THz environmental spectroscopy

Study #1: Development of a low-power terahertz-optical bench

Study #2: Study of THz waveguide

J. Guise[1], H. Ratovo[1], G. Humbert[2], T. Taliercio[1], L. Cerutti[1], J.-B. Rodriguez[1], T. Reck[3], J. Hesler[3], F. Gonzales-Posada Flores[1], A. Pénarier[1], P. Nouvel[1], E. Centeno[4] and S. Blin[1]

[1]IES, Univ. Montpellier, CNRS, Montpellier, France
[2]Institut de recherche XLIM, UMR CNRS, Univ. Limoges, France
[3]Virginia Diodes, Charlottesville, Virginia USA
[4]Institut Pascal, Univ. Clermont-Auvergne, CNRS, Clermont- Ferrand, France

Contact information for curious readers:
julien.guise@umontpellier.fr for study #1
stephane.blin@umontpellier.fr for study #2

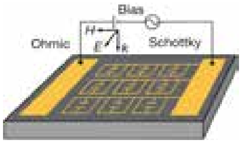
Introduction & Context

Terahertz frequency range (THz)

- In between microwave (5G) & infrared (optical fibers technology) ranges
- Frequencies: 0.1 — 10 THz | Corresponding wavelength: 3 mm — 30 µm
- Applications: spectroscopy, medical imaging, telecomunication, etc.

THz technological gap

- Lack of THz technology: sources & detectors
  - ➲ Not many modulators (efficient, fast, cheap & integrated)
- Good candidates: **active metamaterials**
  - ➲ Electrical: surface resonators (SRR)
  - ➲ Mechanical & Thermal: Vanadium Dioxyde (VO_2)
  - ➲ 2D materials: Graphene, TMDC (MoS_2)
  - ➲ **Optical: control of the device using light**



[1] Y. Yang et al., ACS Photonics, vol.4, no 1, p. 15-21, (2017)

Motivations

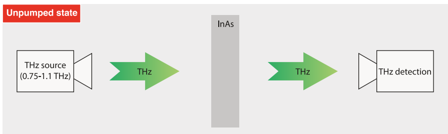
Setting up an experimental bench that can:

- Use the concept of **synchronous detection** for detecting weak signals
  - ➲ To implement synchronous detection, **modulation of the terahertz wave** is required: an optical method developped at **IES laboratory** to control terahertz wave will be used
- Characterize the spectral fingerprint of key **environmental substances** (atmosphere, volatile organic compounds, gases, etc.)
  - ➲ To be able to interact with the free space susbtances, a **novel anti-resonant terahertz waveguide** developped at **XLIM laboratory** will be used

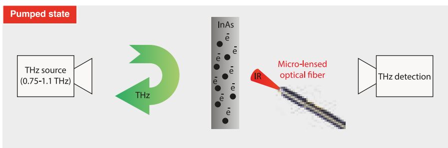
Optical control of THz waves

Optical control of the THz transmission

- **Unpumped state:** InAs is a dielectric (non-intentionnaly doped)
  - ➲ THz wave passes through without interaction (no losses)



- **Pumped state:** InAs behaves like a metal
  - ➲ Infrared (IR) pump is absorbed & creates free carriers
  - ➲ THz wave is reflected (screened by the free carriers)



Thickness of InAs : 1 — 5 µm
(From absorption length of IR pump to maximum diffusion length of free carriers)
Frequency range : 0.75 — 1.1 THz
Wavelength ~ 300 µm
thickness << λ
(meta-surface)

Switched by optical pump & carrier lifetime

Key parameters:
- ➲ Optical density
- ➲ InAs thickness
- ➲ InAs carrier lifetime
- ➲ InAs cristalline quality (linked to the lifetime)

- **The switch dynamic is governed by 2 phenomena:**

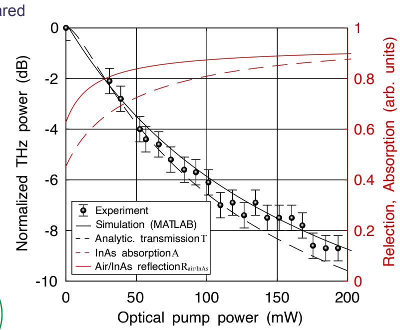
1. Pump is turned on: free carriers are **instantaneously** created
2. When the pump is turned off: **it takes a time before the carriers disapear** (carrier lifetime)

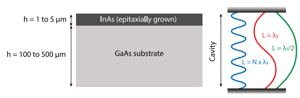
Optical control in "attenuation mode"

How much can terahertz transmission be reduced through pumping ?

