PHOTONICS BASED TERAHERTZ SOURCES

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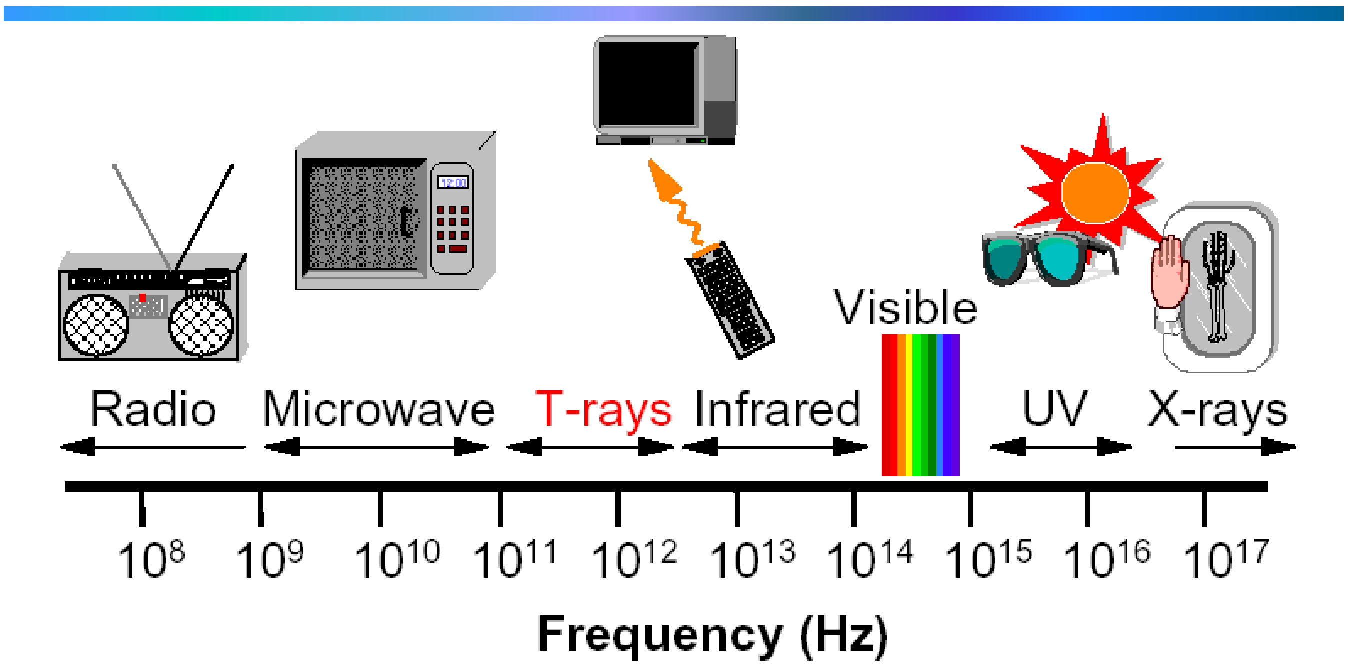
Outline of the talk

1. Introduction
2. Direct emission of THz waves
3. Down-conversion of photonic sources
4. Conclusion

TeraHertz Spectrum

What is terahertz radiation?



ν = 1 THz → λ = 300 μm

→ $h\nu$ = 33 cm^{-1} or 4.1 meV

→ T = 48 K

Different type of applications

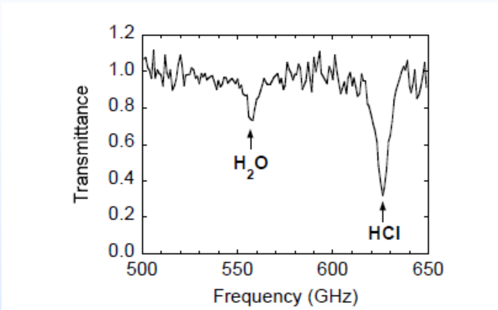
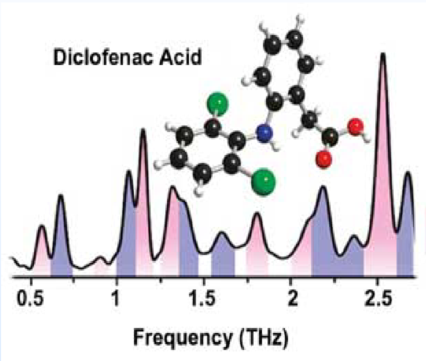
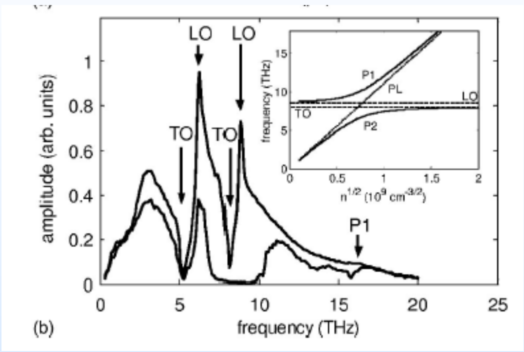


Fig. 3: Absorption spectrum of smoke produced from PVC heated to 350 degree Celsius.

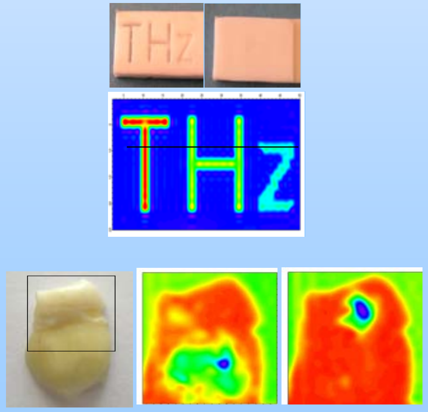
High resolut° spectroscopy



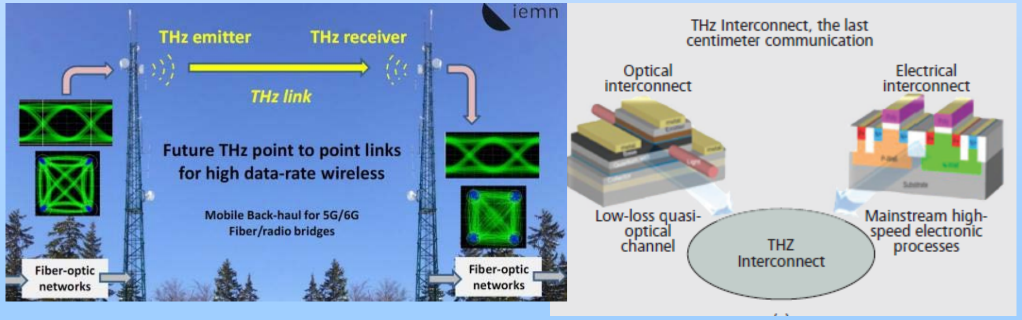
Broadband spectroscopy



Ultra Broadband spectroscopy



Vision and Non destructive Control

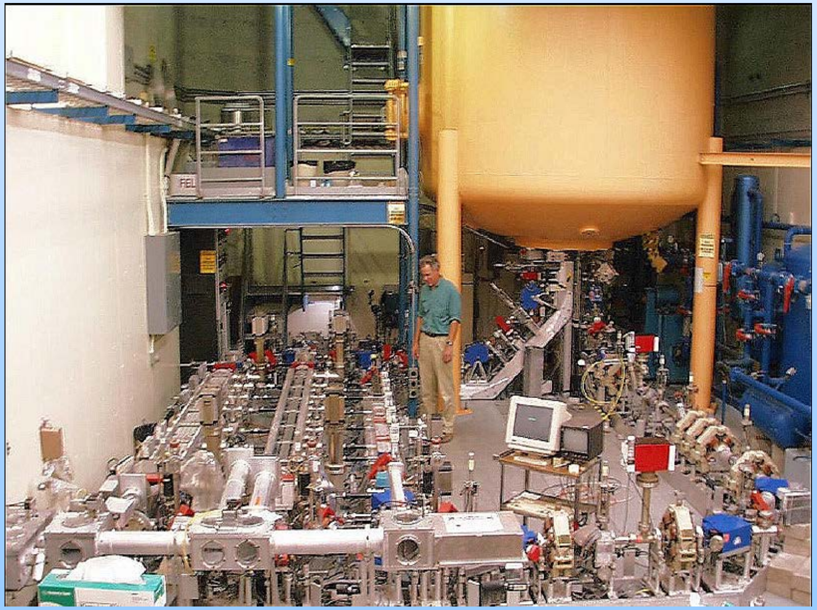


Wireless Telecommunications

Which sources for THz studies ?

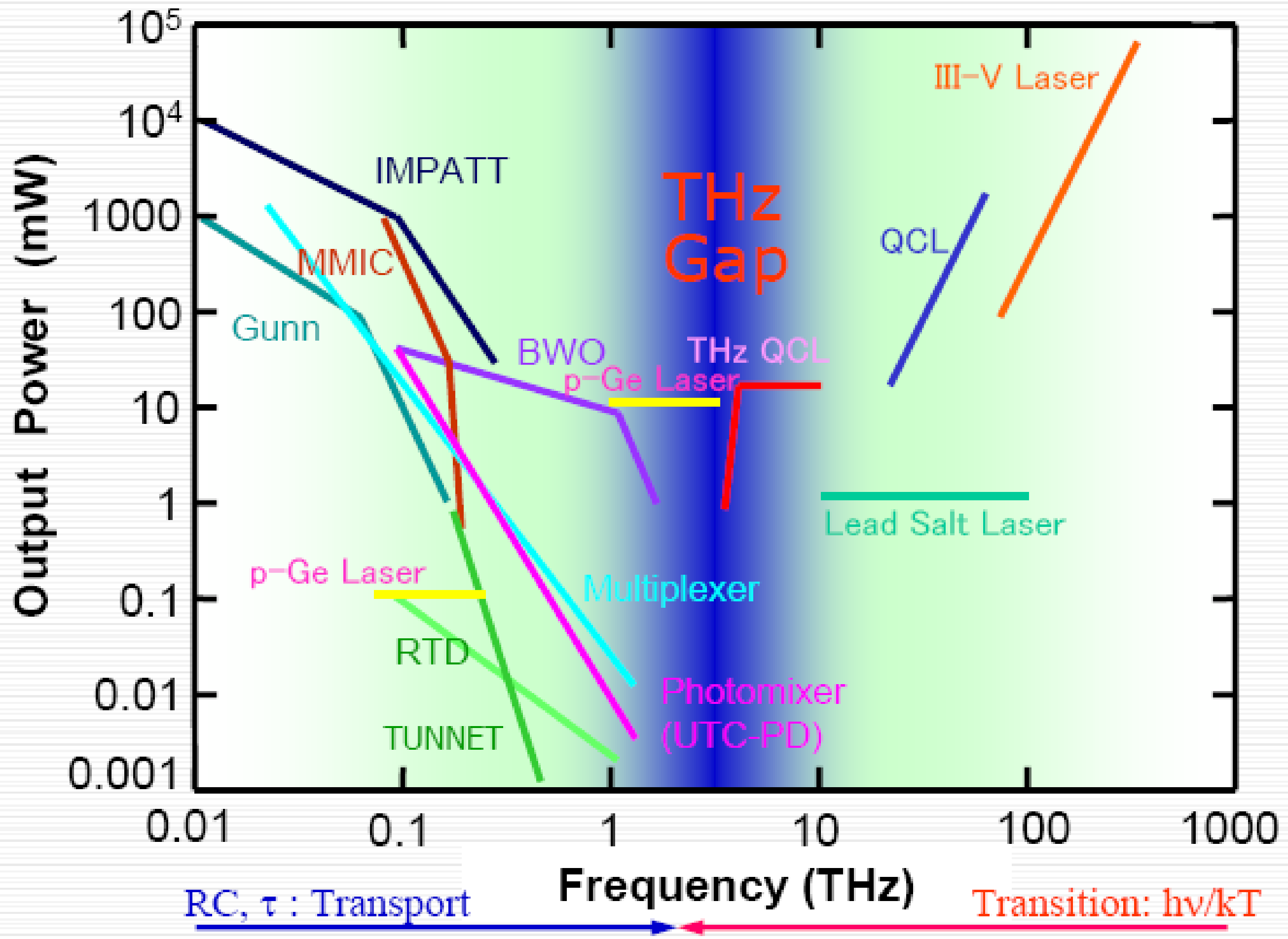
Tape* ?

Or Free Electron laser ?



*Tribocharging effetc : Opt. Lett. 34, 2195–2197; 2009

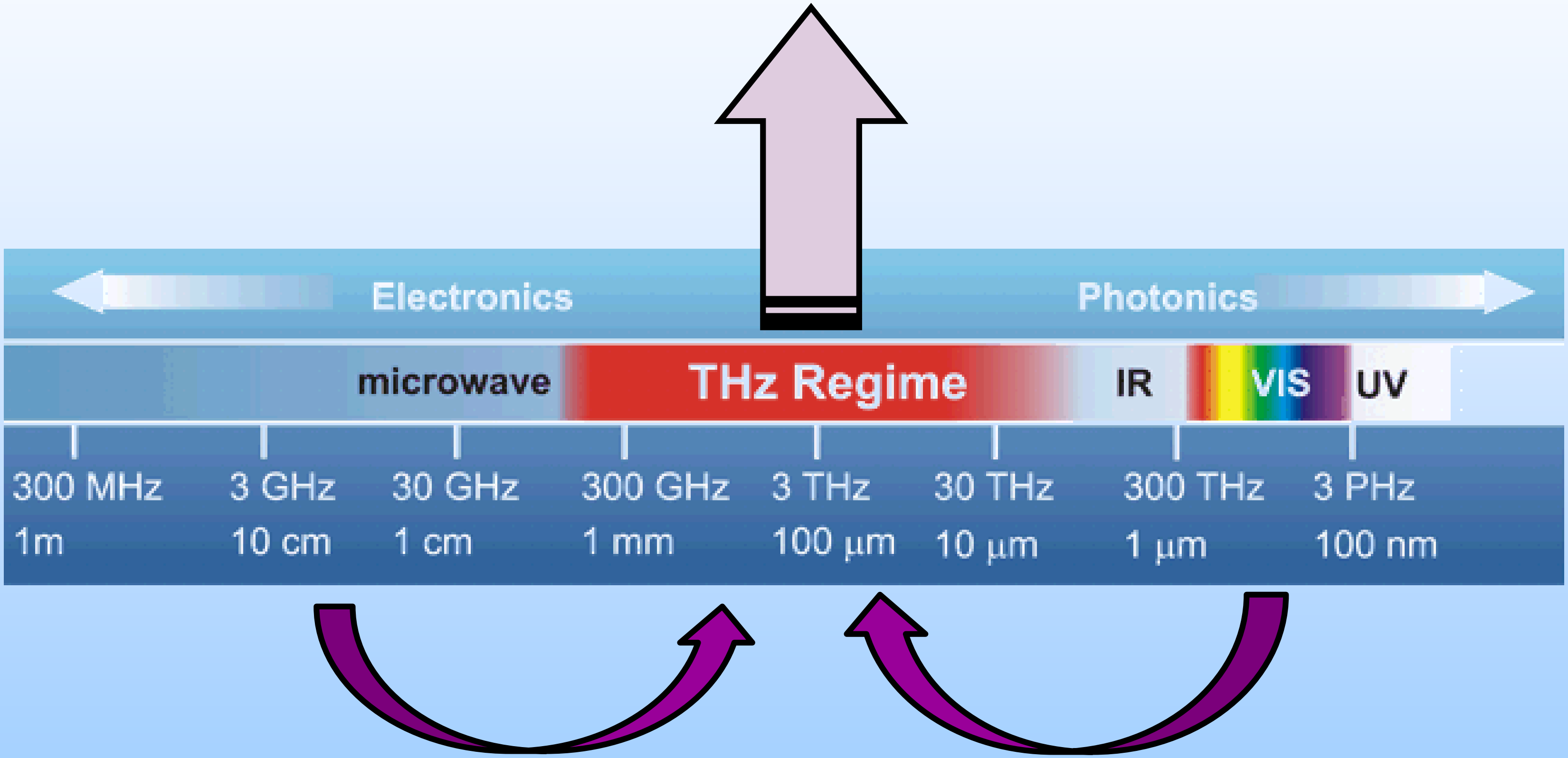
Which sources ? The THz "Gap"



