Institut de Physique et Chimie des Matériaux de Strasbourg

Faculté de physique et ingénierie
Université de Strasbourg

THz dynamics of an antiferromagnet at the nanoscale

CASTILLO GUERRERO Adán
LEROY Victor

IPCMS, under supervision of Drs. M. Bailleul & P. Noel

Introduction

THz domain

Domain of light:

$$\nu \rightarrow 1\mathrm{THz} = 10^3\mathrm{GHz}$$

$$\lambda \rightarrow 1\mathrm{THz} \approx 300\mu\mathrm{m}$$

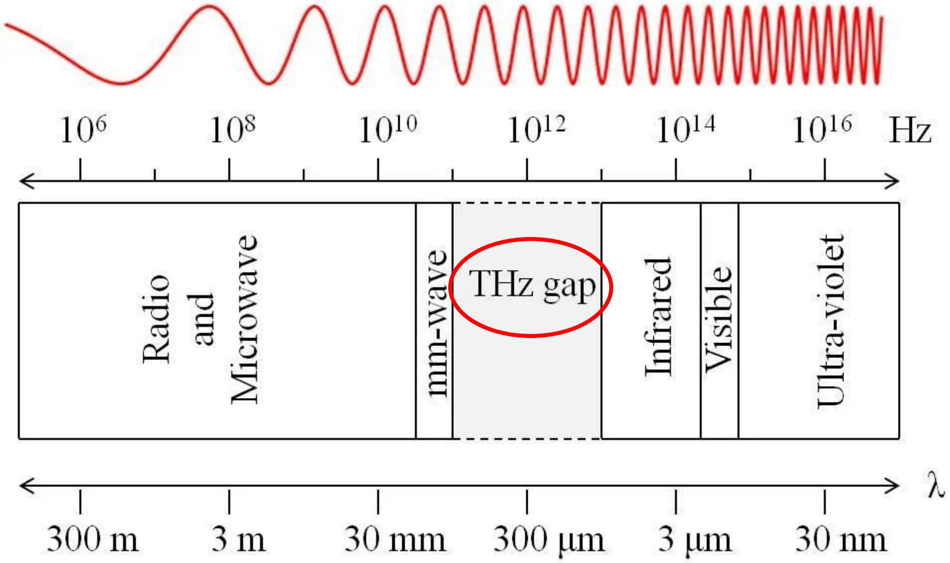


Figure : location of the THz gap in the electromagnetic spectrum (Khiabani, 2019).

THz gap

technological gap

$$0.1 \rightarrow 30\mathrm{THz}$$

THz gap

technological gap

$$0.1 \rightarrow 30\text{THz}$$

- Commercial GHz emission:

    100mW at 10 GHz (5G home router)

THz gap

technological gap

$$0.1 \rightarrow 30\mathrm{THz}$$

- Commercial GHz emission:

  100mW at 10 GHz (5G home router)

- State of the art THz emission:

  10μW at 500GHz (TeraScan 1550)

THz gap

technological gap

$$0.1 \rightarrow 30\mathrm{THz}$$

- Commercial GHz emission:

    100mW at 10 GHz (5G home router)

- State of the art THz emission:

    10µW at 500GHz (TeraScan 1550)

Requirements become bigger and expensive very fast

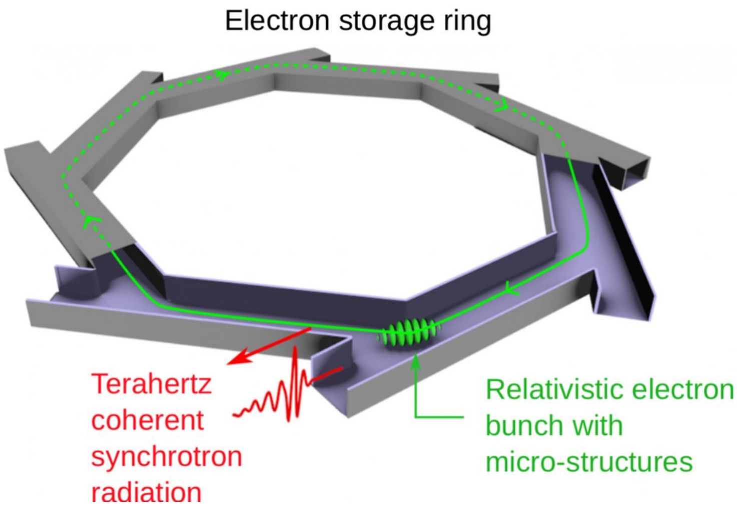


Figure : THz production at SOLEIL (Evain, 2019).

THz gap

technological gap

$$0.1 \rightarrow 30\mathrm{THz}$$

- Commercial GHz emission:

  100mW at 10 GHz (5G home router)

- State of the art THz emission:

  10µW at 500GHz (TeraScan 1550)

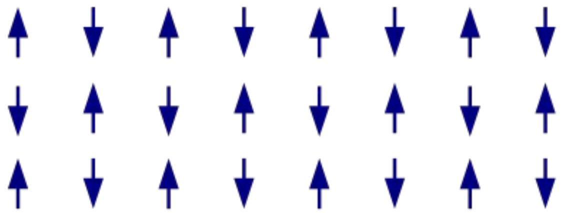
Requirements become bigger and expensive very fast

THz tech is on his infancy

To breach it

Materials !

Antiferromagnets



Solid state lecture reminder:

$$H = -\gamma \sum_{i,j} J_i^z J_j^z + g\mu_B B \sum_i J_i^z - W_{\text{anis}}$$

exchange

external field

anisotropy

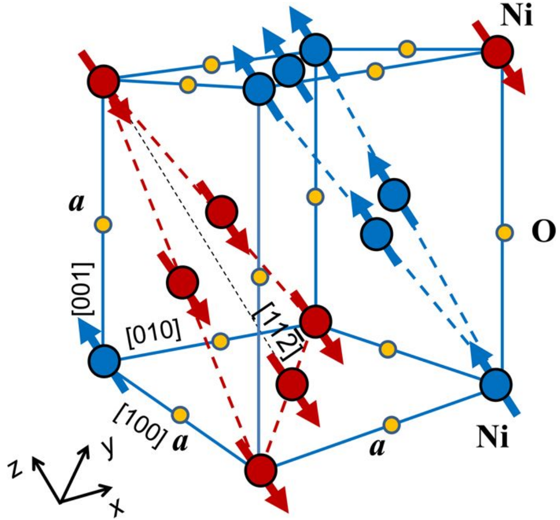


Figure : NiO crystal structure (S. Rezende, et. al, 2019).

Antiferromagnetic resonance

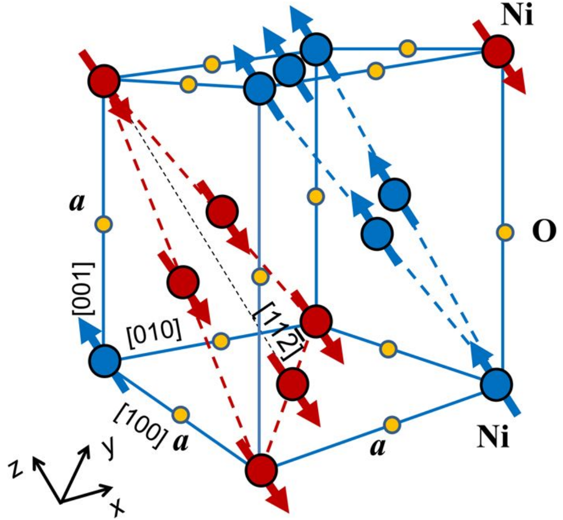


Figure : NiO crystal structure
(S. Rezende, et. al, 2019).

Application of external magnetic field

↓

Spin precession around equilibrium positions

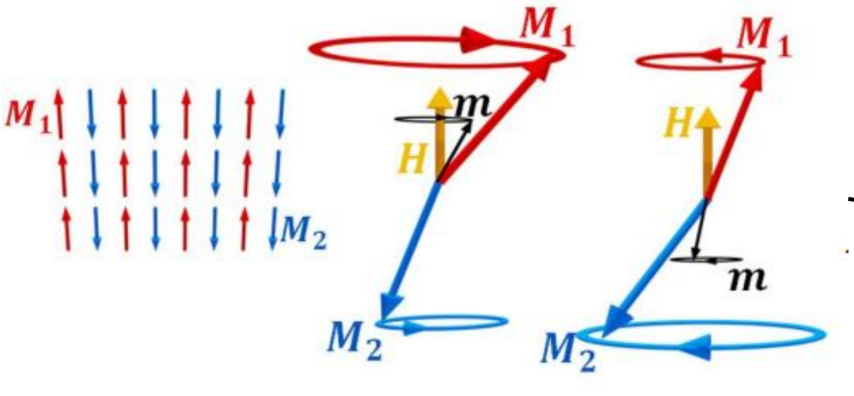


Figure : Precessions of the two modes of antiferromagnetic resonance (P. Noël, 2023).

$$\omega_{res} = \gamma\mu_0\sqrt{2H_AH_E} \pm \gamma\mu_0 H$$

$$\approx 0.1 - 2\mathrm{THz}$$

How can we measure AF resonance ?

How can we measure AF resonance ?

And how can we improve upon it ?

Outline

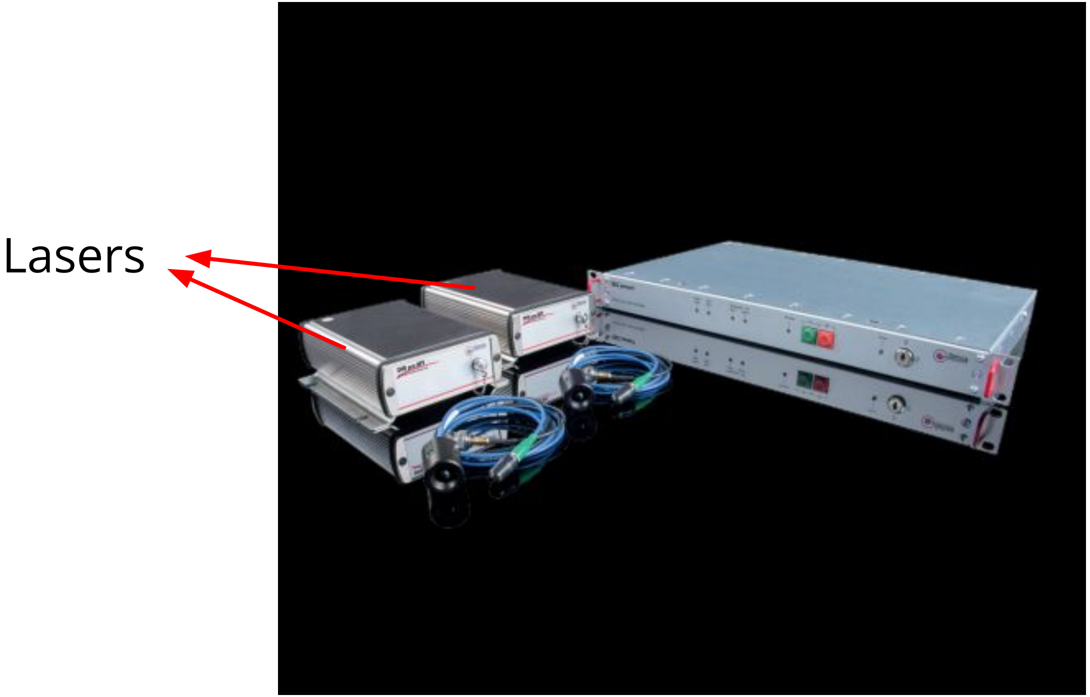
1. Experimental setup :
   - ➔ Refractive index
   - ➔ NiO resonance

