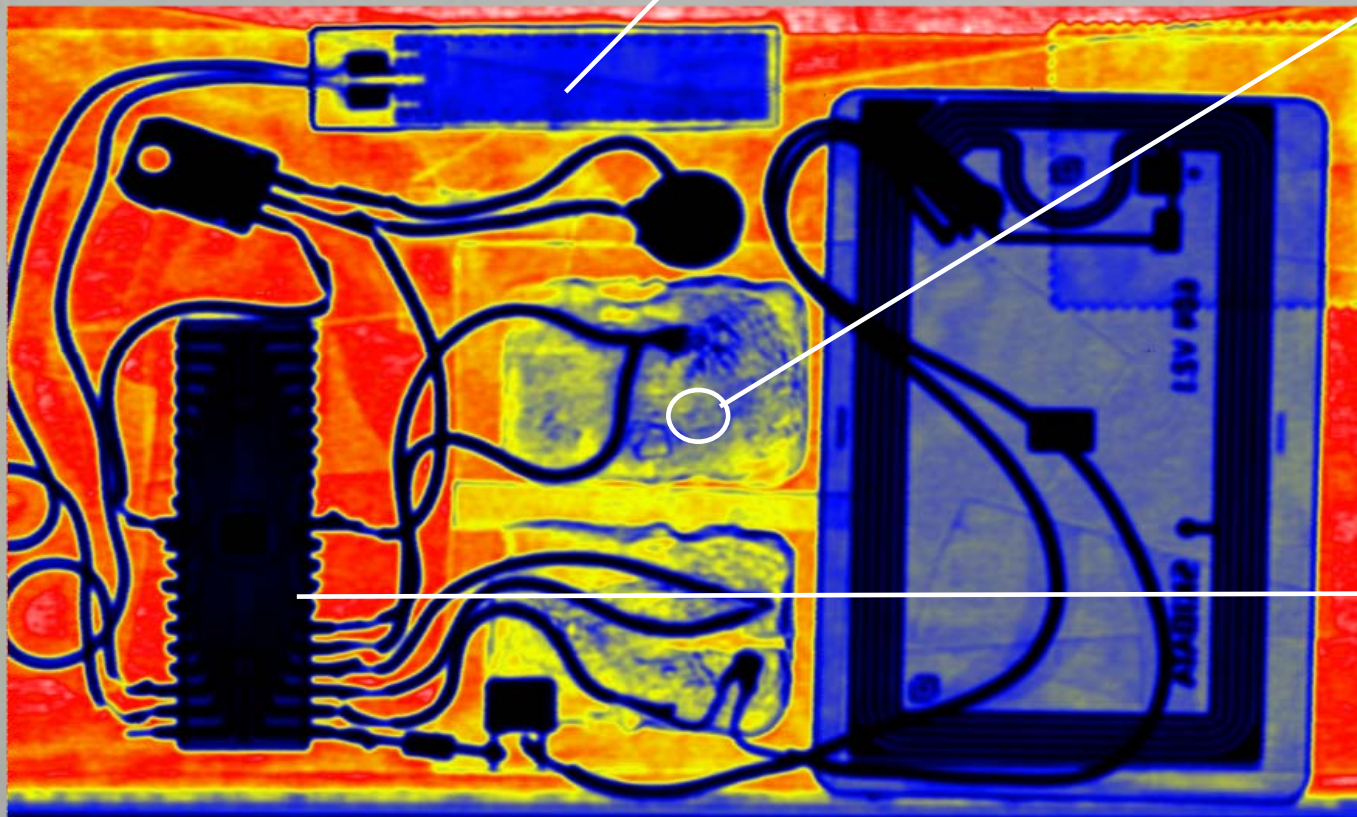
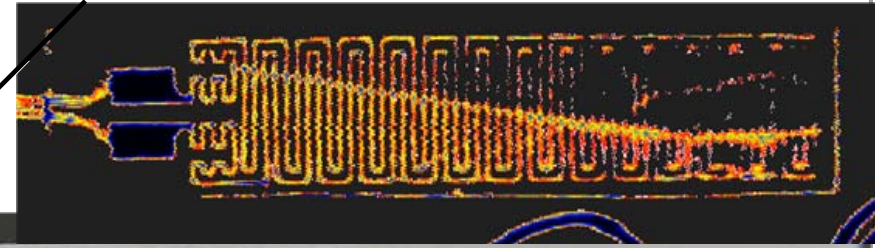
25*12.5mm

Information en Volume



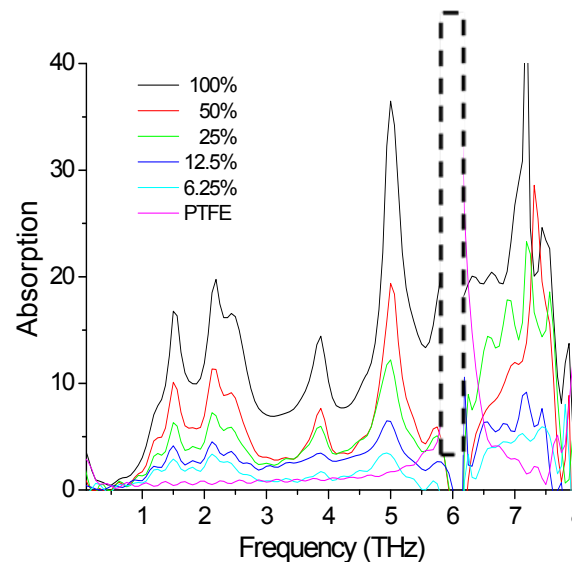
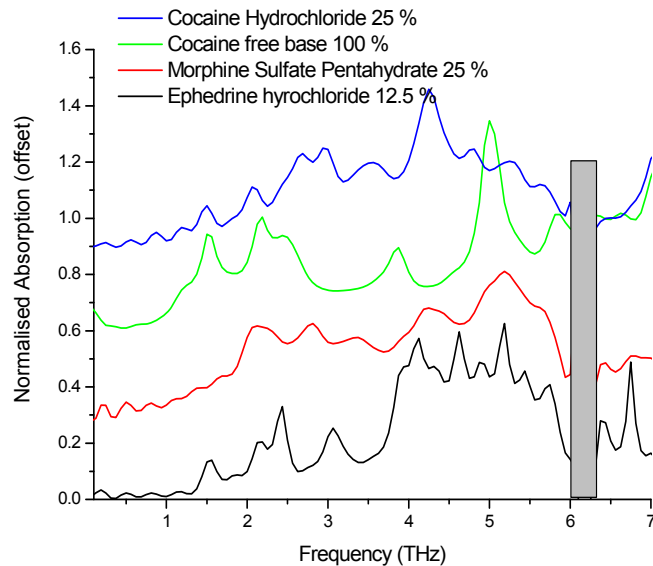
Imaging and Identification d'objets cachés

