A tutorial on meta-materials and THz technology

Thomas Feurer

`thomas.feurer@iap.unibe.ch`

Institute of Applied Physics

Sidlerstr. 5, 3012 Bern

Switzerland

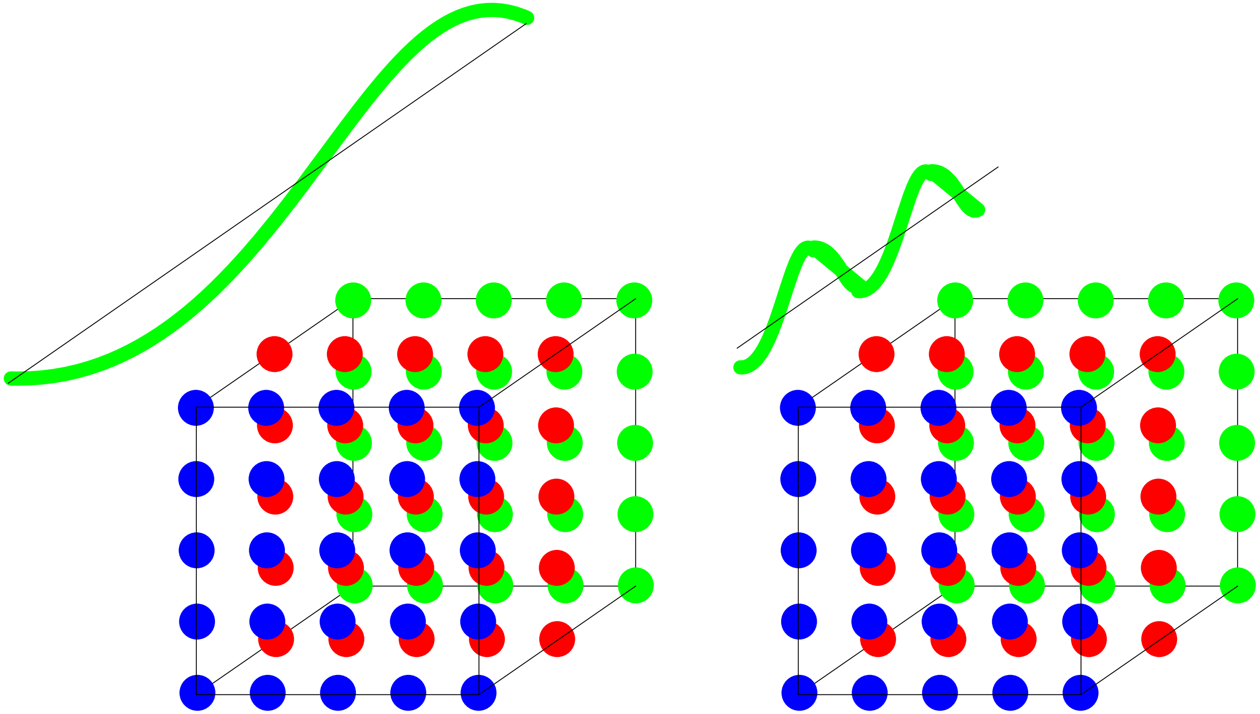
Outline

- Meta-materials
- Super-lenses
- Photonic crystals and fibers
- Extreme guiding
- THz technology
- THz applications
- Integrated THz signal processing
- Summary

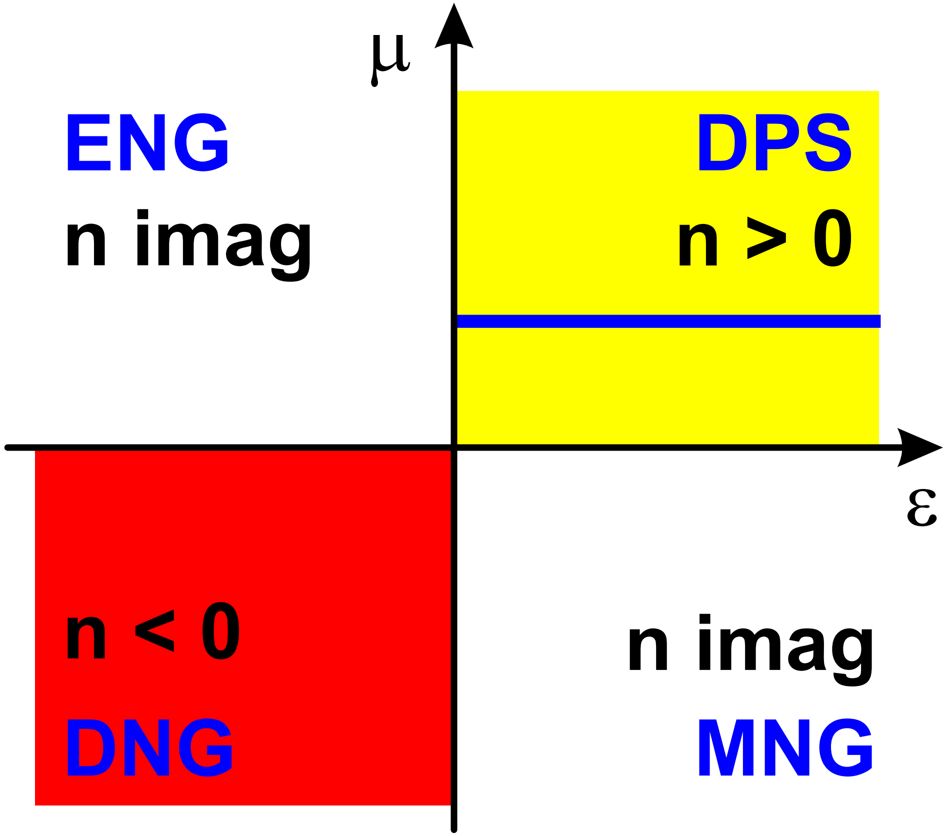
I. Meta-materials and super-lenses

Meta-materials

- Material properties are determined by the properties of the subunits plus their spatial distribution.
- For $a \ll \lambda$ effective medium theory.
- For $a \approx \lambda$ photonic effects.



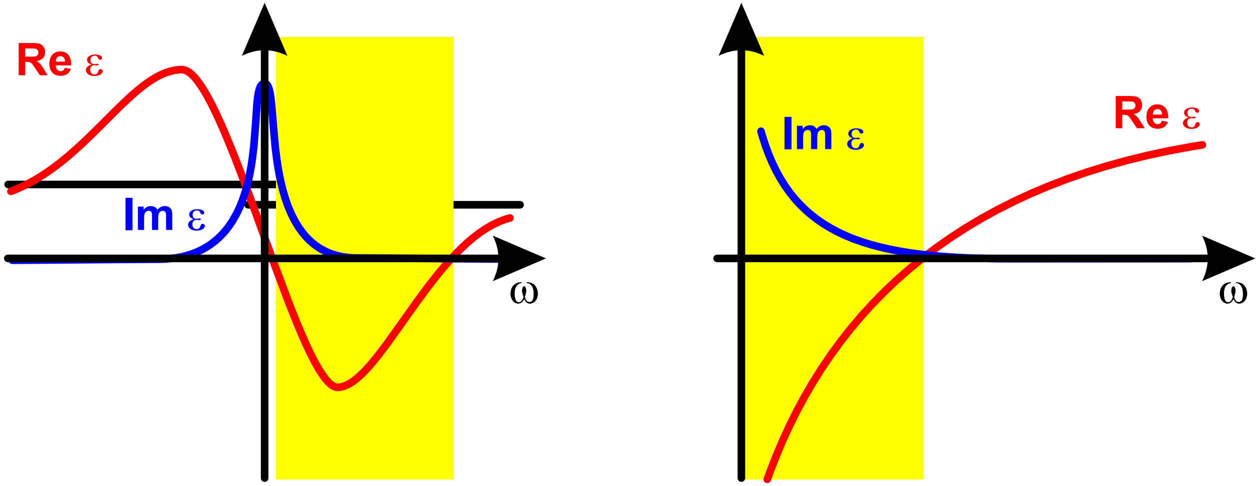
Meta-materials (cont.)



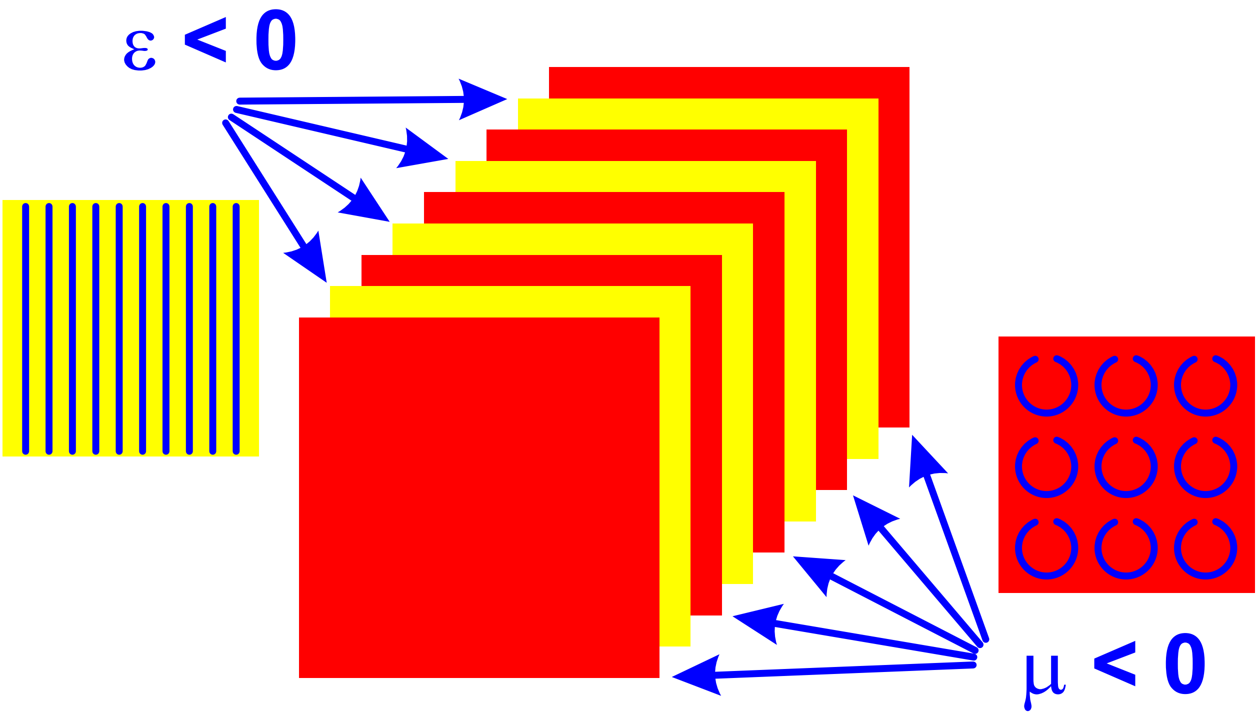
$$\sqrt{\epsilon\mu} = \sqrt{(-|\epsilon|)(-|\mu|)} = \sqrt{e^{i\pi}|\epsilon|e^{i\pi}|\mu|} = e^{i\pi}\ \sqrt{|\epsilon\mu|} = -n$$

Meta-materials (cont.)

- electronic/magnetic resonance
- electron/spin plasma
- scattering resonance (i.e. Mie)
- . . .

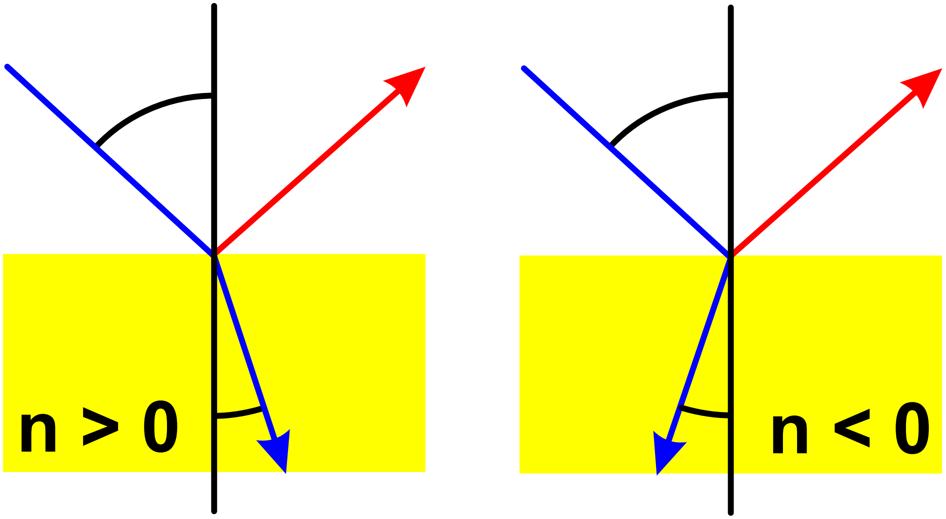


Meta-materials (cont.)



