Terahertz Emitters and Detectors

Martin Vaughan

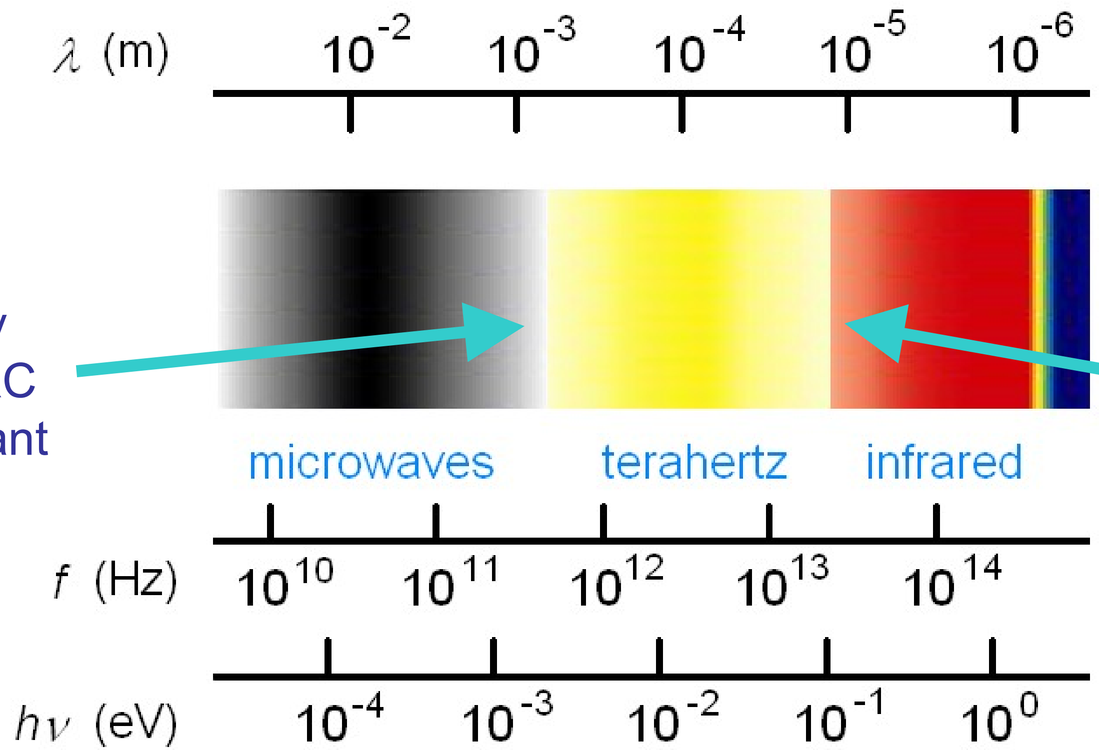
Optoelectronics Research Group – Spring Seminars 2008

Outline

- The THz gap
- Motivation
- THz pulse generation
- THz pulse detection
- Continuous wave THz sources
- Continuous wave THz detectors

The THz gap

limited by parasitic RC time constant



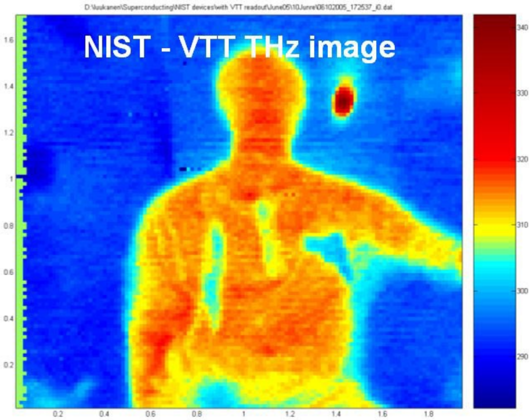
limited by band-gaps and thermal energy

(1 THz ~ 4 meV. At room *T*, $k_B T$ ~ 26 meV)

Motivation

- High transmission for many materials
- Non-ionising
- THz chemical signatures (spectroscopy)
- THz radiation from space of interest

Applications

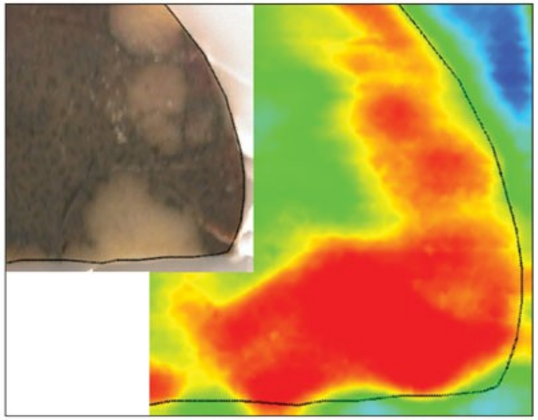


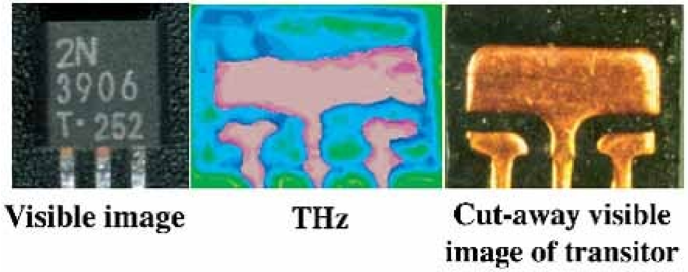
Security scanning

THz image of person with various concealed weapons (NIST)

Medical imaging

THz-transmission image of a specimen of human liver infiltrated by cancer (Physikalisch-Technische Bundesanstalt)





Quality control

THz image of a transistor (Teraview)

Space research

The APEX (Atacama Pathfinder EXperiment) telescope can observe terahertz frequencies.

THz pulses

Pulse generation

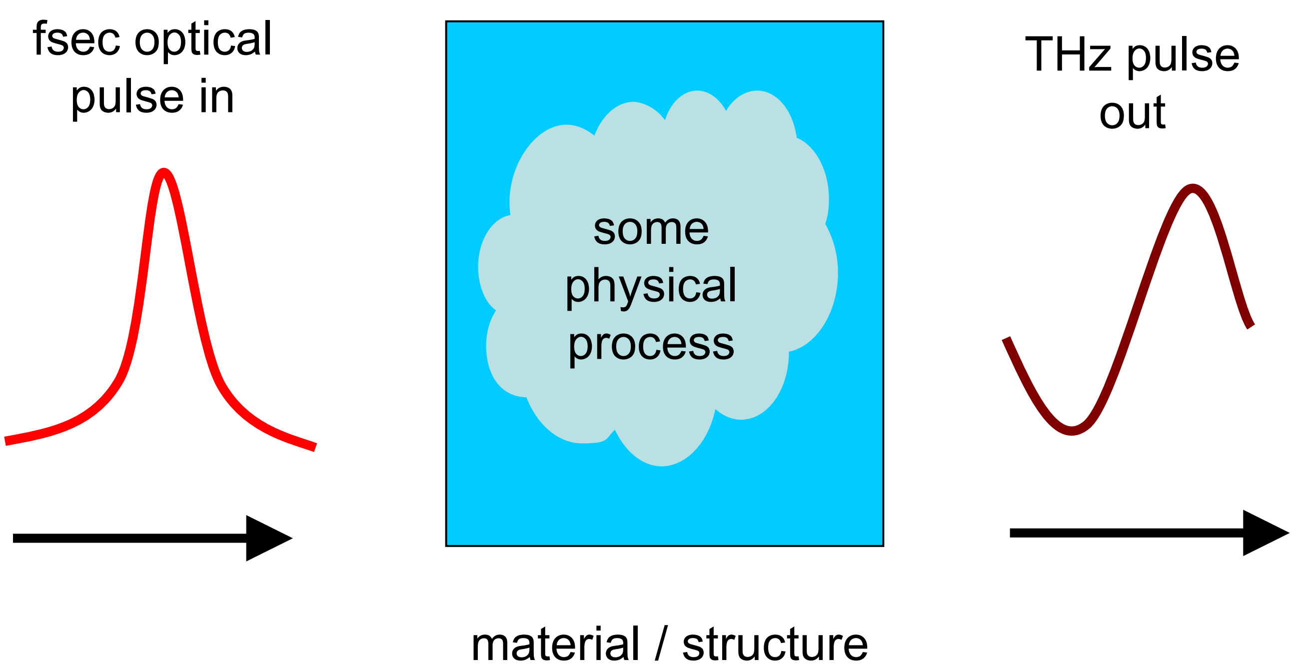
- Non-linear rectification
- Surface surge currents
- Coherent phonons and coupled modes
- Semiconductor structures
- Photoconductive (PC) antennas

Pulse detection

- Electro-optic (EO) sampling
- PC antennas

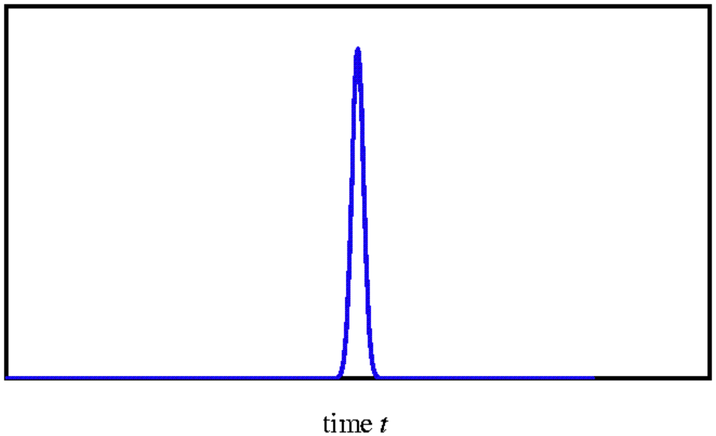
THz pulse generation

General scheme of THz pulse generation

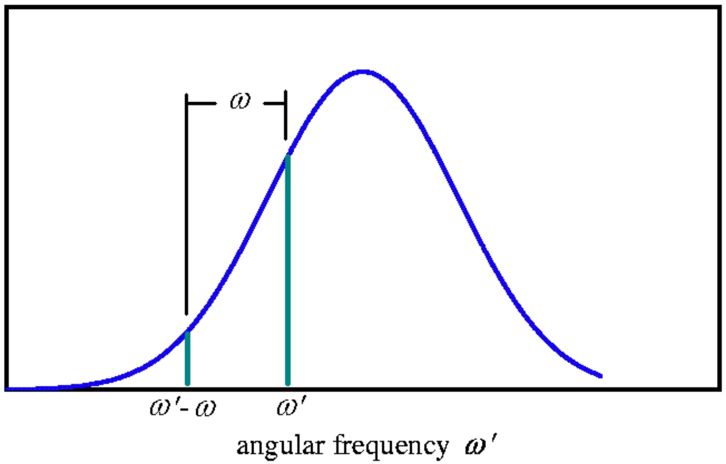


Nonlinear rectification

Short optical pulse



Broad spectrum



Second order polarisation
in non-linear crystal

$$P(\omega)=\varepsilon_0\chi^{(2)}\int_{-\infty}^{\infty}E(\omega')E^*(\omega'-\omega)\,d\omega'.$$

(difference frequency generation)

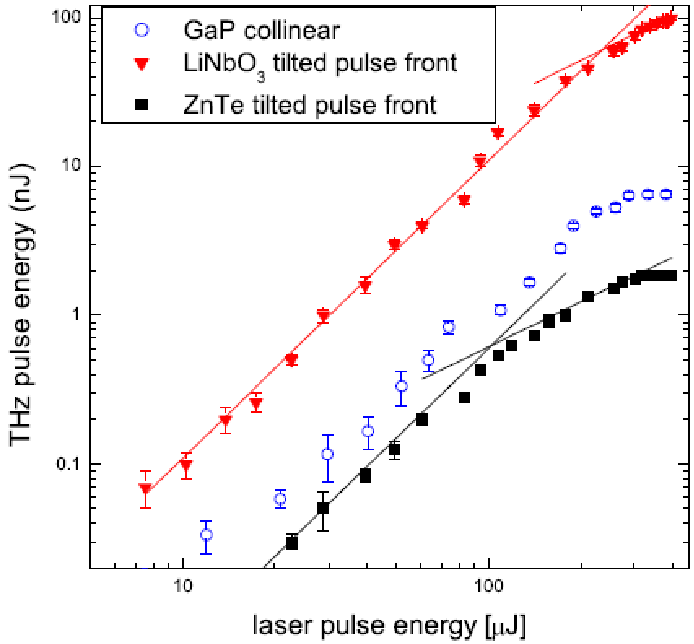
THz field

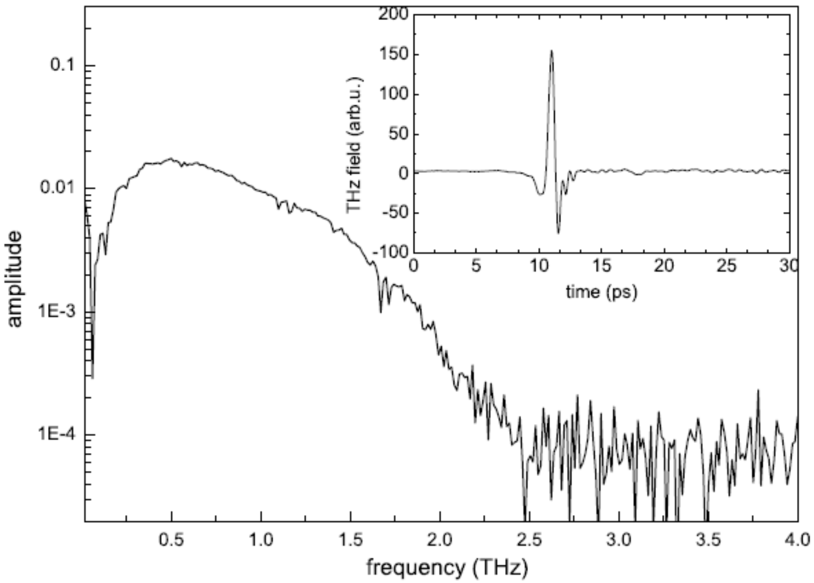
$$E_{\mathrm{THz}}(t)\propto\frac{\partial^2P(t)}{\partial t^2}.$$

Nonlinear rectification [2]

- Non-linear polarisation $P(t)$ is proportional to the optical intensity
- $P(t)$ is optimised via phase-matching
- THz pulse width depends on optical pulse width

Recent results: 100 nJ THz pulses with 400 μJ, 300 fs pulse at 1.03 μm in $LiNbO_3$ (conversion efficiency of 2.5×10^{-4}) *