Mock-up letter bomb

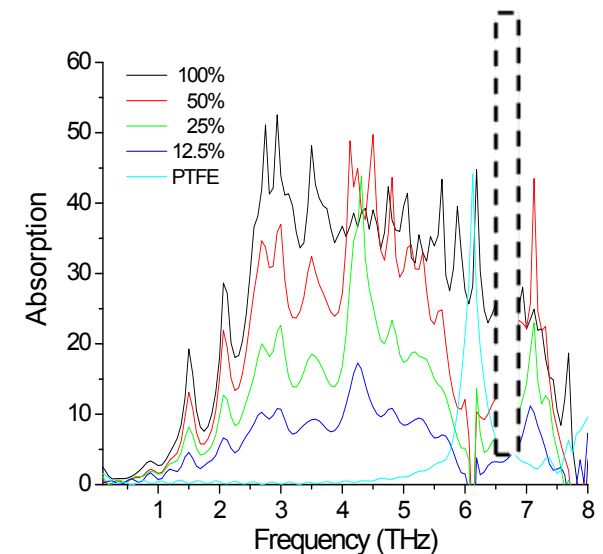


Il y a un certain nombre de drogues , avec une grande variété de structures.
Les échantillons de de rue sont `coupés' avec des contaminants.
Avantage: analyser sans l'ouverture des paquets.

Cocaine free base



Cocaine hydrochloride

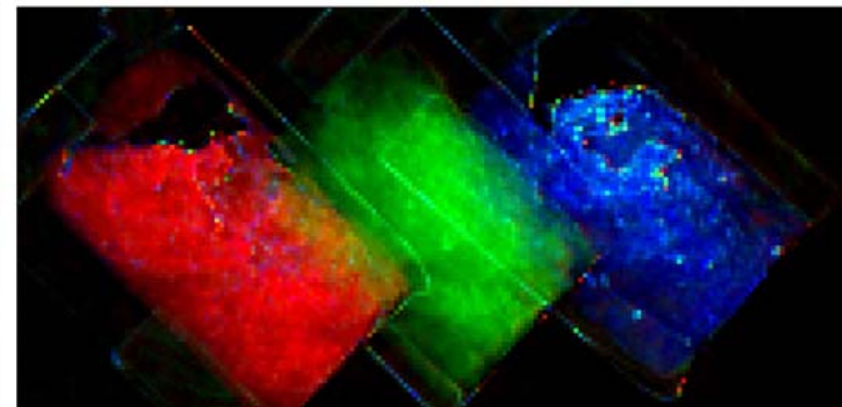
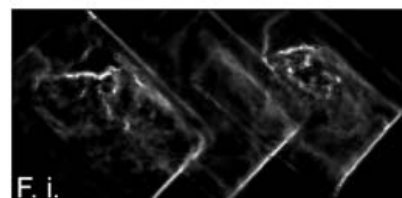
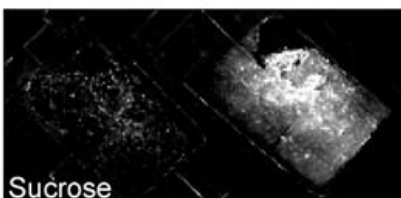
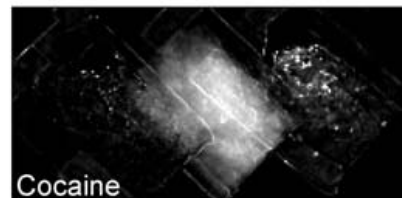
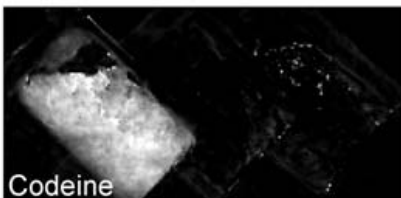
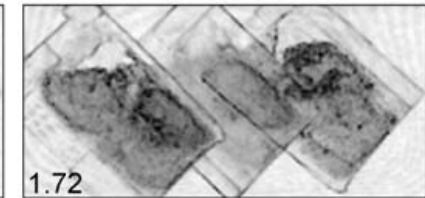
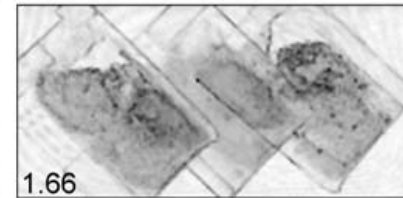
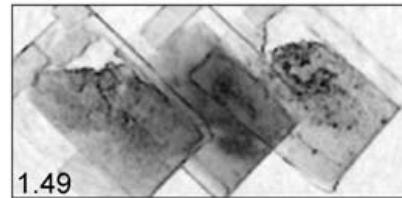
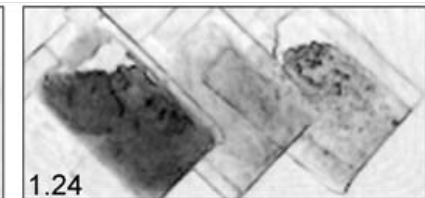
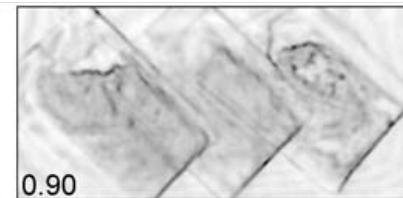
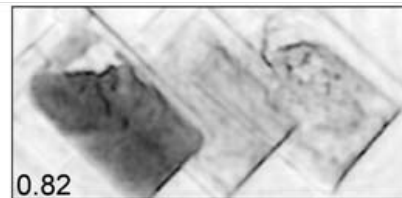


Discrimination claire par analyse sur spectre large.

Kawaze et al



codeine cocaine sucrose (60 mg each)

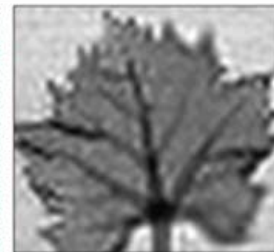


Distribution des poudres identifiée !

