Optoelectronic Terahertz Generation

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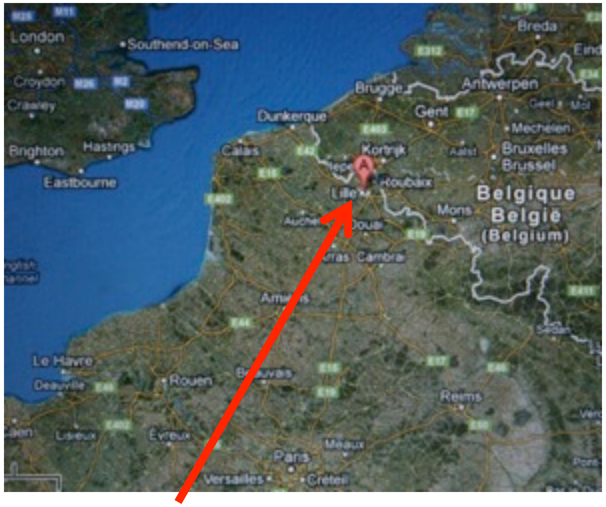
Outline

- Introducing me and my research group
- Some basic concepts
- The photomixing approach
- Photoconductors
- Photodiodes
- Applications of optoelectronic approach

Professional profile

Dr. Jean-François Lampin
Academic researcher (Chargé de Recherche CNRS)

IEMN
Villeneuve d'Ascq



Lille, France

- 1994-1997 Master and PhD in Electronics (Lille University)
- 1997-1998 Post-doc Laboratoire d'Optique Appliquée (Polytechnique, Palaiseau)
- 1999: Permanent position at IEMN
- 2012: Head of THz Photonics Group

14 years of experience in the Terahertz domain

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THz photonics group

Jean-François Lampin (CNRS)

Tahsin Akalin (Ass. Prof.)

Emilien Peytavit (CNRS)

Xiang-Lei Han (post-doc)

Guillaume Ducournau (Ass. Prof.)

Mathias Vanwolleghem (CNRS)

Fabio Pavanello (PhD)

Philipp Latzel (PhD)

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THz photonics group

Research activities:

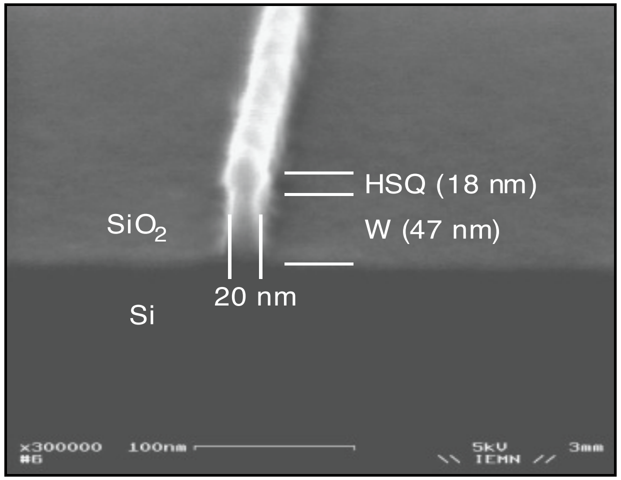
- Semiconductors for THz devices
- Integrated THz antennas and transmission lines
- THz communications
- THz spectroscopy (collaboration LPCA)
- Lasers for THz generation (collaboration PhLAM, IPR)

Set-ups:

- fs pump-probe and TDS
- 0.8 and 1.55 µm THz photomixing
- VNA up to 500 GHz (on-wafer probing)
- pwr meter, spectrum analyser up to 1 THz

Micro and Nano Clean room

III-V
Si



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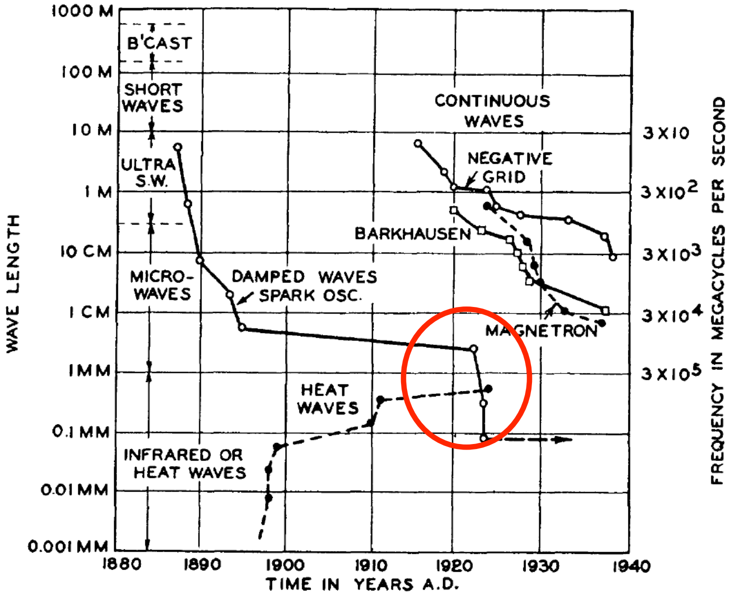
A brief historical introduction…

In the whole electromagnetic spectrum the Man can feel two ranges:
- 0.4 - 0.7 µm wavelength: the visible range (eye)
- 0.7 - >1000 µm wavelength: the infrared range (skin)

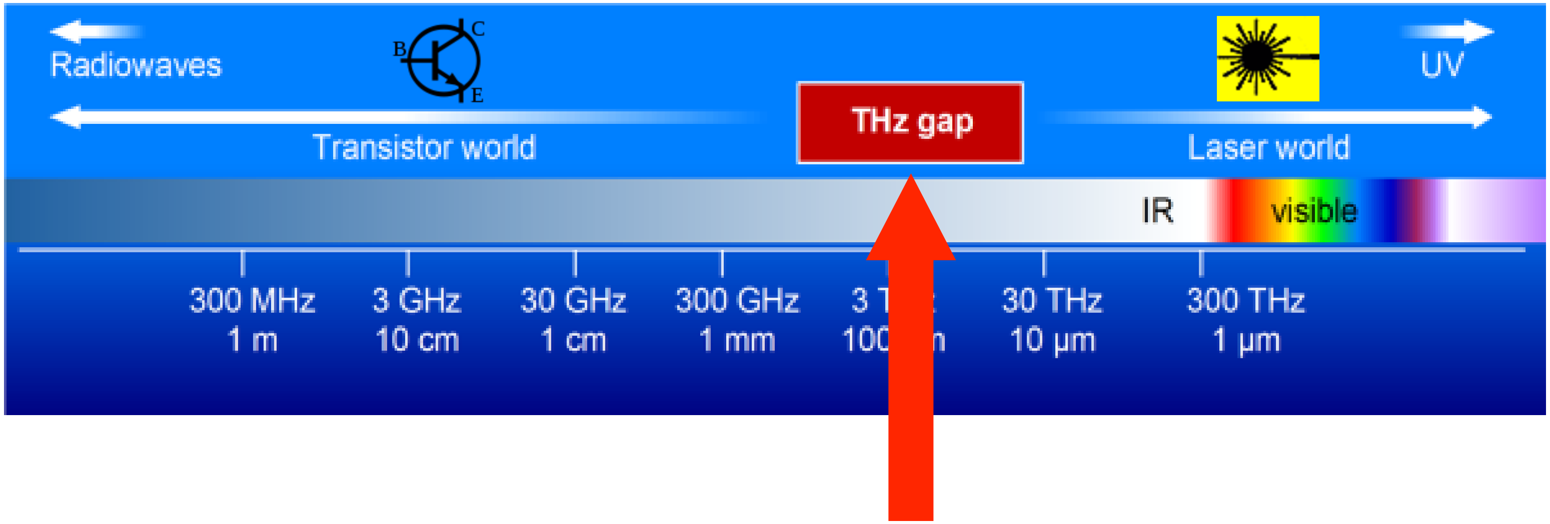
- Near-Infrared (radiant heat) was discovered by **W. Herschel** (1800)
- Mid and far-infrared were investigated by **H. Rubens** (1890-1922)
- **J.C. Bose** produced mm-waves using **Hertz's** technique (1896)



After the WWII:
Electronic tubes reach the submmW at the end of the 50's

Solid state sources ?

Some basic concepts



THz generation : direct generation is difficult ! (ex: QCL)

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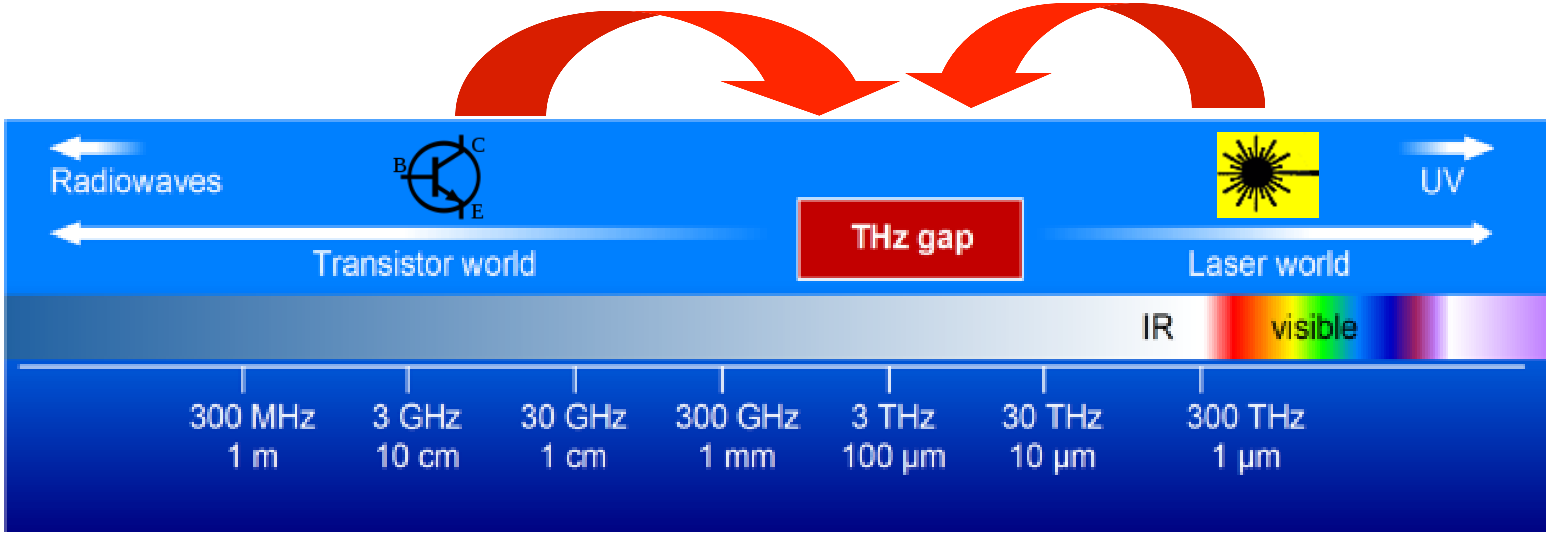
Some basic concepts



⇒ Powerful source + non-linear phenomenon

- « Transistor world » source + harmonic generation
- « Laser world » source + ?

Non-linear optics

⇒ Transparent crystals
Electric field is large ⇒ electron clouds of atoms do not respond linearly

$$\vec{P} = \varepsilon_0\left(\chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}\vec{E} + \chi^{(3)}\vec{E}\vec{E}\vec{E} + \dots\right)$$

Electric field of light wave

$$\cos(\omega_1 t)\times\cos(\omega_2 t) = \frac{1}{2}\left[\cos((\omega_1+\omega_2)t) + \cos((\omega_1-\omega_2)t)\right]$$

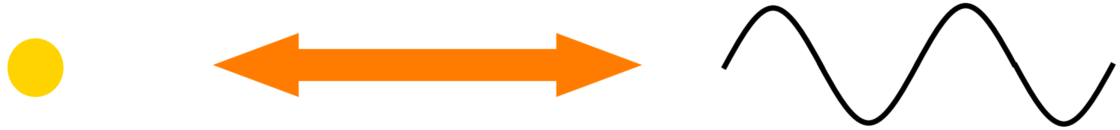
Difference frequency

Example: $\lambda \approx 1$ µm, $\nu_1 = 301$ THz, $\nu_2 = 300$ THz, $\Delta\nu = 1$ THz
Avantage: if the laser is tunable (a few %), the THz source is widely tunable !

Wave – particule duality

Particule

Wave



Photon
- Energy
- moment

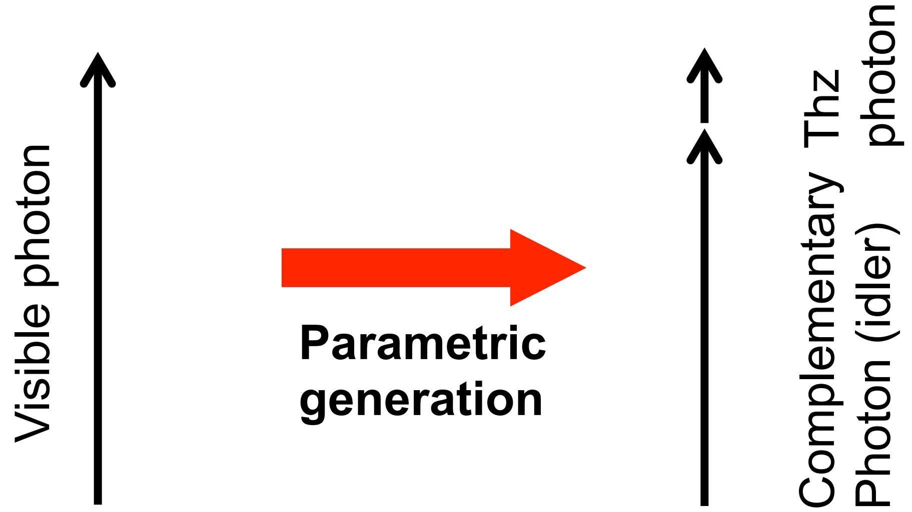
$$E = h\nu$$

$$\vec{P} = \hbar\vec{k}$$

Electromagnetic Wave
- Frequency
- Wave vector

Two aspects of the same phenomenon…

Non-linear optics THz generation



1 visible photon ⇒ 1 THz photon
Maximum power efficiency:

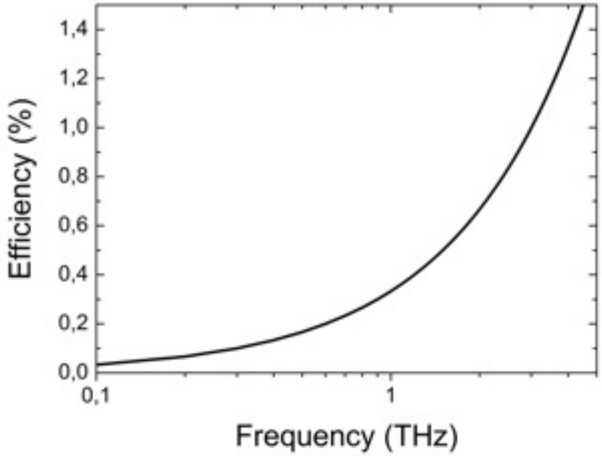
$$\eta = \frac{P_{THz}}{P_{vis}} = \frac{\nu_{THz}}{\nu_{vis}}$$

Manley-Rowe equation

Non-linear dielectric (crystal)

Use the photon concept:
- $E = h\nu$
- Energy must be conserved

λ = 1 μm, ν_{vis} = 300 THz



- Efficiency is very low (<< 1% @ 1THz)
- Non-linear crystal + high power pulsed laser

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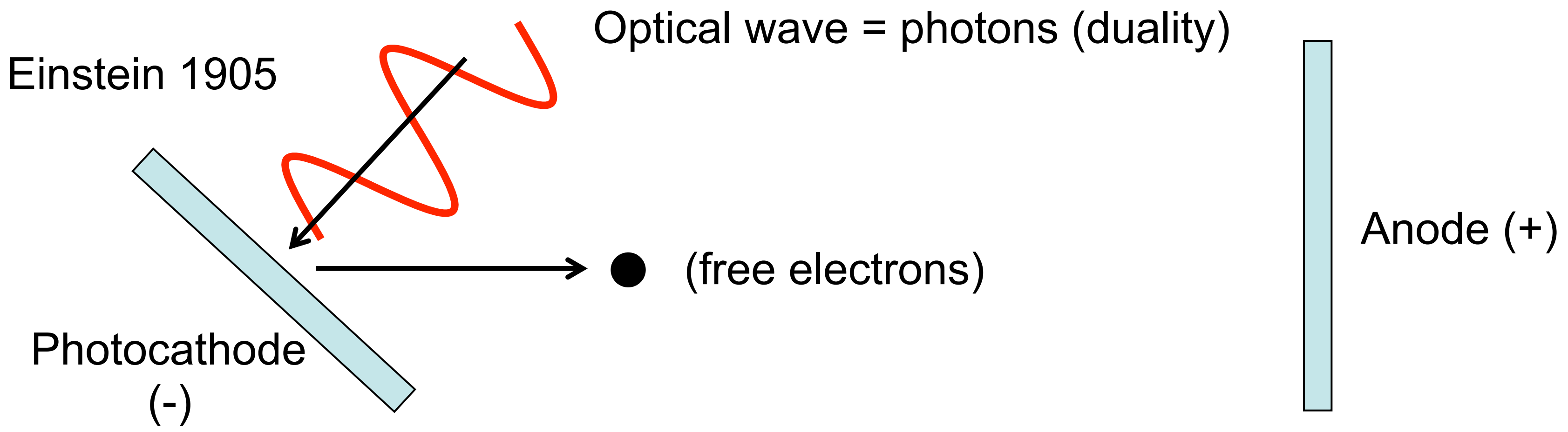
Optoelectronic approach

Photoelectric effect is intrinsically non-linear !



Einstein 1905

Optical wave = photons (duality)

Anode (+)

(free electrons)

Photocathode (-)

One photon ⇒ one free electron (if quantum eff.=1)

Photocurrent $\propto$ Number of electrons $\propto$ Number of photons $\propto$ optical power $\propto |E|^2$

Non-linearity: photoelectric effect + Poynting vector

Electric field of light wave

Photoelectric mixing = **Photomixing** the Forrester experiment

On the Possibility of Observing Beat Frequencies between Lines in the Visible Spectrum

A. Theodore Forrester, William E. Parkins,
and Edward Gerjuoy
University of Southern California, Los Angeles, California

August 29, 1947

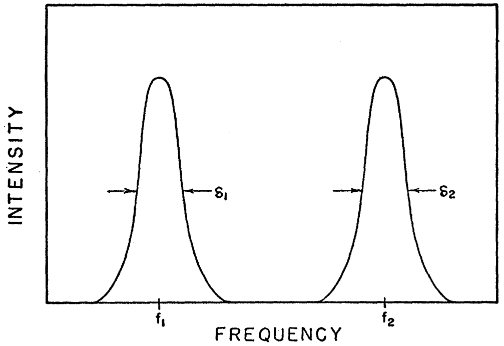
PHYSICAL REVIEW VOLUME 99, NUMBER 6 SEPTEMBER 15, 1955

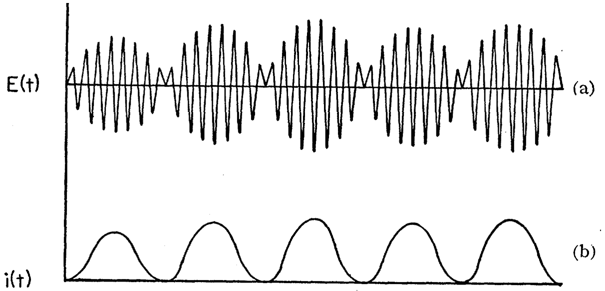
Photoelectric Mixing of Incoherent Light*

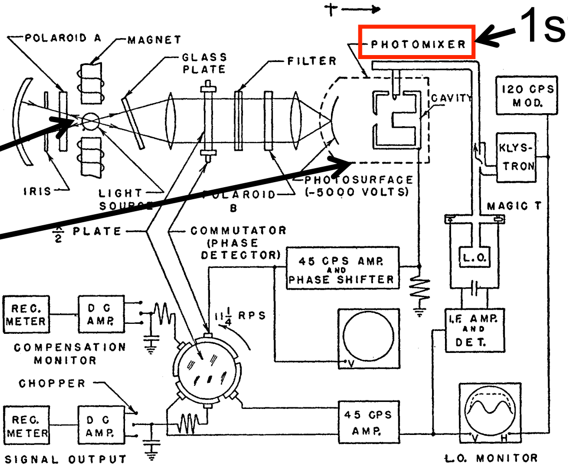
A. Theodore Forrester,† Richard A. Gudmundsen,‡ and Philip O. Johnson§
University of Southern California, Los Angeles, California

(Received April 20, 1955)

Beats have been obtained between incoherent light sources by mixing Zeeman components of a visible spectral line at a photosurface. Periodicity in emission was observed through the excitation of a 3-cm cavity. Because of incoherence between the spectral lines and incoherence between the beats from different photocathode areas, the signal-to-shot-noise ratio at the cavity is only 3×10^{-6} but the beats were modulated optically, while maintaining constant total intensity and our receiver was able to yield a signal-to-noise ratio of two at the indicator. The basic idea is that, in the photoelectric process, the emission probability for electrons is proportional to the square of the resultant electric field amplitude, implying an interference between light originating in independent sources. This is a point of view which does not appear to be tested in any other experiment involving quantum effects. The experiment also demonstrates that any time delay between photon absorption and electron release must be significantly less than 10^{-10} second.