2. Improving measures :
   - ➔ Planar antennas
   - ➔ Optimization + testing

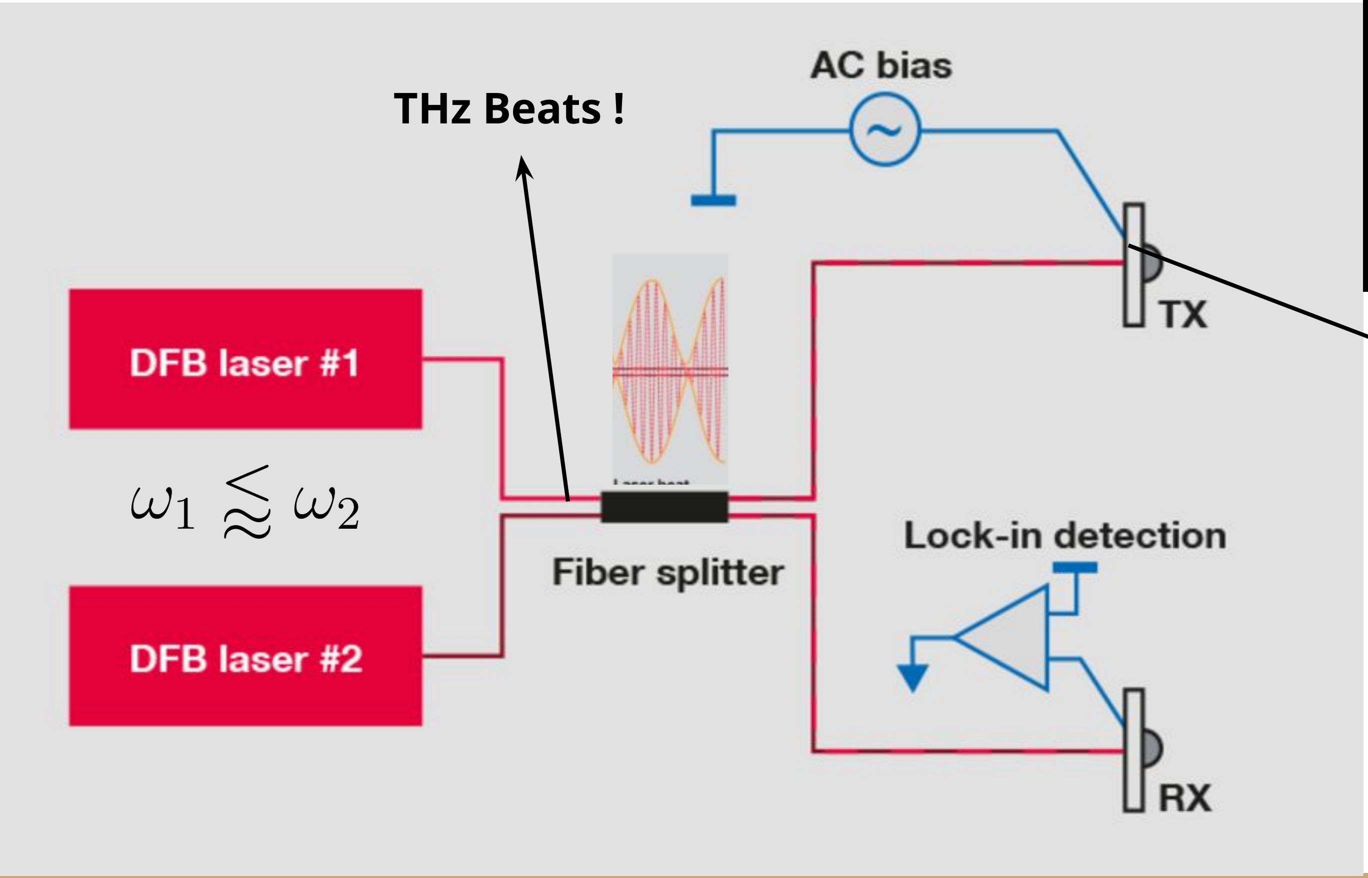
3. Conclusion

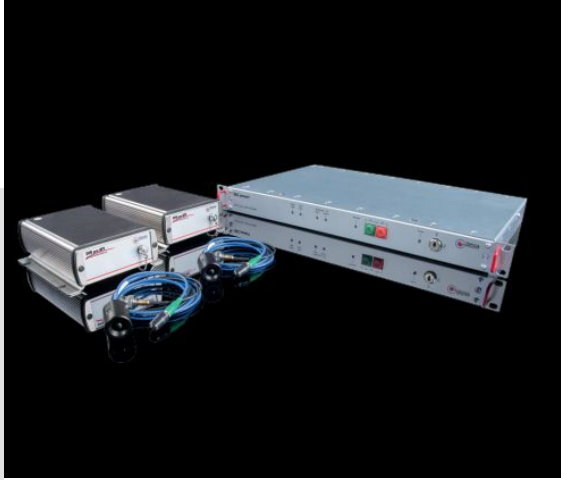
I. Experimental setup

Toptica TeraScan 1550



Toptica TeraScan 1550





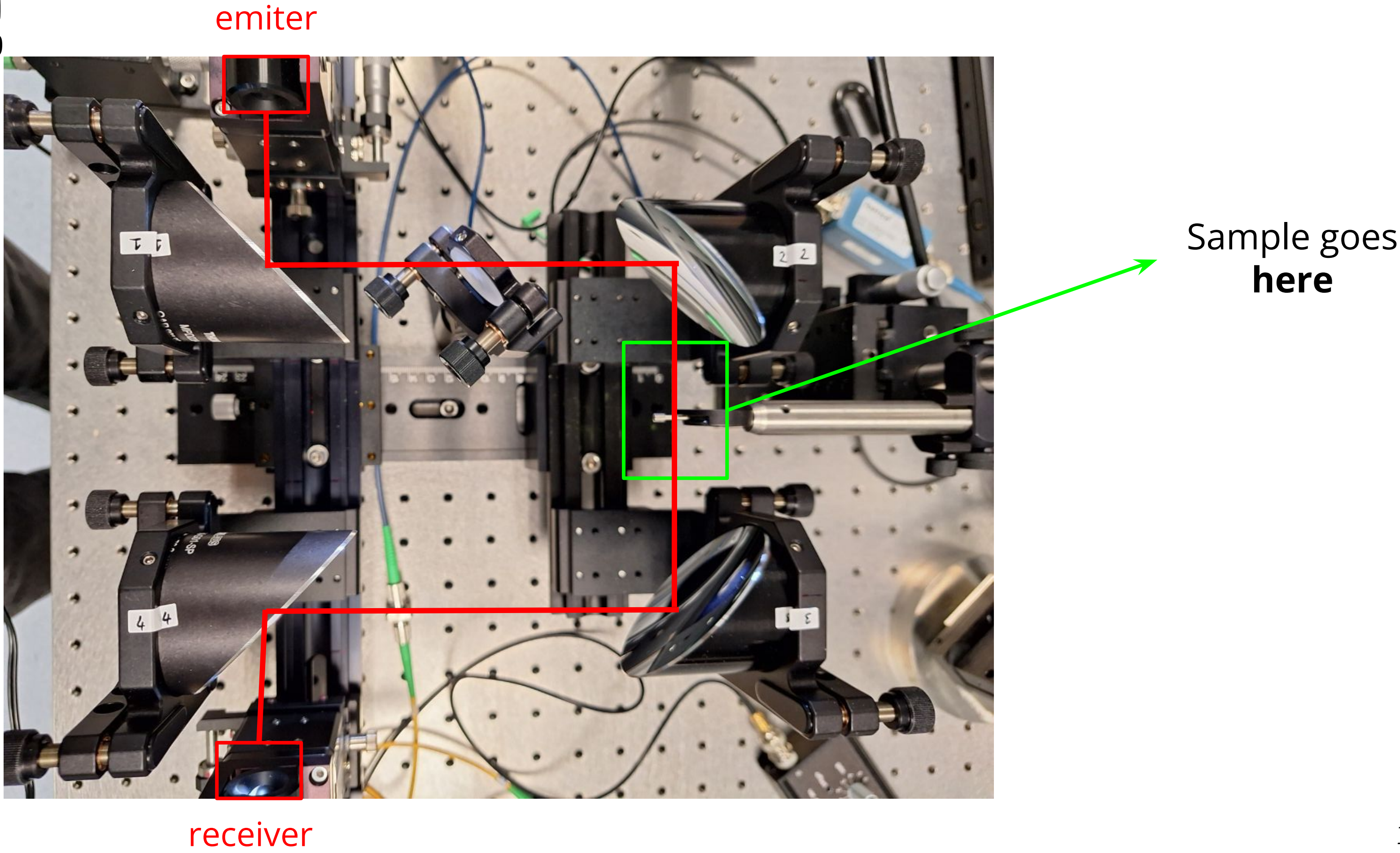
Photodiode (InGaAs / GaAs)

↓

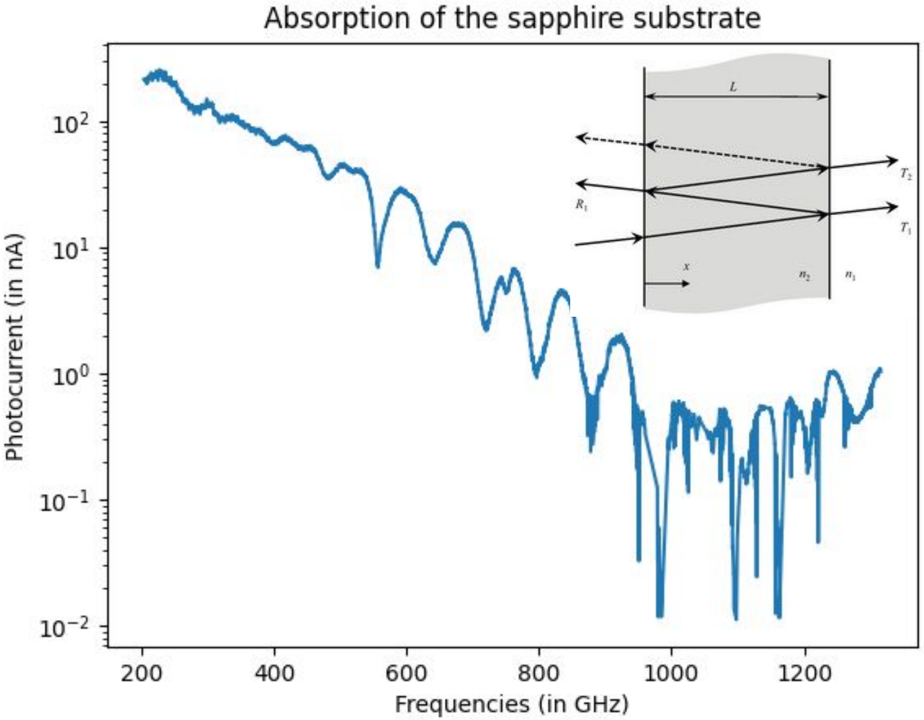
THz emission

(not the only way)

Testing



What can we measure with this setup ?

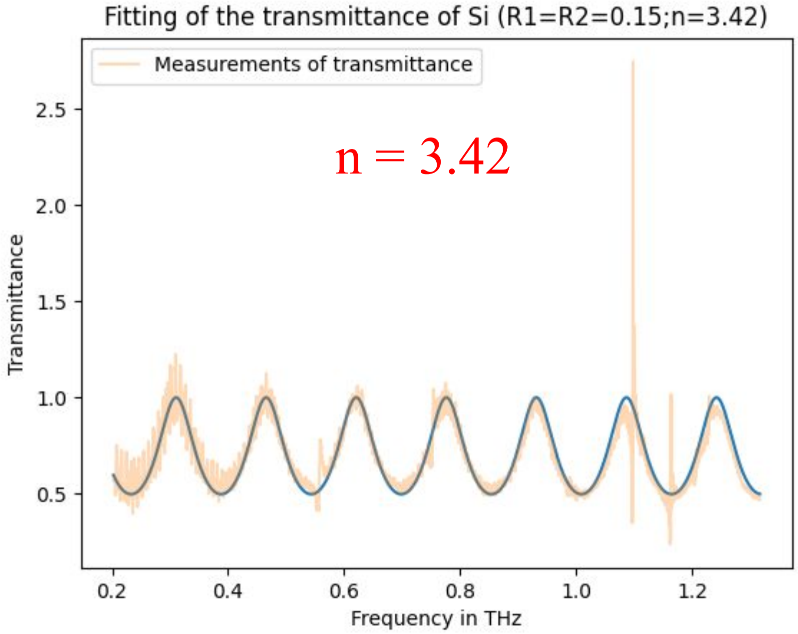


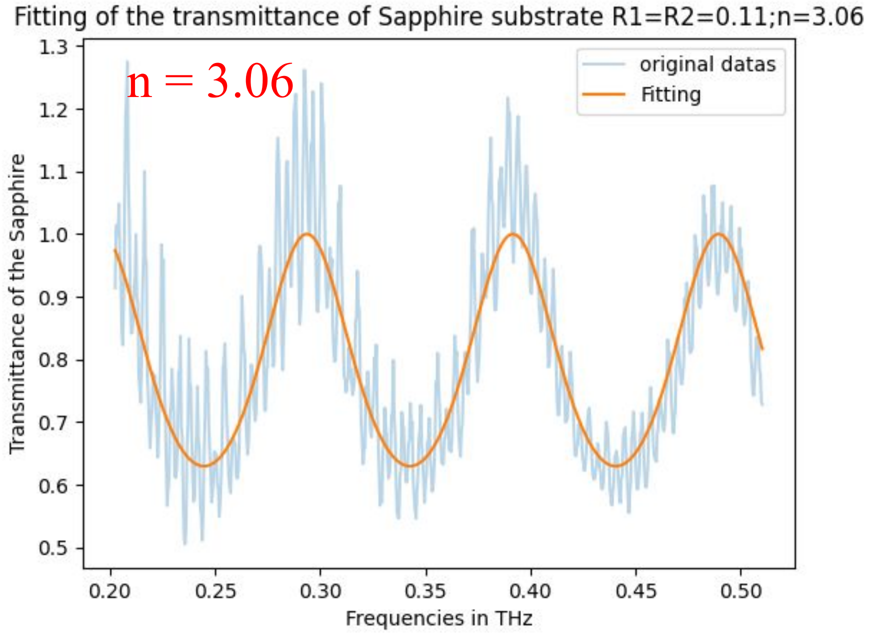
Measuring specific peak of absorption for different samples.