Courtesy of Terahertz Technology Trend Investigation Committee, MIC, Japan

Different ways of generating THz

Direct THz Emission



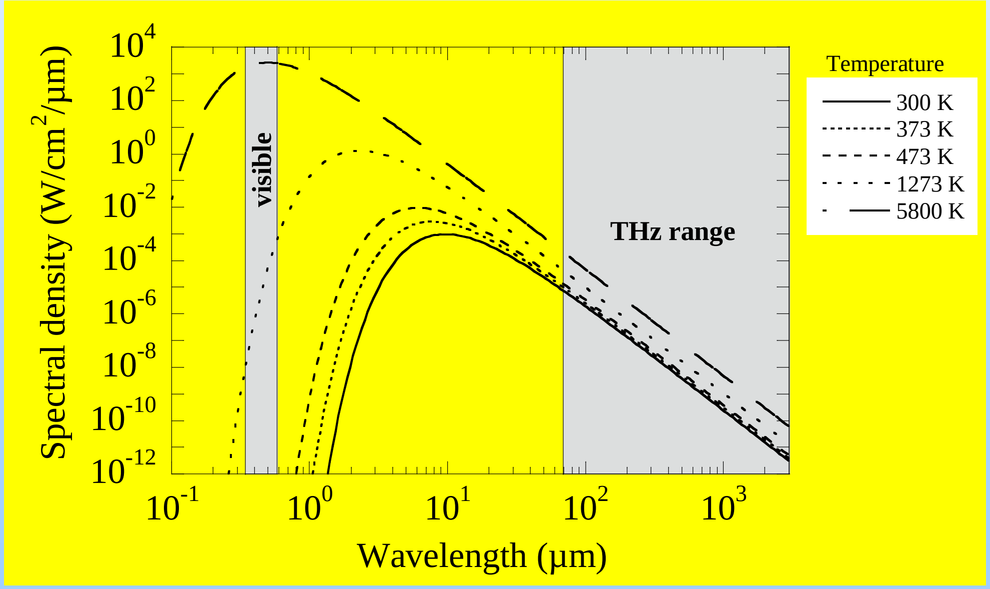
Up- conversion

Down- conversion

Direct emission of THz signal

- Blackbody radiation :

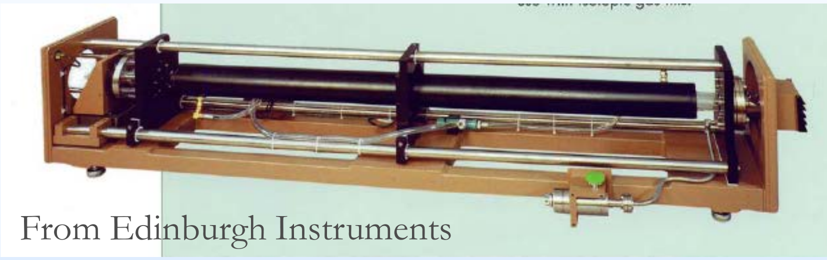
  incoherent, broadband, very weak power (~ nW)



- Commonly used in FTIR spectrometer

THz lasers

- **Molecular lasers**



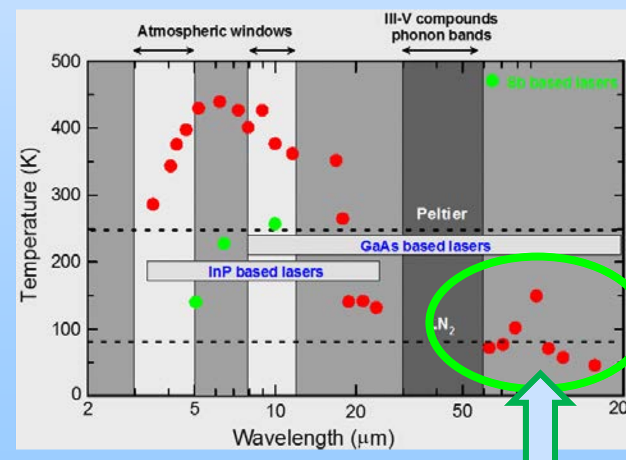
« Not very stable », « powerful »

FIRL100 FAR INFRARED OUTPUT SPECIFICATION

λ (µm)	FIR MOLECULE	CO_2 PUMP LINE	POWER
96.5	CH_3OH	9R10	>60mW
118.8	CH_3OH	9P36	>150 mW
184.3	CH_2F_2	9R32	>150mW
432.6	HCOOH	9R20	>30mW
513.0	HCOOH	9R28	>10mW

- **Quantum cascase lasers**

1 mW average power in the 1.8 – 5 THz range
20 mW pulsed power
20 000 $ (QCL) + 100 000 $ (cryo-cooler)

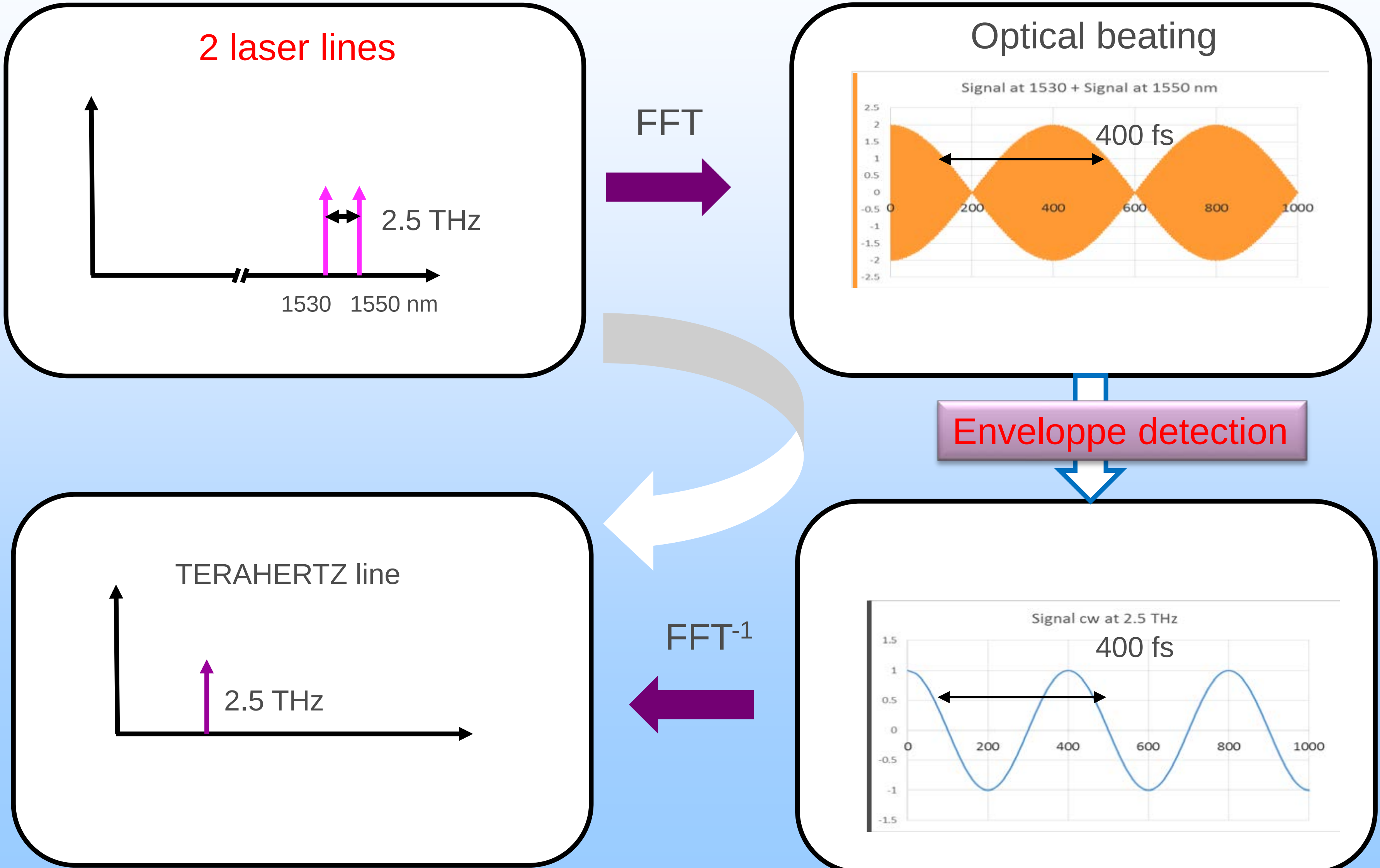


THz QCL's (f> 3 THz)

Down Conversion of Photonic sources

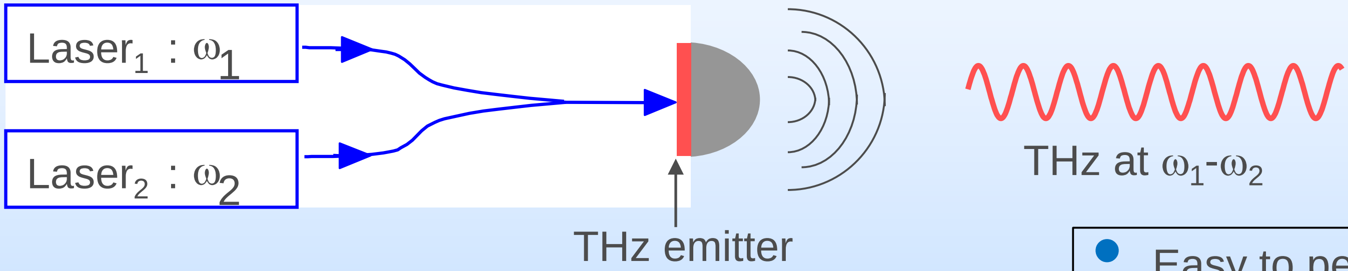
- Down-conversion of two cw laser frequency
  - Dedicated dual wavelength lasers
  - THz cw generation in ultrafast photodetectors
- Down-conversion of fs laser pulses
  - THz pulse generation in ultrafast photoswitches
  - THz pulse generation in non-linear crystals

From IR down to THz: case of CW regime



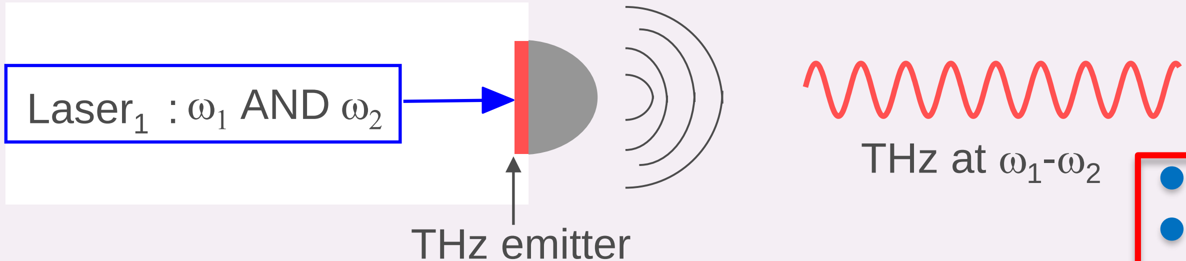
Dedicated dual-wavelength lasers for THz CW generation

- Classical cw THz generation by optical beating of two lasers



- Easy to perform
- Tunable
- Reduced frequency stability

- CW THz generation using dual-wavelength laser

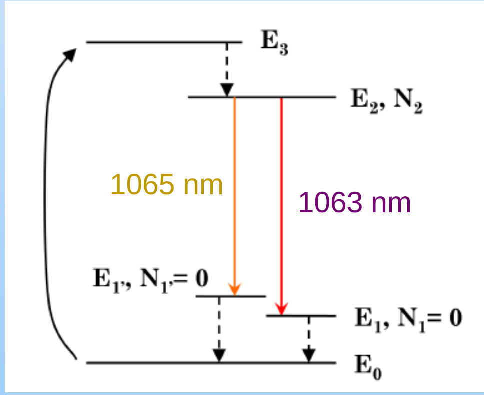


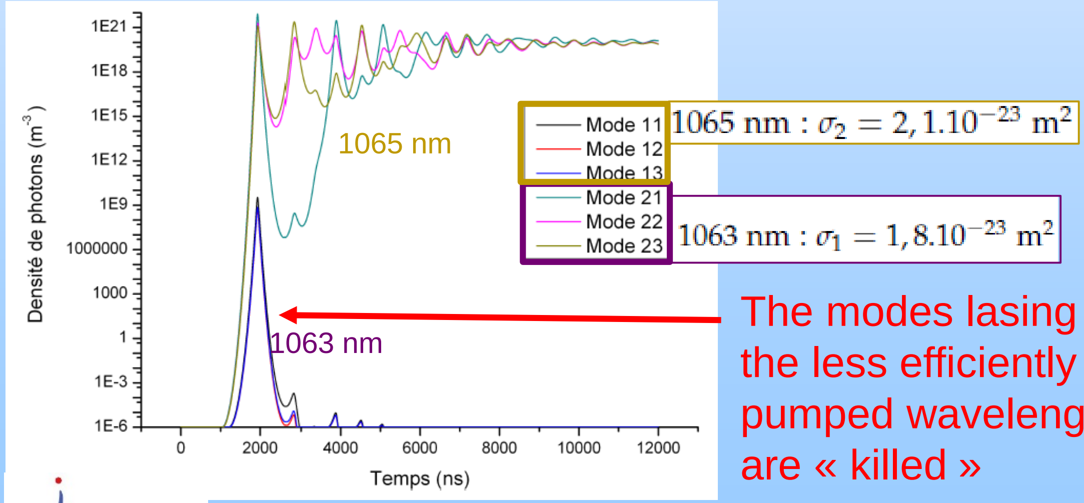
- Stable
- Compact
- Tunable ?

Dual-wavelength micro-lasers for THz generation

- Neodyme based laser offer high gain and large panel of available crystals
- CW or Q:switch regime
- Central wavelength has to match THz emitter technology
- Gain competition in between different laser modes

Example : Dual wavelength operation in $Nd:GdVO_4$





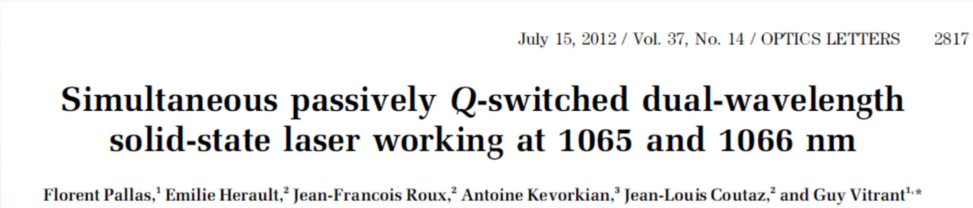
The modes lasing at the less efficiently pumped wavelength are « killed »




IMEP-LAHC

2-color micro-laser externally triggered

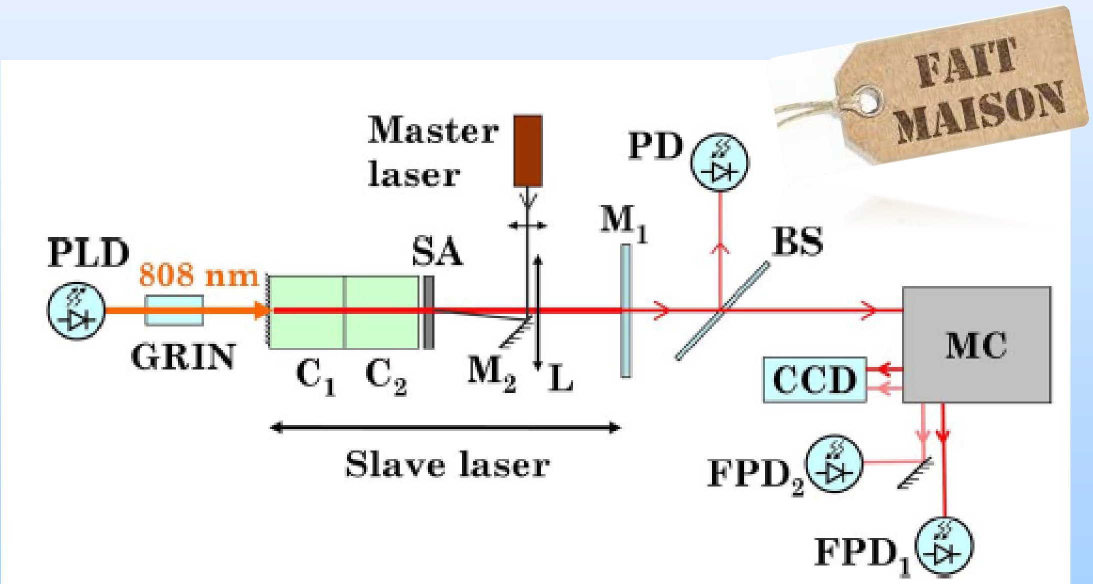
- Beating in between two lasing transitions of two different crystal placed in 1 cavity



July 15, 2012 / Vol. 37, No. 14 / OPTICS LETTERS 2817

Simultaneous passively *Q*-switched dual-wavelength solid-state laser working at 1065 and 1066 nm

Florent Pallas,[1] Emilie Herault,[2] Jean-Francois Roux,[2] Antoine Kevorkian,[3] Jean-Louis Coutaz,[2] and Guy Vitrant[1,*]



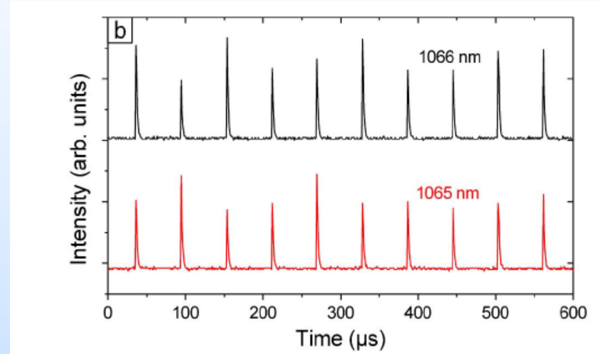
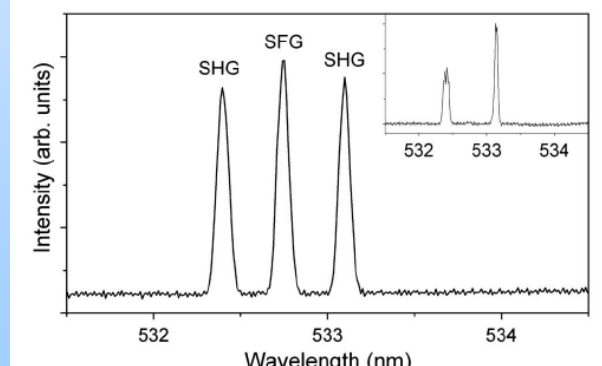


Fig. 2. (Color online) Typical pulse train: a, without external triggering; b, with optimal triggering.



