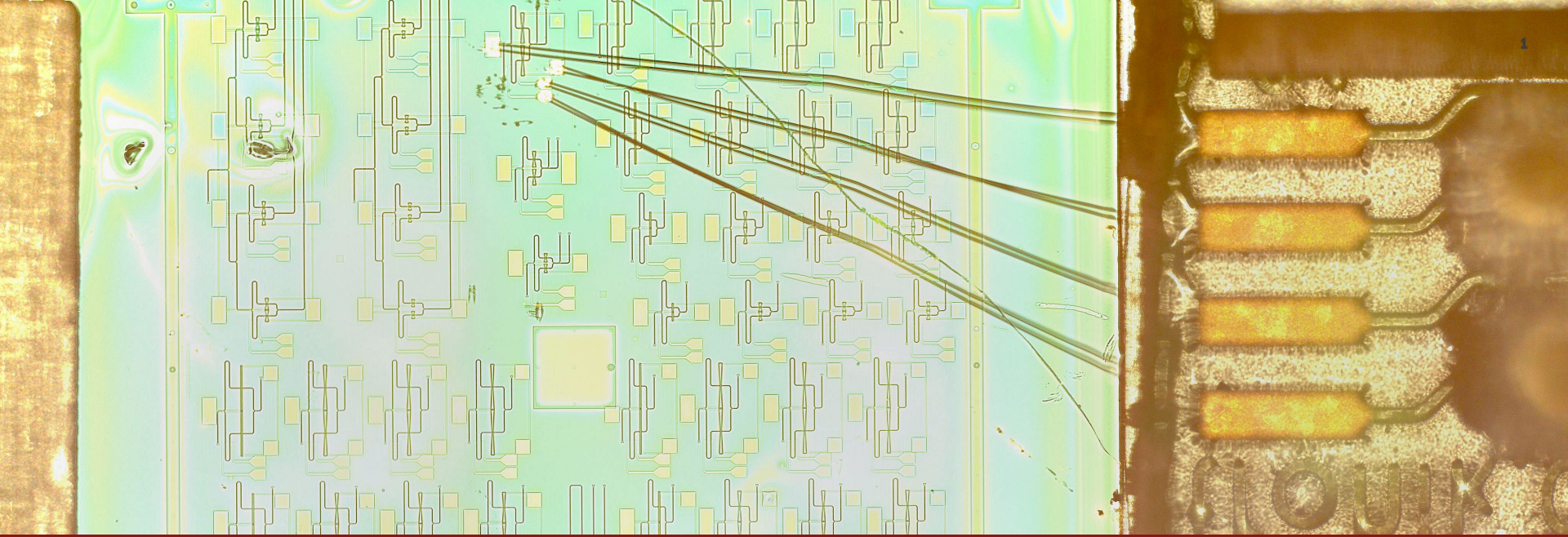


The Future on a Chip: Exploring Photonic Integrated Circuits

Yazan Lampert[1], Aleksei Gaier[1], Amirhassan Shams-Ansari[2],
Alessandro Tomasino[1], Francesco Bertot[1],Shima Rajabali[1,2], Marko Loncar[2],
Cristina Benea-Chelmus[1]
[1]Hybrid Photonics Laboratory (HYLAB), EPFL
[2]Laboratory of Nano-optics, Harvard University

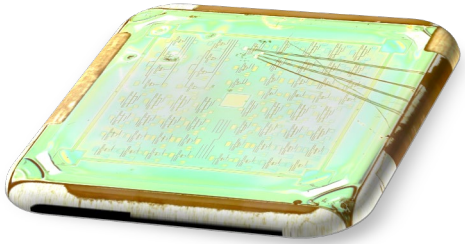

#epflcampus
Started in January 2022 ☺

Ileana-Cristina Benea-Chelmus

Applications of integrated photonic circuits

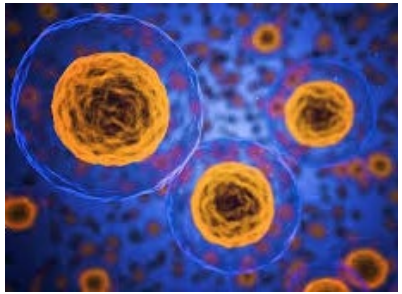
High-performance computing

Atomic clocks for timing

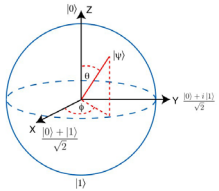


Telecom

Sensing
Biosensing

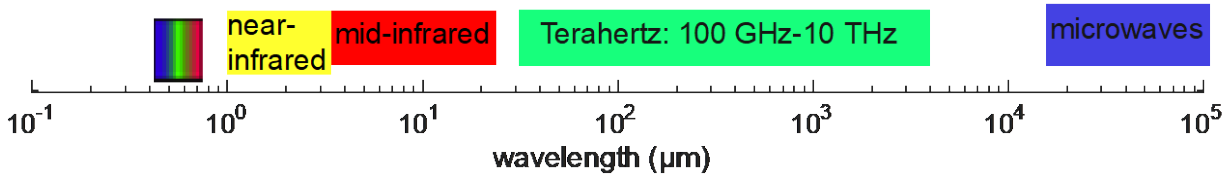


Quantum technologies



Aerospace &
High-end instrumentation

Applications of integrated photonic circuits



Atomic physics

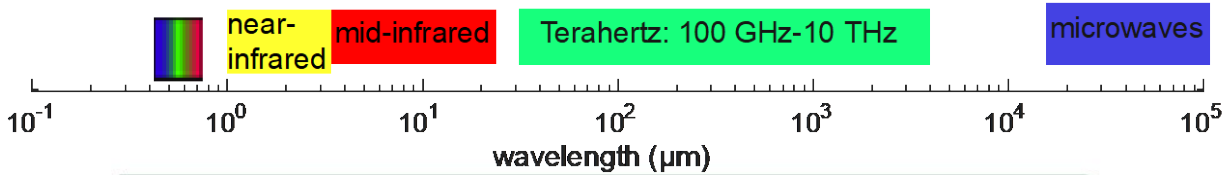
sensing

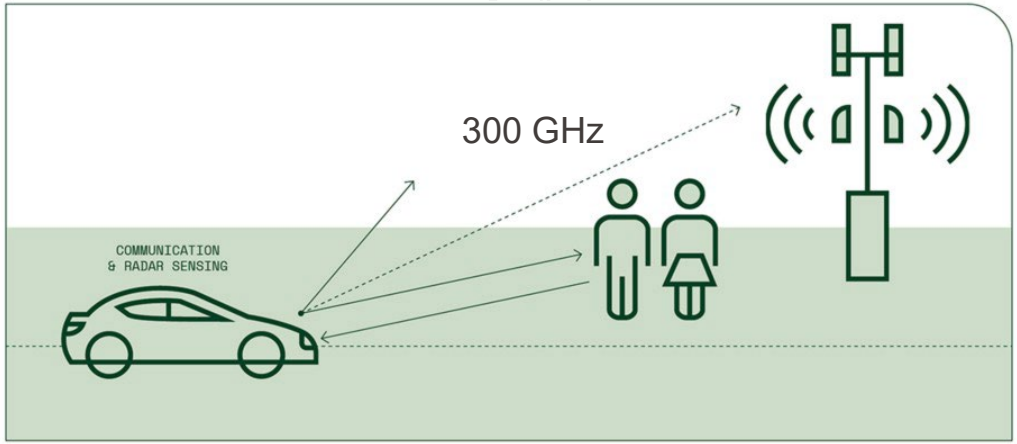
Communications/high-end

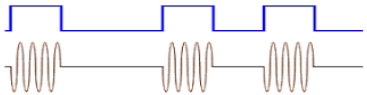
computing

quantum

Vision of 6G : joint communication, sensing and localisation







RF signal

300 GHz carrier

On-off keying: bits on = 1 and off = 0

www.ni.com

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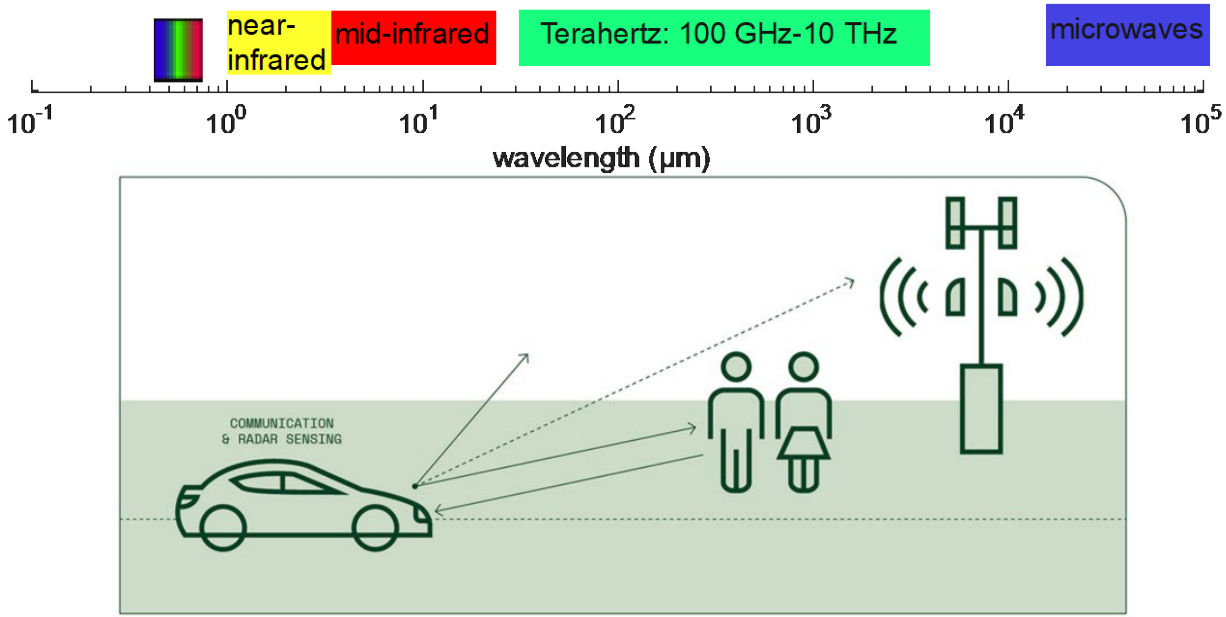
Vision of 6G : joint communication, sensing and localisation



- Communications:
  - means to modulate THz in amplitude and phase
  - Versatile detectors with high SNR
- Sensing: frequency-domain capabilities
- Time of flight: time-domain capabilities

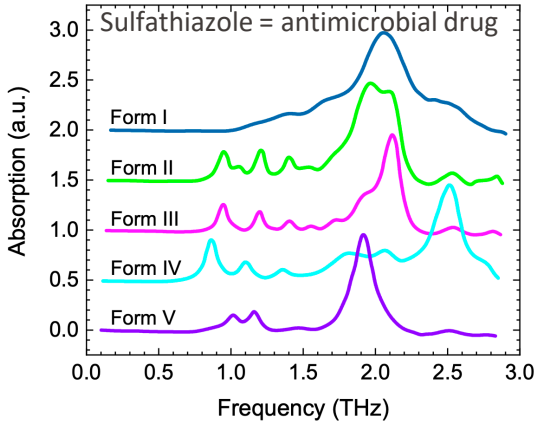
www.ni.com

Non-invasive terahertz spectroscopy

Terahertz imaging

Sequestim/Cardiff Univ.

