Extreme Confinement and Propagation Regimes of THz Surface Waves on Planar Metallic Waveguides

J. Mangeney[1], D. Gacemi[3], R. Colombelli[2] and A. Degiron[2]

[1]*Laboratoire Pierre Aigrain, UMR 8551, Ecole Normale Supérieure, France*

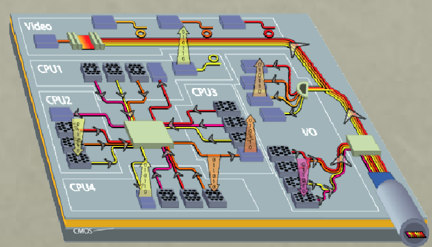
[2]*Institut d'Electronique Fondamentale, UMR 86622, CNRS, Univ-Paris Sud, France*

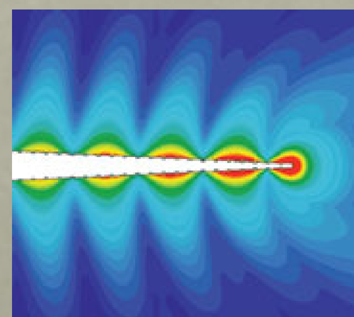
[3] *Laboratoire Matériaux et Phénomènes Quantiques, UMR 7162, CNRS, Université Paris, France*

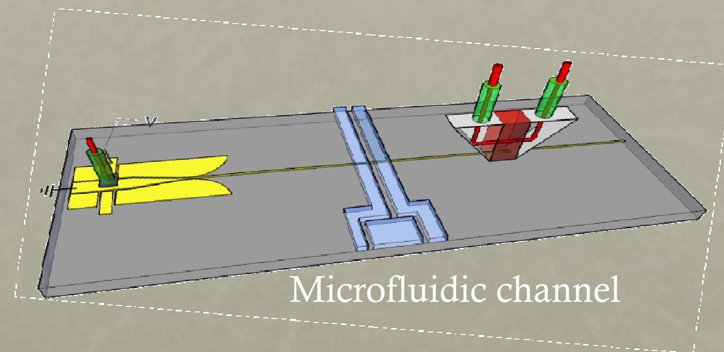
CONFINEMENT OF THZ WAVES

✓ **Requirement of highly confined THz waves**

- Integrated THz technology (high-speed electronic circuits,…)
- Imaging and spectroscopy of small objects
- Biological sensing
- …



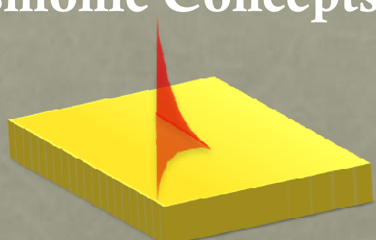




✓ **Diffraction limit of THz waves ~150 µm**

✓ **Plasmonic for confining THz waves (<λ)**

Plasmonic Concepts -> Sub-λ confinement at optical frequencies



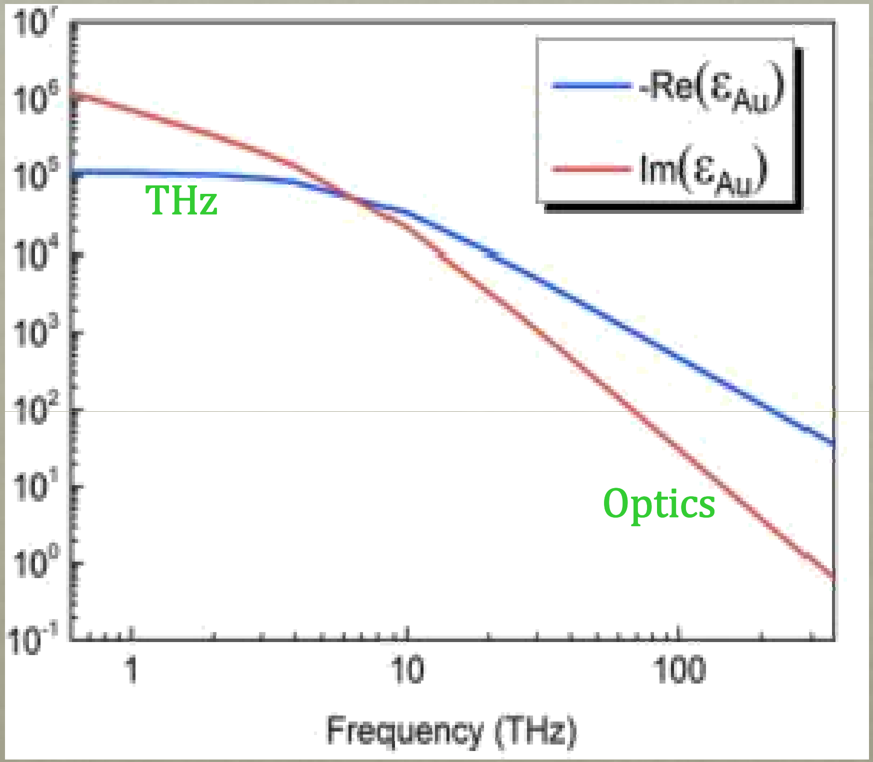
Surface waves propagating at the interface between a dielectric and a conductor.

✓ **Can sub-λ confinement be achieved at THz frequencies ?**

DISPERSION RELATION

Surface waves at the interface of metal and dielectric :

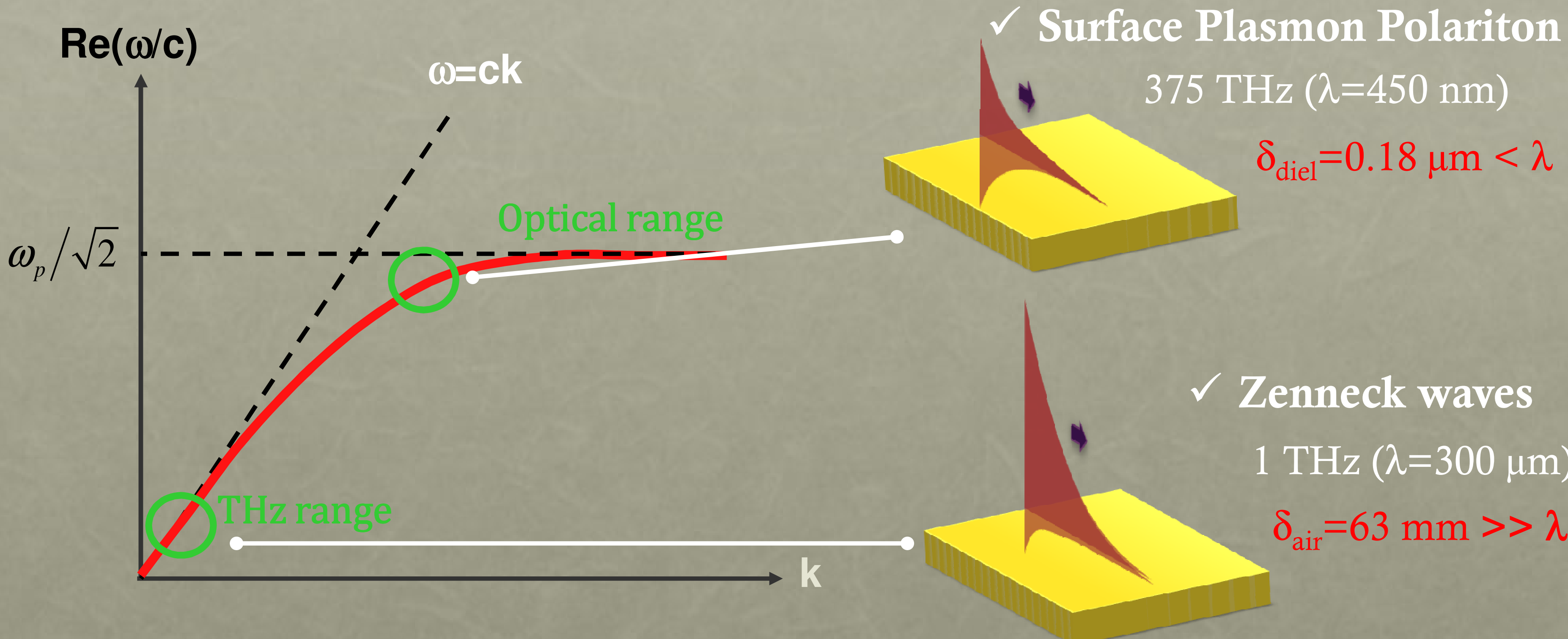
$$k = \frac{\omega}{c}\left(\frac{\varepsilon_m}{\varepsilon_1 + \varepsilon_m}\right)^{1/2}$$