1st time !

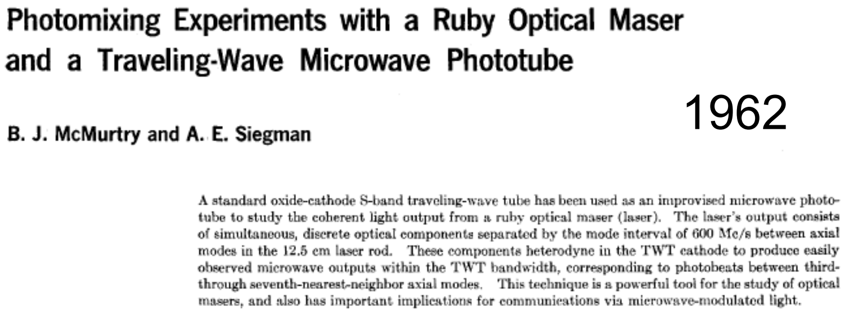
Hg Lamp + Zeeman effect

Photoelectric tube

Generation of ultra-low power at 10 GHz !

History: photomixing with lasers

1960: The ruby LASER is invented by T. Maiman

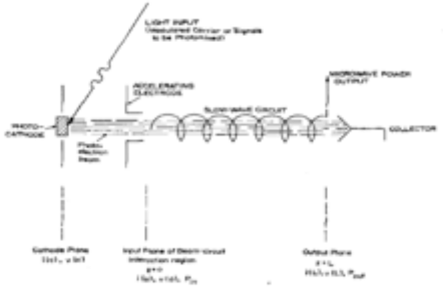


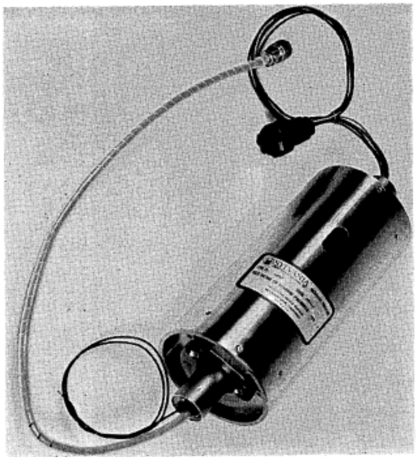
Photomixing Experiments with a Ruby Optical Maser and a Traveling-Wave Microwave Phototube

B. J. McMurtry and A. E. Siegman

A standard oxide-cathode S-band traveling-wave tube has been used as an improvised microwave phototube to study the coherent light output from a ruby optical maser (laser). The laser's output consists of simultaneous, discrete optical components separated by the mode interval of 600 Mc/s between axial modes in the 12.5 cm laser rod. These components heterodyne in the TWT cathode to produce easily observed microwave outputs within the TWT bandwidth, corresponding to photobeats between third- through seventh-nearest-neighbor axial modes. This technique is a powerful tool for the study of optical masers, and also has important implications for communications via microwave-modulated light.

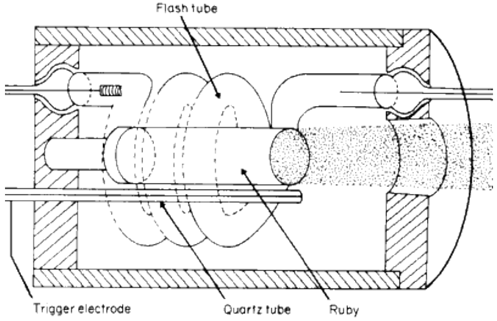
1962





Beating of modes of a ruby laser:
1-5 GHz

Sylvania SY4302
Microwave Phototube (1962)



- Not CW !
- Pulsed output with huge peak power
- Not monomode

⇒ Several frequency that can beat

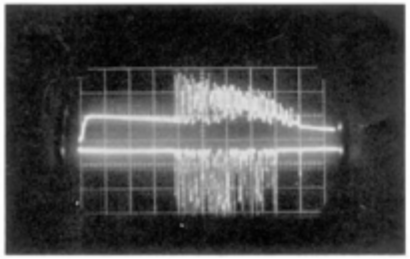
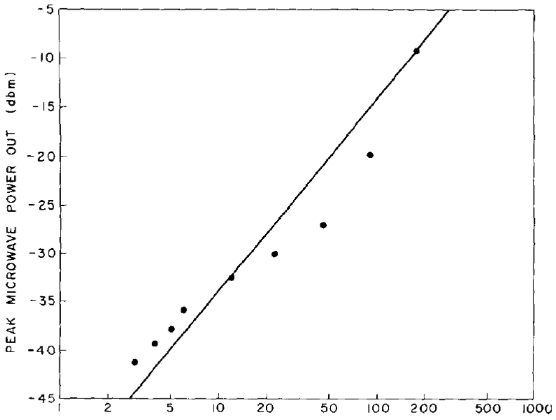


Fig. 1. Upper trace: light output from the laser. Lower trace: microwave output from the TWT helix. Sweep speed: 100 μsec/div. Sweep triggers at start of laser pumping flash.

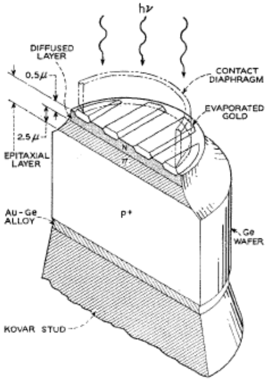
Solid-state photomixing

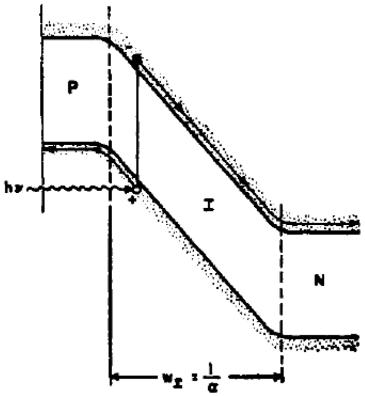
Semiconductors: photons with enough energy can create free carriers (similar to photoelectric effect)



Di Domenico (1962):

- Ruby laser + CdSe photoconductor
- A few GHz





In the 1960s:

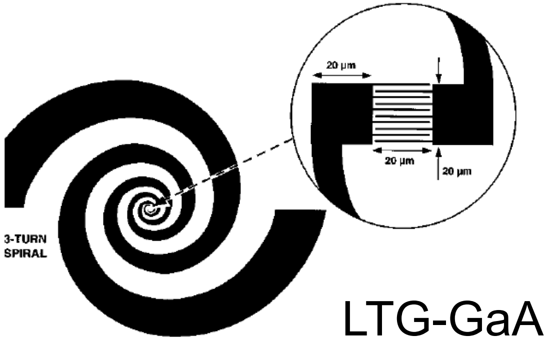
- First demonstrations of Ge pin photodiodes
- Photomixing with He-Ne lasers at few GHz

The THz range ?

THz generation using photomixing is possible but:
A robust THz bandwidth photodetector is needed !

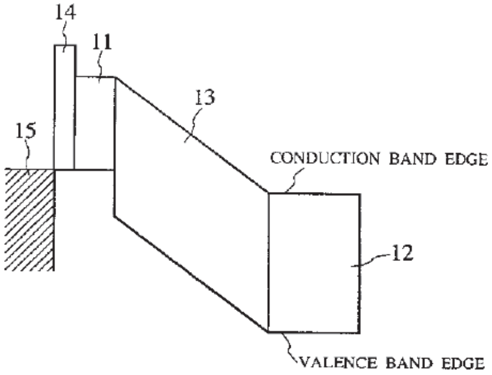
Two approaches:

- Photoconductor: Elliott Brown et al. (1995)



LTG-GaAs

- New photodiodes: Tadao Ishibashi et al. (1997)

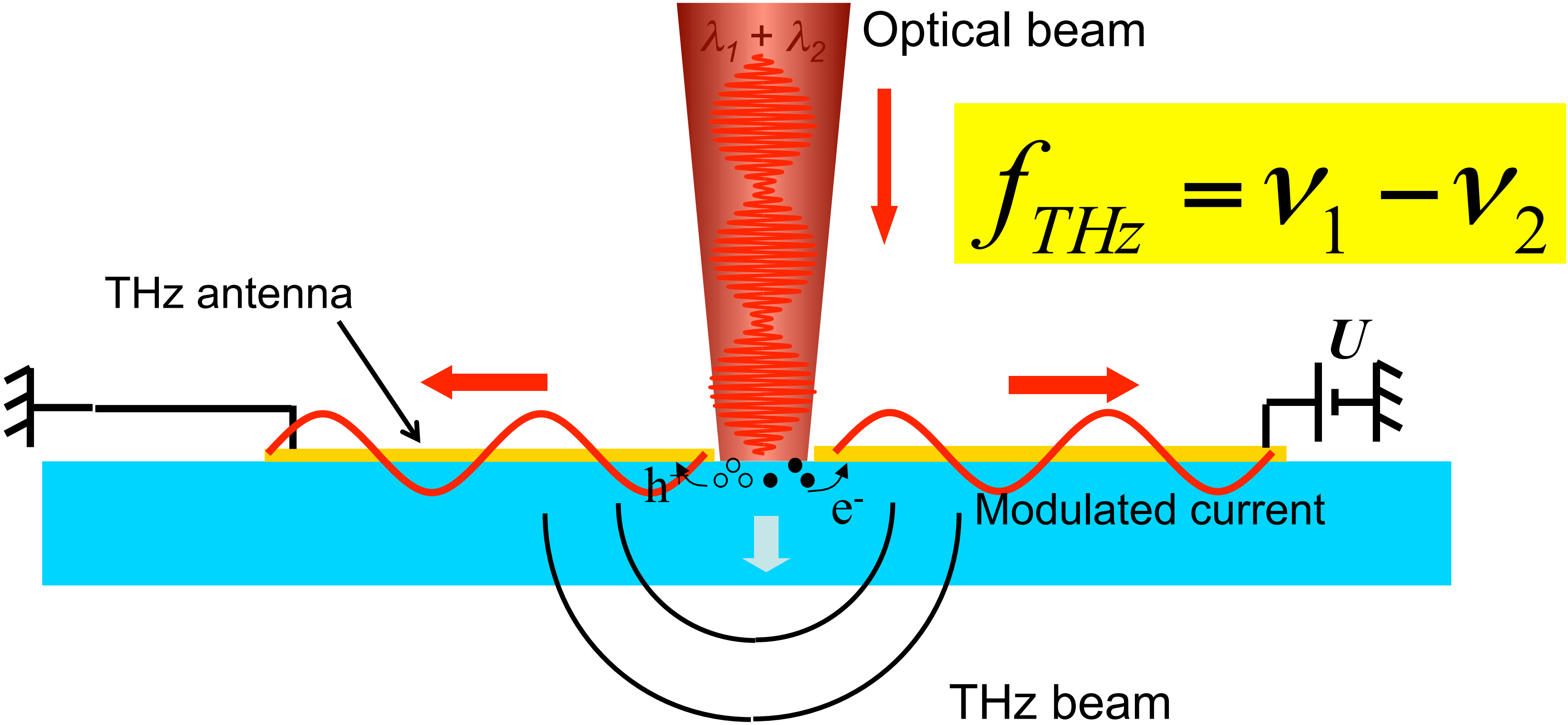


11… p-TYPE LIGHT ABSORPTION LAYER
12… n-TYPE ELECTRODE LAYER
13… CARRIER TRAVELING LAYER
14… p-TYPE CARRIER BLOCK LAYER
15… ANODE ELECTRODE
16… CATHODE ELECTRODE
17… SEMI-INSULATING SUBSTRATE

UTC-PD

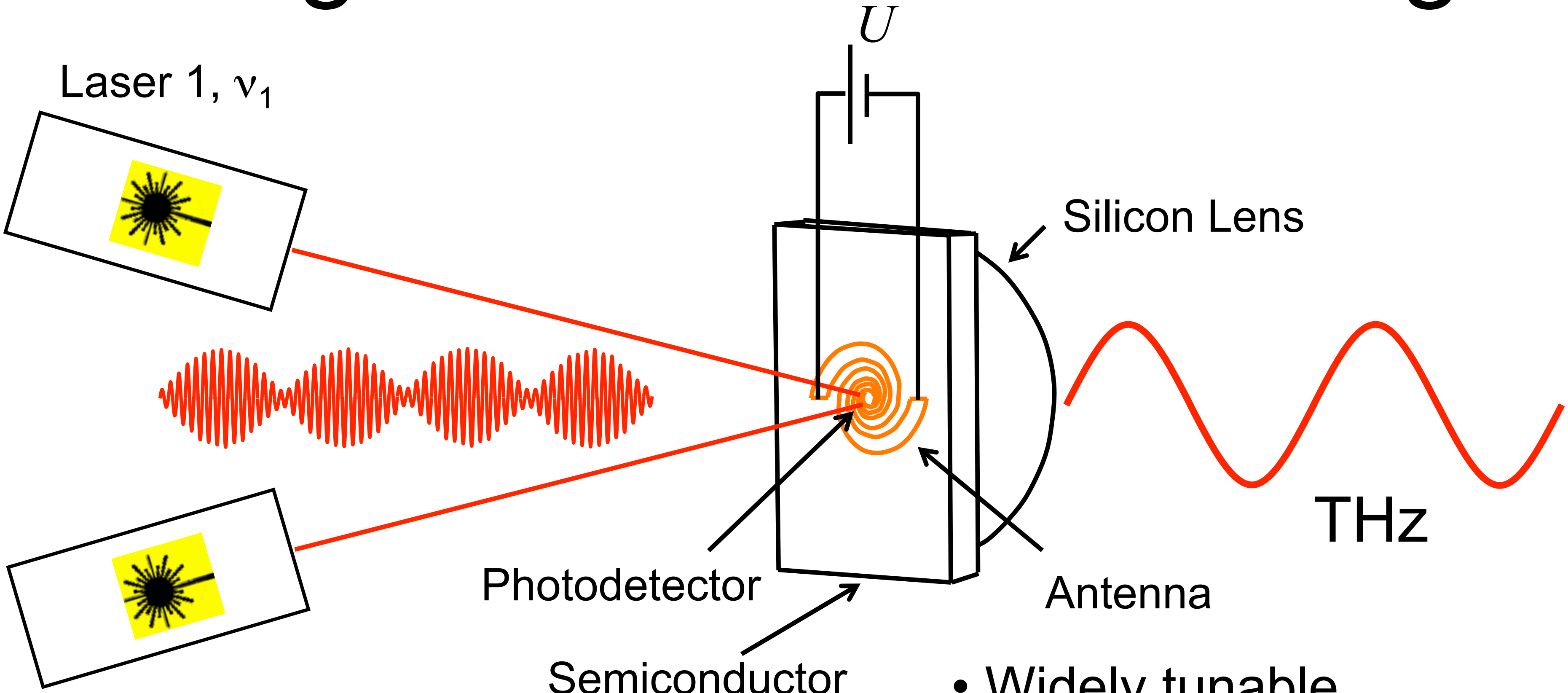
Semiconductor THz photomixer

- The photodetector generates a photocurrent modulated at the beating frequency
- At THz frequencies, λ_{THz} is small, an antenna can be directly integrated



$$f_{THz} = \nu_1 - \nu_2$$

THz generation: Photomixing



U

Laser 1, ν_1

Silicon Lens

THz

Photodetector

Antenna

Semiconductor substrate

Laser 2, ν_2

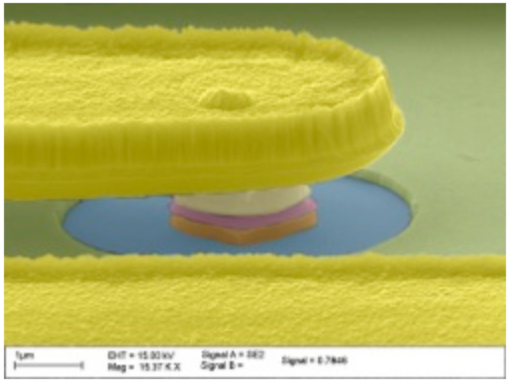
- Widely tunable
- Very simple (2 stages)

Difference with non-linear optics: free carriers are accelerated !

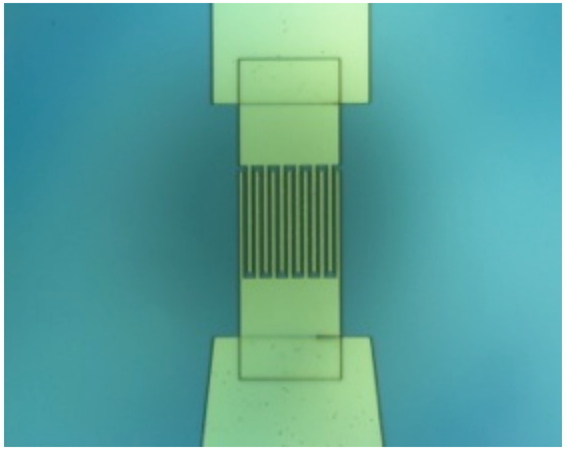
Photodetectors

THz photodetectors:
2 families: **Photodiodes** and **Photoconductors**

- Internal electric field (pin)
- Limited by transit-time and RC

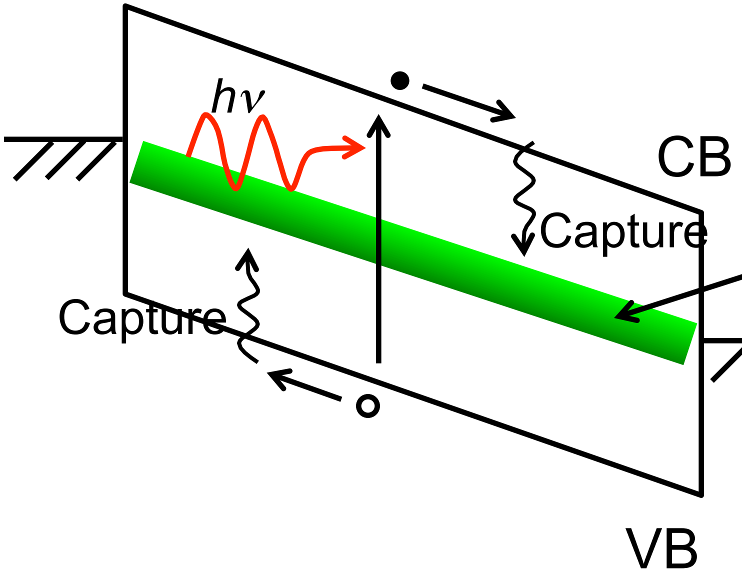


- No internal electric field
- Limited by lifetime and RC
- Usable also for detection



Photoconductors

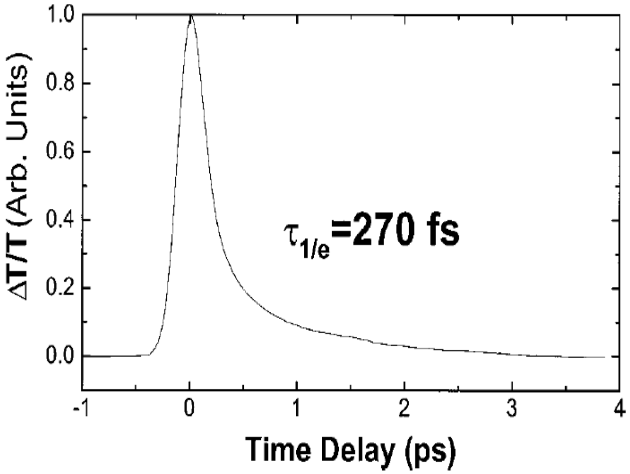
Low-temperature-grown GaAs is the preferred material



Defect states (semi-insulating)

Biased photoconductor

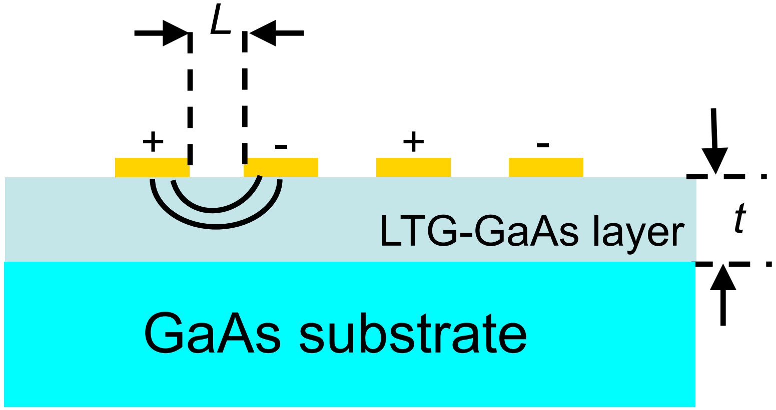
MBE growth at low temperature (≈ 200°C)
⇒ Defects

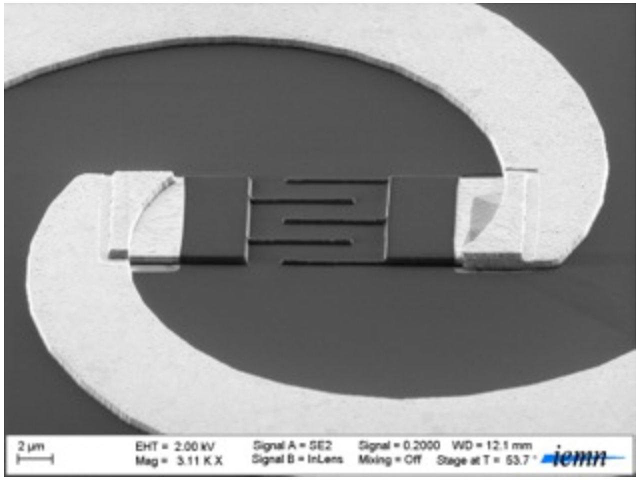


Time resolved pump-probe measurement
(Carrier lifetime)