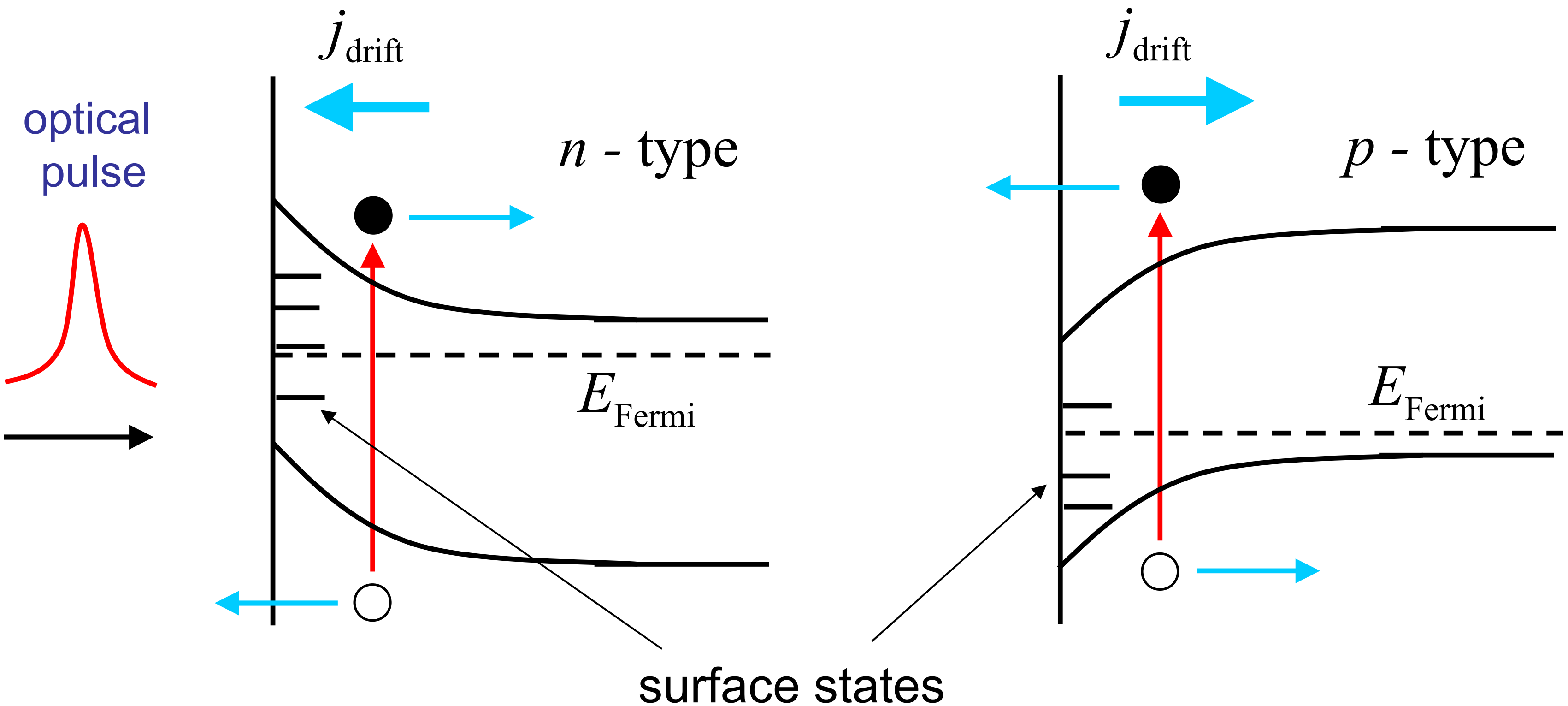




* Hoffman et al, Optics Express, **15**, 11706 (2007)

Surface surge currents

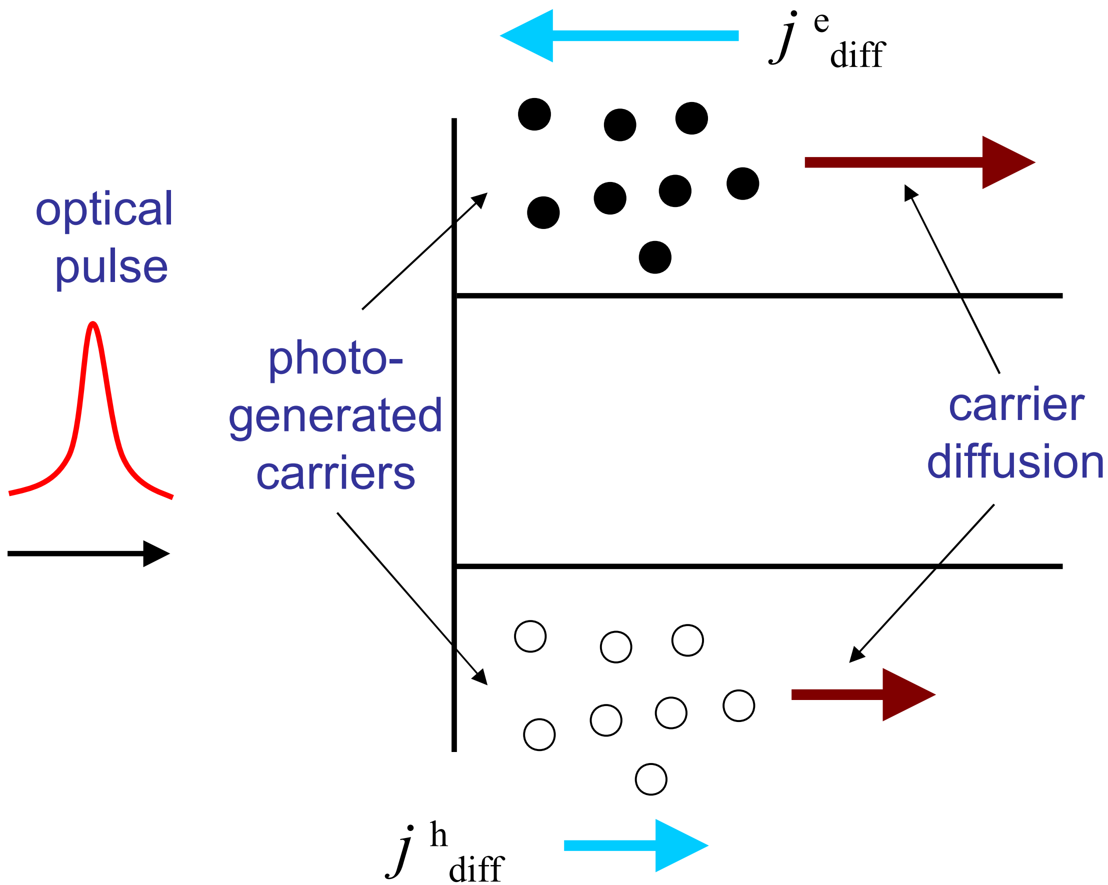
Surface depletion field



Surge current induces dipole normal to surface

Surface surge currents [2]

Photo-Dember effect



$$j = j^{e}_{diff} + j^{h}_{diff}$$

$$= -e\left(D_e \frac{\partial \Delta n}{\partial x} - D_h \frac{\partial \Delta p}{\partial x} \right)$$

But

$$D_i = k_B T \mu_i / e$$

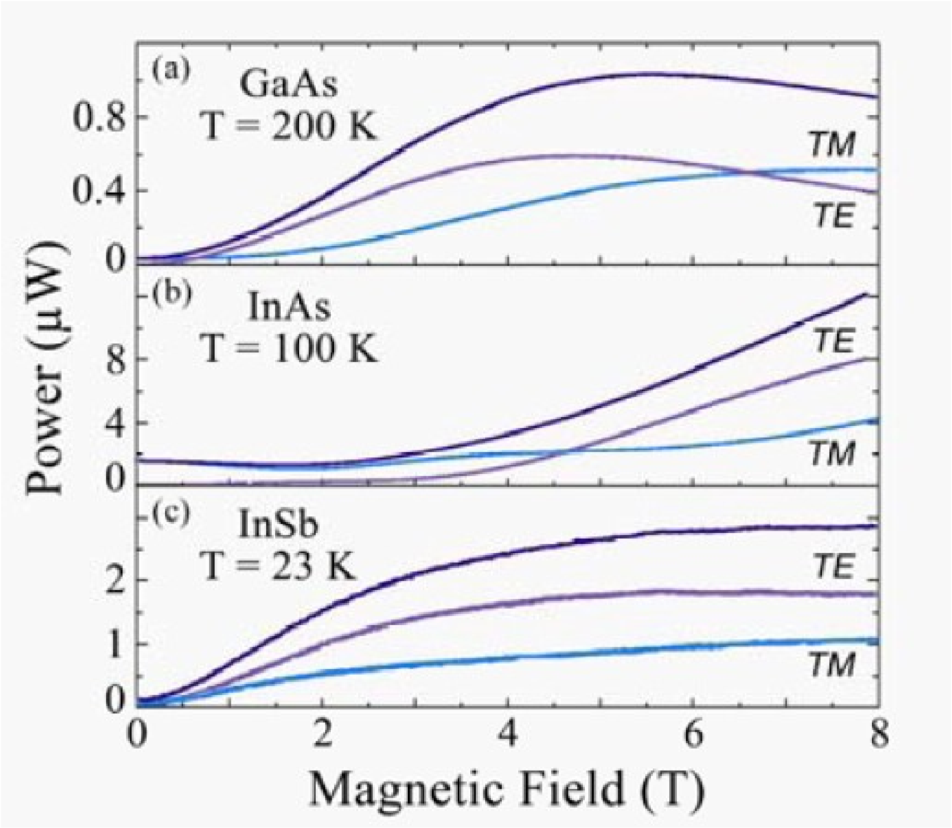
and

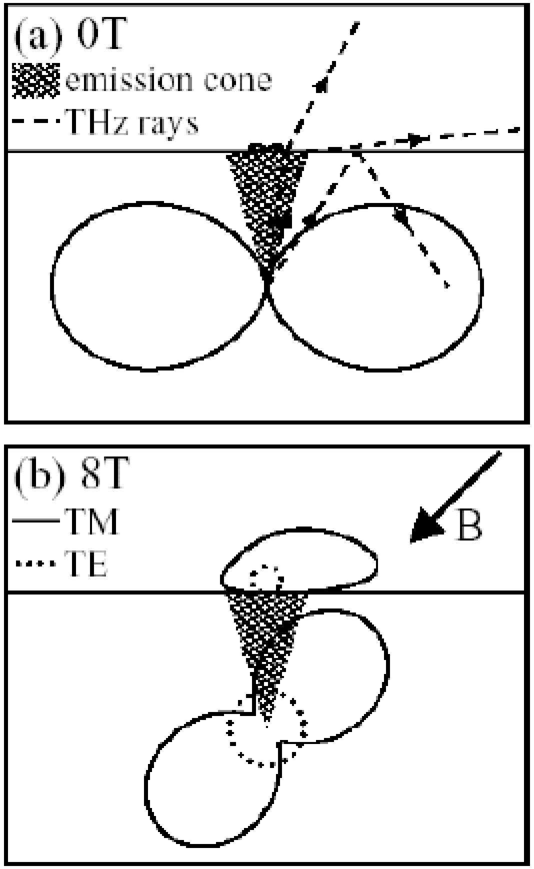
$$\mu_e > \mu_h$$

so net current flow.

For narrow band gap semiconductors, band-bending is small.

Magnetic field enhancement of surface field THz





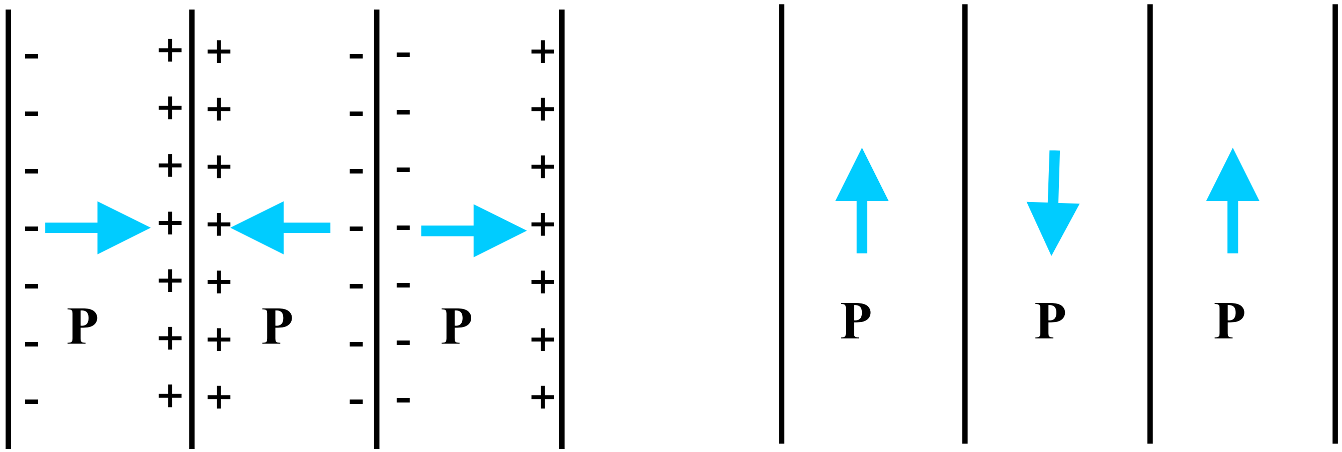
* Linfield *et al*, Central Laser Facility Annual Report 2001/2002

Phonon-polaritons

Coherent phonons induced by ultra-fast
surface field screening or photo-Dember field build up.

LO modes
– net polarisation charge

TO modes
– no net polarisation charge



However, LO modes do not couple with EM. For small phonon wavevector $\mathbf{q}$ $\omega_{LO} = \omega_{TO}$ (degenerate). For non-zero incident angle of optical radiation $\mathbf{q}$ has TO component – coherent phonons then hybrid LO-TO mode.

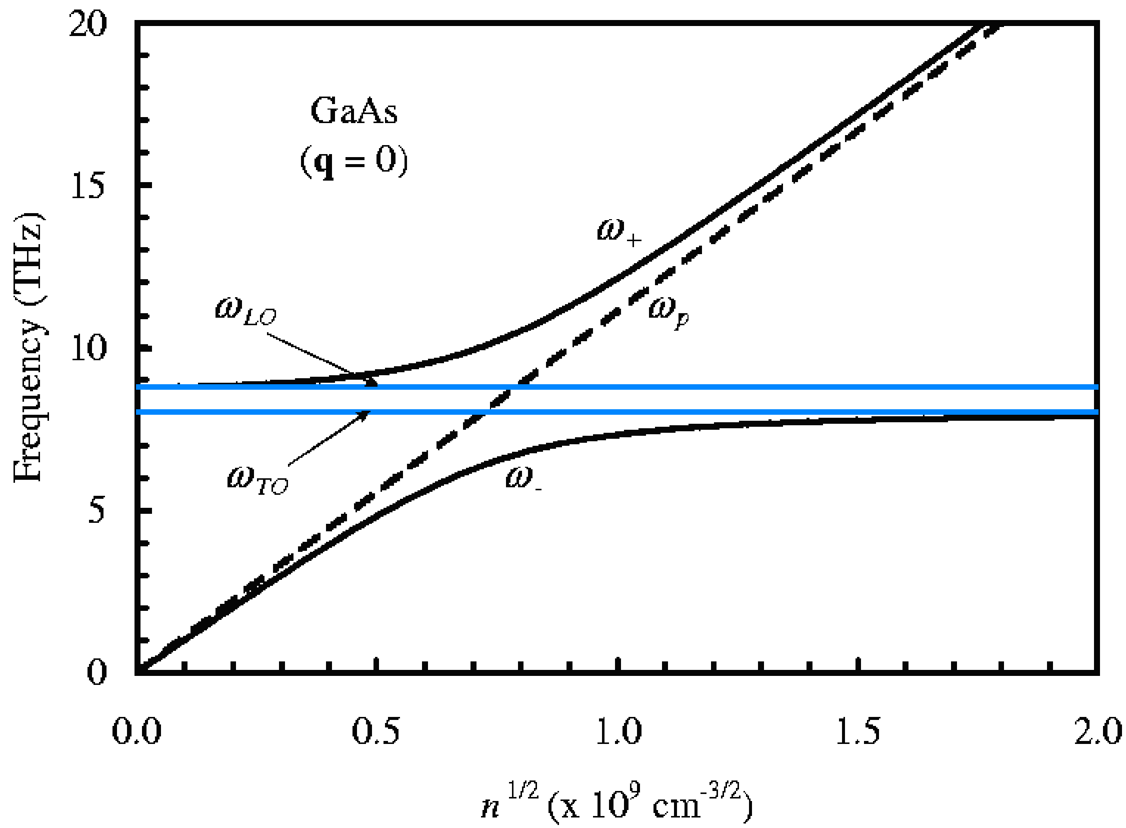
Plasmons and coupled modes

Similar considerations regards plasmon coupling to EM as for phonons

Plasma frequency:

$$\omega_p = \sqrt{\frac{4\pi e^2 n}{\varepsilon \varepsilon_0 m^*}}$$

In polar materials, we can get coupled *plasmon-phonon modes*.