- ✓ **Surface wave's properties highly change from optics to THz**

DISPERSION RELATION

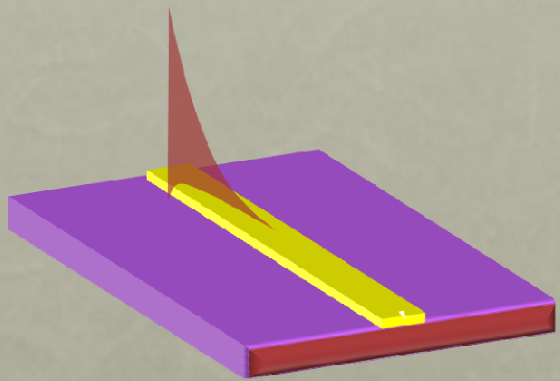
$$k = \frac{\omega}{c}\left(\frac{\varepsilon_m}{\varepsilon_1 + \varepsilon_m}\right)^{1/2}$$



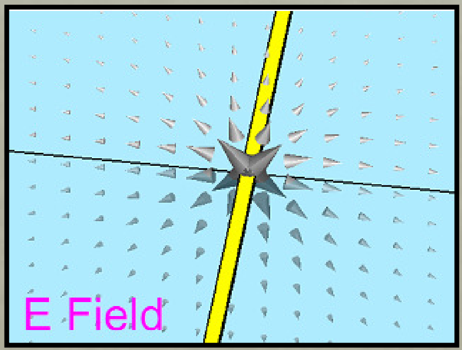
✓ **Challenge : achieve sub-λ confinement of the THz surface waves**

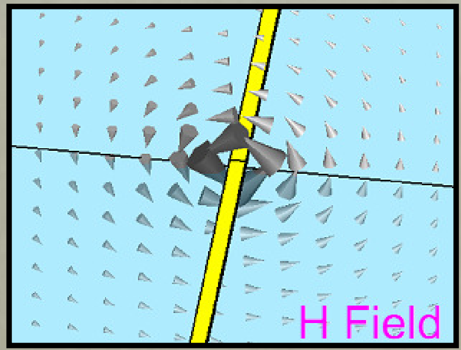
Planar Metallic Waveguide

✓ **Single conductor deposited on thin dielectric layer**



Yansheng Xu et al., MOTL. **43**, 290, (2004).
Christopher Russell, et al., Lab Chip, to be published 2013
Treizebre, A, *Int. J. Nanotechnol.* **5**, 784-795 (2008).





Akalin at al, IEEE VOL **54**, N°6,2762 (2006).

✓ **Extremey simple geometry adapted for complex integrated schemes with high functionalities**

✓ **Physical mechanisms that bind the surface wave to the surface :**

1/ Coupling between EM fields and the free electrons at the metal surface

2/ Interaction of the EM fields with the metal surface modified by the thin dielectric layer.

OUTLINE

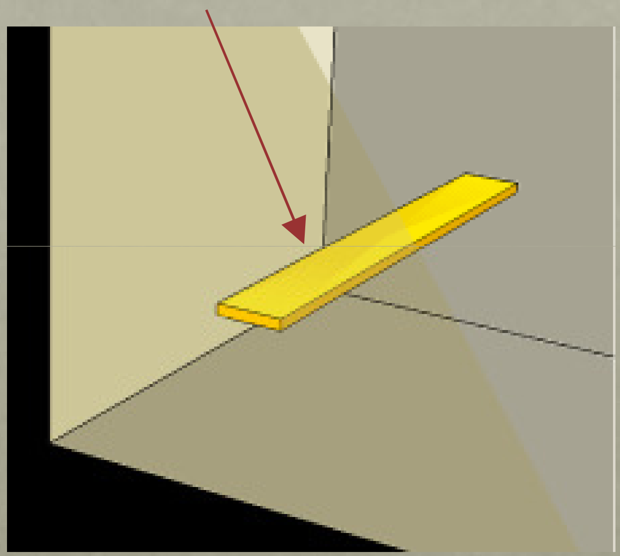
- ❖ **Study of planar metallic waveguides to achieve electric field confinement**
  - **Planar metallic waveguides based on the coupling between EM fields and free electrons at the metal surface** ***(Simulation)***
  - **Planar metallic waveguides based on the interaction of the EM fields with a metal surface modified by the thin dielectric layer** ***(Simulation)***
  - **Planar metallic waveguides based on hybrid mode** ***(Experiments)***
- ❖ **Study of the propagation regimes of planar metallic waveguides**

Single Au Stripe

1/ Coupling between EM fields and the free electrons at the metal surface

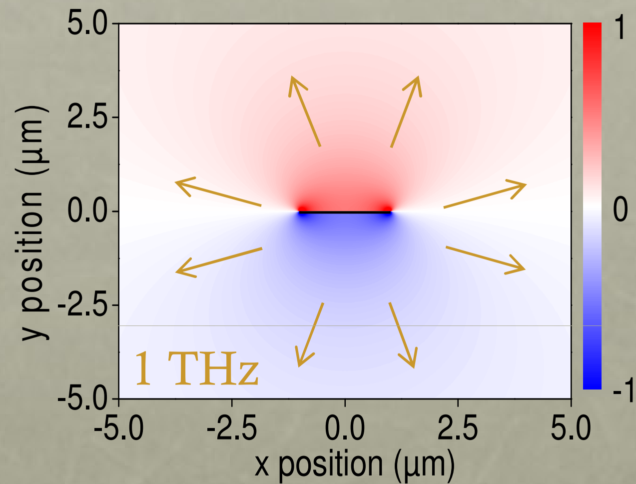
Single Au stripe embedded in a homogeneous medium

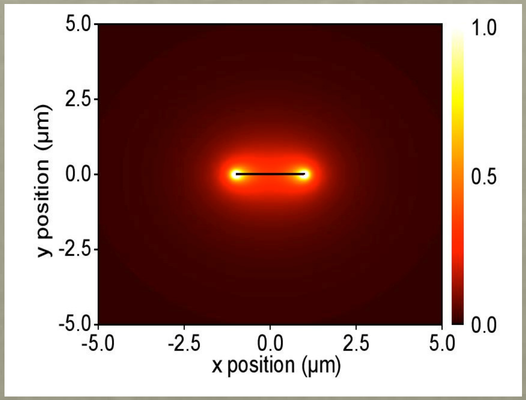
Au: metal with finite conductivity



Comsol MultiPhysics :

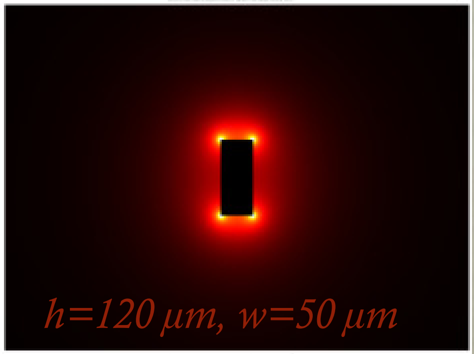
- Cross Section of the power
- Effective index of propagating modes

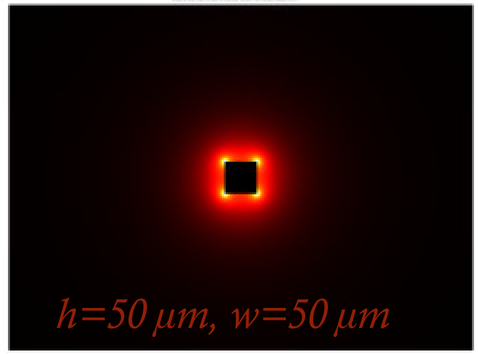


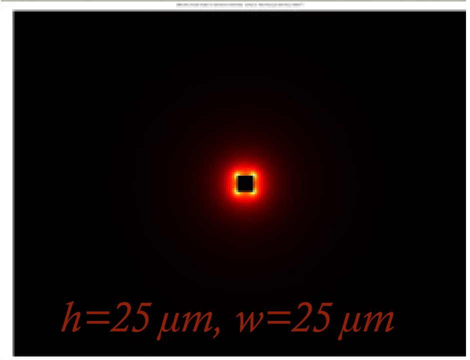


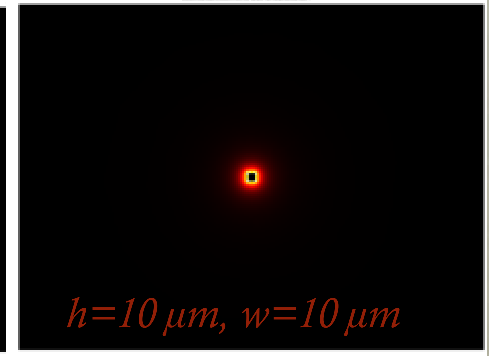
✓ **Existence of only one mode at 1 THz : radial field distribution**