Planar photoconductors

Standard approach:
Interdigitated structure





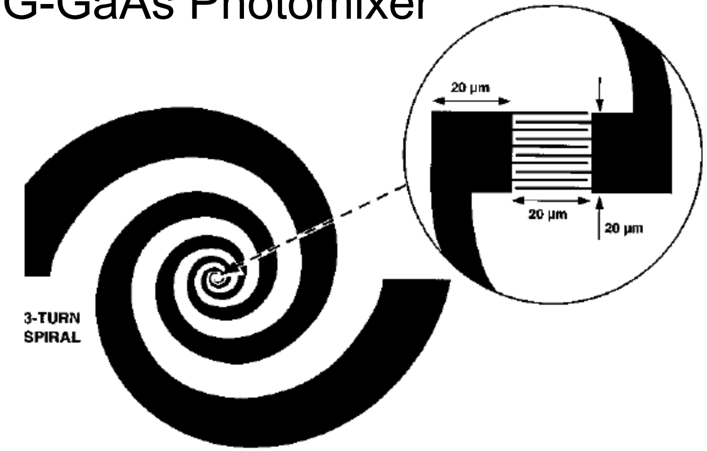
t ≈ 1-2 µm (absorption in GaAs)
L : same order

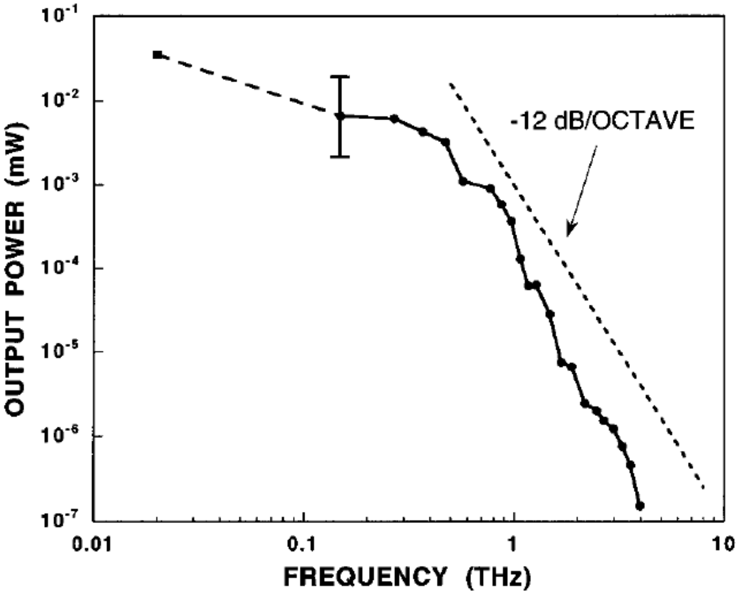
- Easy process
- Low capacitance
- Almost 100% light absorbed (AR coating)

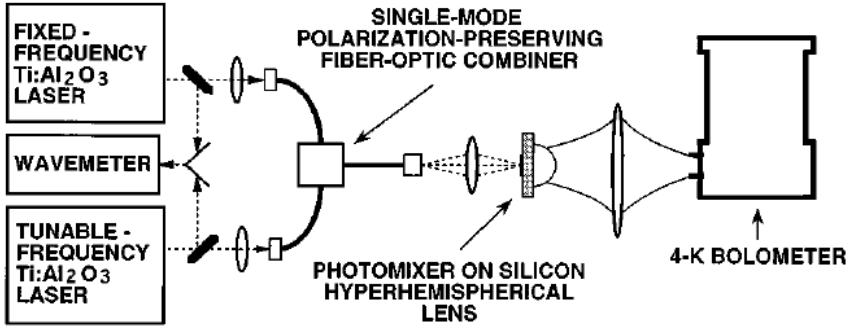
For 1 ps lifetime:
Responsivity ≈ **0.01 A/W at 10 V**
Quite low !

First THz photomixers

LTG-GaAs Photomixer







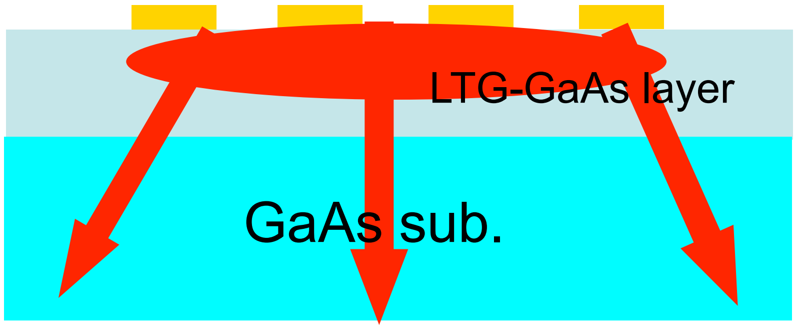
Brown *et al.* (1995)
Efficiency ≈ 10^{-3} % @ 1 THz !
Second order roll-off:

- Carrier lifetime
- RC time constant

Thermal aspects

Maximum output power is limited by **thermal destruction** !

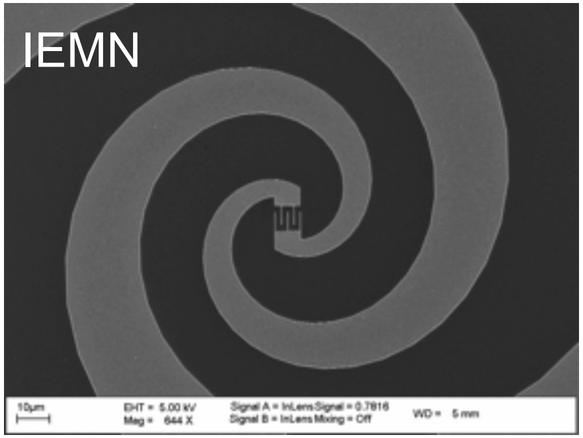
Thermal conductivity of GaAs: 45 W/m/K (Si: 150 W/m/K !)
Thermal conductivity of LTG-GaAs: ≈ 20 W/m/K



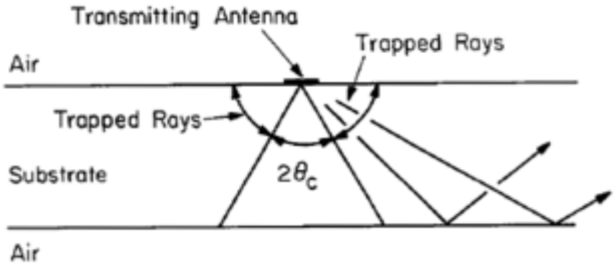
- Spreading of heat through a thick and low thermal conductance layer
- Low thermal conductivity substrate

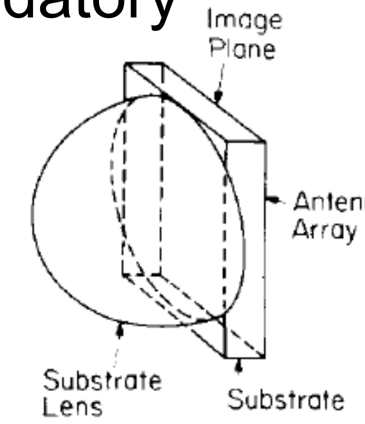
≈ 100 mW is generally the maximum for 10x10 µm^2 photoconductor
≈ **100 kW/cm^2**
⇒ 1-2 mA maximum at 10-15 V ⇒ $V_0/I_0 \approx$ **5-10 kΩ**

Self-complementary spiral antenna



Self-complementary spiral antenna:
- Compact and simple geometry
- Circular polarization
- Widely used with LTG-GaAs THz photomixers
- Silicon lens mandatory





$$Z_{Ant} Z_{Comp} = \frac{Z_0^2}{4}$$

$$Z_{SC} = \frac{Z_0}{2} = 188.5\Omega$$

71 Ω on GaAs
<< source impedance

Impedance of the ∞ antenna is purely resistive

Power delivered to the antenna

If $V_0/I_0 >> R_L$ the source can be considered as a current source :

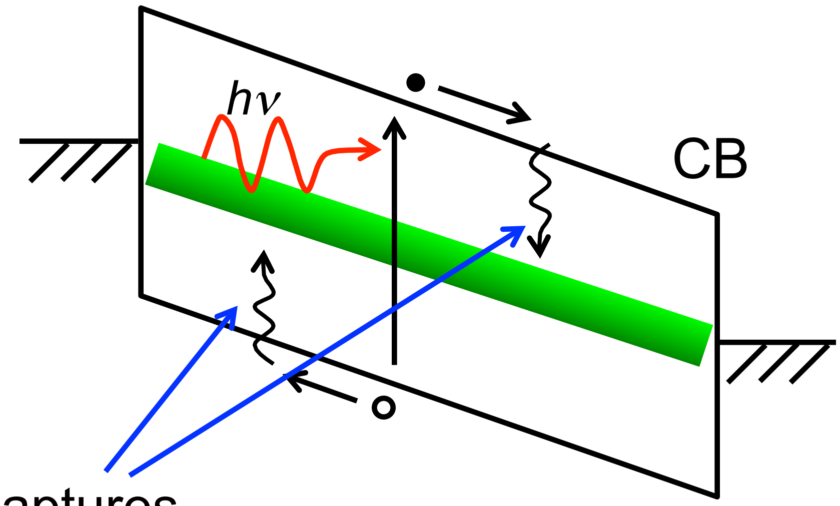
$$P_L = \frac{1}{2} R_L I_0^2 \frac{1}{\left(1+\omega^2\tau_c^2\right)\left(1+\omega^2 R_L^2 C^2\right)}$$

More power:

- Increase R_L *and* I_0
- Decrease τ_c and C

- *Increase* I_0*, decrease* C*,* τ_c *: thermal limit …*
- *The antenna impedance (*R_L*) is always small (for large bandwidth antennas)*

Efficiency



Captures
(non-radiative process)
⇒ **Heat**

We need the lasers photons to create free carriers but the energy provided is totally transformed in **heat** !

- If the bias voltage is zero ⇒ no THz (free carriers are not accelerated)
- In the fact the only the DC power is partially transformed to THz !

$$\eta_{elec,\max} = \frac{P_L}{P_{dc}} = \frac{1}{8} \times \frac{4}{3} = \frac{1}{6}$$

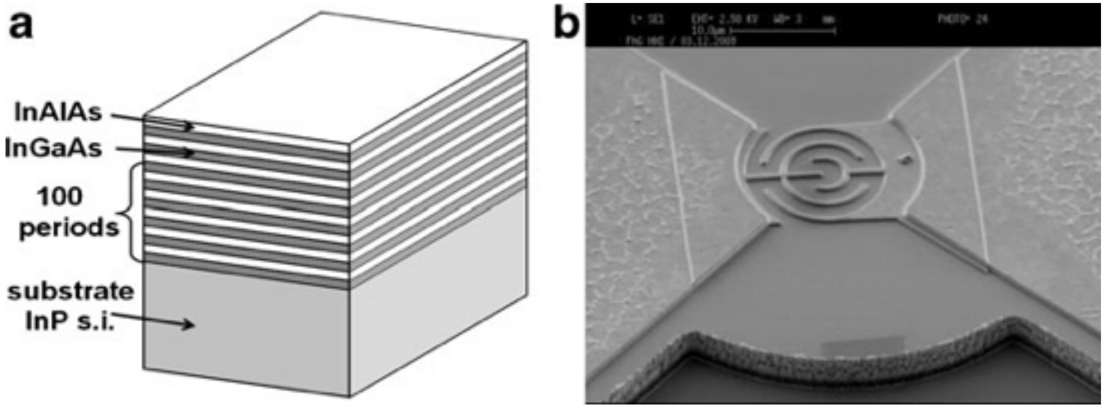
16.67% if impedance matching is achieved

$$\eta_{total,\max} = \frac{P_L}{P_{dc} + P_{opt}}$$

1.55 µm photoconductors

Why ?
- Longer wavelength: more photons/W (efficiency increased)
- Telecom wavelength

LTG-GaAs is not suitable
The gap of InGaAs : Mobility of carriers is higher

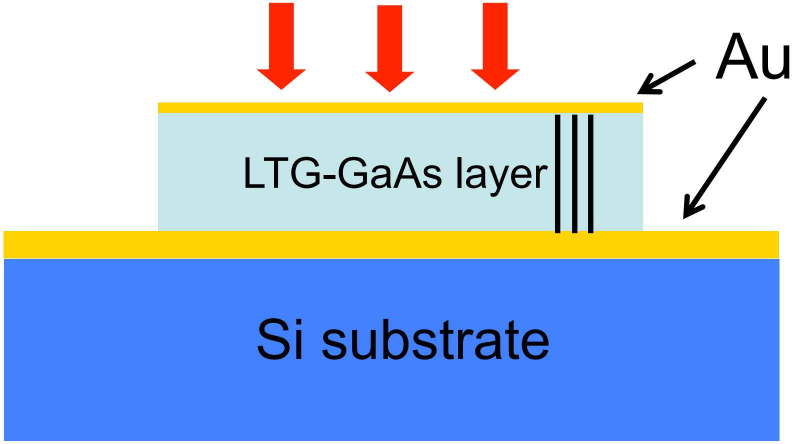


4.5 µW@500 GHz
P_{opt}= 20 mW

Stanze *et al.* (2010)

Increasing efficiency: vertical PC

IEMN new photomixer concept:
Vertical structure + Fabry-Perot resonance



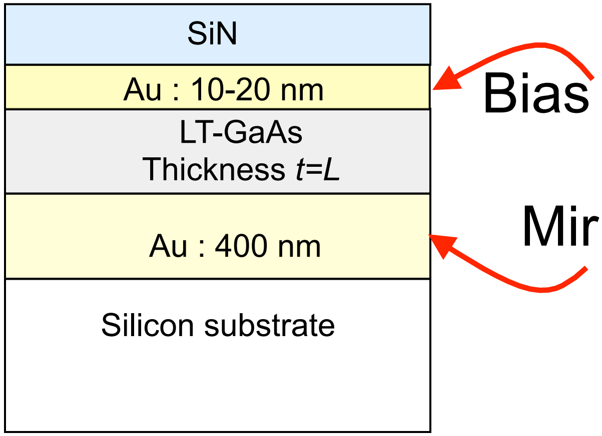
Advantages:

- Higher responsivity
- More uniform (E-field)
- Higher thermal conductivity

Drawbacks:

- Higher capacitance per unit area
- Bonding process (1 more step)

The vertical resonant photodetector



SiN

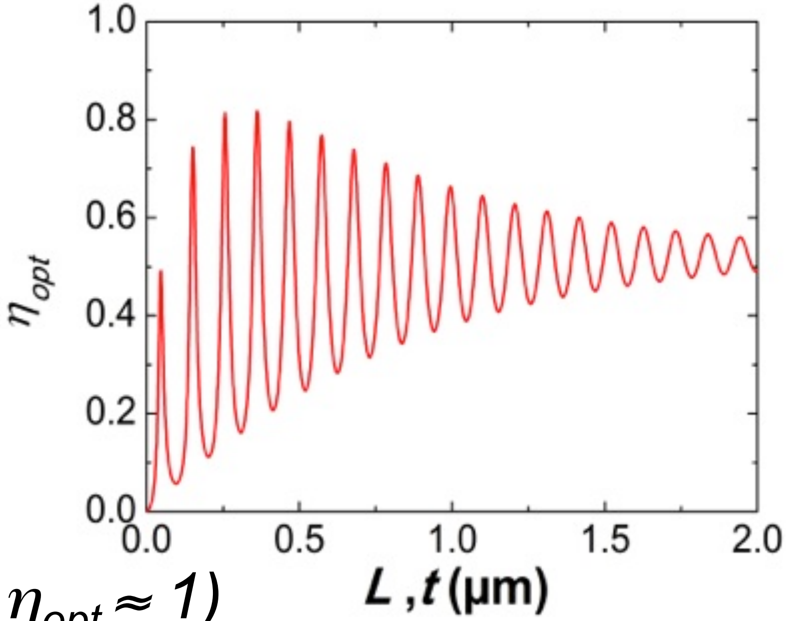
Au : 10-20 nm

LT-GaAs
Thickness $t=L$

Au : 400 nm

Silicon substrate

Bias electrodes
AND
Mirror cavity



Thickness can reduced (but with $\eta_{opt} \approx 1$)

$\Rightarrow$ same number of carriers in smaller volume $\Rightarrow$ increase of conductance

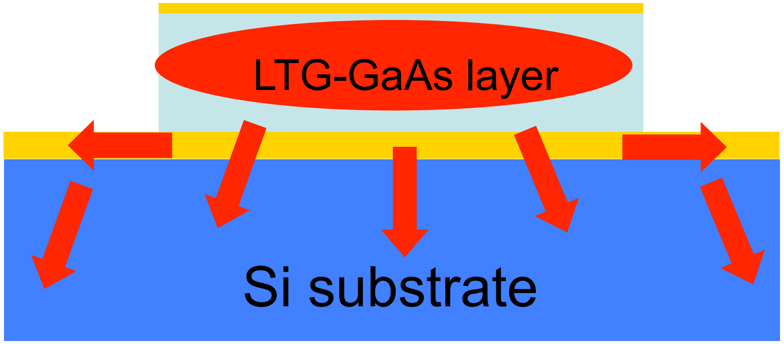
$\Rightarrow$ **Responsivity is higher (more current)**

$\Rightarrow$ Electric field is higher for the same voltage

$\Rightarrow$ **Responsivity is higher at a lower voltage**

Lower impedance !

Thermal aspects

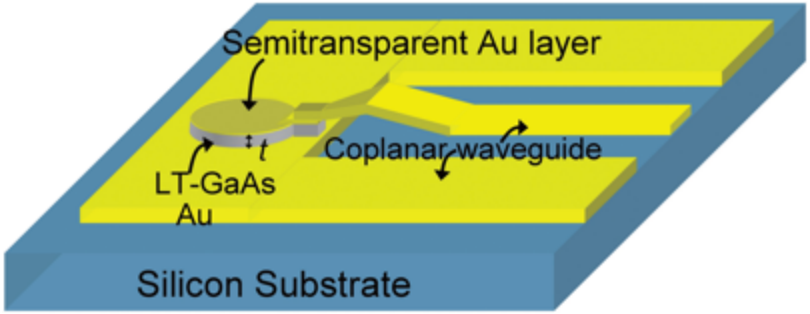


- LTG-GaAs layer is **thinner**
- Silicon substrate has a **higher thermal conductivity**
- Gold layer can also acts as a **heat spreader**
- Non-absorbed optical power is **reflected**

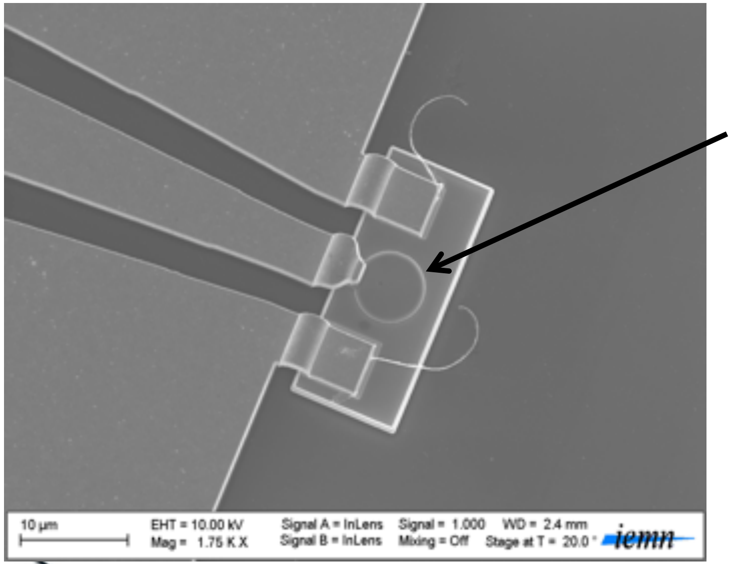
⇒ Vertical structure is far better

We have obtained destruction for **> 600 kW/cm^2 !**

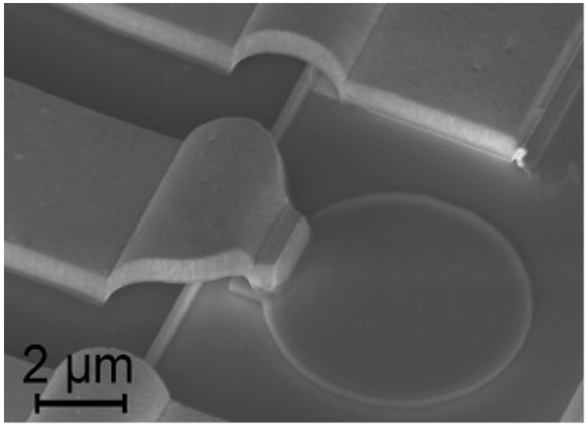
Technological realization



C = 13 fF
τ_c = 500 fs
t = 280 nm (3rd absorption peak)