Distance between the single slabs a is much less than a wavelength λ. Typically $a \approx \lambda/10$, ideally $a \approx \lambda/1000$

Negative index materials: NIM



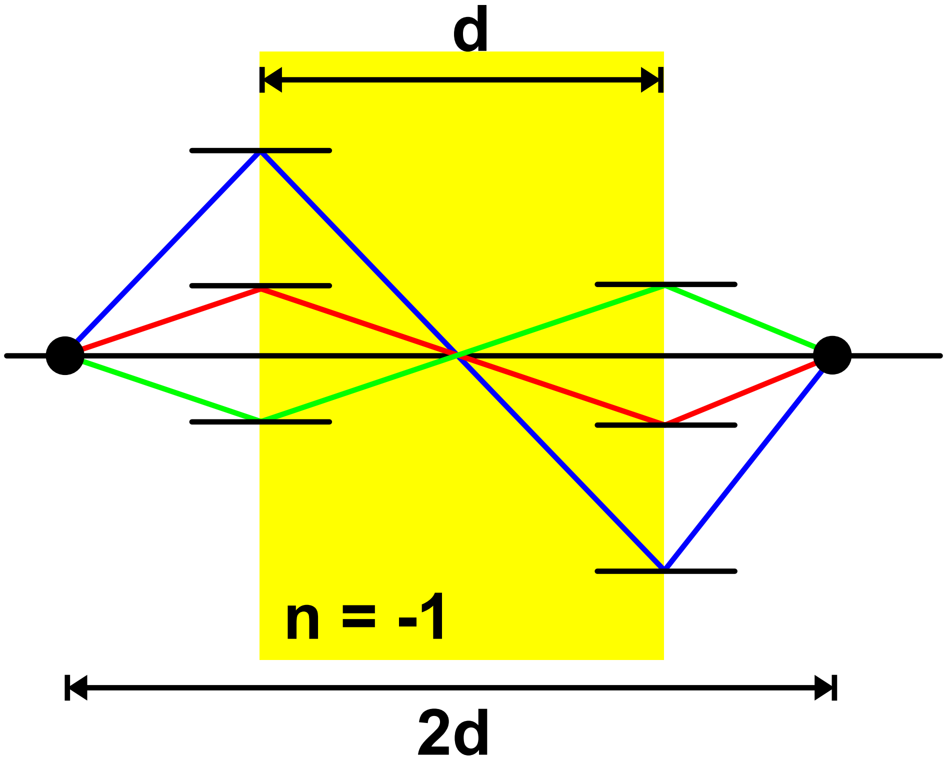
Snell's law:

$$n_1 \ \sin\theta_1 = n_2 \ \sin\theta_2$$

with one medium being air $n_1 = 1$ and the other a NIM $n_2 = -n$ we find

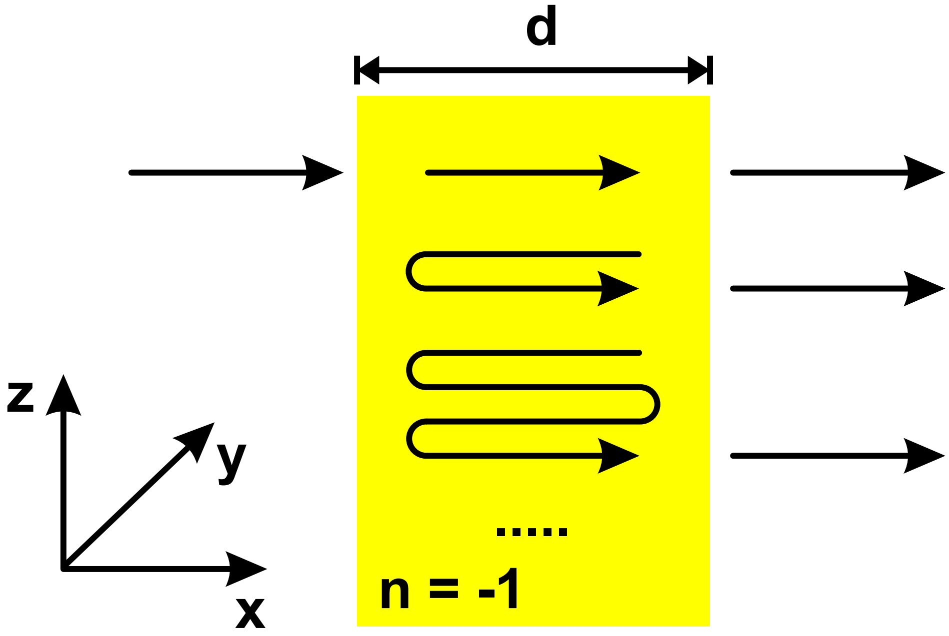
$$\sin\theta_1 = -n \ \sin\theta_2 \Rightarrow \theta_2 < 0$$

Imaging properties of a NIM slab



A slab of NIM produces two images of an object, one inside and one outside of the slab.

Fabry-Perot



$$
\begin{aligned}
t_{FP} &= t_{12}\, \mathrm{e}^{-ik_{2x}d}\, t_{21} + t_{12}\, \mathrm{e}^{-ik_{2x}d}\, r_{21}\, \mathrm{e}^{-ik_{2x}d}\, r_{21}\, \mathrm{e}^{-ik_{2x}d}\, t_{21} + \ldots \\
&= t_{12}\, t_{21}\, \mathrm{e}^{-ik_{2x}d} \sum_{n=0}^{\infty} \left(r_{21}^2\, \mathrm{e}^{-2ik_{2x}d}\right)^n \\
&= \frac{t_{12}\, t_{21}\, \mathrm{e}^{-ik_{2x}d}}{1 - r_{21}^2\, \mathrm{e}^{-2ik_{2x}d}}
\end{aligned}
$$

Fabry-Perot (cont.)

For $\epsilon_1 = \mu_1 \equiv 1$ and $\epsilon_2 = \mu_2 \equiv -1$ it follows

$$t_{FP} = \frac{-4 k_{1x} k_{2x} \, \mathrm{e}^{-ik_{2x}d}}{(k_{2x} - k_{1x})^2 - (k_{2x} + k_{1x})^2 \, \mathrm{e}^{-2ik_{2x}d}}$$

For propagating waves $k_{1x} = -k_{2x} = \sqrt{\frac{\omega^2}{c^2} \, |\epsilon\mu| - k_z^2}$ and evanescent waves $k_{1x} = k_{2x} = i\sqrt{k_z^2 - \frac{\omega^2}{c^2} \, |\epsilon\mu|}$, the result is identical

$$\begin{aligned} t_{FP} &= \frac{4k_{1x}^2 \, \mathrm{e}^{ik_{1x}d}}{4k_{1x}^2} = \mathrm{e}^{ik_{1x}d} \\ t_{FP} &= \frac{-4k_{1x}^2 \, \mathrm{e}^{-ik_{1x}d}}{-4k_{1x}^2 \, \mathrm{e}^{-2ik_{1x}d}} = \mathrm{e}^{ik_{1x}d} \end{aligned}$$

Fabry-Perot (cont.)

That is, the transmission through a NIM slab of thickness d produces an image of an object at a distance of $2d$ and exactly cancels the free space phase.

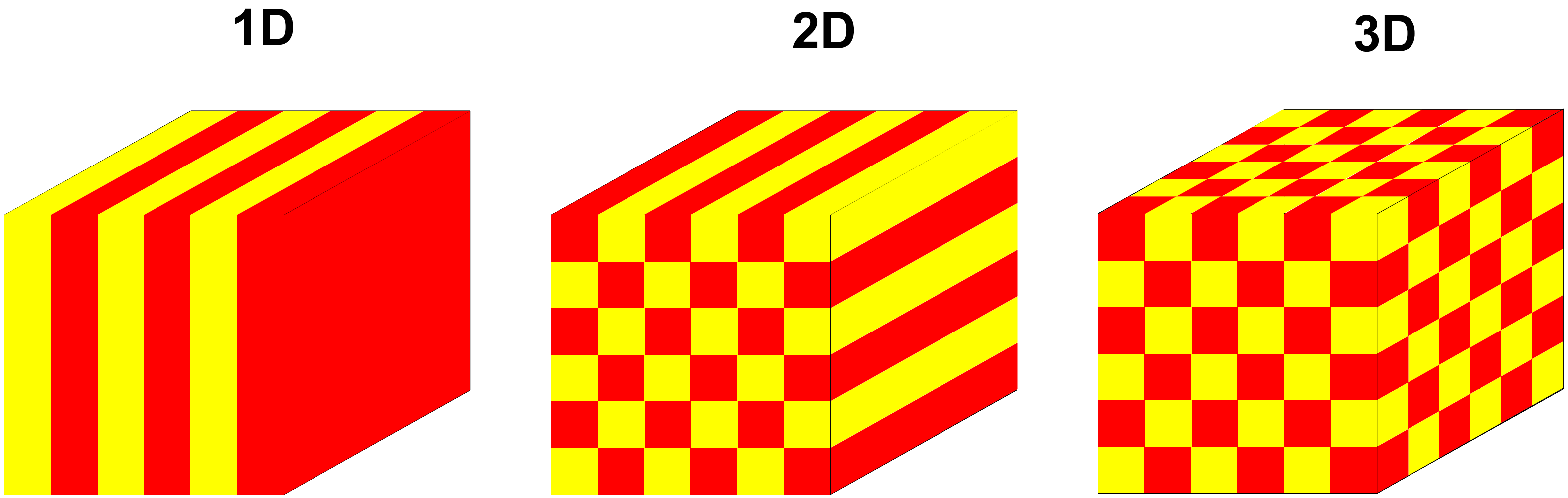
free space phase	$\mathrm{e}^{-ik_{1x}d}$
NIM slab phase	$\mathrm{e}^{+ik_{1x}d}$

Note, waves that are evanescent outside grow exponentially inside, thus, making the NIM slab a super-lens as all waves with arbitrary transverse k-vectors contribute to the image formation.

II. Photonic crystals,

photonic crystal fibers, and extreme guiding

Photonic crystals



- Bragg mirrors (1D)
- Slab waveguides (2D)
- Woodpile structures (3D)
- Photonic crystal fibers (2D)
- . . .

Problem is solved numerically

- In time domain by finite difference time domain (FDTD)

$$\begin{aligned}\nabla \times \mathbf{E}(\mathbf{r},t) &= -\mu_0 \frac{\partial}{\partial t}\mathbf{H}(\mathbf{r},t)\\ \nabla \times \mathbf{H}(\mathbf{r},t) &= \epsilon_0\epsilon(\mathbf{r},\omega) \frac{\partial}{\partial t}\mathbf{E}(\mathbf{r},t)\end{aligned}$$

- In frequency domain by plane wave expansion (PWE)

$$\nabla \times \left[\frac{1}{\epsilon(\mathbf{r},\omega)} \nabla \times \mathbf{H}(\mathbf{r},\omega)\right] = \frac{\omega^2}{c^2}\,\mathbf{H}(\mathbf{r},\omega)$$

Bloch's theorem

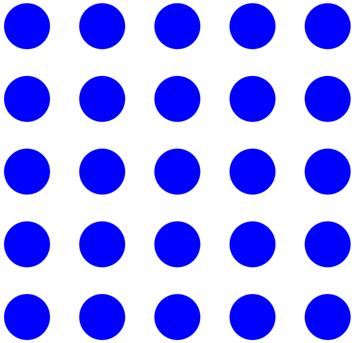
$$\begin{aligned}\mathbf{H}(\mathbf{r},\omega) &= \exp[-i\mathbf{k}(\omega)\cdot\mathbf{r}]\,\mathbf{u}_{\mathbf{k}}(\mathbf{r})\\ \mathbf{u}_{\mathbf{k}}(\mathbf{r}) &= \mathbf{u}_{\mathbf{k}}(\mathbf{r}+\mathbf{R})\end{aligned}$$

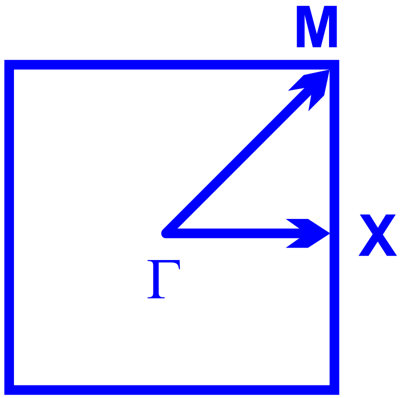
All solutions $\omega(\mathbf{k})$ within the first Brillouin zone.