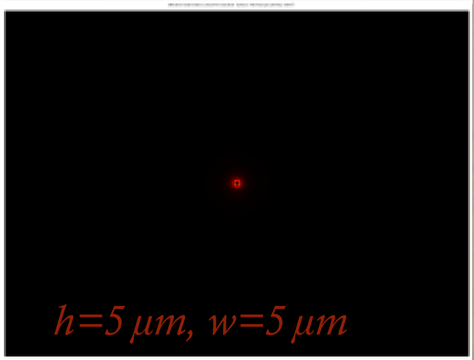
Tranverse Size of Metal Stripe

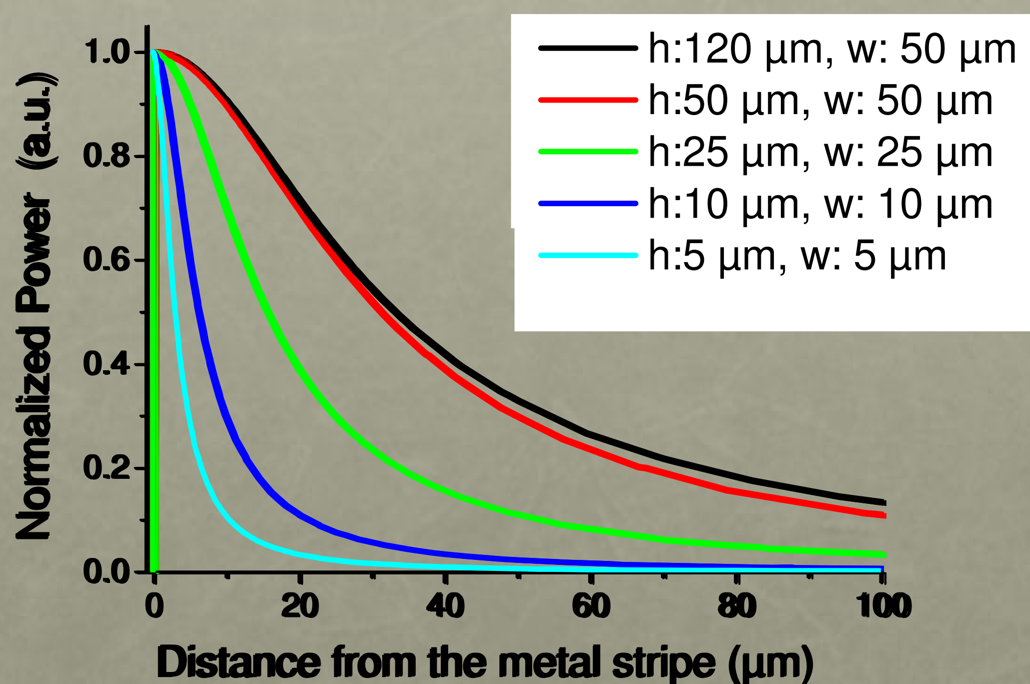






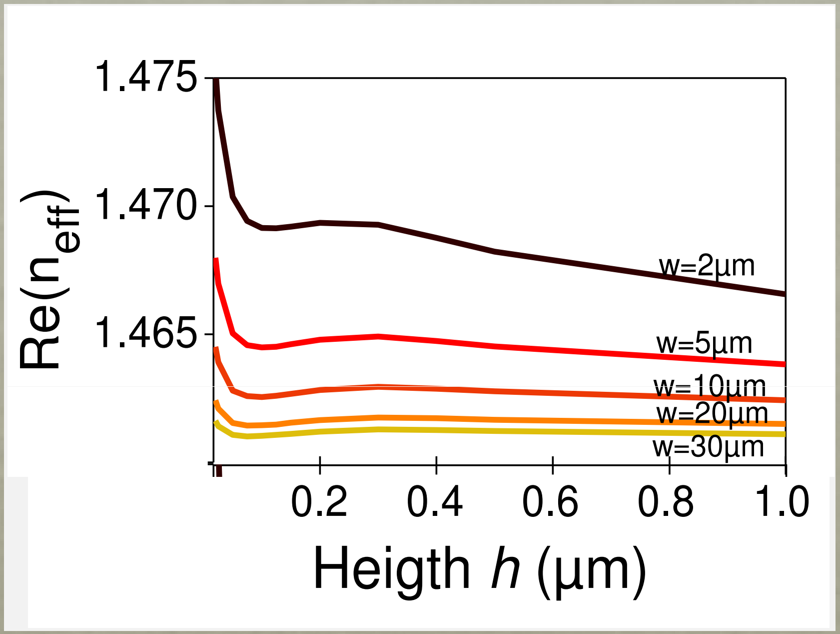


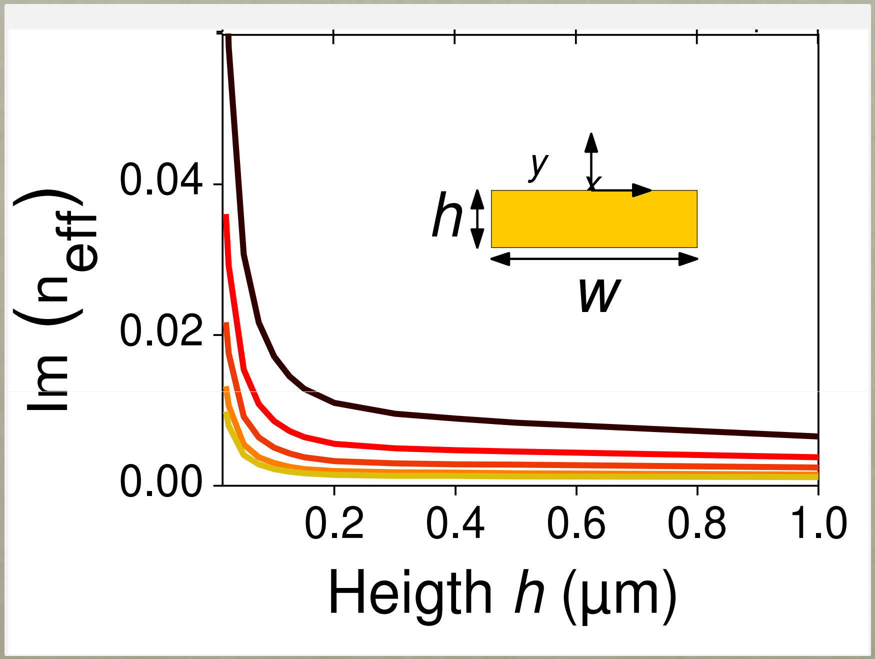




INFLUENCE OF THE STRIPE SIZE

Frequency : 1 THz





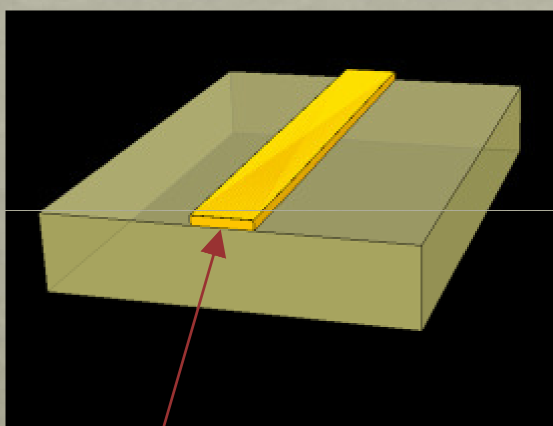
Re(neff) ↗ ⟶ Field confinement ↗

Im(neff) ↗ ⟶ Field confinement ↗

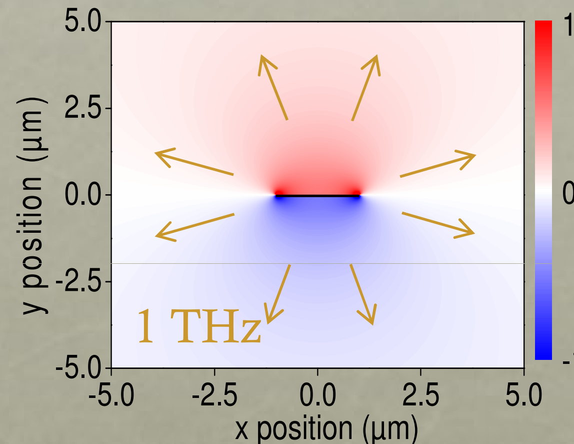
✓ The mode evolves into a highly confined solution as the transverse dimensions of the metal waveguide tend to zero