6 µm diameter photoconductor



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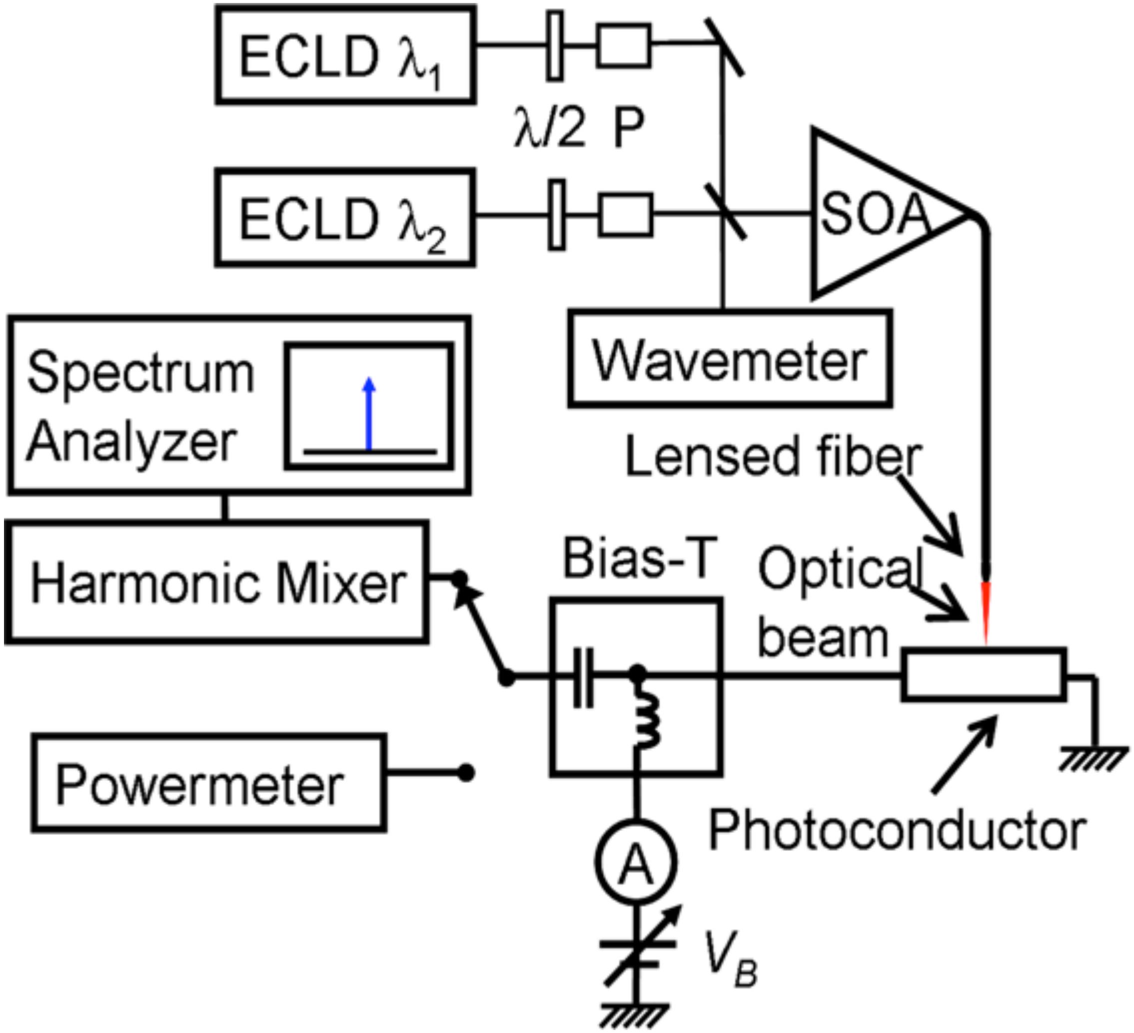
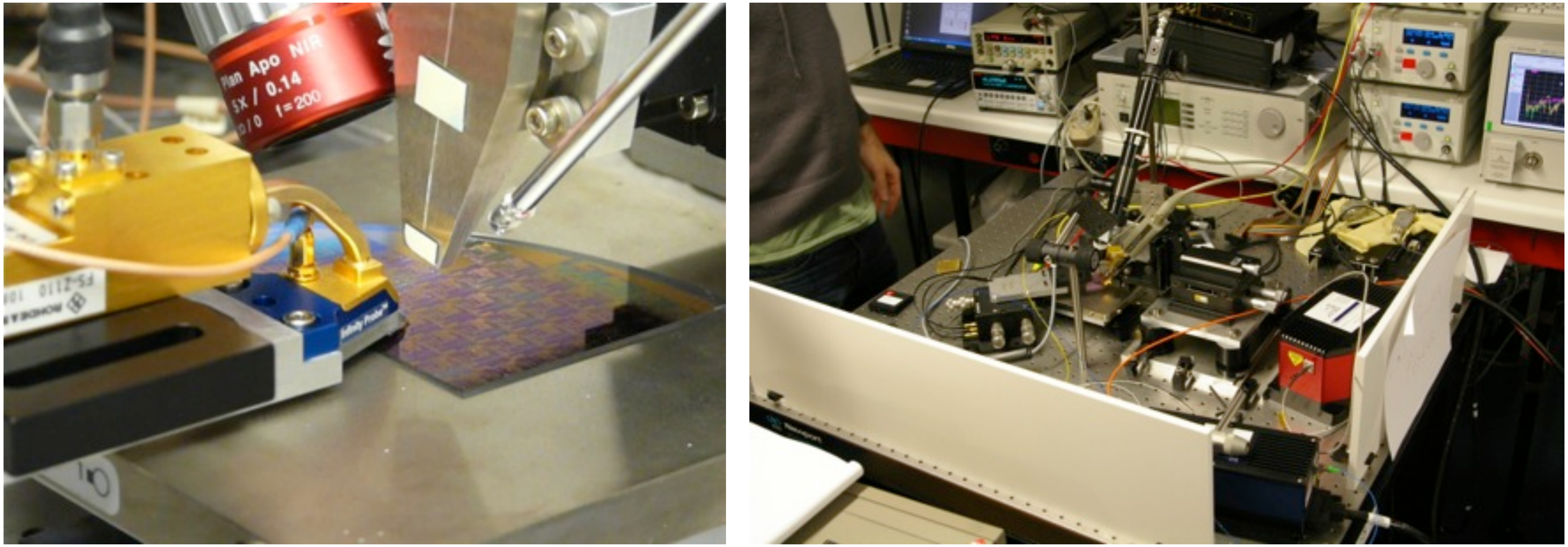
Experimental Set-up



Experimental set-up



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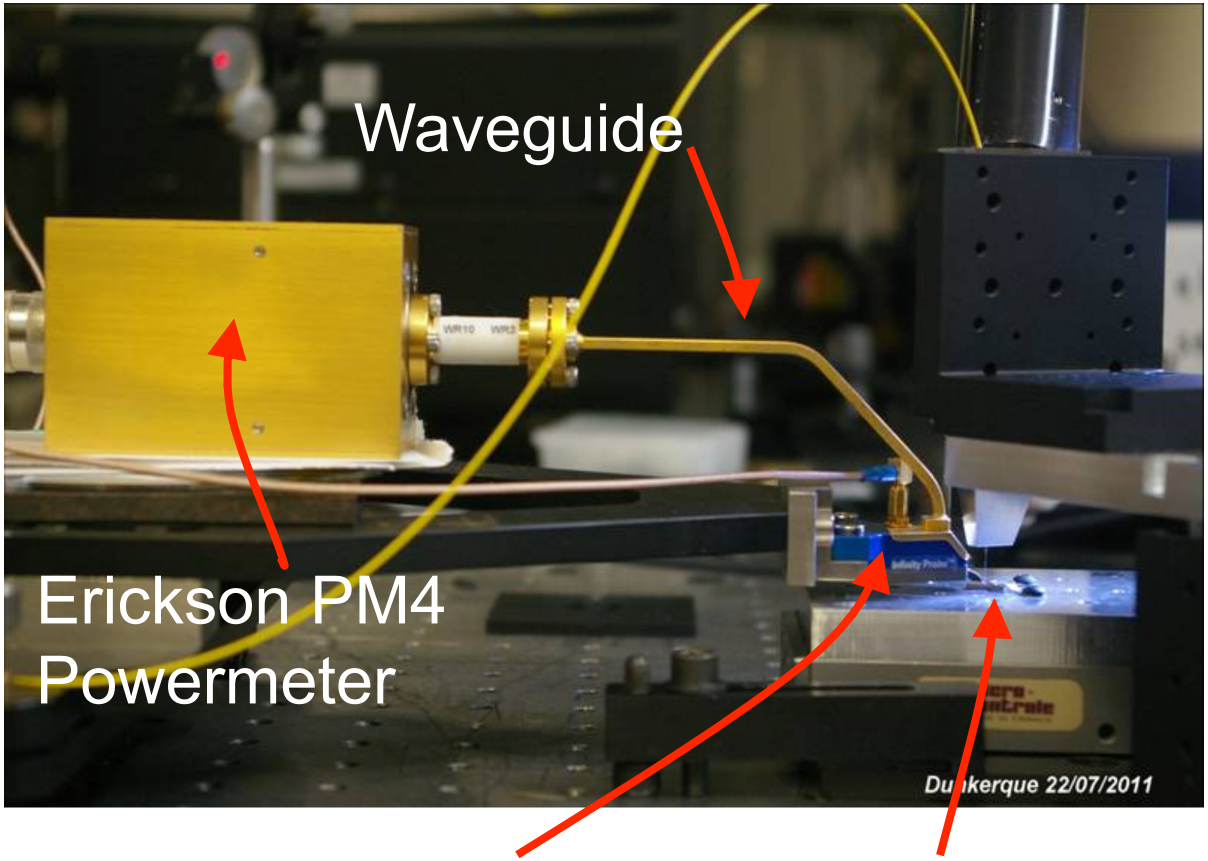
Experimental Set-up



Waveguide

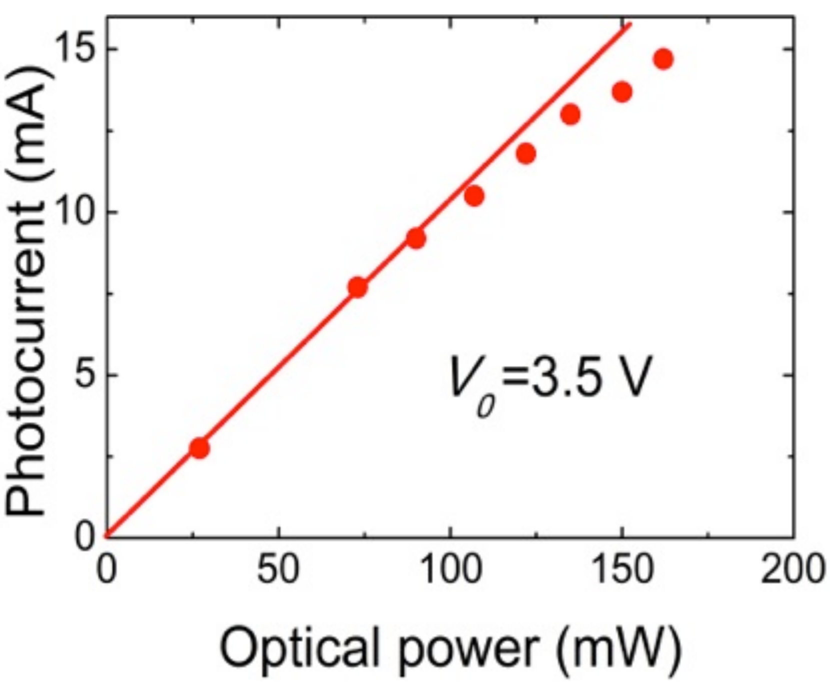
Erickson PM4 Powermeter

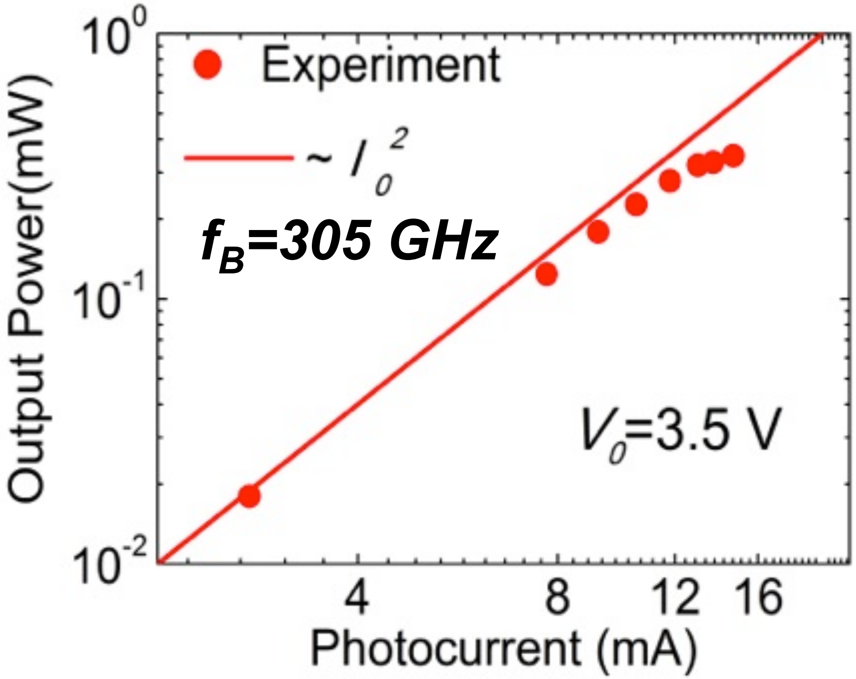
Dunkerque 22/07/2011

220-325 GHz
50Ω coplanar probe

Device under test

Results





I_{0max} = 14.7 mA (0.1 A/W) @ V_0=3.5 V

$1/G_{0max} = 240\ \Omega$!!

Maximum power : 350 μW !

About 100× previous values

1.2 mW @50 GHz (I_0 =14 mA and V_0=6 V)

Peytavit *et al.*, Appl. Phys. Lett. **99**, 223508 (2011).

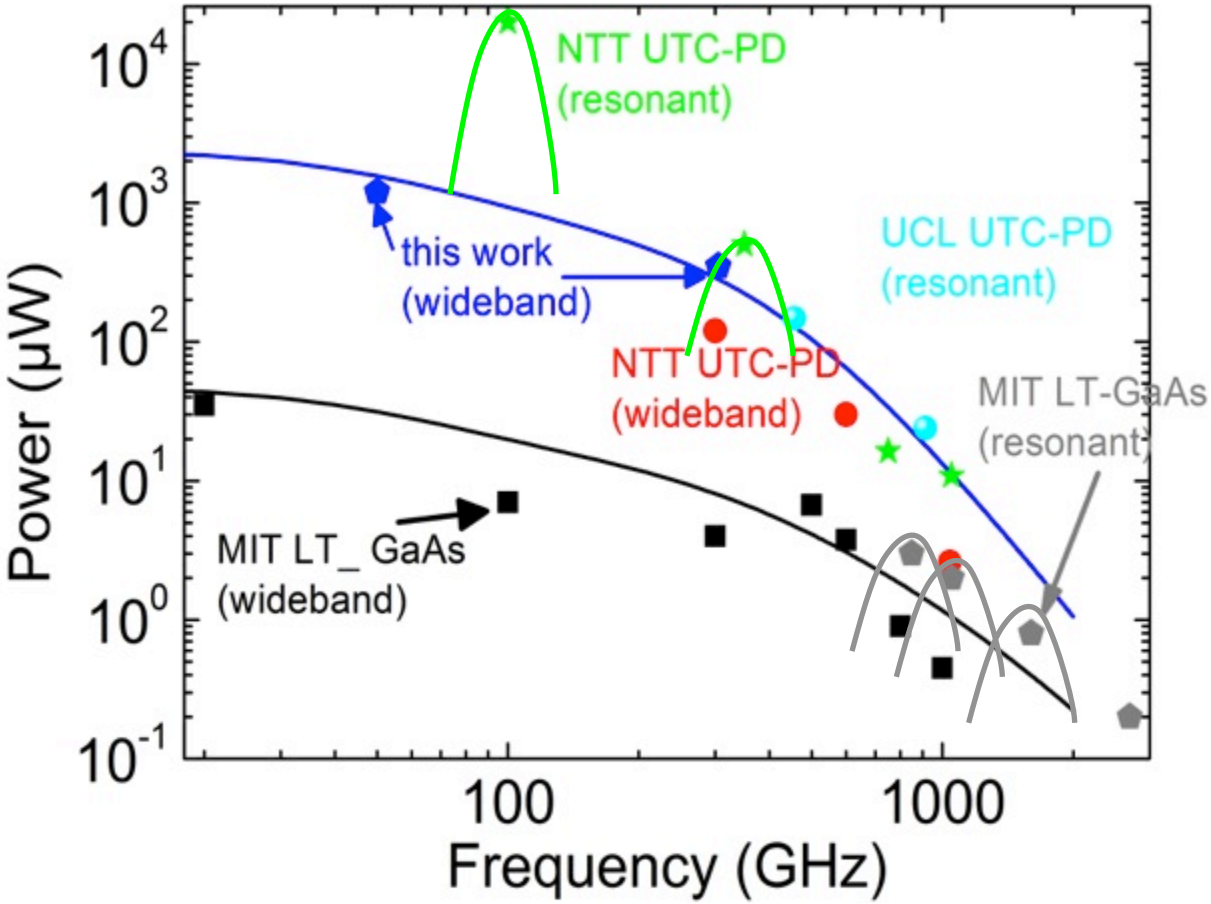
Efficiency

- *f* = 50 GHz:
RF power: 1.2 mW
dc power: 6 V × 14 mA = 84 mW
η_{elec} = 1.4 %

- *f* = 300 GHz:
RF power: 0.35 mW
dc power: 3.5 V × 15 mA = 52 mW
η_{elec} = 0.7 %

- 16 % is not reached …
- Not matched: 240 Ω ≠ 50 Ω, no LC resonator
- but efficiency is about **100×** better than standard LTG-GaAs photomixers

State of the art



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Ongoing works

- Integration with a **wideband antenna** for higher frequencies measurements

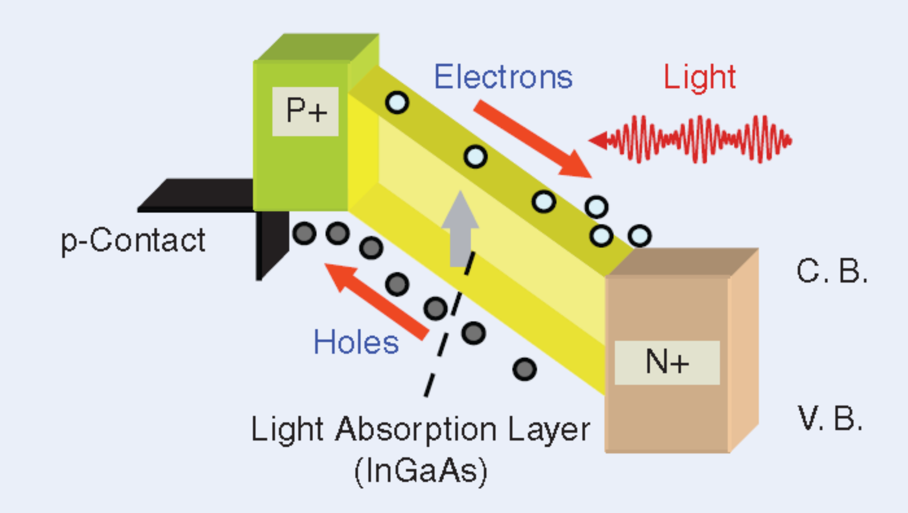
60 µW @600 GHz and 13 µW @1THz are expected with R_L=25 Ω

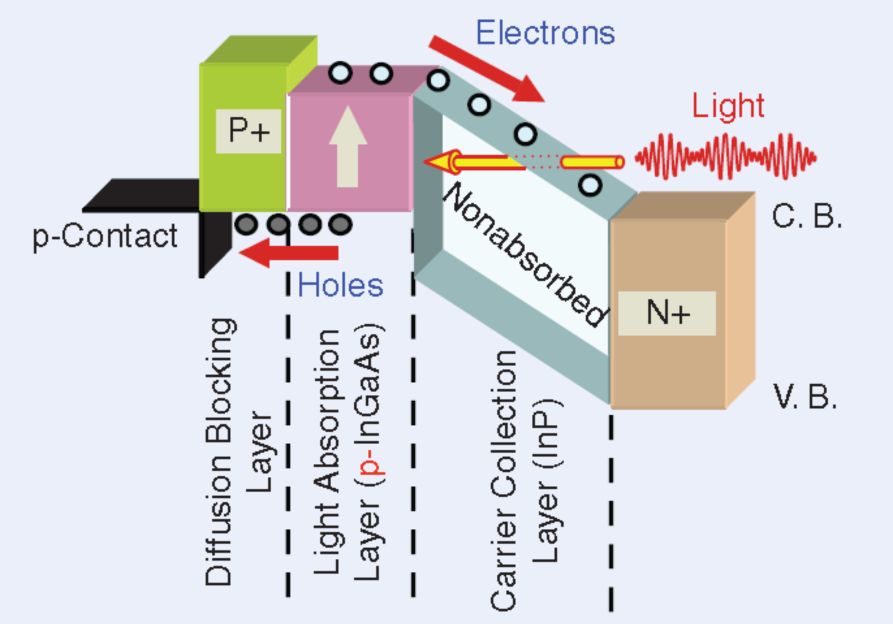
- **Thermal management**:
  - active cooling (Peltier cooler)
  - SiC substrate (490 W/m/K) instead of Si (150 W/m/K)
- Vertical photoconductor **as a detector**