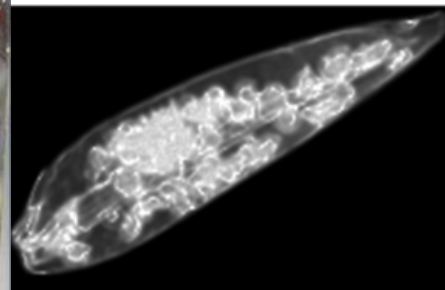
64 water lines between 0,4 & 2,5 THz

0,424 ; 0,437 ; 0,448 ; 0,475 ; 0,488 ; 0,504 ; 0,530 ; 0,557 ; 0,572 ; 0,596
 0,621 ; 0,646 ; 0,670 ; 0,688 ; 0,713 ; 0,737 ; 0,752 ; 0,799 ; 0,841 ; 0,891
 0,916 ; 0,934 ; 0,946 ; 0,970 ; 0,988 ; 1,097 ; 1,113 ; 1,163 ; 1,208 ; 1,229
 1,253 ; 1,308 ; 1,322 ; 1,345 ; 1,376 ; 1,411 ; 1,432 ; 1,518 ; 1,530 ; 1,542
 1,602 ; 1,661 ; 1,717 ; 1,762 ; 1,797 ; 1,868 ; 1,919 ; 1,941 ; 1,954 ; 1,997
 2,016 ; 2,040 ; 2,074 ; 2,095 ; 2,164 ; 2,196 ; 2,222 ; 2,264 ; 2,298 ; 2,318
 2,347 ; 2,366 ; 2,392 ; 2,447 ; 2,463 ; 2,488

Fresh Leaf



Dried Leaf



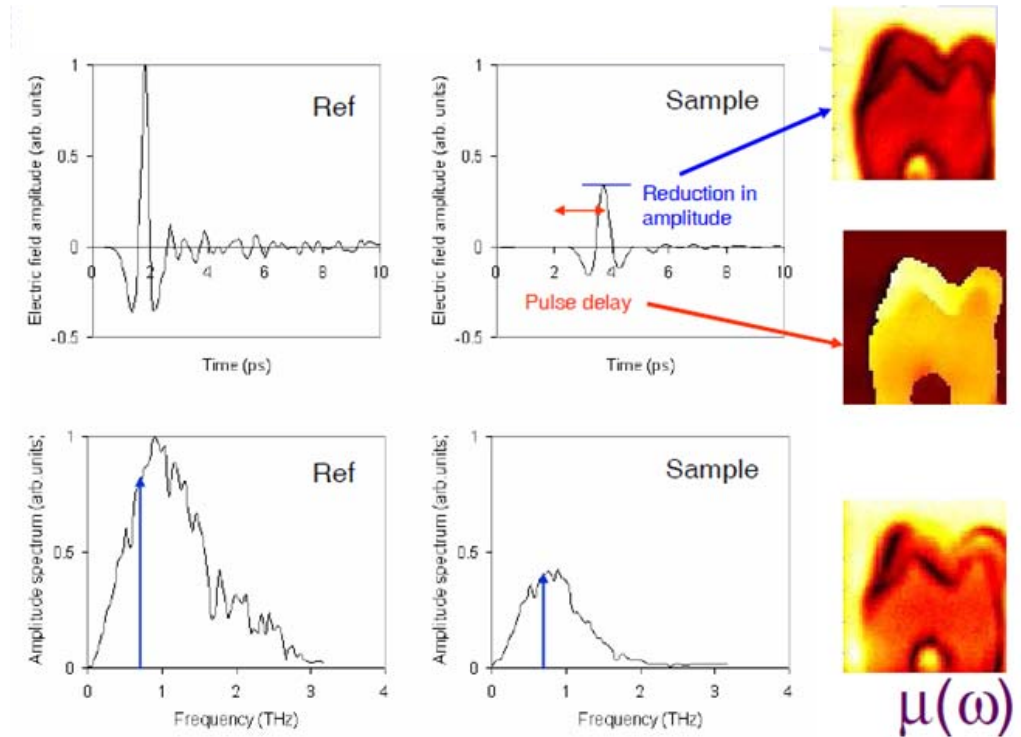
Evaluation du comportement des tissus en très haute fréquence

Ex vivo tissue studies

Defining contrast - investigation of imaging parameters

Systematic measurement of tissue optical properties

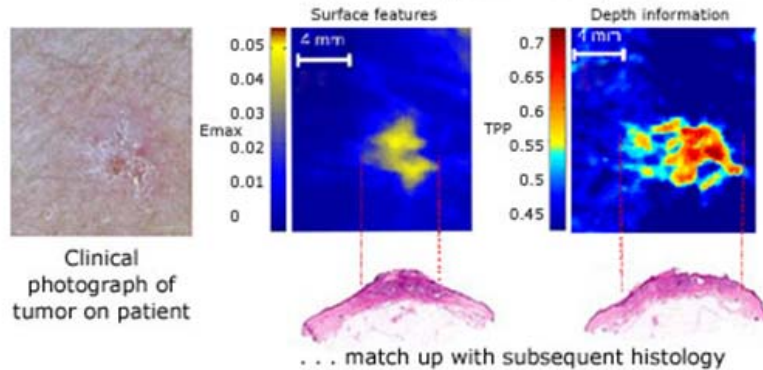
Tissue catalogue



Santé dentaire

Material	N_B	$\langle n \rangle$	N_B	$\langle \mu \rangle / \text{cm}^{-1}$
Deionized water	16	2.04 ± 0.07	13	225 ± 21
Tooth enamel	44	3.06 ± 0.09	44	62 ± 7
Tooth dentine	72	2.57 ± 0.05	72	70 ± 7
Skin	36	1.73 ± 0.29	36	121 ± 18
Adipose tissue	37	1.50 ± 0.47	37	89 ± 23
Striated muscle	37	2.00 ± 0.35	37	164 ± 17
Cortical bone	59	2.49 ± 0.07	59	61 ± 3
Vein	33	1.58 ± 0.49	33	110 ± 43
Artery	12	1.86 ± 0.40	24	151 ± 25
Nerve	12	1.95 ± 0.46	12	246 ± 27

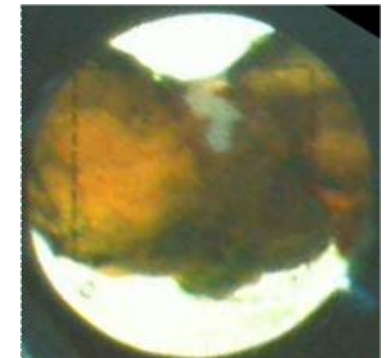
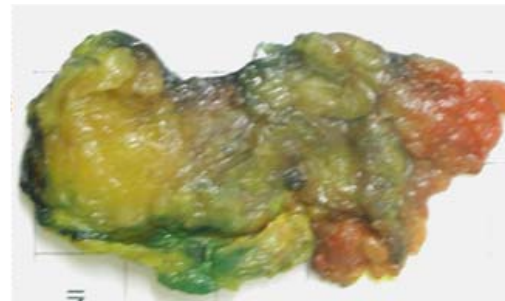
Terahertz images in vivo on patient . . .