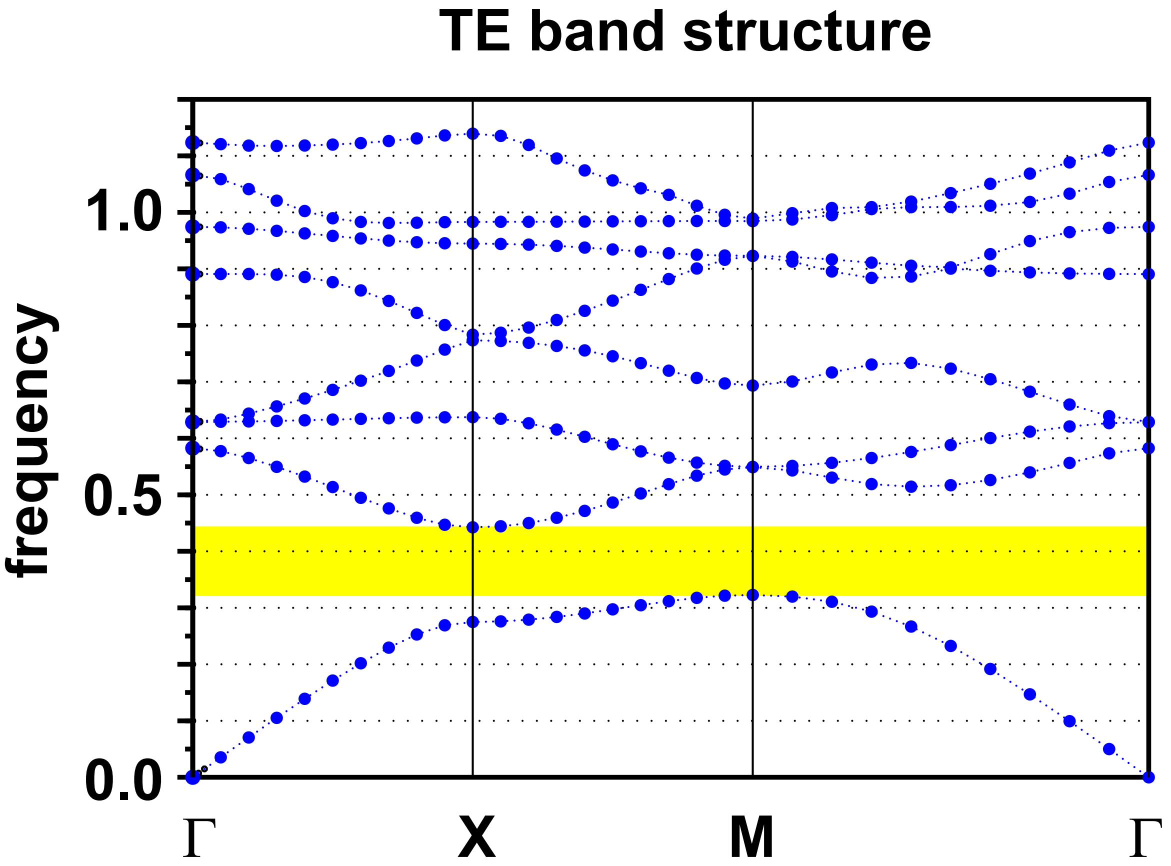
$$(-i\mathbf{k}+\nabla)\times\left\{\frac{1}{\epsilon(\mathbf{r},\omega)}\,(-i\mathbf{k}+\nabla)\times\mathbf{u}_{\mathbf{k}}(\mathbf{r})\right\}=\frac{\omega^2}{c^2}\,\mathbf{u}_{\mathbf{k}}(\mathbf{r})$$

The band structure is usually calculated for straight paths connecting points of high symmetry. If band gaps are found here they also exist for all other wave vectors.

Band structure

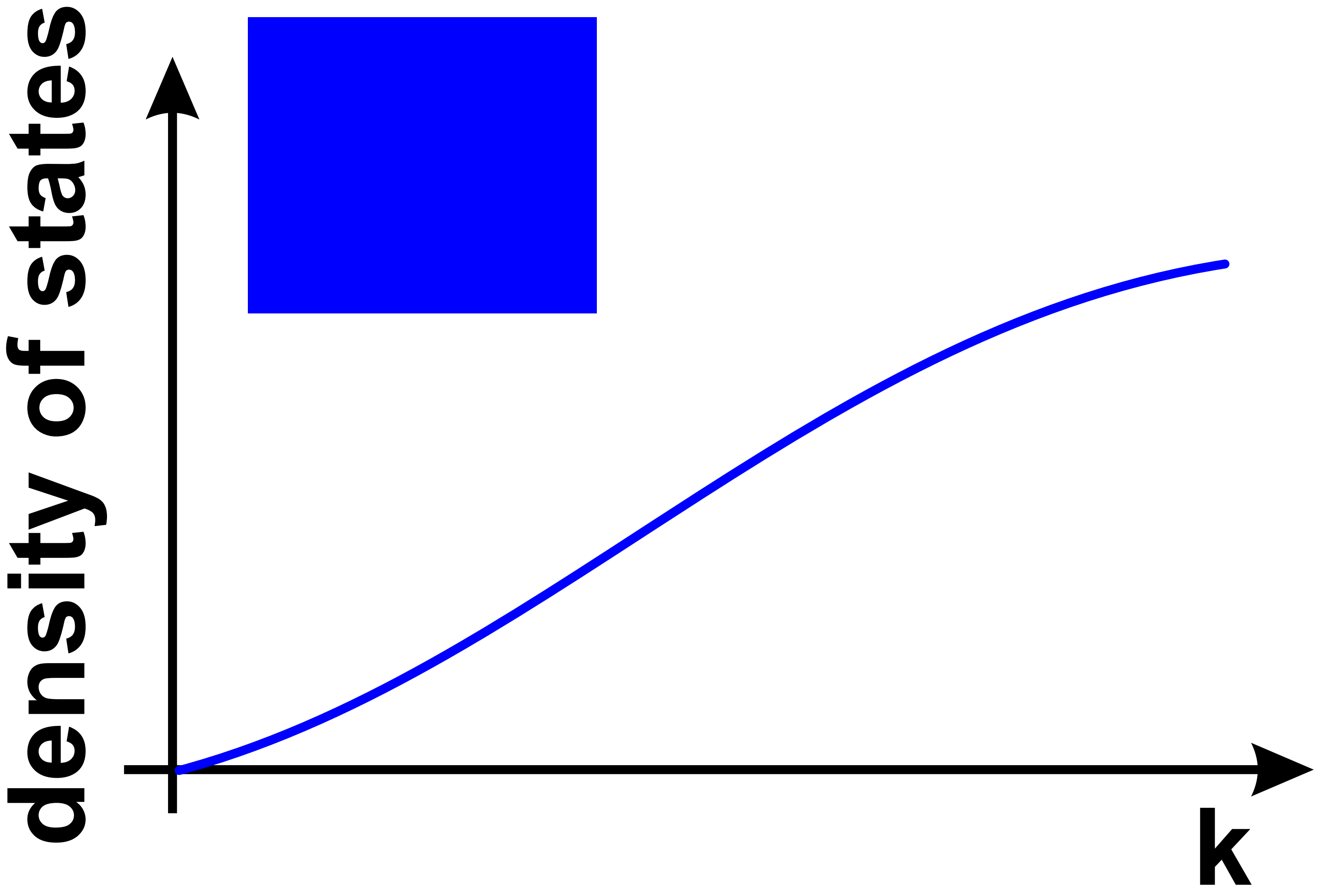






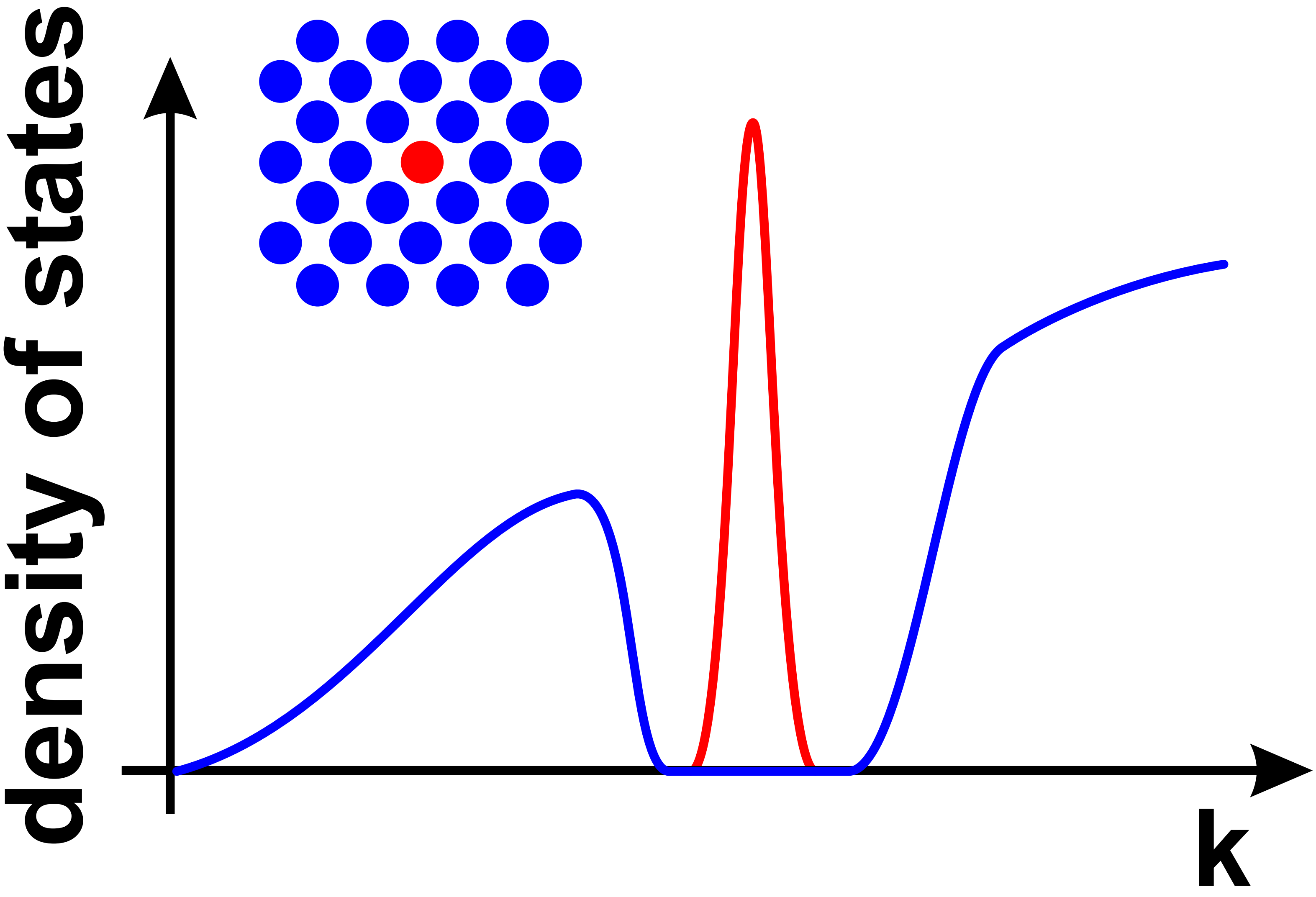
Band structure for TE modes in a square 2D lattice. Nomenclature is identical to solid state physics.

Density of states



Band gap engineering leads to desired guiding properties.

Density of states



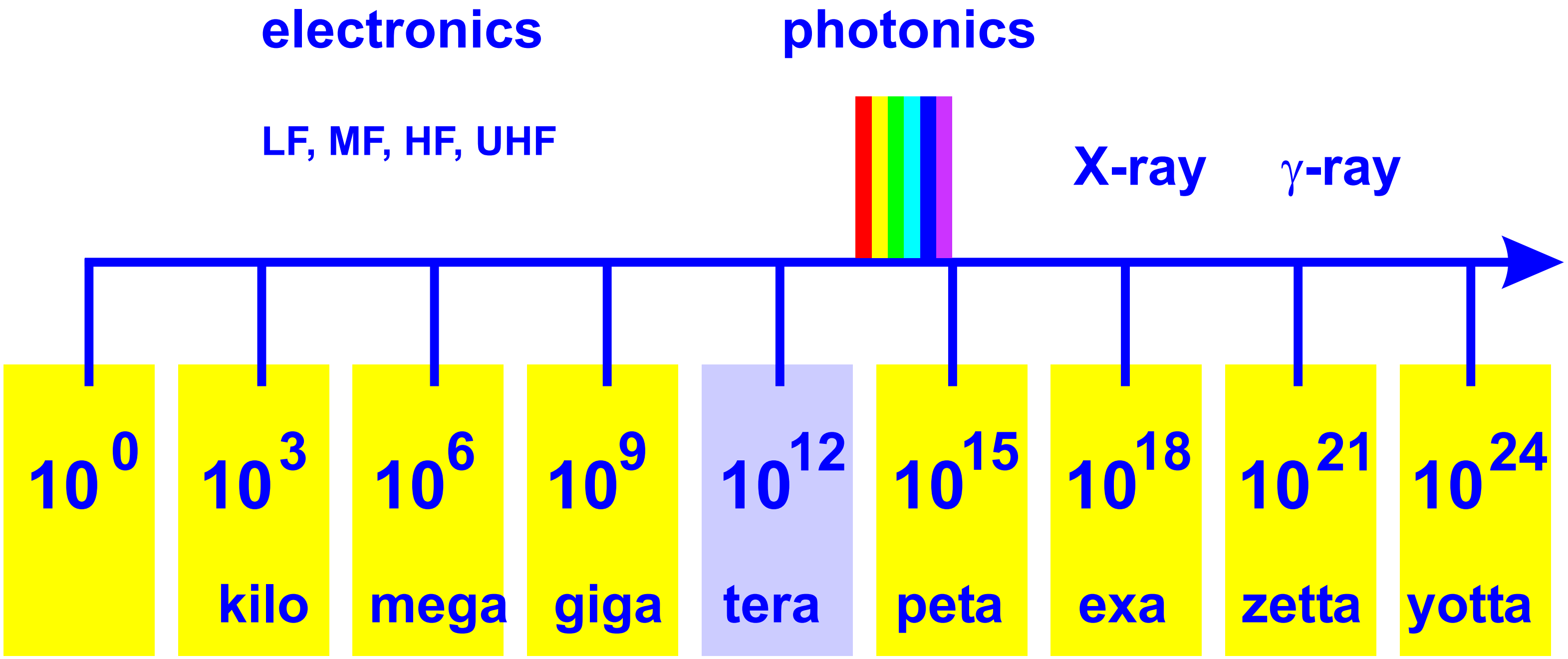
Band gap engineering leads to desired guiding properties.

Extreme guiding in single mode PCF

- solid core, large mode area, dispersion management
- solid core, small mode area
- hollow core, large mode area
- hollow core, gas-filled
- PCFs for 3 μm wavelength range
- PCFs for THz applications
- . . .