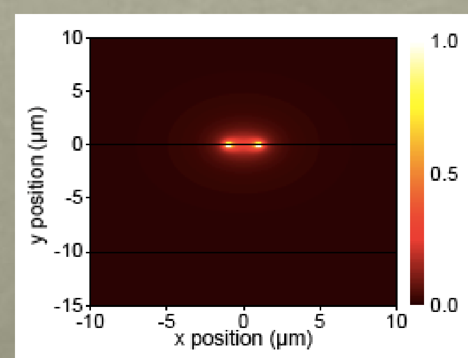
A PERFECTLY CONDUCTING STRIPE SUPPORTED BY A DIELECTRIC LAYER

2/ Interaction of the EM fields with the metal surface modified by the thin dielectric layer



Perfect electric conductor

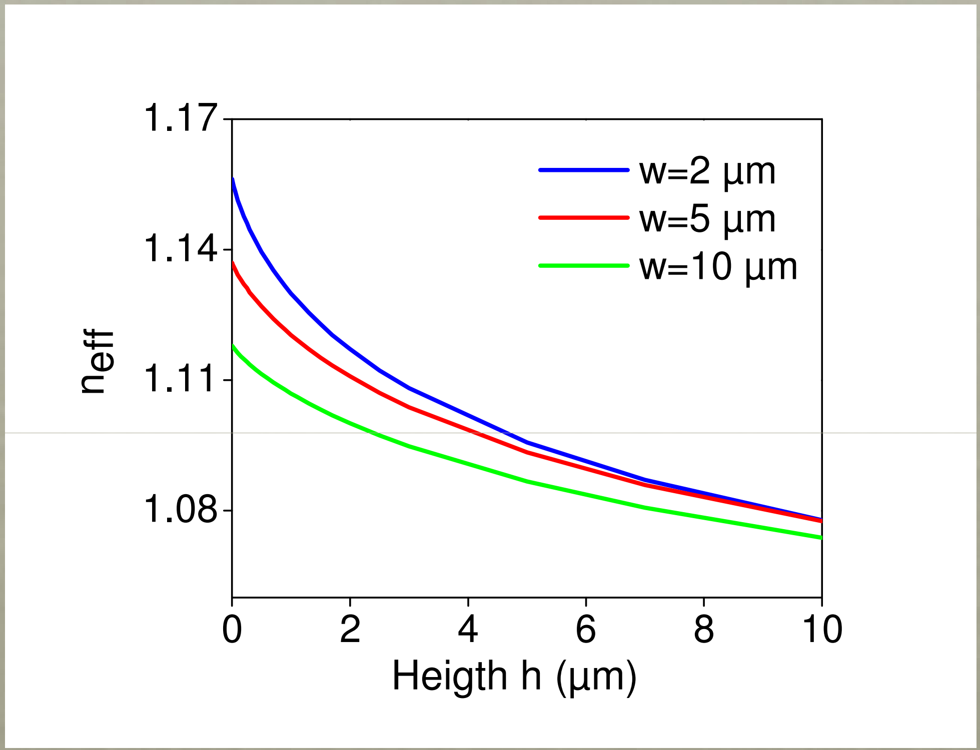




✓ **Existence of only one mode at 1 THz : : radial field distribution**

INFLUENCE OF THE STRIPE SIZE

Frequency : 1 THz



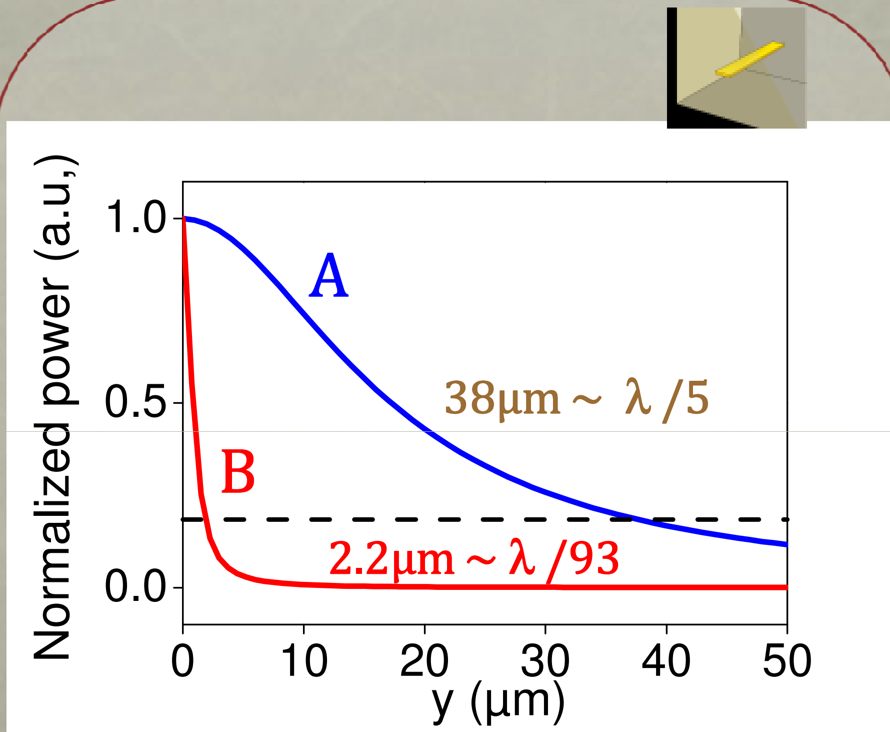
neff ↗ -> Field confinement ↗

- ✓ **Shrinking the transverse size of perfect conducting stripe increases the electric field confinement at THz frequencies**