Cosmétique , cancer de la peau

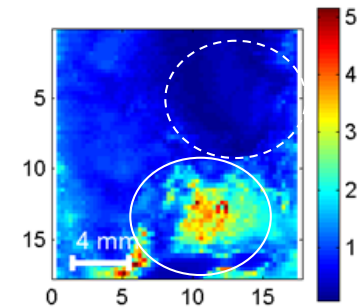
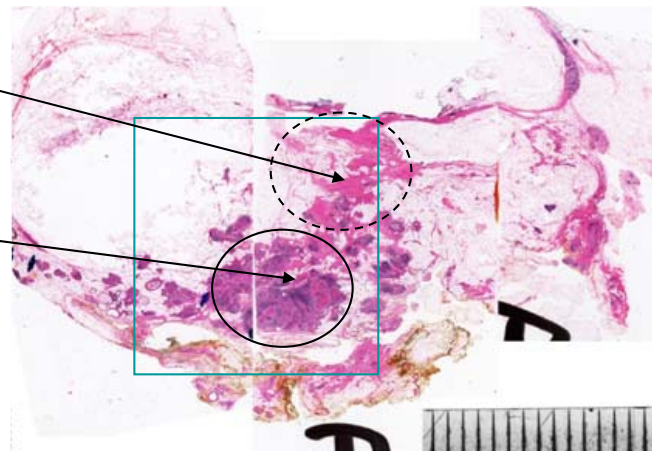
Oncologie

Progress to date - Breast



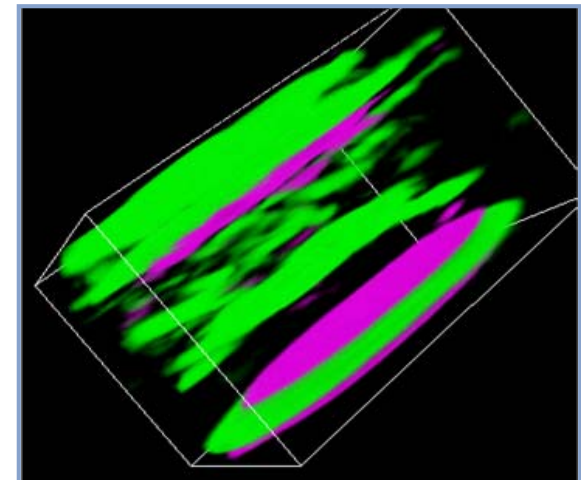
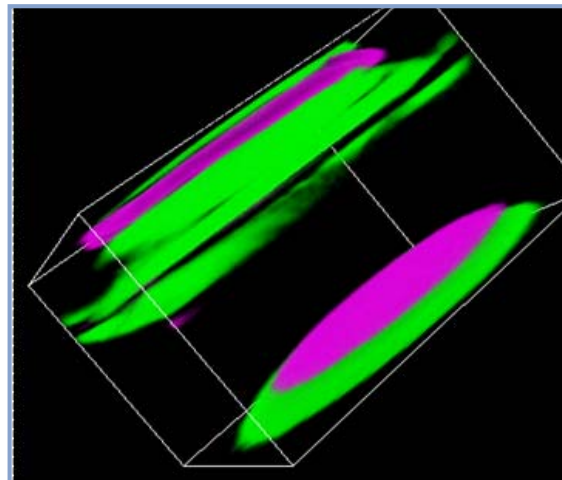
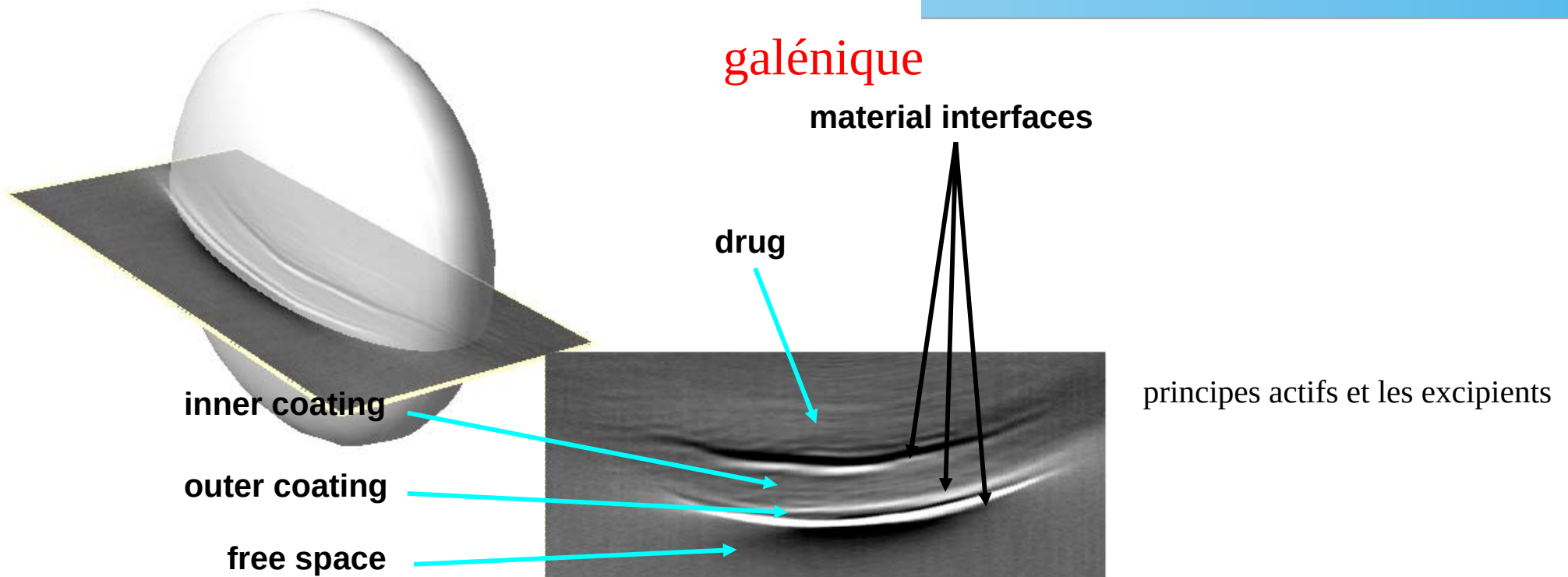
Fibrosis

DCIS

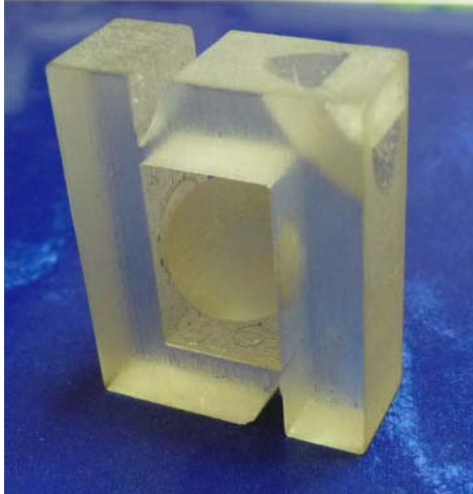
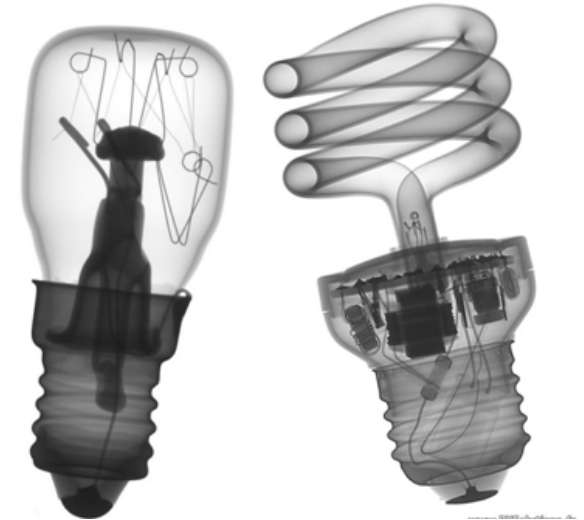