Visible :
Fabry-Perot interferences
+
absorption of substrate

Fitting of the Airy distribution function

$$A'_{\text{trans}} = \frac{I_{\text{trans}}}{I_{\text{inc}}} = (1 - R_1)(1 - R_2)A_{\text{circ}} = \frac{(1 - R_1)(1 - R_2)}{\left(1 - \sqrt{R_1 R_2}\right)^2 + 4\sqrt{R_1 R_2}\sin^2(\phi)}.$$





Values found within the literature

Table I. Refractive index and intensity absorption coefficients of studied materials.

Material	n	α (cm^{-1})	Comments
Silica	1.98 ± 0.02	4.2 ± 0.4	Eq. (3)
Silicon	3.56 ± 0.14	88 ± 7	High conductivity
Sapphire	3.31 ± 0.25	18 ± 4	Commercial quality

Federico Sanjuan et al. 2012

Testing - NiO

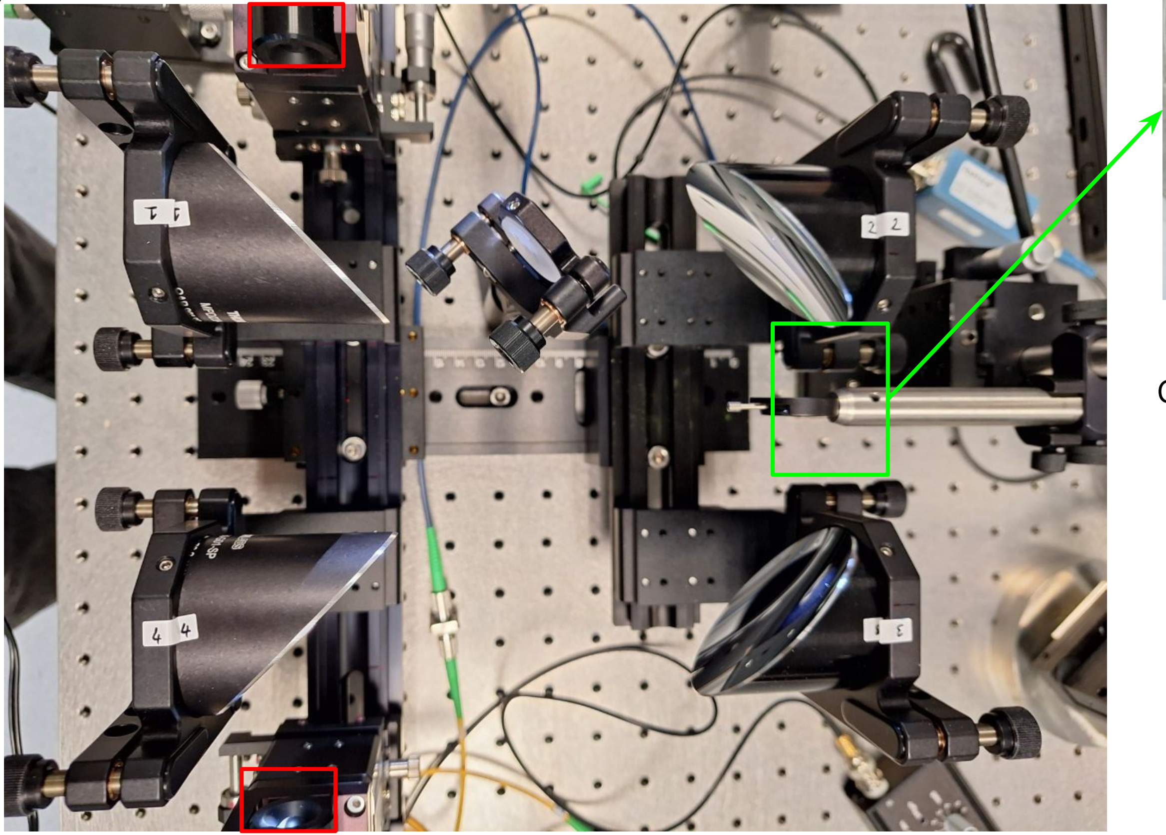


Figure : NiO sample by Christophe Lefevre (IPCMS).

Measuring AF resonance: NiO

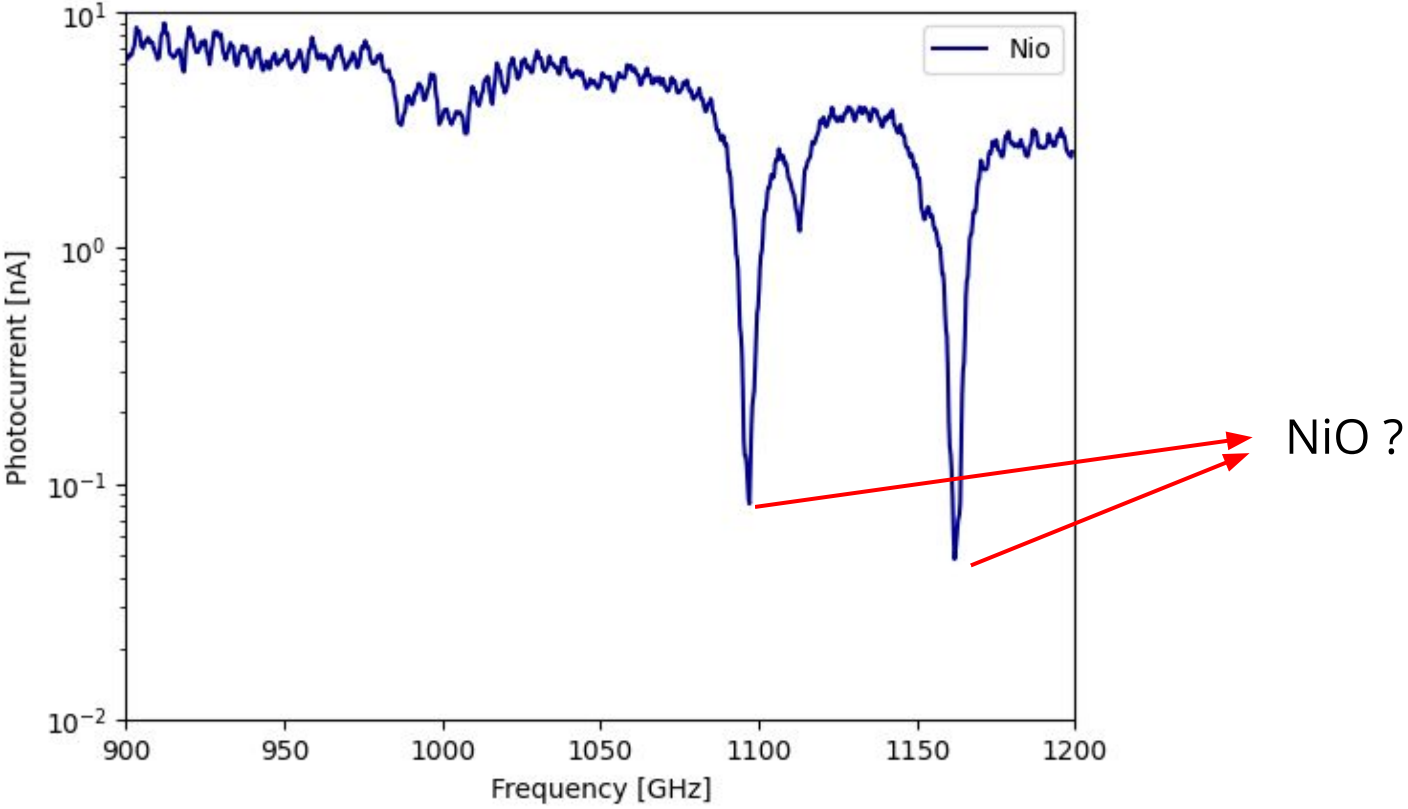


Figure : NiO sample by Christophe Lefevre (IPCMS).

Measuring AF resonance: NiO

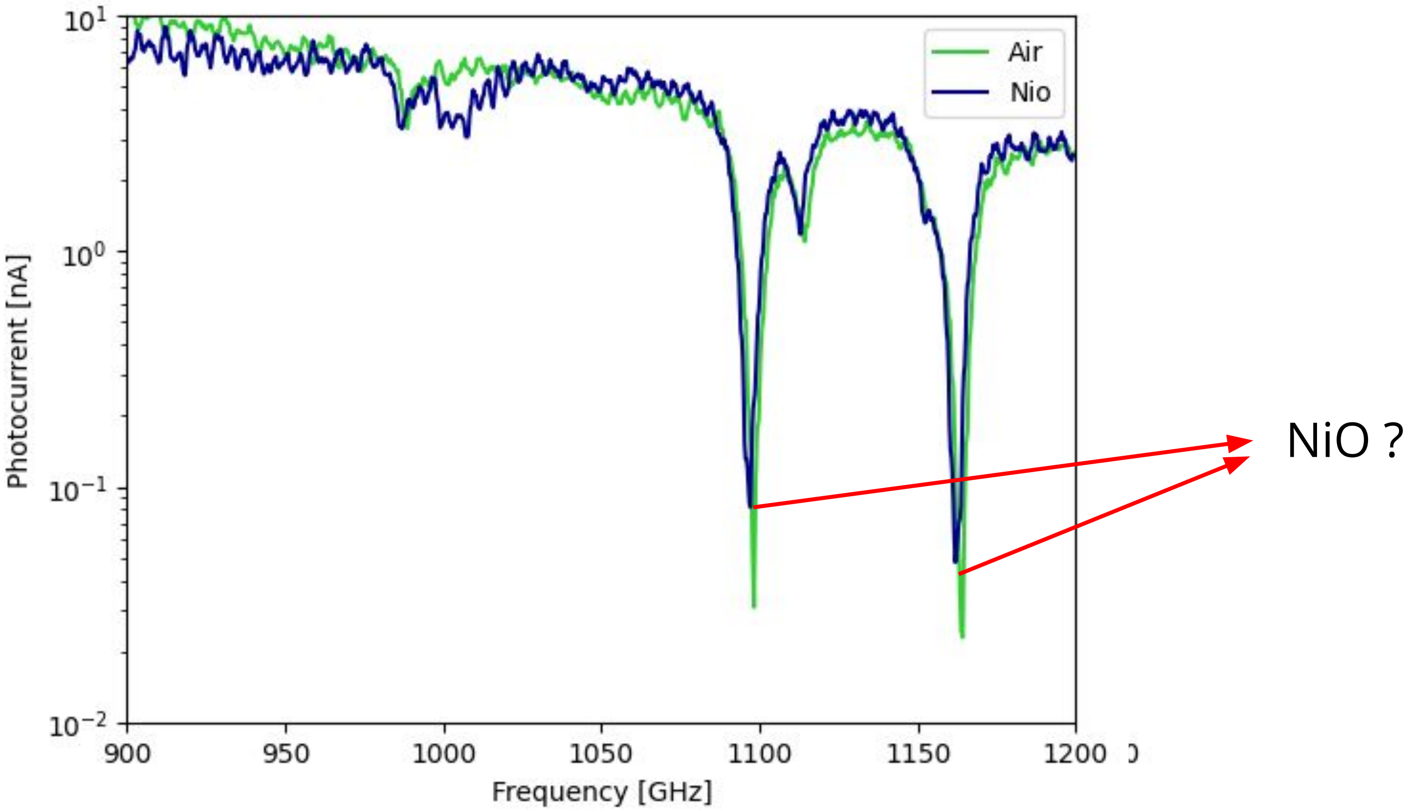


Figure : NiO sample by Christophe Lefevre (IPCMS).