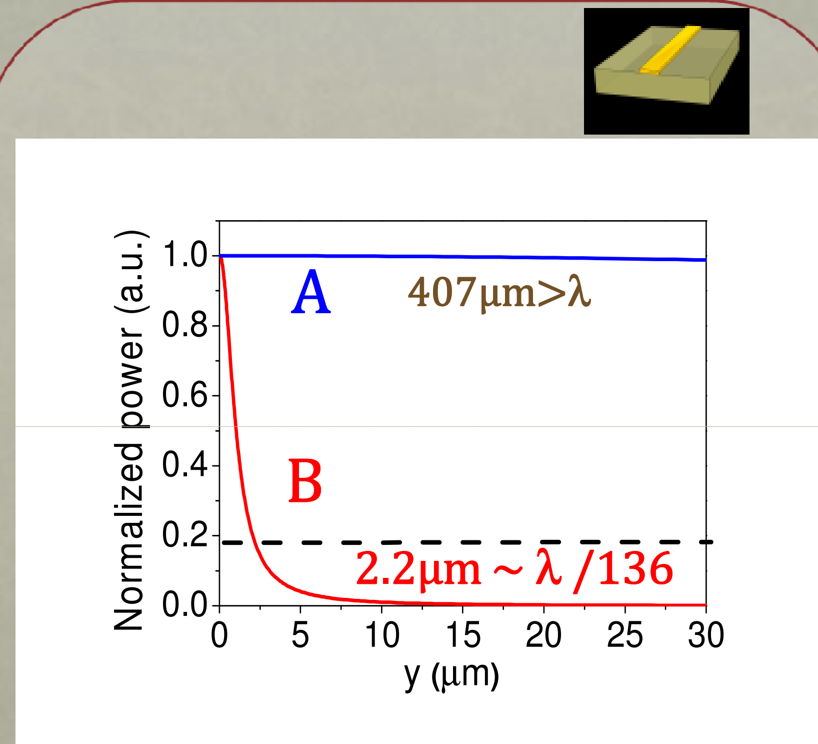
TRANSVERSE SIZE ROLE

A : w=30μm, h=10μm

B : w=2μm, h=20nm



Frequency : 1 THz



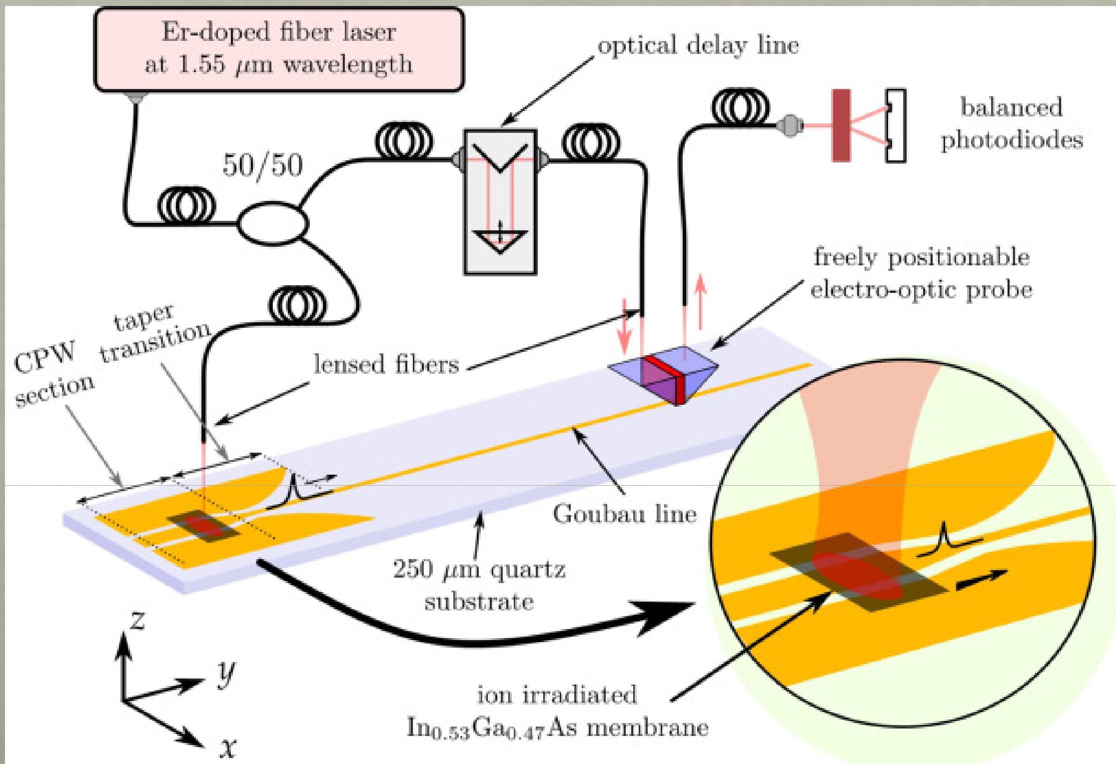
Frequency : 1 THz

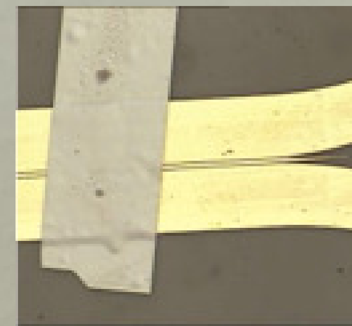
✓ **Extreme confinement (sub-λ) of the electric field at THz frequencies whatever the binding mechanisms**

D. Gacemi *et al.*, *Scientific Reports* 3, 1369 (2013)

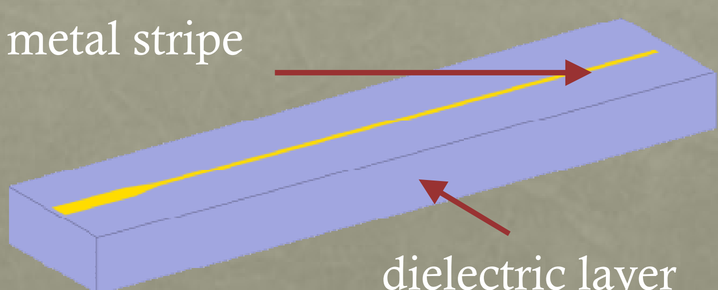
EXPERIMENTAL STUDY

Guided –wave time domain THz spectroscopy





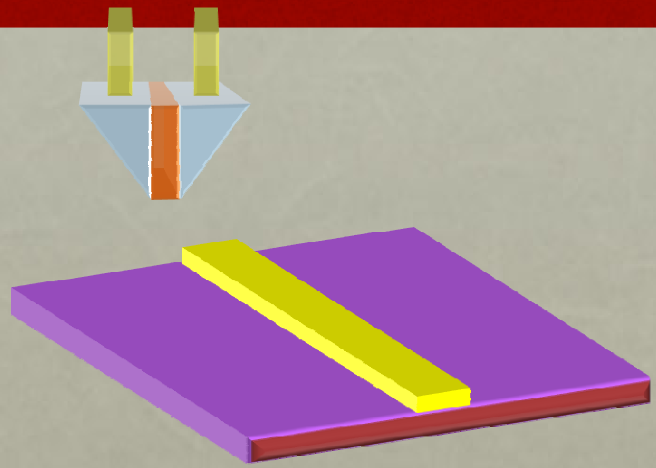
3/ Hybrid Mode : a combination of both mechanisms



1/ Coupling between EM fields and the free electrons at the metal surface

2/ Interaction of the EM fields with the metal surface modified by dielectric layer.

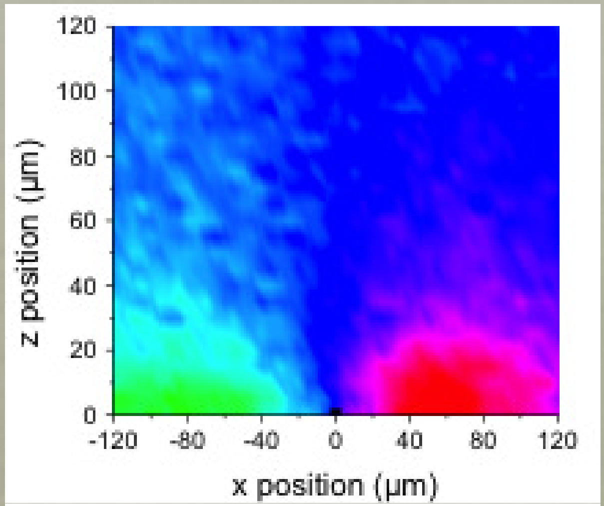
SURFACE MODE PROPERTIES



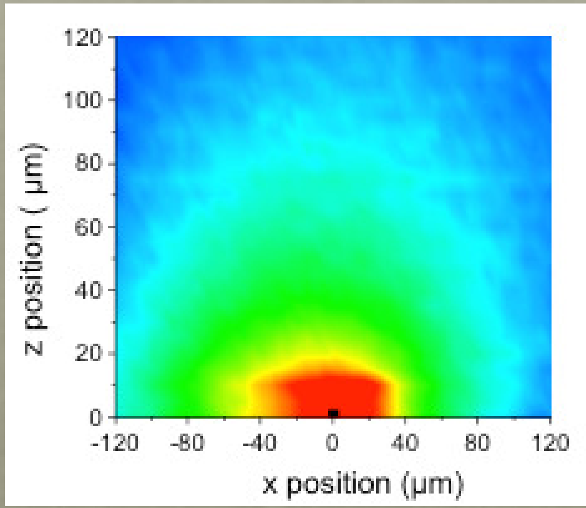
w=10 µm , t=200 nm, quartz substrate 250 µm

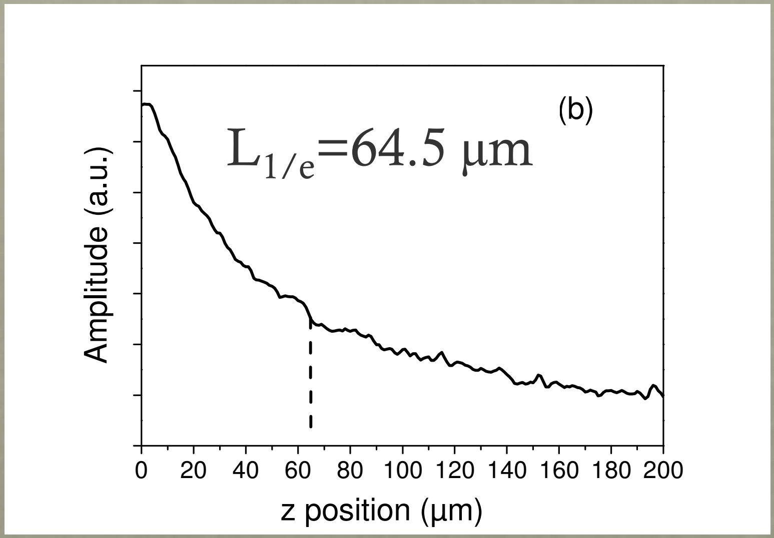
D. Gacemi *et al.* Optics Express 20, 8466 (2012)