Terahertz Pulsed Imaging of
Human Breast Tumors¹

Imagerie , Spectroscopie THz et Santé



- ✓ assembling control,
- ✓ Recherche de défauts : porosity, cracks, bubbles, delaminating, inclusion, fibers, etc.
- ✓ Modélisation 3D et Reverse Engineering, prototypage



Phantom 3D

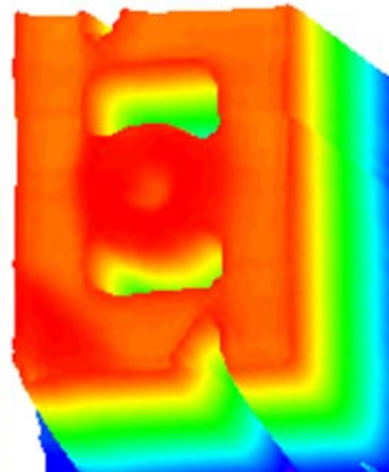
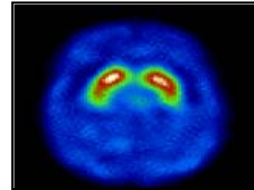
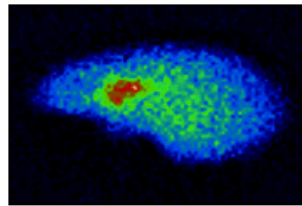


Image THz



Paléontologie

The Radon inverse transform



$p(u, \Theta)$

Fourier Transform

Filtering

Back projection

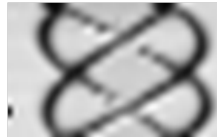
inverse Fourier transform

$P(\rho, \Theta)$

$|\rho| P(\rho, \Theta)$

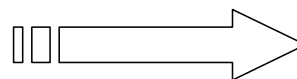
$p'(u, \Theta)$

Sinograms

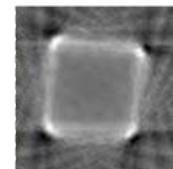
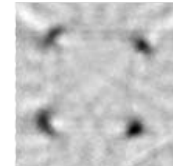


Transparent plastic cell

Amplitude image



Delay image



Advantages & drawbacks

Experimental

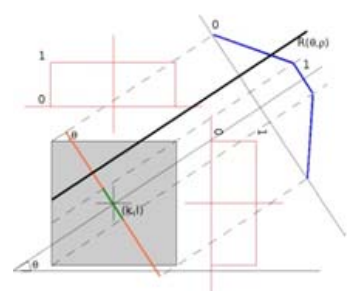
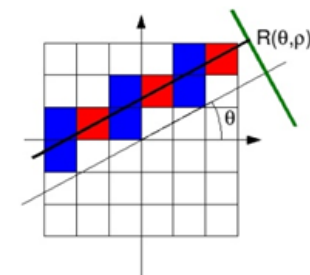
Amplitude

Phase

} Images

Absorption and refraction losses

Numerical



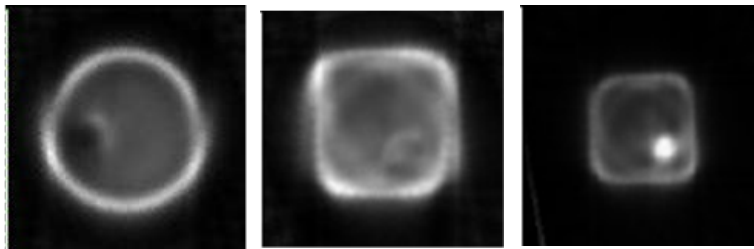
Trade off: complexity, precision
Time acquisition

For each pixel, the THz waveform as a function of time.
Final tomographic THz images can be obtained
maximum value of the THz amplitude signal (amplitude)
time delay : average of the different peaks (delay image).

3D tomographie

- ✓ Phantoms reconstructed from CW acquisitions
- ✓ To determine the reconstruction quality with usual CT-Scan methods,
- ✓ Acquisition of phantoms made of Foam or Teflon, with hole or metallic bars, 18 projections sized around 100*100.

Foam (n=1.05)

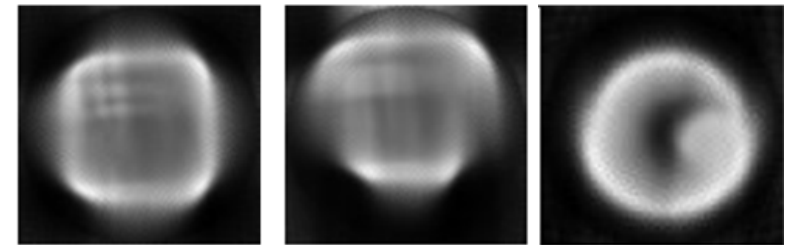


cyl/hole

cube/hole

cube/metal

Teflon (n=1.51)



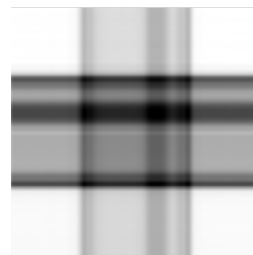
cube/hole

cube/metal

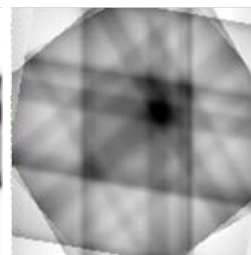
cyl/metal

- Hyper signal at interfaces due to the signal losses,
- Hyper signal at contours in reconstructed images
- Non uniform signal loss near the interfaces.