LC1 : $Nd:GdVO_4$
LC2 : $Nd:YVO_4$

30 ns pulse duration
70 W peak power
100 % synchronizat°

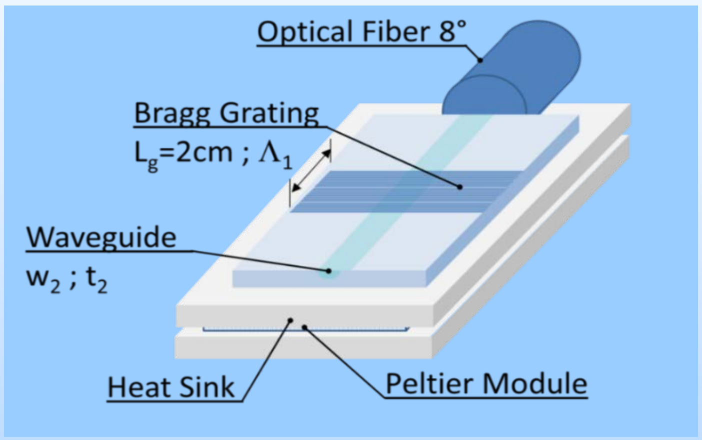
IMEP-LAHC

teem photonics

Integrated lasers on glass for THz generation

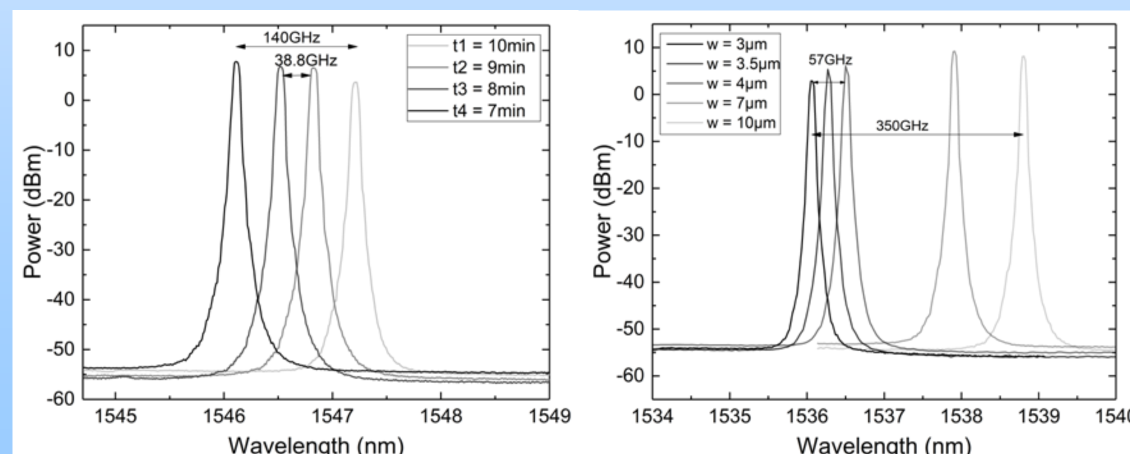
- Verre IOG1 co-dopé Er-Yb
- Cavité DFB

- Guide monomode w
- Pompage à ~980nm



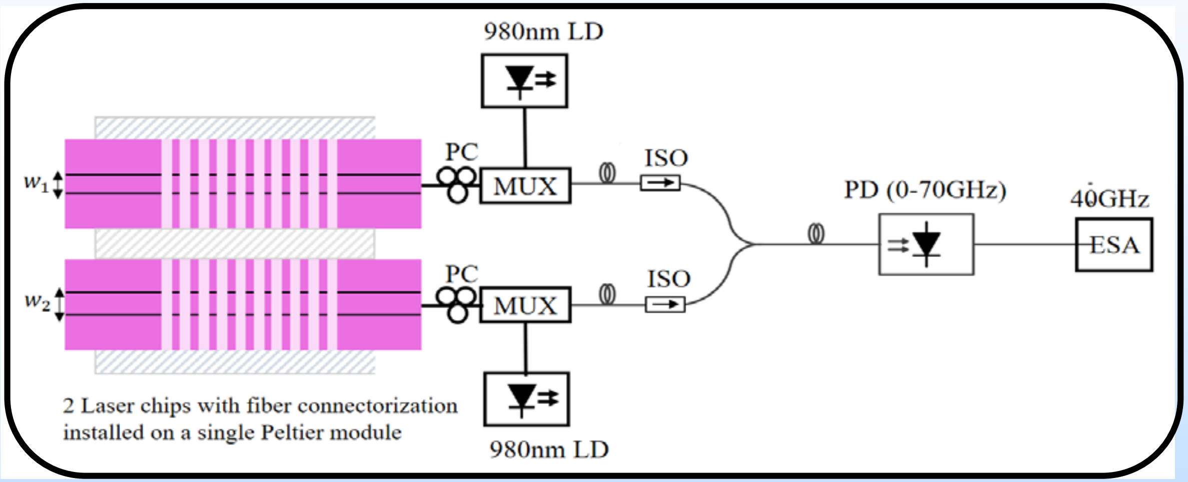
Contrôle de la longueur d'onde émise

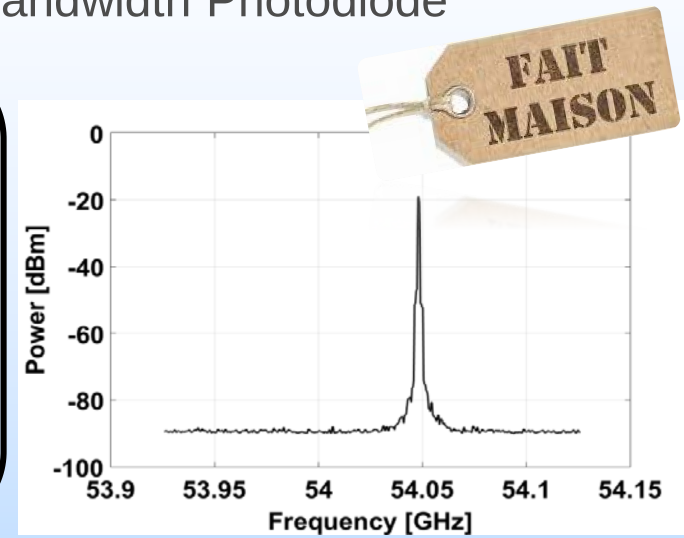
- Cavité optique — réseau
- Largeur du guide — masque
- Profondeur du guide — temps d'échange
- Température — utilisation



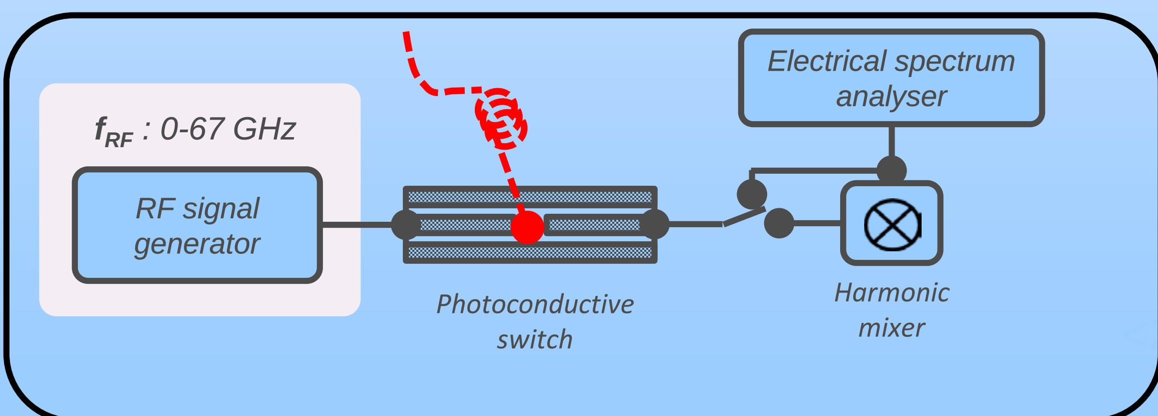
Integrated lasers : RF generation and detection

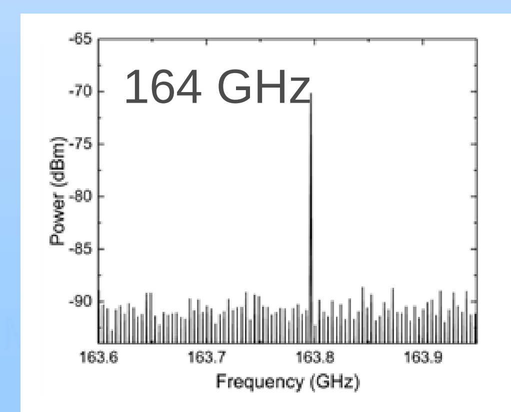
Photodetection of a sub-THz laser beat using a High Bandwidth Photodiode





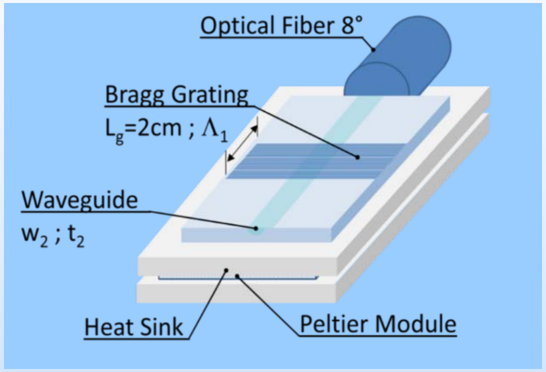
Heterodyne detection set-up for above 70 GHz generation and detection



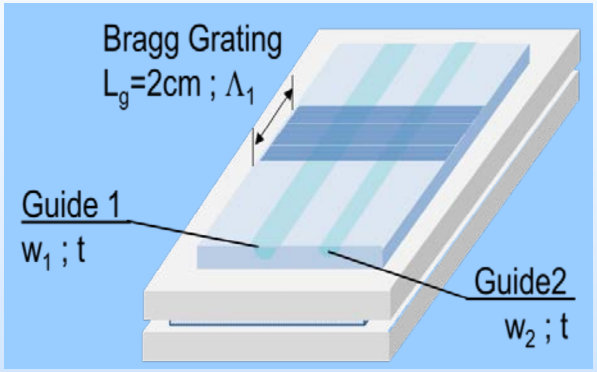


Integrated lasers : basic and advanced solutions

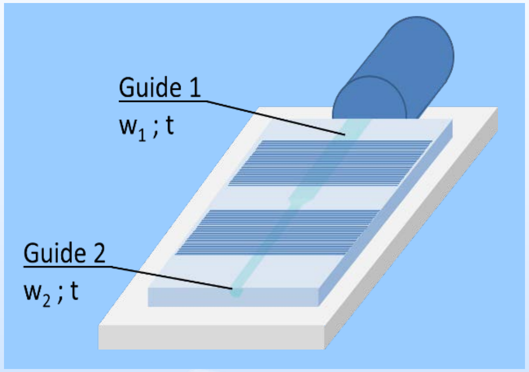
Beating of 2 lasers



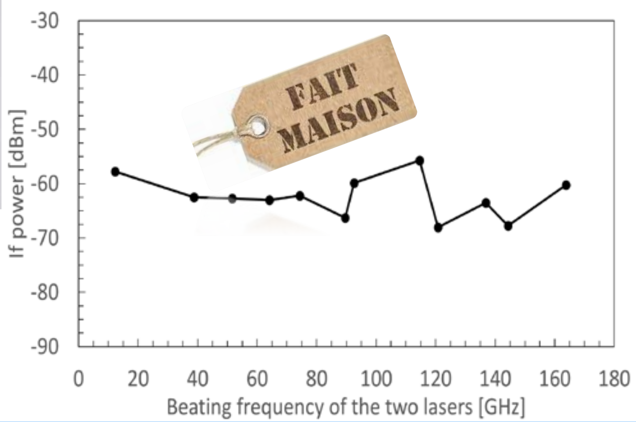
Co-integrated lasers



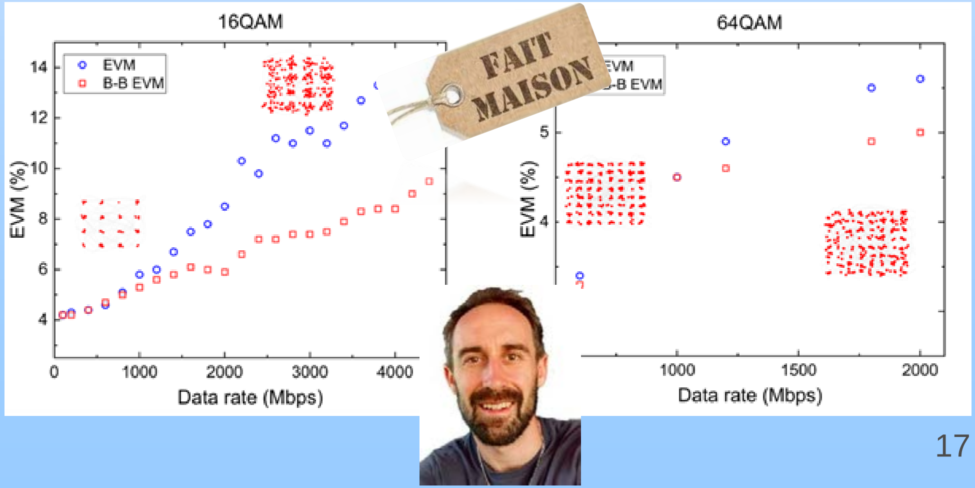
Dual wavelength lasers



Up to 170 GHz detected beating

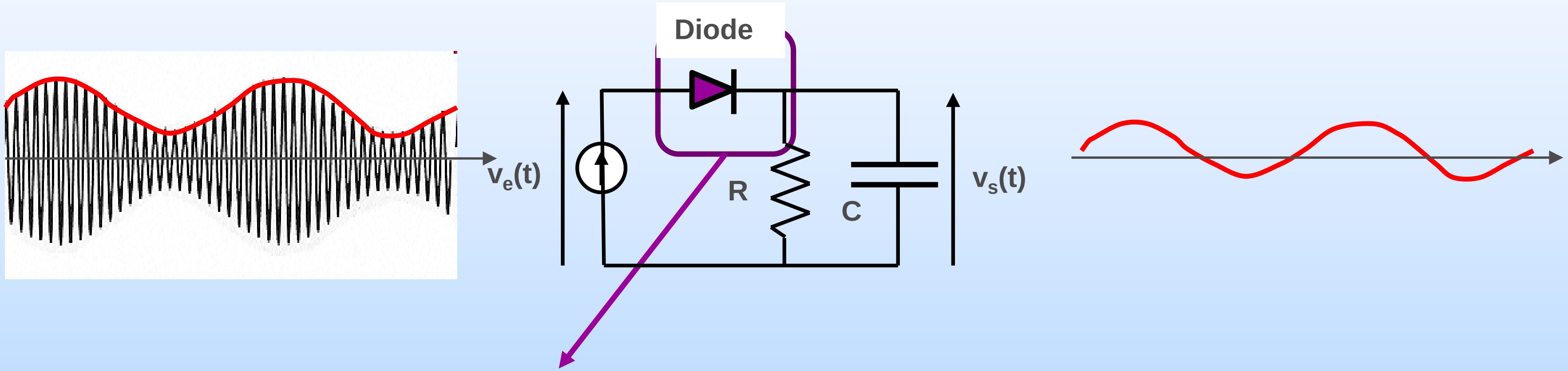


Demonstration of Multi-Gigabits RoF solutions



Optical mixers for Down Conversion of Photonic sources

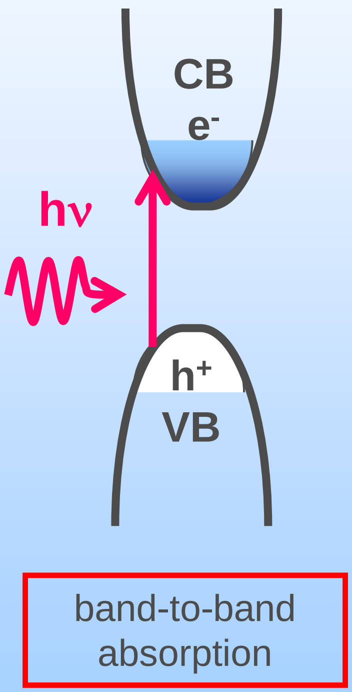
- Amplitude demodulation in Radio = Enveloppe detection = frequency downconversion