Measuring AF resonance: NiO

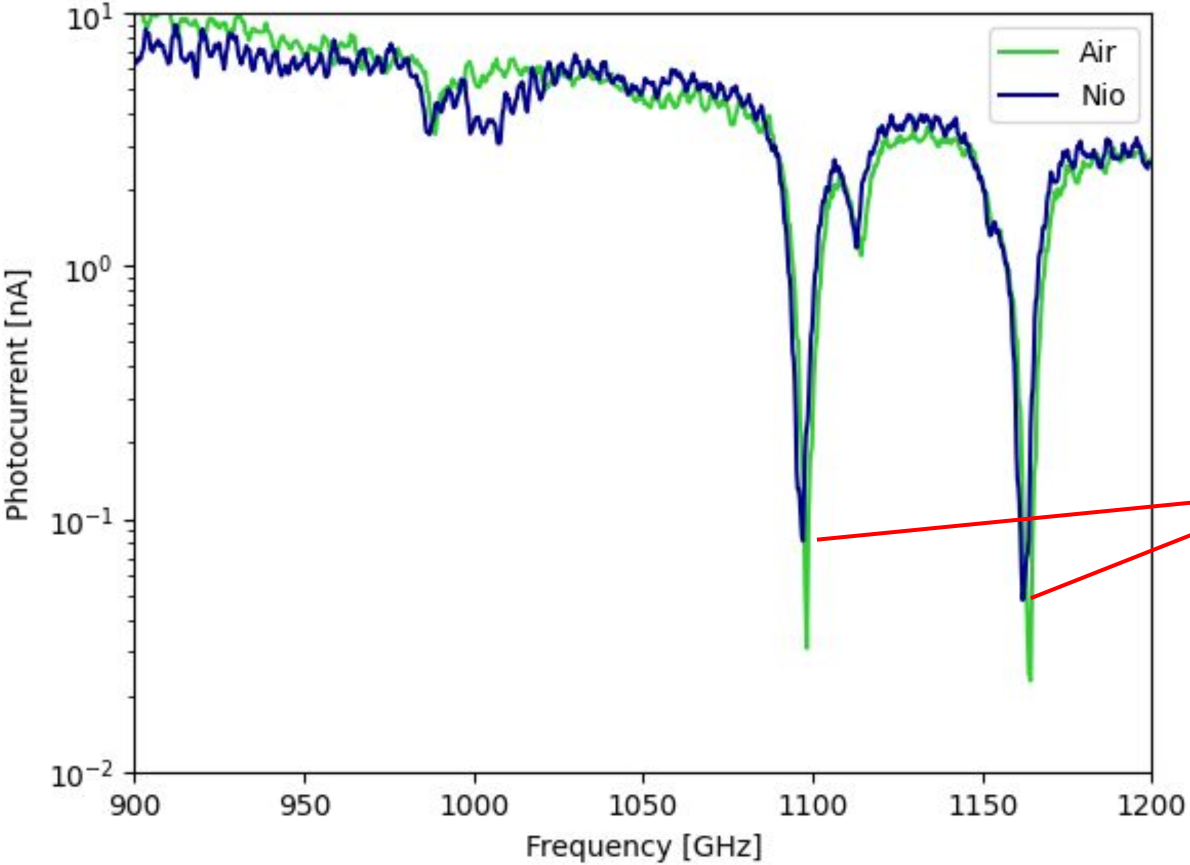


Figure : NiO sample by Christophe Lefevre (IPCMS).

~~NiO~~ ? Air absorption !

Measuring AF resonance: NiO

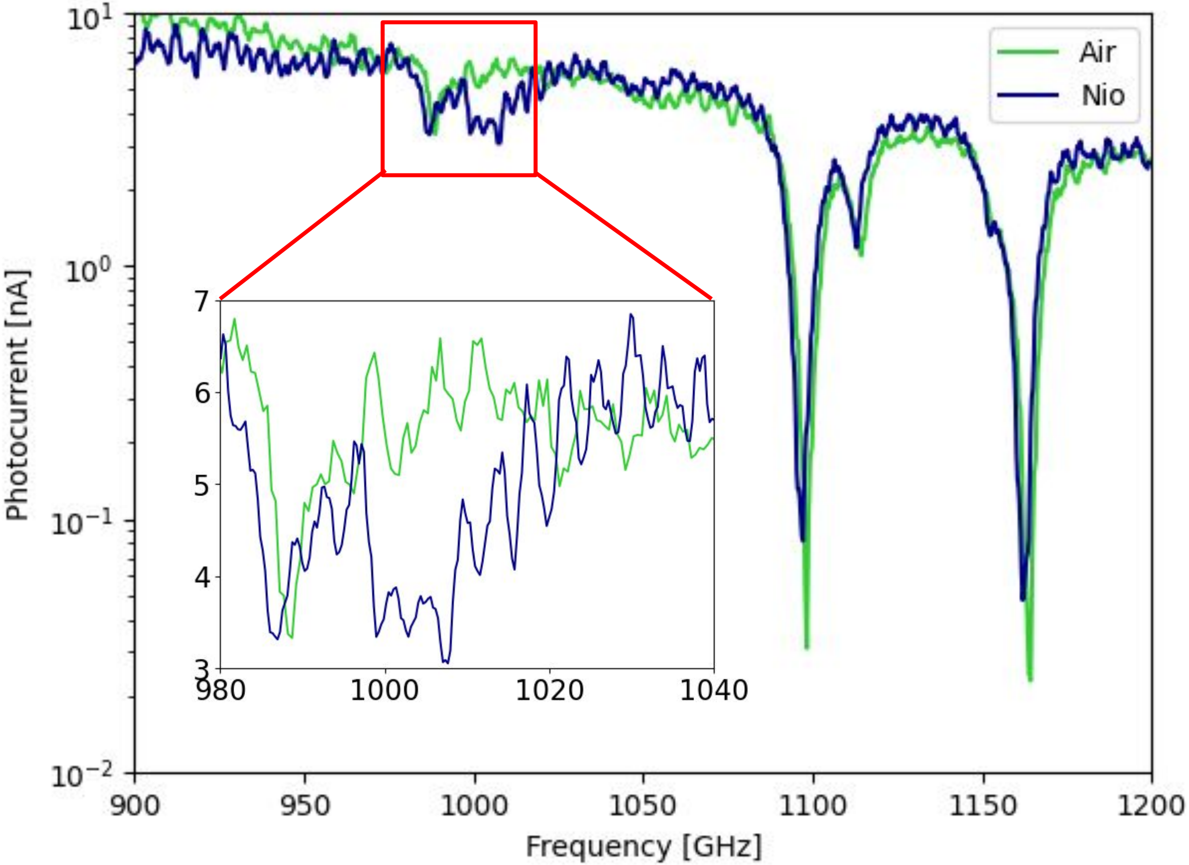
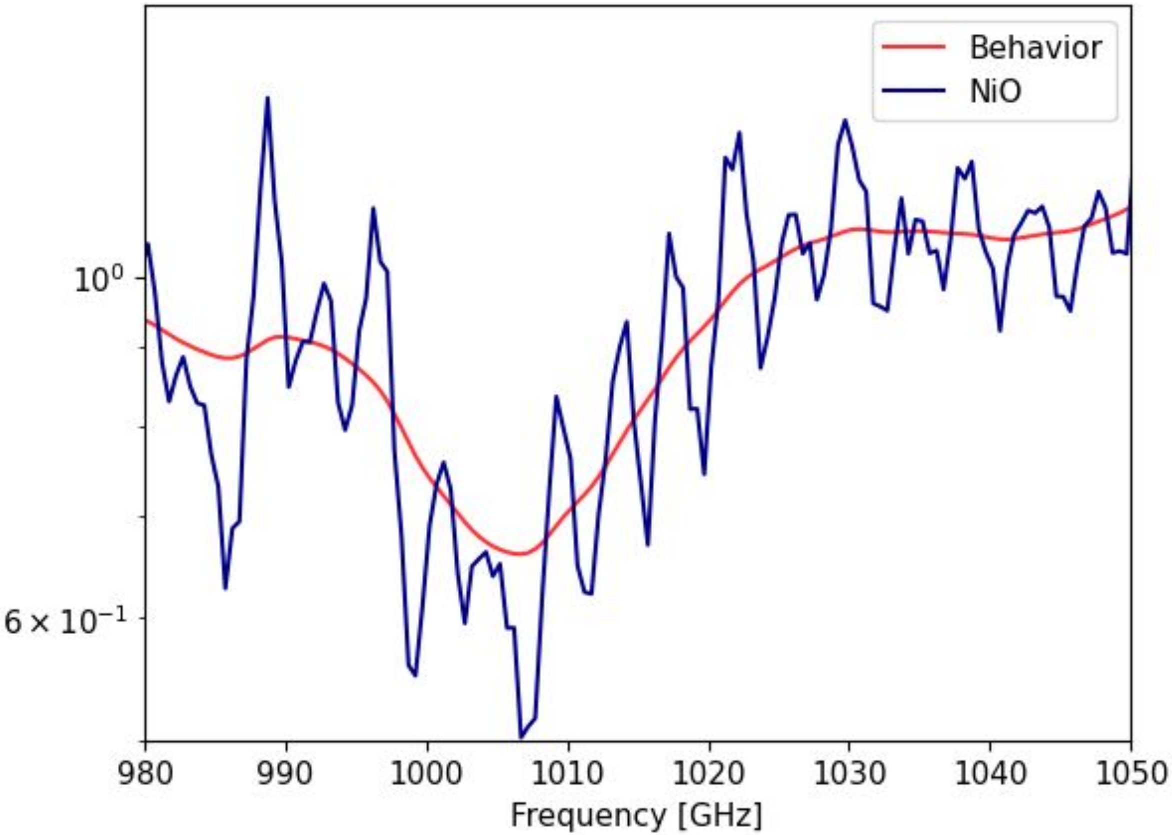


Figure : NiO sample by Christophe Lefevre (IPCMS).

~~NiO~~ ? Air absorption !

NiO behaviour visible at around 1000 GHz

Measuring AF resonance: NiO



Some things to consider:

This is a **bulk** measurement

↓

How can we improve this ?

Amplify it ?

Localize it ?

II. Improving measures

Antennas, how do they work ?

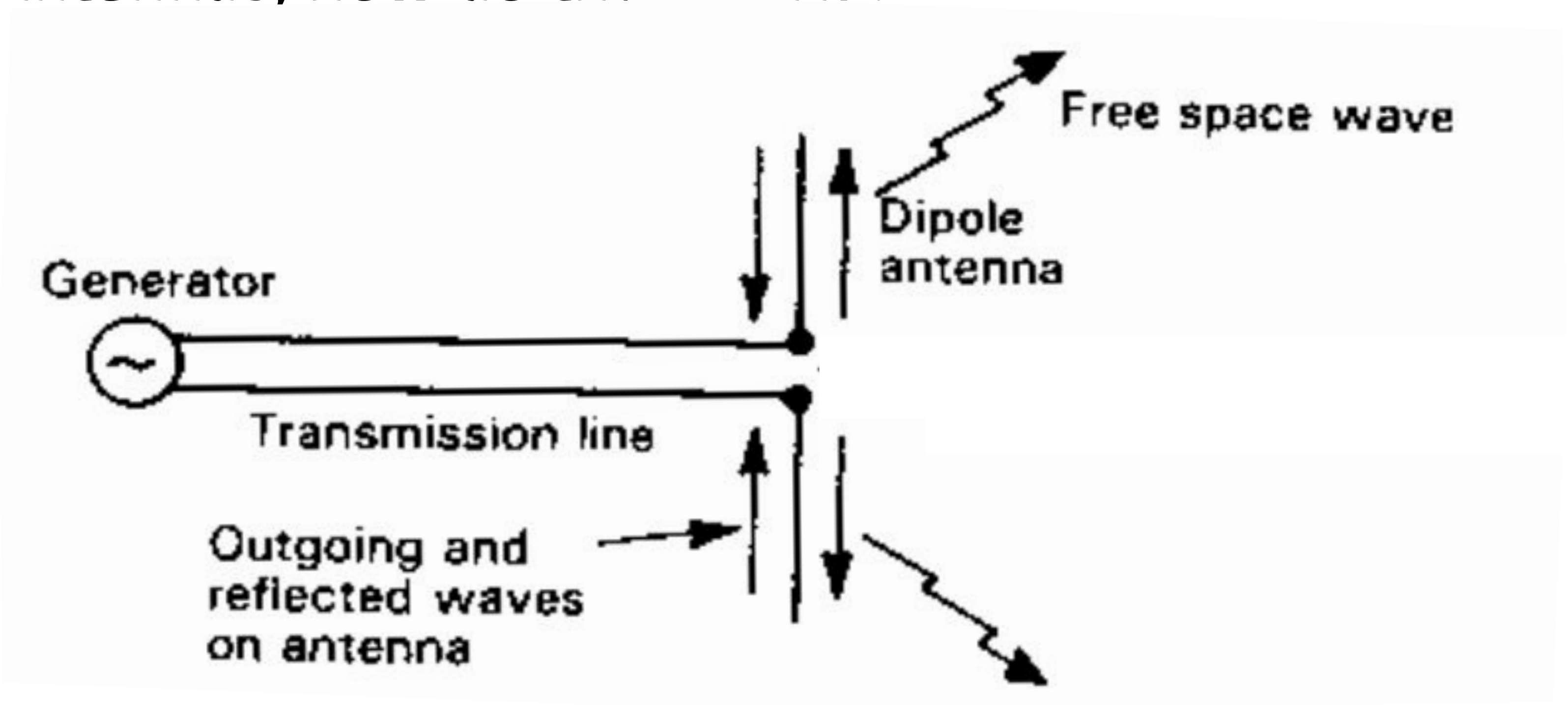


Figure : Antennas are the transition between a guided wave and a free propagating one, J. Kraus, 1988.

Antennas for THz local amplification

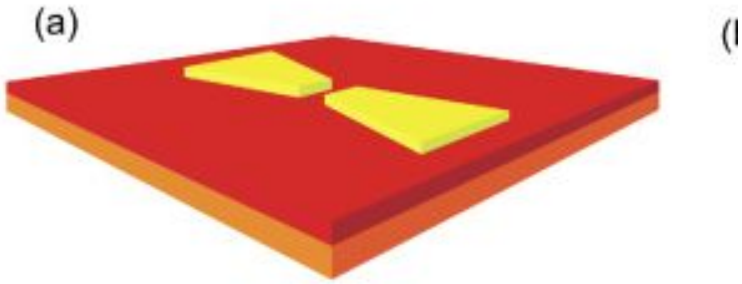


Figure : Planar antenna over substrate, Runge et al., 2020.