Conformation of molecules



Free-space applications from 100 GHz to 3 THz.

Z. Song et al. *IEEE Trans. on Terahertz Sc. and Techn*. 8, 5 (2018)

Y.-C. Shen, *Int. J. Pharm. 417*, 48–60 (2011)

Current state of commercial products

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electronics approach → photonics approach

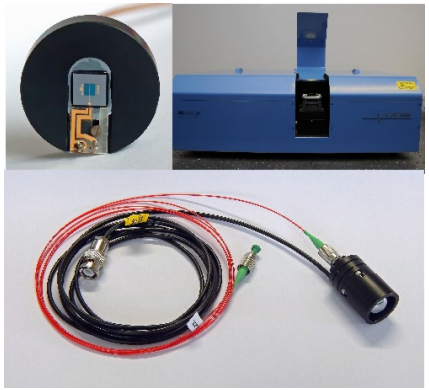
Multiplier chains (e.g. 27 x 11 GHz)

- Needs an RF source
- Loses power with THz frequency (multiplication)

Current state of commercial products

electronics approach

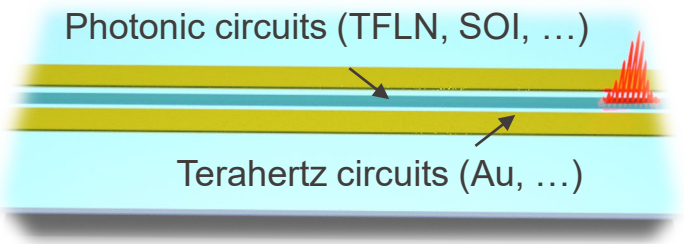
photonics approach



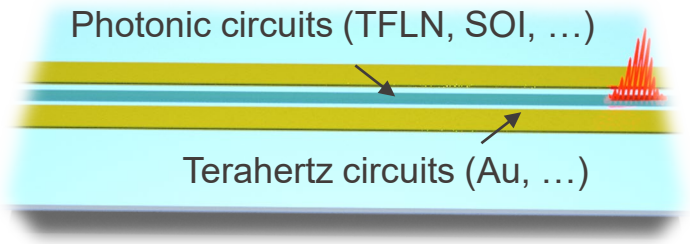
Multiplier chains (e.g. 27 x 11 GHz)
- Needs an RF source
- Loses power with THz frequency (multiplication)

Photoconductive antennas
- Loses power with THz frequency (RC time constant)

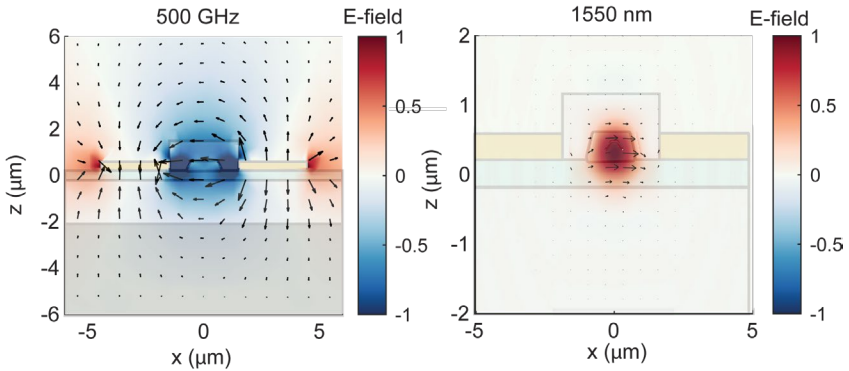
Photonics-integrated terahertz circuits @ EPFL



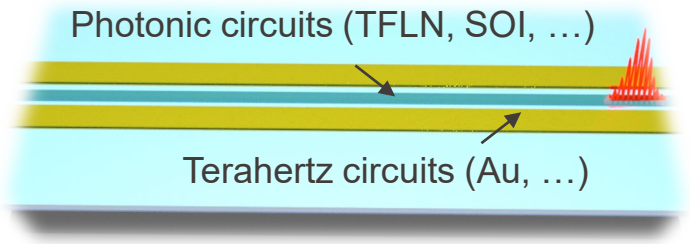
Photonics-integrated terahertz circuits @ EPFL



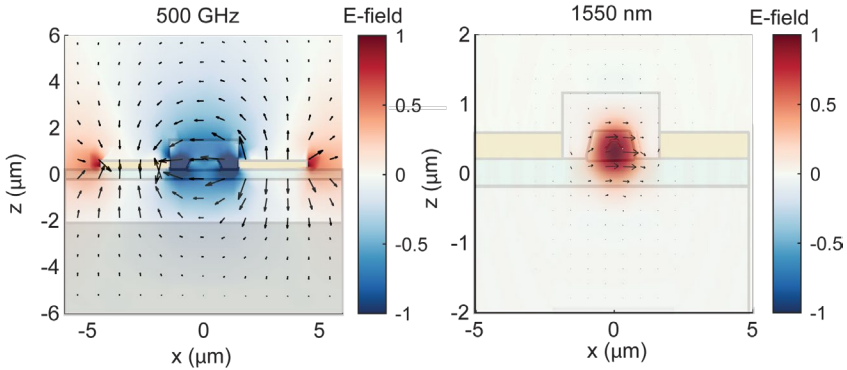
Free choice of geometry!



Photonics-integrated terahertz circuits @ EPFL



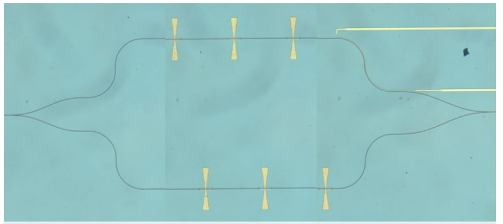
- **Dispersion engineering** of THz and optical (detection and generation efficiency, …)
- **Ultrawide analog bandwidth of photonics**
- **Fiber components** in the telecom for:
  - **Modulation,**
  - **parallelisation,**
  - **Compactness**
- **Nonlinear optics:**
  - **Frequency conversion**



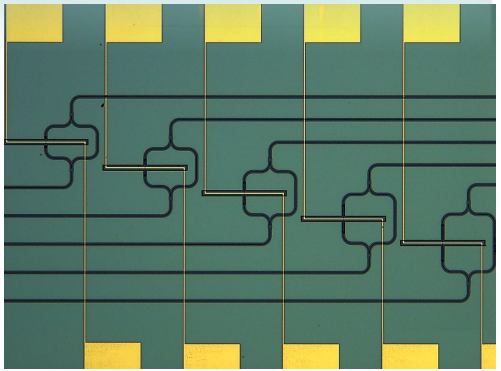
Photonics-integrated terahertz circuits @ EPFL

- THz platforms under investigation

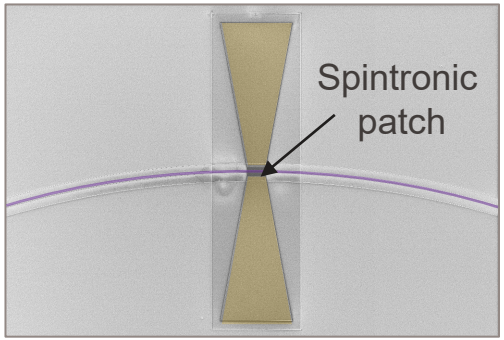
1. Thin-film lithium niobate (TFLN)



2. Hybrid silicon-organic plasmonic integrated circuits

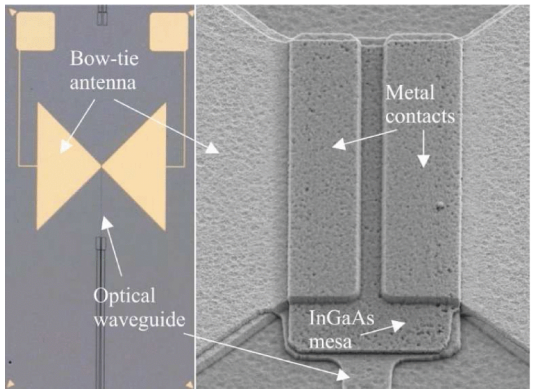


3. Spintronic emitters on silicon-on-insulator



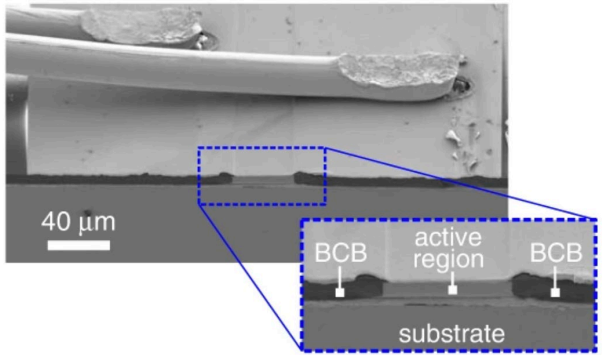
Integrated photonic technologies for the terahertz

Integrated photoconductive technologies



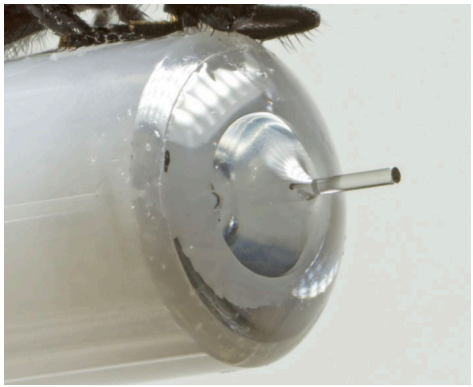
[1]

QCL-on-polymer



[2]

Fiber-tip spintronic



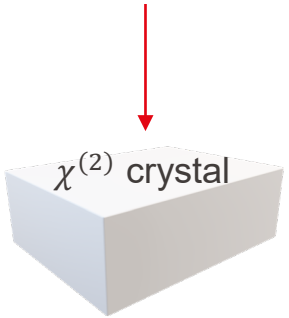
[3]

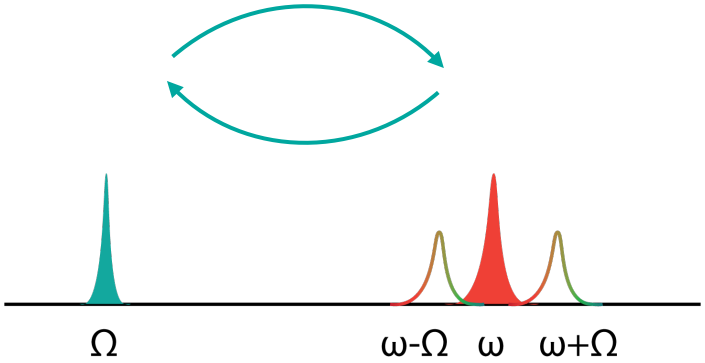
[1] M. Deumer et al., "Waveguide-integrated photoconductive THz receivers," 2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz), Delft, Netherlands, 2022, pp. 1-2, doi: 10.1109/IRMMW-THz50927.2022.9895580.
[2] Senica, U., Forrer, A., Olariu, T. *et al.* Planarized THz quantum cascade lasers for broadband coherent photonics. *Light Sci Appl* **11**, 347 (2022).
[3] https://arxiv.org/pdf/2305.01365.pdf (2023)

