What is meant by “terahertz”?

The spectral region around 1 THz (0.1-10 THz) is the transition from electronics to optics.

It tends to suffer from the most difficult aspects of both.

References:
Electronics \rightarrow Optics

What’s the difference between electronics and optics?

Electronics:
- Measure voltages ($E$)
- Device size $\ll$ wavelength
  - Propagate signals on “wires”
- Photon energies are small compared to $kT$
  - $1 \text{ GHz} \rightarrow 0.4 \text{ K}$

Optics:
- Measure intensity ($|E|^2$)
- Device size $\gg$ wavelength
  - Propagate signals in free space
- Photon energies are large compared to $kT$
  - $500 \text{ nm} \rightarrow \sim 3000 \text{ K}$

1 THz:
- $\lambda = 300 \mu\text{m}$
- $h \nu/k = 44 \text{ K}$
Why is THz radiation interesting?

Sensing:
Molecules have complex ro-vibration spectra at THz frequencies
Spectra can act as “fingerprints” for identifying molecules

Imaging:
Many materials that are opaque in the visible are transparent in the THz
   - paper, plastic, cloth
Possible to image through packaging
No health concerns
   - advantage over x-rays
Combination of these is being investaged for medical applications
What is the connection to ultrafast?

Ultrafast pulses are good for generating & detecting terahertz frequencies

Generation:
- Convert *intensity* envelope of pulse into an *electric* field
  - Photoconductive switch
  - Optical rectification
- Alternative view:
  - Difference frequency mixing between components that make up pulse

Detection:
- Gated – rejects most black body radiation, room temperature!
  (does not require detector temperature ~ photon energy)
- Two methods:
  - Photoconductive switch
  - Electro-optic sampling
Hit a **biased** photoconductor (semiconductor) with a short pulse

Carrier generation rate proportional the intensity

Total number of carriers a given time $t$ is (assuming relaxation is slow enough to be ignored):

$$N(t) \propto \int_{-\infty}^{t} \hat{E}(t') dt'$$

Because of the bias this will result in a current that is proportional to the number of carriers ($J \sim N \times V_B$)

The source term in Maxwell’s equations is

Radiated field roughly tracks envelope (derivative of integral)
Illuminate unbiased photoconductor with short optical pulse and terahertz field

Terahertz E-field causes carriers move
small but measurable current results
Change delay between optical pulse and THz pulse
map out E-field of THz pulse
Carrier lifetime of photoconductor now becomes important
sets detection bandwidth
early implementations used radiation damaged silicon
currently low-temperature grown GaAs usually used

lifetimes typically < 1 ps ("best" around 250 fs)
measurable signal up to 5-6 THz
Typical Setup

Modelocked Laser

THz emitter

ball lens

off-axis paraboloid

THz receiver
Our simple description of THz generation suggests it is a **half** cycle pulse

Experiments show a single full cycle pulse – why?

Propagation of THz pulse must be considered

  Close to point source, low frequencies diffract strongly

Using a larger area emitter (gap ~ cm) it is possible to generate a half cycle pulse at reasonable distances

  Large area increases beam size, range of near field

  High pulse energy used to generate comparable carrier density

  Large field strengths achievable (few 100 kV/cm)
Optical rectification – emitter

Consider a laser incident on a second harmonic crystal:

\[ E_{out} = E_{in}^2 = \left( \hat{E}_{in}^2 \cos^2(\omega t) \right) = \hat{E}_{in}^2 \frac{1}{2} \left( 1 + \cos(2\omega t) \right) \]

second harmonic

optical rectification (DC)

Physically:
Consider anharmonic oscillator
When it is driven hard, the average position actually shifts

If \( \hat{E}(t) \) is a pulse this term will track the pulse intensity

(can also be viewed as difference frequency generation
(optical rectification occurs for single mode CW, but it is not a pulse)
Electro-optic effect detection

Detection of THz also possible using $\chi^{(2)}$

Electrooptic effect:

- $n$ depends on an applied electric field
- THz pulse acts as applied field
- Polarization of copropagating fs pulse is modified
  - $45^\circ$ relative polarizations
- Change in polarization measured using balanced detection

Much larger bandwidth

- response effectively instantaneous
- phonon resonance limit
  - walk-off between THz and optical frequencies
Generation of “Intense” THz pulses

Plasmas
Two-color pulse

Asymmetric ionization by two-color field

Tilted pulse front generation in electro-optic crystal

Can achieve μJ pulses, 15 MV/cm fields (3 mJ, 800 nm pump pulses)
Applications of THz

Physics
  Transport
  Onset of screening
  Hall-effect at THz frequencies

Spectroscopy
  Ro-vibrational spectra of molecules

Imaging
  See inside certain types of packaging
  Chemical sensitivity
  Density sensitivity
  Tomography
Transport

Onset of screening

Inject electrons & holes into semiconductor to generate plasma
Probe with THz field around plasma frequency
Response changes as carriers correlate to screen

n-doped semiconductor sample placed in magnetic field
Results in transfer of energy between polarization states of THz wave
THz time-domain spectroscopy

Acquire terahertz waveform in time-domain
Take FFT to obtain spectrum
Similar to FT-IR spectroscopy
   Main advantage is that gated detection
   allows room temperature operation

Images can be made using THz pulses
   Based on absorption or delay
Similar setup to TD THz spectroscopy, except THz beam is focused by second set of parabaloids
Sample is rastered through focus
Commercially available

Plate 1. THz image of a packaged semiconductor integrated circuit (plastic packaging).

Terahertz tomography

It is possible to perform tomographic reconstruction of an object using THz pulses

The best application of Terahertz...

...detection of contaminants in a chocolate bar.