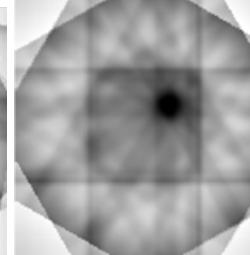
**Number of projections
Foam cube and metallic bar
(240 GHz)**



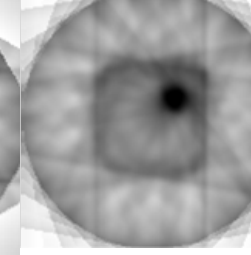
step : 90°
2 projections



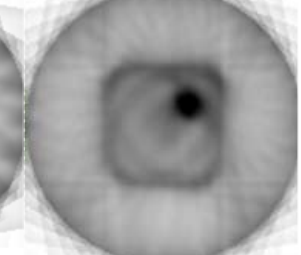
step : 50°
4 projections



step : 30°
6 projections



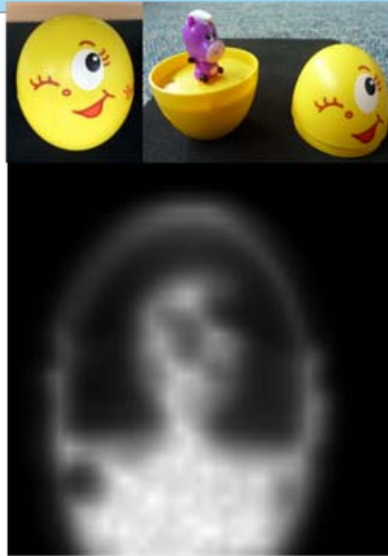
step : 20°
9 projections



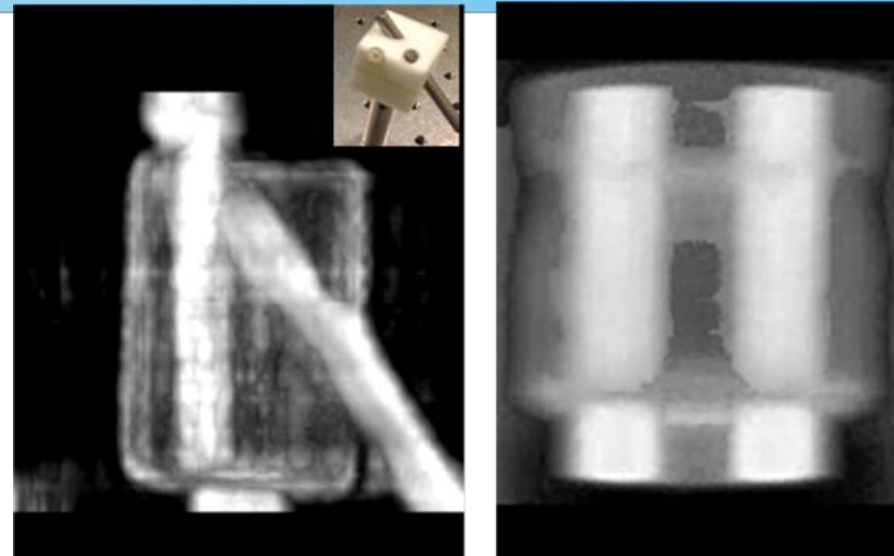
step : 10°
18 projections

3D THz tomography : opaque materials

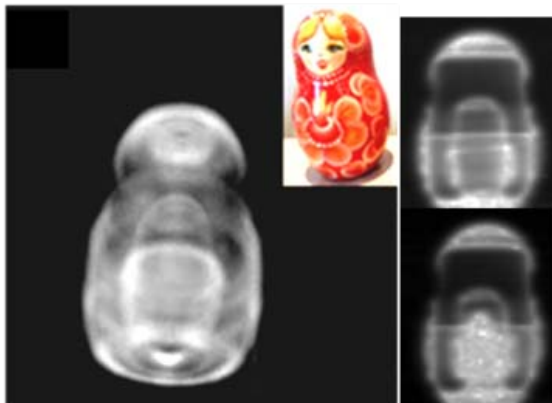
Plastic toy



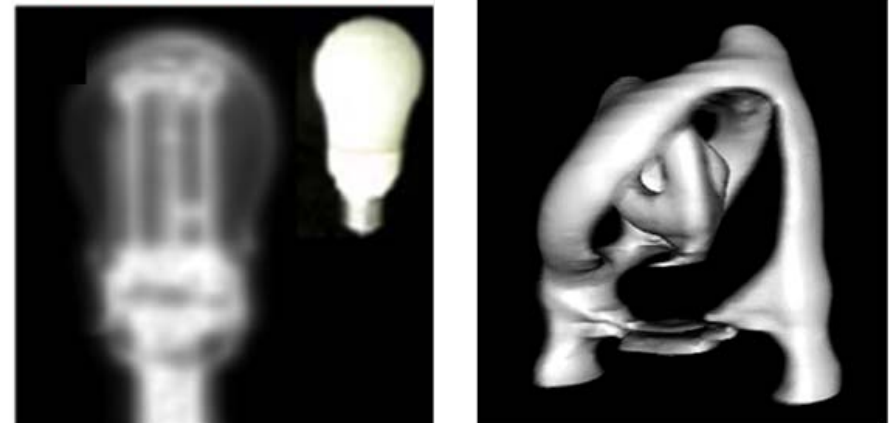
Metallic bars (Steel and foam)



Russian dolls (Woods and vernis)



Industrial inspection
(fluorescent light bulb)



CW acquisition allows a simultaneous 3D tomographic and surface acquisition.