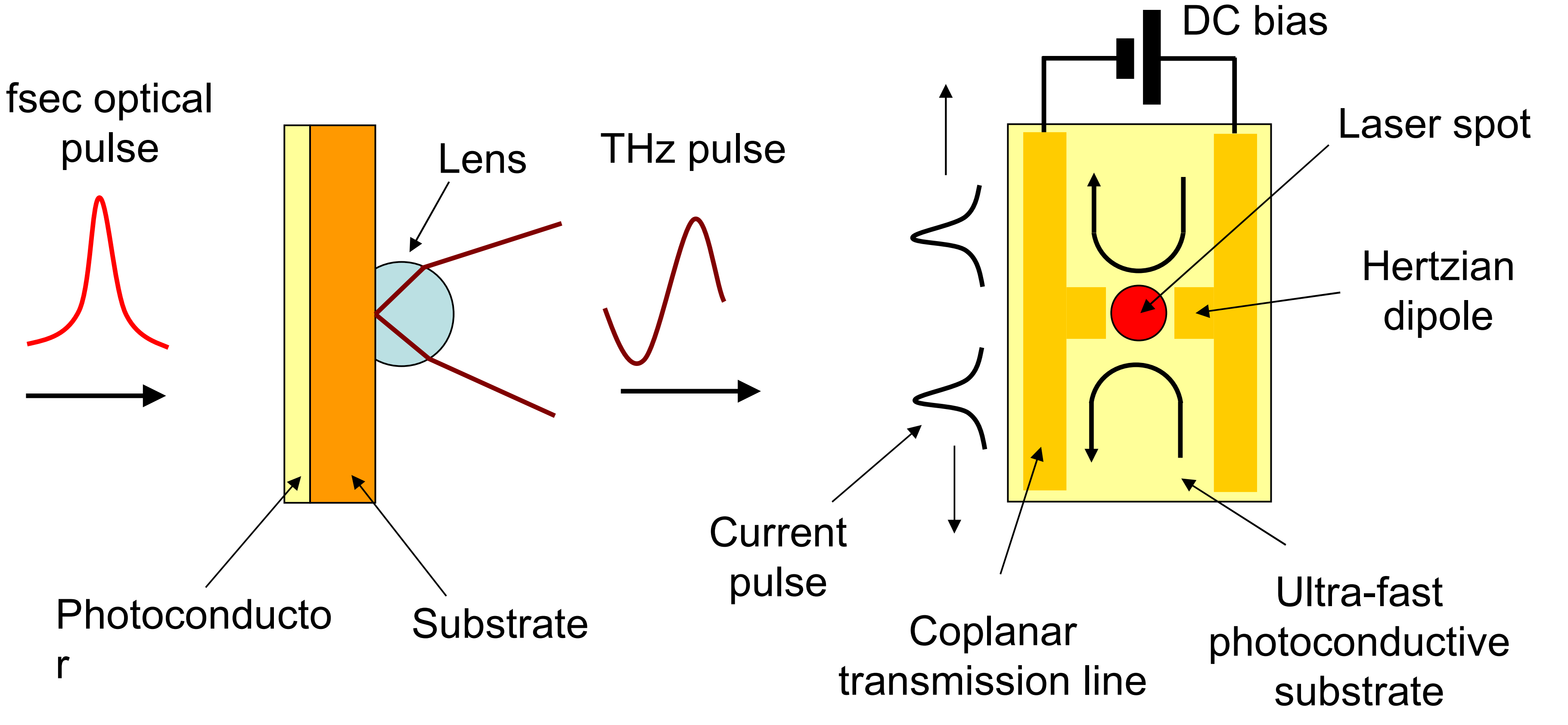
Coupled mode frequency (**q** = 0)*:

$$\omega_{\pm}^2 = \tfrac{1}{2}\left(\omega_{LO}^2 + \omega_p^2 \pm \left[\left(\omega_{LO}^2 + \omega_p^2\right)^2 - 4\omega_{TO}^2\omega_p^2\right]\right)$$

* From B.K. Ridley, *Quantum Processes in Semiconductors*, Clarendon Press (1999)

PC antennas

PC (photoconductive) or Austin switching



Side view **Top view**

Diagram based on Saki and Tani, *Introduction to Terahertz Pulses* in *Terahertz Optoelectronics*, Sakai (Ed.), Springer 2005

PC antennas [2]

Requirements for photoconductive (PC) material:

- Short carrier lifetime (for short current pulses)
- High mobility (for fast carrier transport)
- High resistivity (to reduce dark current when bias applied)

Typical materials:

- Radiation damaged silicon on sapphire (RD-SOS)
- Low temperature grown GaAs (LT-GaAs)

Material	Carrier lifetime (ps)	Mobility (cm^2/Vs)	Resistivity (Ωcm)
RD-SOS	0.6	30	-
LT-GaAs	0.3	150 – 200	10^6

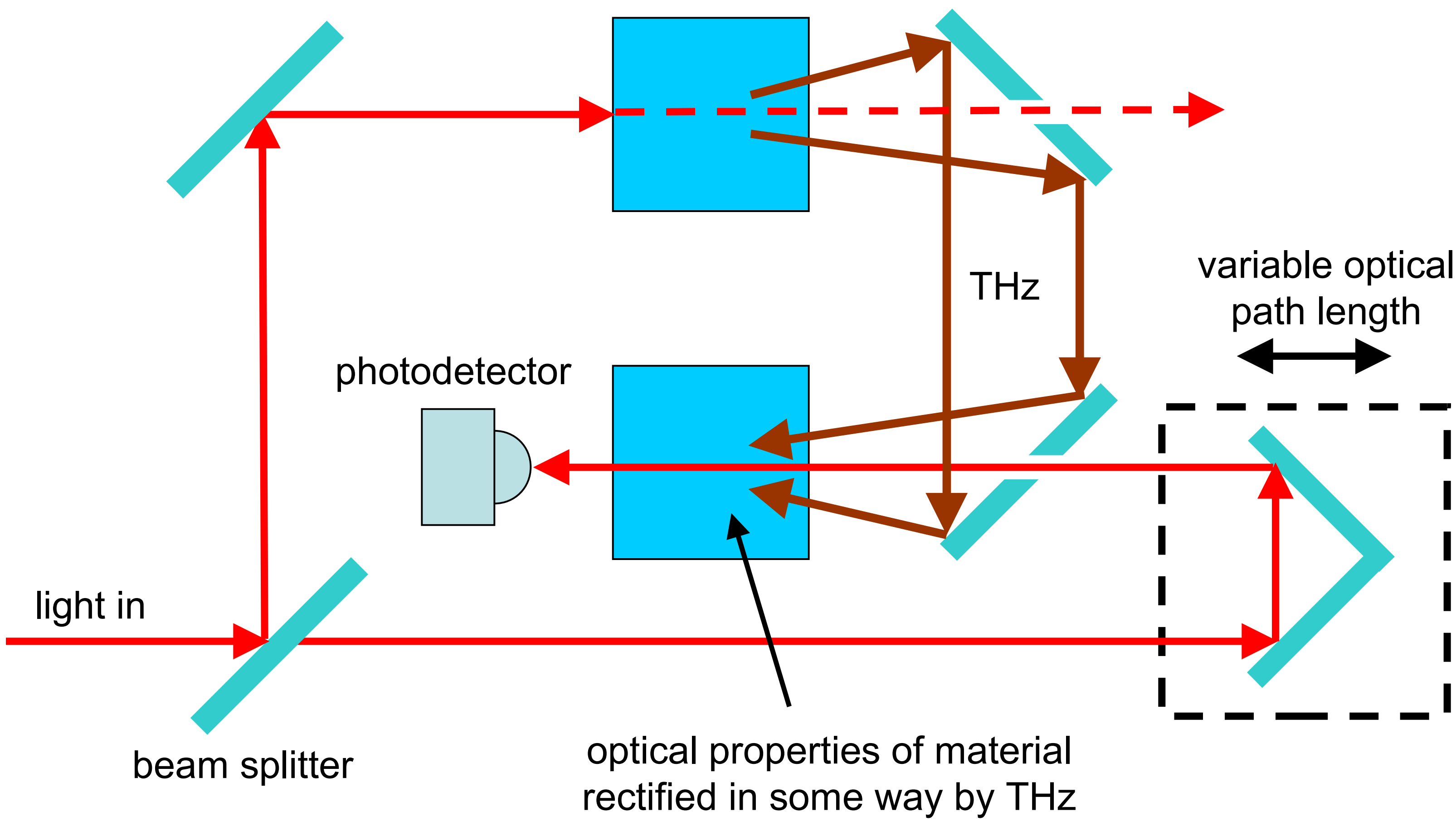
Data from Saki and Tani, *Introduction to Terahertz Pulses* in *Terahertz Optoelectronics*, Sakai (Ed.), Springer 2005

Other mechanisms

- Semiconductor structures
  - typically based on resonant tunnelling between adjacent quantum wells
- Non-linear transmission lines

THz pulse detection

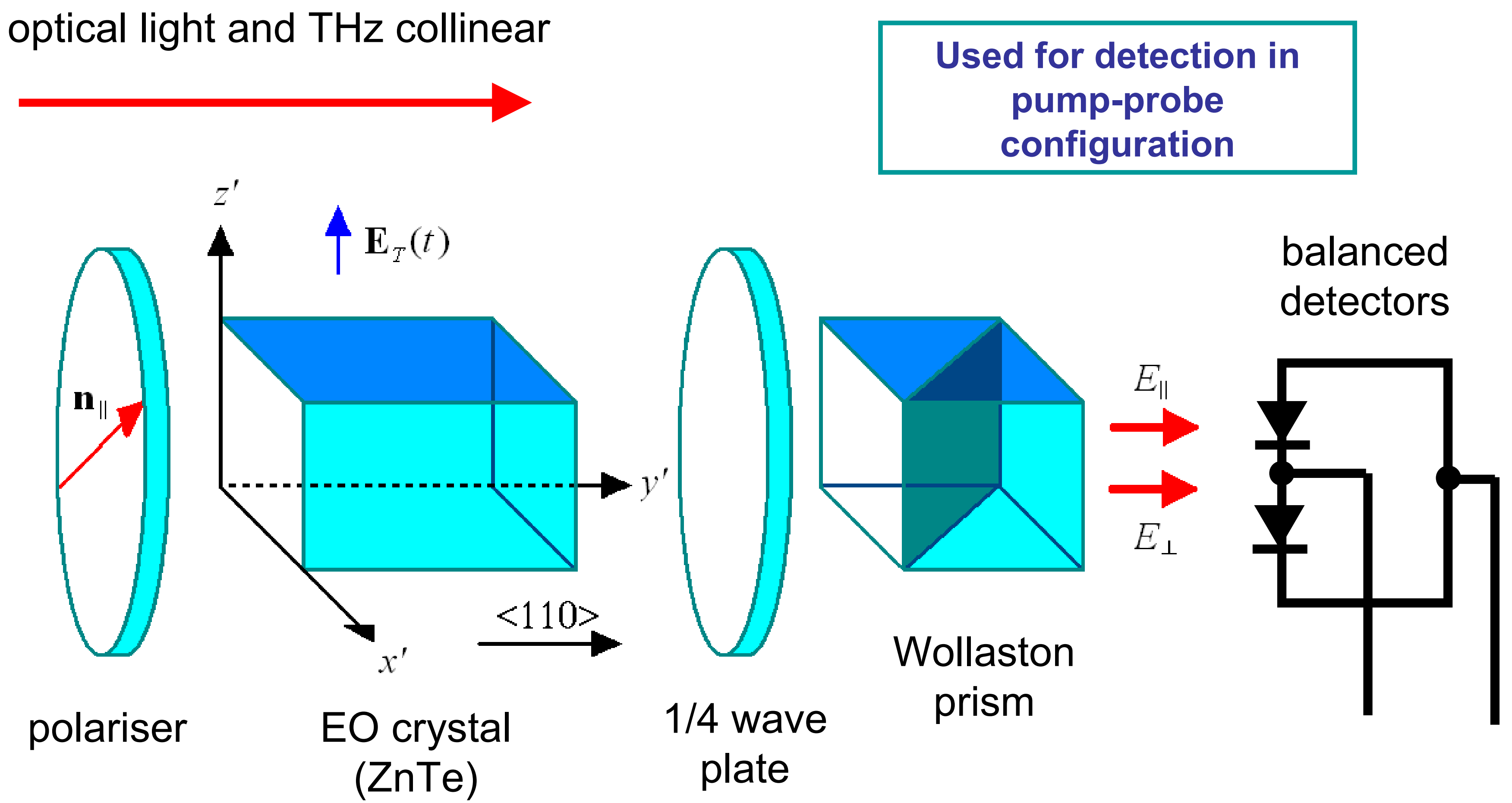
General schematic of pump-probe configuration