Making light interact with light

Ileana-Cristina Benea-Chelmus

$$E(t) = E_p e^{i\omega t} + E_{THz} e^{i\Omega t}$$

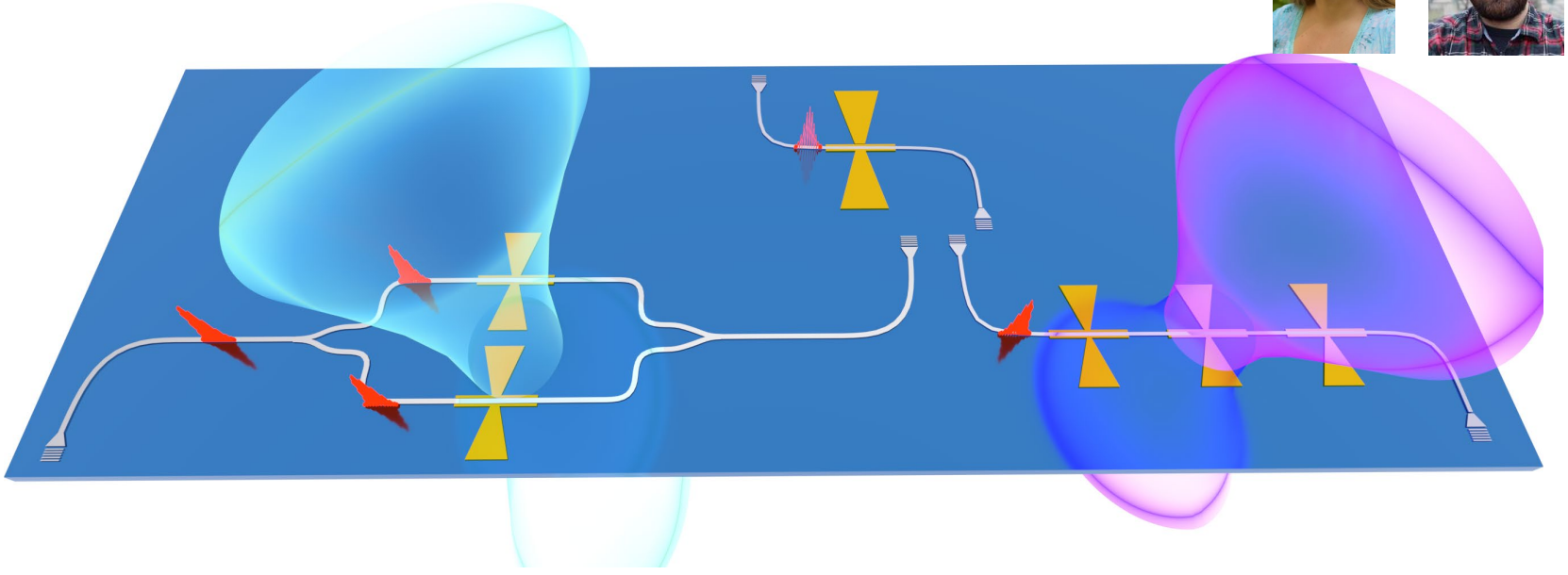




Coherent process: phase, amplitude and frequency information is preserved.

Manley-Rowe limit: efficiency scales with frequency! $\eta = \frac{\Omega_{THz}}{\omega}$

Develop one single platform for both detection and generation!

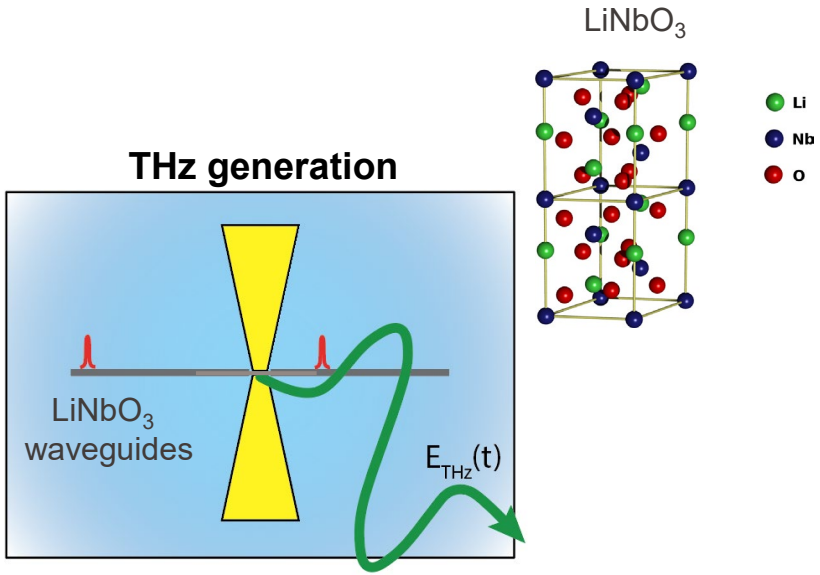


1. Arbitrary waveform synthesis

Ileana-Cristina Benea-Chelmus

Basic device concept

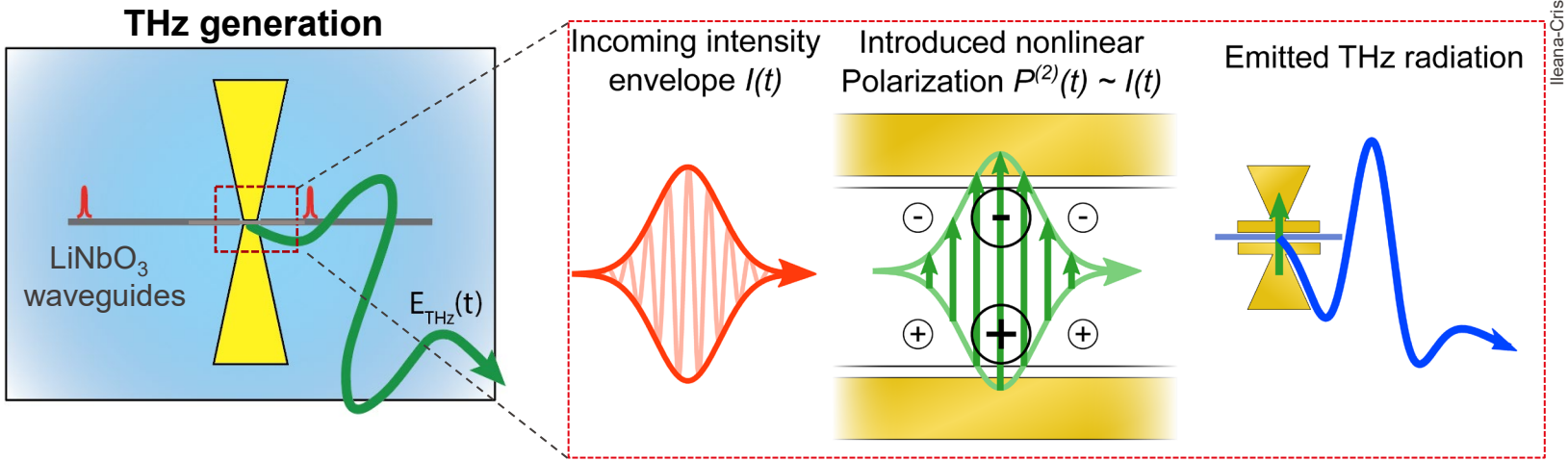
printed antennas



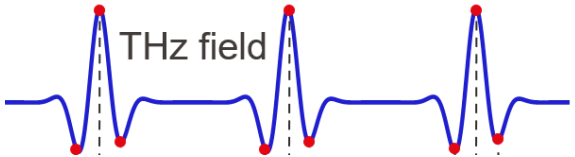
Monolithic lithium niobate photonic circuits for terahertz
Optimized for low loss

Herter, Shams-Ansari, Settembrini, Warner, Faist, Loncar and Benea-Chelmus, Nature Communications 14, 11 (2023)

Basic device concept

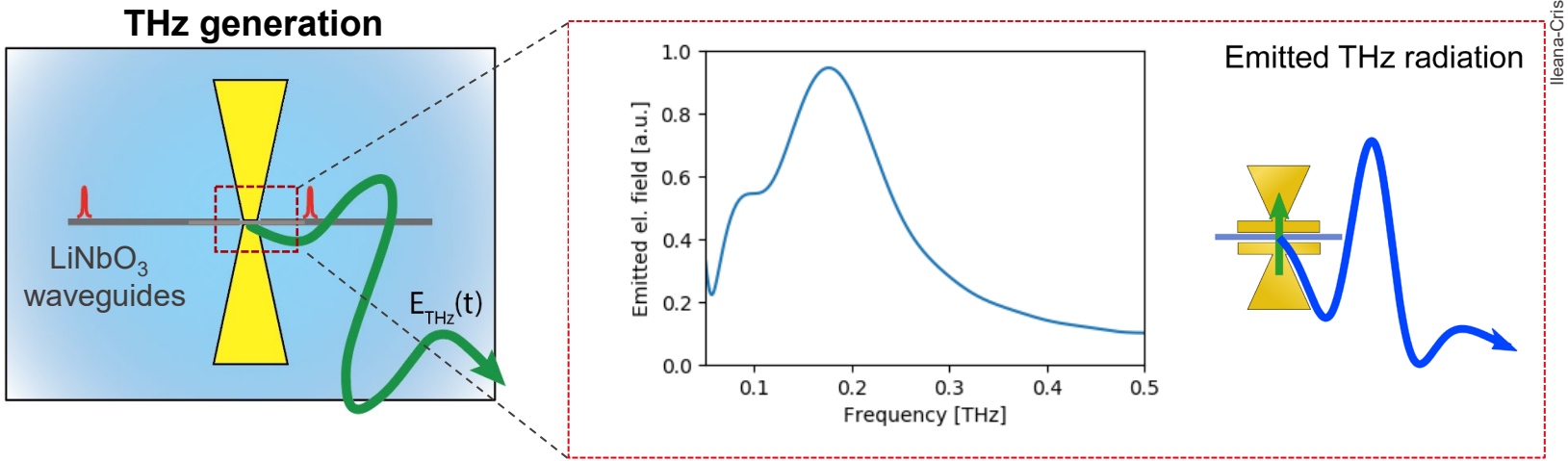


Phase-locked THz generation!