Imagerie THz : Technologie de plus en plus robuste

Reste une technique de laboratoire

Future

THz video camera



Remerciements : Collègue du *LOMA*

Région Aquitaine

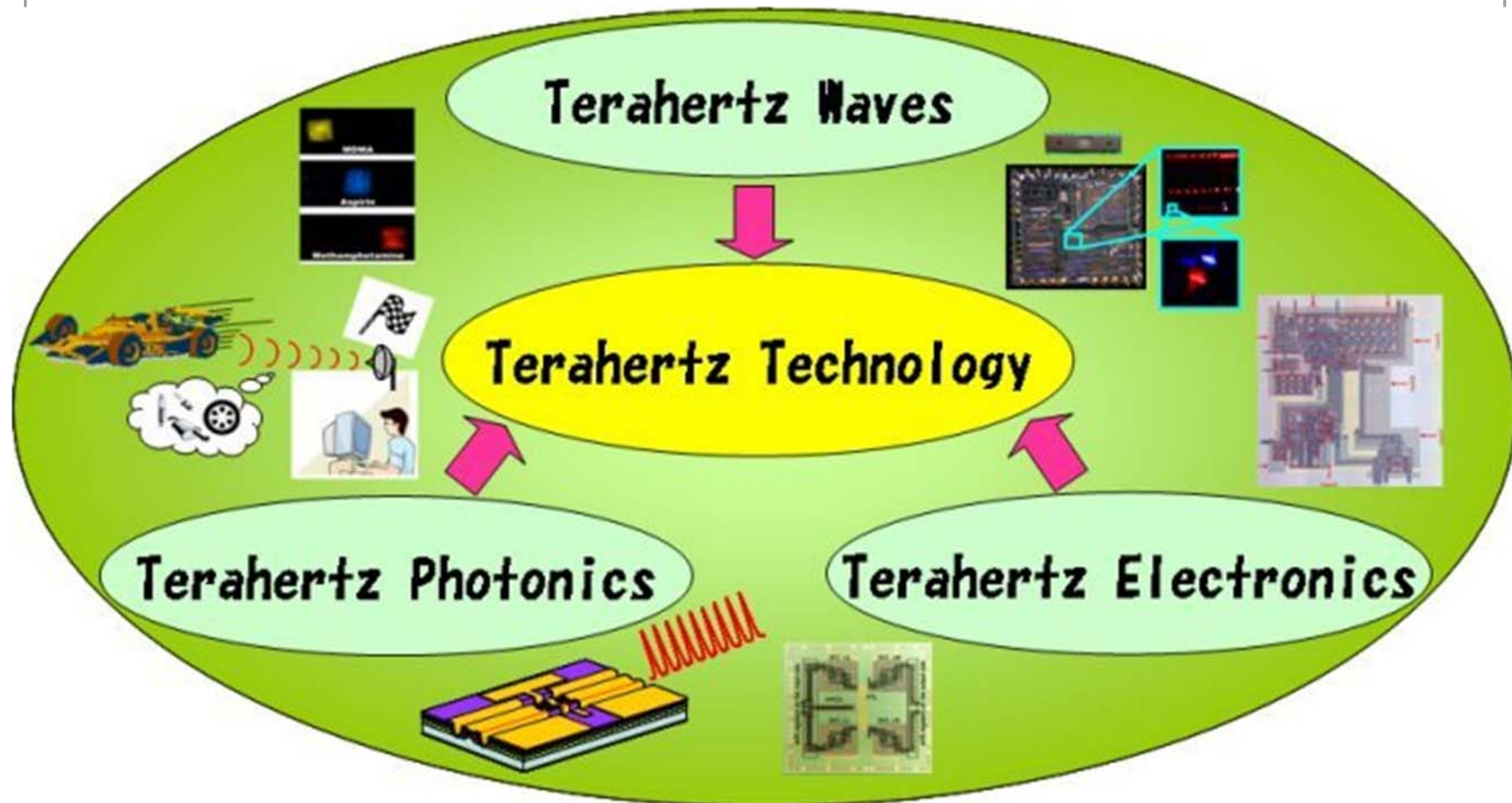
LABRI : P. Desbarats,

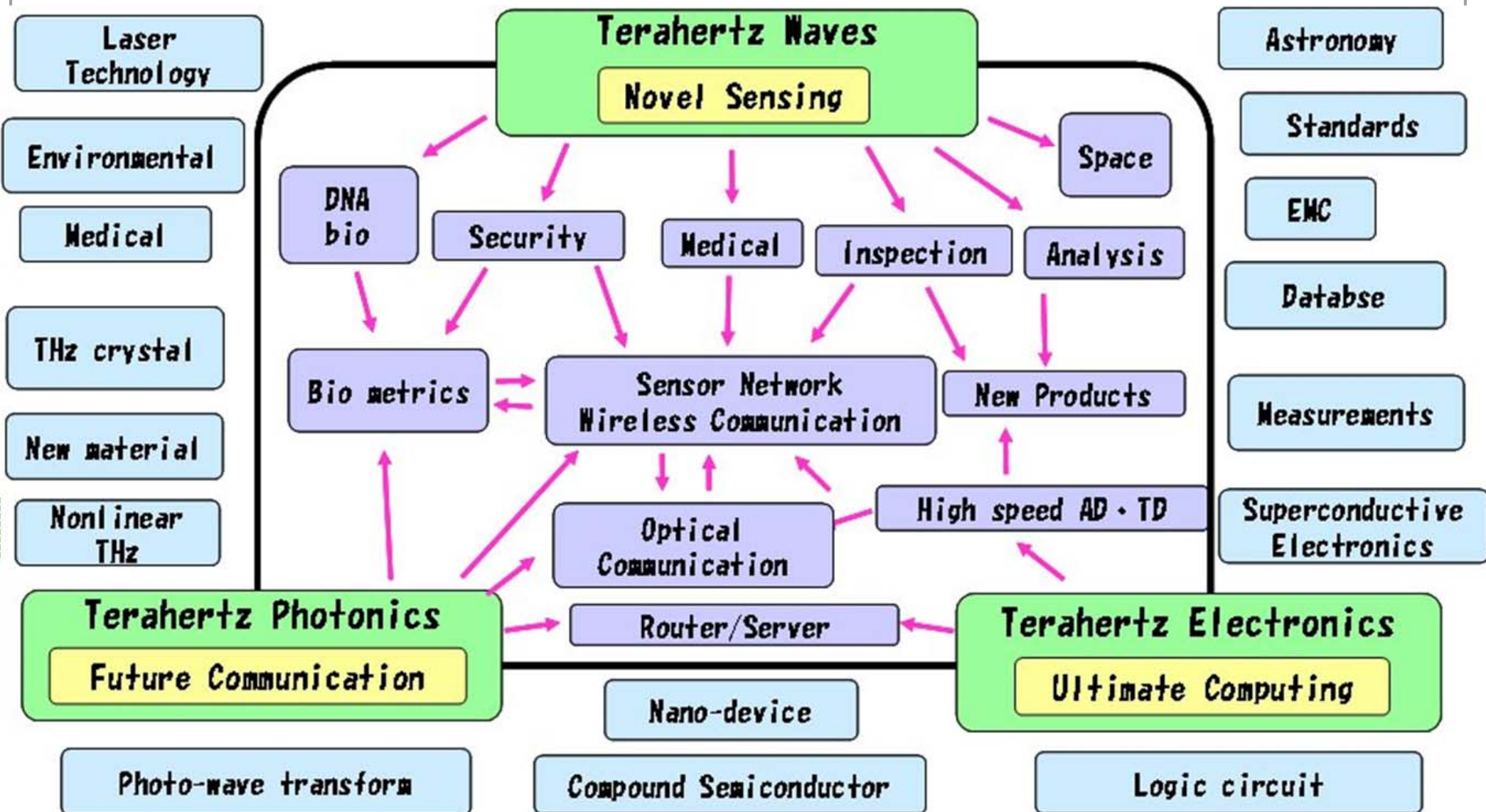
I2s : www.i2s.com

Pole de compétitivité :

Alpha - Route des Lasers

Alphanov : Plateforme imagerie THz (J.P Caumes)