Horizontal component of E



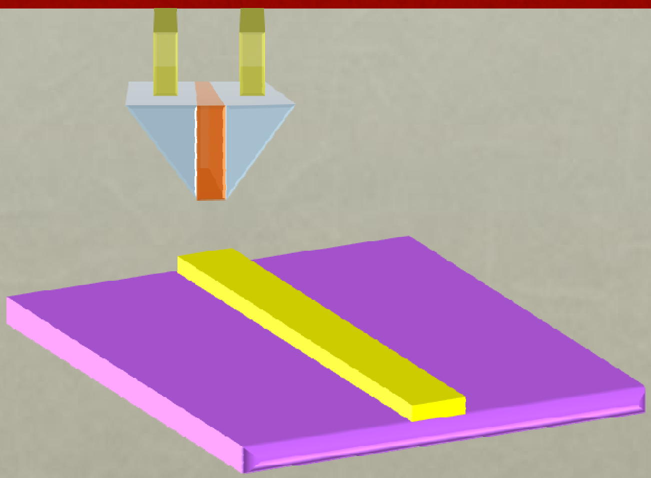
Vertical component of E

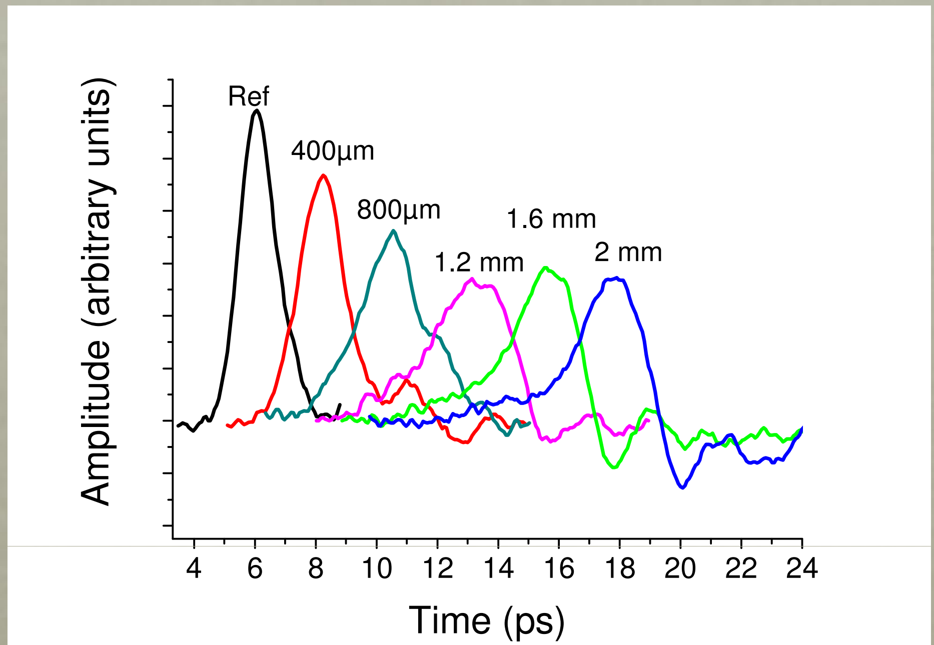


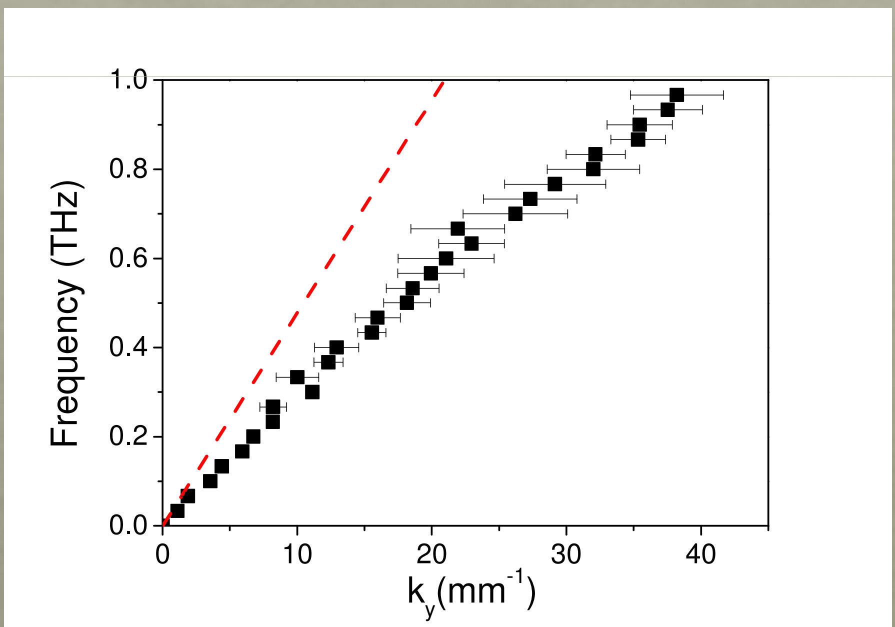


✓ **Experimental determination of the mode confinement ~ λ/10**

PROPAGATION CHARACTERISTICS







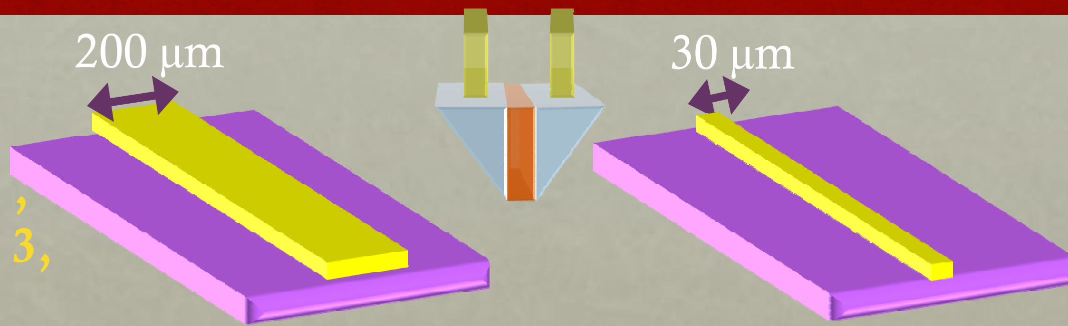
Decay Length

$$\delta L = \frac{1}{\sqrt{k_y^2 - k_0^2}}$$

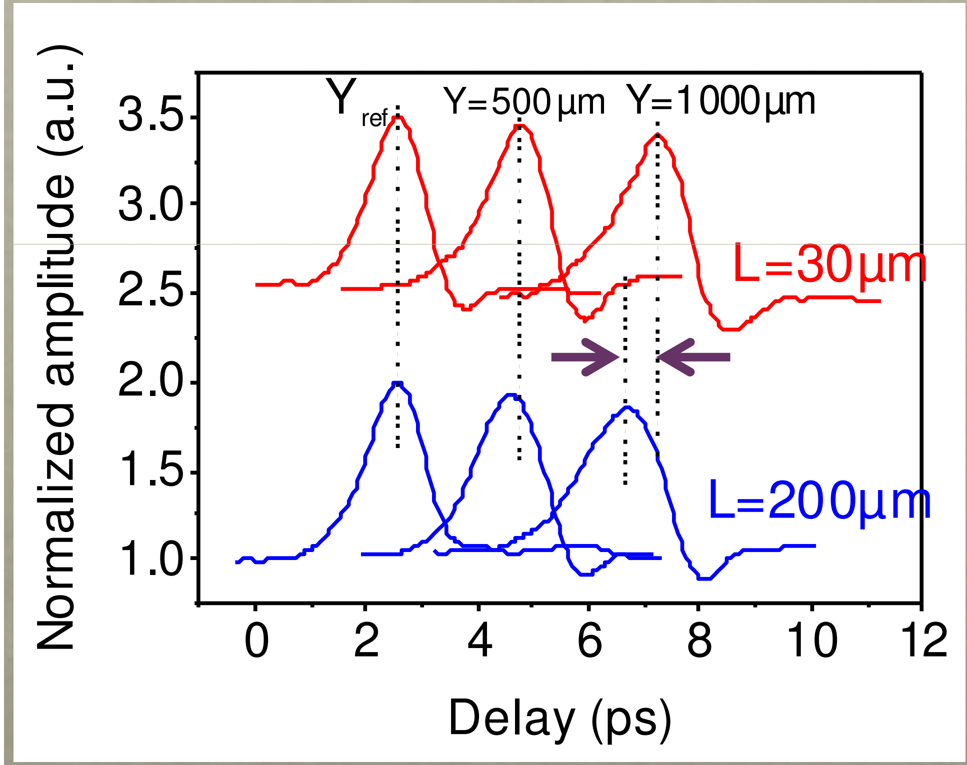
at 0.5 THz, δL= 54 µm

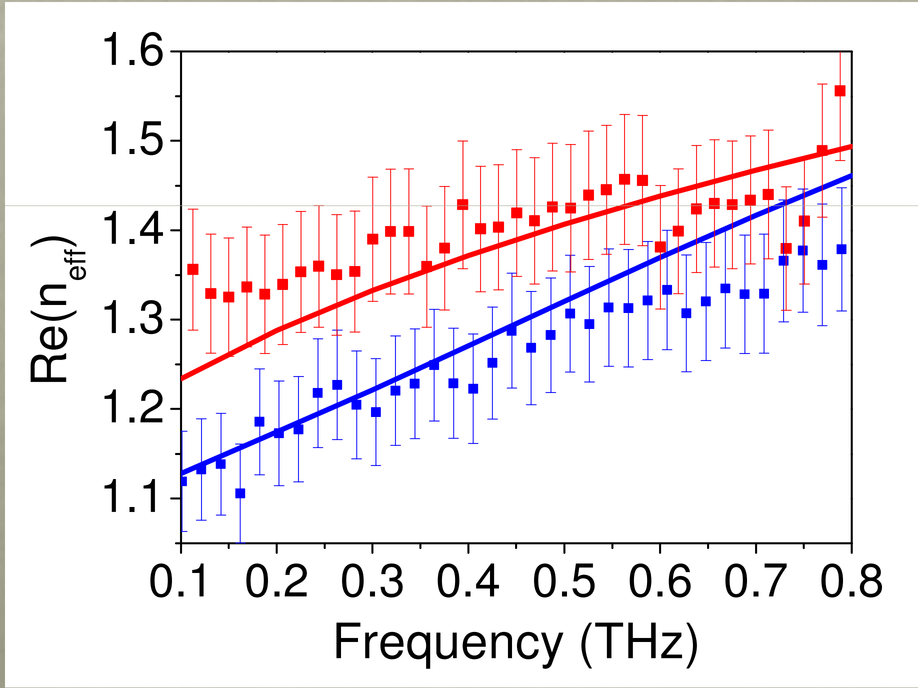
✓ **Experimental determination of the mode confinement ~ λ/10**