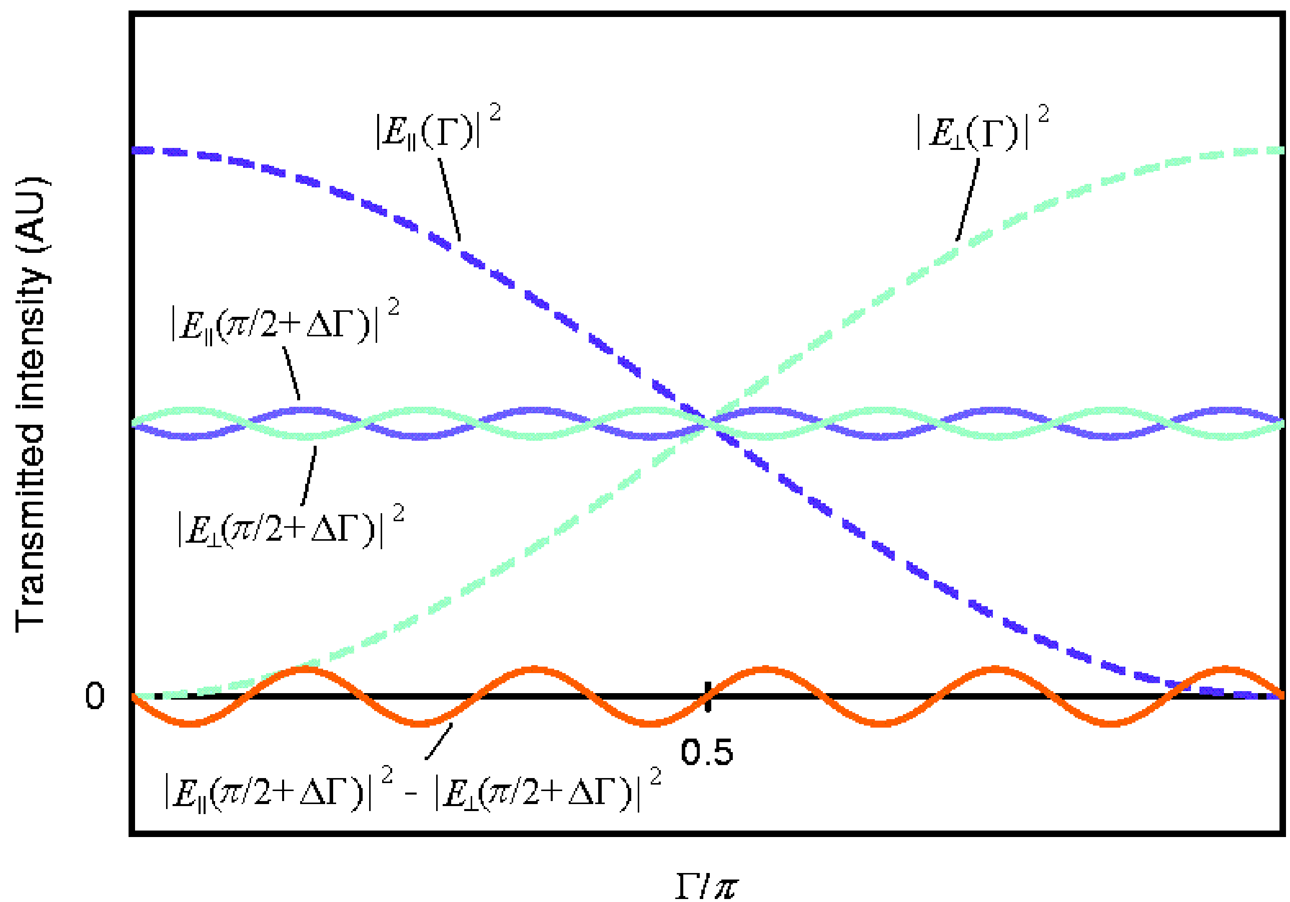
Electro-optic (EO) sampling

Principle based on electro-optic amplitude modulation

Used for detection in pump-probe configuration



Electro-optic (EO) sampling [2]



(amplitude and time period of modulation exaggerated for clarity)

PC antennas

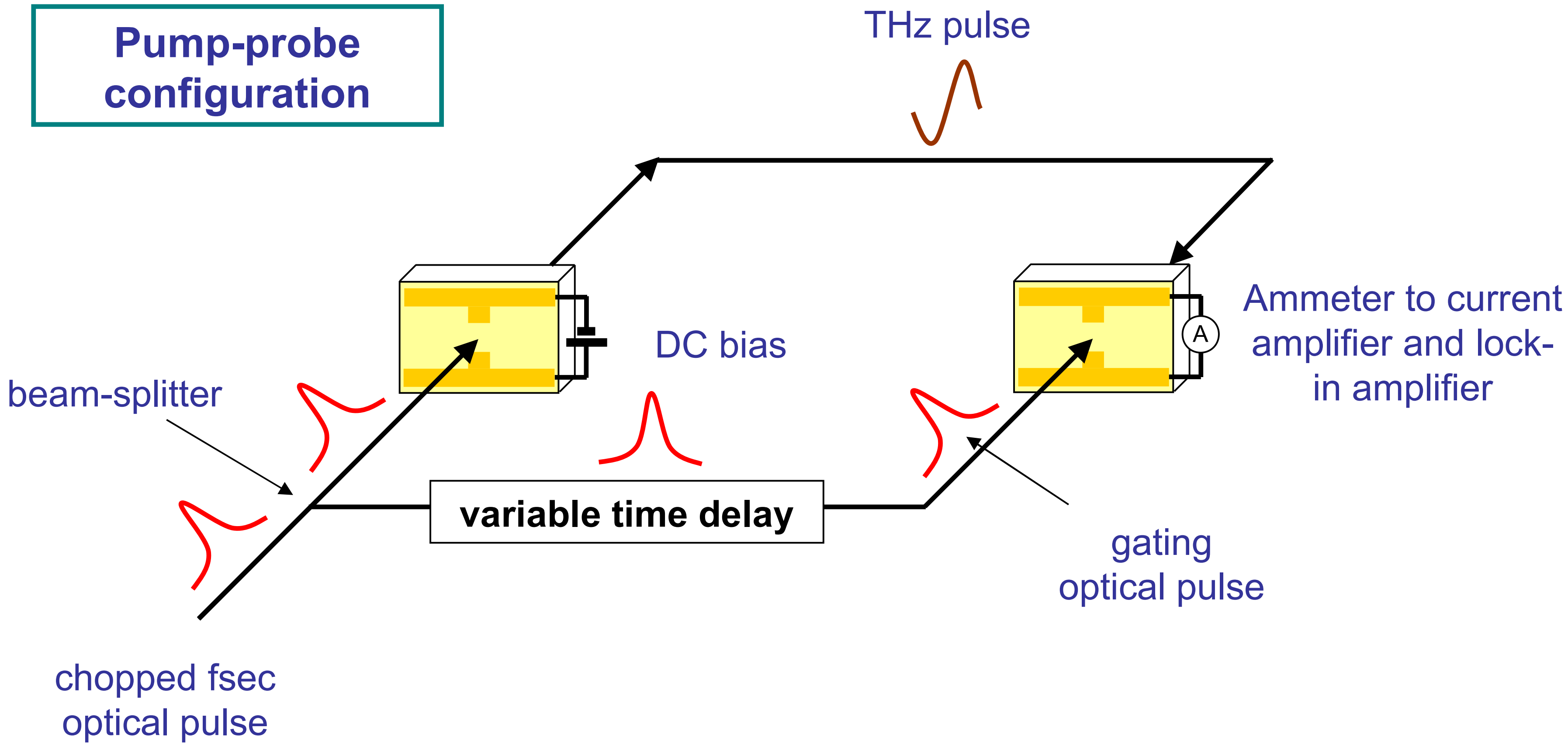


Diagram based on Saki and Tani, *Introduction to Terahertz Pulses* in *Terahertz Optoelectronics*, Sakai (Ed.), Springer 2005

PC antennas [2]

Sampling versus integrating detector – role of carrier lifetime

The current density is given by

$$j(t) = e\mu \int_{-\infty}^{\infty} E(t')n(t'-t)\, dt',$$

When the carrier lifetime << THz pulse width, $n(t'-t) \sim \delta(t'-t)$,

$E(t) \propto j(t)$ and the set up performs like a sampling detector.

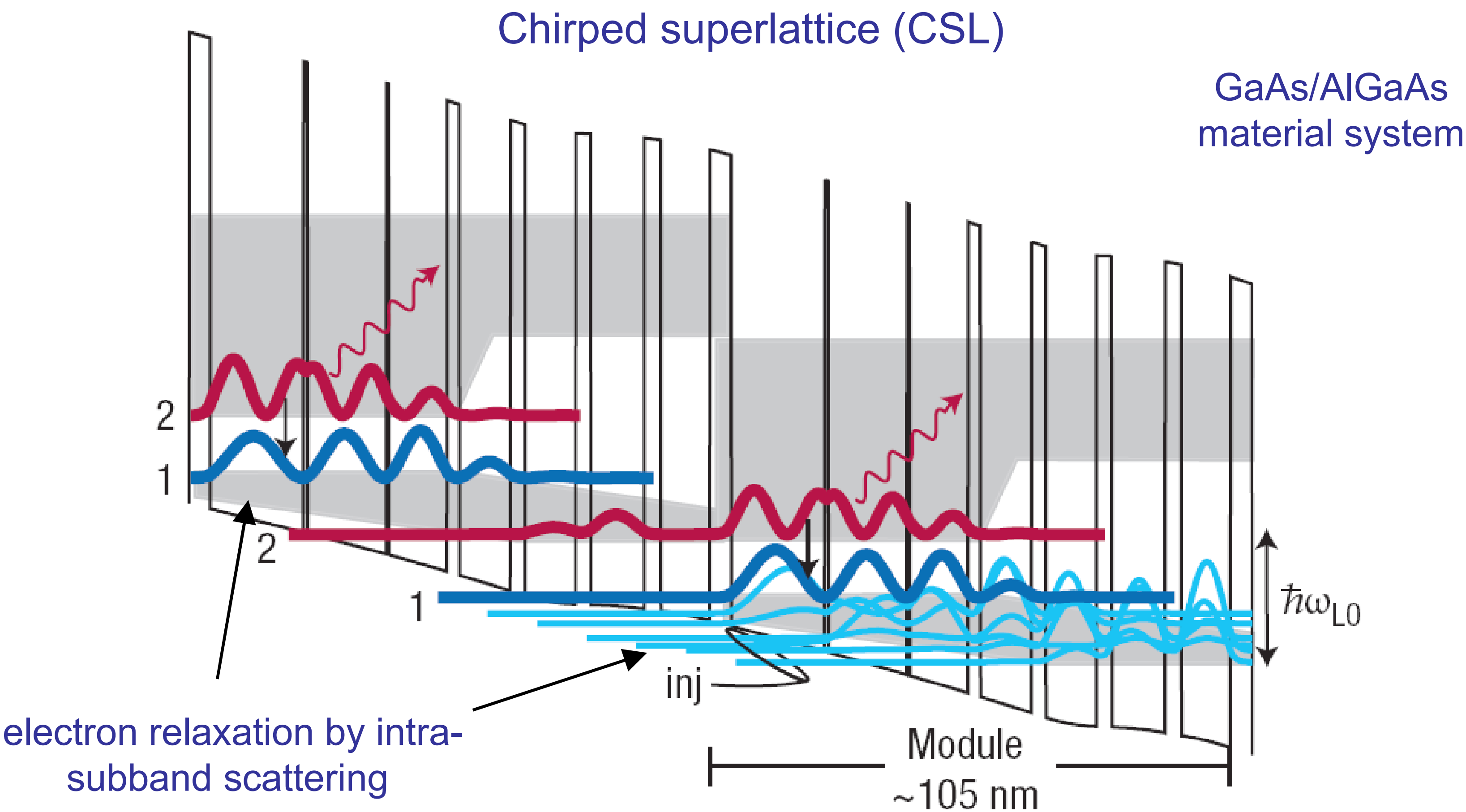
When the carrier lifetime >> THz pulse width, $n(t'-t) \sim \theta(t'-t)$ (a step function), the set-up performs like an integrating detector and

$$E(t) \propto \frac{dj(t)}{dt}.$$

Continuous wave THz sources

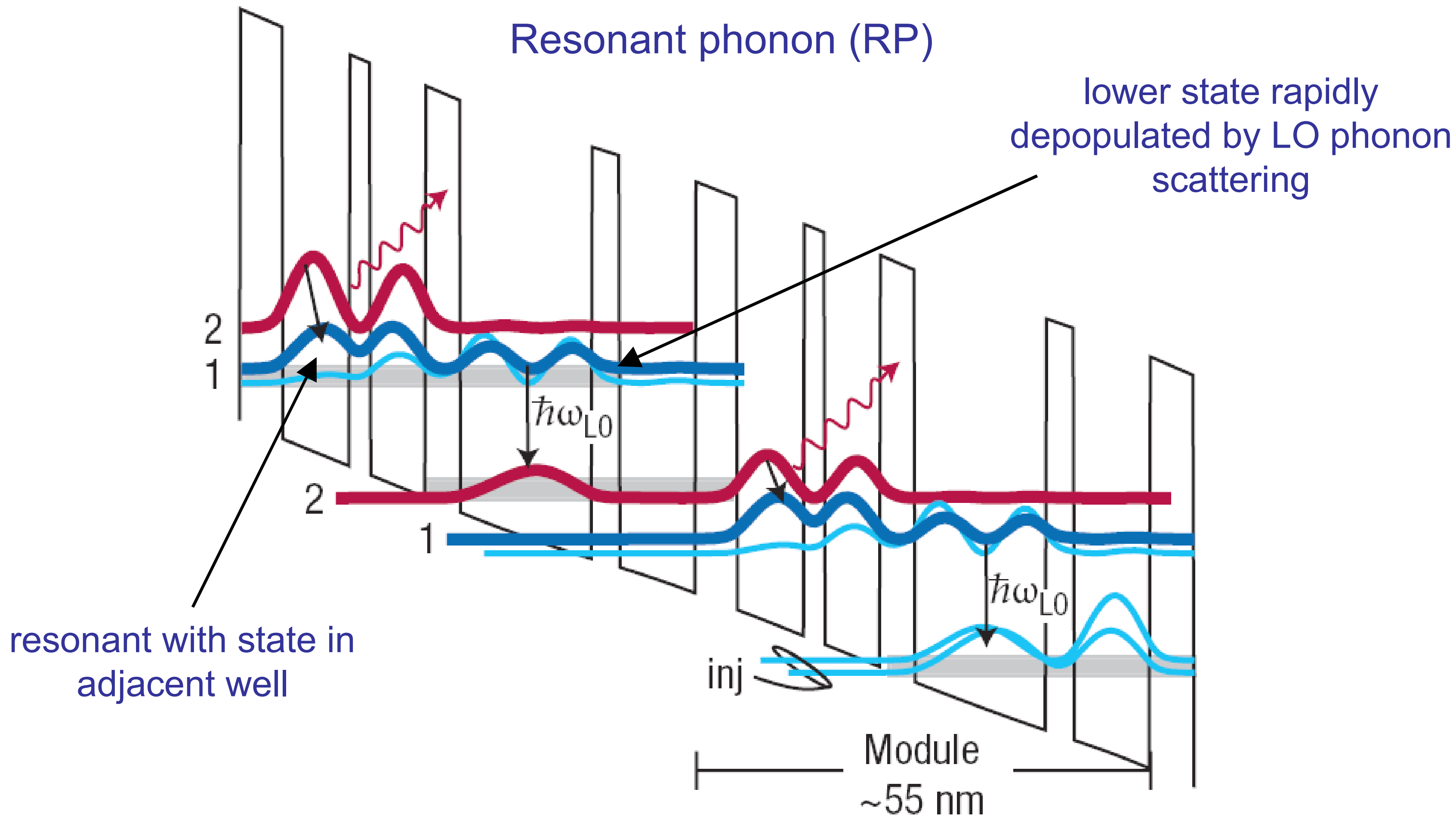
- Quantum cascade laser (also pulse source)
- Photomixing
- Schottky multipliers