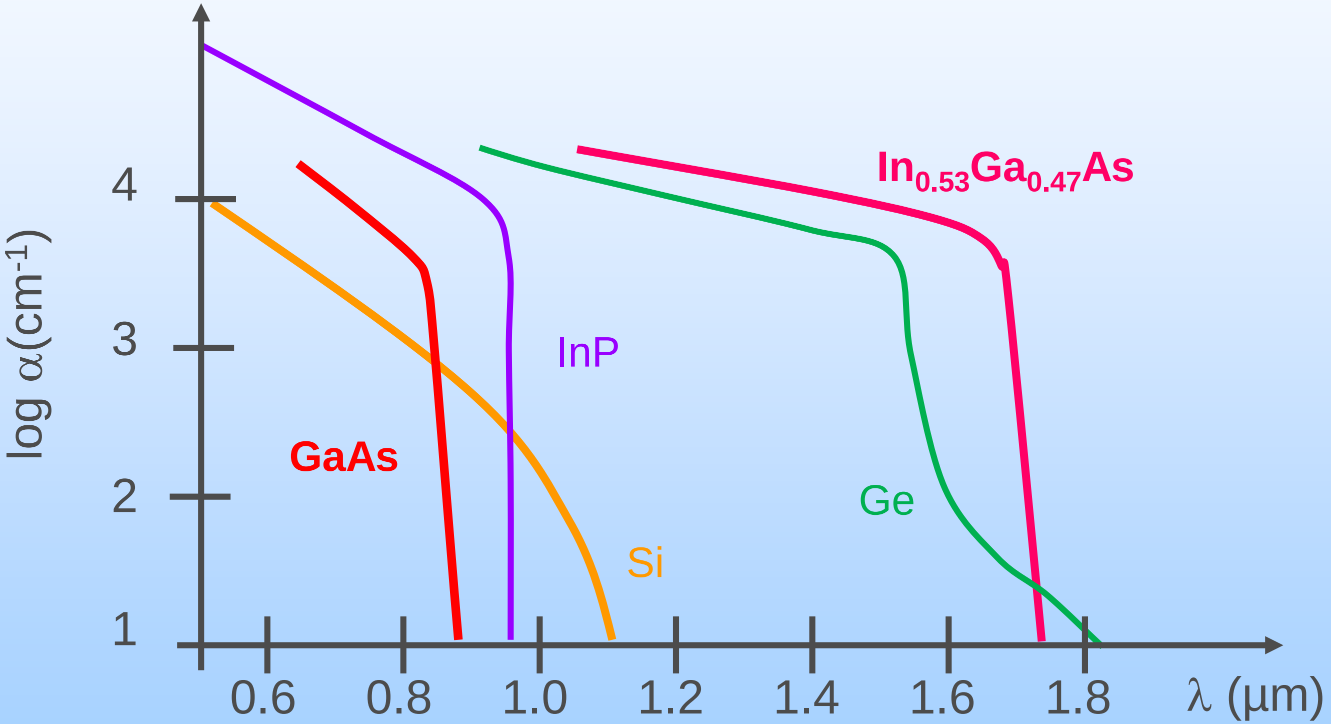


Which nonlinear element sensitive to optical frequencies ?

Resonant nonlinear phenomena	Non-resonant nonlinear phenomena
Electron/ holes pair generation by absorption in an opaque media	Difference frequency generation in a transparent nonlinear media

Optical absorption in semiconductors reminder





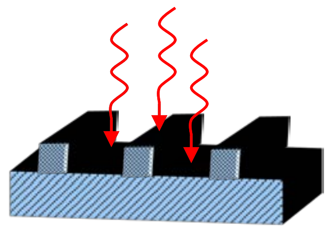
Visible Range GaAs absorbs 10 times more than Si
NIR Range : Onlmy InGaAs or Ge can be used

Different kind of photodetectors

Photoswitches

Absorption Layer

Contact layers



Metal electrodes
Intrinsic GaAs

Features

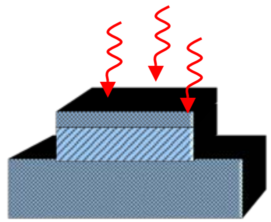
Simple, Planar,
No internal Field
Lifetime or transit time limited
Low Capacitance
Low Quantum Efficiency

Photodiodes

Absorption Layer

Contact layers

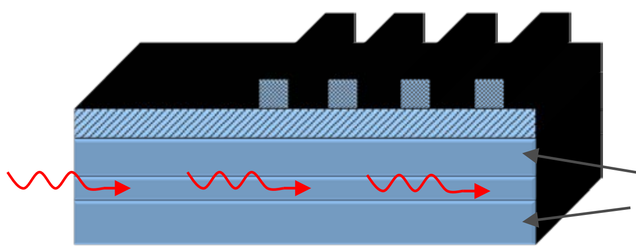
PIN



P+ Contact
Intrinsic Absorption
N+ Contact

Trade-off Between
Quantum efficiency
and Speed

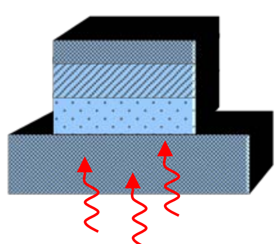
Waveguide



Absorption Layer
Guide Layers

High efficiency
High speed
Difficult to couple into

Uni Travelling Carrier

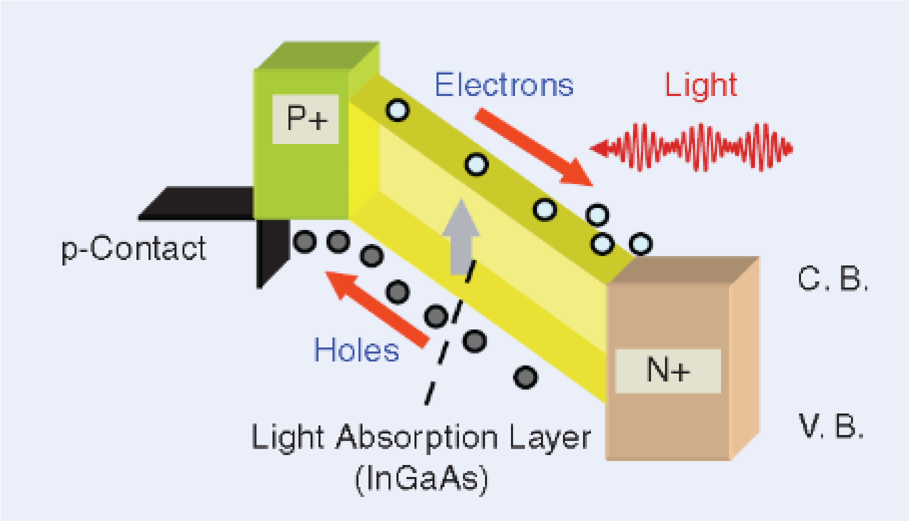


P+ Contact
P Absorption layer
Transparent intrinsic layer
N+ Contact

Very High Speed
High Efficiency

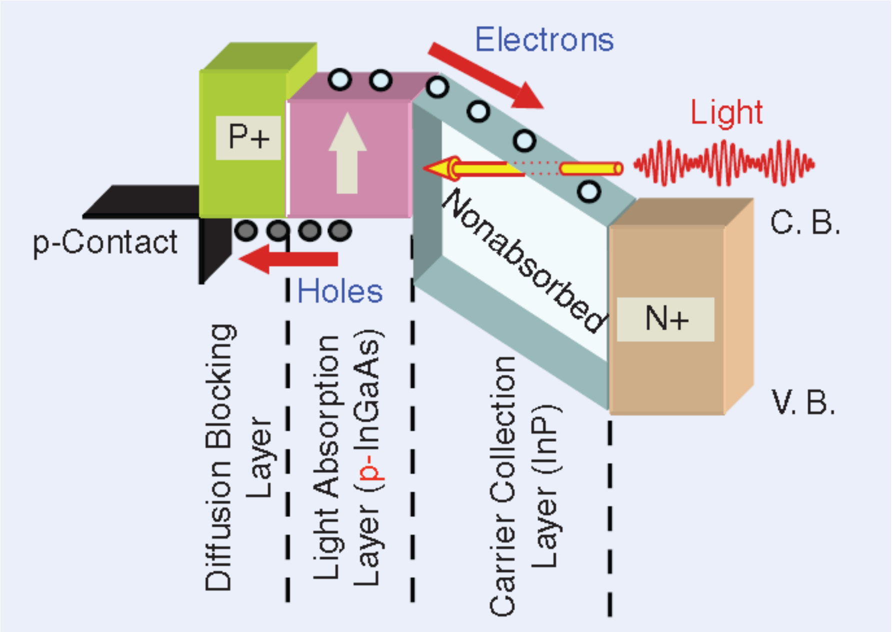
High-Frequency detection at 1.55 µm

pin-PD



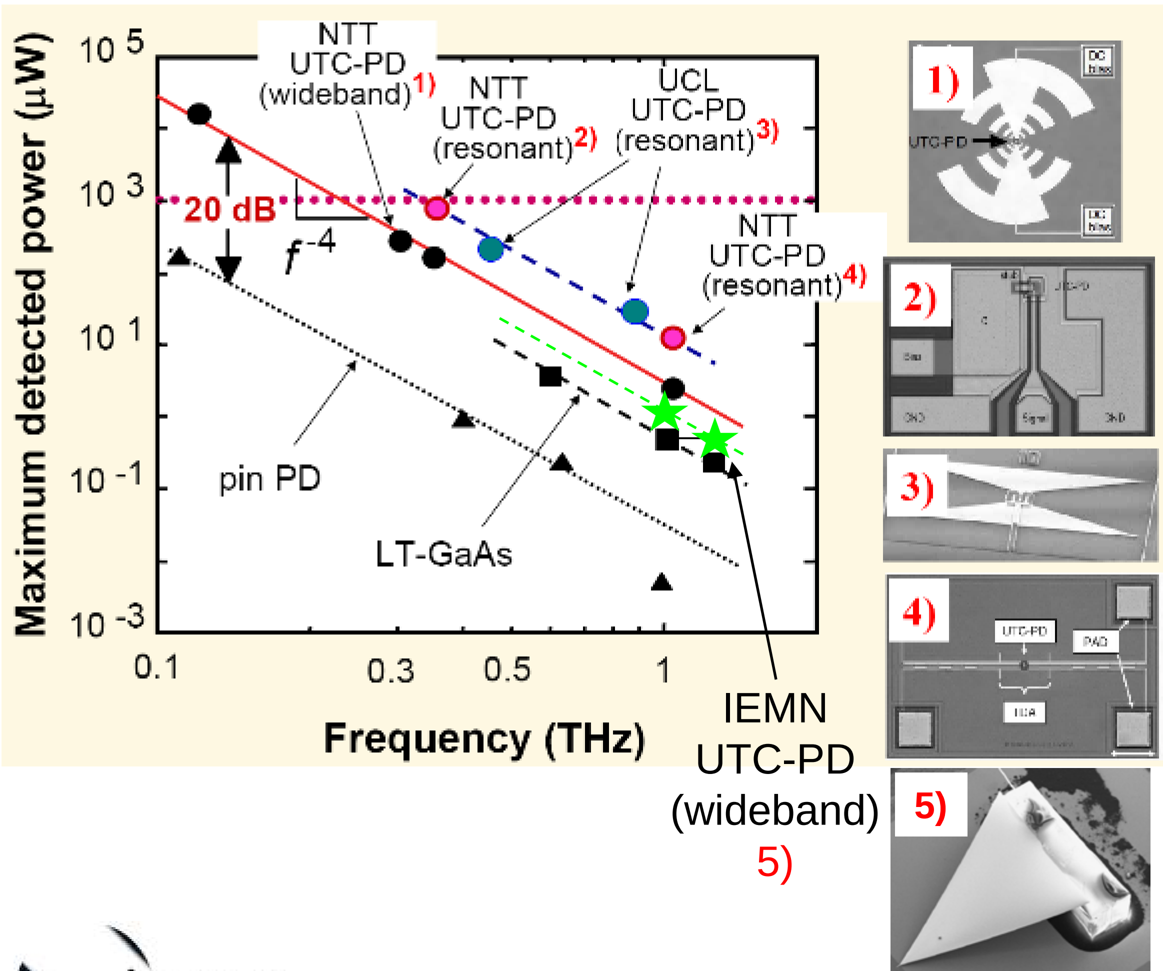
Holes are slow !
- Low frequency cut-off
- Saturation

Uni-Travelling Carrier-PD



Proposed at NTT in 1996
(T. Ishibashi *et al.*)

UTC-PD: State of the art



- Wideband antenna
≈1-2 µW @ 1 THz

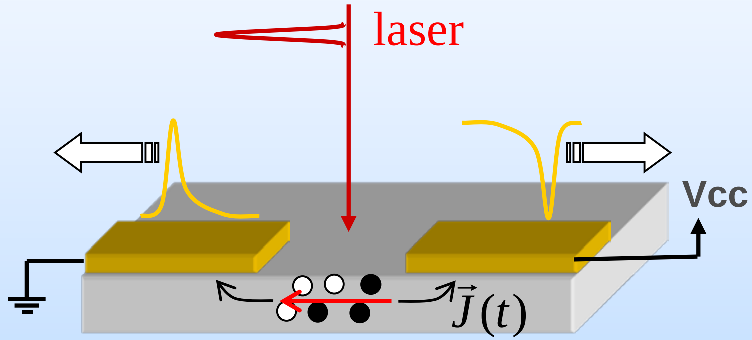
- Resonant antenna
≈ 10-20 µW @ 1 THz
≈ 500 µW @ 350 GHz

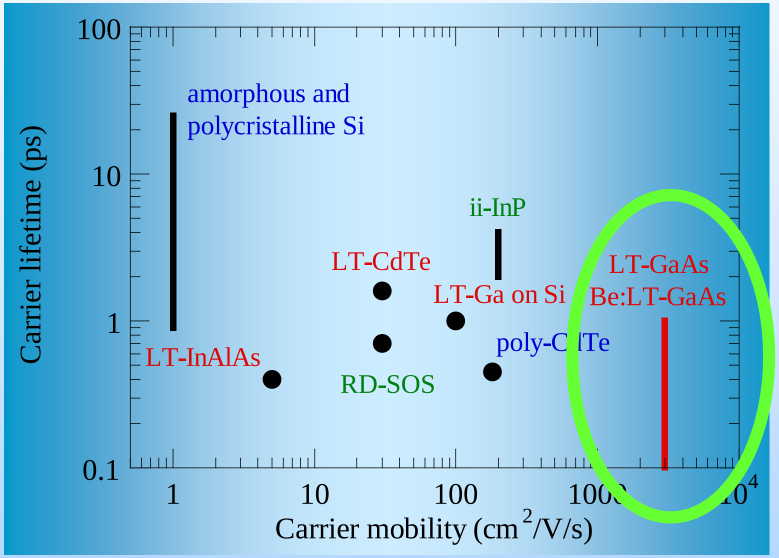
iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

J.-F. Lampin

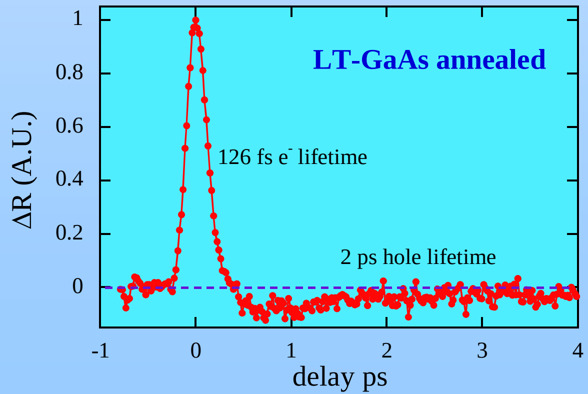
Principle of Ultrafast photoswitches

- Optically controled resistor with carrier lifetime limited response :