III. THz technology and applications

Where are we?



electronics

photonics

LF, MF, HF, UHF

X-ray

γ-ray

10^0

10^3 kilo

10^6 mega

10^9 giga

10^{12} tera

10^{15} peta

10^{18} exa

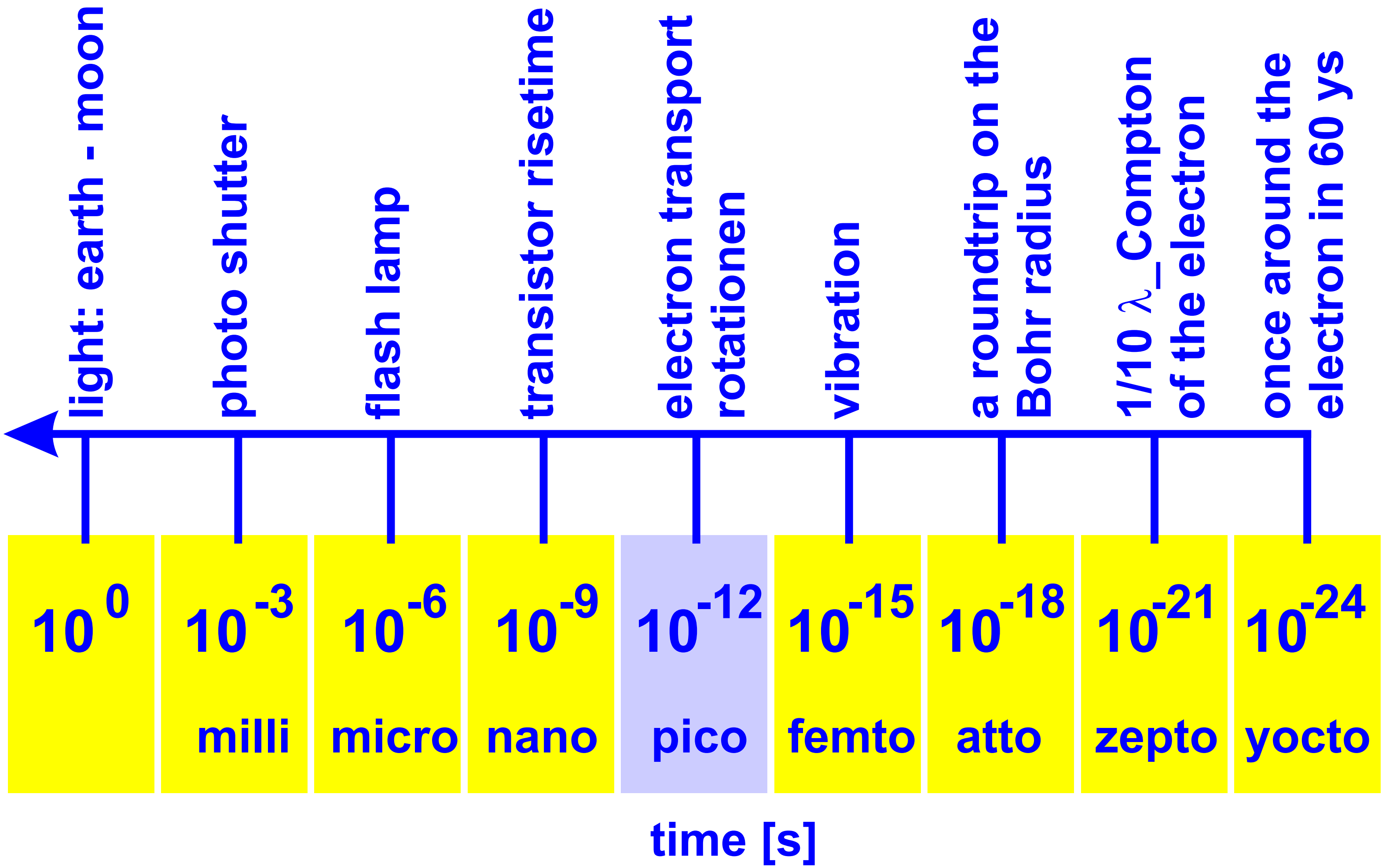
10^{21} zetta

10^{24} yotta

frequency [Hz]

1 Thz ~ 1 ps ~ 300um ~ 33 cm^{-1} ~ 4.1 meV ~ 47.6 K

Where are we? (cont.)



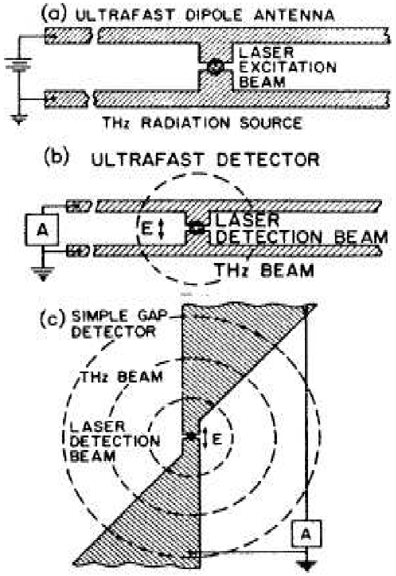
light: earth - moon	10^{0}	
photo shutter	10^{-3}	milli
flash lamp	10^{-6}	micro
transistor risetime	10^{-9}	nano
electron transport rotationen	10^{-12}	pico
vibration	10^{-15}	femto
a roundtrip on the Bohr radius	10^{-18}	atto
1/10 λ_Compton of the electron	10^{-21}	zepto
once around the electron in 60 ys	10^{-24}	yocto

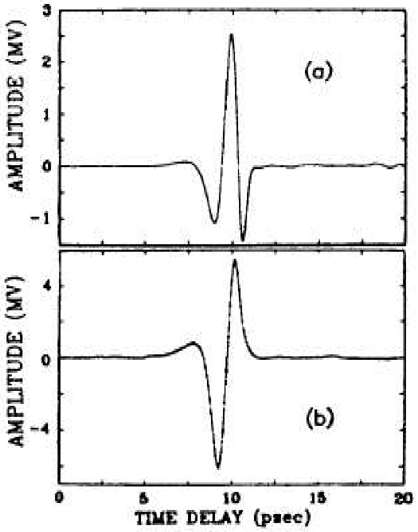
time [s]

THz sources

- Nonlinear effects: primary source VIS laser
- Nonlinear effects: primary source MW
- Synchrotron, free electron laser
- Quantum cascade laser
- Semiconductor switches (Auston switch)

Radiating Antenna



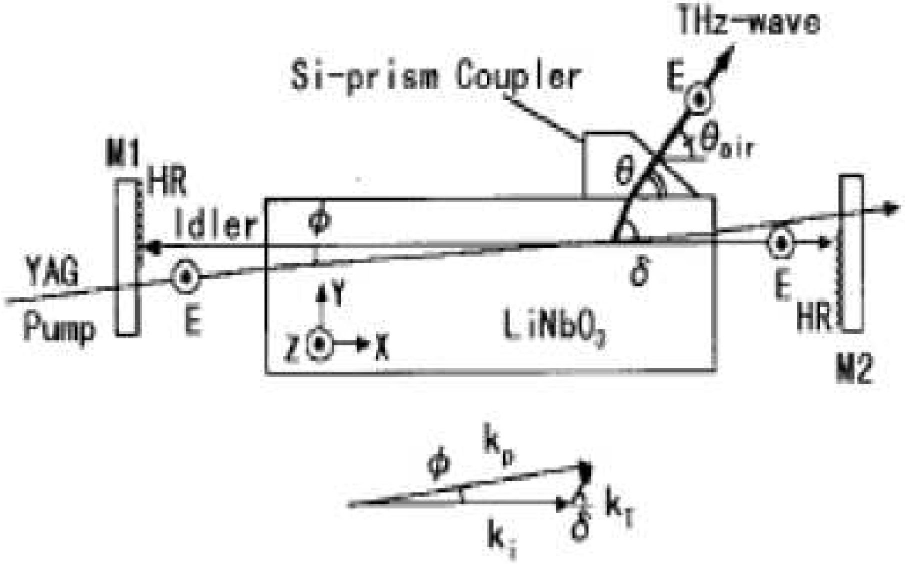


A biased gap is triggered by a femtosecond laser pulse with $\hbar\omega > E_g$. The current flow radiates as

$$\mathbf{E}(t) \propto \frac{\partial}{\partial t}\mathbf{j}(t) \quad \text{with} \quad \mathbf{j}(t) = -eN(t)\,\mu\,E_{\text{bias}}$$

APL 55, 337 (1989)

Quasi cw THz generation

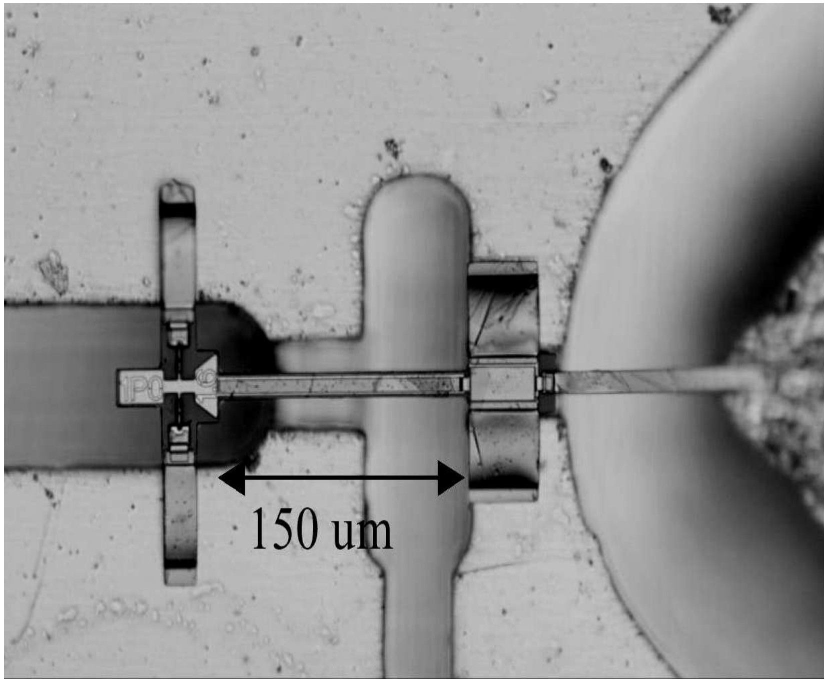


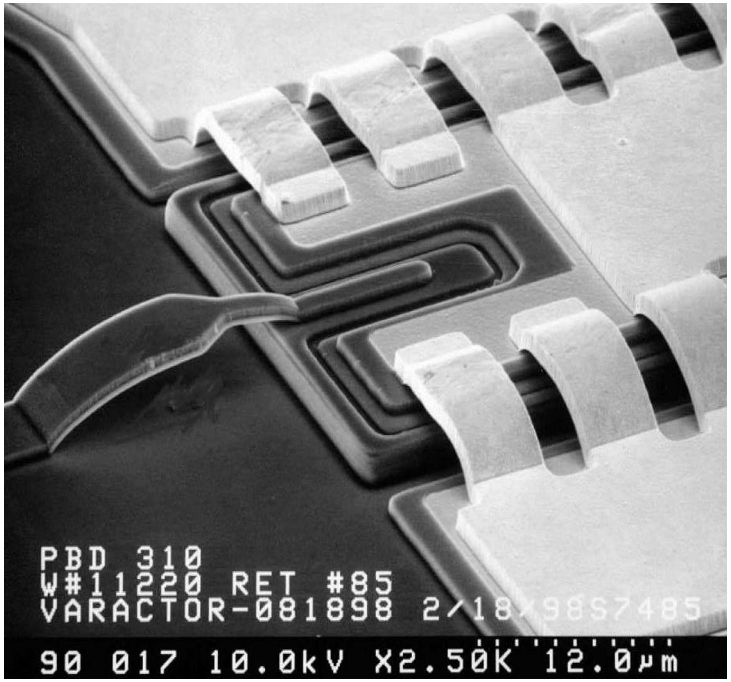
Three-wave mixing process in a NLO crystal

$$\mathbf{E}(t) \propto \frac{\partial^2}{\partial t^2}\mathbf{P}(t) \quad \text{with} \quad \mathbf{P}(\omega) \propto \chi_2\, \mathbf{E}(\omega_1)\, \mathbf{E}^*(\omega_2)$$

OL 24, 1605 (1999)

Up-conversion of MW

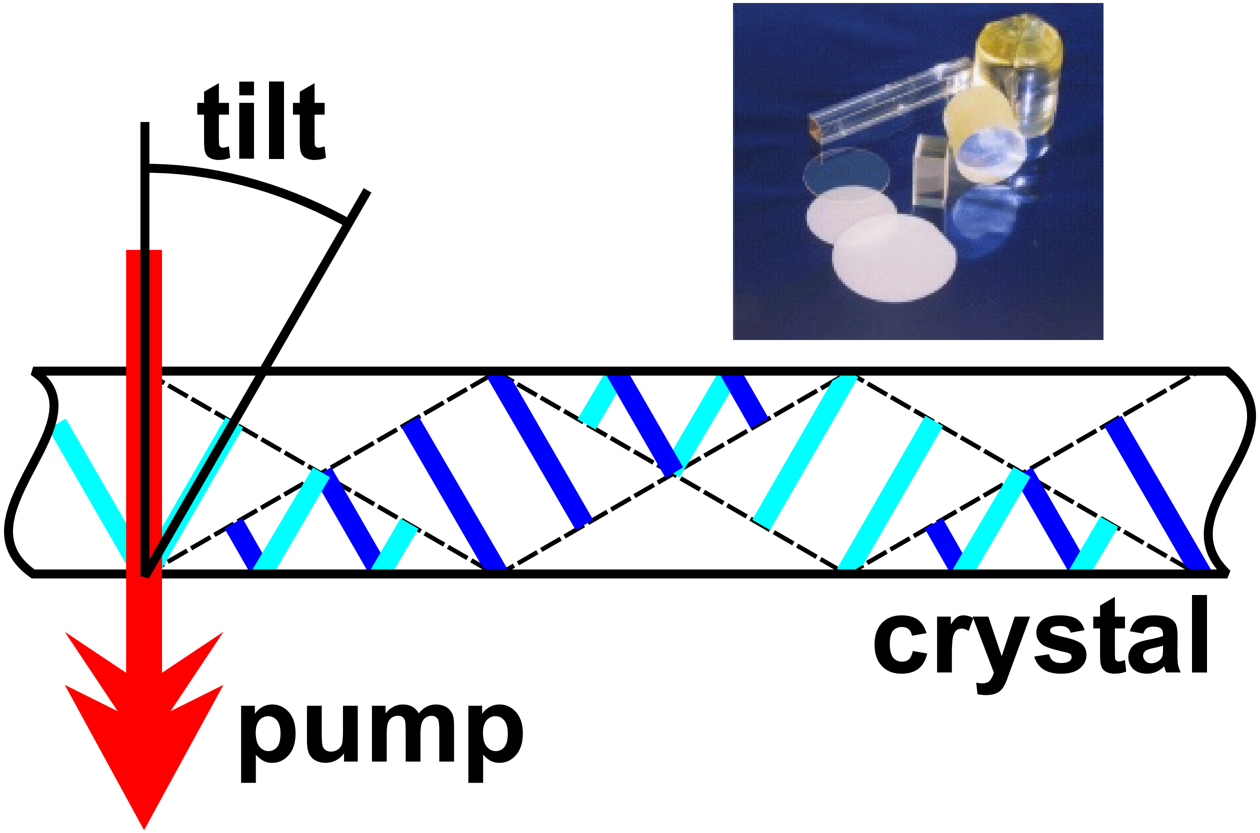




Standard microwave sources combined with high precision diode manufacturing allows cascading the frequency up to 1.6 THz.