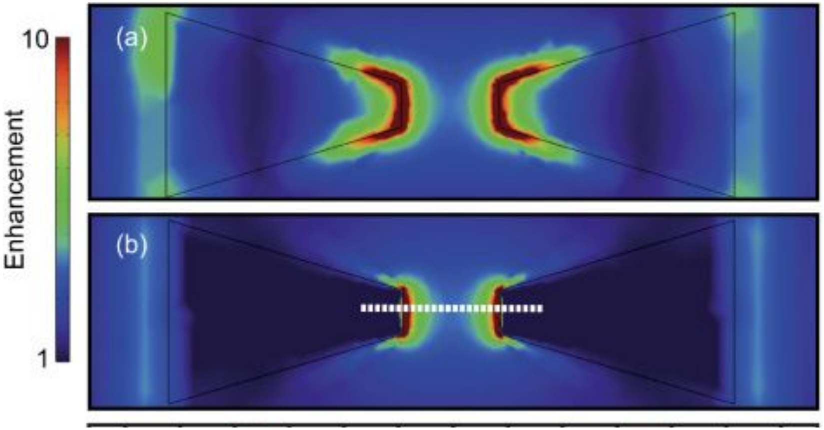
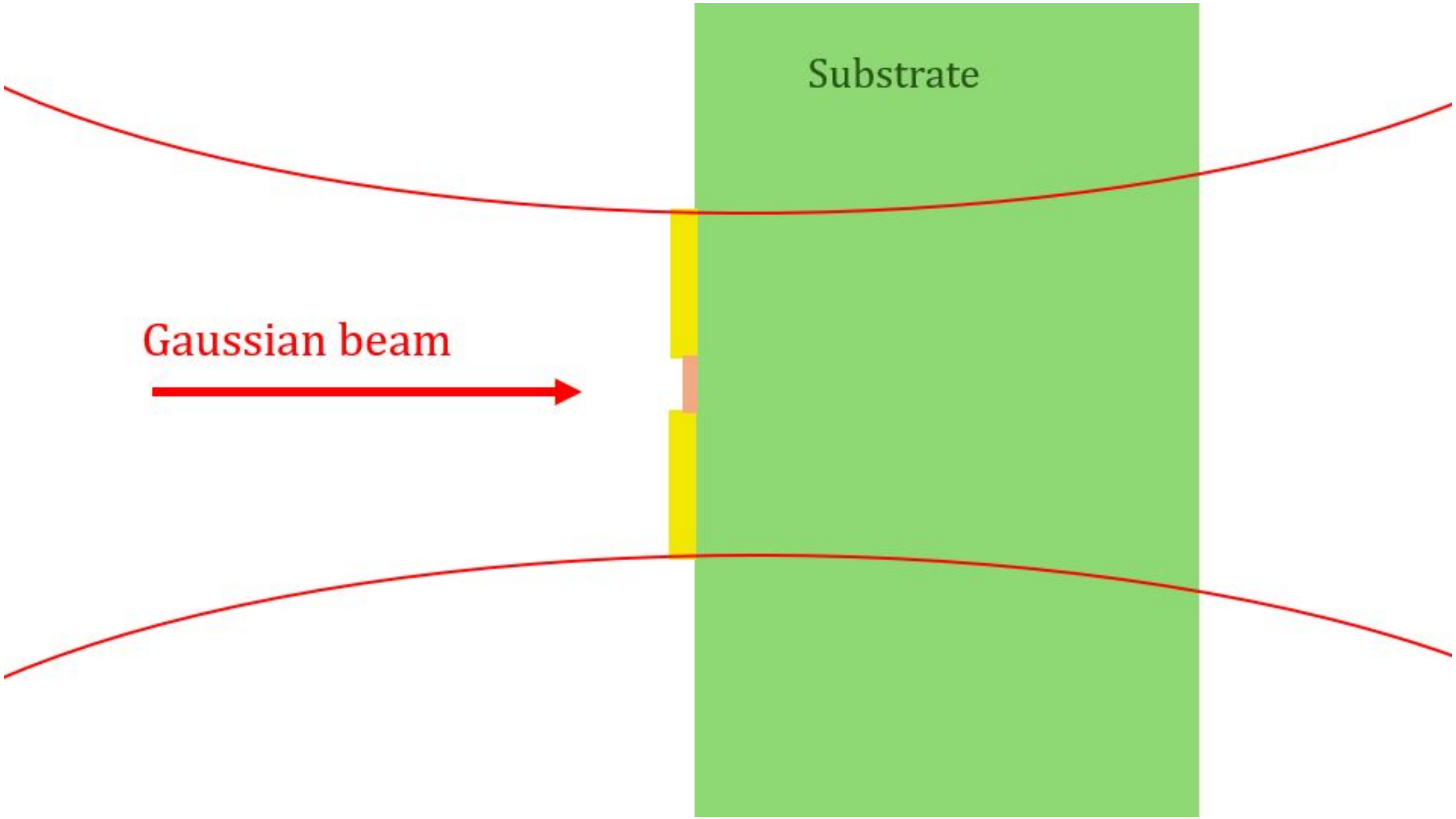


Figure : Local amplification of EM field, Runge et al., 2020.

Antennas → Field amplification

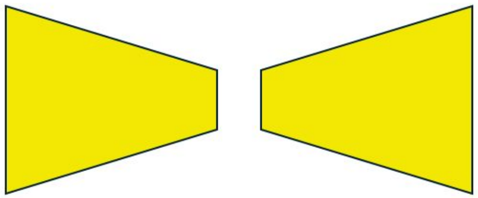
What are we doing ?



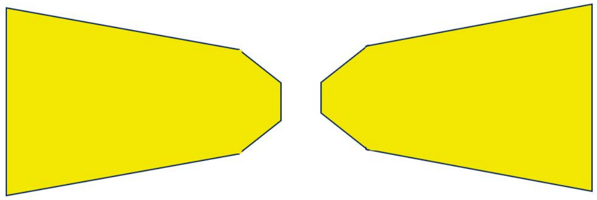
What we are looking at

Three antenna designs

Dipole



Simple bow tie

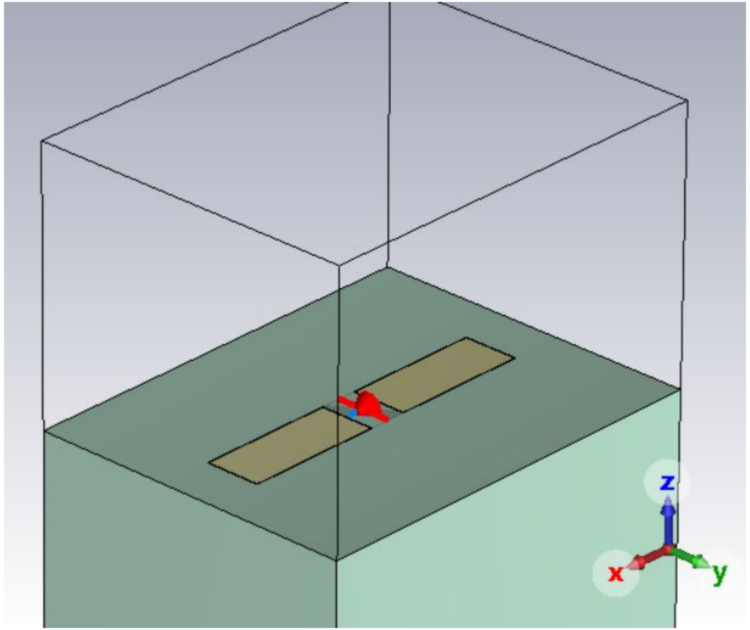


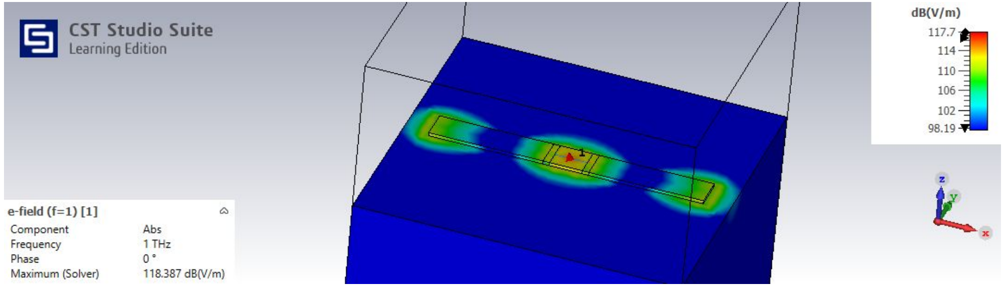
Fancy bow tie

Simulation and optimization

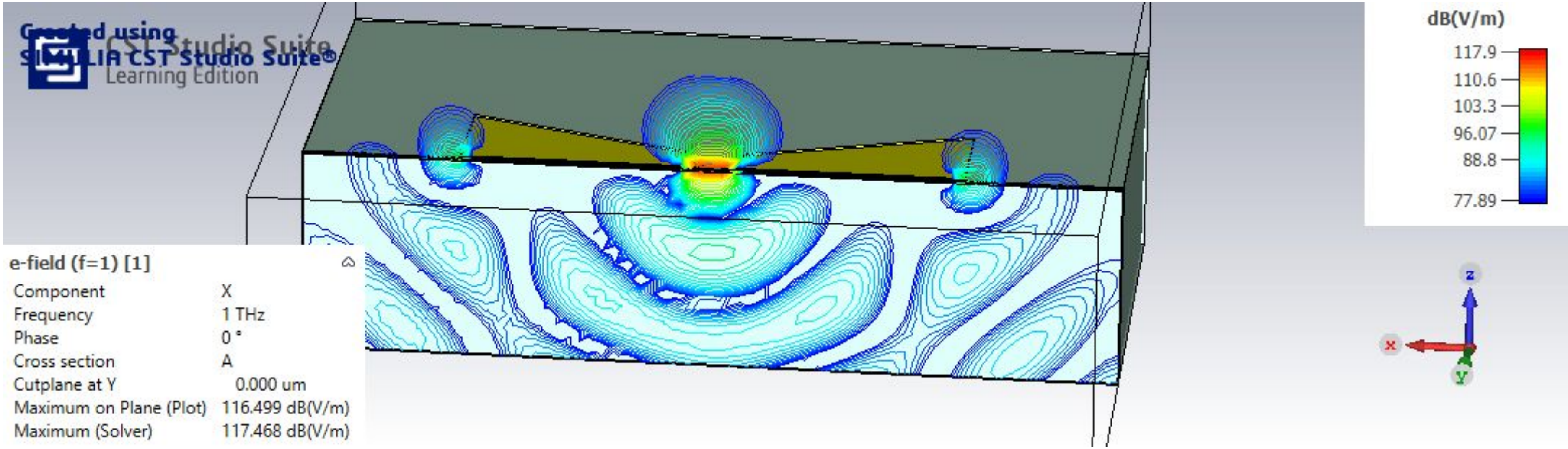
Optimization with CST.

- Over all relevant parameters
- Two ways:
    - Using plane waves
    - Using local excitation (port)





Visualisation of the absorption by the antennas:



Antennas comparison

Simulations made using a port signal

$$F = \sqrt{1 - |S|^2}$$

S : The scattering parameter

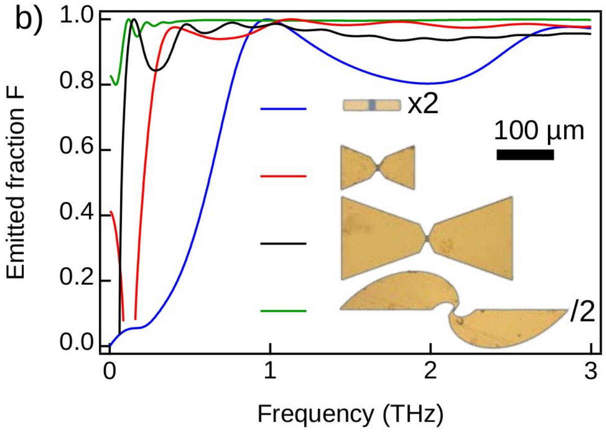
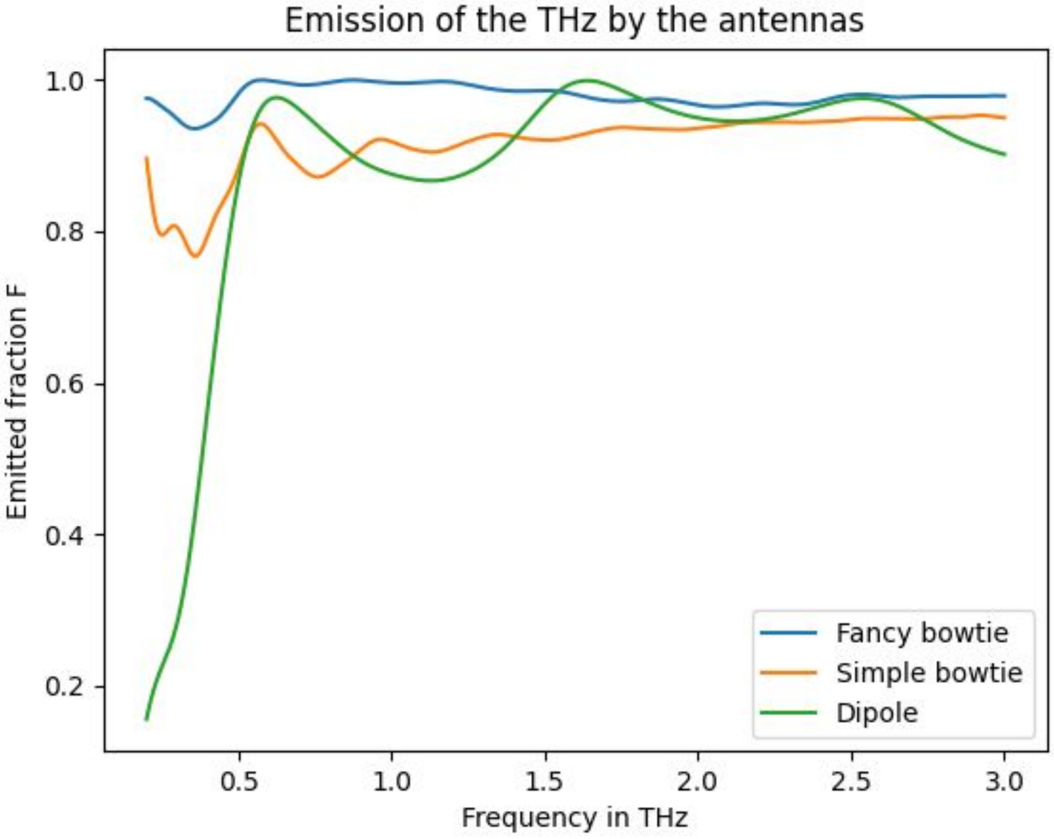
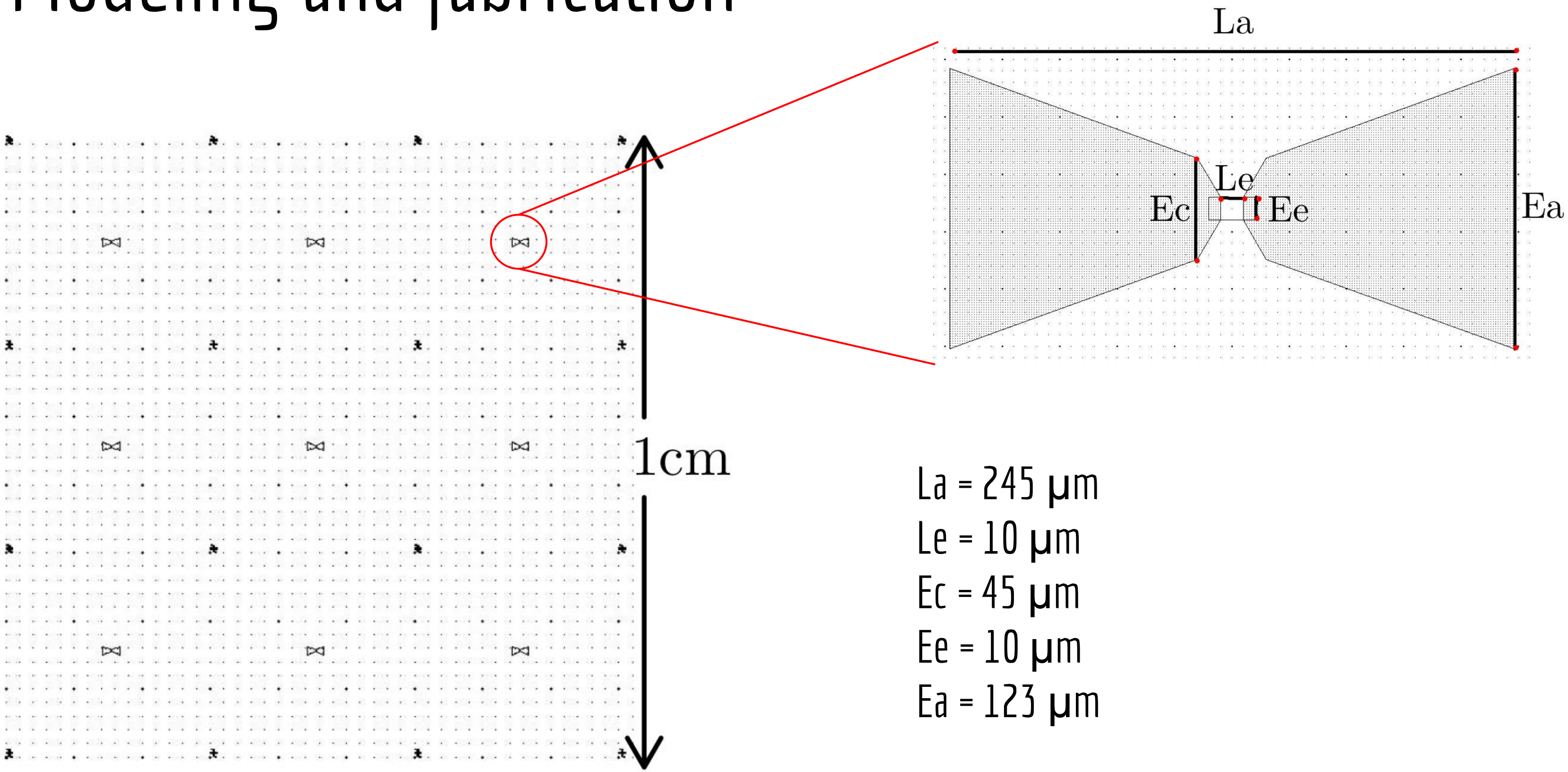


Figure : Antenna emission,
(M. Pacé, et al. 2024)