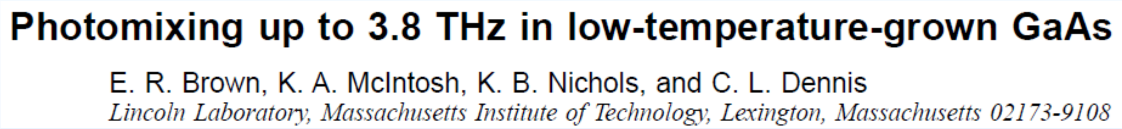




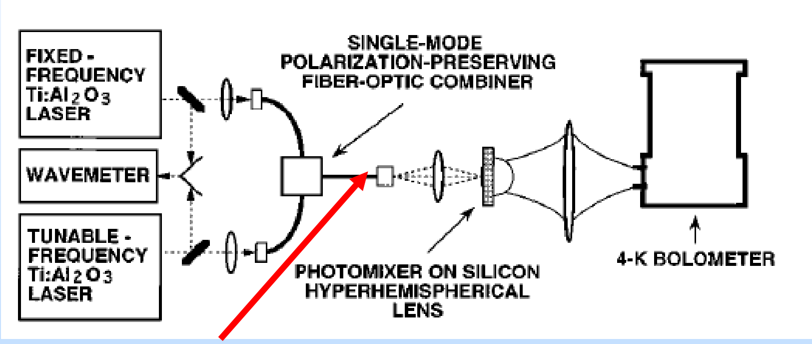
- *No internal Field*
- *High Bandwidth due to ultrashort carrier Lifetime limited*
- *Low Capacitance*
- *Low Quantum Efficiency*



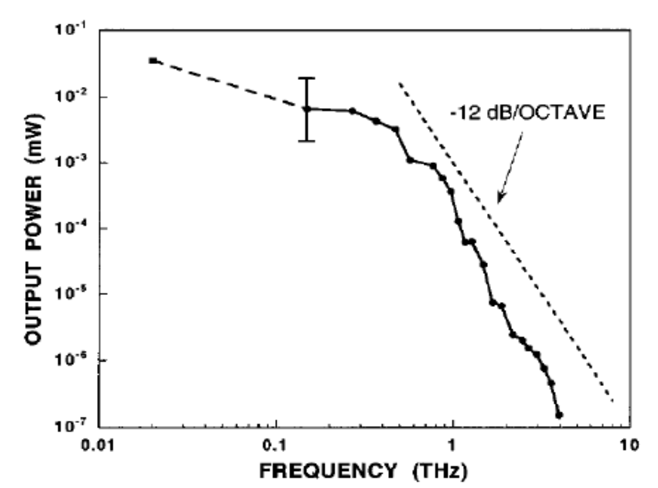
CW photoconducting emission with interdigitated LTG-GaAs structures


Photomixing up to 3.8 THz in low-temperature-grown GaAs

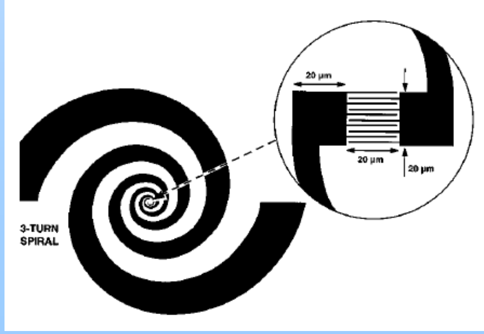
E. R. Brown, K. A. McIntosh, K. B. Nichols, and C. L. Dennis
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts 02173-9108



Beating of 2 Ti:Sa CW lasers



Broadband spiral antenna



$$P_{rad} \propto \frac{P_1 P_2}{\left(1+(\omega R_L C)^2\right)\left(1+(\omega \tau_c)^2\right)}$$

$$\tau_c = 270\ fs$$

$$R_L C = 210\ fs$$

$$P_{Rad} = 0.01\,mW$$

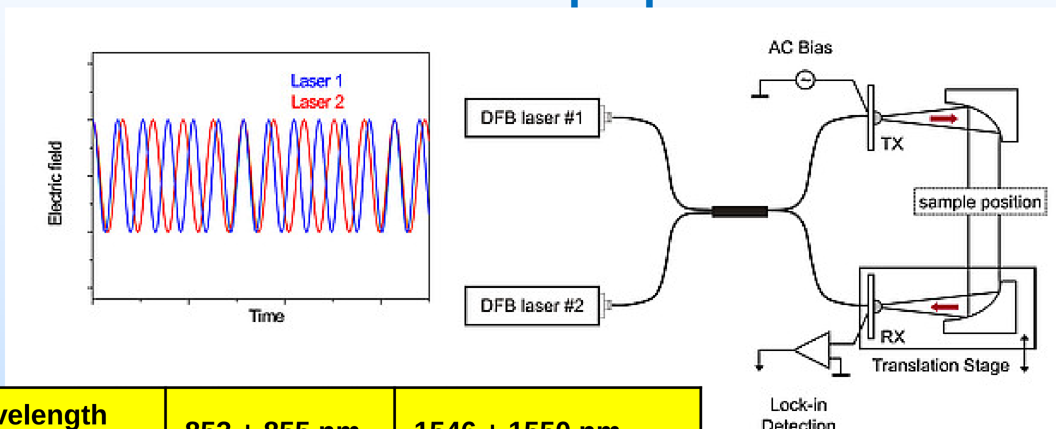
$$P_{opt} = 100\,mW$$

Low efficiency ! Requires further improvements

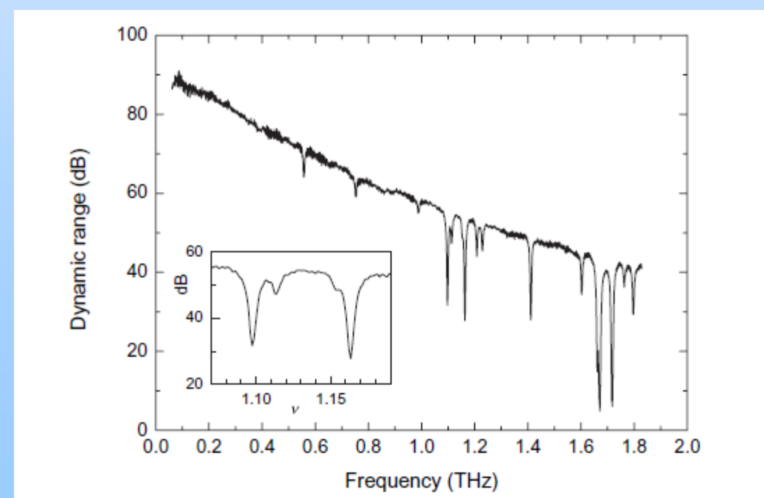
Appl. Phys. Lett., vol. 66, p. 285 (1995)

2-laser diodes CW THz systems

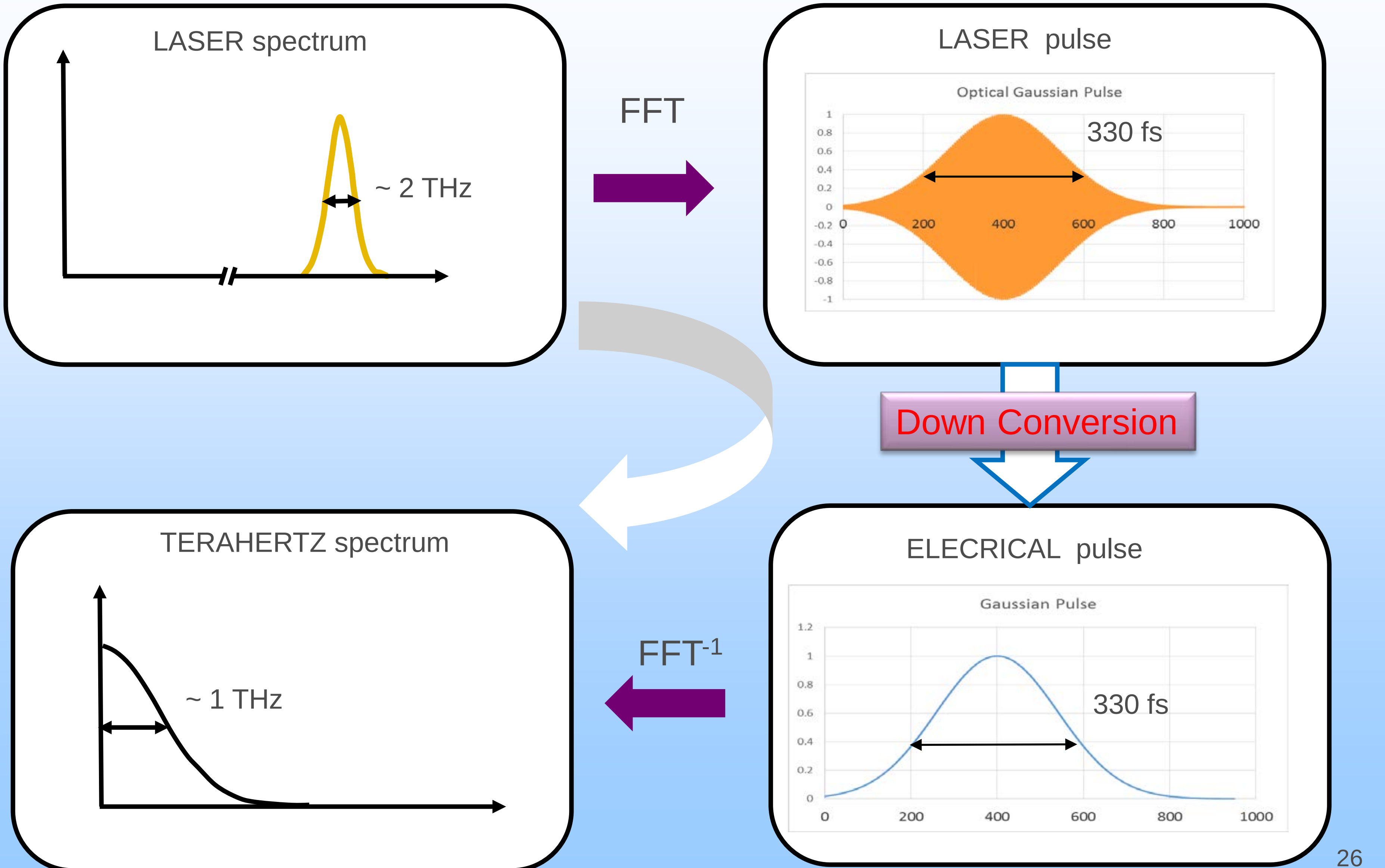
Commercial equipment, Germany)



Wavelength range*	**853 + 855 nm**	**1546 + 1550 nm**
Lasers	**2x DL DFB**	**TeraBeam 1550**
Laser power (fiber output)	**2 x 50 mW**	**2 x 30 mW**
Scan range per diode	**± 1.3 nm**	**± 2.2 nm**
Frequency accuracy	**2 GHz absolute , 10 MHz relative**	
THz scan range	**Typ. 0 – 1800 GHz**	**Typ. 0 – 1200 GHz**
Optical isolation	**60 dB per laser**	**80 dB per laser**



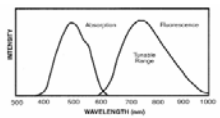
From Optics down to THz: case of pulsed regime

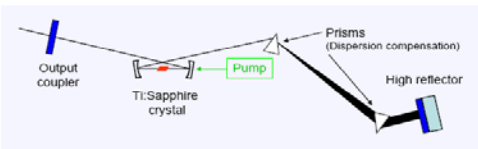


Femtosecond lasers for THz pulse generation

Kerr lens modelocked Ti:Sa

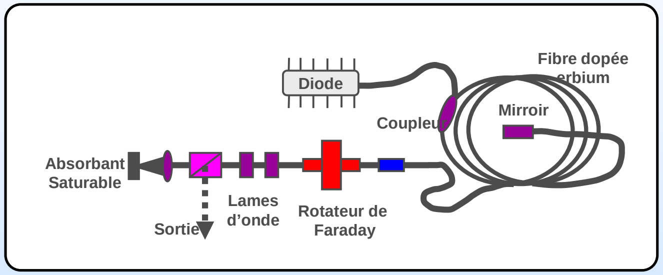
- Ti:sapphire has large bandwidth
- Supports shortest pulses
- Simple (amazingly)



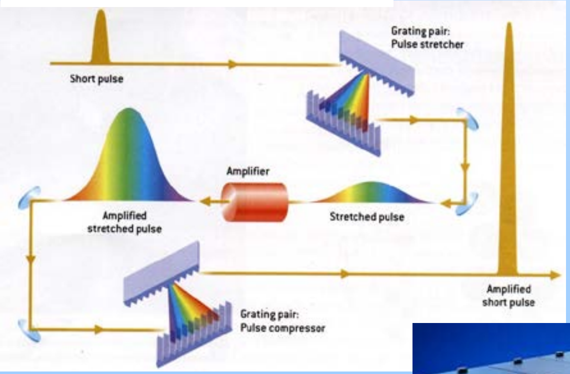


M.T. Asaki, et al, Opt. Lett. 18, 977 (1993)

Erbium doped fiber modelocked laser



Amplified Systems



Plenty of Commercial lasers available

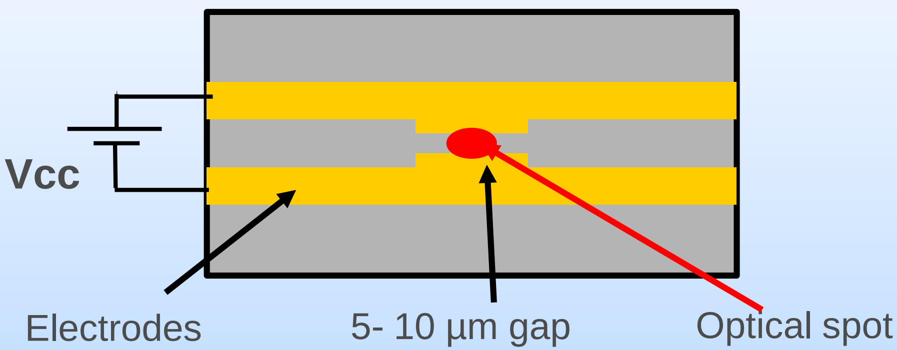
- from 800 to 2200 nm wavelength
- from 12 to 250 fs
- from 1 kHz to 1 GHz rep. Rate
- from nJ to mJ per pulse
- from 20 k€ to 300 k€

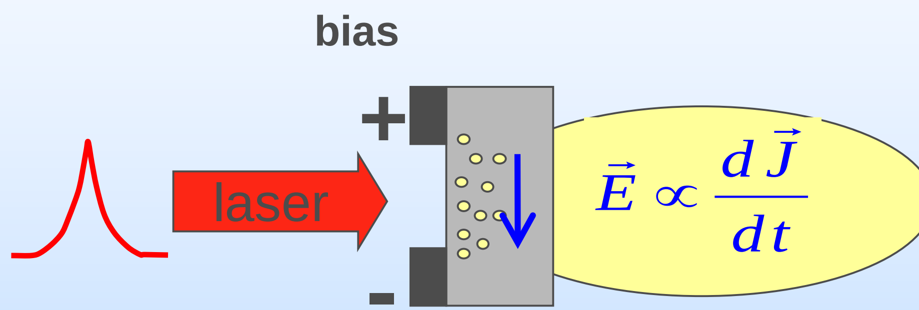
Pulsed THz emission with a dipole antenna

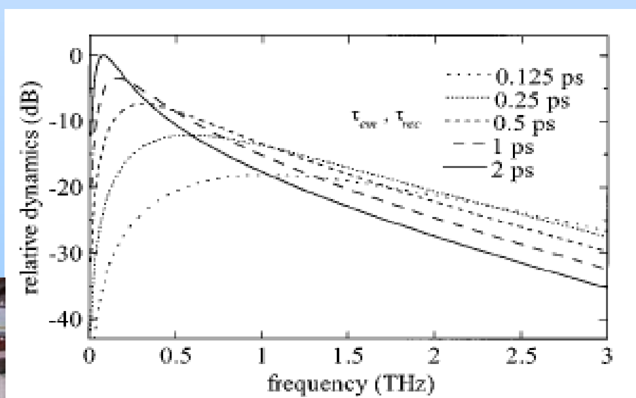
IMEP-LAHC

FAIT MAISON

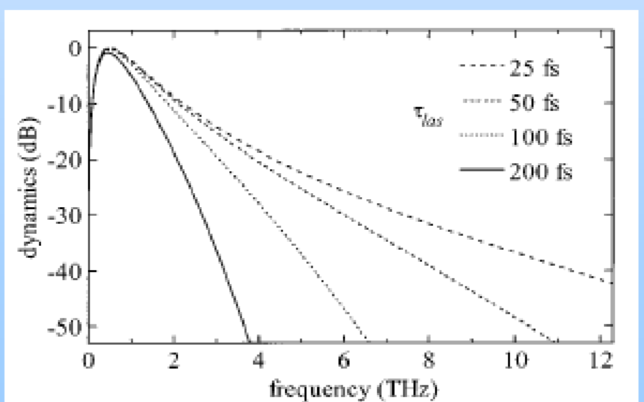
Typical photoconductive antenna







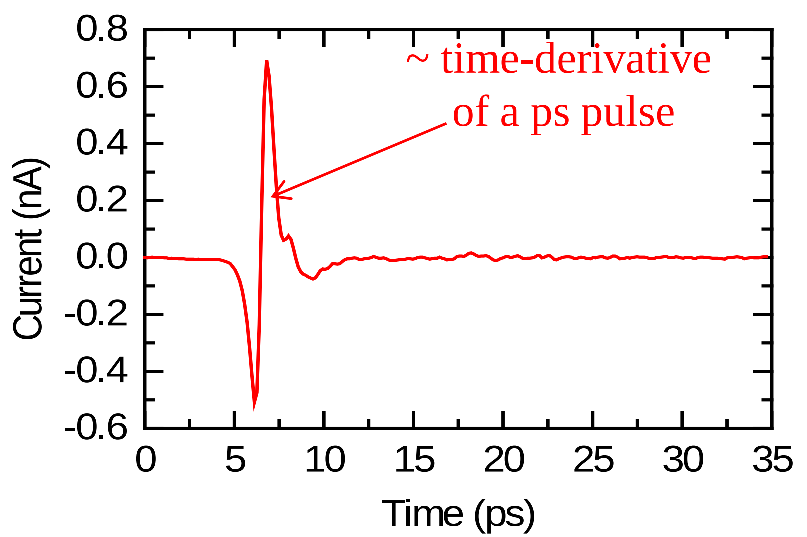
Spectre calculé pour différents
temps de vie des porteurs
(Δt laser = 80fs)