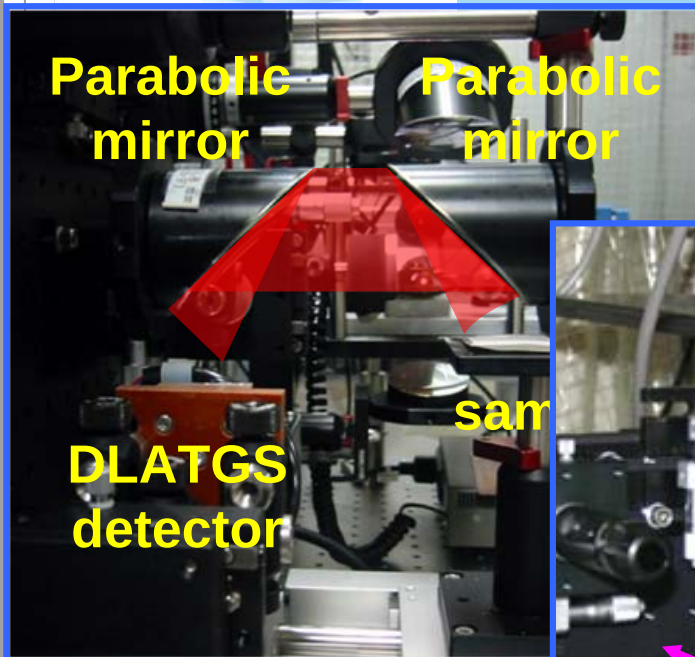




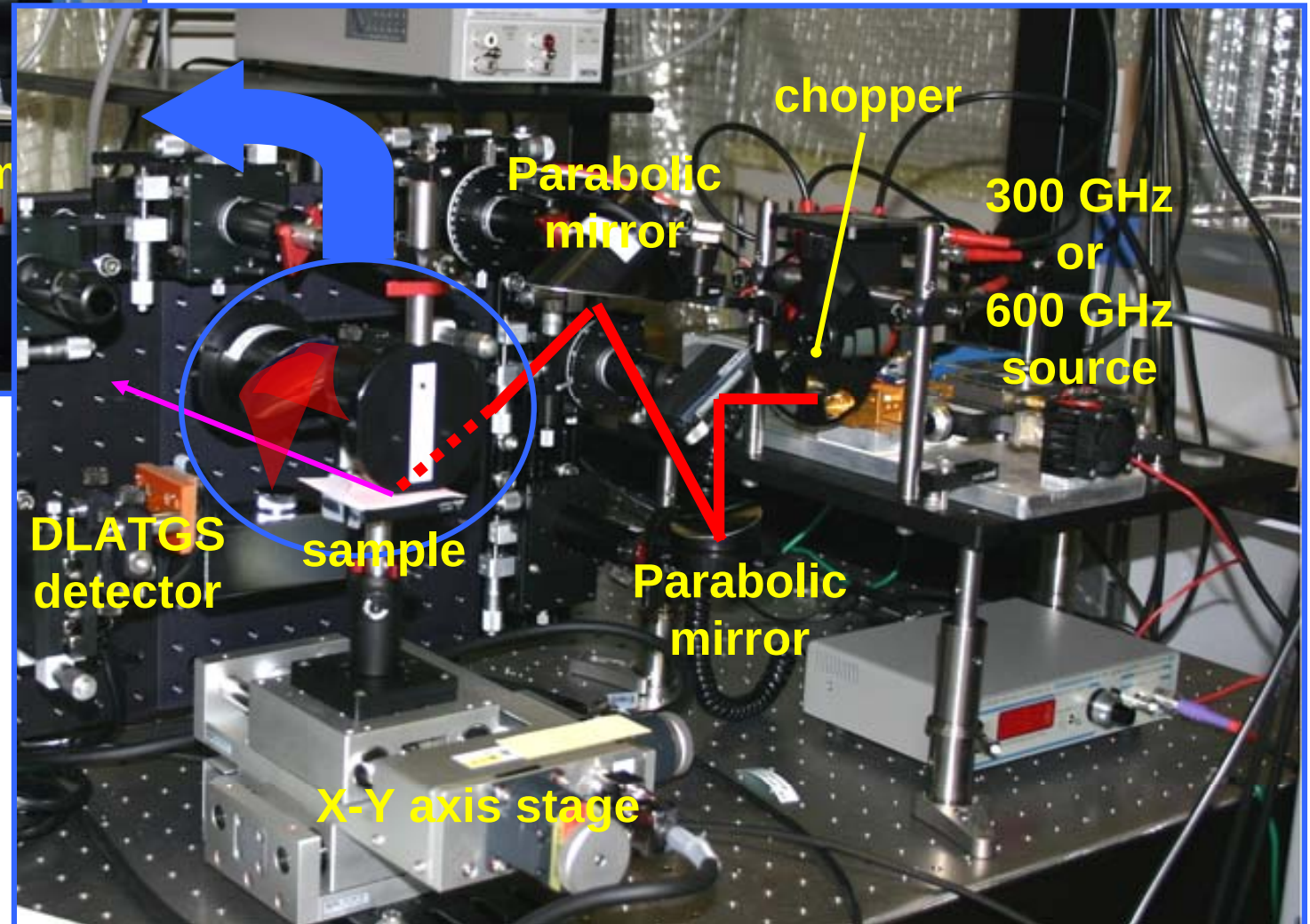
Screening of mails by scattering measurement



Otani Lab. in RIKEN and SI Seiko Inc.

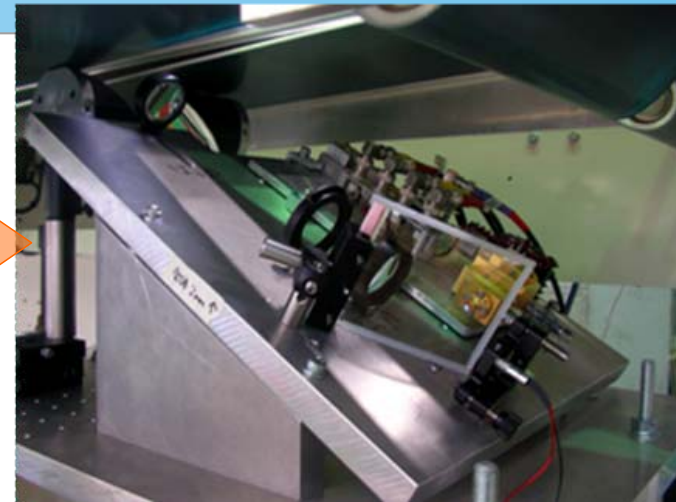


Source: YIG diode source (300 or 600 GHz)
Detector: DLATGS pyroelectric detector

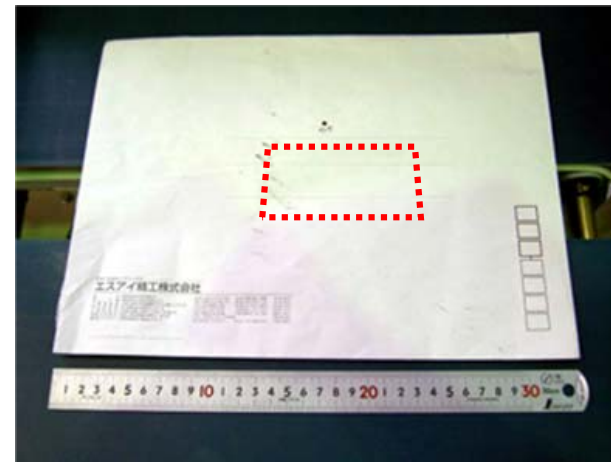




Belt conveyer system



Back-scattering measurement



Powder in envelope