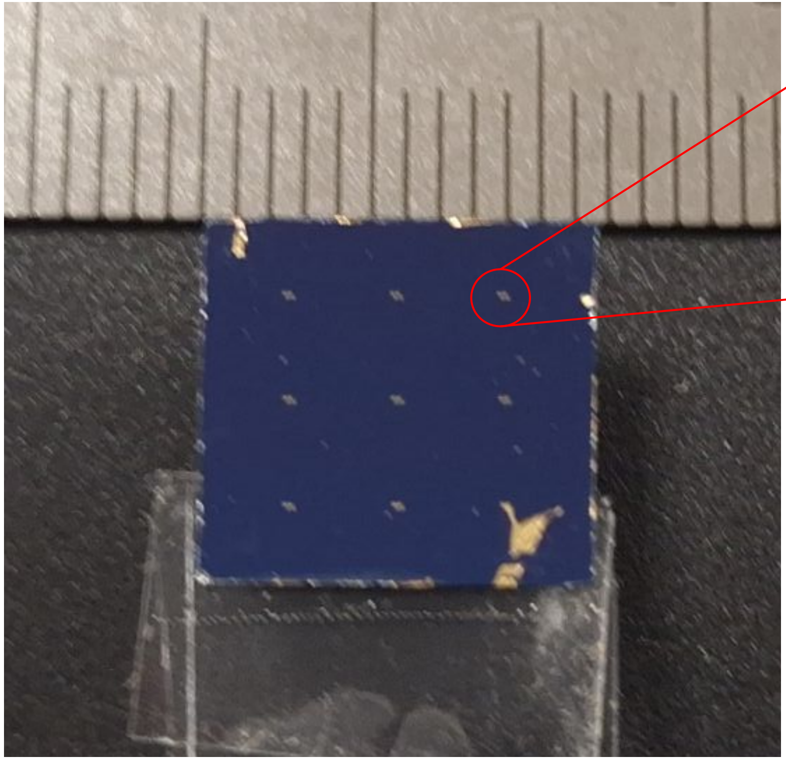


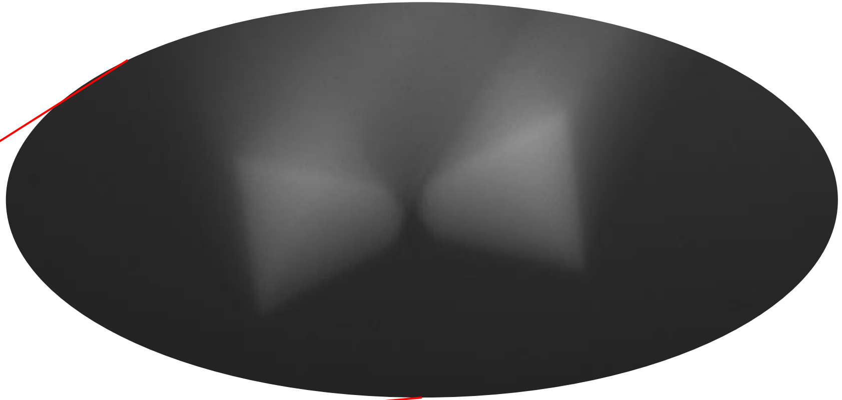
Modeling and fabrication



La = 245 µm
Le = 10 µm
Ec = 45 µm
Ee = 10 µm
Ea = 123 µm

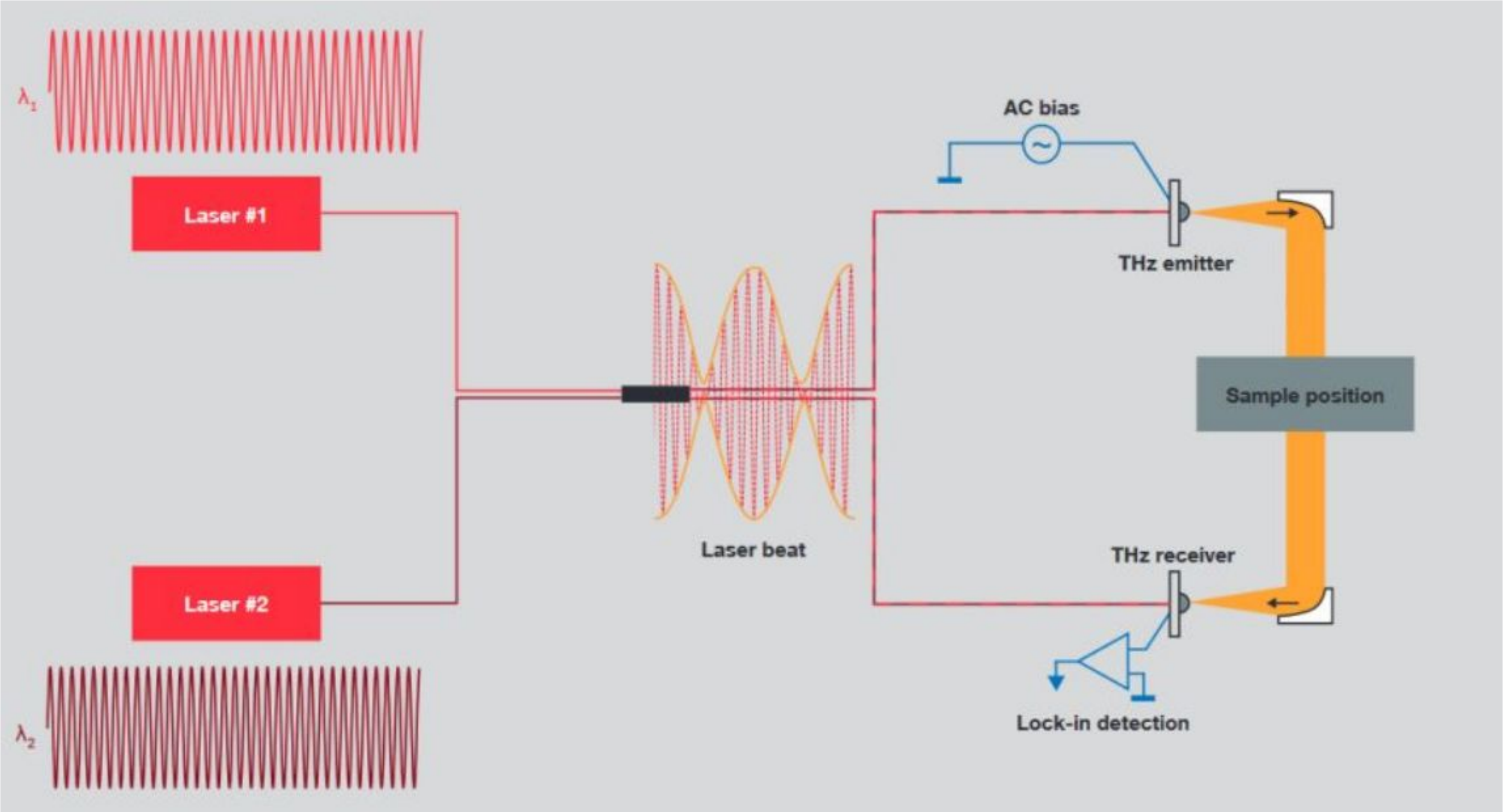
Modeling and fabrication



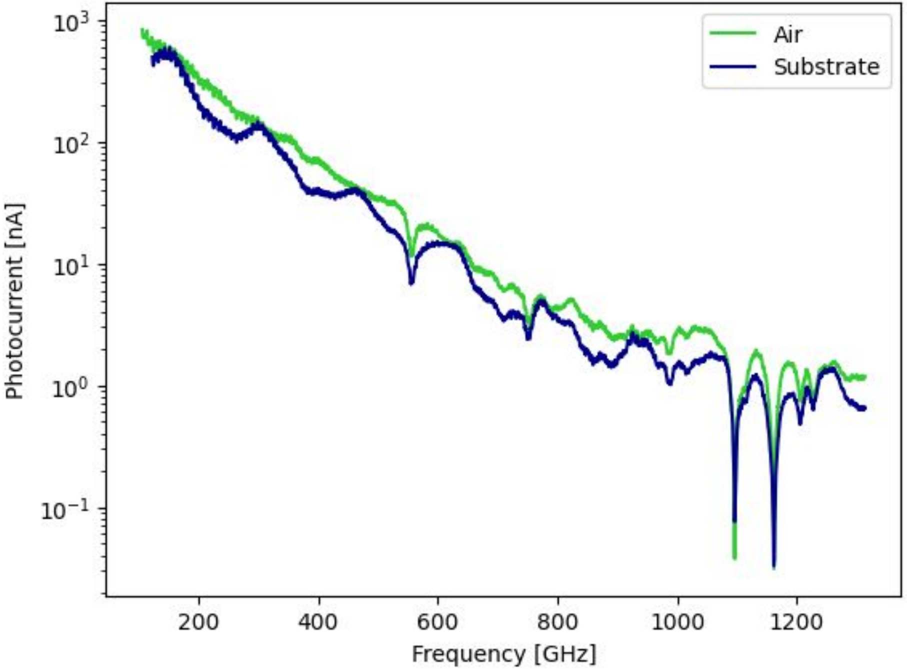


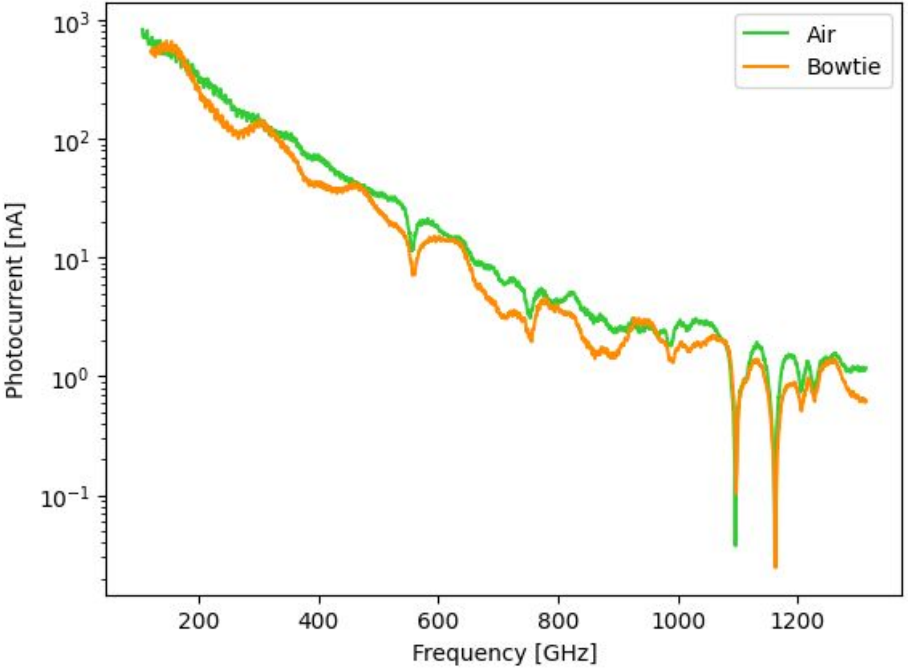
La = 245 µm
Le = 10 µm
Ec = 45 µm
Ee = 10 µm
Ea = 123 µm

Testing - reminder



Spectrum

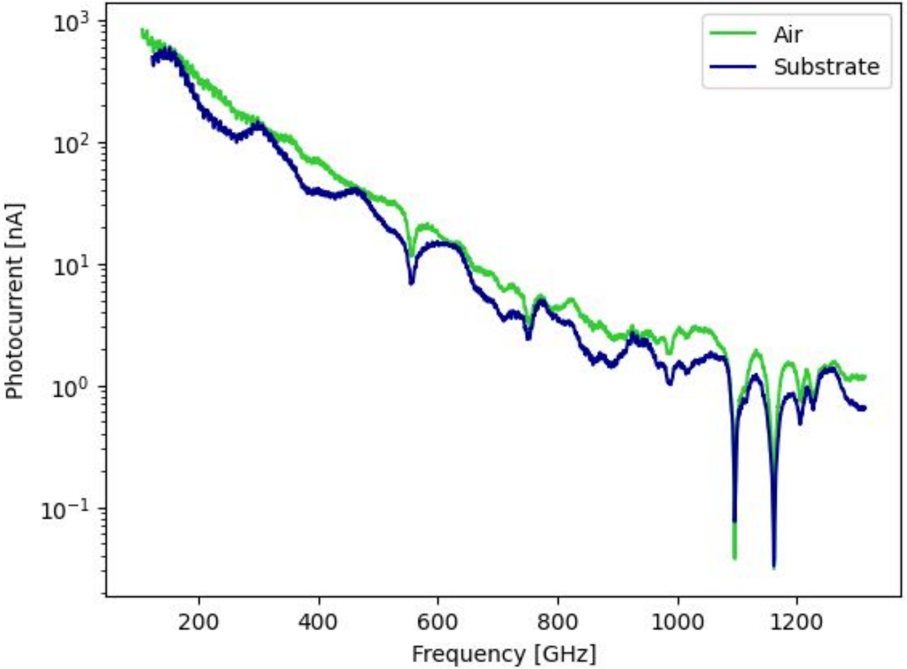


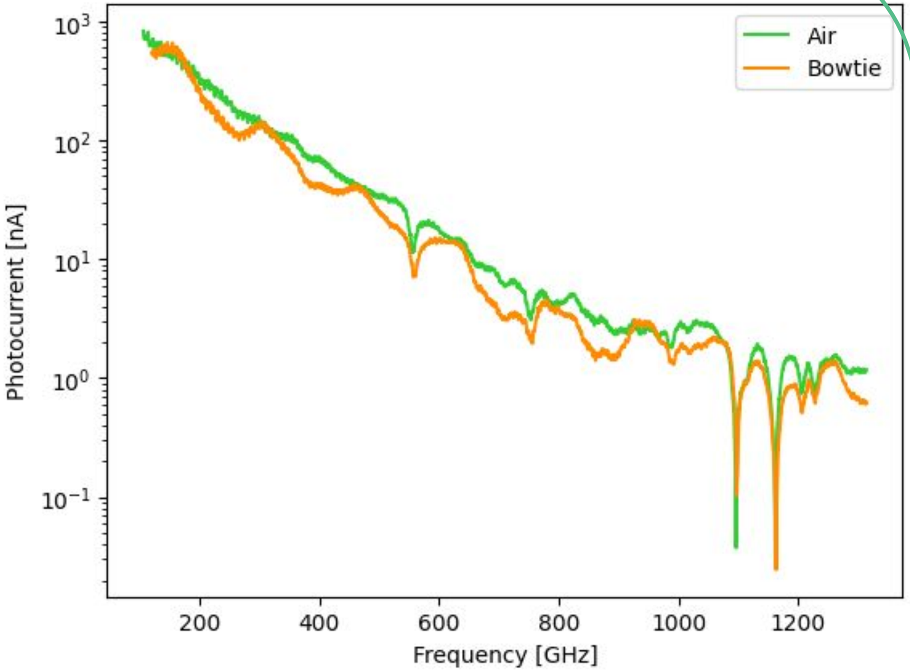


Comparing spectrum of the SiO2 substrate and the antenna with air

Spectrum

We can get the transmittance!

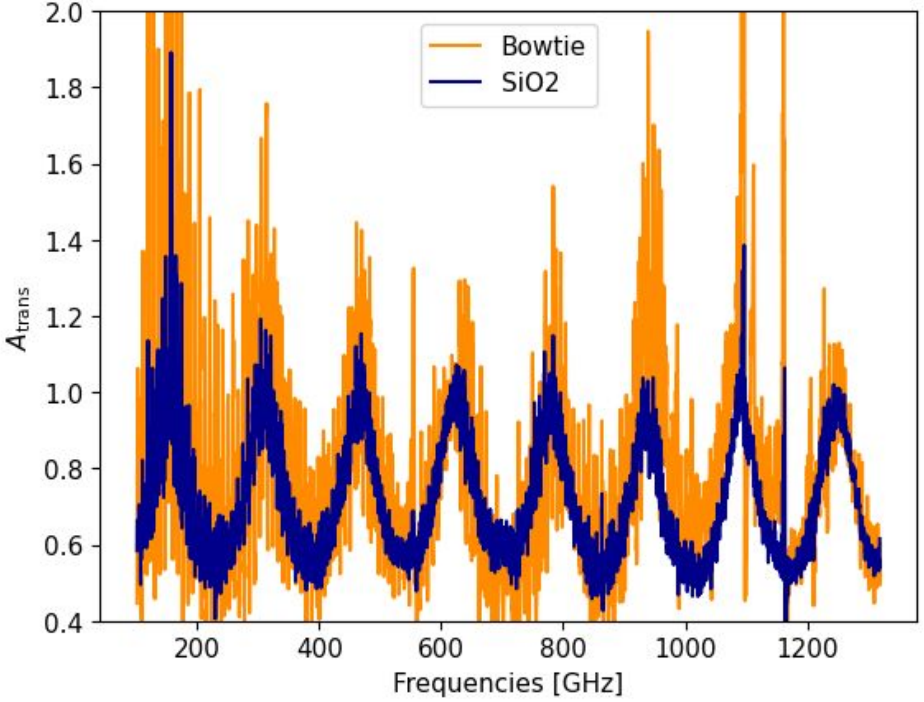


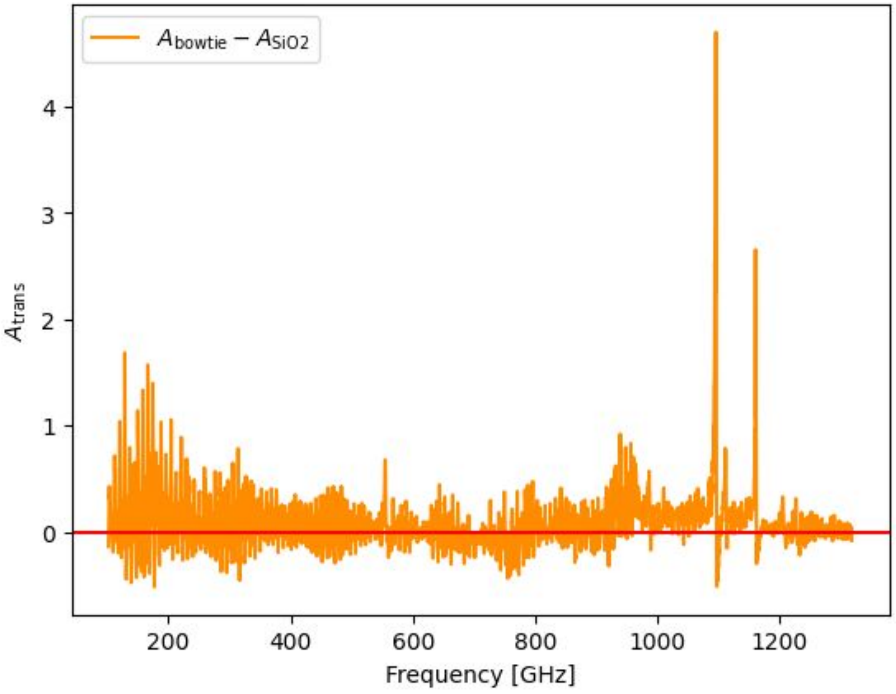


Comparing spectrum of the SiO2 substrate and the antenna with air

Transmittance

$$A'_{\text{trans}} = \frac{I_{\text{trans}}}{I_{\text{inc}}}$$





III. Concluding remarks

Conclusion - what did we learn ?

➔ Antiferromagnetic effects show great promise
➔ AF resonance is at the heart of new spintronic developments
➔ Antennas might be used to improve AF spintronic technology
➔ We were able to perform measurements of optical index
➔ Antenna effect was not noticeable due to noise

Conclusion - what did we learn ?