JPL

Cherenkov radiation in $LiNbO_3$

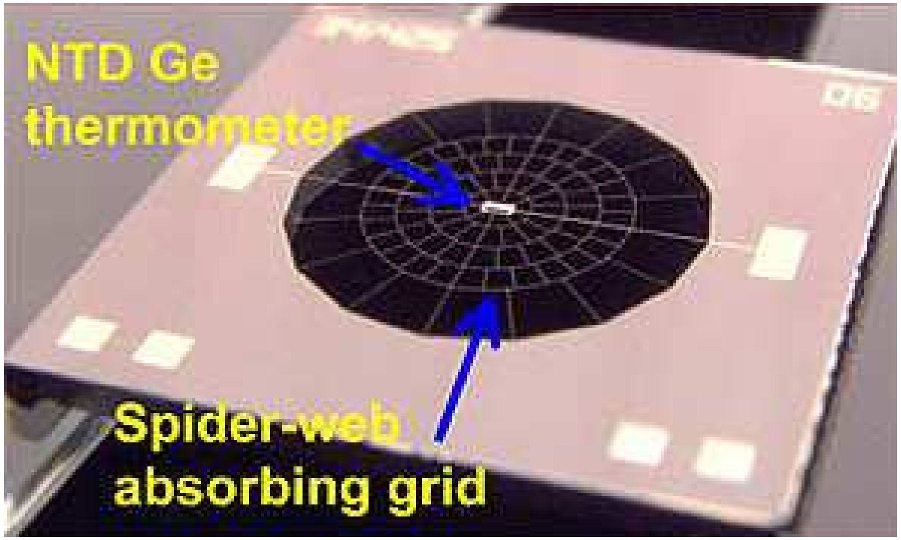


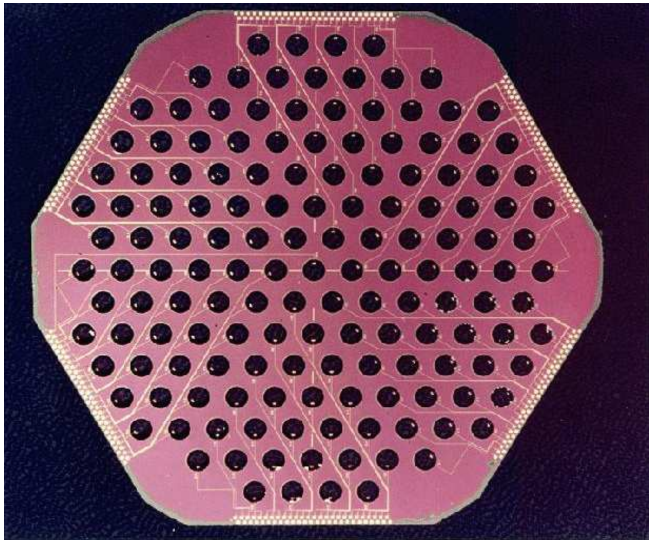
In this case the spectrum of the THz pulse is mainly dominated by the spatial profile of the excitation pulse

THz detectors

- Bolometer
- Pyroelectric detector
- Quantum-well inter-subband detector
- Schottky diode
- coherent (electro-optic) detection

Bolometer

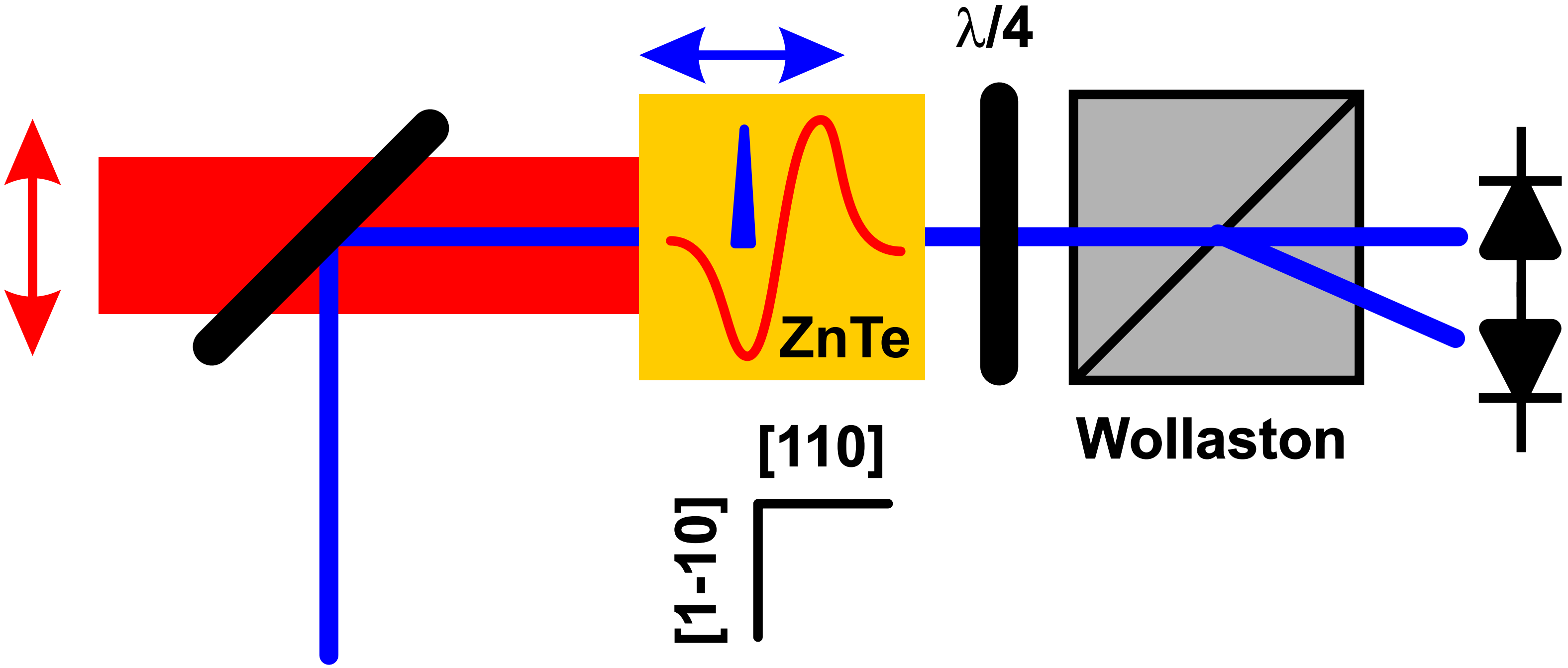




Bolometers come as single area detectors but since recently also as arrays of detectors for imaging applications. They need to be cooled but are extremely sensitive.

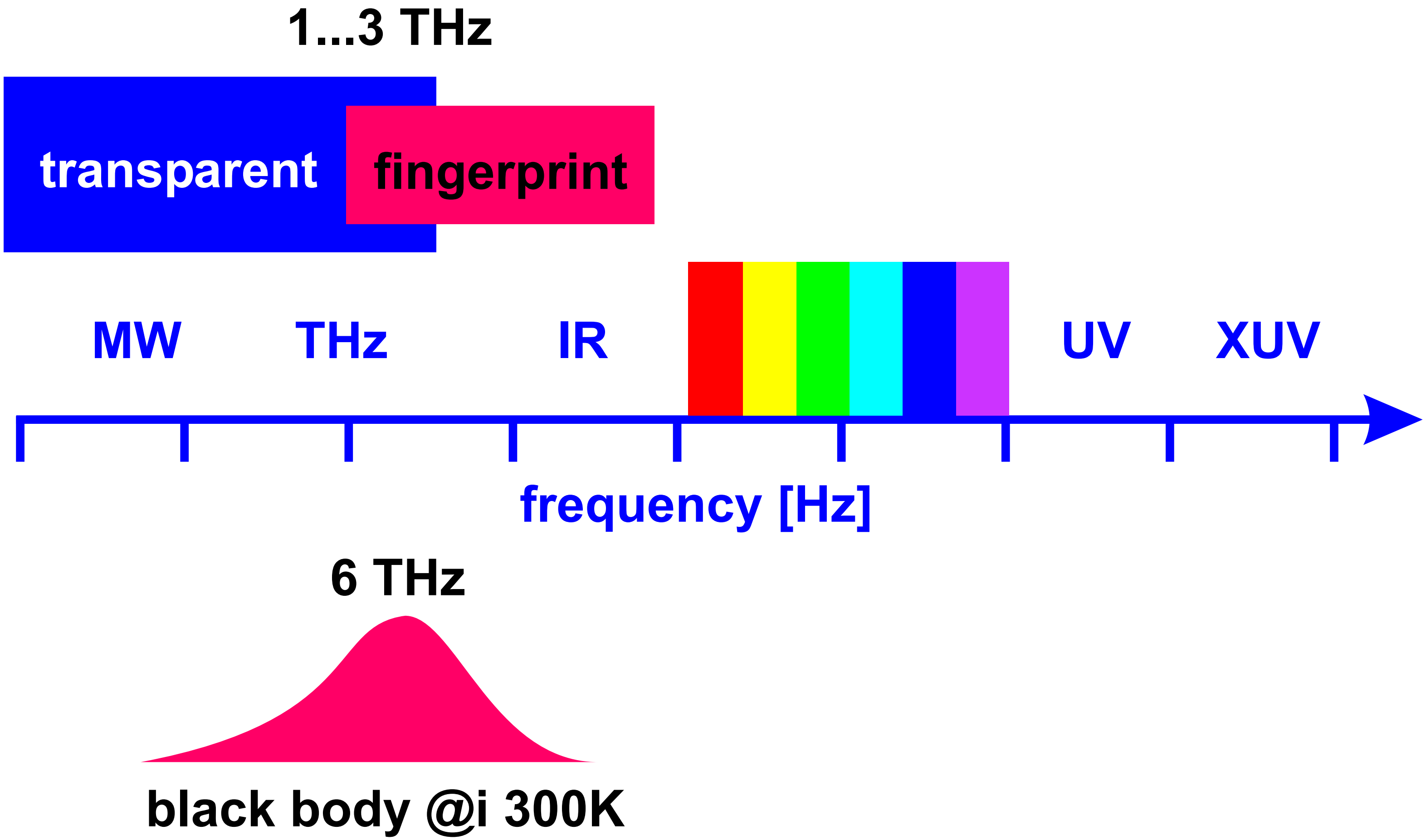
http://casa.colorado.edu/ jglenn/bolocam.html

Coherent electro-optic detection



Coherent electro-optic sampling allows for a complete field measurement, and therefore, to determine amplitude and phase. In addition, spatial scanning yields imaging information.