Quantum cascade laser



From B.S. Williams, *Nature photonics*, **1**, 517 (2007)

Quantum cascade laser [2]



From B.S. Williams, *Nature photonics*, **1**, 517 (2007)

Quantum cascade laser [3]

Problems with wave-guiding

- Evanescent tail beyond active region $\propto \lambda$
- Free carrier absorption in cladding layers ~ λ^2

Semi-insulating surface plasmon

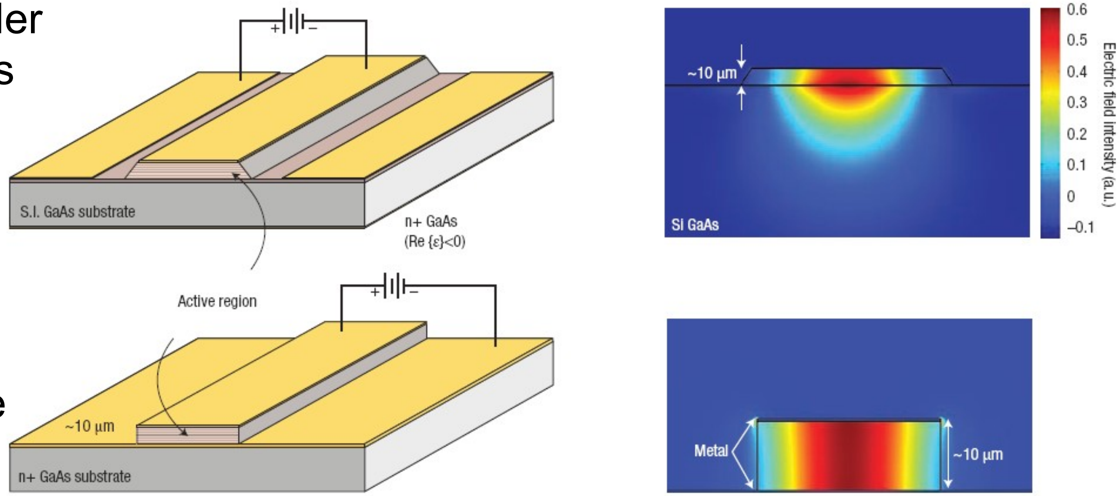
heavily doped layer grown under active region on top of SI GaAs

$\Gamma = 0.1 – 0.5$

Metal-metal waveguide

metal layer grown under active region

$\Gamma \approx 1$

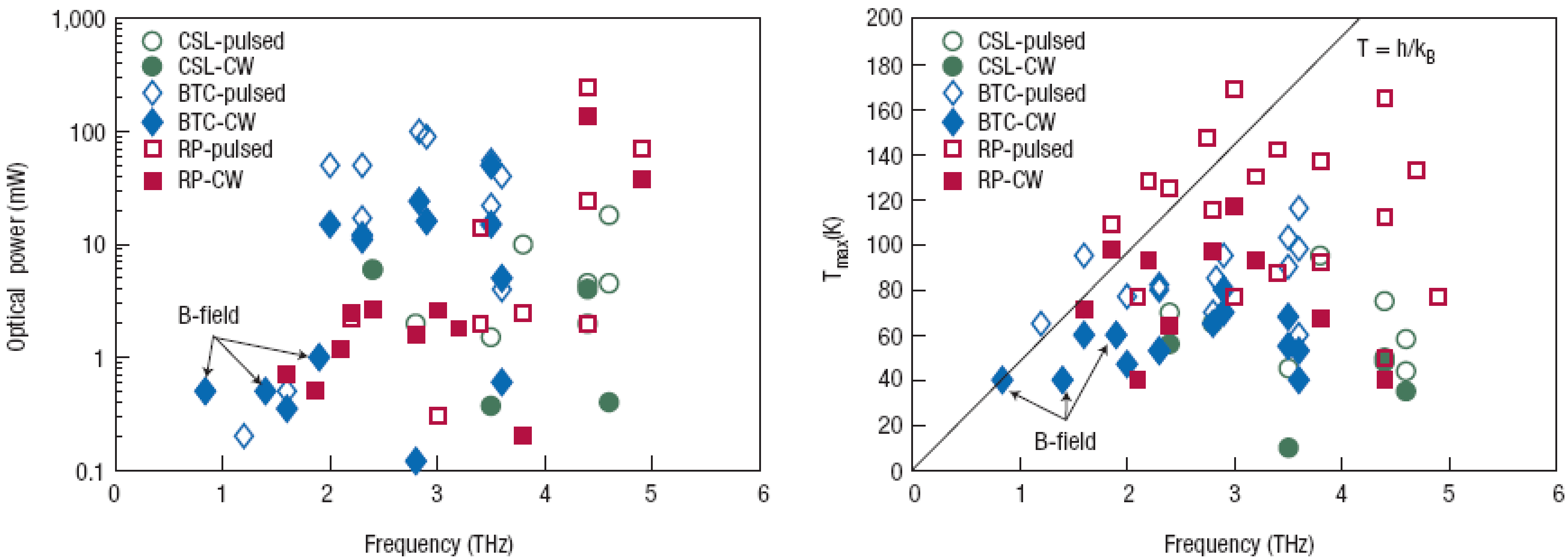


From B.S. Williams, *Nature photonics*, **1**, 517 (2007)

Quantum cascade laser [4]

Other QCL designs:

- Bound-to-continuum (BTC) – upper state replaced by bound 'defect' state
- Hybrid designs



High temperature degradation of population inversion due to thermal backfilling of lower state and thermally activated phonon scattering.

From B.S. Williams, *Nature photonics*, **1**, 517 (2007)

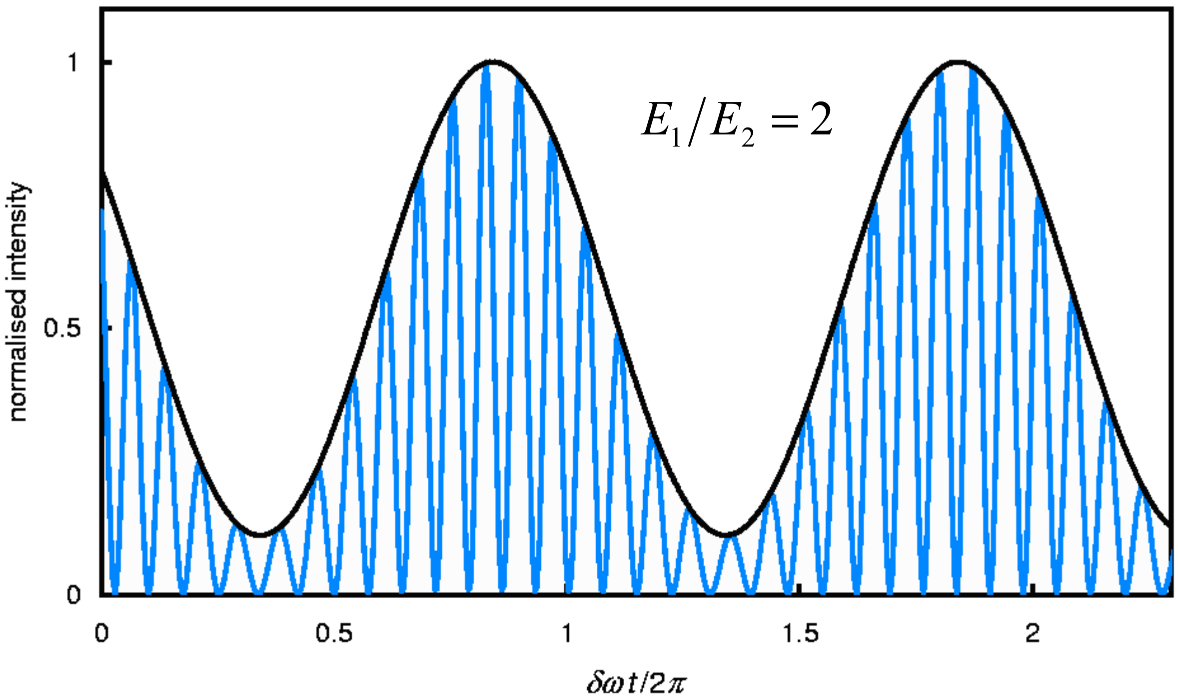
Photomixing

Mixing of two de-tuned optical sources

$$E = E_1 e^{i\omega_1 t} + E_2 e^{i\omega_2 t+\phi},$$

where

$$\omega_1 - \omega_2 = \delta\omega$$



In a square law detector, response is proportional to the intensity:

$$|E|^2 = \left(E_1^2 + E_2^2\right)\left(1 + \frac{2E_1E_2}{E_1^2+E_2^2}\cos(\delta\omega t - \phi)\right).$$

Uni-travelling carrier diode

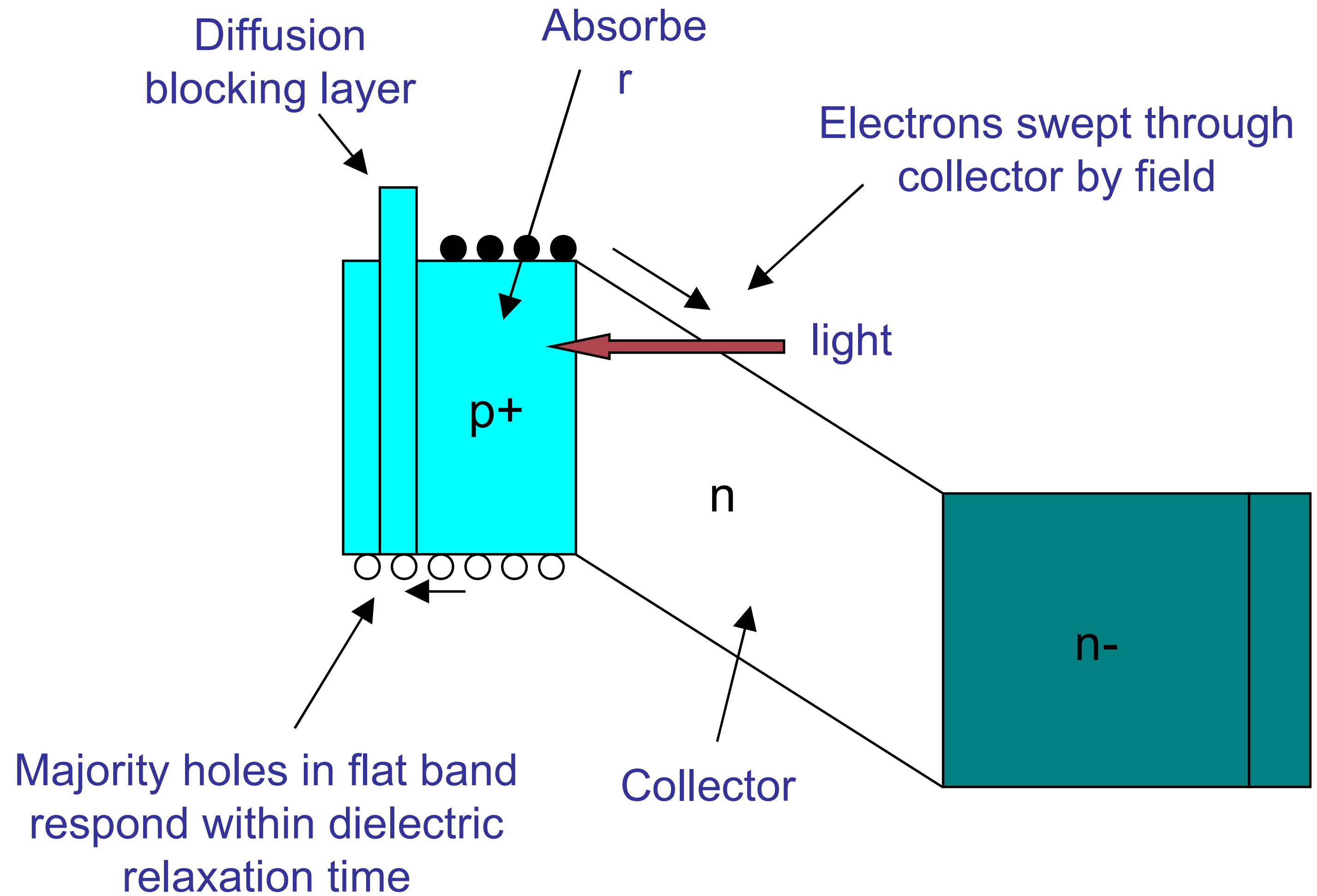
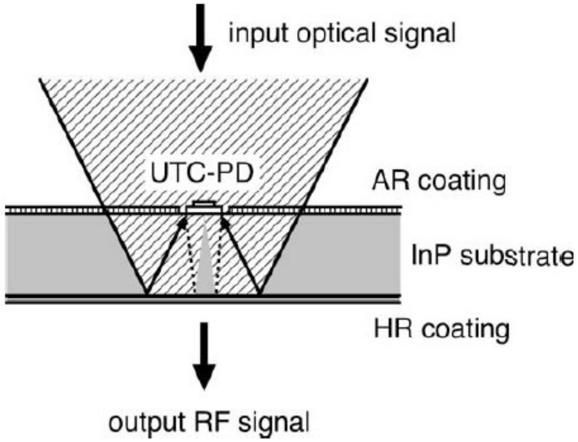
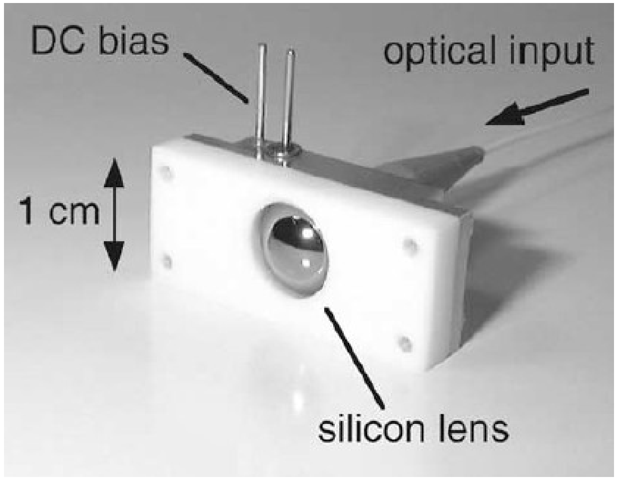
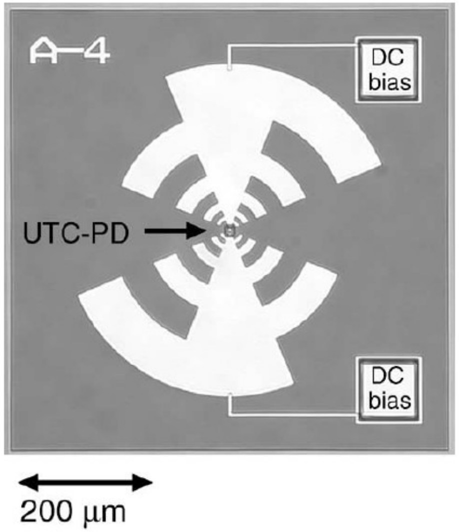