Herter, Shams-Ansari, Settembrini, Warner, Faist, Loncar and Benea-Chelmus, Nature Communications 14, 11 (2023)

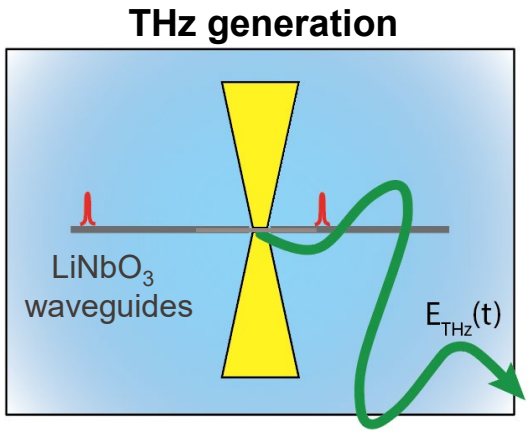
Basic device concept

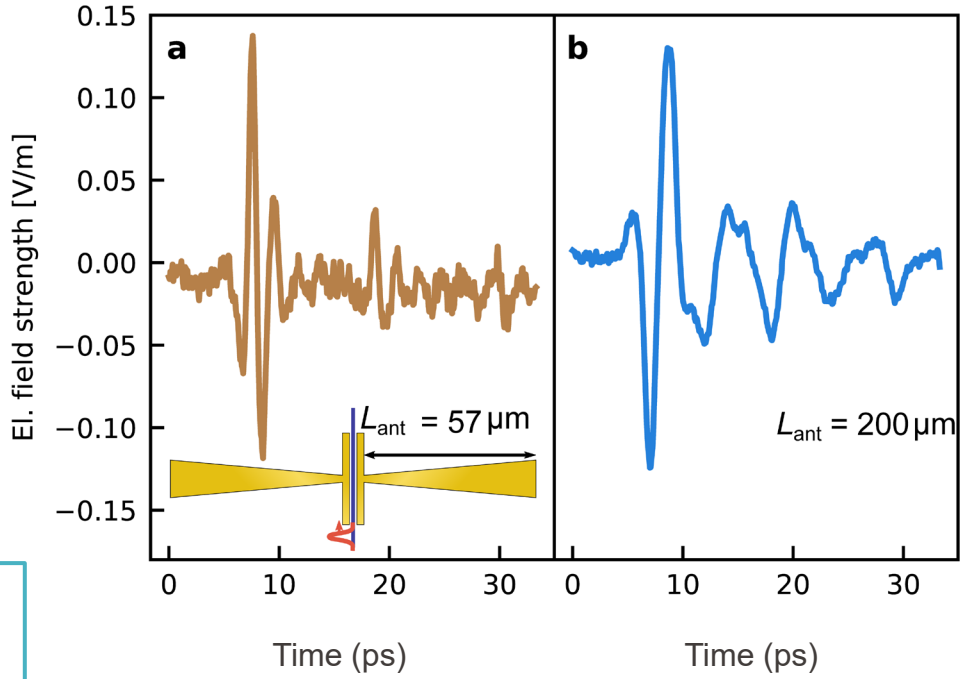


- custom tailoring of emission spectrum by antenna design
- engineered farfield

Herter, Shams-Ansari, Settembrini, Warner, Faist, Loncar and Benea-Chelmus, Nature Communications 14, 11 (2023)

Measurements single antenna emitters

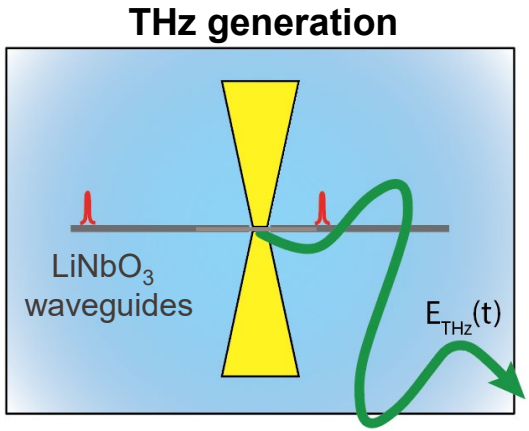


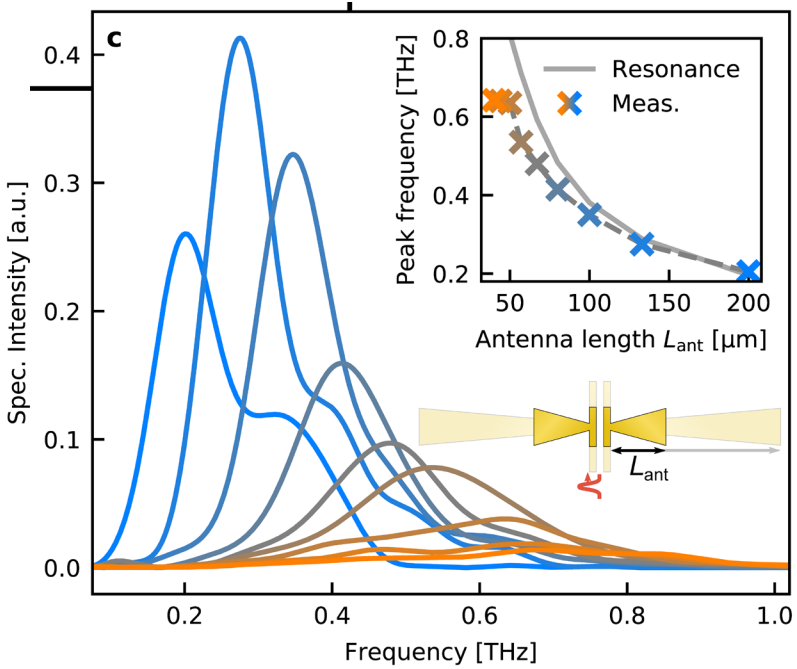


- custom tailoring of emission spectrum by antenna design
- engineered farfield: ~0.1 V/m

Herter, Shams-Ansari, Settembrini, Warner, Faist, Loncar and Benea-Chelmus, Nature Communications 14, 11 (2023)

Measurements single antenna emitters

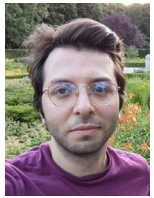




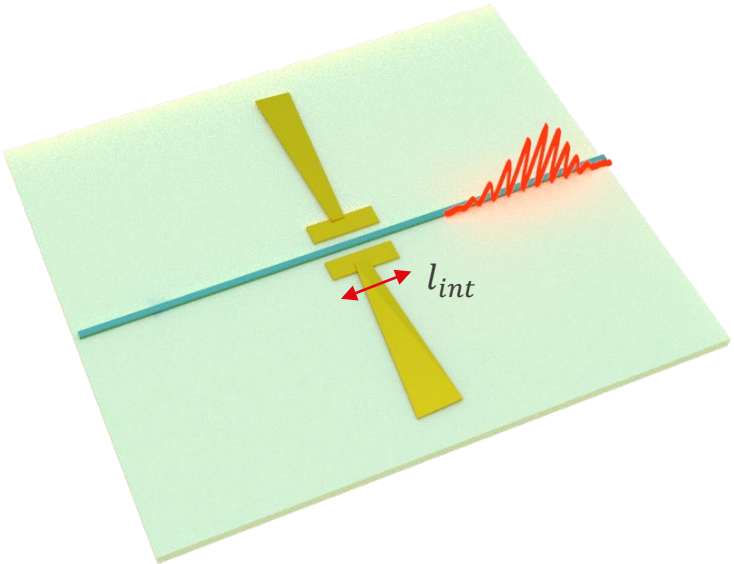
- Emission up to 680 GHz

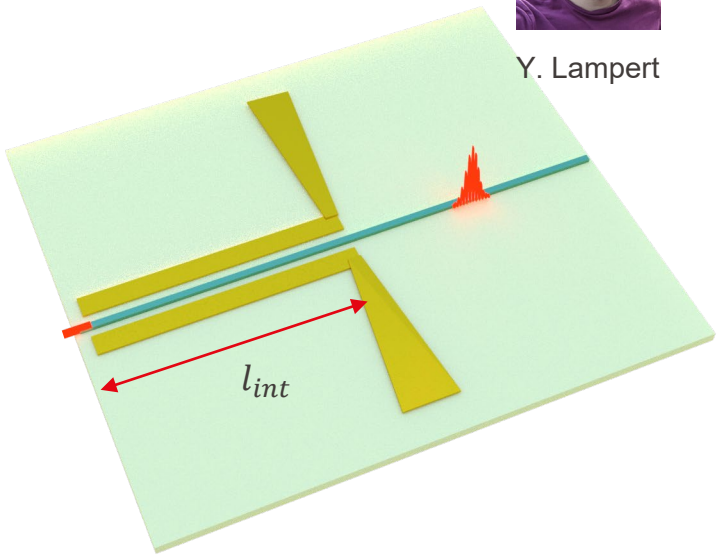
Herter, Shams-Ansari, Settembrini, Warner, Faist, Loncar and Benea-Chelmus, Nature Communications 14, 11 (2023)

Phase-matched terahertz transmission lines



Y. Lampert



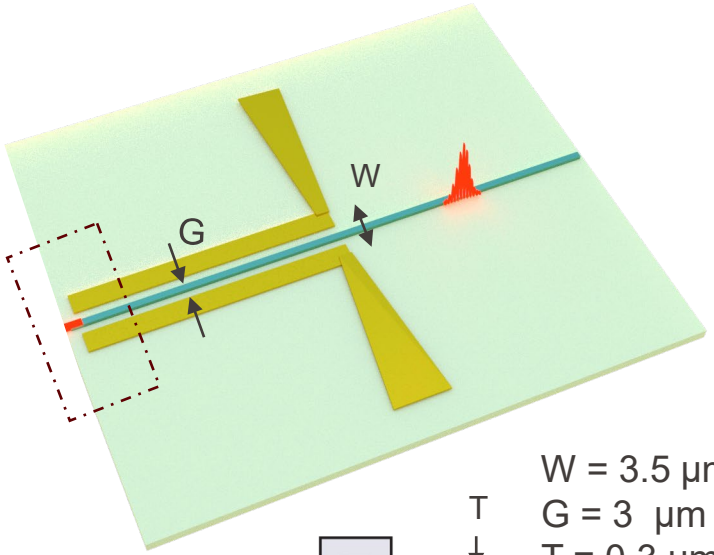


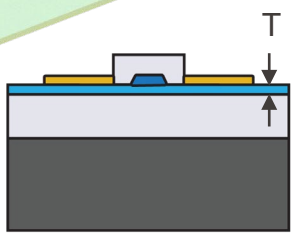
$< \frac{\lambda_{THz}}{2}$ $>> \lambda_{THz}$

interaction length l_{int}

Lampert, Shams-Ansari, Gaier, Tomasino, Rajabali, Loncar, Benea-Chelmus, *arxiv submit 5681801* (2024)

Phase-matched terahertz transmission lines

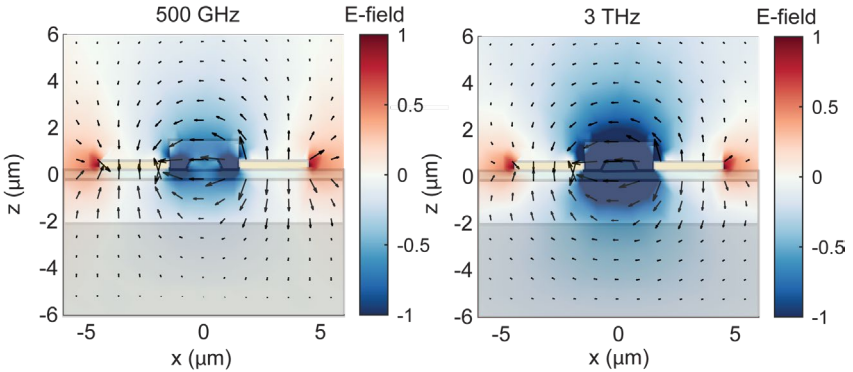




LiNbO3 Au SiO2 HR-Si

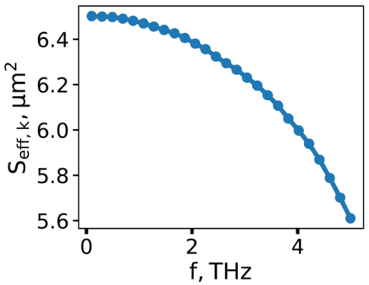
W = 3.5 μm
G = 3 μm
T = 0.3 μm

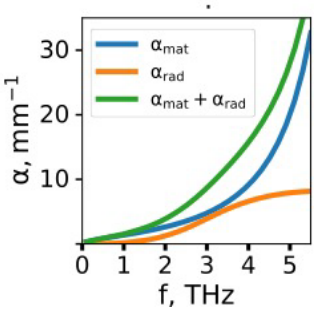
Broadband strip line



Strongly sub-wavelength confinement **very important**!