The fingerprint region



1...3 THz

transparent

fingerprint

MW THz IR UV XUV

frequency [Hz]

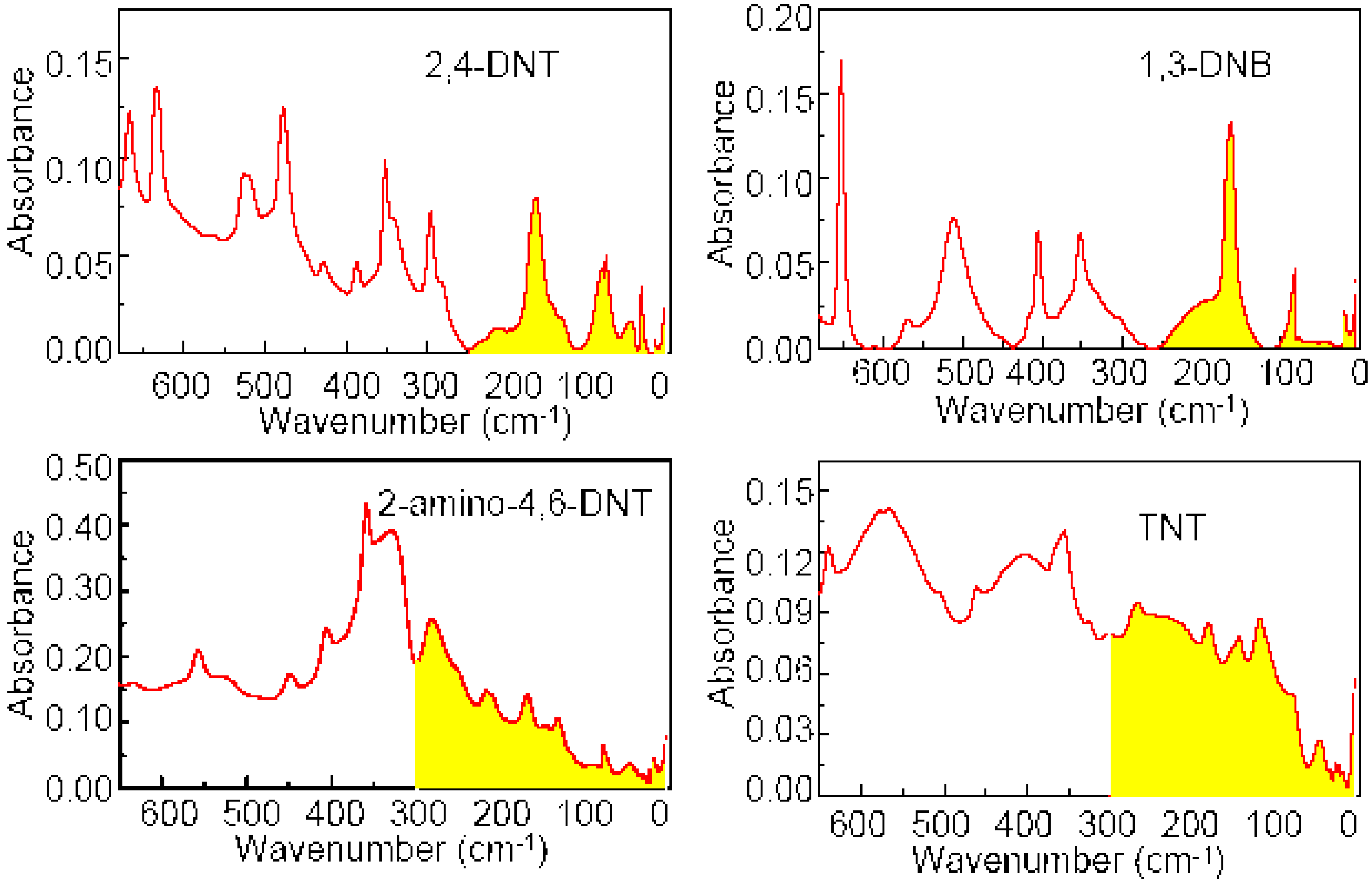
6 THz

black body @i 300K

Where do we need THz?

- Detection of chemical and biological materials
- Detection of hazardous organic materials
- Detection of explosives
- Detection of hidden objects
- Scanning of mail and packages
- Dental applications
- Cancer diagnostics
- Detection of forgery and counterfeits
- THz lidar, microscopy, astronomy
- . . .

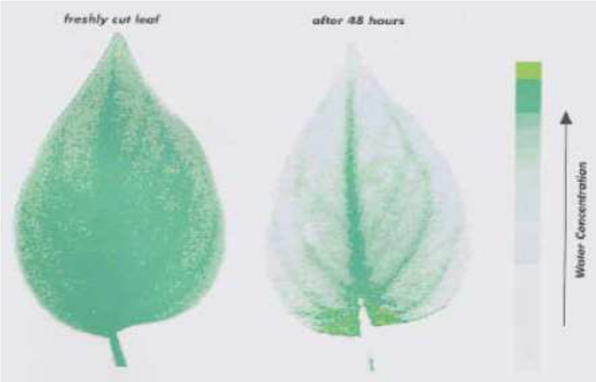
Spectra of explosives



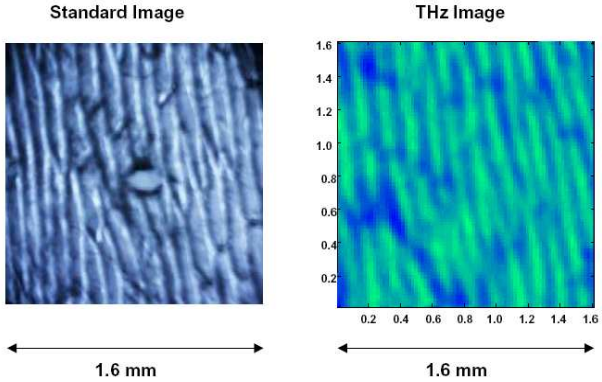
In the THz region explosives and most other organic materials do have a very specific absorption spectrum.

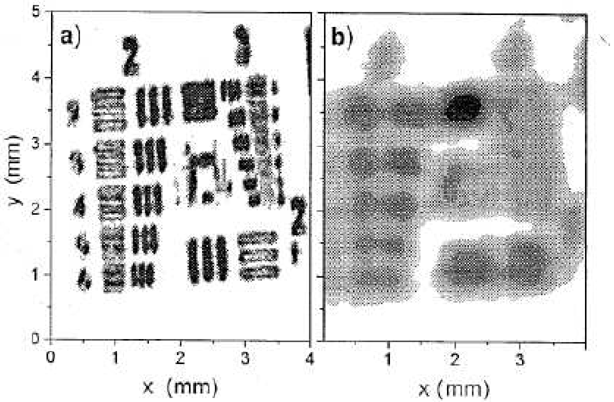
http://www.rpi.edu/ zhangxc

Imaging



Imaging
Microscopy
Near-field imaging

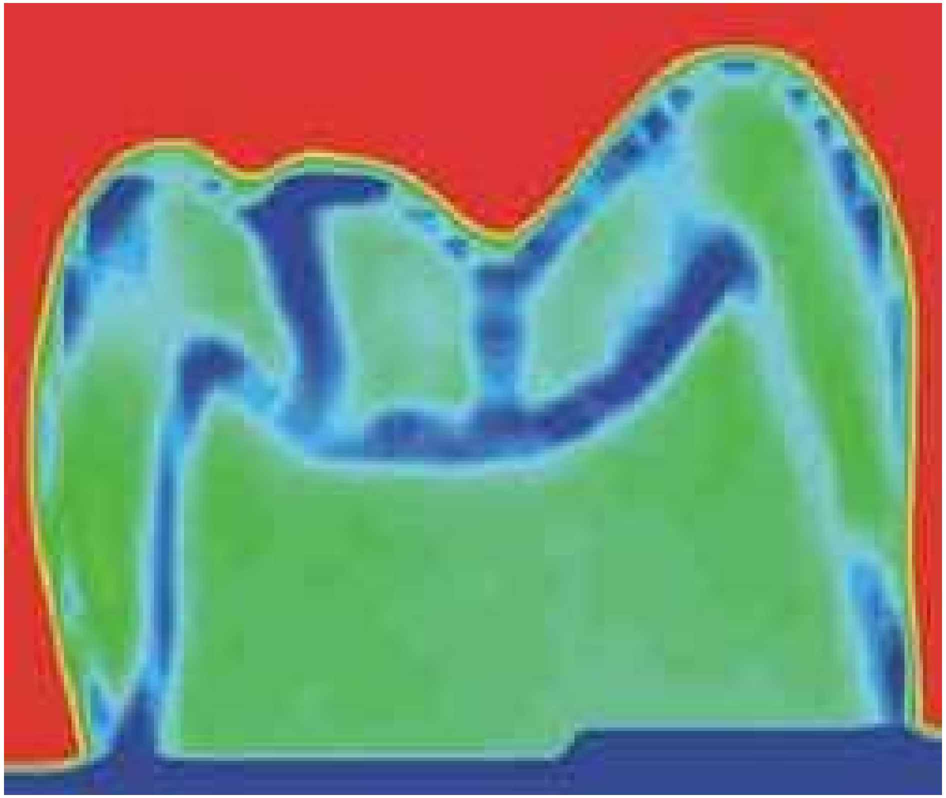




Different imaging techniques, such as remote sensing, imaging, microscopy, and near-field imaging have been demonstrated.

OL 20,1716 (1995), LEOS IEEE 2, 368 (1996)

Imaging teeth



As teeth contain very little water, THz radiation may be used to image hidden cavities etc.

http://www.comp.leeds.ac.uk/comir/research/medicalterahertz/teeth.htm

Imaging hidden metal objects

This guy tries to hide a knife behind a news paper. THz imaging penetrates through most cloths and anorganic species, except water. Water absorbs extremely well at THz frequencies.

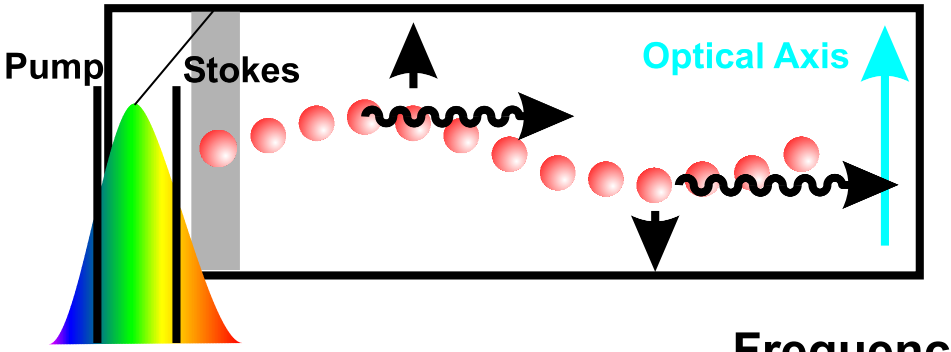
’New Focus’ in Science, 8. Feb. 2002

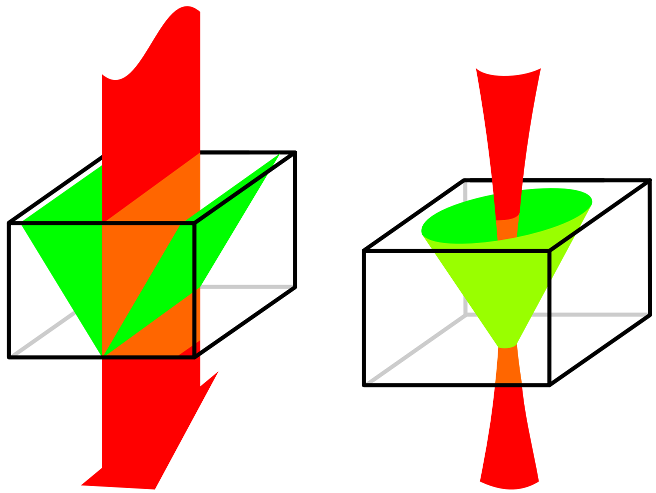
IV. Integrated THz signal processing

What is it all about?

- Plattform for integrated THz applications
- THz generation through laser
- High dielectric contrast
- Simple ways of structuring
- Possibility to observe fields

Excitation of polaritons





Frequency:
0.1 - 5 Thz

Wavelength:
20 - 200 micron

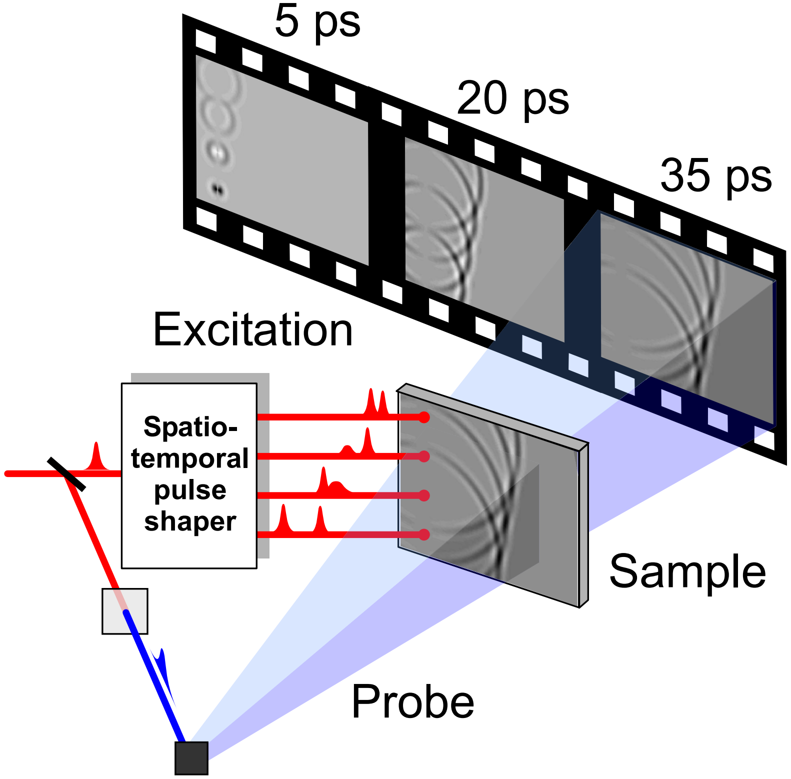
Dielectric constant:
40

Field strength:
10 kV/cm

Excitation by impulsive stimulated Raman scattering.

Phonon mode has to be Raman as well as IR active.