- ➔ Antiferromagnetic effects show great promise
- ➔ AF resonance is at the heart of new spintronic developments
- ➔ Antennas might be used to improve AF spintronic technology
- ➔ We were able to perform measurements of optical index
- ➔ Antenna effect was not noticeable due to noise

Outlook

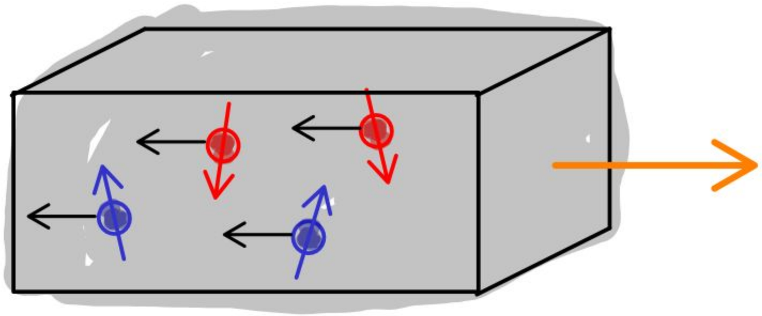
- ➔ Vacuum measurement
- ➔ Put antenna in NiO (how ?)
- ➔ Use a laser probe and other material to study local effect (appendix)
- ➔ Combine with local electric measurements

Appendices

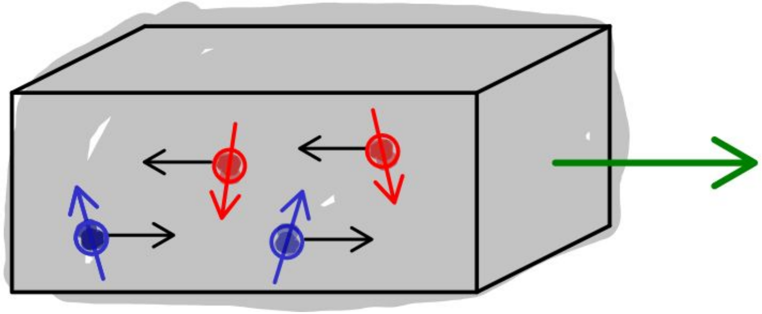
To answer good and bad questions

Charge and spin current

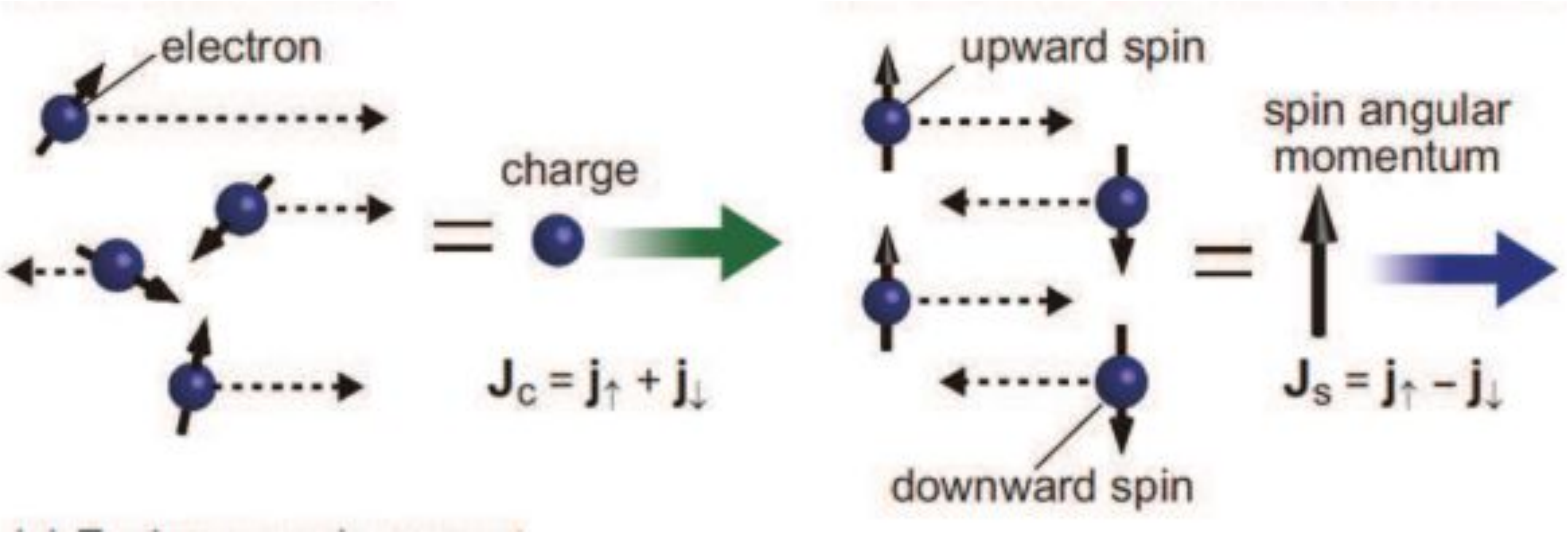
$$\vec{J}_c = \vec{j}_\uparrow + \vec{j}_\downarrow$$



$$\vec{J}_s = \vec{j}_\uparrow - \vec{j}_\downarrow$$

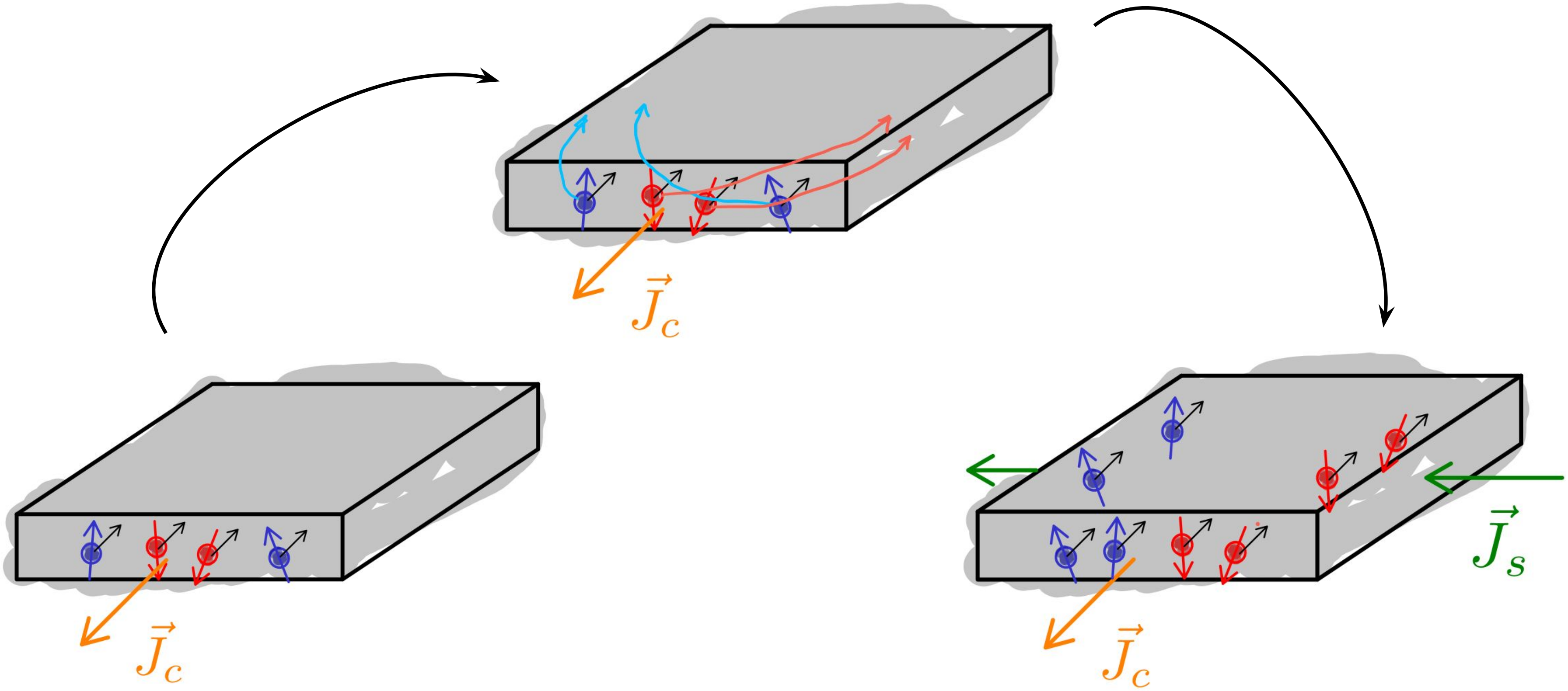


Charge and spin current



https://arxiv.org/abs/2211.02241

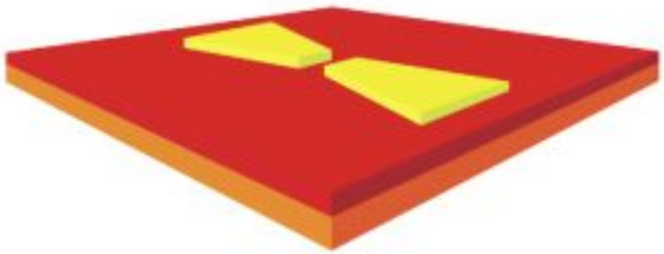
Direct Spin Hall Effect

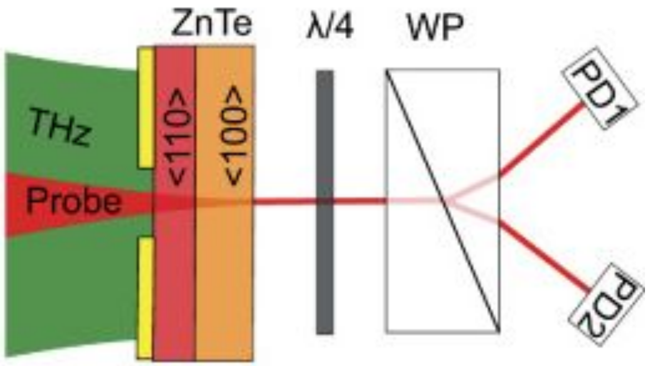


Antennas for local THz detection

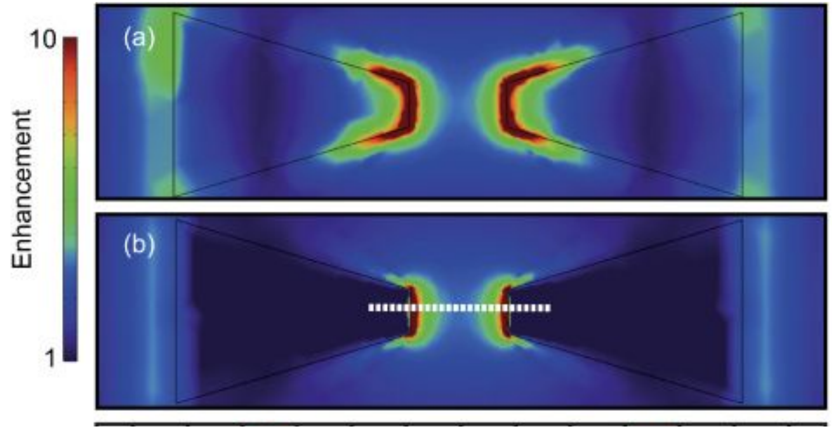
Use an antenna to amplify local field

Improved measurements !





Runge et al., , Opt. Express (2020)

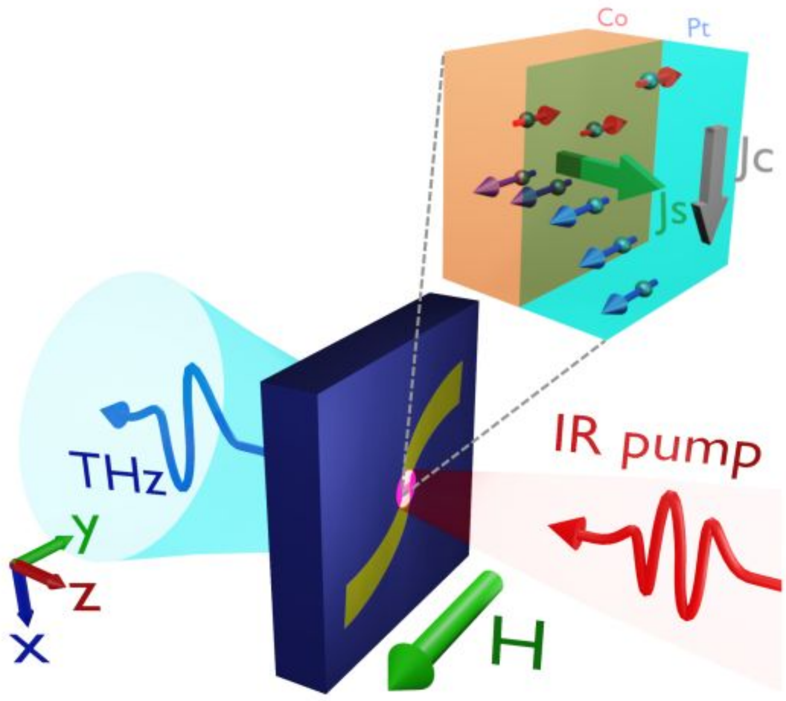


Runge et al., , Opt. Express (2020)

Antennas for THz emission

How ? ⟶ Spin Hall effect !

1. IR PUMP absorbed by FM Pt
2. Spin current -> Electric current
3. THz radiation



Thz emission using planar antennas, from *Increasing TeraHertz spintronic emission with planar antennas,* Matthias Pacé, et. al.

But we are not doing this !