- Low radiative losses

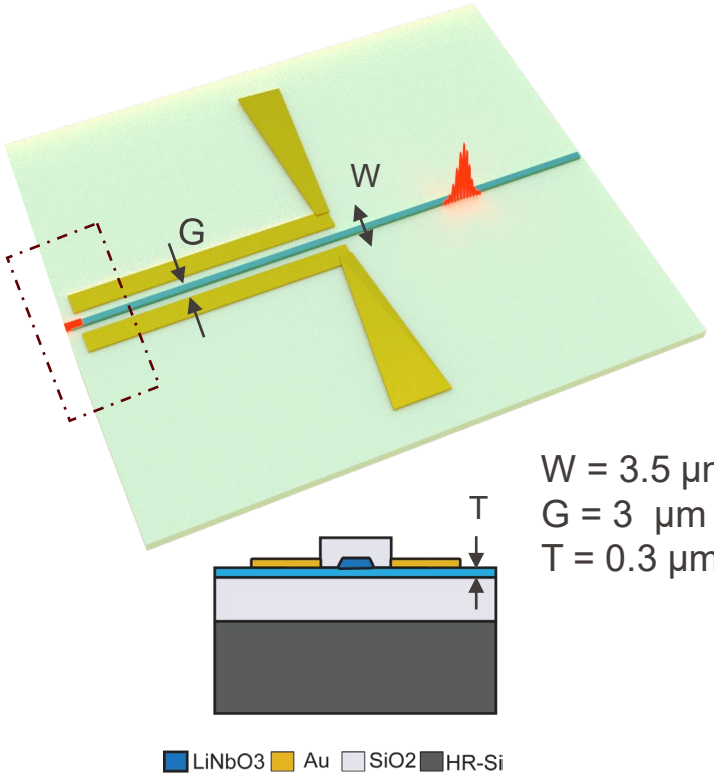




Lampert, Shams-Ansari, Gaier, Tomasino, Rajabali, Loncar, Benea-Chelmus, *arxiv submit 5681801* (2024)

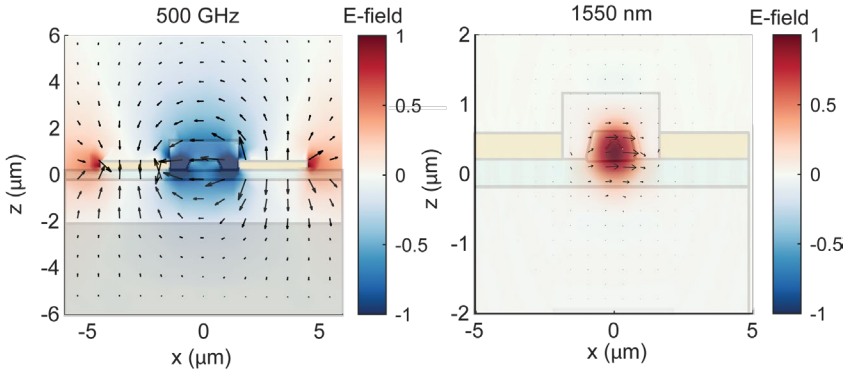
Phase-matched terahertz transmission lines

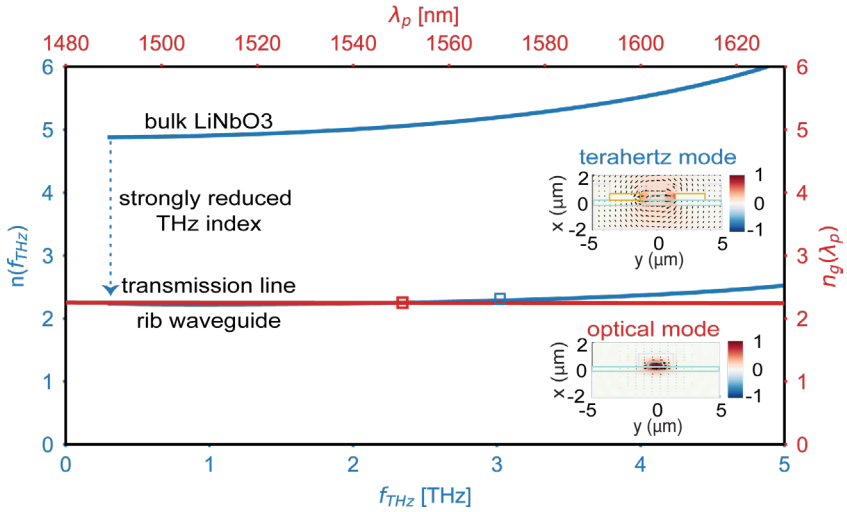
Ileana-Cristina Benea-Chelmus



W = 3.5 μm
G = 3 μm
T = 0.3 μm

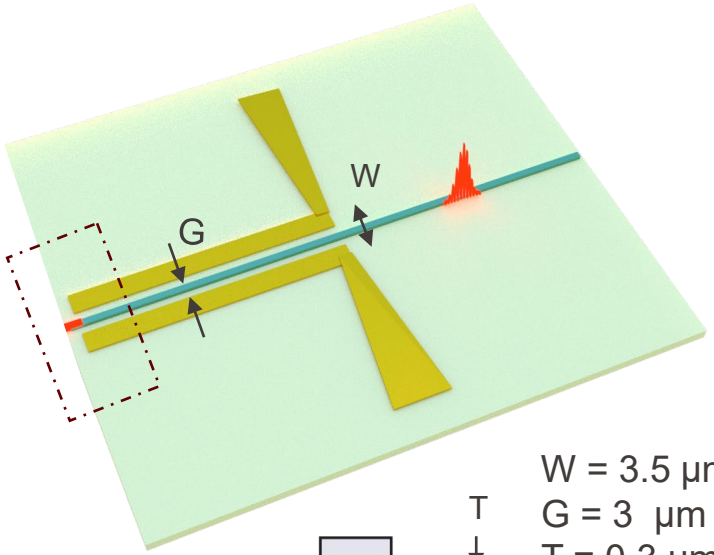
Broadband strip line





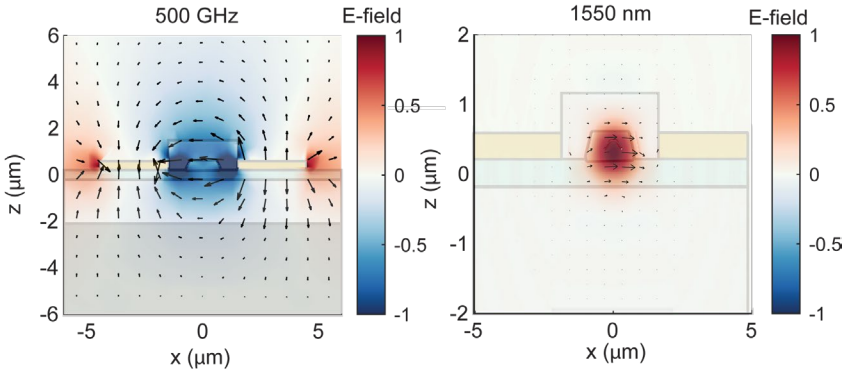
Phase-matched terahertz transmission lines