Diagram based on Matsuura and Ito, *Generation of CW Terahertz Radiation with Photomixing* in *Terahertz Optoelectronics*, Sakai (Ed.), Springer 2005

Uni-travelling carrier diode [2]







Work by NTT Electrical Communication Labs

Obtained 2.3 µW at 1.04 THz (2005)*

f_{3dB} (intrinsic) 170 GHz

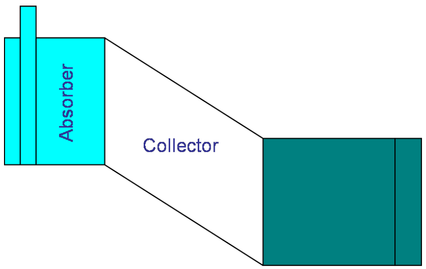
f_{3dB} (RC-limited) 210 GHz

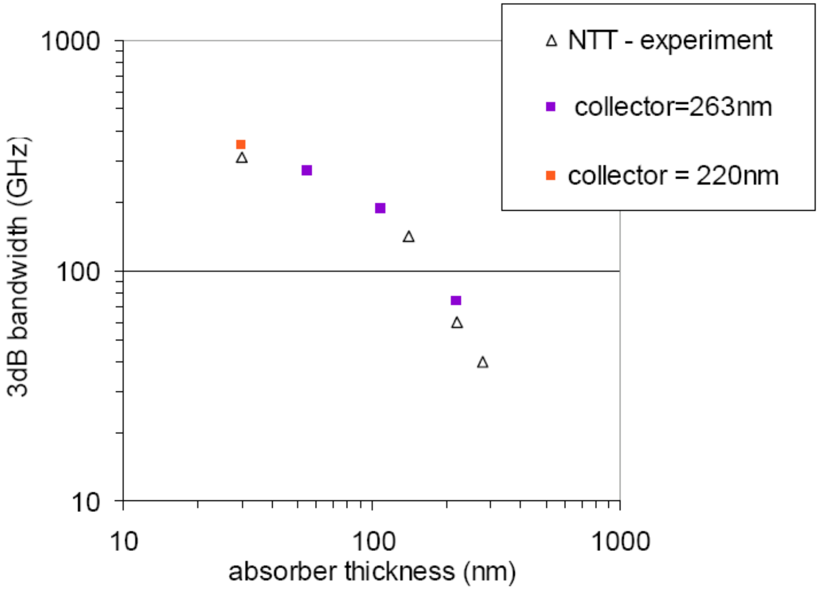
Since obtained 10.9 µW at 1.04 THz (2006)

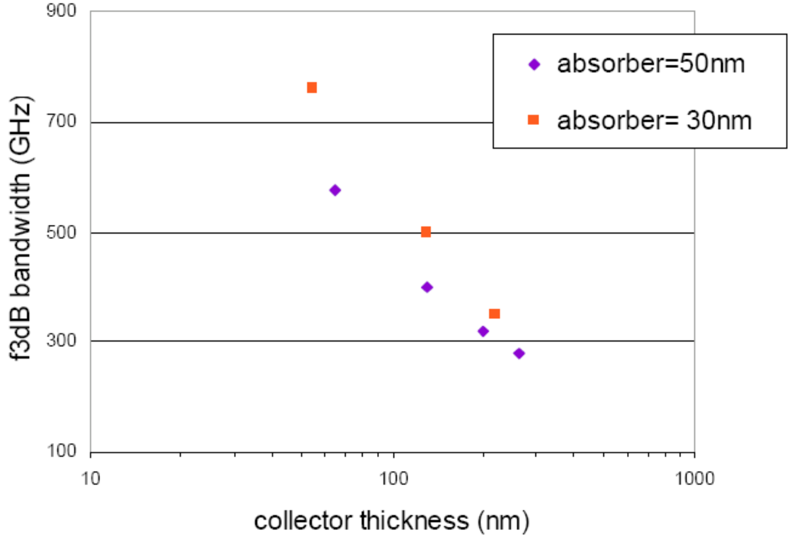
*H. Ito *et al*, J. Lightw. Technol., **23**, 4016 (2005).

Uni-travelling carrier diode [3]

Device modelling with Dessis by A. Dyson







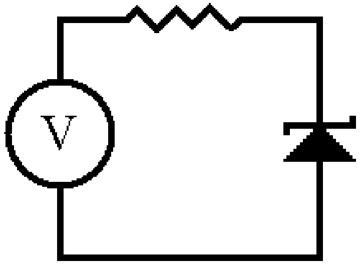
Model calculations* for UTC with reverse bias of 2V (RC constant of external circuit not accounted for).

*A. Dyson *et al*, *Proc. SPIE*, **6468**, 64681Q (2007).

Schottky multipliers

Basic principles

$$V(t) \sim V_0 \sin(\omega t)$$

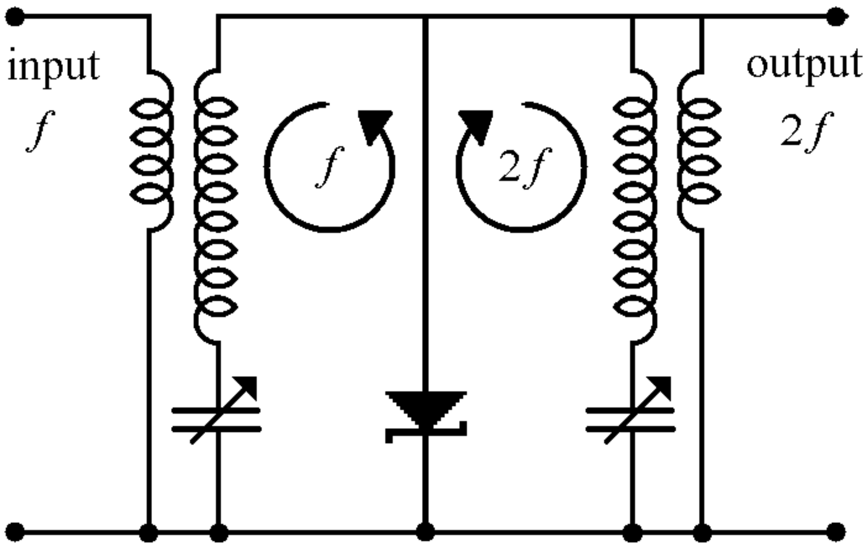


Due to non-linear dependence of junction capacitance on voltage

$$C(V) = \sum_{n=0} C_n \sin(n\omega t)$$

(Also non-linear resistance)

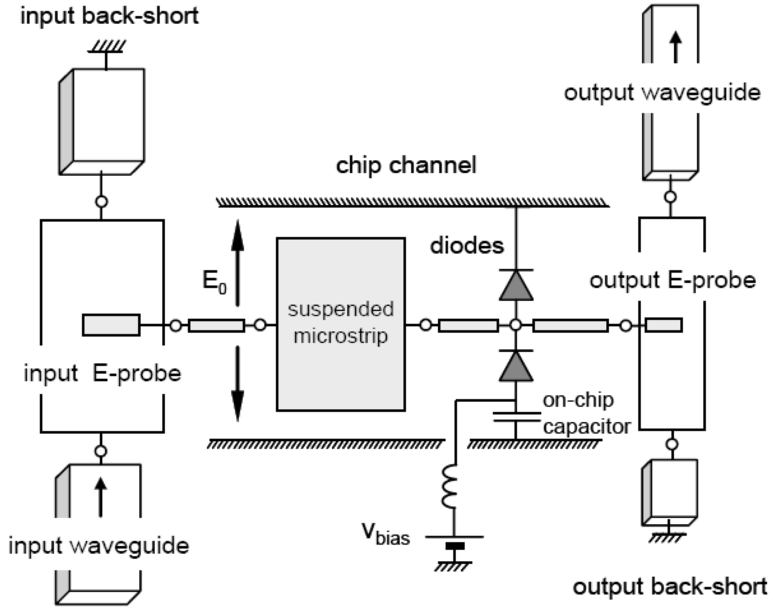
Example: schematic of frequency doubler

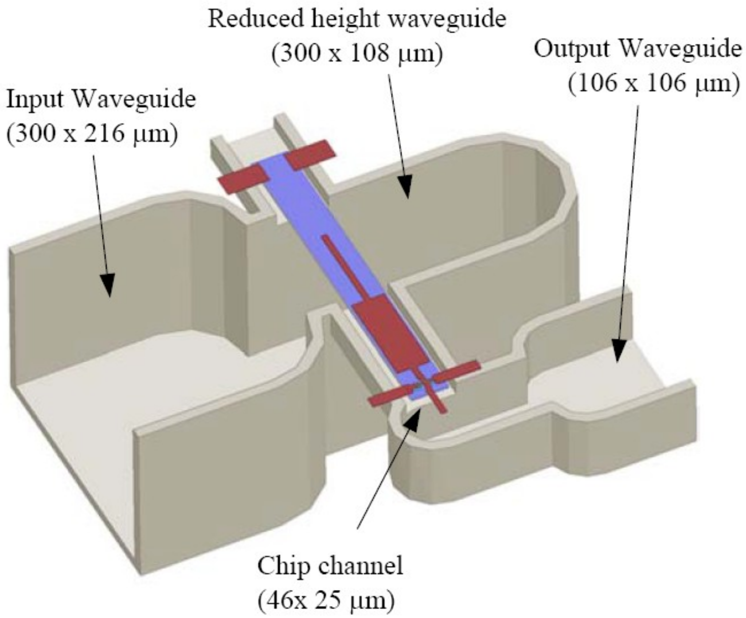


Resonant circuits coupled by Schottky varactor.

Schottky multipliers [2]

Work of Maestrini *et al* – Planar Schottky Diode Triplers



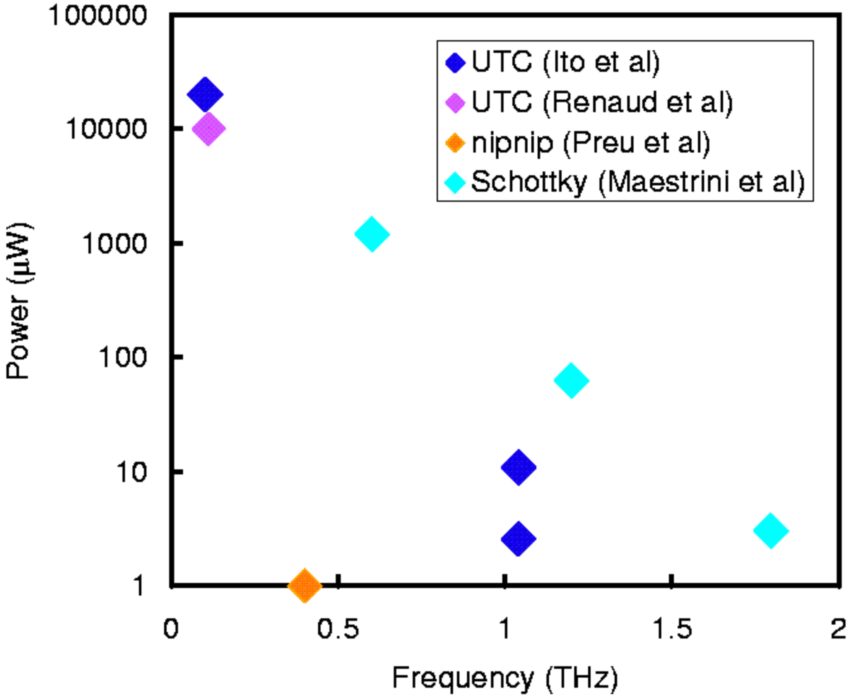


Frequency (THz)	Efficiency (%)	Output power
0.6	4 – 8	0.8 – 1.6 mW
1.2	1	25 – 100 µW
1.8		3 µW

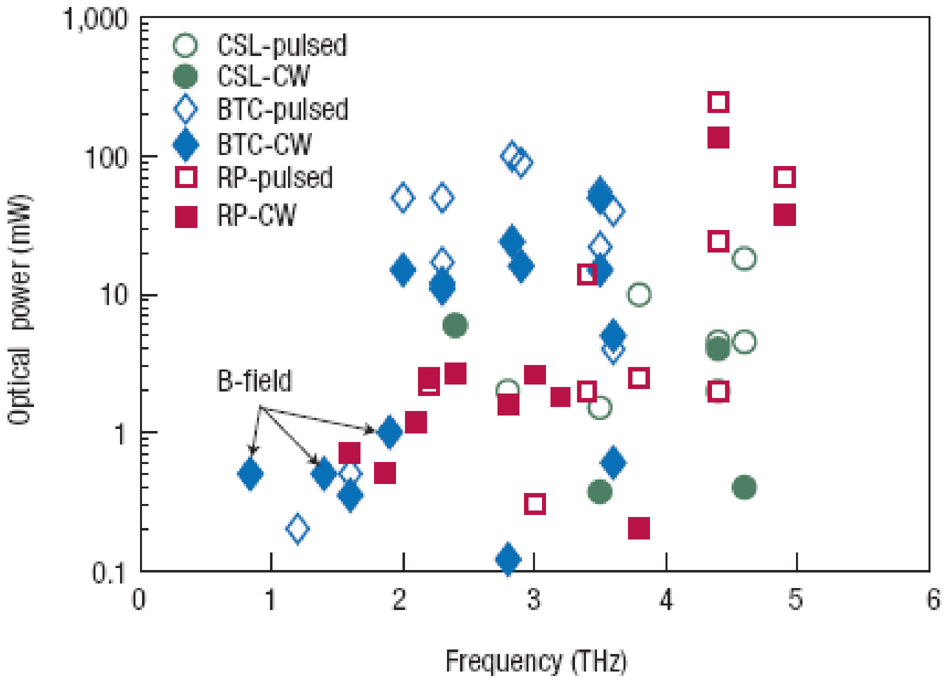
*A. Maestrini *et al*, *IEEE Mediterranean Microwave Symposium*, Marseille, France, June 2004

CW generation summary

Room temperature devices



Quantum cascade lasers



Detectors

Thermal detectors

- Hot electron bolometer
- Photo-acoustic detector
- Golay cell
- Pyroelectric detector