Acknowledgements: ANR-JST WITH

The other way: Uni-travelling-carrier photodiodes (UTC-PD)

pin-PD Vs. UTC-PD



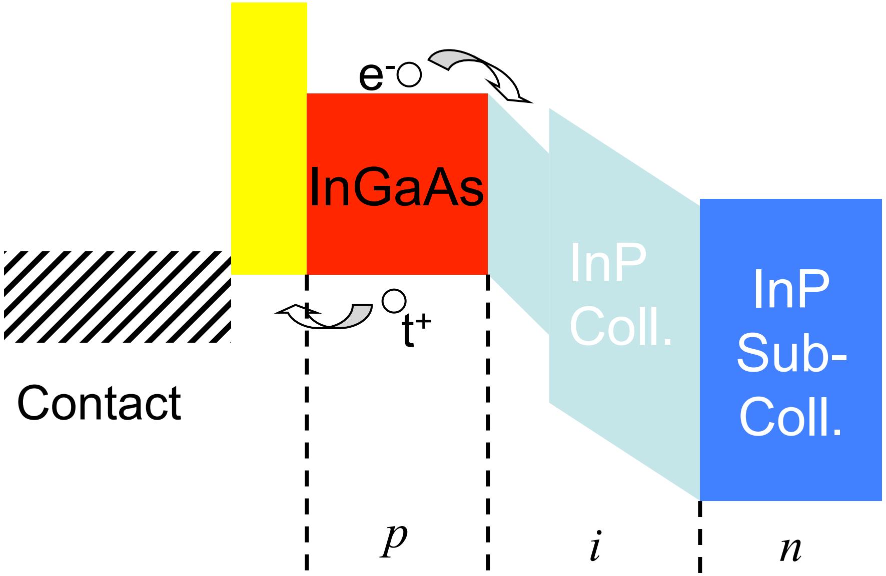


Holes are slow !
- Low cut-off frequency
- Saturation

Initially proposed by NTT in 1996

Figures: T. Nagatsuma *et al.*, IEEE Microwave mag. (2009)

Frequency response of UTC-PD



⇒ No short carrier lifetime materials

⇒ Structure close to HBT

- Cut-off frequency fixed only by electrons
- Compatible with λ=1.55 µm
- Good response
- High saturation photocurrent

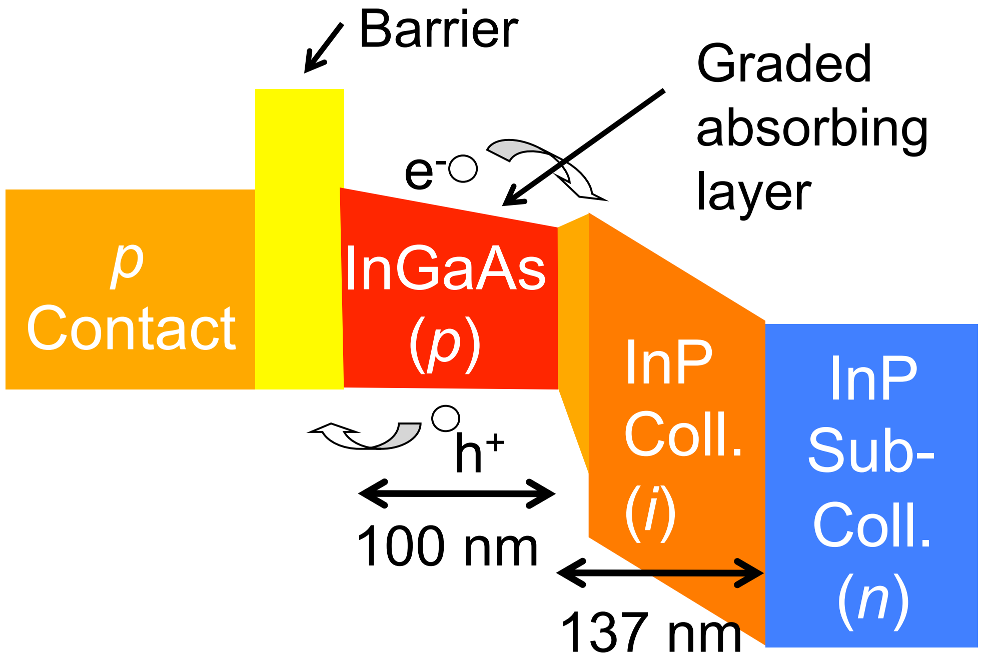
$$|i(\omega)| = \frac{I_0}{\sqrt{1+(\omega\tau_a)^2}\sqrt{1+(\omega\tau_c)^2}}\left|\frac{\sin(\omega\tau_t/2)}{\omega\tau_t/2}\right|$$

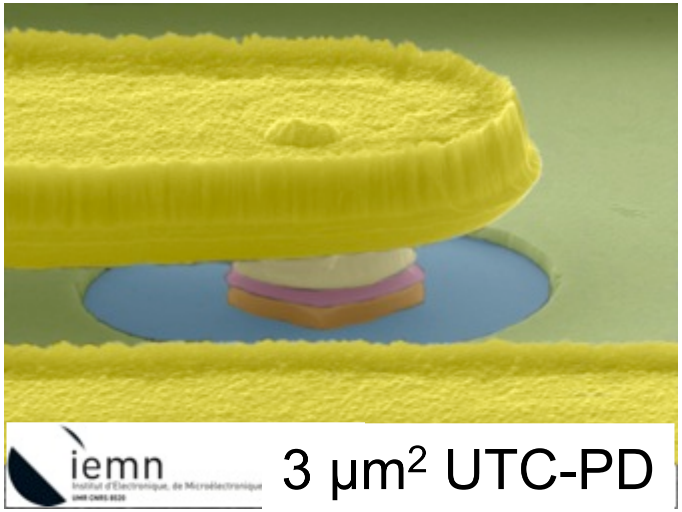
Transit-time in collector

Diffusion time in absorbing layer

RC time constant

Graded absorber UTC-PD





3 μm² UTC-PD

No window: 1.55 μm beam through the substrate

To increase cut-off frequency:

- Short collector (137 nm)
- Small area (3 μm²)
- Pseudo-field in absorbing layer: 46 % ⇒ 60 % Indium

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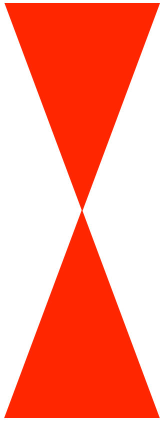
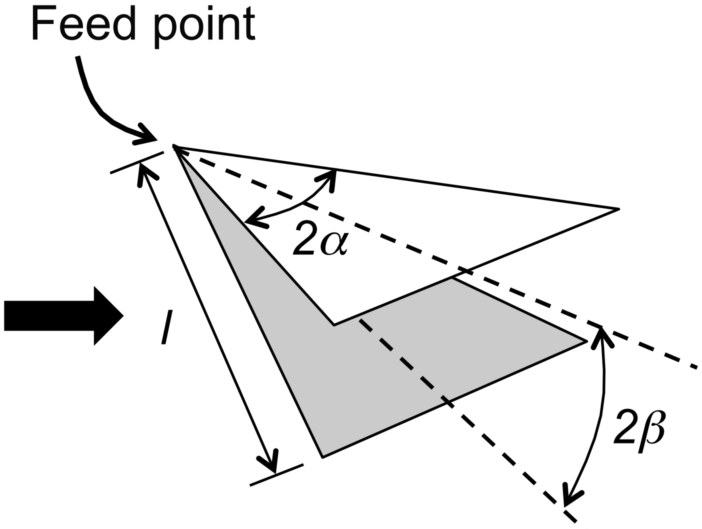
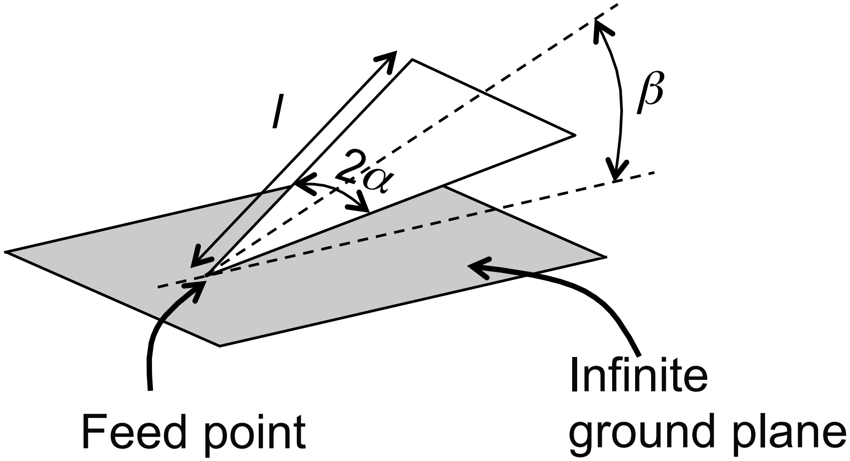
The TEM-horn antenna (TEM-HA)



Bow-tie



Dipole TEM-HA

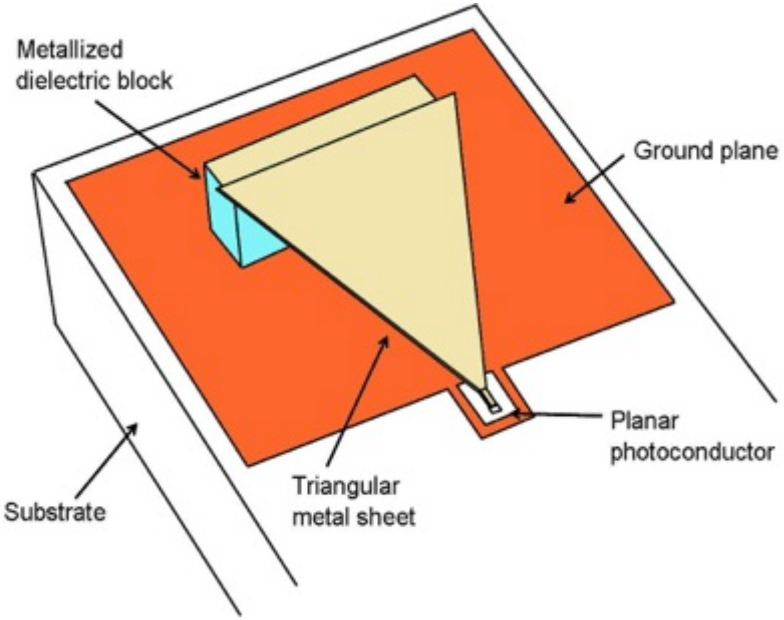


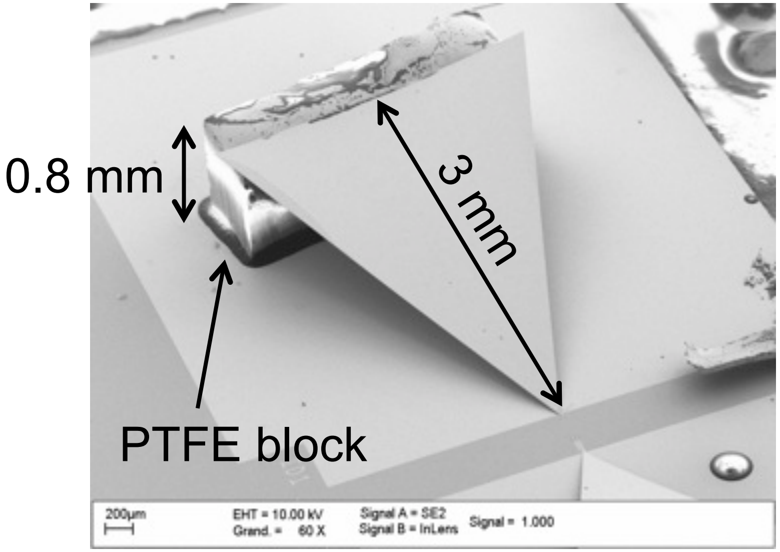
Monopole TEM-HA

TEM-HA is a wideband antenna:
Infinite antenna verify the Rumsey’s principle (defined only by angles)

The monopole TEM-HA is particularly interesting for THz:
- Wideband and low dispersion
- No substrate losses, no Si lens (ground plane)

Design of the THz TEM-HA

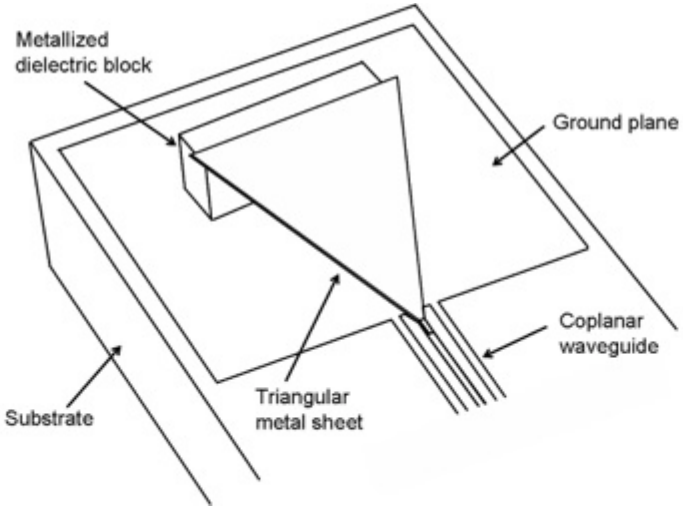


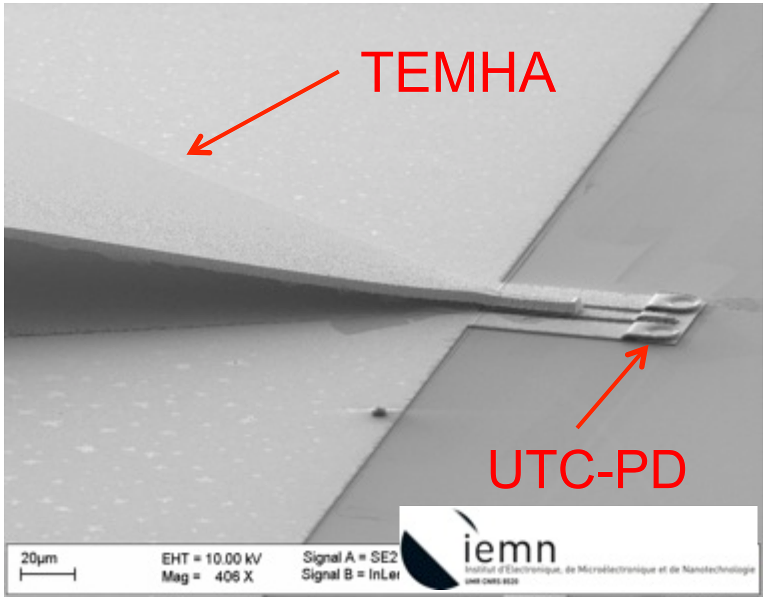


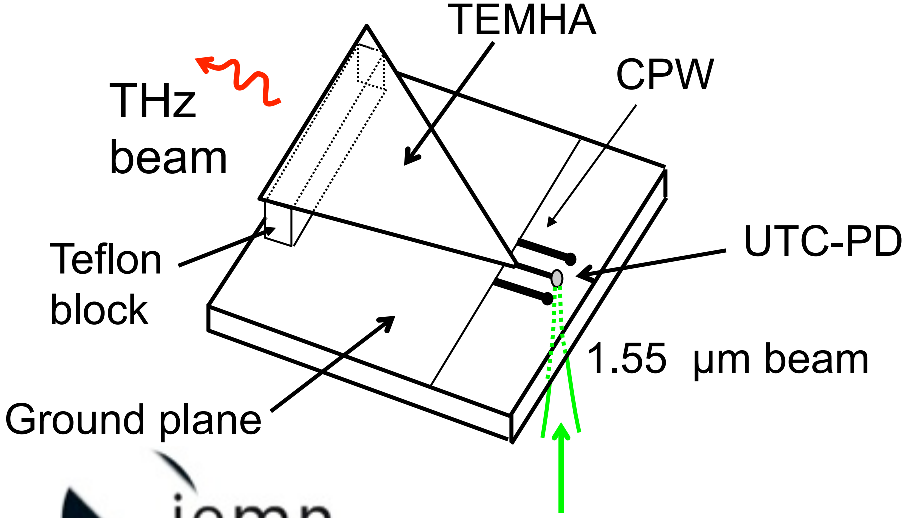
SEM view of TEM-HA on LTG-GaAs

Peytavit *et al.*, APL **93**, 111108 (2008)

Integration of UTC-PD with TEMHA

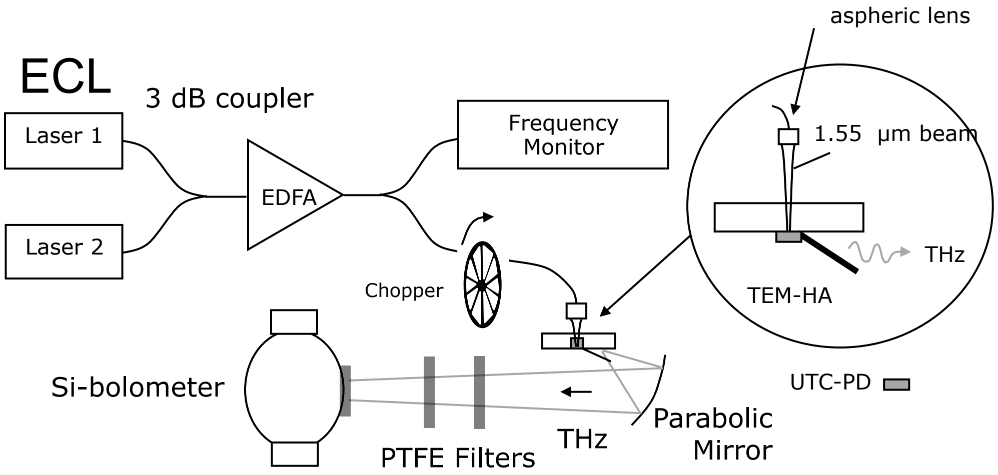


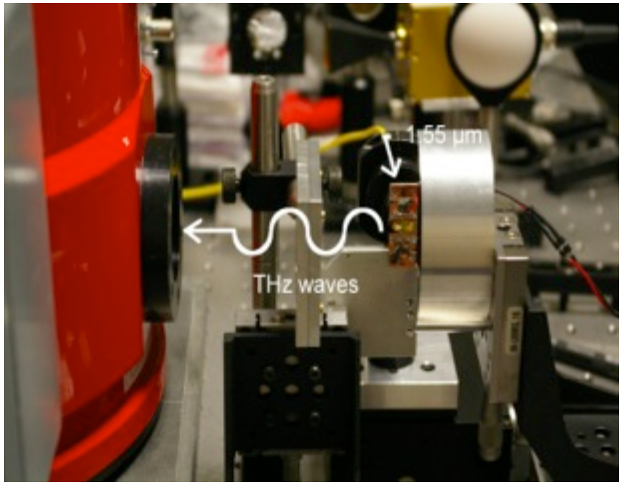




UTC-PD + TEMHA :
Natural separation of the 1.55 µm beam and the THz beam.