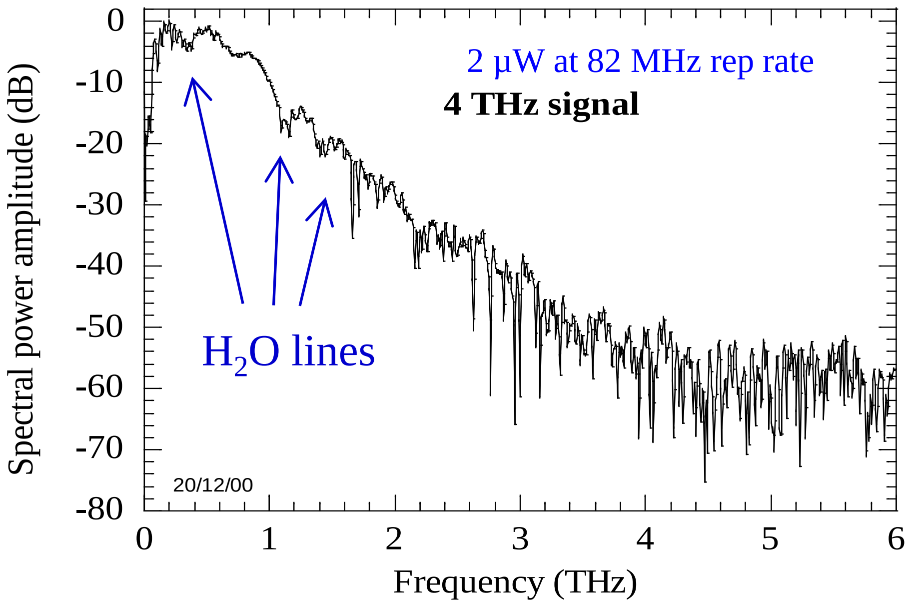


Spectre calculé pour différents
Durée d'impulsion laser
($\tau_{porteurs}$ = 300fs)

Typical THz signal radiated by a photoswitch

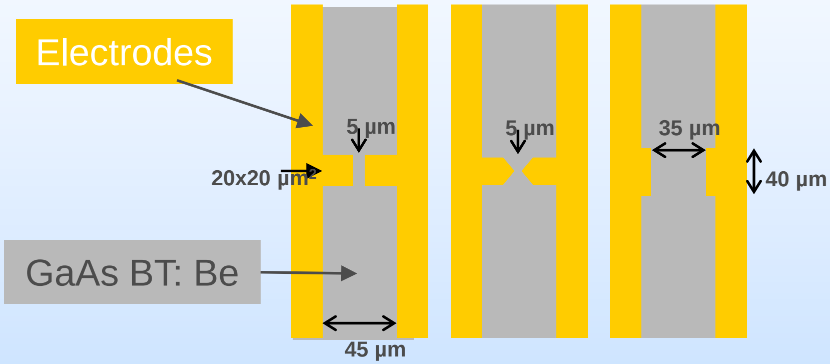
- Photoconductive emission using a femtosecond Ti:Sa Oscillator (100 MHz, 500 mW)

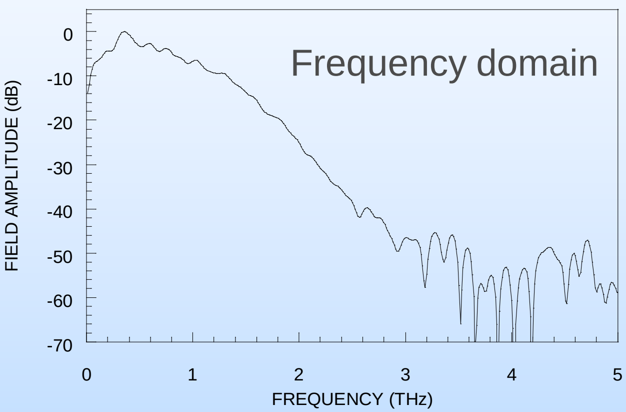


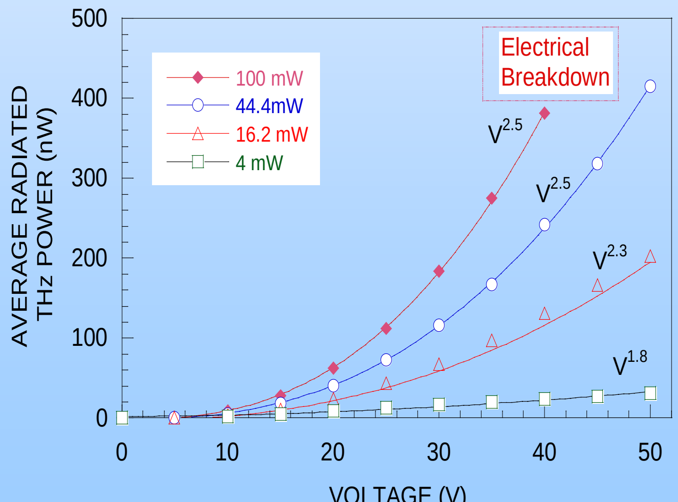


Pulsed THz emission with dipole antenna PSW

- Photoconductive emission using optimized dipole antenna







P_{THz}= 10 µW broadband
Cost = 1500 €

P(THz) varies with V_{bias}^2 and P_{opt}^2

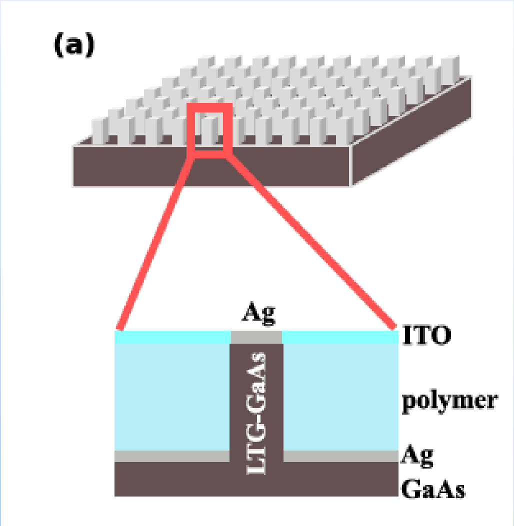
H. Eusebe's PhD work in 2004

Improved 3D device based on nano-photonics and plasmonic effects

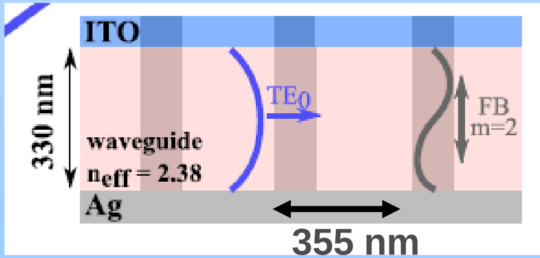
FAIT MAISON

- Our goal is to have very efficient component to generate ps pulses with very low amount of optical power

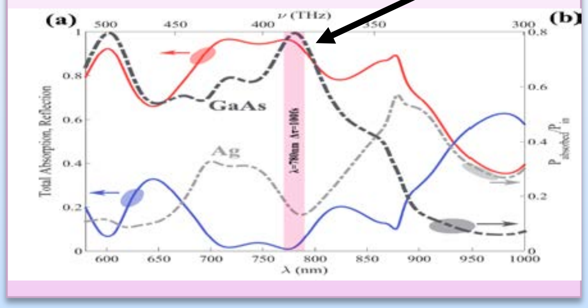
Array of GaAs nano-pilars



Waveguide resonance
+
Fabry- Perot resonance
+
Plasmon excitation

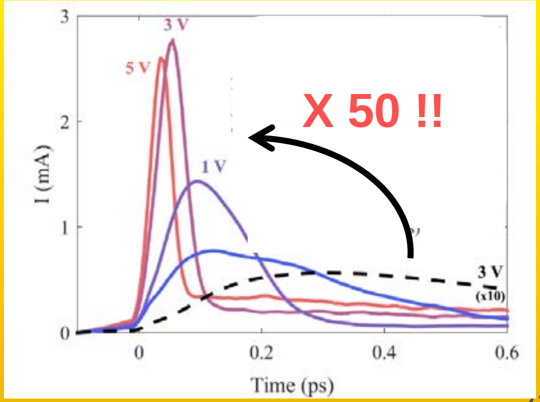


99 % optical absorption in GaAs



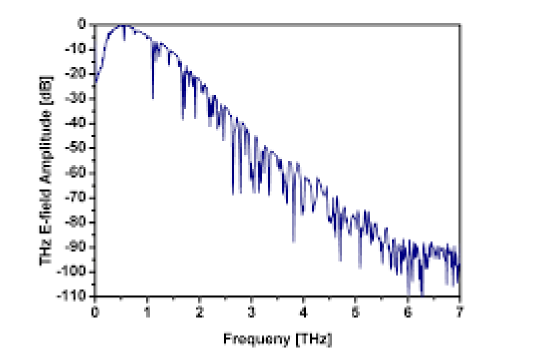
Simulation results

Pulsed current 50 times larger than in classic device



Submitted to ACS Photonics

THz Time Domain Spectroscopy Systems based on pulsed THz generation in photoswitches



Prog. Quant. Electr., Vol. 4, pp. 207–232. Pergamon Press, 1976. Printed in Great Britain

FAR-INFRARED GENERATION BY OPTICAL MIXING

Y. R. Shen

Department of Physics, University of California and Inorganic Materials Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720, U.S.A.

The motivation for studying far-infrared generation by this method is twofold. First, the far-infrared generation is closely related to other nonlinear optical processes such as the electro-optical effect, sum-frequency generation, etc. By studying the various nonlinear optical processes, we can have a better understanding of not only the nonlinear optical properties of matter, but also optical wave propagation in a nonlinear medium. Secondly, we hope to find a new far-infrared source which is superior to those presently available. This second aspect is clearly of practical importance; let us therefore elaborate a little on it.

Non-linear Optics : second order effects

$$\frac{\partial^2 \vec{E}}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \vec{P}}{\partial t^2}$$

With

$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + \varepsilon_0 \left[\chi^{(2)} \vec{E}^2 + \ldots \right]$$

P_{NL} generaly very weak…

- Consider the interaction between 2 waves at ω_1 et ω_2 in a non-linear $\chi^{(2)}$ media

$$E(t) = \frac{1}{2}\{A_1 \exp(i\omega_1 t - ik_1 z) + cc\} + \frac{1}{2}\{A_2 \exp(i\omega_2 t - ik_2 z) + cc\}$$

The non-linear polarization is proportionnal to :

$$E(t)^2 \propto A_1^2 \exp(2i\omega_1 t - 2ik_1 z) + cc$$ **2nd-harmonic gen**

$$+ A_2^2 \exp(2i\omega_2 t - 2ik_2 z) + cc$$ **2nd-harmonic gen**

$$+ 2A_1 A_2 \exp\left[i(\omega_1 + \omega_2)t - i(k_1 + k_2)t\right] + cc$$ **Sum-freq gen**

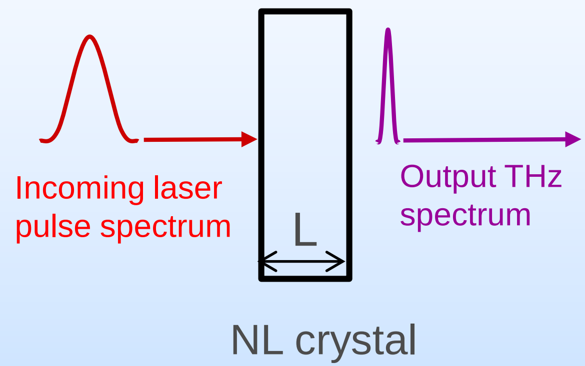
$$+ 2A_1 A_2^* \exp\left[i(\omega_1 - \omega_2)t - i(k_1 - k_2)t\right] + cc$$ **Difference-freq. generation**

$$+ 2|A_1|^2 + 2|A_2|^2$$ **Rectification**

THz Generation by optical rectification

NL Helmotz equation

$$\frac{\partial^2 E\left(\omega_{THz}, z\right)}{\partial z^2} + k_{THz}^2 E\left(\omega_{THz}, z\right) = -\frac{\omega_{THz}^2}{\varepsilon_0 c^2} P_{NL}\left(\omega_{THz}, z\right)$$



Source term at ω_{THz}

$$P_{NL}\left(\omega_{THz}, z\right) = \varepsilon_0 \cdot \chi^{(2)}\left(\omega_{THz}\right) \cdot E_{laser}^2 \cdot S\left(\omega_{THz}\right) \cdot \exp\left(i \frac{\omega_{THz}}{V_g} z\right)$$

Generated Field at ω_{THz}

$$E_{THz}(\omega_{THz}, L) = i \frac{\omega_{THz}^2}{c^2} \cdot \frac{\chi^{(2)}\left(\omega_{THz}\right) \cdot E_{laser}^2 \cdot S\left(\omega_{THz}\right) \cdot L}{\left(k_{THz} + \frac{\omega_{THz}}{V_g}\right)} \exp\left(i\left(k_{THz} + \frac{\omega_{THz}}{V_g}\right)\frac{L}{2}\right)\left[\frac{\sin(\Delta k\, L/2)}{\Delta k}\right]$$

Nonlinear coeff of the crystal

Laser peak amplitude

Spectral density depends on laser pulse duration

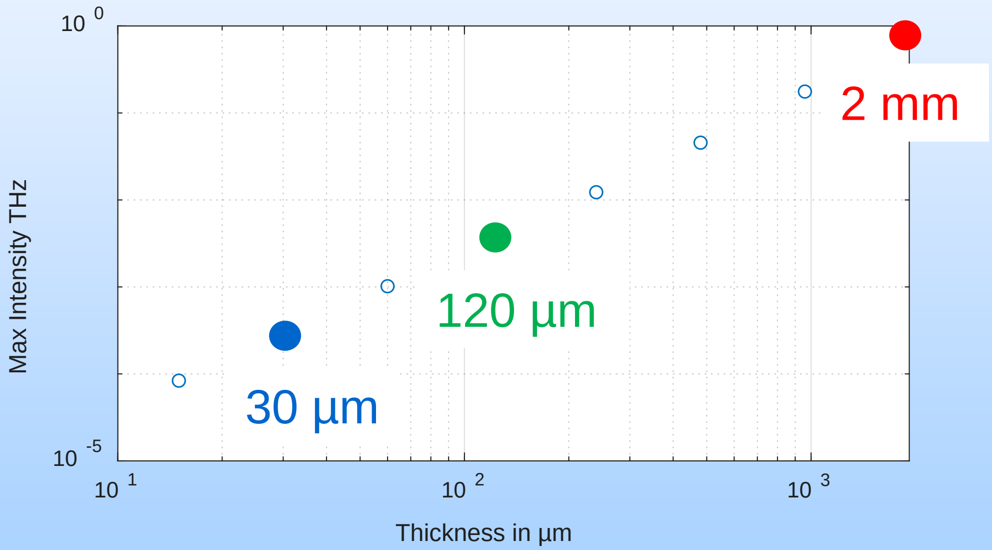
$$\Delta k \equiv \omega_{THz}\left(\frac{n_{THz}}{c} - \frac{1}{V_g}\right)$$