Influence of the stripe width



D. Gacemi *et al.* ,
***Scientific Reports* 3,**
1369 (2013)

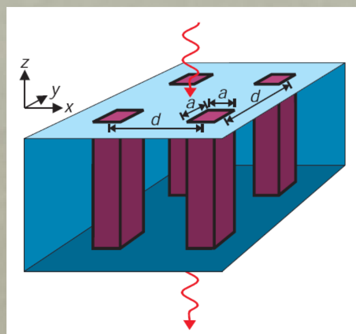




✓ **Reducing transverse size of a metallic structure provides a powerful tool for confinement of THz surface waves**

STATE OF THE ART

corrugated metal

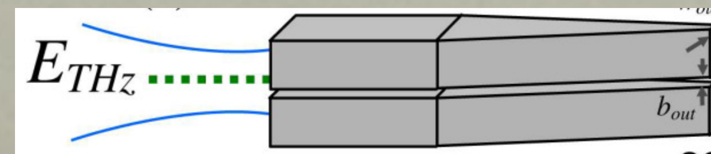


~λ

J. B. Pendry *et al.*, *Science* **305**, 847 (2004)
C. R. Williams *et al.*, *Nature Photonics* **2** (2008)

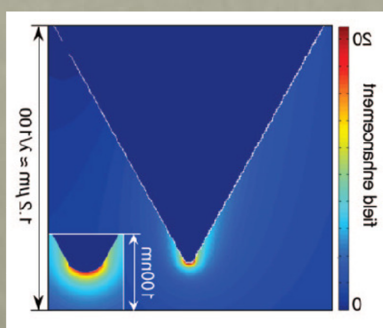
parallel-plate waveguides

λ/250



Astley, V., *App. Phys. Lett.* **95**, 031104-031106 (2009).
Liu, J. *Appl. Phys. Lett.* **100**, 031101-031103 (2012).
Zhan, *Opt. Express* **18** ,9643-9650 (2010).
Zhan, H., *JOSA B*, **28**, 558-566 (2011).

metal tip apexes

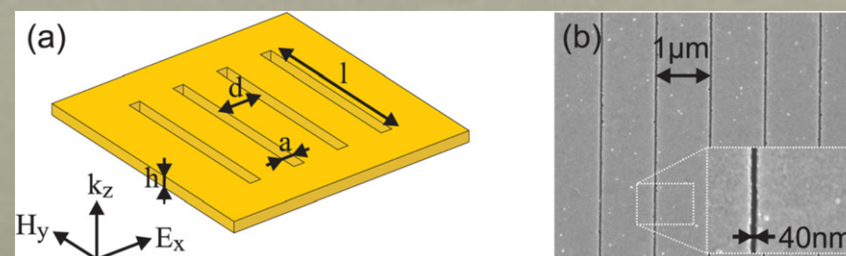


λ/3000

A.J. Huber, *Nano Lett.* **8**, 3766-3770 (2008)
J.A. Deibel, *Proc. of IEEE* **95** 1624-1640 (2007)

metallic nanoslits

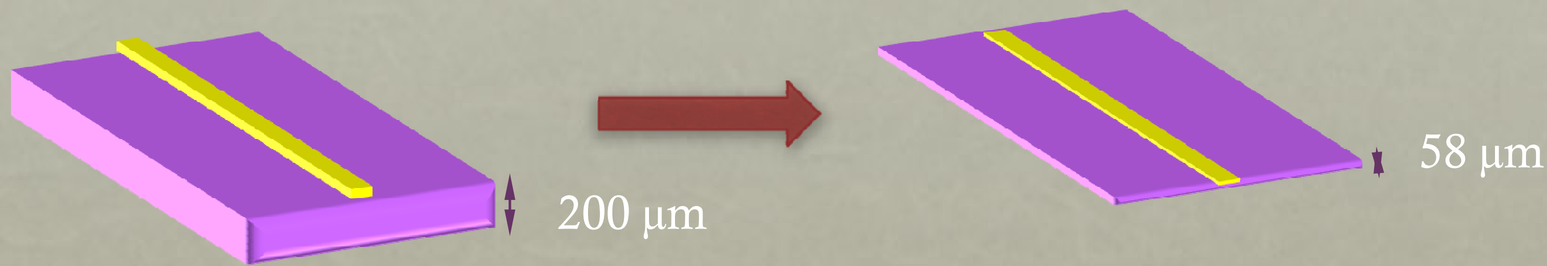
λ/25

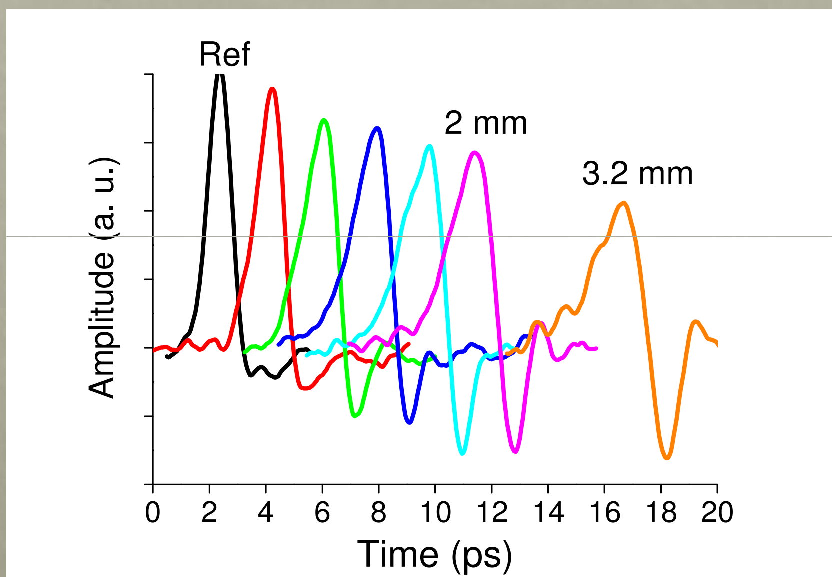


Seo M. A. *et al.*, *Nature Photon.* **3**, 152-156 (2009).
Sholaby M. *et al*, *Appl. Phys. Lett.* **99**, 041110-041112 (2011).

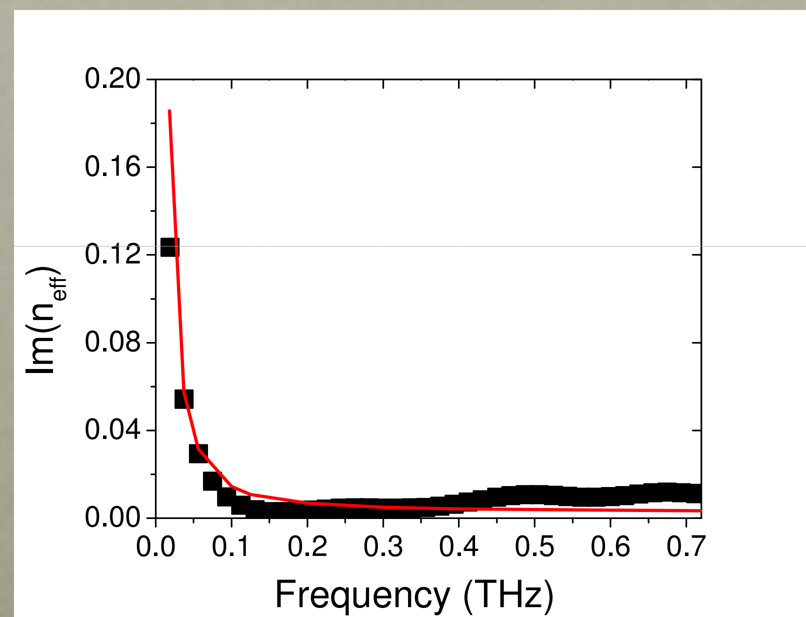
✓ **All design strategies involved reduced dimensions of metal structures**