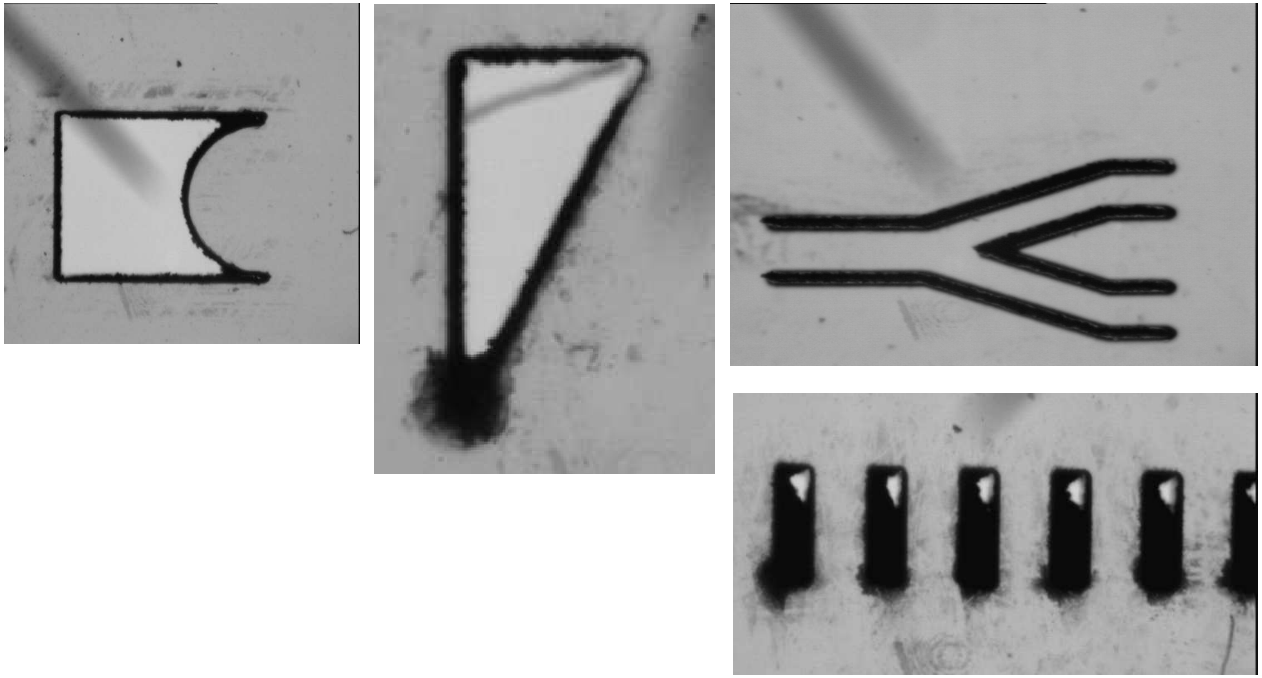
Detection of polaritons



Detection through linear and nonlinear phase contrast methods:

- Interferometry
- Talbot imaging
- Schlieren imaging
- Kerr effect
- THz induced SHG
- . . .

Fundamental building blocks



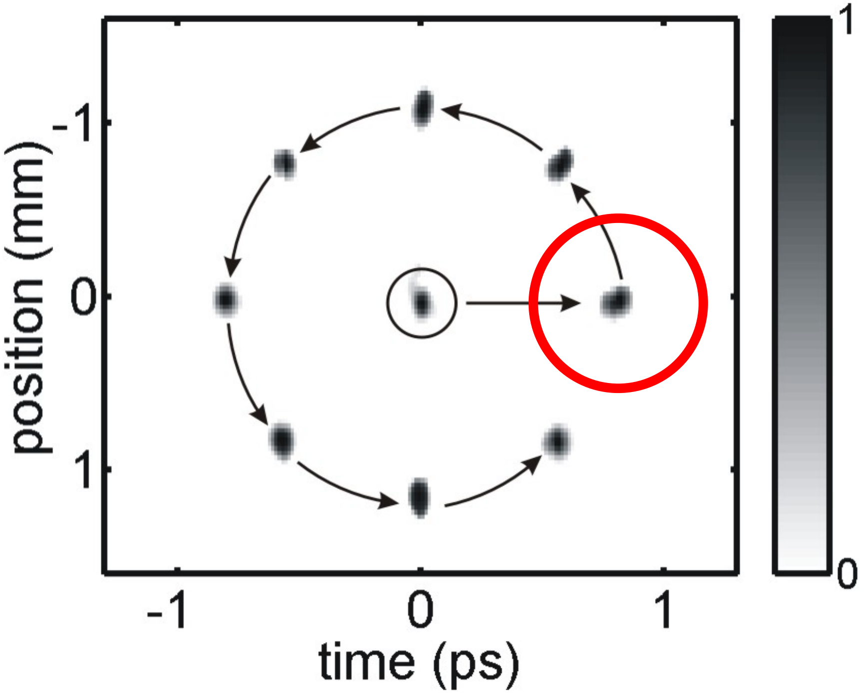
Fundamental building blocks can be manufactured through laser machining in crystals of appropriate thicknesses, i.e. mirrors, lenses, prisms, gratings, waveguides, interferometers, resonators, etc.

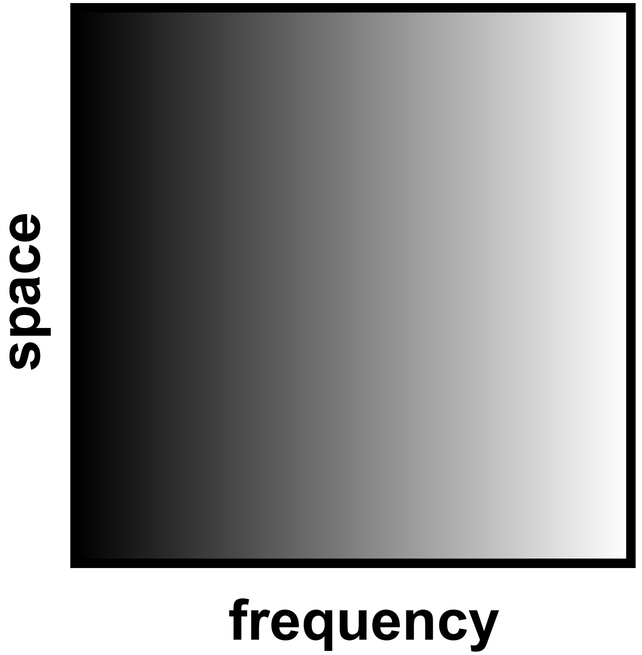
Femtosecond pulse shaping

$$\begin{tikzcd}
 & \mathbf{E}_{\mathrm{in}}(t,x) \arrow[dl, Rightarrow, "\mathcal{F}[t \to \omega]"'] \arrow[dr, Rightarrow, "\mathcal{F}[x \to k_x]"] & \\
\mathbf{E}_{\mathrm{out}}(\omega,k_x) \arrow[dr, Rightarrow, "\mathcal{F}^{-1}[\omega \to t]"'] & = & \mathbf{E}_{\mathrm{in}}(\omega,k_x)\,\mathbf{A}(\omega,k_x)\ \exp[i\Phi(\omega,k_x)] \arrow[dl, Rightarrow, "\mathcal{F}^{-1}[k_x \to x]"] \\
 & \mathbf{E}_{\mathrm{out}}(t,x) &
\end{tikzcd}$$

Modulation is done through 1D or 2D SLM, AOM, or MEM devices. Update speeds typically vary between 100 Hz and a few kHz.

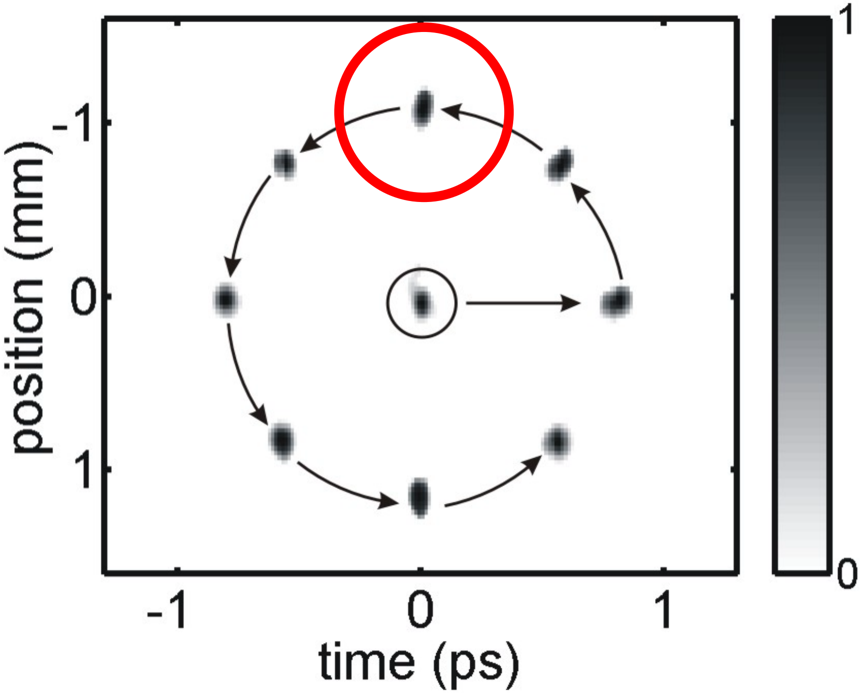
Two-dimensional pulse shaping

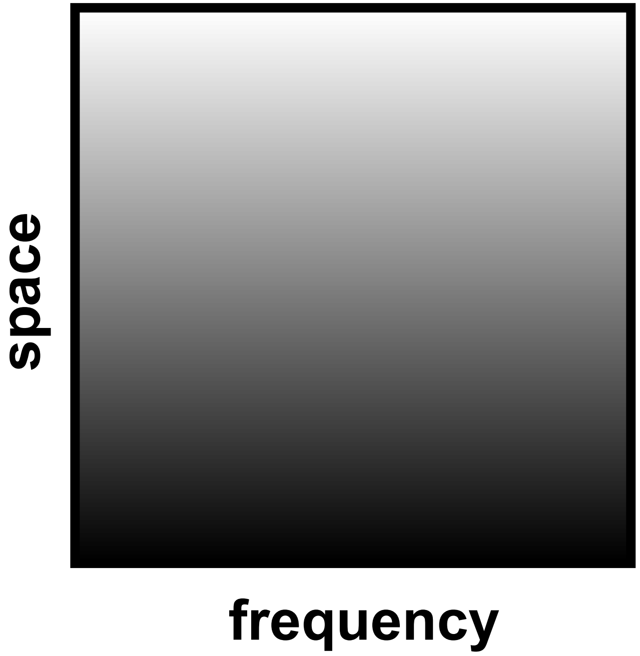




In two-dimensional phase-only pulse shaping the temporal axis is shaped through spectral manipulations and one spatial coordinate through wave vector manipulation.

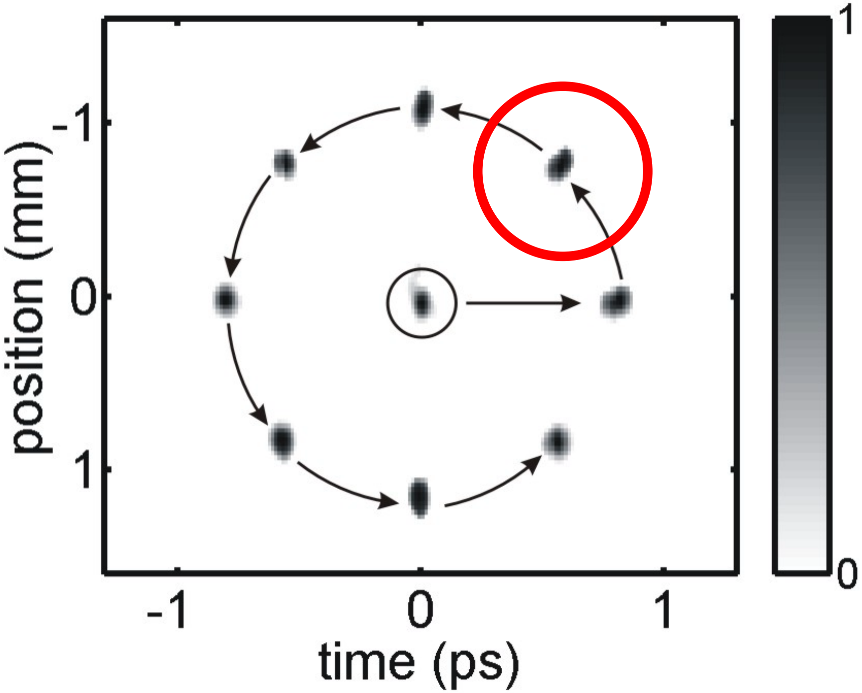
Two-dimensional pulse shaping

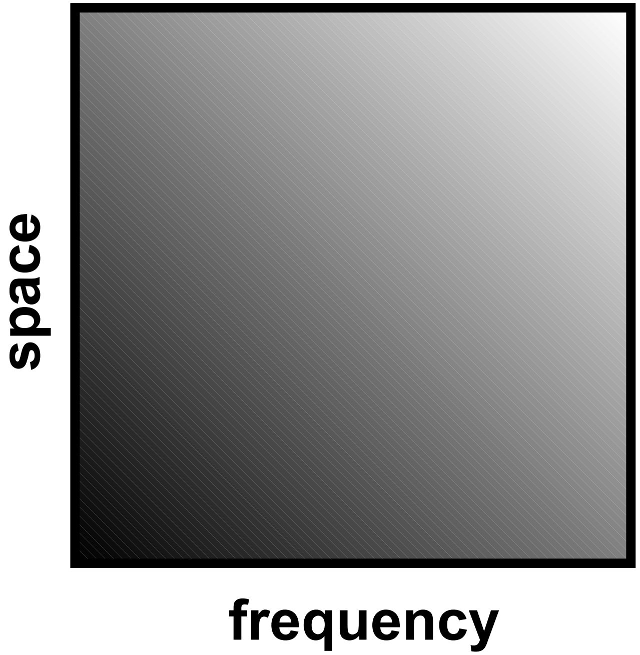




In two-dimensional phase-only pulse shaping the temporal axis is shaped through spectral manipulations and one spatial coordinate through wave vector manipulation.