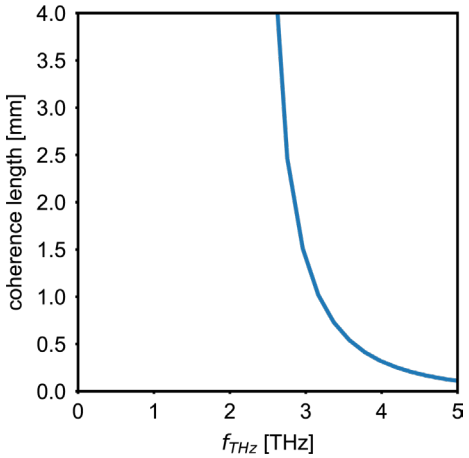
Ileana-Cristina Benea-Chelmus



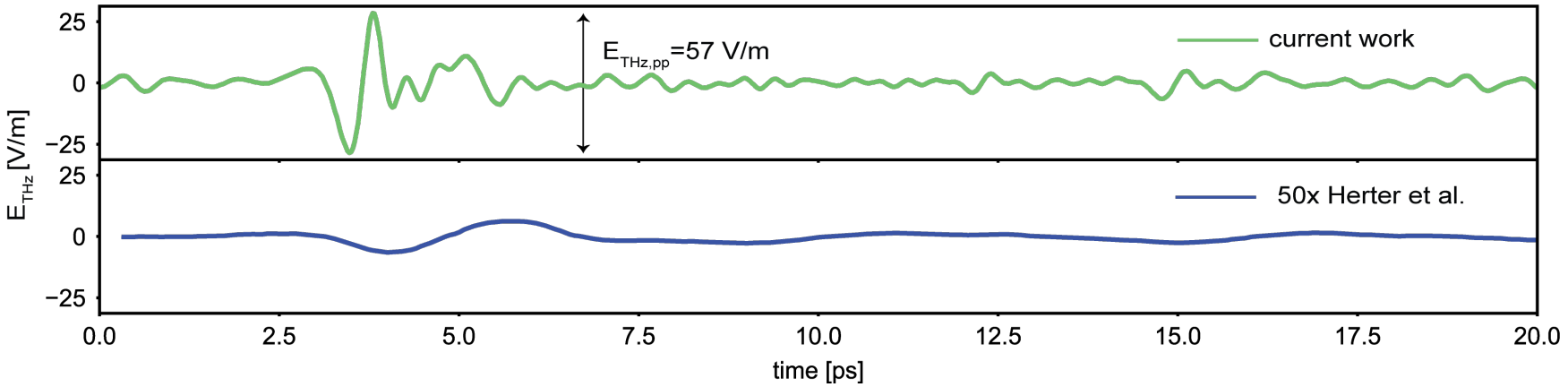
W = 3.5 µm
G = 3 µm
T = 0.3 µm

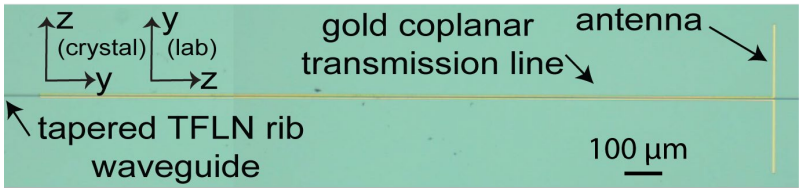
Broadband strip line





Performance





J_{pump} = 50 pJ

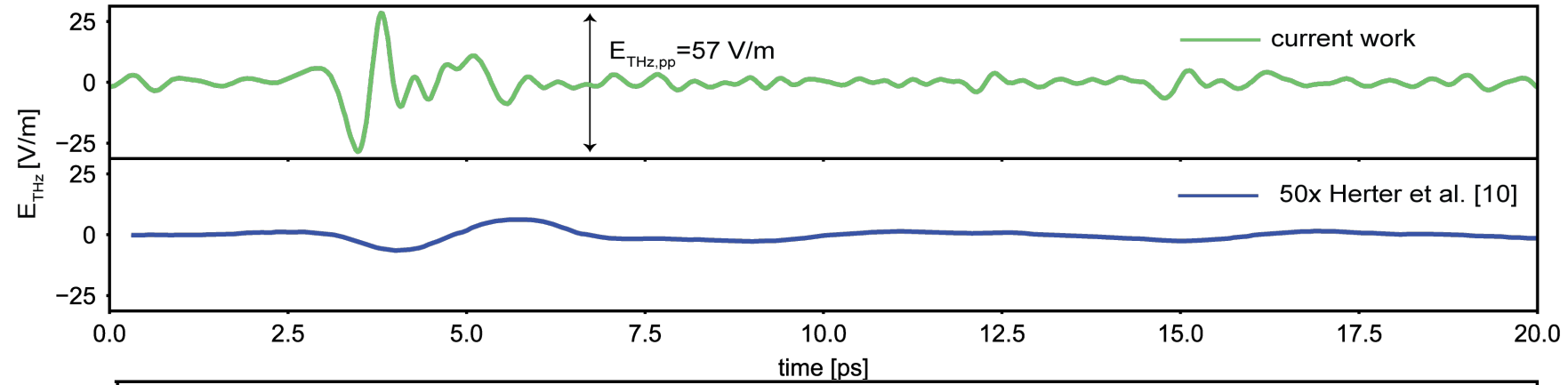
$\eta = 1000 \frac{V/m}{nJ}$

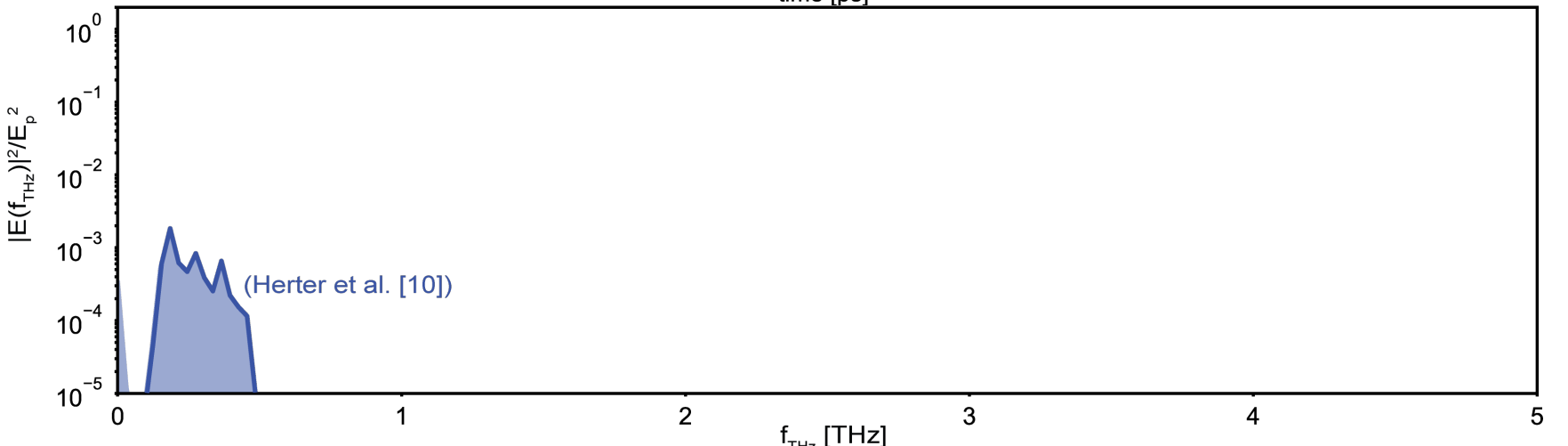
l_{int} = 2 mm

~ 100 x in field amplitude!

Lampert, Shams-Ansari, Gaier, Tomasino, Rajabali, Loncar, Benea-Chelmus, *arxiv submit 5681801* (2024)