UTC-PD Photomixing experiment





- Max power: 1.13 µW @ 0.94 THz

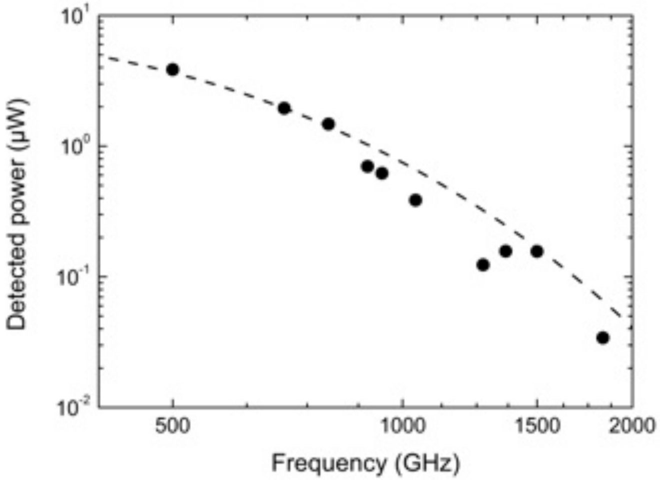
Optical power = 50 mW

- >10 times higher efficiency:

0.46 µW @ 1.04 THz for 50 mW (IEMN)

Collaboration with LPCA (Dunkerque)

Beck *et al.*, El. Lett. **44**, 1320 (2008)



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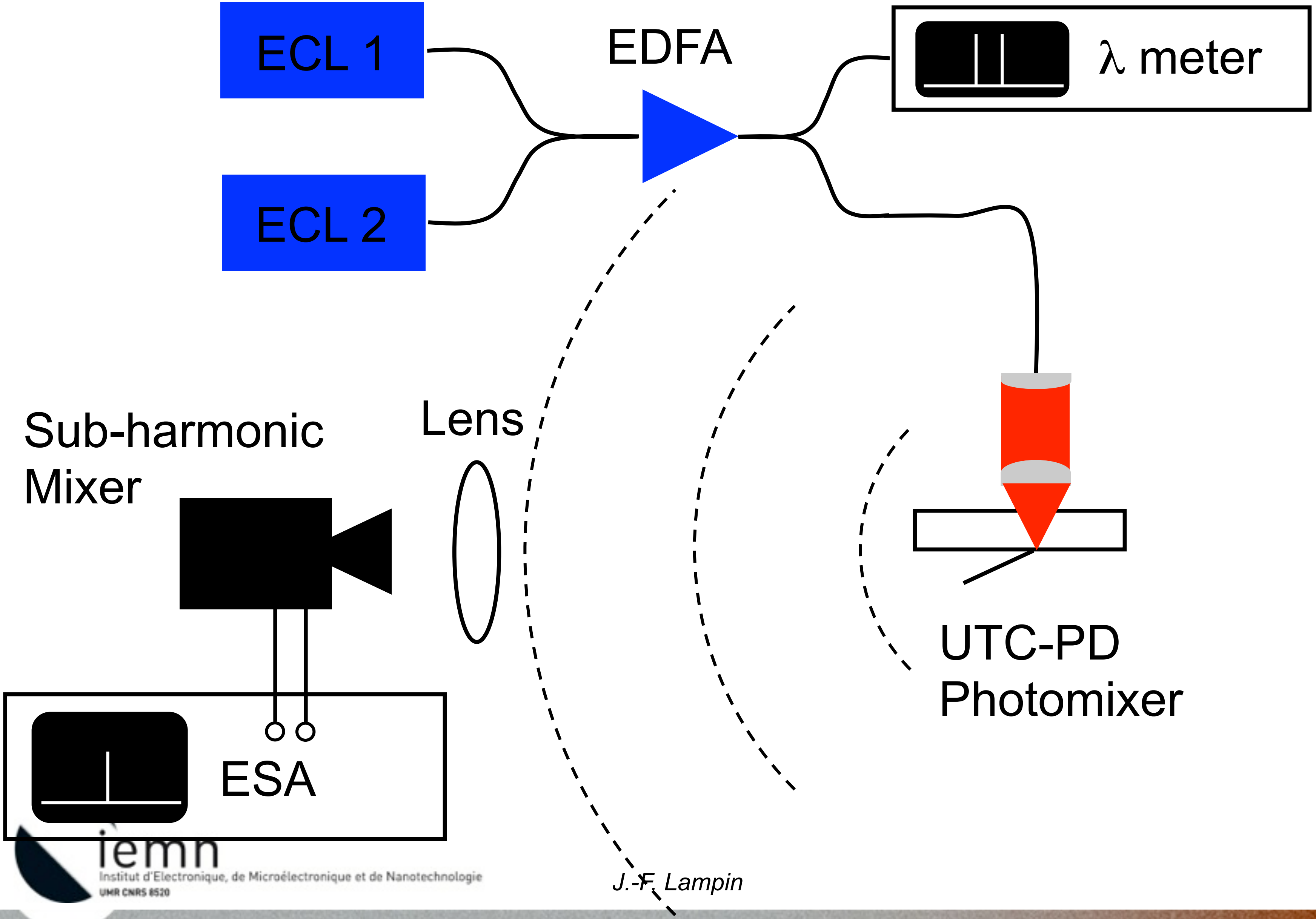
Heterodyne detection



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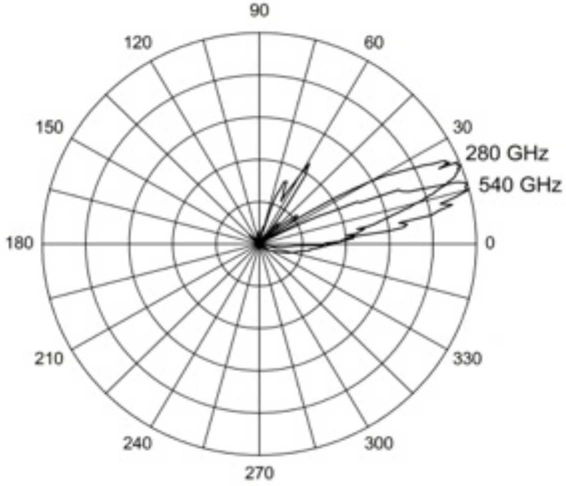
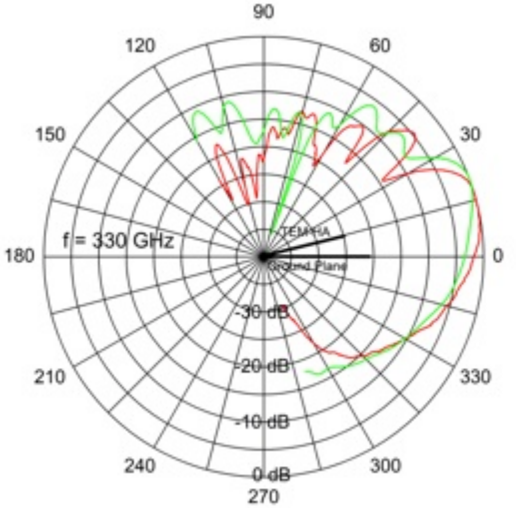
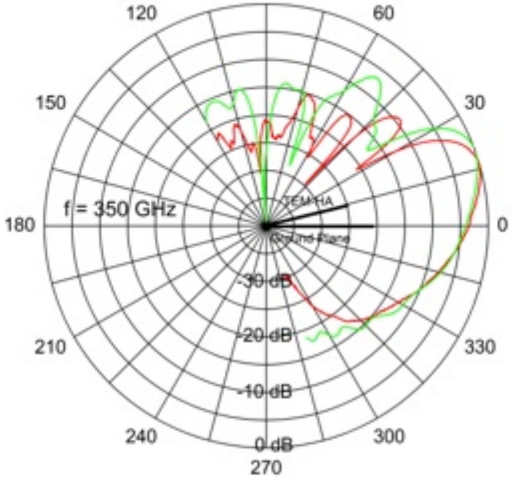
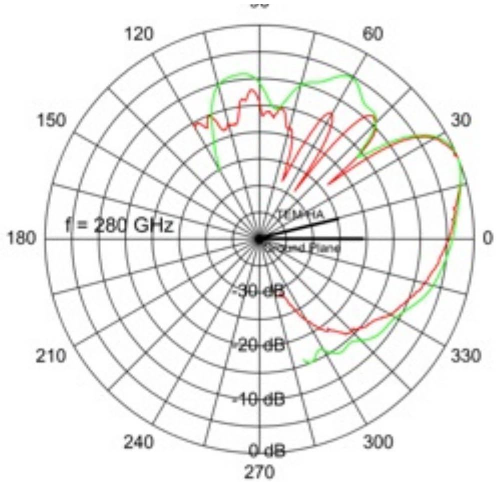
Radiation patterns

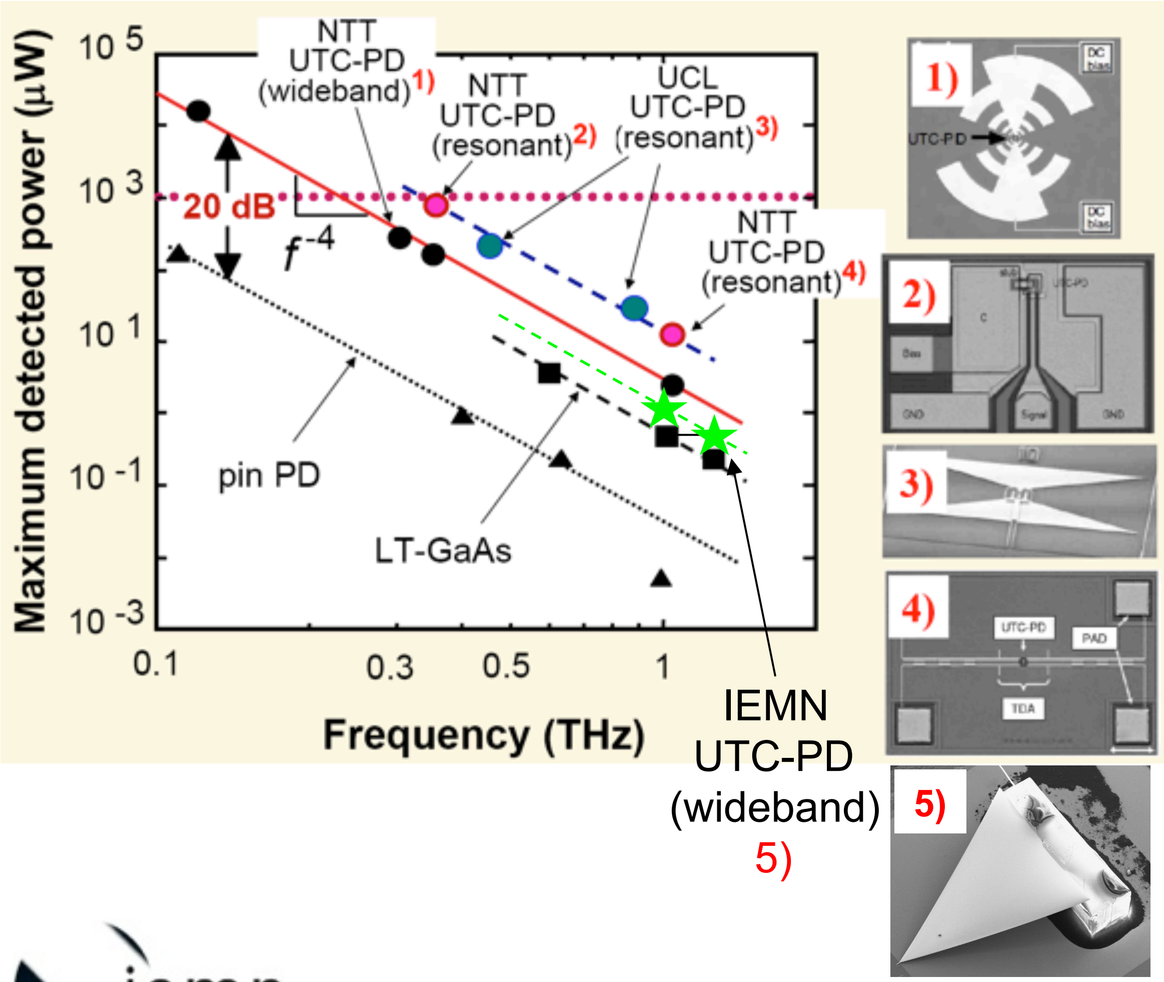








UTC-PD: State of the art



- Wideband antenna
≈1-2 μW @ 1 THz

- Resonant antenna
≈ 10-20 μW @ 1 THz
≈ 500 μW @ 350 GHz

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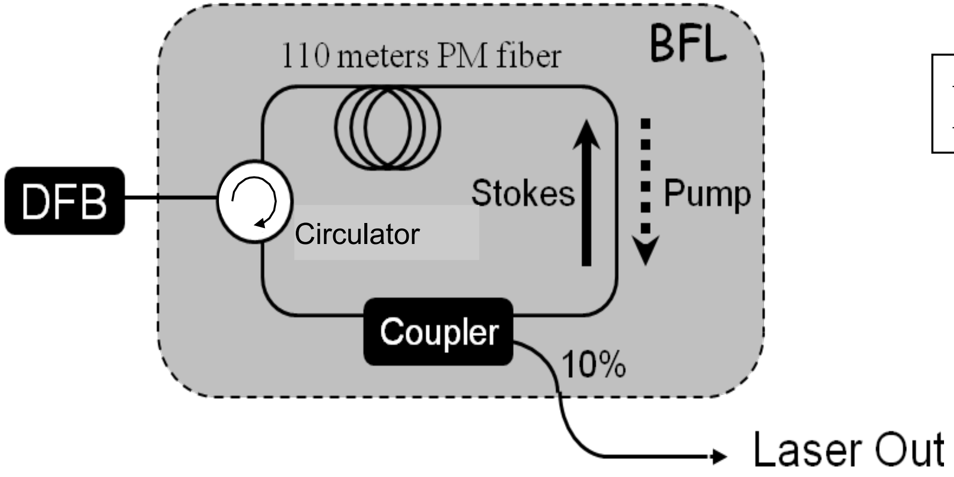
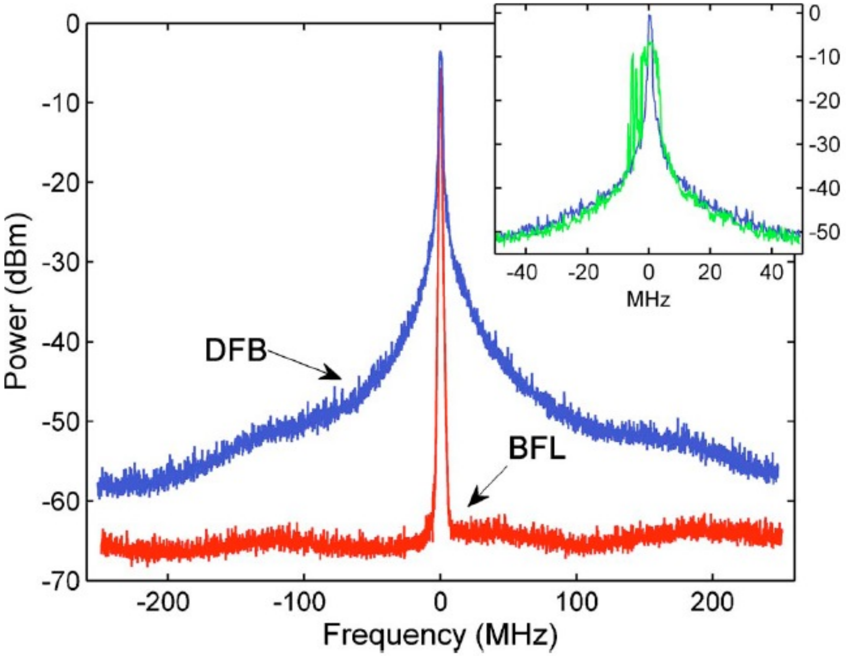
Brillouin Fiber Laser: from MHz to kHz



$$\text{FSR}_{\text{expected}} = c/n.L \approx 1.75 \text{ MHz}$$



Pump: not resonant thanks to the circulator

DFB: FWHM ≈ 1 MHz

Collaboration with PhLAM

F. Mihelic *et al.,* Opt. Lett., 35, p. 432 (2010)

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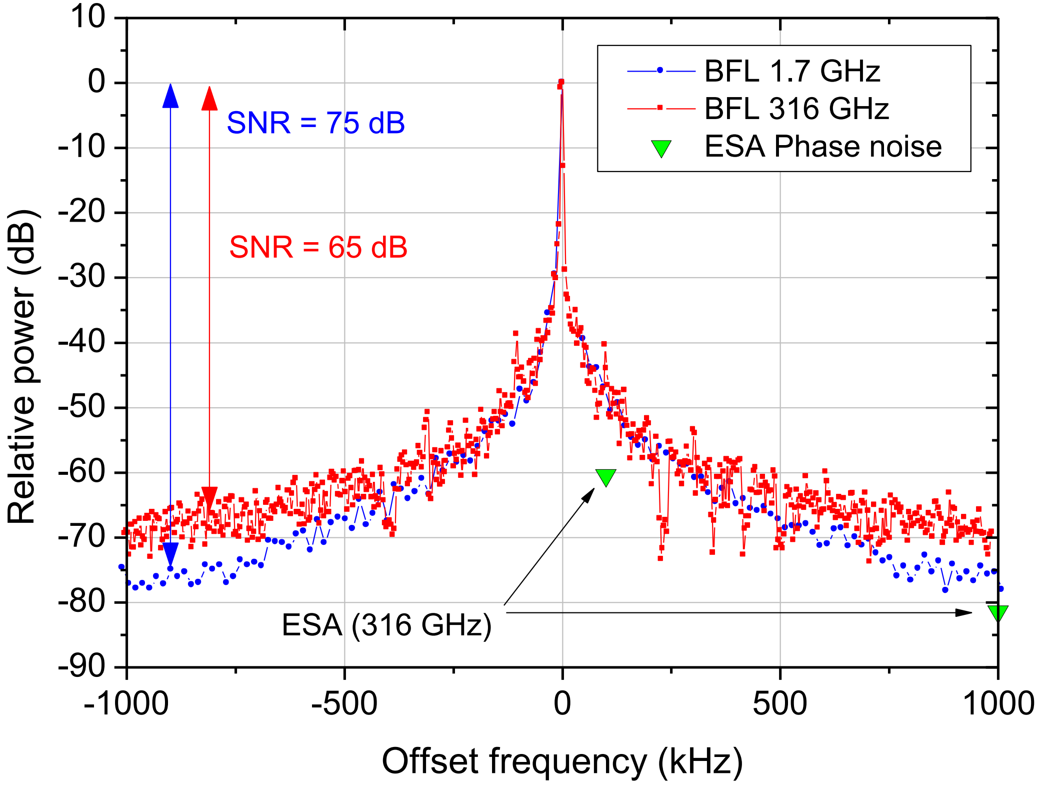
Photomixing Results with BFL



G. Ducournau et al. OPTICS LETTERS / Vol. 36, No. 11 / June 1, 2011

SNR = 70 dB

RBW = 1 kHz

FWHM ~1 kHz

- Same performance (FWHM) between 1.7 GHz and 316 GHz
- Comparison with the spectrum analyzer electrical phase noise
- ESA O.L. is (at 316 GHz) only 10 dB better @ 100 kHz offset carrier

Advantage: No 20.log(N) factor

Photomixing: pros and cons

Pros :

- Widely tunable, high res. compared to TDS
- Can be modulated at high frequency
- Small and lightweight
- Easy to separate laser source and THz source

Cons:

- Power still low (mW possible)
- Linewidth poor compared to multiplication (standard lasers)
- Sophisticated lasers for high spectral purity (< 1 MHz)

Clean spectrum far from the carrier

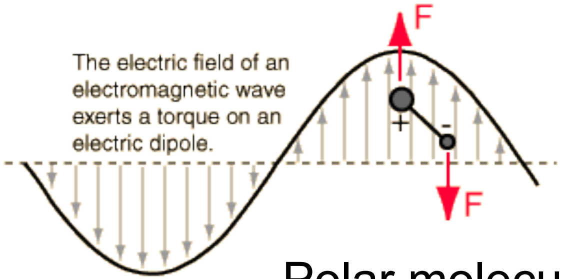
- Almost no spurious
- Low phase noise

Applications of photomixing

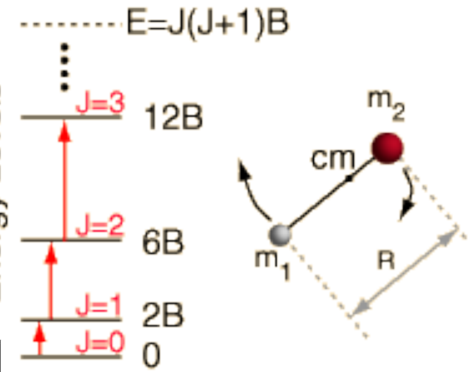
- Spectroscopy
  - ⇒ Security, astrophysics
- Telecommunications
  - ⇒ Short range, high data rate
- Imagery ?

Gas spectroscopy

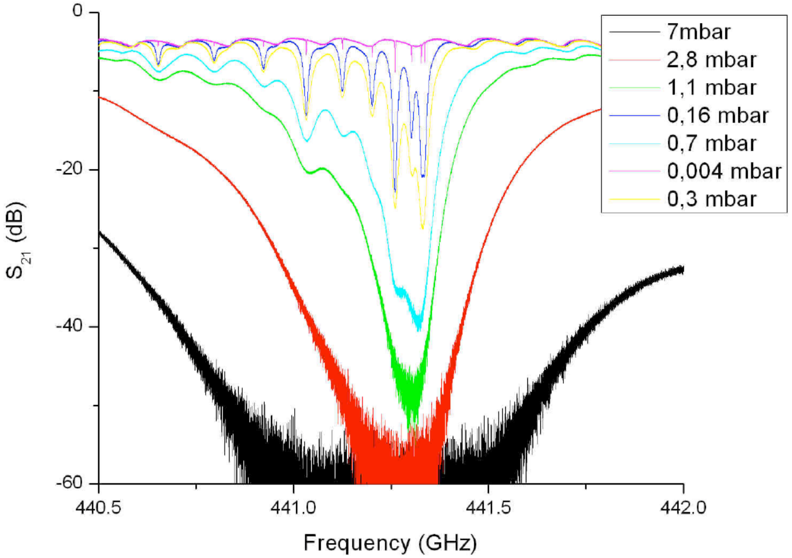
Gas molecules are THz top !