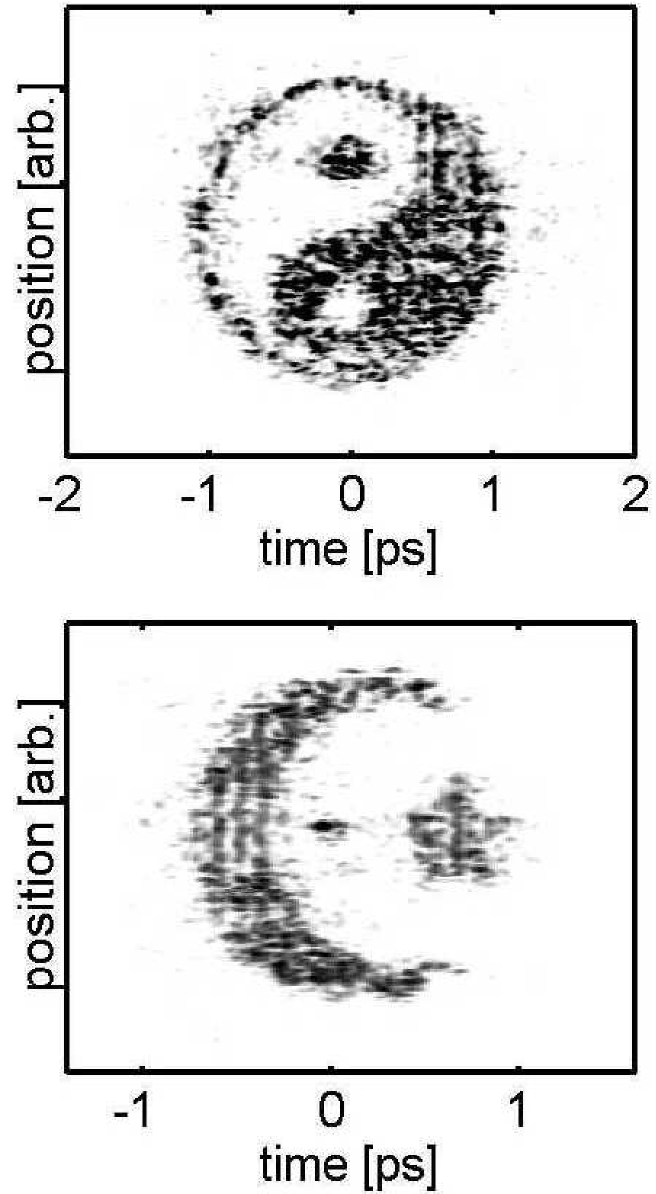
Two-dimensional pulse shaping



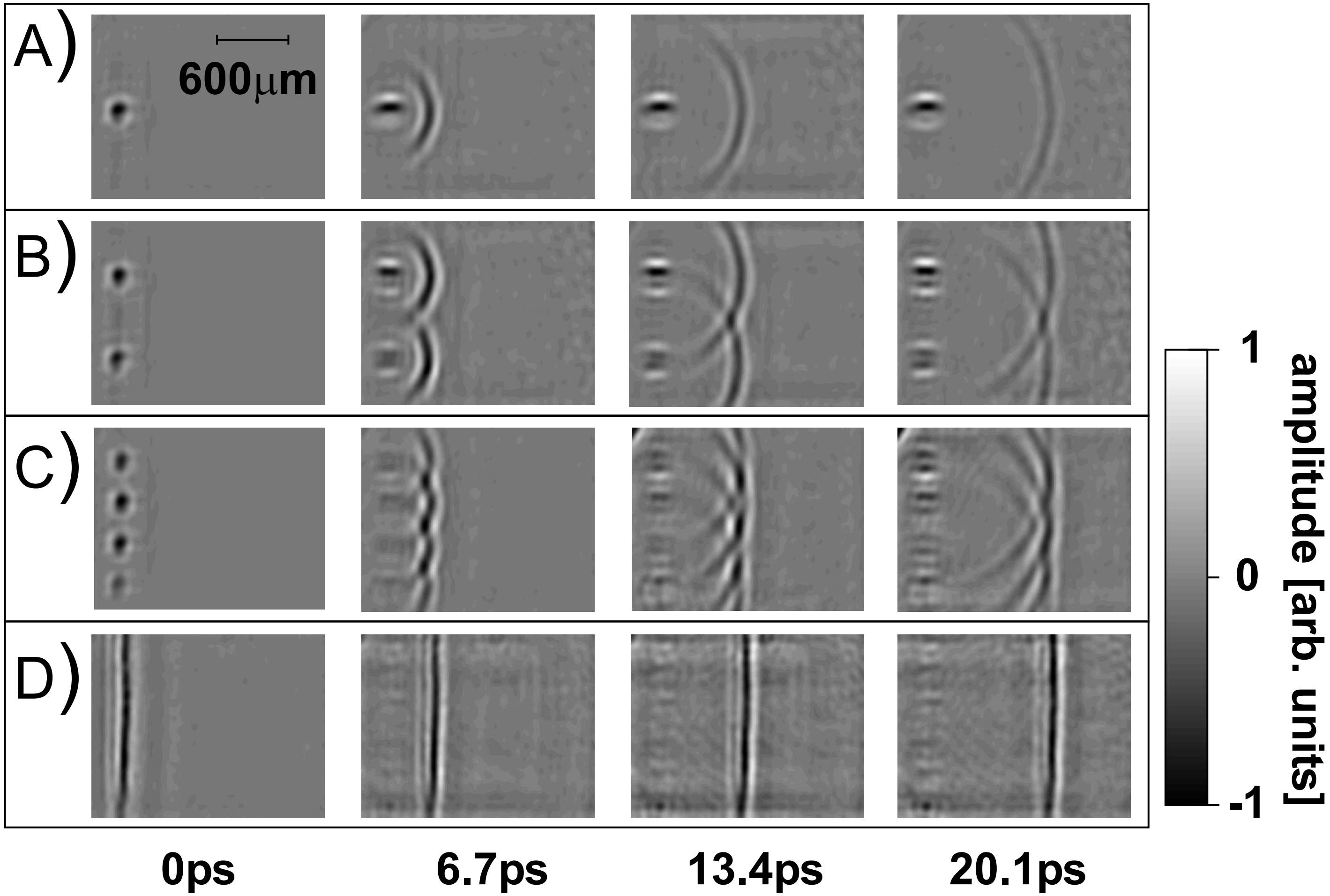


In two-dimensional phase-only pulse shaping the temporal axis is shaped through spectral manipulations and one spatial coordinate through wave vector manipulation.

Xmas greetings with the speed of light

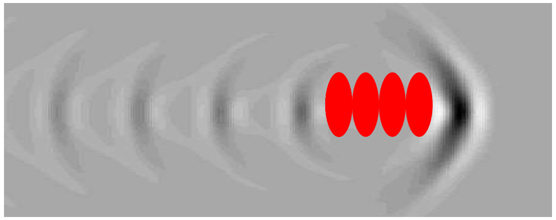


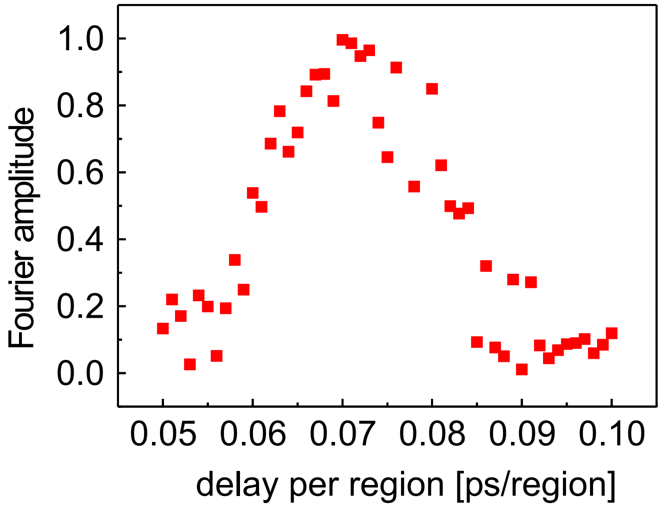
Near-field far-field transition

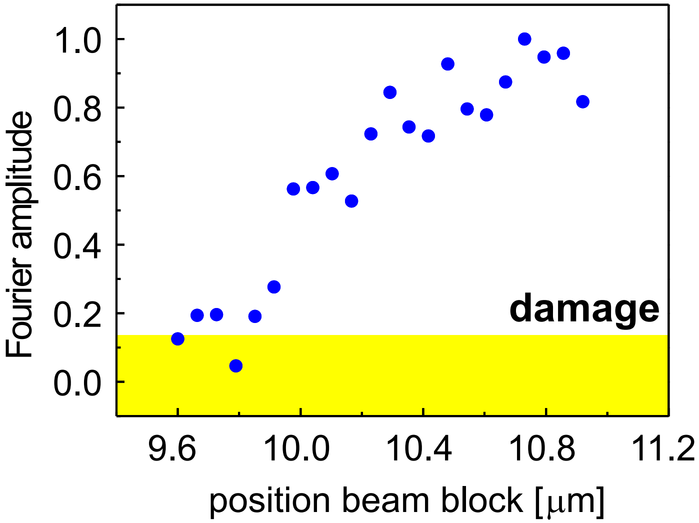


By increasing the number of single excitations the transition from near-field to far-field optics becomes obvious.

Polariton amplification

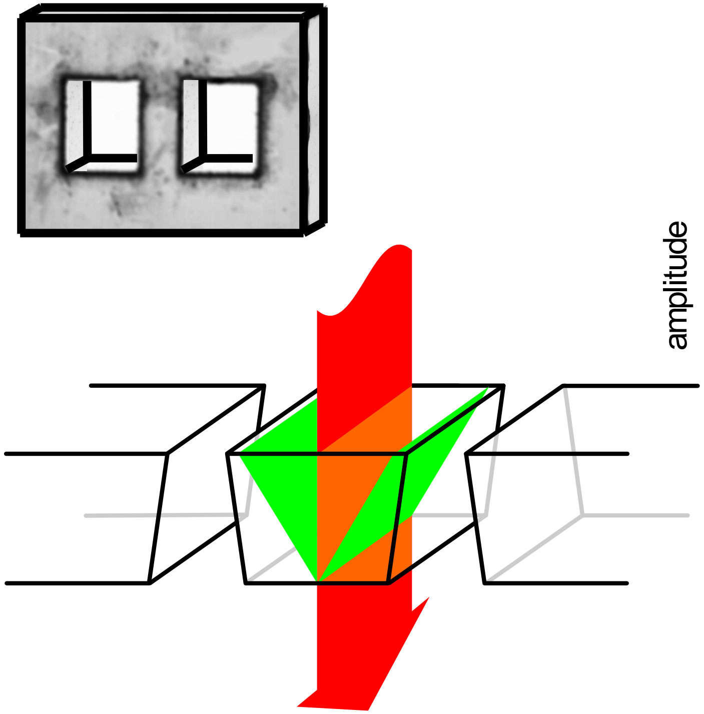


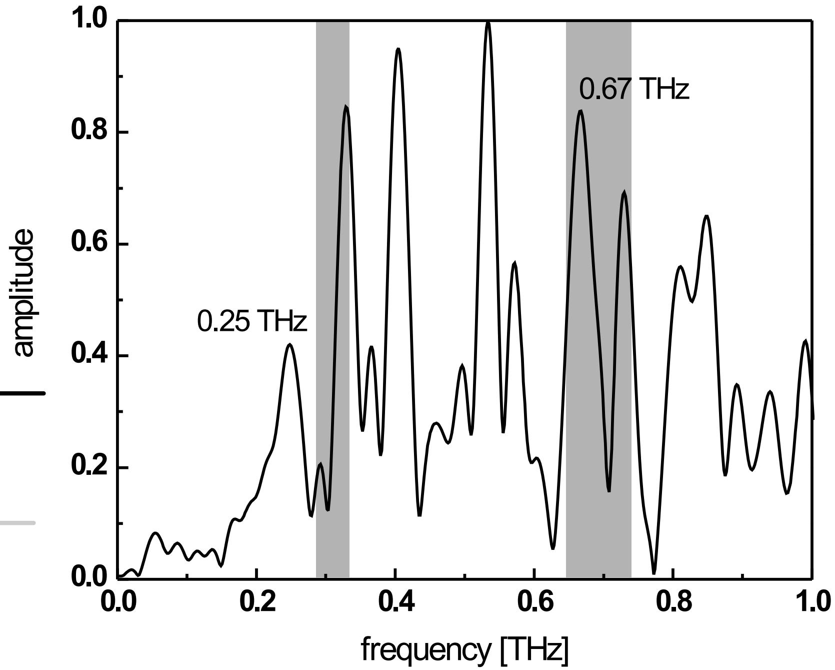




Amplification or more precisely coherent addition is realized through sweeping subsequent excitation pulses exactly with the polaritons group velocity.

Polariton resonator





Resonators are amongst the most important building blocks for integrated signal processing.

V. Summary

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- The laser group at IAP
- The Nelson group at MIT
- The organizing committee