Semiconductor devices

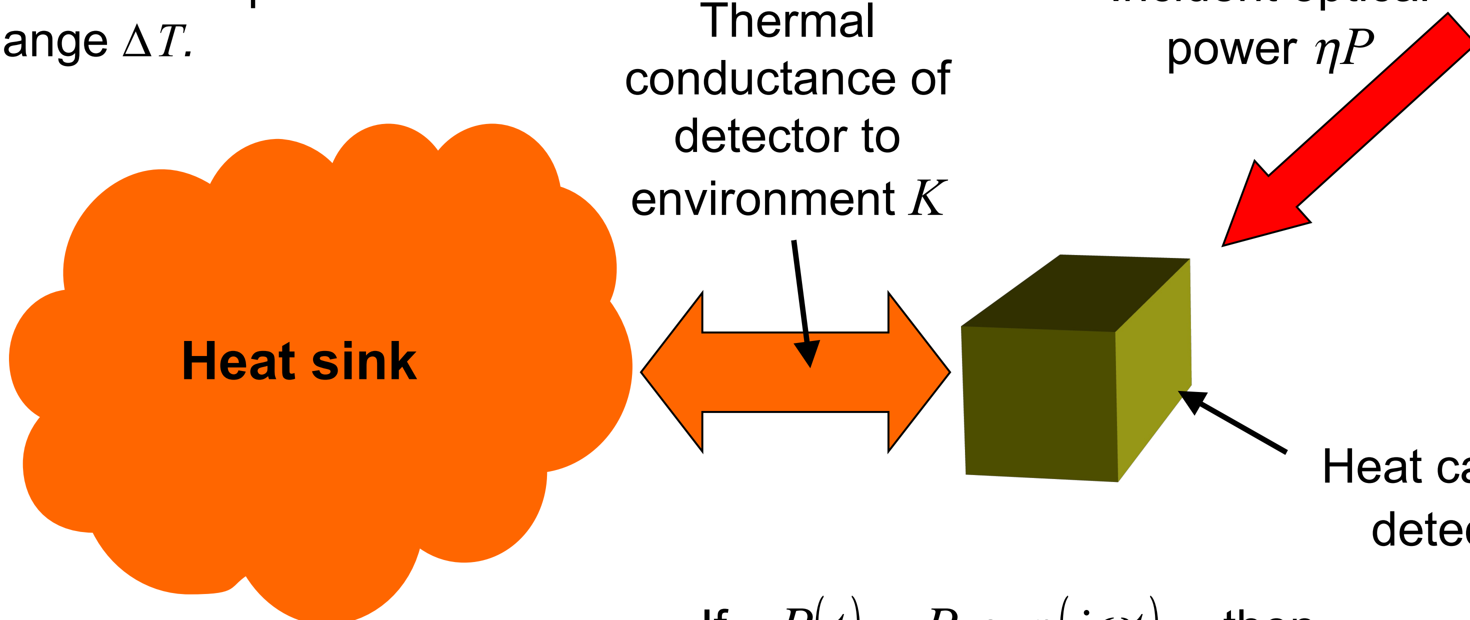
- Quantum well infrared detectors (QWIPS)
- Homojunction devices

Coherent detectors

- Electro-optic (EO) detection
- Heterodyne detection

Thermal detectors

Based on temperature change ΔT.



Thermal detector equation

$$\eta P(t) = C_H \frac{d\Delta T}{dt} + K\Delta T$$

If $P(t) = P_0 \exp(i\omega t)$, then

$$|\Delta T| = \frac{\eta P_0}{K} \frac{1}{\left(\omega^2 \tau_T^2 + 1\right)^{1/2}},$$ where

$\tau_T = C_H / K$ is the *thermal time constant* (typically ~ms)

Hot electron bolometer

For a bolometer $V = I\Delta R = IR\alpha\Delta T,$

where $\alpha = \frac{1}{R}\frac{dR}{dT}$ is the *temperature coefficient.*

For a ***hot electron bolometer***, increase in resistance is due to an increase in ***electron temperature*** due to free carrier absorption.

Hence a hot electron bolometer may be considered as either

an electronic bolometer *or* a free carrier photoconductor

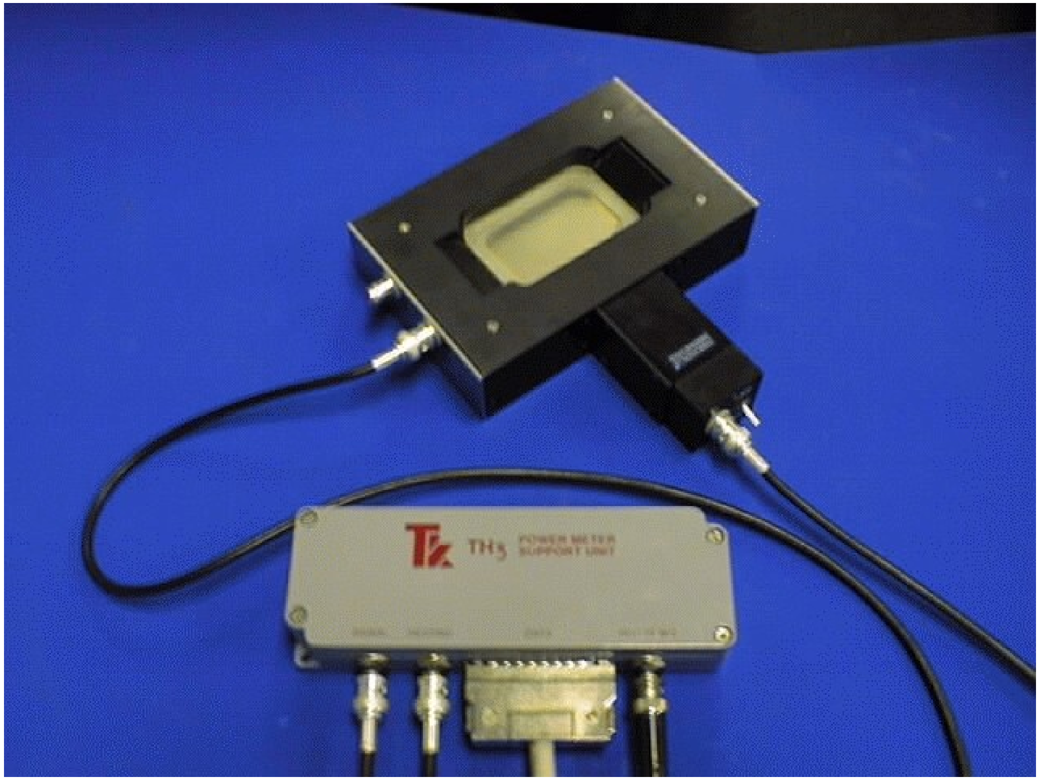
Hot electron bolometer [2]

- Resistance changes with increased electron temperature large, so high sensitivity
- Time constant related to electron relaxation time, so fast for thermal detector

But

- Requires cooling to liquid helium temperatures

Photo-acoustic detector



Thomas Keating (TK) meter.

Closed air-filled cell with thin metal between windows

Known fraction of radiation absorbed by metal film, heating air

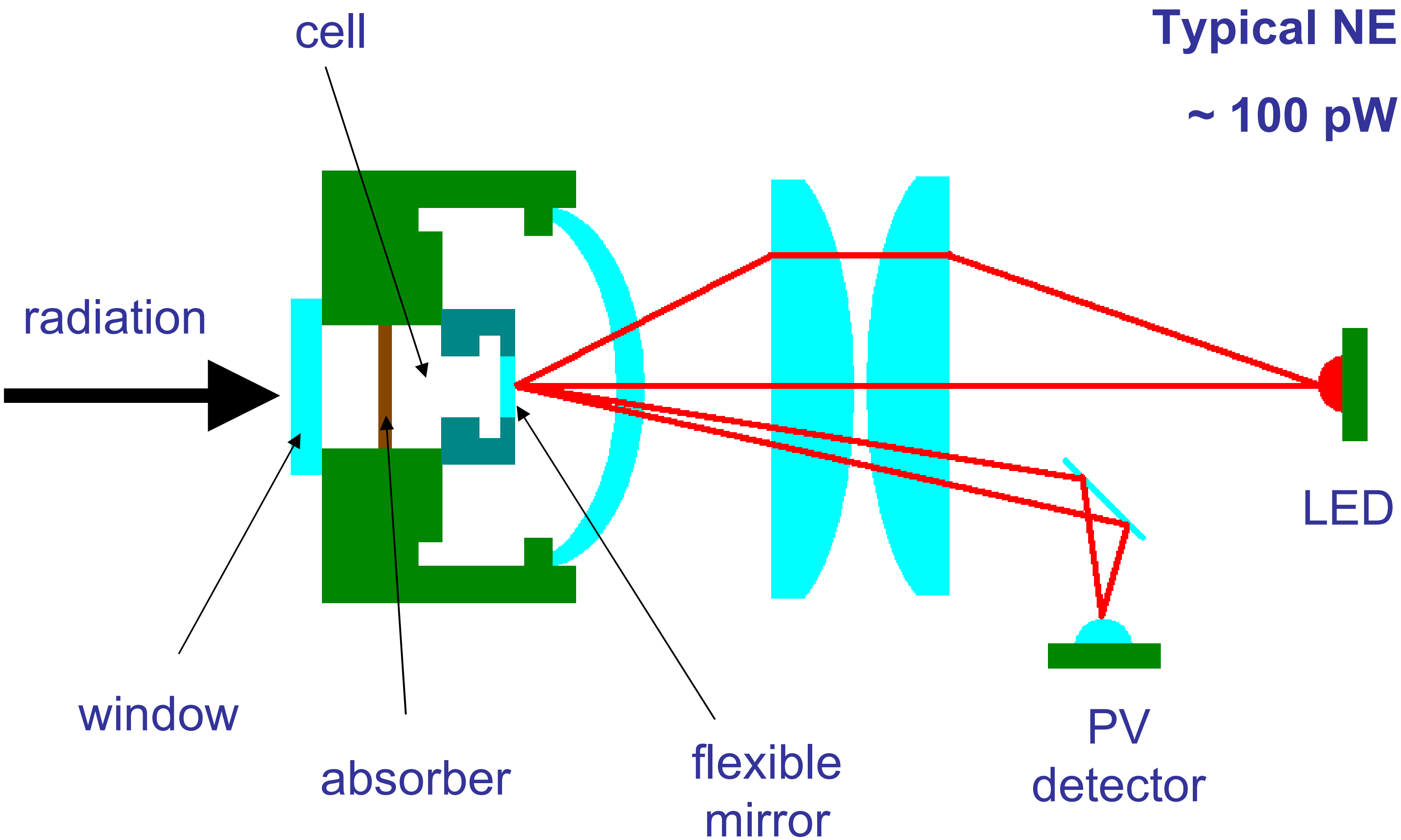
Pressure changes measured by pressure transducer.

Typical NEP (RT)

~ 5 μW Hz$^{-1/2}$

(very noisy!)

Golay cell



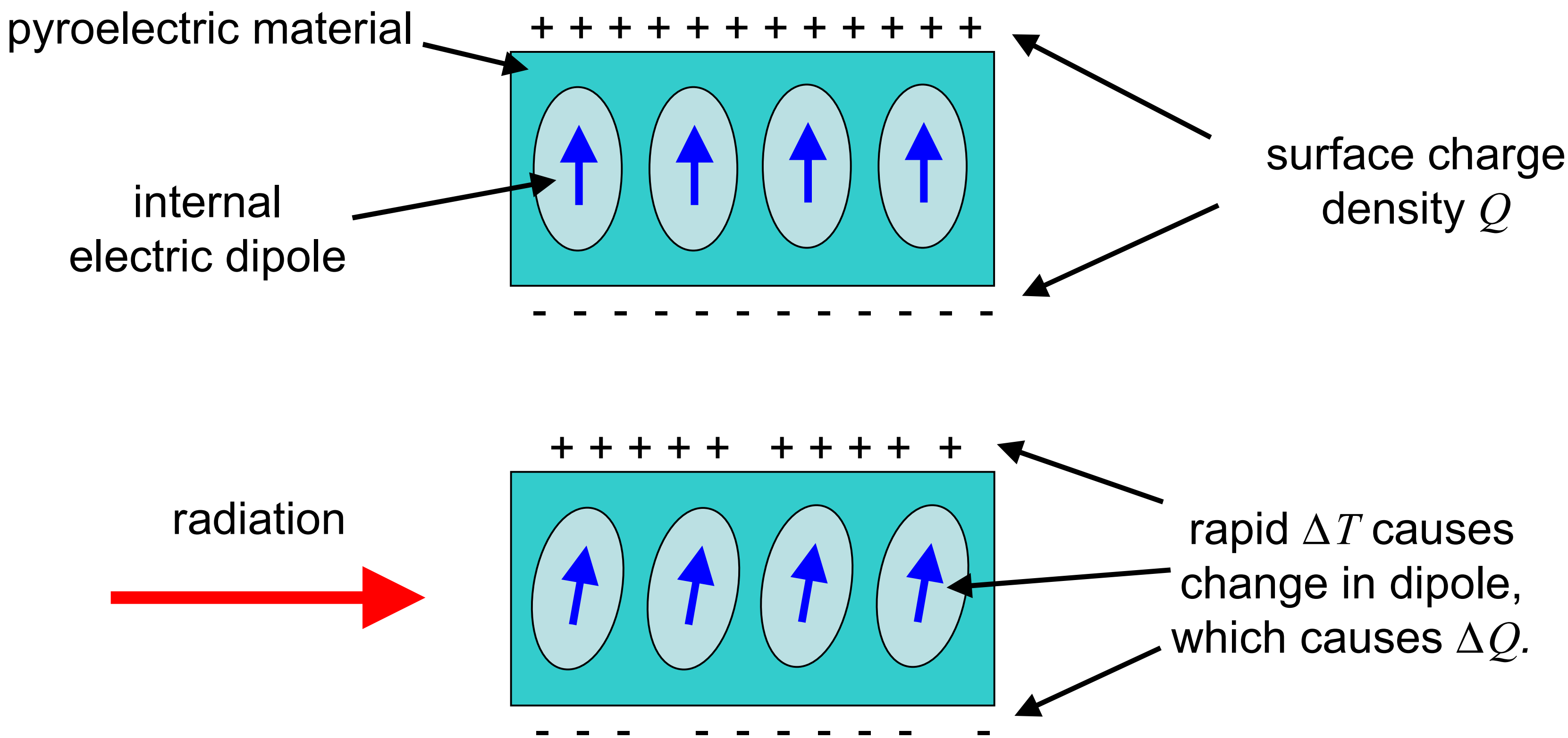
Typical NEP (RT)

~ 100 pW Hz$^{-1/2}$

Golay cell - disadvantages

- Fragile
- Very sensitive to vibration
- Slow response time (typical rise time 25 ms)
- Rare as hen's teeth!