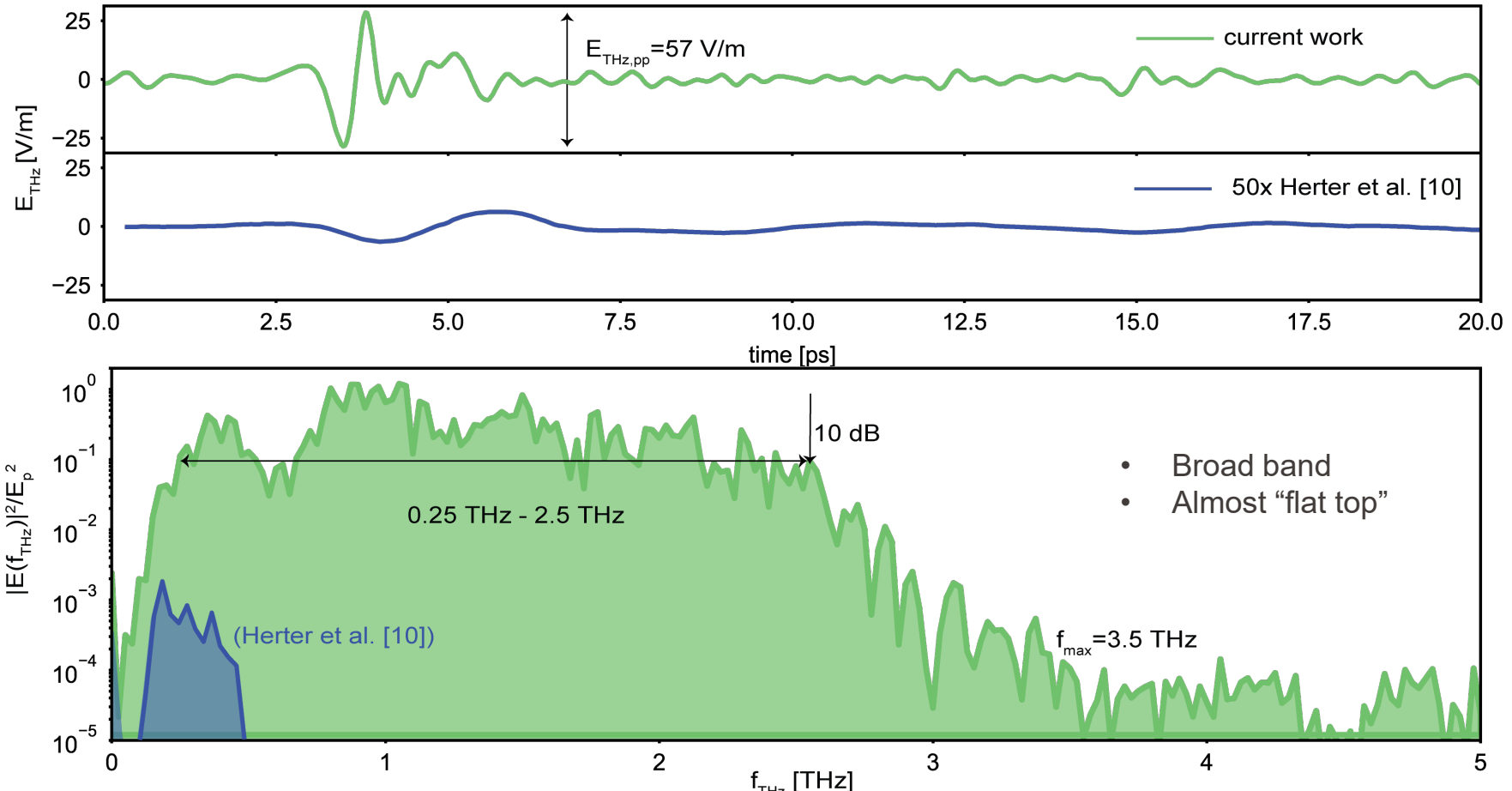
Performance





Ileana-Cristina Benea-Chelmus

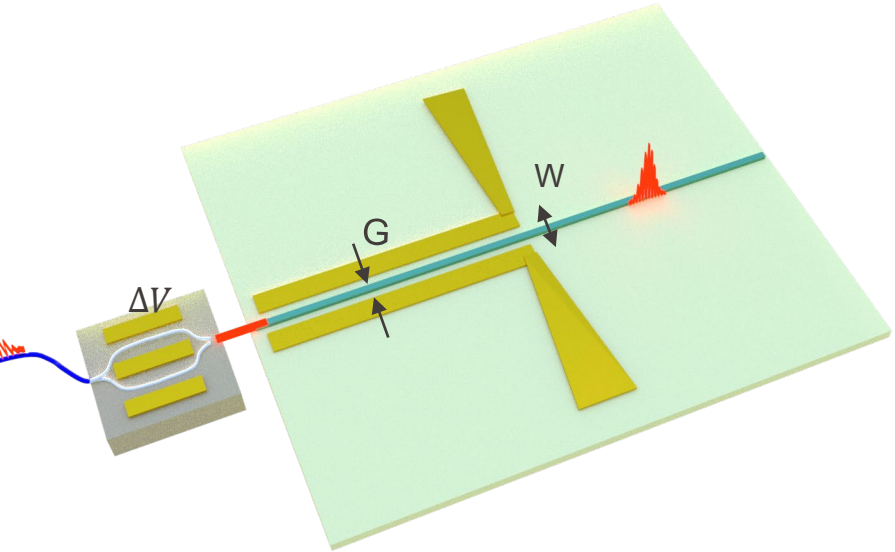
Performance

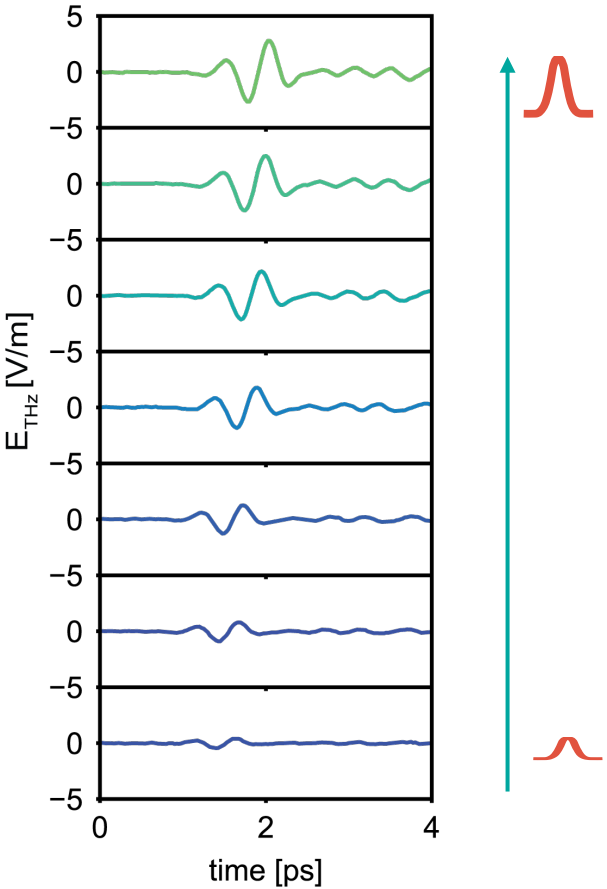


Ileana-Cristina Benea-Chelmus

Ileana-Cristina Benea-Chelmus

Terahertz transmitter





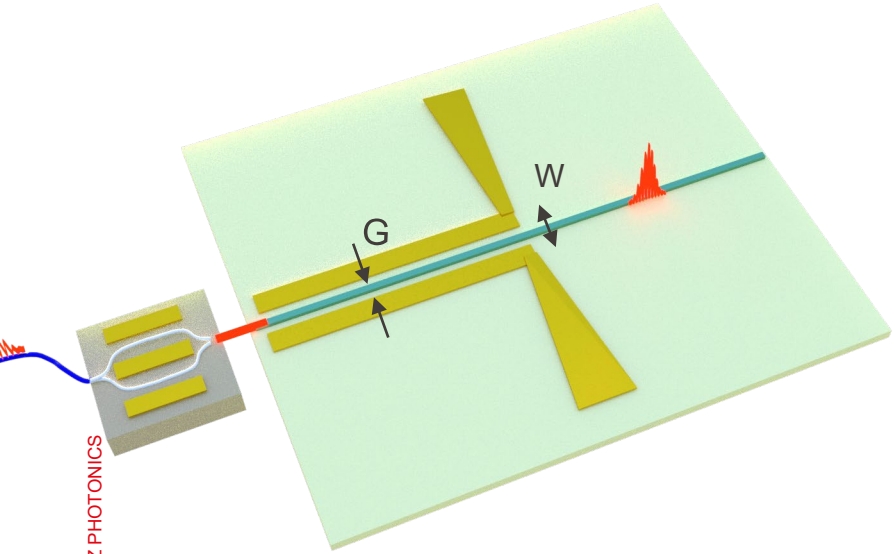
Y. Lampert

Voltage @ 1 MHz

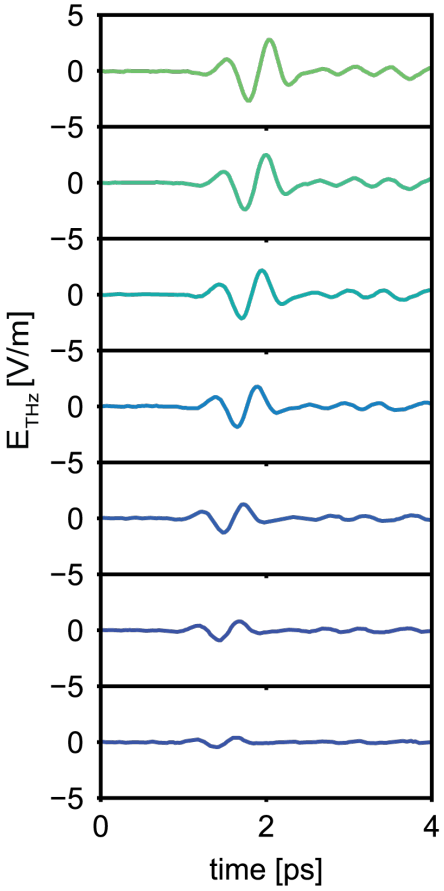
Control the intensity of the pump pulse
-> control the THz amplitude

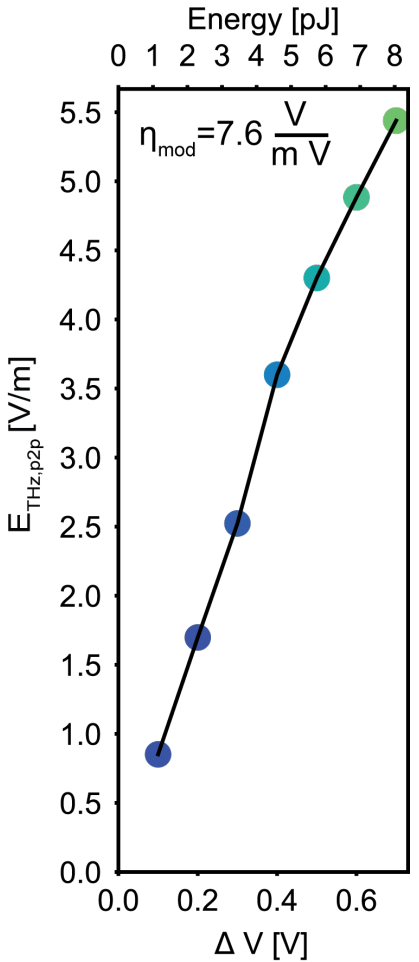
Lampert, Shams-Ansari, Gaier, Tomasino, Rajabali, Loncar, Benea-Chelmus, *arxiv submit 5681801* (2024)

Terahertz transmitter



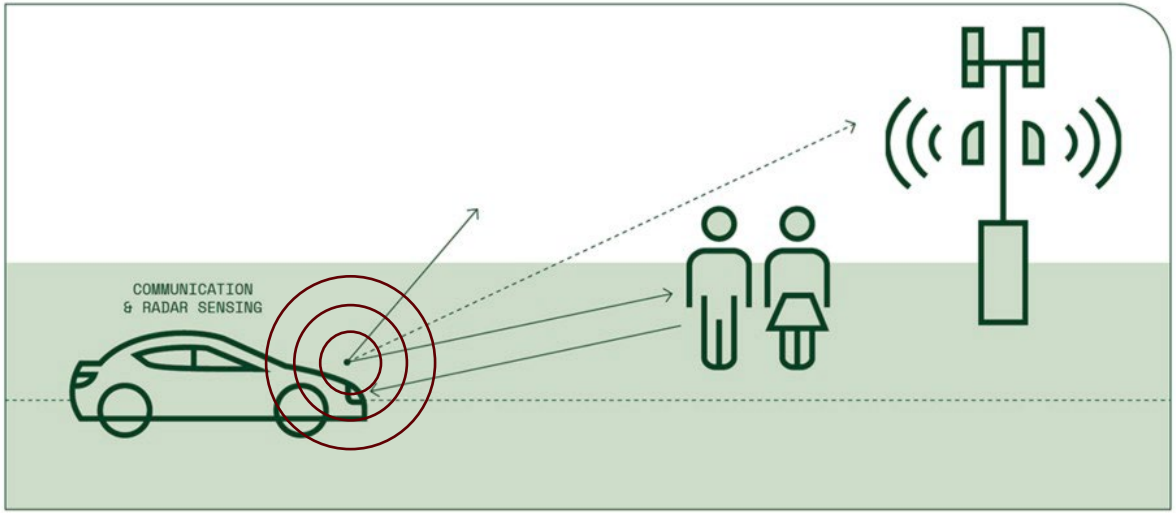
- A terahertz transmitter with continuous amplitude control
- GHz speed analog bandwidth





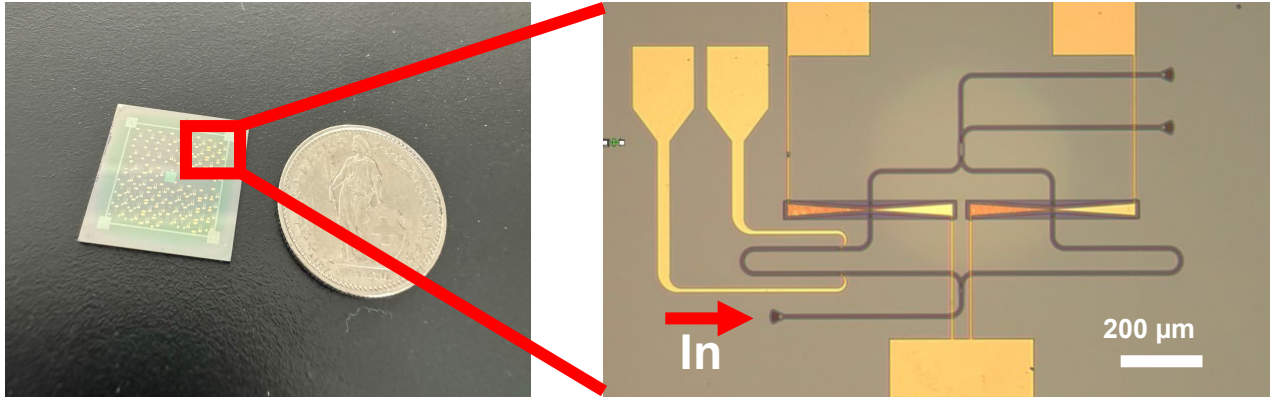
Lampert, Shams-Ansari, Gaier, Tomasino, Rajabali, Loncar, Benea-Chelmus, *arxiv submit 5681801* (2024)

Vision of 6G : joint communication, sensing and localisation



- Engineering of emitters bandwidth, farfield and modulation.
- What about detection?