Polar molecule



Rotation transitions



CH_3CN@441 GHz

- Absorption lines are a few GHz wide at atmospheric pressure

- When the pressure is reduced the lines can be a few MHz wide ! ⇒ very selective

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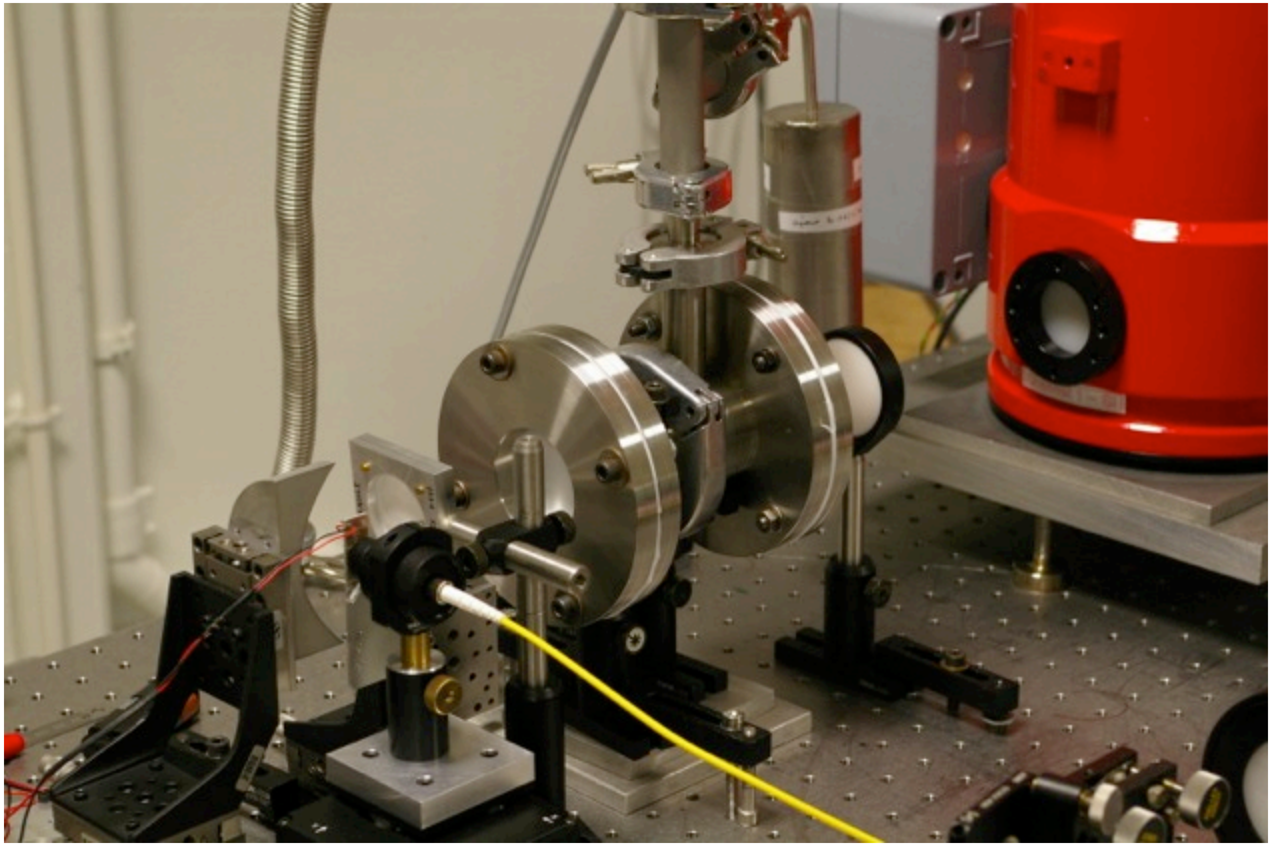
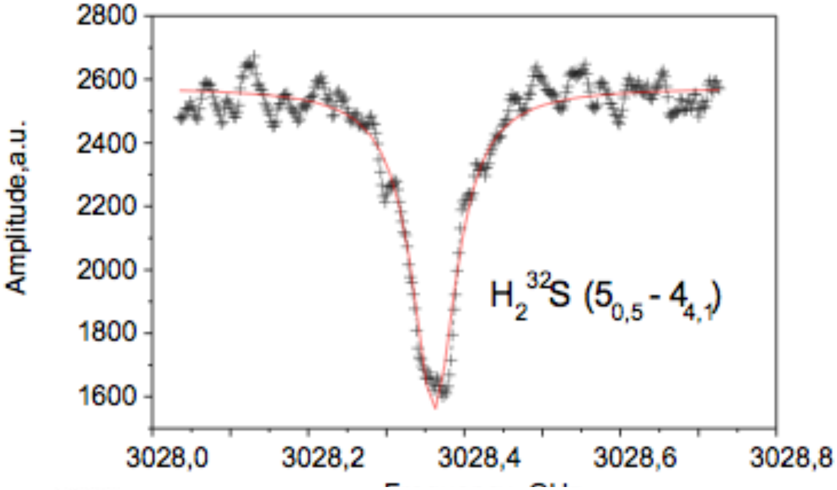
Gas spectroscopy experiment

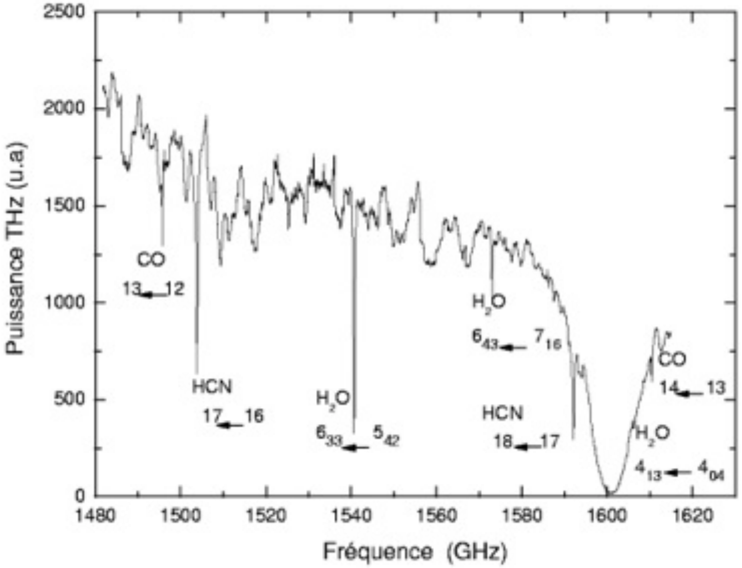


LPCA
Dunkerque

Gas spectra: applications



Absorption of H_2S measured around 3 THz thanks to photomixing
⇒ Pollutant detection, security



Detection of H_2O, CO and HCN in cigarette smoke (LPCA, Dunkerque)
⇒ Low sensitivity to diffusion

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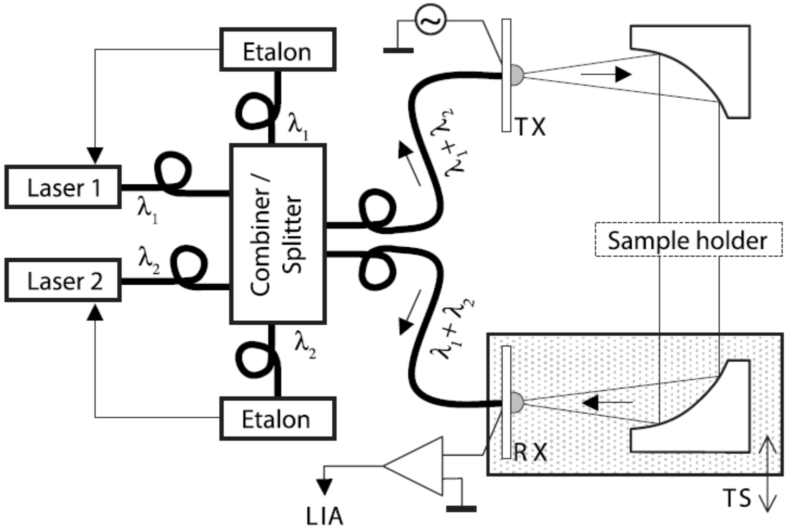
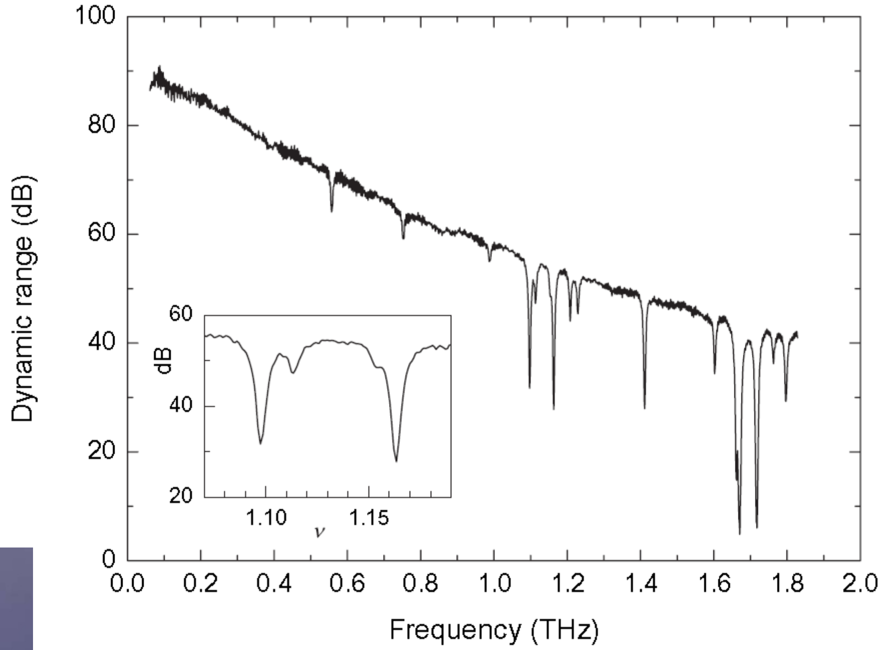
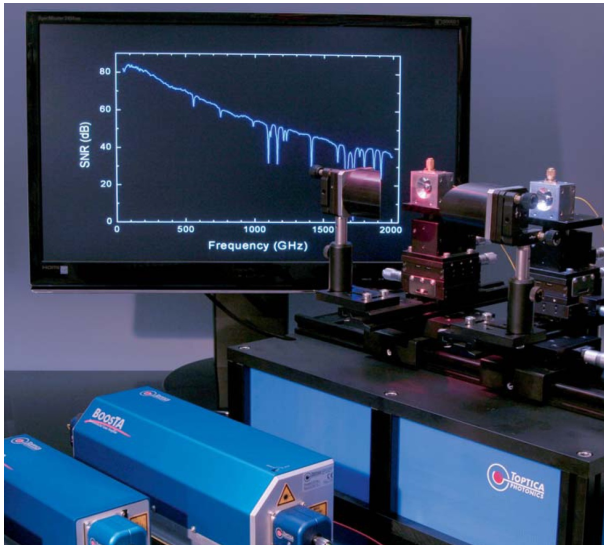
Homodyne detection

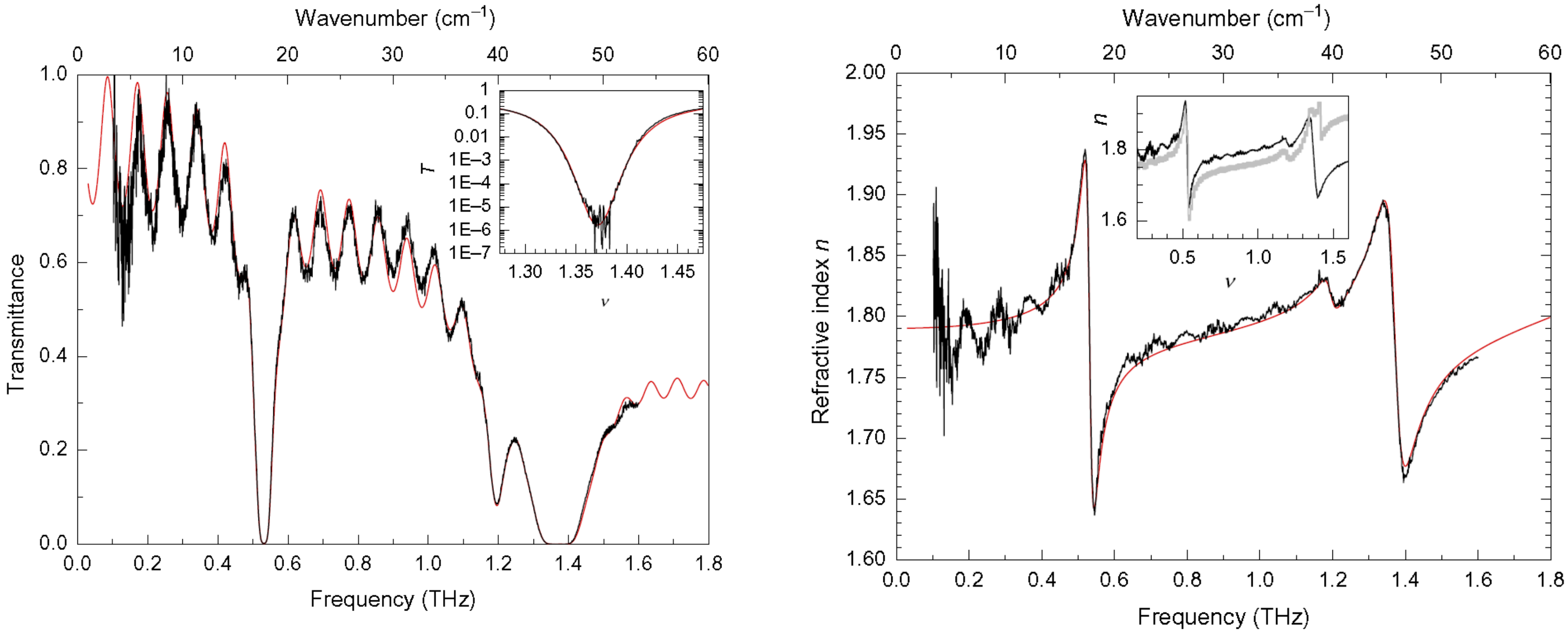




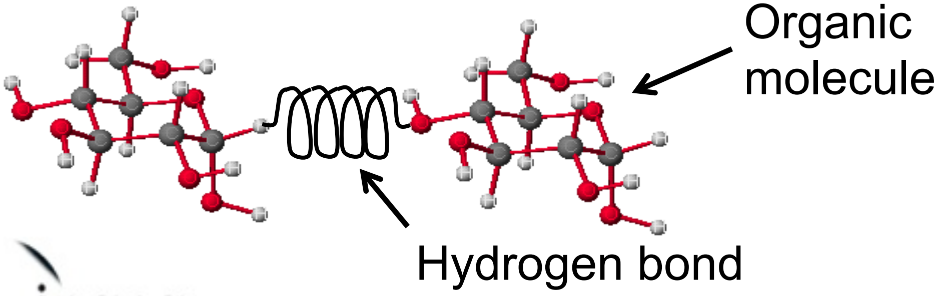


Spectrum obtained by the photomixing set-up from Toptica Photonics AG

Homodyne detection



Spectra of α-lactose monohydrate (Toptica Photonics AG)



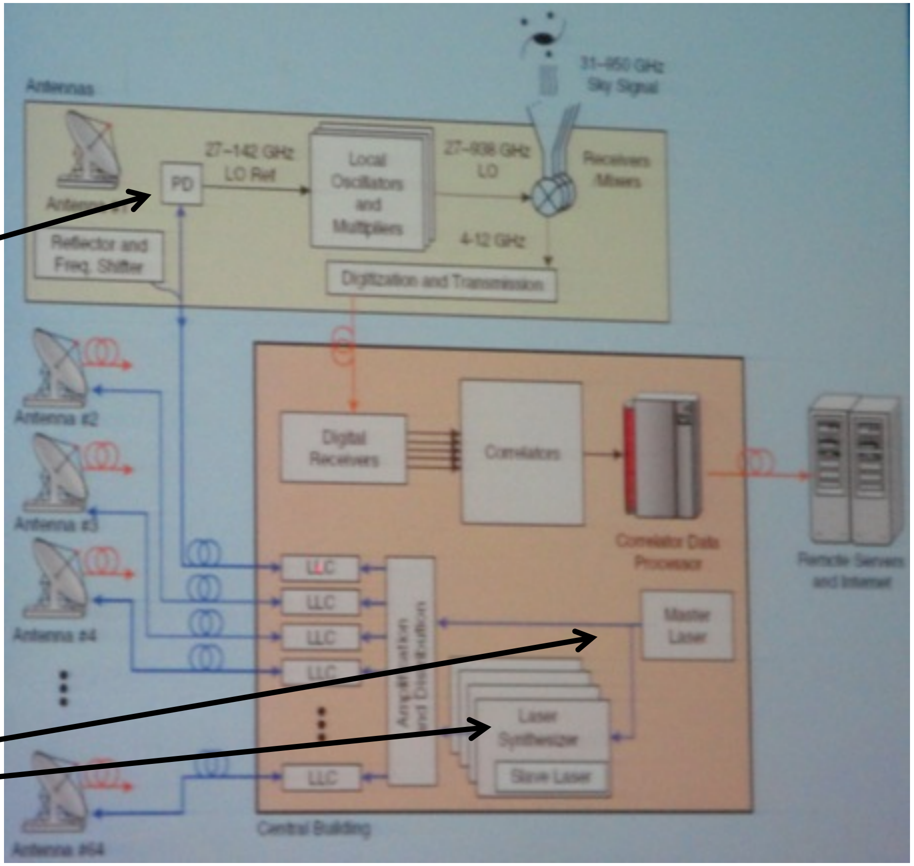
Spectra very sensitive to crystal structure !

⇒ Pharmacy applications

Astrophysics applications

ALMA radiotelescope:
To distribute LO@100 GHz over kms ! ⇒ Photomixing

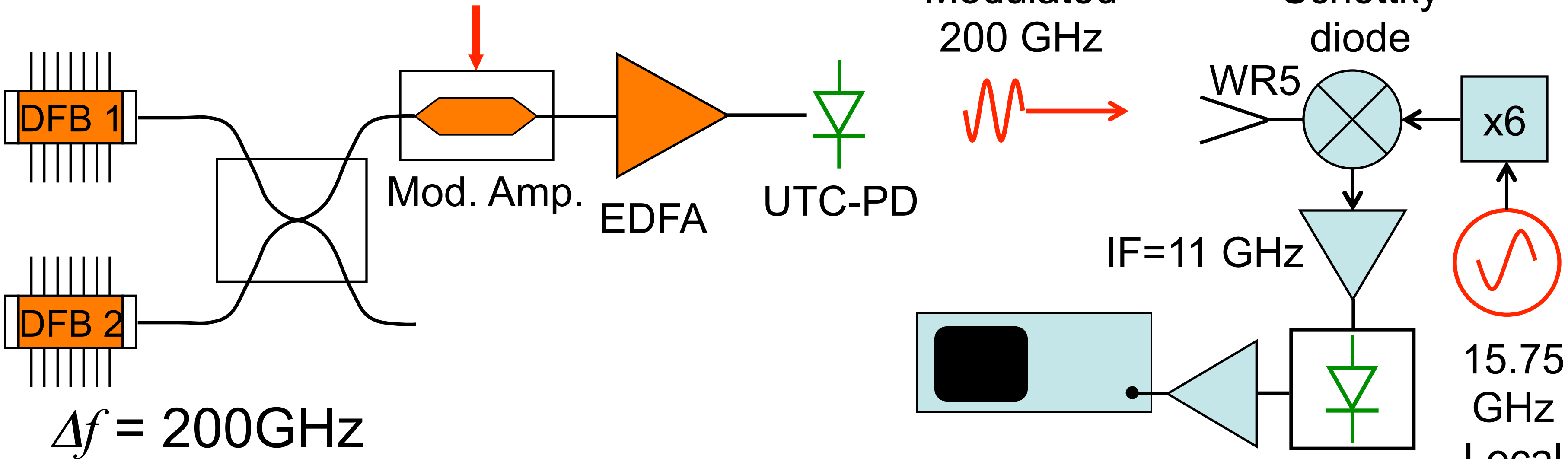
See J. Hesler Talk



Photodiode
(photomixer)
From RAL

Very stable lasers
@ 1.55 µm

1 Gb/s transmission @ 200 GHz



Gb/s datas

Modulated
200 GHz

Schottky
diode

WR5

DFB 1

DFB 2

Mod. Amp.