Dielectric Layer Properties





Dispersion coefficient of 0.28 ps/mm



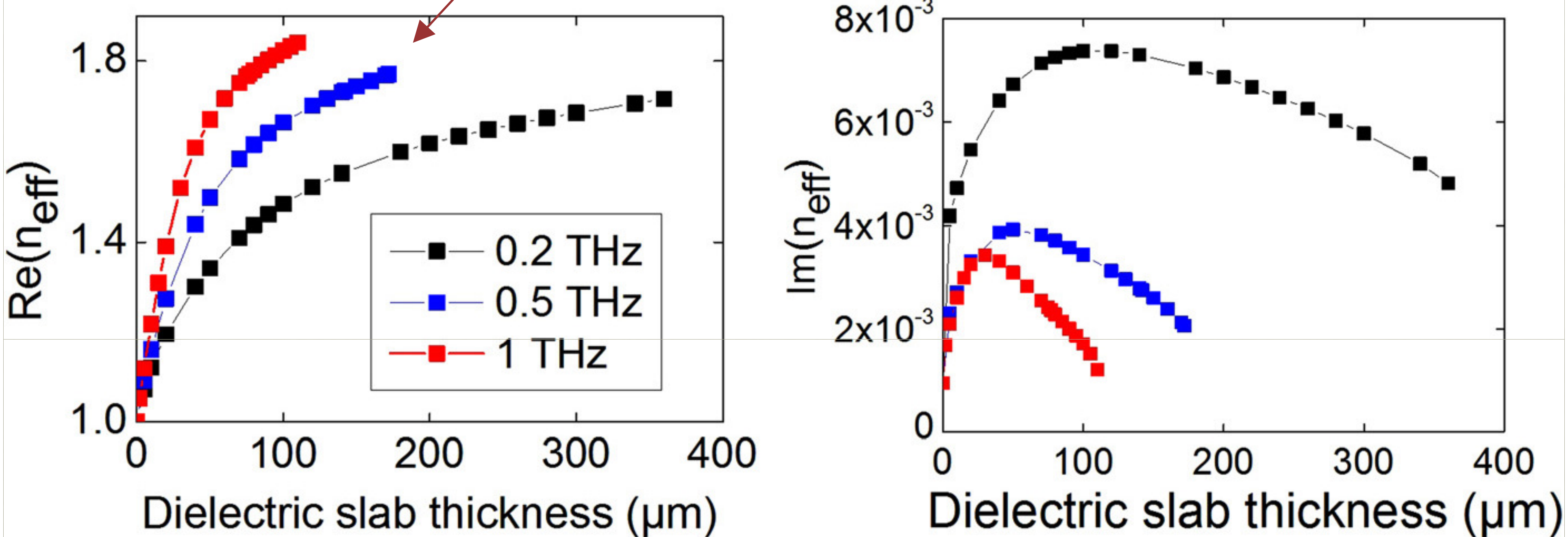
Low losses (< 0.4 mm^{-1}) up to 0.8 THz

✓ **Performances of these single conductor waveguides are fully compatible with key THz applications**

DISTINCT PROPAGATION REGIMES

D. Gacemi *et al.* APL 191117 (2013)

$\lambda_{eff} \approx \lambda_0 / (0.5\sqrt{\varepsilon_{diel}} + 1)$



- ✓ ***e*=0, the mode is bound to the metal stripe because of its finite conductivity**

  a variant of a Sommerfeld wave

- ✓ ***e* ->λ_{eff}/4, the dielectric film provides additional confinement to the mode.**

  a Goubau mode

- ✓ ***e*>λ_{eff}/4, the mode looses its confinement to the point that it ceases to be bound beyond a certain cut-off condition.**

  cut-off frequency

CONCLUSIONS

- ✓ **Size effects can be used as a simple formidable tool for high electric field confinement at THz frequencies (smaller than $\lambda/100$).**

- ✓ **Au planar single conductor supported by thin layers of dielectric show remarkable performances**

- ✓ **Further works :**
  - **to generalize this result into a unified theory (universality).**
  - **Develop Bends, Mach-Zender, Y-splitting**

`Collaborations

- **Institut d'Electronique Fondamentale**

    P. Crozat

- **Institut d'Electronique de Microelectronique et de Nanotechnologie**

    T. Akalin, J-F. Lampin, C. Blary

- **Laboratoire Ondes et Matière d'Aquitaine**

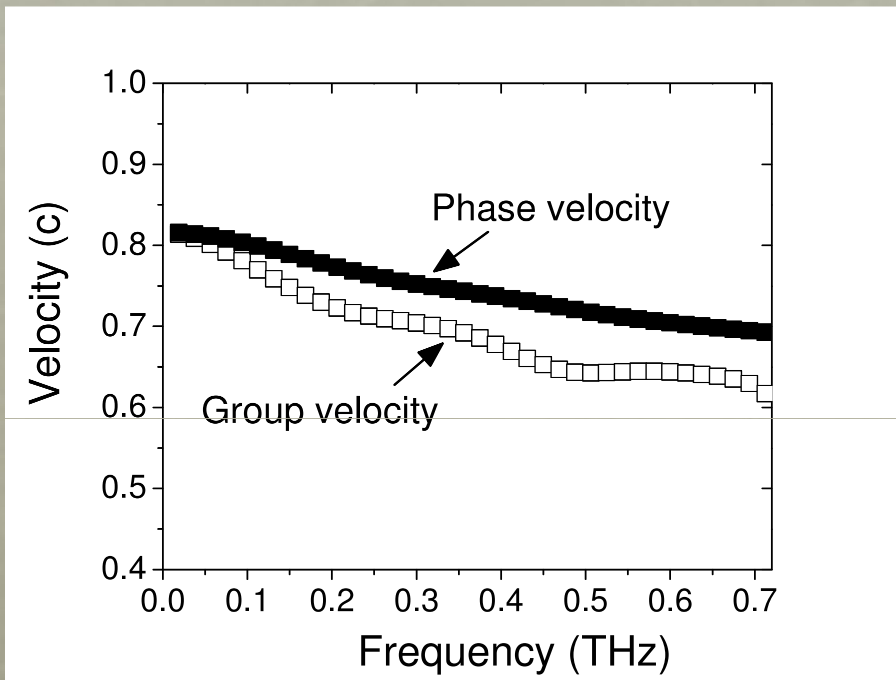
    R. Yahiaoui

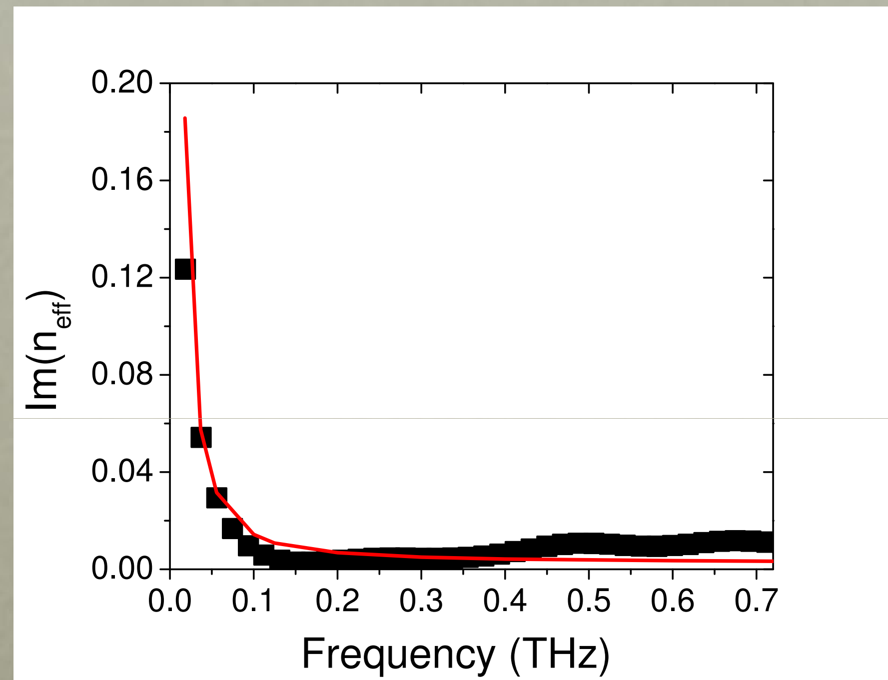
EURAMET
European Association of National Metrology Institutes

Funding support from:

EMRP Researcher Grant NEW07
Research Project 'THz Security'

Dispersion Relation





Maximum GVD of $5.6x10^{-22}$ s^2/m

Low Losses