Pyroelectric detector



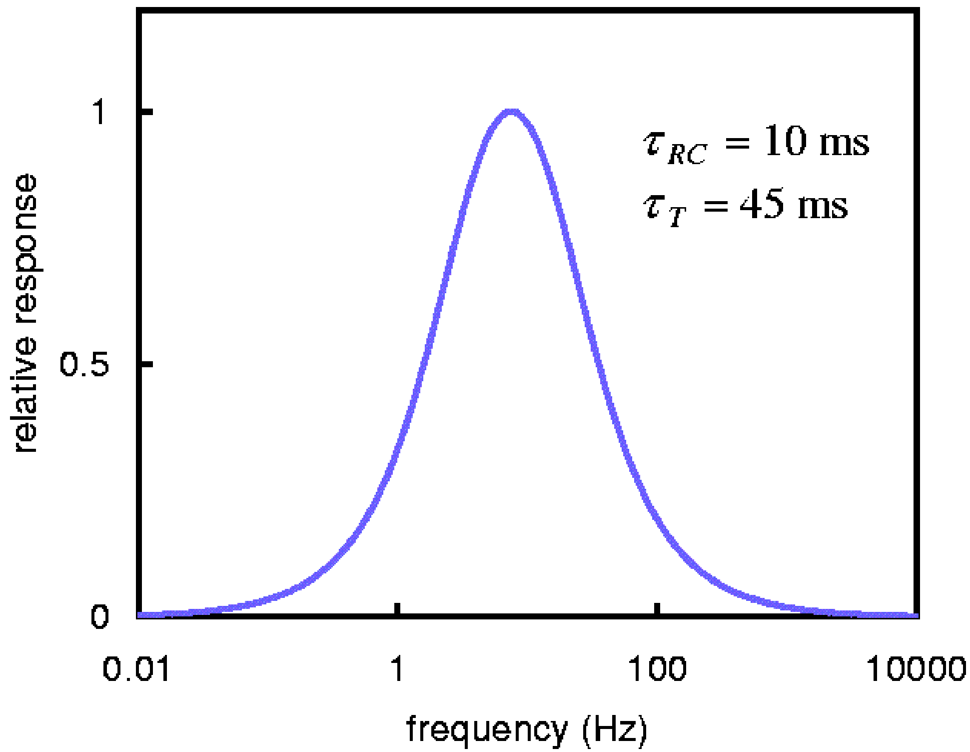
current density proportional to ***rate of change*** *of* ΔT.

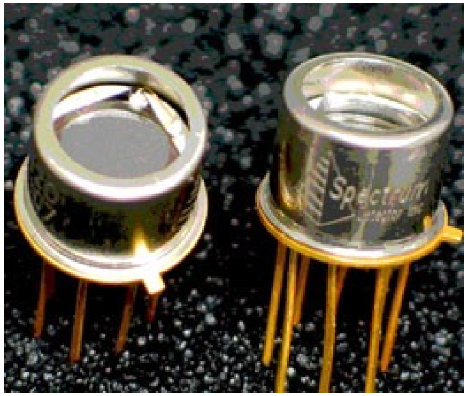
$$j(t) = \frac{d\Delta Q}{dt} = \Gamma(T)\frac{d\Delta T}{dt},$$

$\Gamma(T)$ is the *pyroelectric coefficient*

Pyroelectric detector

Voltage frequency response (very narrow bandwidth!)





Detectors are essentially big capacitors, so electronic *RC* time constant is long.

Typical NEP (RT)

~ 400 pW Hz$^{1/2}$

NEP comparable to Golay. However, PE detectors robust, cheap (and available!)

Thermal detector summary

Type	Typical NEP ($WHz^{-1/2}$)	Bandwidth (Hz)	Operating temperature (K)
Hot electron bolometer	10^{-13}*	~10^6	< 4.2
Photo-acoustic (TK)	5×10^{-3}	~20	300
Golay cell	10^{-10}	~10	300
Pyroelectric	4×10^{-10}	30 – 40	300

* Based on commercially available devices canvassed – figures of 10^{-17} $WHz^{-1/2}$ reported in literature.

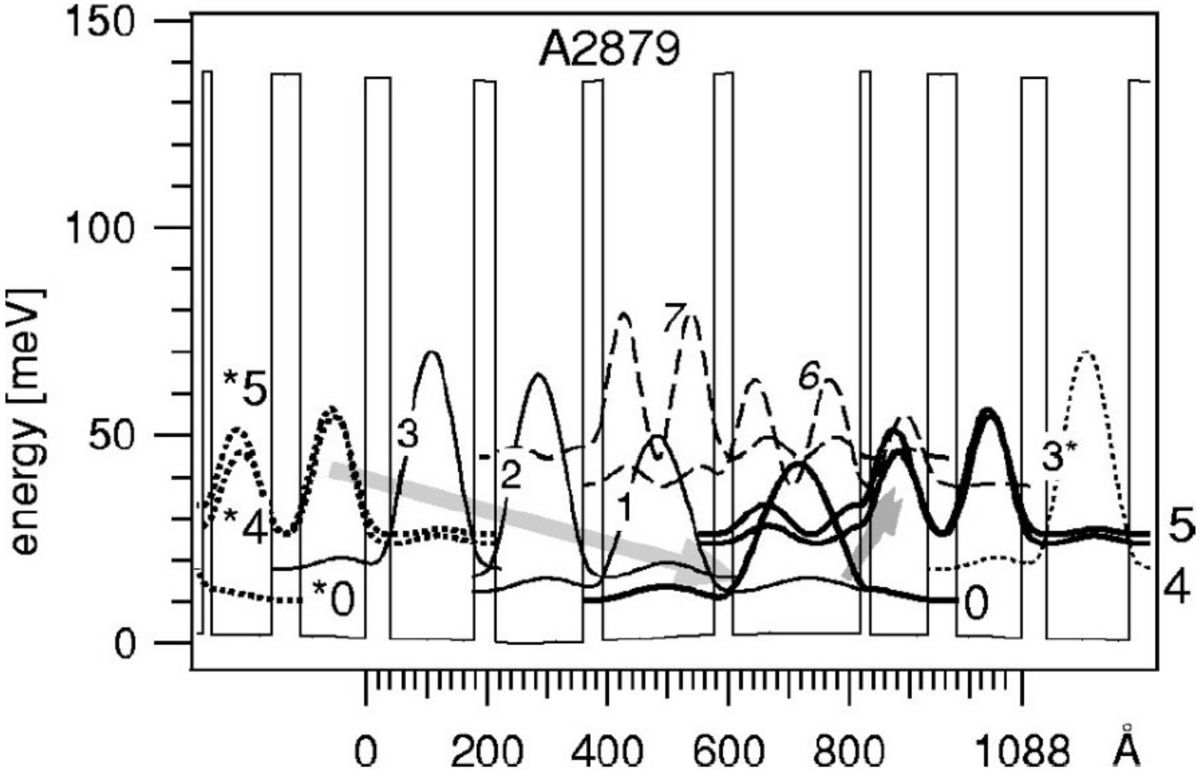
Semiconductor devices

- Quantum well infrared detectors (QWIPS)
- Homojunction devices

Quantum well infrared photodetector (QWIP)

QCL-like structure

Operating T = 10 – 50 K



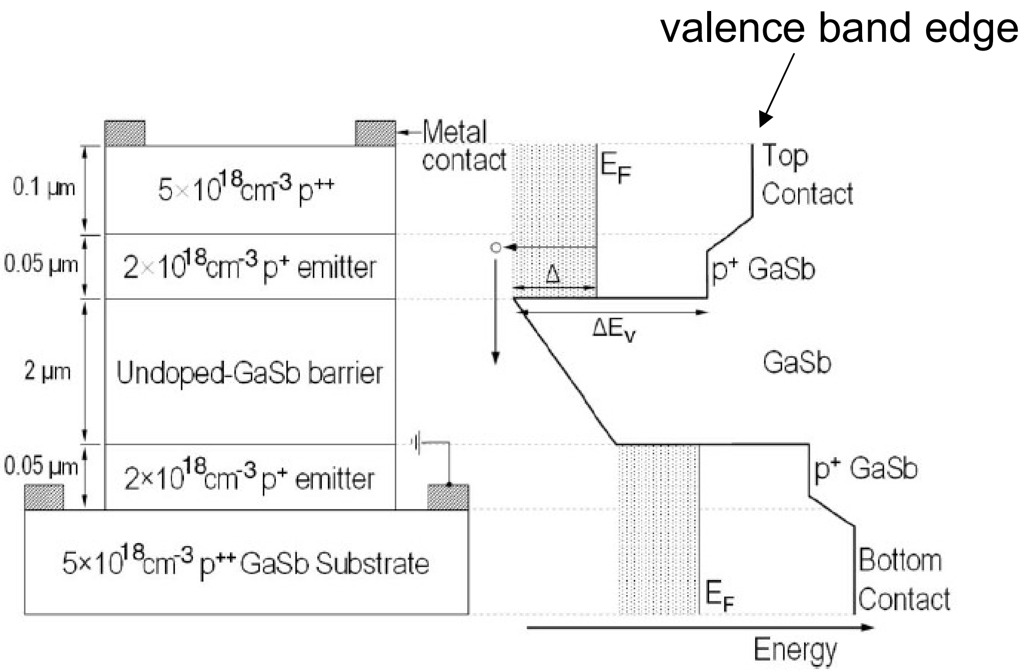
Photon transitions from 0 to 4 and 5

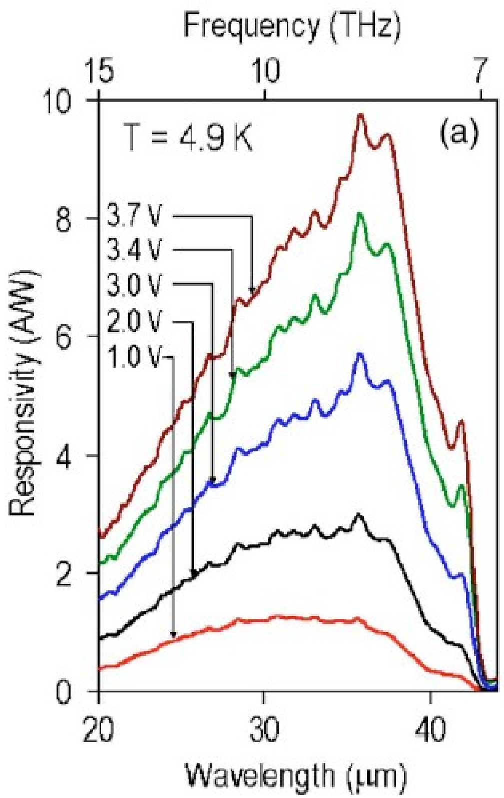
Relaxation via states 3, 2 and 1 to 0 state in next module

* M. Graf *et al*, *Appl. Phys. Lett.*, **84**, 475 (2004)

GaSb homojunction

THz detection by free carrier absorption





Note liquid He temperature

* P. V. V. Jayaweera *et al*, *Appl. Phys. Lett.*, **90**, 111109 (2007)

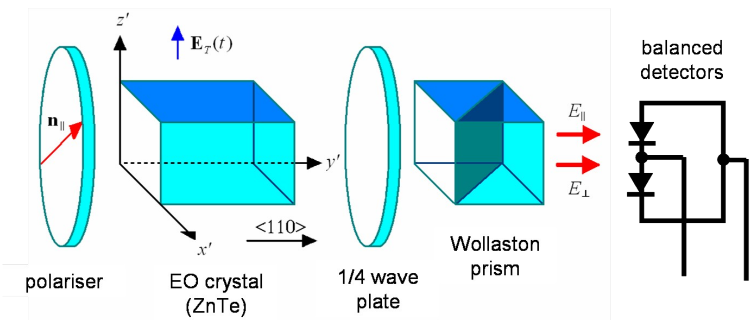
Coherent CW detectors

- Heterodyne detection using hot-electron bolometers with QCL as local oscillator
- Homodyne detection using the EO detection with photomixing

Electro-optic detection

Reminder

optical light and THz collinear



When used in homodyne arrangement below*

$$|E_\perp|^2 - |E_{||}|^2 = R_{EO} E_1^0 E_2^0 E_T^0 \cos\left(\frac{\Delta d \Omega_T}{c} + \theta_0\right),$$

where Δd is optical path difference

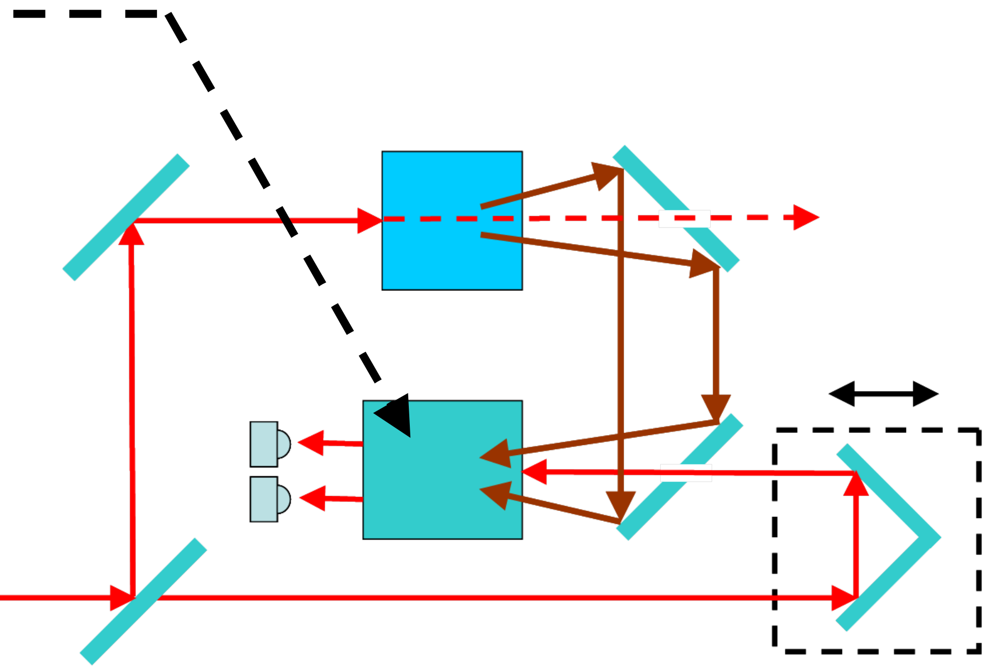


photo-mixed light in

General expression for above

$$|E_\perp|^2 - |E_{||}|^2 = R_{EO} E_1^0 E_2^0 E_T^0 \times$$

$$\times \cos\left(\Delta k_{12} L + (\Omega_T - \Delta\omega)t + \Delta\theta_{12}(t) - \theta_T(t)\right),$$

where

$$R_{EO} = \frac{(\omega_1 + \omega_2) r_{41} n_0^3 L}{4c}.$$

* A. Nahata, J.T. Yardley and T.F. Heinz, *Appl. Phys. Lett.*, **75**, 2524 (1999)

Summary - sources

Terahertz pulses can be produced by

- Non-linear rectification
- Surface surge currents (surface depletion field and photo-Dember effects)
- Plasmon, phonon and coupled mode oscillations
- Austin or PC switching with micro-fabricated antennas
- Quantum cascade lasers (require cooling)

Terahertz CW can be produced by

- Photomixing (PC switching or using UTC)
- Schottky multiplier chains
- Quantum cascade lasers (require cooling)

Summary - detectors

Terahertz pulses can be detected by

- Electro-optic effect (in pump-probe configuration)
- PC antennas (in pump-probe configuration)
- Thermal detectors (usually hot electron bolometer)

Terahertz CW can be detected by

- Thermal detectors (HEBs need cooling)
- Semiconductor devices (need cooling)
- Electro-optic effect
- Heterodyning using QCL as a local oscillator (needs cooling)

Cheap, portable room temperature devices

Best performance technologies often need cooling and are not easy to implement in portable devices.

Possible candidates for compact room temperature sources:

- UTC integrated with lasers
- Schottky multiplier chains

Possible candidates for robust room temperature detectors:

- Photo-acoustic detectors (although very noisy)
- Pyroelectric detectors (very slow)
- Heterodyne detectors using Schottky multiplier chains
- Electro-optic effect?