- ➲ Optical pump : pumping in near infrared **0—400 mW @1064 nm**
- ➲ THz frequency: **810 GHz** (on a Fabry-Perot) resonance
- ➲ Spectrum analyzer : transmitted or reflected power measurement

- ☑ Modulation efficiency of 9 dB
- ☑ ~ 90 % signal suppression
- ☑ 20 MHz modulation bandwidth
- ☑ Simplicity of design
- ☑ Low power consumption
- ☒ Deleterous Fabry-Pérot effect





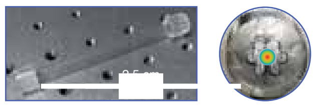
[2] J. Guise, IEEE Trans. on Tera. Sci. and Technol. (2026)

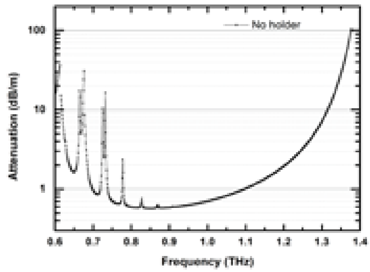
Guided propagation of THz waves

Hollow-core and anti-resonant capillaries waveguides

- Silica capillaries (silica loss at 1 THz: 900 dB/m)
- Anti-resonance of the capillaries = confinement within the core
- Performance: < 1 dB/m in the 0.75–1.1 THz range
- Structure comparable to "revolver fibers" (AR-HCF) and ARROW guides
- Tunability of the frequency range as a function of geometry
  - ➲ Capillary thickness, capillary spacing = mode size
  - ➲ Technological maturity: manufacturing in a fiber drawing tower

- ☑ Linear losses < 1 dB/m
- ☑ Frequency tunability
- ☑ Single-mode operation (HE_{11})
- ☑ Circular-geometry modes
- ☑ Simplicity of design (silica)
- ☒ Modes diameters > 1 mm
- ☒ Sensitivity of structural defects
- ☒ Rigid structures



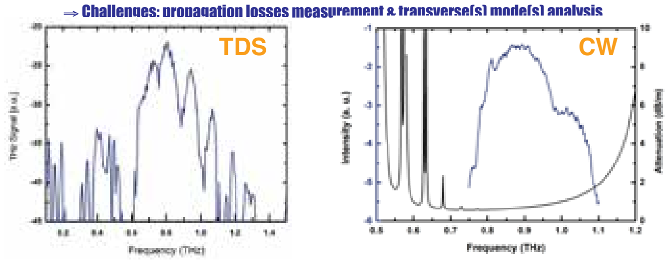


[3] G. Humbert, IRMMW-THz, pp 1-2 (2023)

Characterization in transmission

- Measurements in pulsed (TDS) and continuous-wave (CW) modes
- In CW: TE10 modes with rectangular geometry in WR1.0 waveguides
- Unmeasurable losses on guides a few centimeters long

⇒ **Challenges: propagation losses measurement & transverse(s) mode(s) analysis**

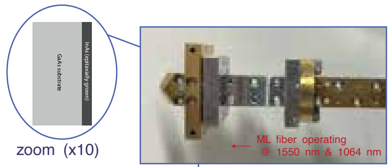


Example of experimental bench

Optical-terahertz characterization bench in transmission

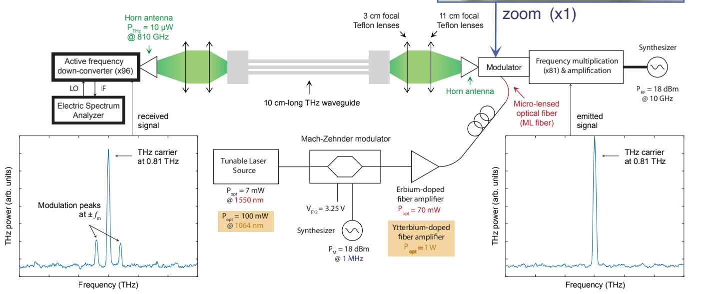
- **Free-space** system combining optical and terahertz **guided** components
  - ➲ THz: electronic frequency-multiplying source (x 81) and detector (0.75–1.1 THz)
  - ➲ Optics: (1550 nm & 1064 nm): tunable, coherent laser sources, optical amplifiers (Erbium, Ytterbium), Mach-Zehnder modulators (10 GHz), polarization-maintaining fibers, micro-lensed fibers (M. Thual, Foton)
  - ➲ Instruments: GPIB-controlled electrical spectrum analyzer

Sample features :
5-µm-thick InAs epitaxial layer
500-µm-thick GaAs substrate
Hall measurements: $n_0 \approx 10^{16}$ cm^{-3}
Insertion losses : ~ 5 dB



zoom (x10)

zoom (x1)



Objectives

By the end of the internship, we expect:

- ➲ To be able to measure the waveguide losses, to calibrate the bench for quantitative analysis
- ➲ To optimize the modulation of the terahertz wave using optics, in transmisison mode or reflection mode, to increase the signal-to-noise ratio of the synchronous detection method

☺ **Thank you for taking the time to read this poster !**