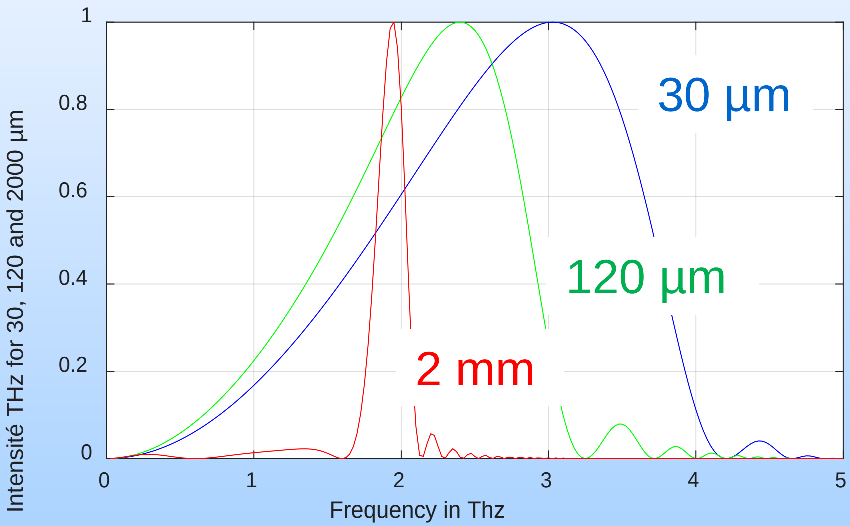
Phase mismatch due to velocity mismatch:

- the NL terms propagates at the IR group velocity Vg
- The THz wave propagates at the THz phase velocity…

THz Generation by optical rectification

$$I_{THz}(\omega_{THz}, L) \propto \frac{\omega_{THz}^4}{c^4}\left[\chi^{(2)}(\omega_{THz})\cdot I_{laser}\cdot S(\omega_{THz})\right]^2 \cdot L^2\left[\frac{\sin(\Delta k\, L/2)}{\Delta k}\right]^2$$





- Thick Crystal = High power
- Thin Crystal = large THz spectrum

Figure of Merit of usual non-linear crystals for DFG

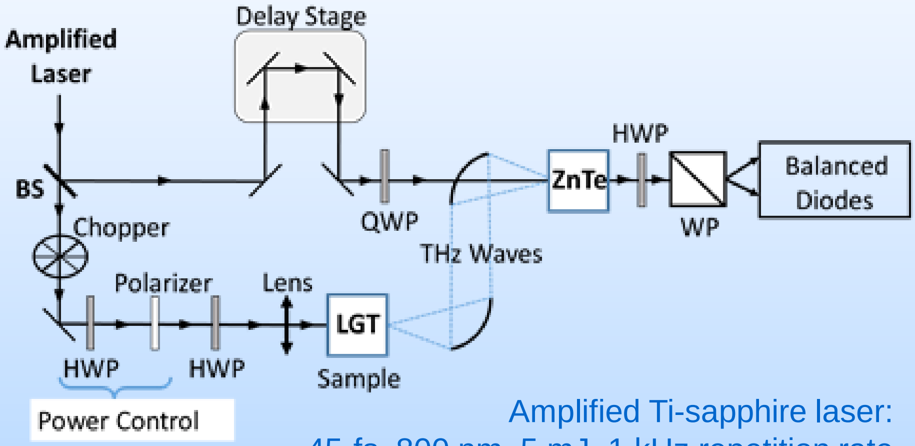
crystal	EO coefficient	refractive index	DC dielectric constant	figure of merit (rectification)	GVD	EOS V_π	phonon f_{TO}
	(pm/V)			(pm/V)	(ps/mm)	(kV)	(THz)
ZnTe	r_{41}= 4,04	n=2,853	ε=10,1	~ 45	**1,1**	6,75	5,3
$LiTaO_3$	r_{33}= 30,5 r_{13}= 8,4	n_o=2,176 n_e=2,180	$\varepsilon_{1,2}$ =41 $\varepsilon_{1,2}$ =43	≤ 85	14,1	2,01 7,27	6,23
$LiNbO_3$	r_{33}= 30,9 r_{51}= 32,6	n_o=2,286 n_e=2,200	$\varepsilon_{1,2}$ =43 ε_3 =28	≤ 110	14,2	1,71 1,82	4,5
KTP	r_{33}= 36,3 r_{23}= 15,7	n_e=1,866	$\varepsilon_{1,2}$ =11 ε_3 =15	≤ 109	5,4	2,68	
DAST	r_{11}= 77	n_o=2,46 n_e=1,70	8,0 2,9	≤ 600	**1,22**	0,71 2,16	**2.28 i=1** **1.13 i=2** **1.50 i=3**

Choice of the crystal depends on the application… and on the source

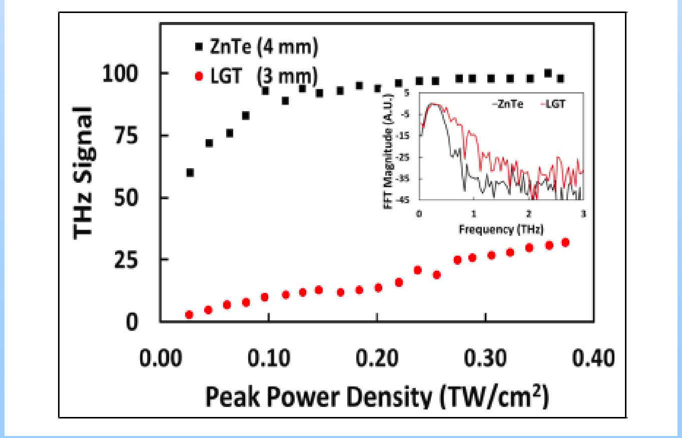
Terahertz generation in a langatate crystal by optical rectification

Langatate crystal
$La_3Ga_{5.5}Ta_{0.5}O_{14}$

- Piezoelectric properties
- No phase change up to its melting point (1450 ° C)
- Piezoelectric constant (d_{11}) stable up to 600°C
- Damage threshold 6 times higher than $LiNbO_3$



Amplified Ti-sapphire laser:
45-fs, 800 nm, 5 mJ, 1 kHz repetition rate

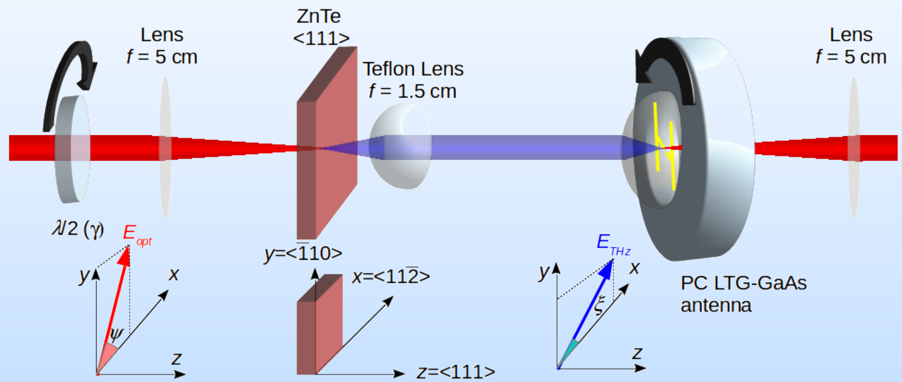


- ZnTe crystal generates more THz signal than LGT, it starts to saturate over 0.1 TW/cm2.
- However, LGT crystal presents a good linearity up to 0.37 TW/cm2

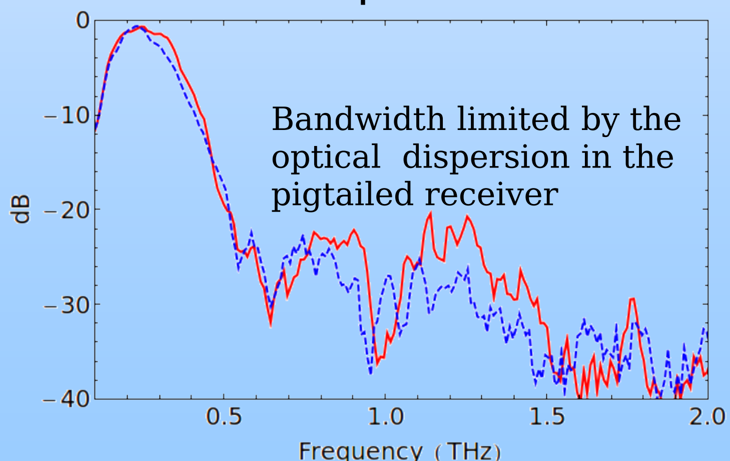
*G. Soylu, F. Aljammal, G. Gaborit, M. Dumortier, H. Cabane, E. Herault and J.-L. Coutaz ,"Optical rectication in a langatate crystal for terahertz generation", Optics Letters journal (To be submitted)

Control of the THz polarization state by optical rectification within a cubic crystal

- OR is linked to the group symetry of the crystals : use of a cubic crystal to control THz polarization by rotating the IR pulses polarization

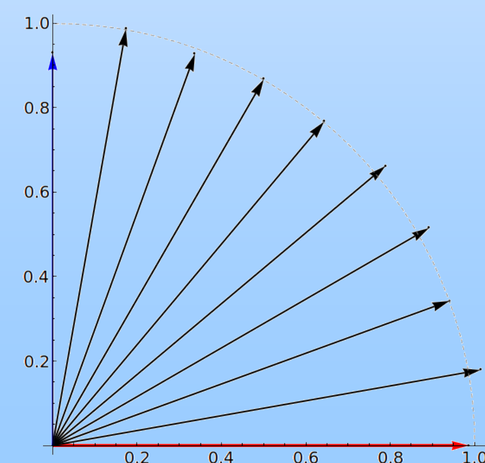


THz spectrum



THz polarization state

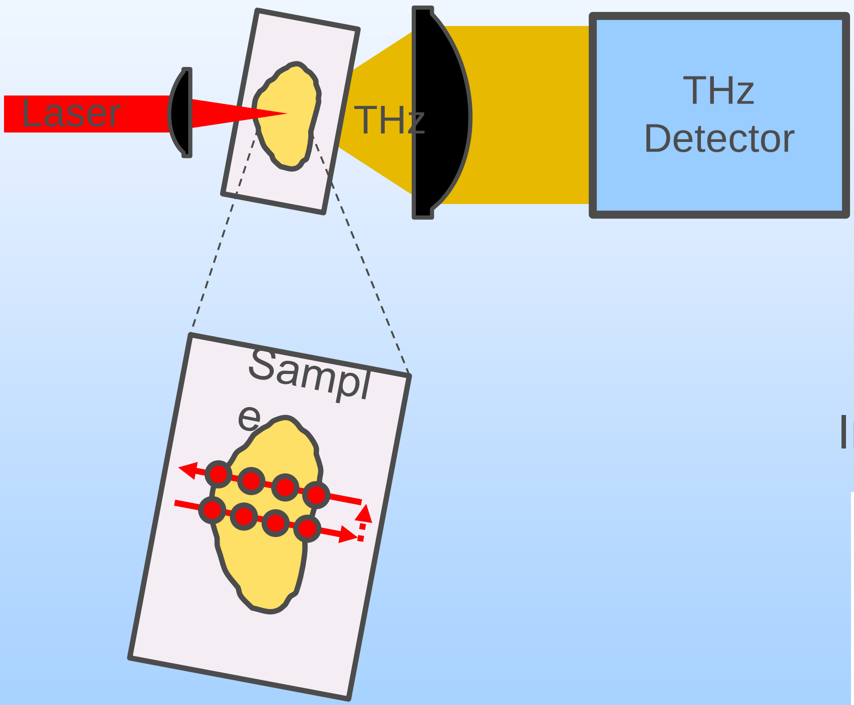
0°
90°



G. Gaborit et al. ICOPS 2015

Optical rectification TeraHertz Imaging

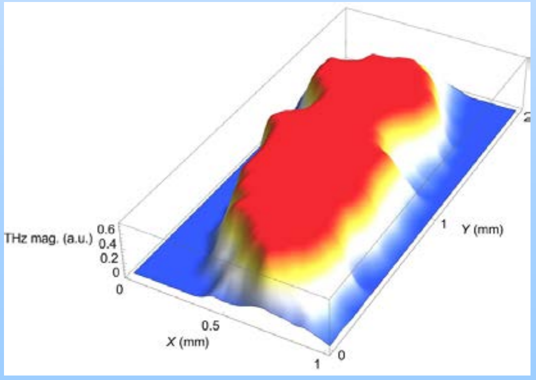
Idea : Probing and imaging the structure of a material by probing its NL « local » properties through THz generation



→ Imaging point by point by moving the sample

→ Resolution depends on laser spot size not on THz wavelength

Imaging of a sugar grain

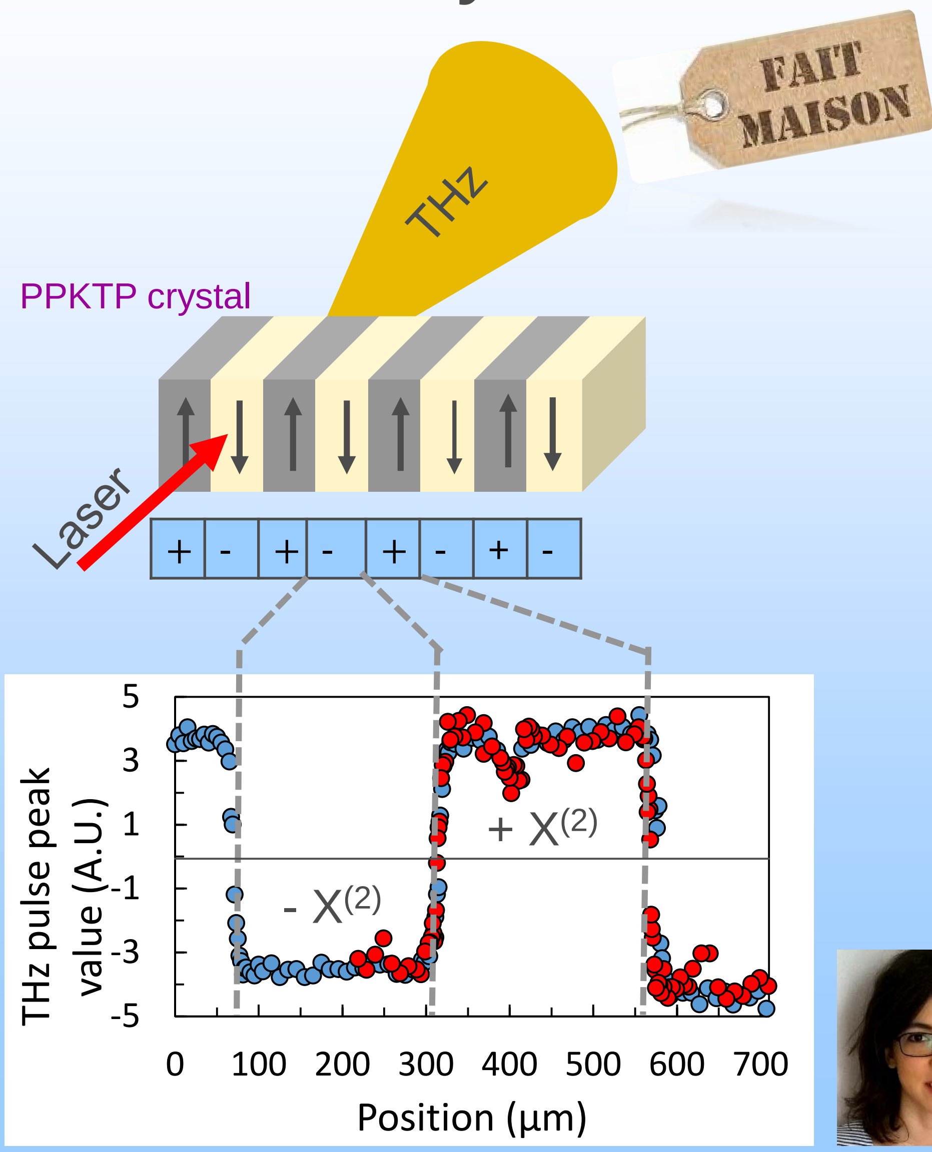


Scientific Reports 2018

IMEP-LAHC

Federico

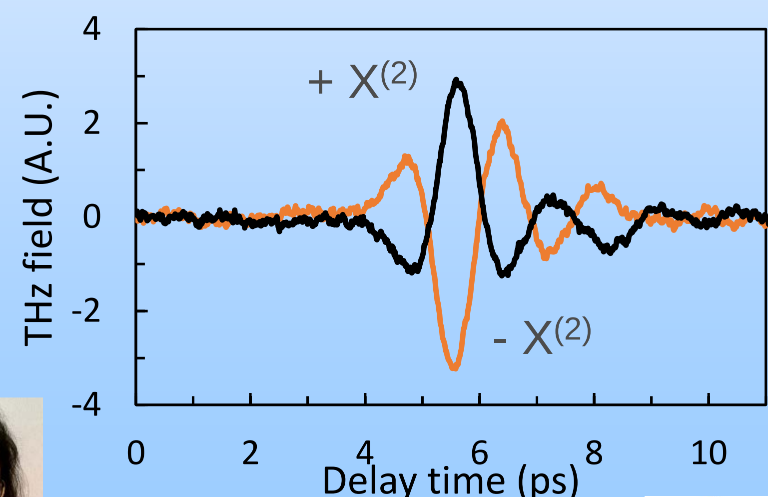
Optical rectification TeraHertz Imaging in PPKTP crystals



→ Imaging point by point by moving the sample

→ Resolution depends on laser spot size not on THz wavelength

→ Imaging PPKTP crystal: Generated THz waves should inverted as the crystal orientation is flipped !