EDFA

UTC-PD

x6

IF=11 GHz

15.75
GHz
Local
Osc.

Δf = 200GHz

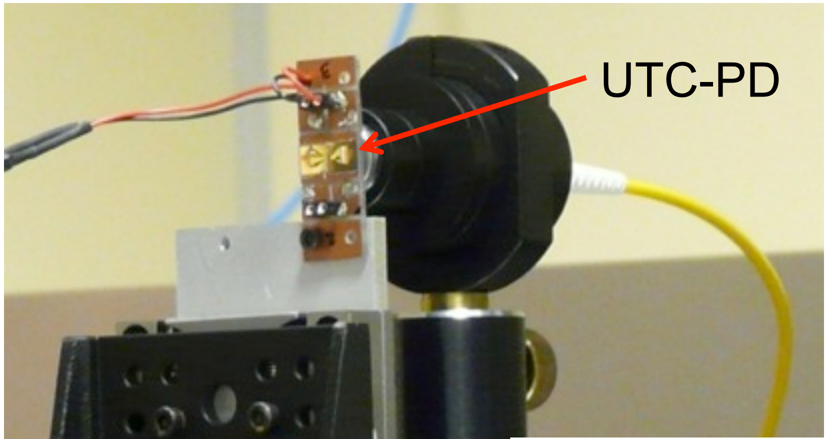
Optoelectronic emitter

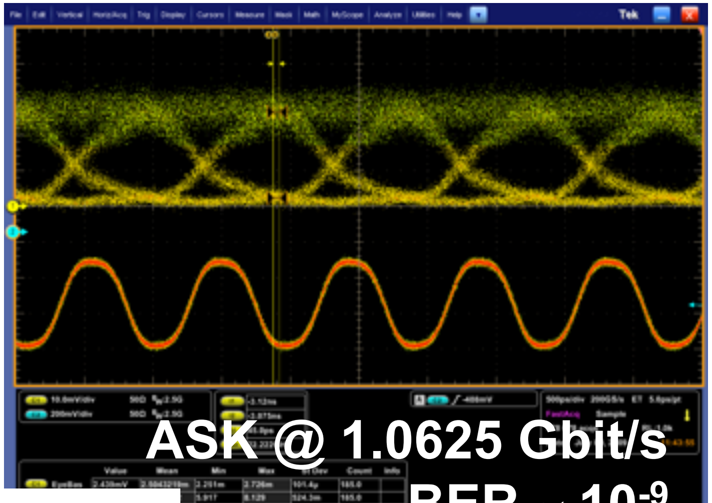
Heterodyne receiver

Ducournau *et al.*, El. Lett., 2010

1 Gb/s transmission at 200 GHz

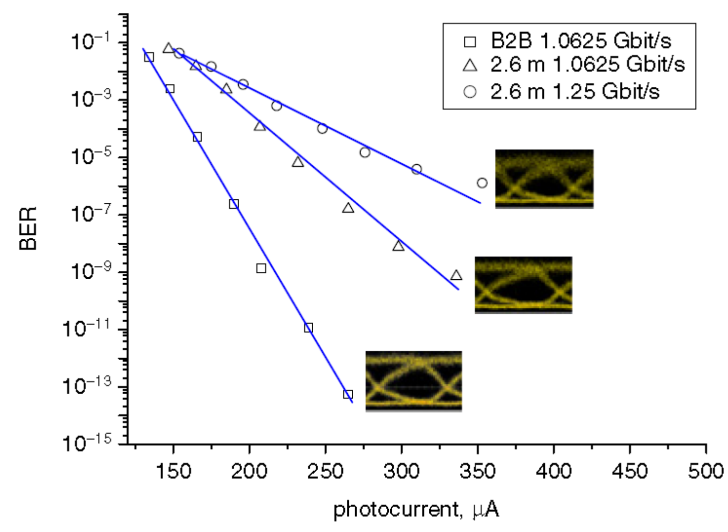
Optically powered (no bias)





ASK @ 1.0625 Gbit/s

BER ≈ 10^{-9}



Remote wireless spot

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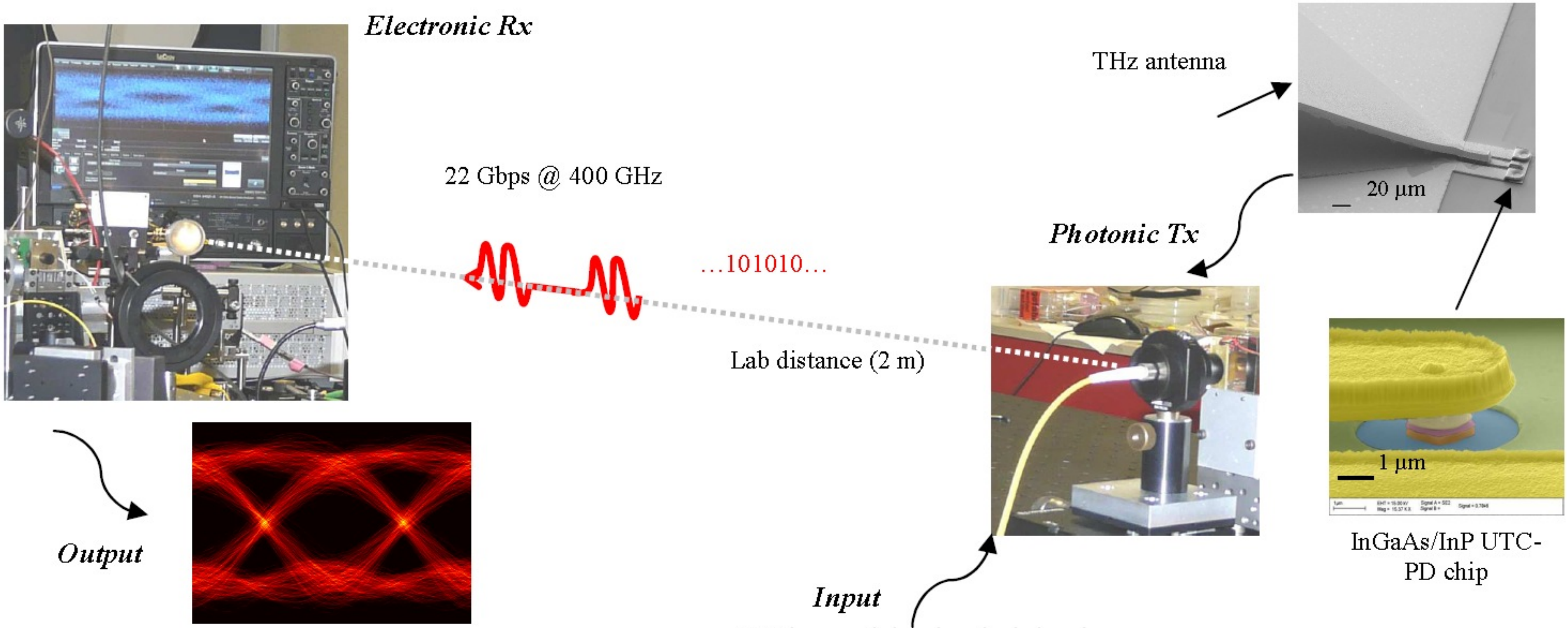
22Gbps communications @ 400 GHz



Electronic Rx

THz antenna

22 Gbps @ 400 GHz

Photonic Tx

...101010...

Lab distance (2 m)

Output

InGaAs/InP UTC-PD chip

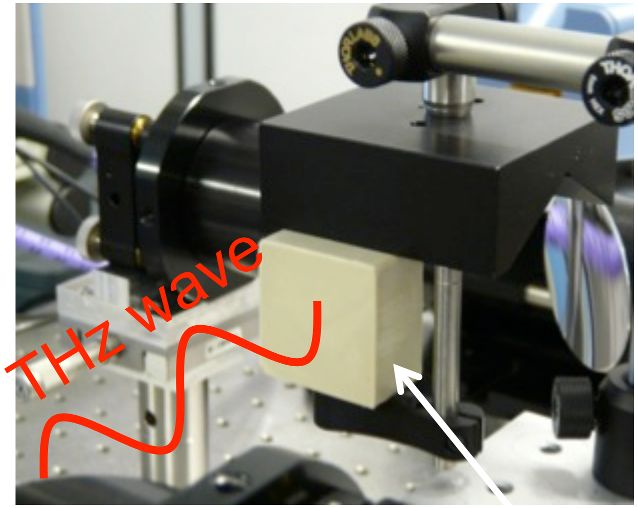
Input

THz transmitted eye diagram @ 22 Gbps

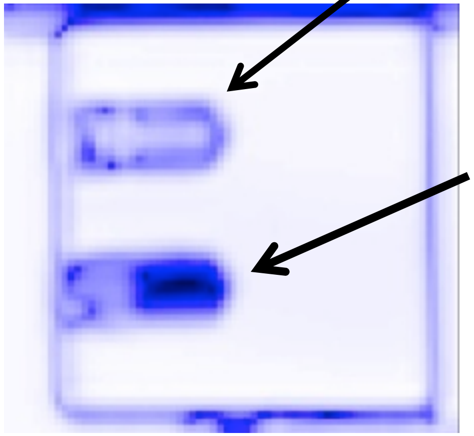
22 Gbps modulated optical signal

Ducournau *et al.*, 2013

Imagery ?



Plastic object



6 mm hole (empty)

Water

Image obtained @ 400 GHz

- Photomixing: power still low
- Acquisition time still too large

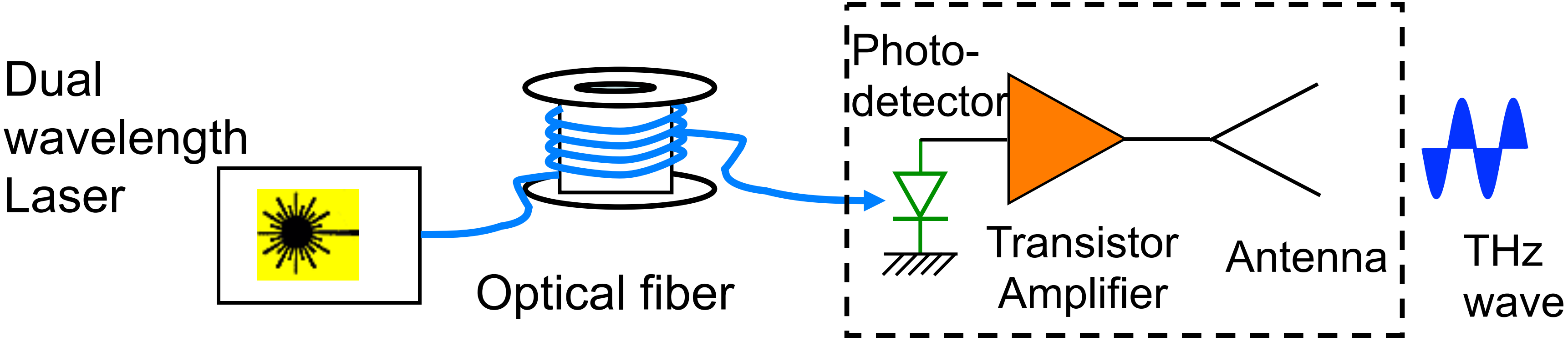
Future of THz optoelectronics

Research :

- Increasing power
- Decreasing cost (integration laser+ photomixer)
- 1.55 µm detectors

Markets opportunties :

- Lab spectrometers
- « THz hot spots »
- Special app. (cryogenic…)



The end

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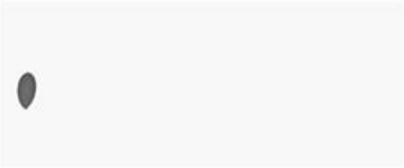
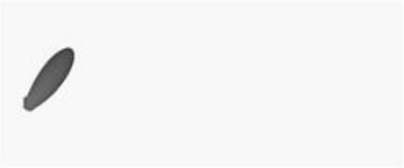
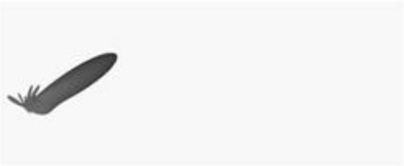
Simulated radiation patterns


f=50GHz


F=100GHz


f=200GHz


f=250GHz


f=350GHz


f=500GHz

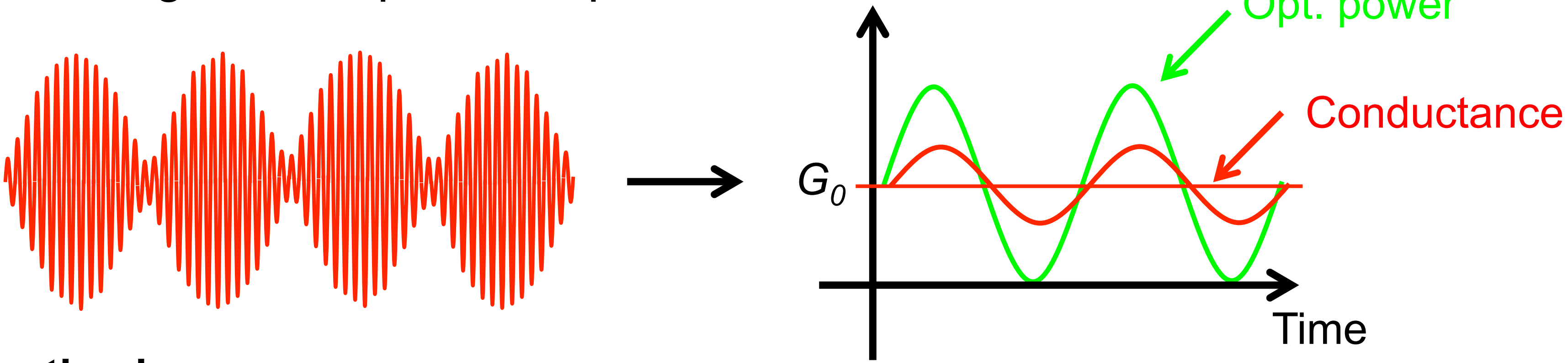

f=700GHz


F=800GHz


f=1000GHz

Photomixing model

Beating of two optical frequencies:



Hypothesis:

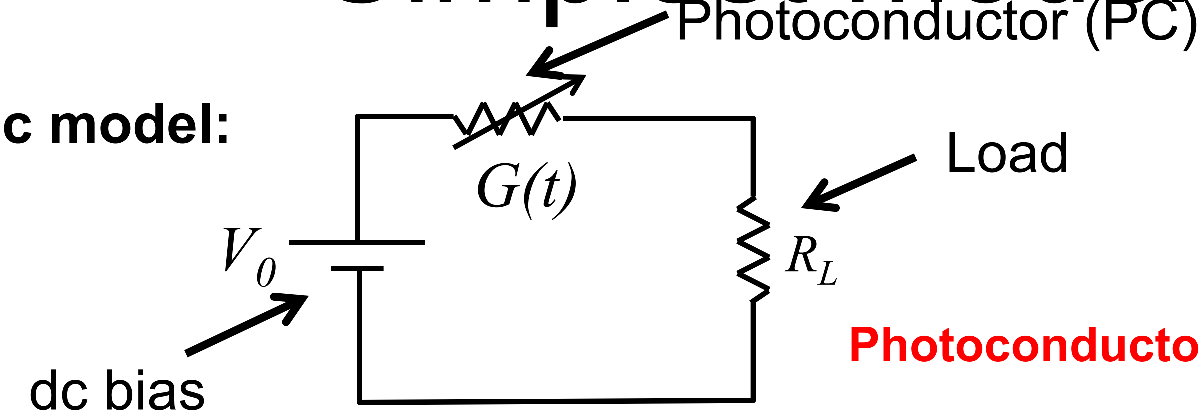
- Photoconductor is modeled as perfect linear conductance
- Conductance is proportional to optical power with a time constant (carrier lifetime)
- Dark current negligible

$$P(t) = P_0\left(1 + \sin(\omega_B t)\right)$$

$$\left\{ \begin{array}{l} G(t) = G_0 + G_1 \sin(\omega_B t) \\ G_1 = \dfrac{G_0}{\sqrt{1 + \omega_B{}^2 \tau_c{}^2}} \end{array} \right.$$

Simplest model

Basic model:

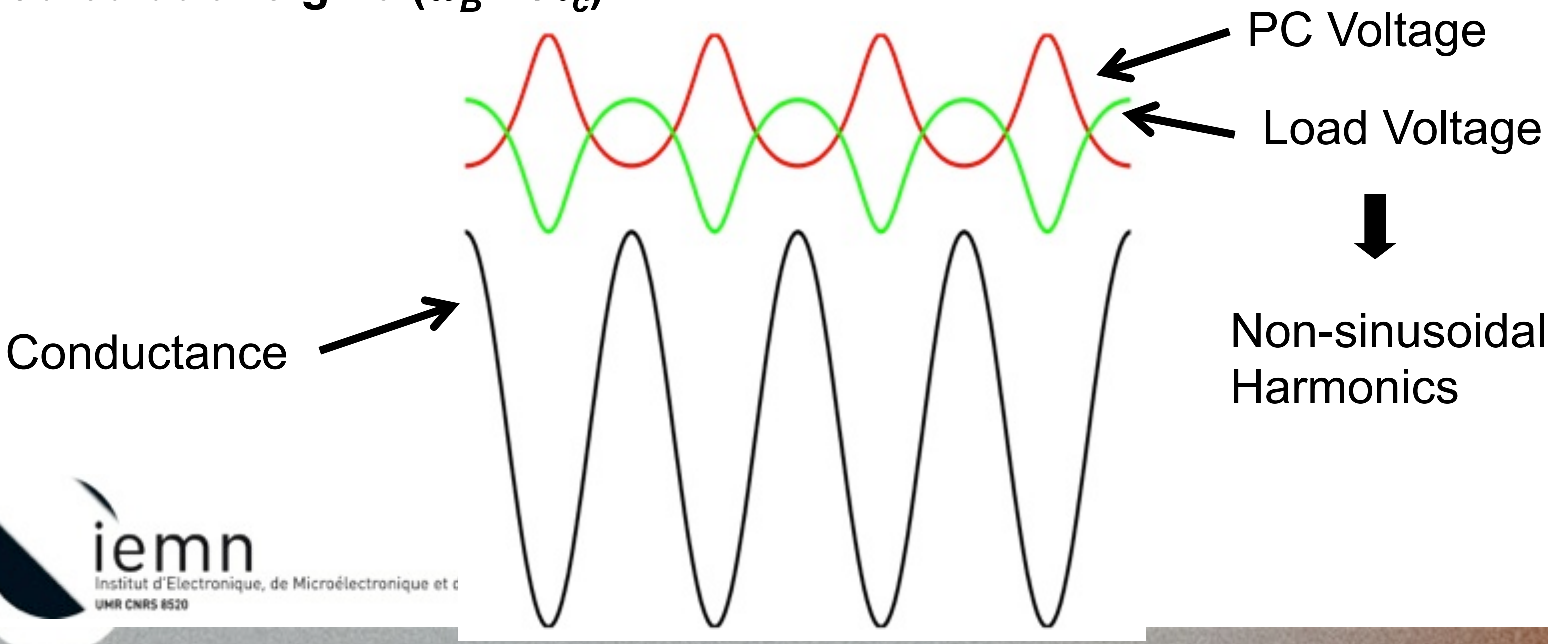


Photoconductor ≡ Parametric conductance

⬇

ac source

Calculations give ($\omega_B<1/\tau_c$):



⬇

Non-sinusoidal !
Harmonics

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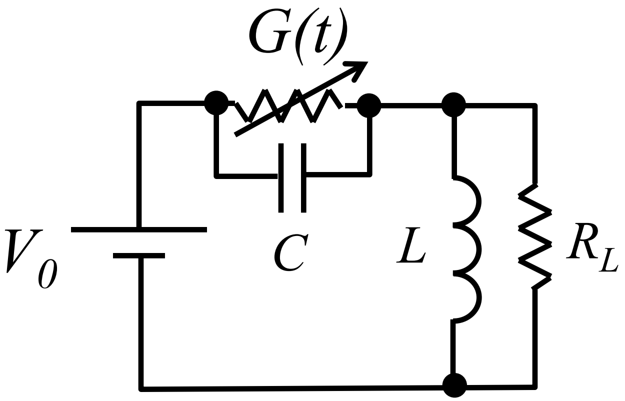
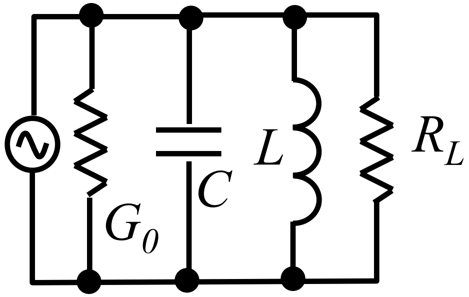
Analytical model



With a LC resonator:
We can consider that there is no harmonics
⇒ Calculation is simple
⇒ Effect of the capacitance is suppressed

Impedance
Matching term !



ac schematic

$$P_L = \frac{V_0^2 G_0^2}{2} \frac{G_L}{(G_0 + G_L)^2} \frac{1}{1 + \omega_B^2 \tau_c^2}$$

Results: two cases

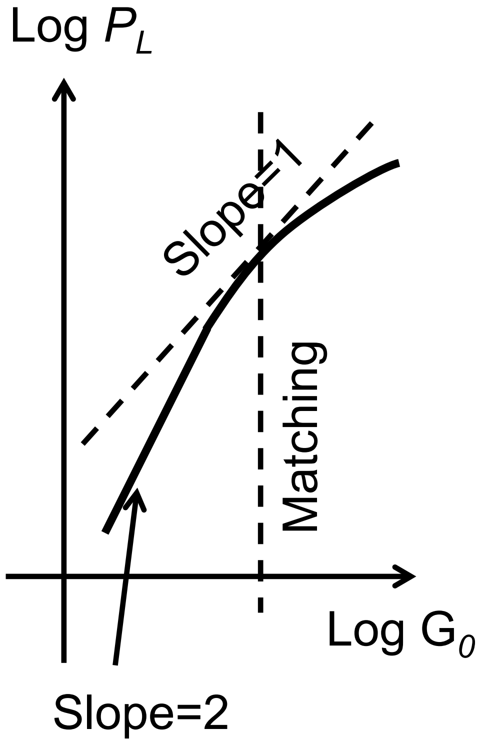
High impedance case, $G_0 << G_L$ **:**

$$P_L = \frac{V_0^2 G_0^2}{2} R_L \frac{1}{1+\omega_B^2 \tau_c^2}$$

Impedance matching case, $G_0 = G_L$ **:**

$$P_L = \frac{V_0^2 G_0}{8} \frac{1}{1+\omega_B^2 \tau_c^2}$$

For an antenna: $R_L \approx 20\text{-}100\ \Omega$



Maximum efficiency ?

For matching condition ($G_L = G_0$):

We can demonstrate that:

If $\omega_B << \tau_c$:

$$P_{dc} = \frac{3}{4} V_0^2 G_0$$

$$\eta_{elec,\max} = \frac{P_L}{P_{dc}} = \frac{1}{8} \times \frac{4}{3} = \frac{1}{6}$$

16,67 %, does not depend on the ratio between optical frequ. and THz frequ.

We can define also a total efficiency (electrical+optical):

$$\eta_{total,\max} = \frac{P_L}{P_{dc} + P_{opt}}$$

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