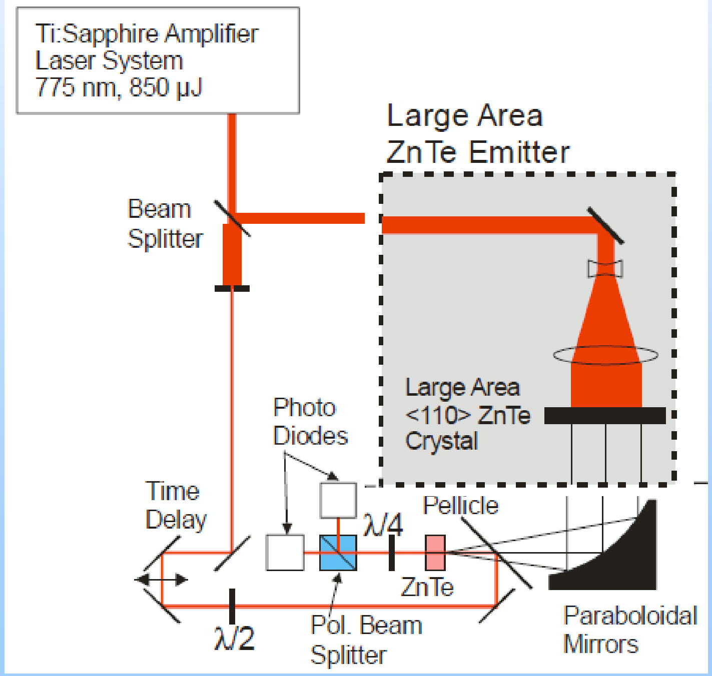


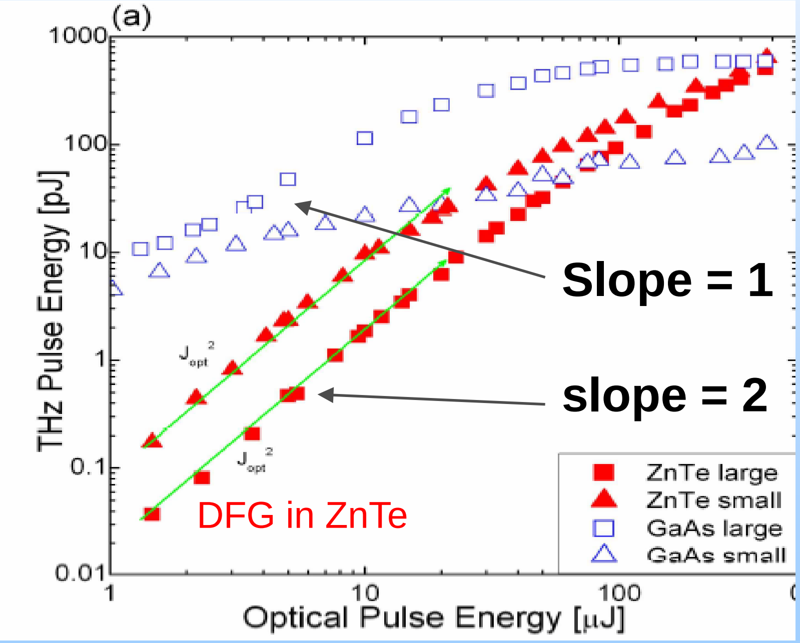
Gizem Soylu’s work

Towards high THz power generation using amplified pulsed lasers

- Use of large area nonlinear crystal (ZnTe)

850 µJ/pulse (150 fs)
Rep. Rate = 1 kHz



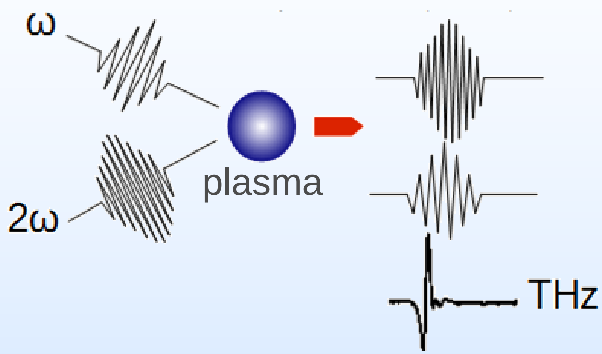


Max THz field = 10 kV/cm

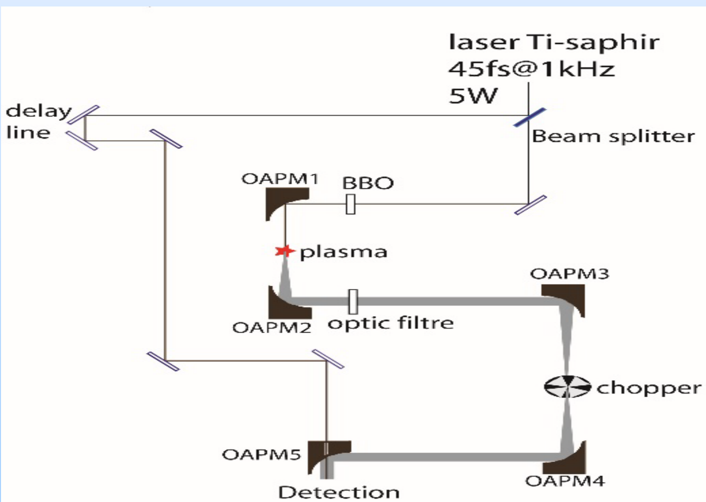
From Loefler et al. Optics Express 2005.

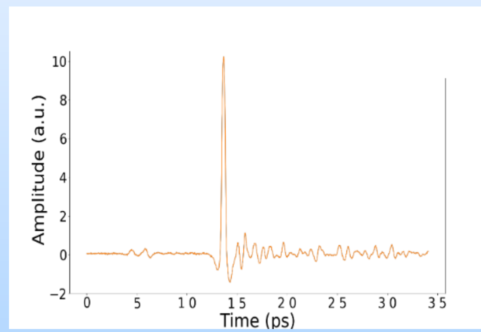
THz emission by DFG in ZnTe appears promising for high intensity generation

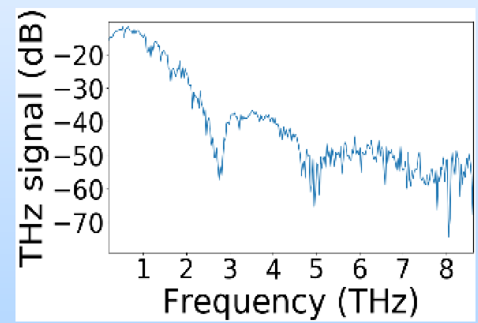
THz generation in Plasma

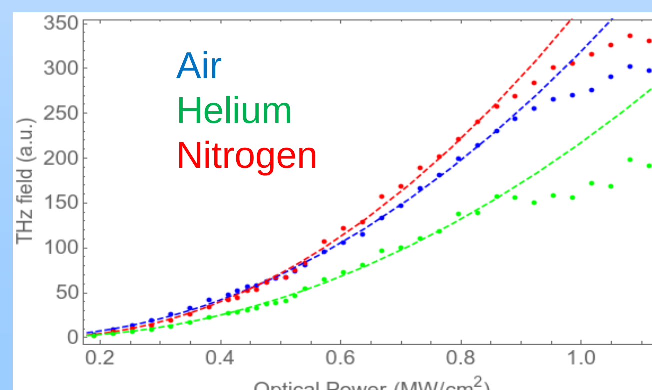


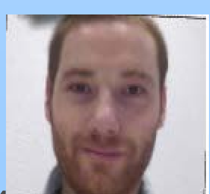
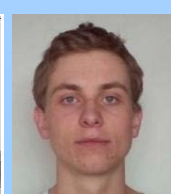
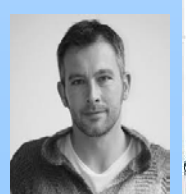
- Photo-generated plasma by femtosecond optical breakdown in air
- Acceleration of ions and e- by charge repulsion and ponderomotive force
- Radiation of electromagnetic signal by the accelerated charges
- ω and 2ω light beams induce a dipole-like symmetry breaking
- Intense THz peak power (THz fields over MV/cm)





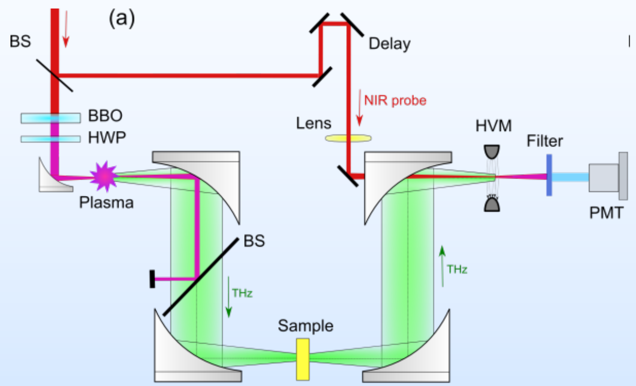


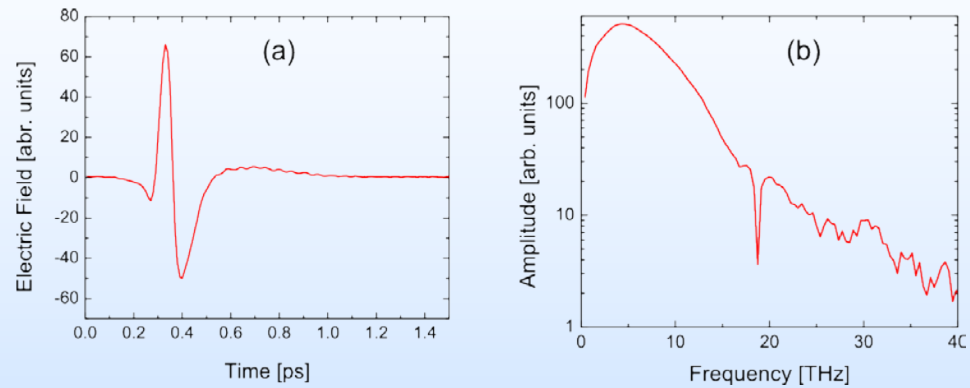



IMEP-LAHC

Spectroscopie THz ultra-large bande à l'Université Technologique du Danemark (P. Jepsen)





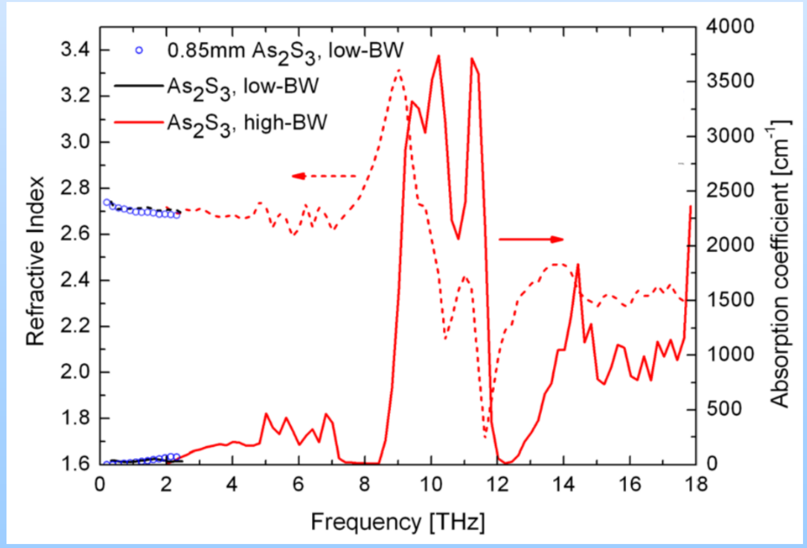


Figure 3: Refractive index (dashed line) and absorption coefficient (solid line) of As2S3. The high bandwidth measurements are performed by THz-ABCD system (red) for 13.6 µm thick sample. For comparison the spectroscopy results by photoconductive antenna-based THz-TDS system on thin (black) samples and on a 0.85 mm thick (blue circles) sample

THz sources: who is the winner ?

CW sources

below 600 GHz: **Transistors based oscillators are** Ultra-compact, Powerful, Versatile, CMOS Integrated, Low-Cost (?)

above 4 THz: **Quantum Cascade Lasers are** working at « Room Temperature » (quasi), Ultra-compact, Powerful, Efficient

fr. 0.6 to 4 THz: **Down Conversion of Photonic Sources** offers large panel of possibilities such as tunability, narrow linewidth, CW or pulsed regime etc…

Broadband sources

incoherent: **Blackbody radiation is** popular, low cost, reliable

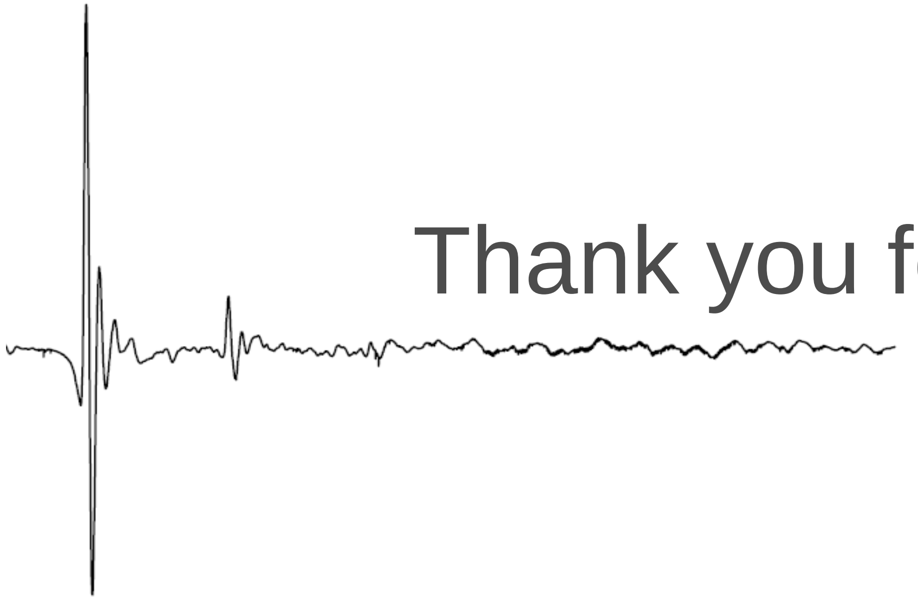
coherent: **Down conversion of fs pulses** offers ultrastable THz pulses, large measurments dynamics, versatile, potentially High Peak power

CONCLUSION

source	gamme spectrale (THz)	puissance	avantages	inconvénients
corps noir	toute la gamme	pW à 0,1 THz μW à 10 THz	simplicité large bande	puissance incohérent
Gunn	0,1$\rightarrow$1	100 mW CW 1 mW CW	compact	fréquence limitée
Impatt	$\rightarrow$0,3	10 mW	compact	fréquence limitée
Tunett RTD	$\rightarrow$0,4	10 μW	compact	puissance fréquence limitée
Smith-Purcell	toute la gamme	100 nW	accordable	gros appareil
FEL	toute la gamme	très puissants $\rightarrow$ 100 W CW	puissance spectre	grands instruments
BWO	$\rightarrow$0,2	10 μW	compact accordable	bruyant fréquence limitée
lasers moléculaires	lignes spectrales	ex : CH_3OH 100 mW à 2,52 THz	pureté spectrale	stabilité, volumineux
lasers QCL	1,9 $\leftarrow$	10 mW	compact, rendement	cryogénie puissance
optoélectronique				
impulsionnel	0,1 $\rightarrow$ 60	μW	spectre cohérent, aspect temporel	puissance limitée, résolution spectrale
CW battement optique	$\rightarrow$ 3	μW	compact, pureté spectrale	puissance faible

Acknowledgements

- Farah Al-jammal, Nisrine Arab, Lionel Bastard, Maxime Bernier, Jean Emmanuel Broquin, Jean Louis Coutaz, Frédéric Garet, Gwenaël Gaborit, Giorgos Georgiou, Emilie Hérault, Robert Horvath, Bastien Muller, Florent Pallas, Federico Sanjuan, Gizem Soylu, Guy Vitrant from IMEP-LAHC
- Jean-François Lampin and E. Peytavit and G Ducourneau from IEMN, Lille
- Antoine Kervorkian and Grégoire Souhaité from Teem Photonics



Thank you for your attention,