Francesco Bertot

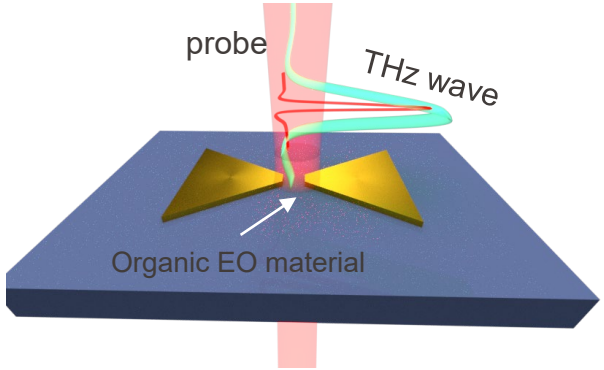


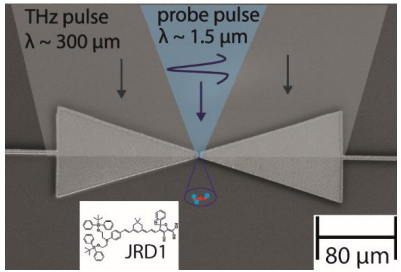
Haffner, C., *et al. Nature Photon* **9**, 525–528 (2015)
Salamin, Y., *et al. Nat Commun* **10**, 5550 (2019)
Ummethala, S., *Nat. Photonics* **13**, 519–524 (2019)

2. Terahertz detection in low-power and compact silicon-organic chips

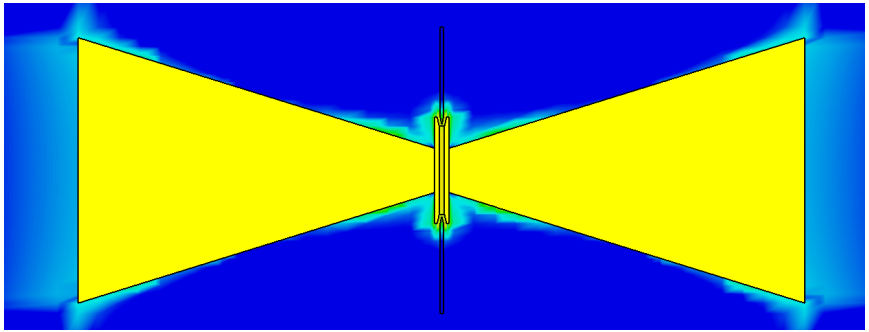
A bit of history

Free-space optical light





- I.-C. Benea-Chelmus et al. *ACS Photonics* **5** (2018)
  Collaboration with J. Leuthold & L.Dalton (UW)

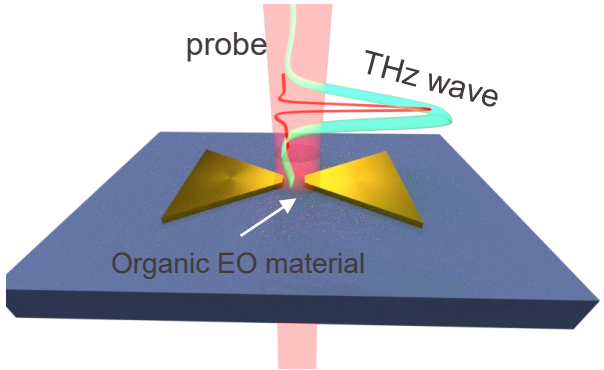


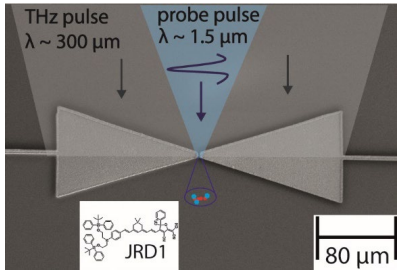
- Good cavity confinement of the terahertz wave
- High r33 by organic material

- Difficult to pass the optical light through the antenna gap

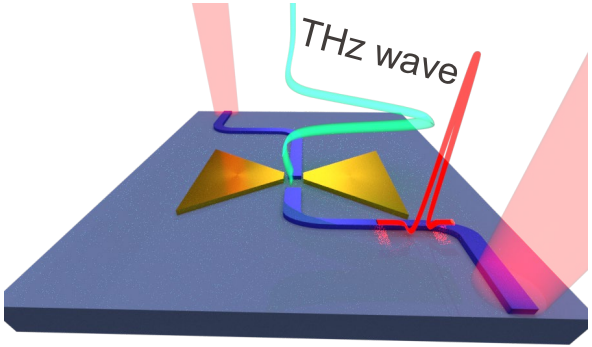
A bit of history

Free-space optical light





Guided optical light



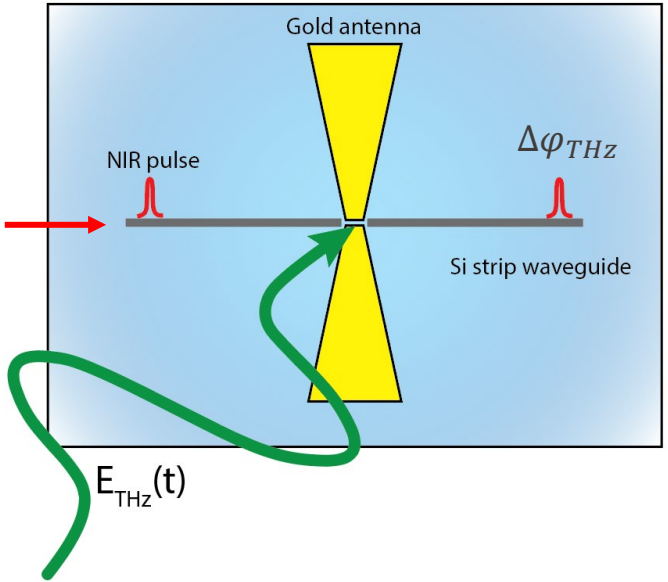
Fiber-coupled light

Interaction region defines all important parameters:
Overlap, field enhancement, losses and interaction time!

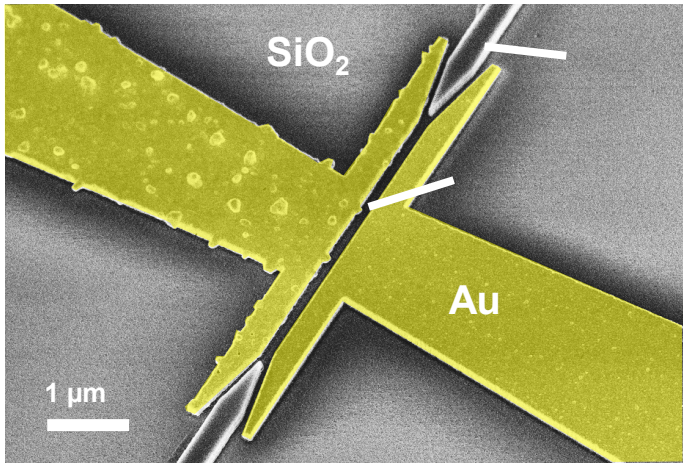
- I.-C. Benea-Chelmus et al. *ACS Photonics* **5** (2018)
  Collaboration with J. Leuthold & L.Dalton (UW)

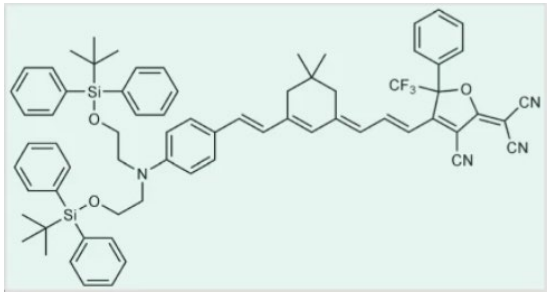
Y. Salamin*, I-C Benea-Chelmus* *et al. Nature Comm.* **10,** 5550 (2019)
Collaboration with L.Dalton (UW), J. Leuthold (ETHZ)

Integrated THz EO sampling



- Cross propagation
- **phase modulation** of probe



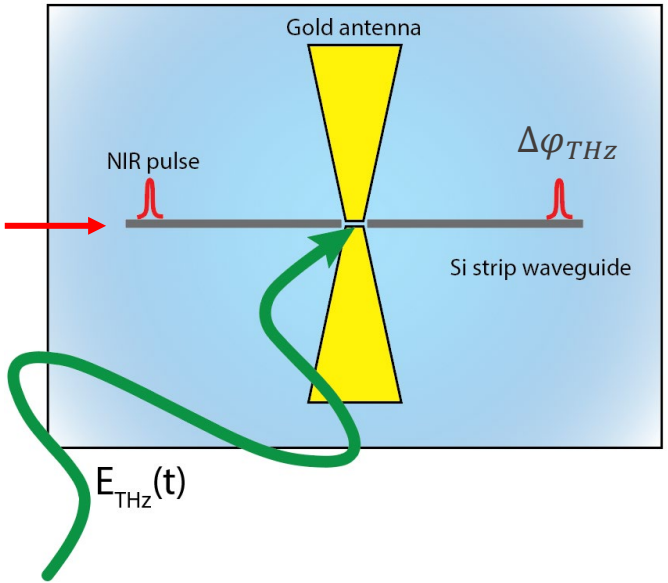


$$\Delta\varphi_{THz}(t) \propto \Gamma_c \cdot L \cdot n_g \cdot r_{33} \cdot E_{THz}(t)$$

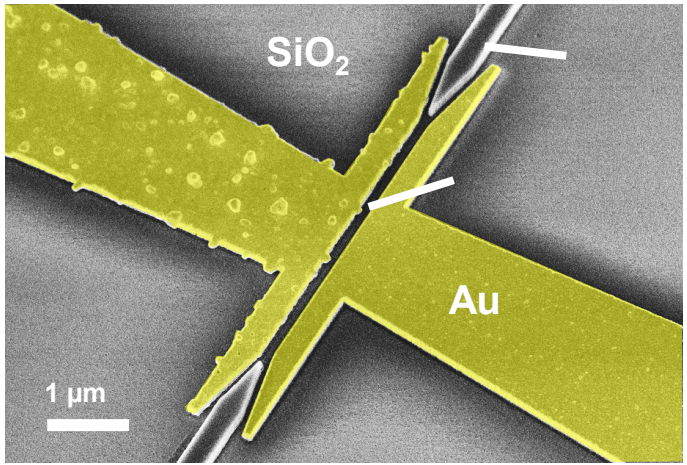
Addition of non-linear polymer JRD1

$$\mathbf{r_{33} = 120\ \frac{pm}{V}} \left(\gg 4\ \frac{\text{pm}}{\text{V}}\ \text{for ZnTe} \right)$$

Integrated THz EO sampling



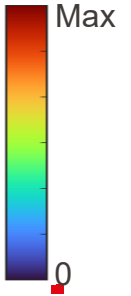
- Cross propagation
- **phase modulation** of probe

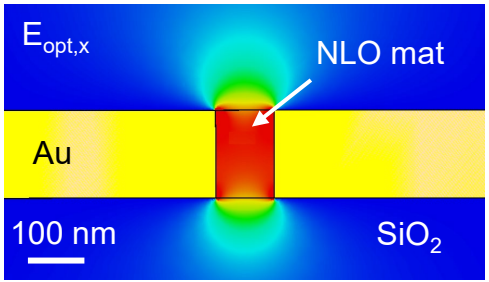


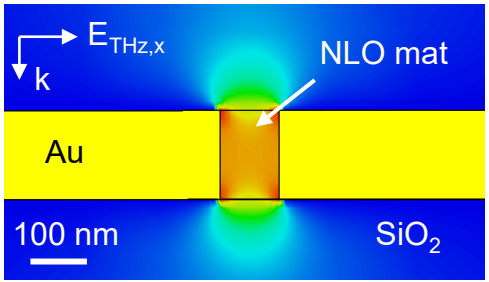
$$\Delta\varphi_{THz}(t) \propto \Gamma_c \cdot L \cdot n_g \cdot r_{33} \cdot E_{THz}(t)$$

THz-probe overlap

Interaction length

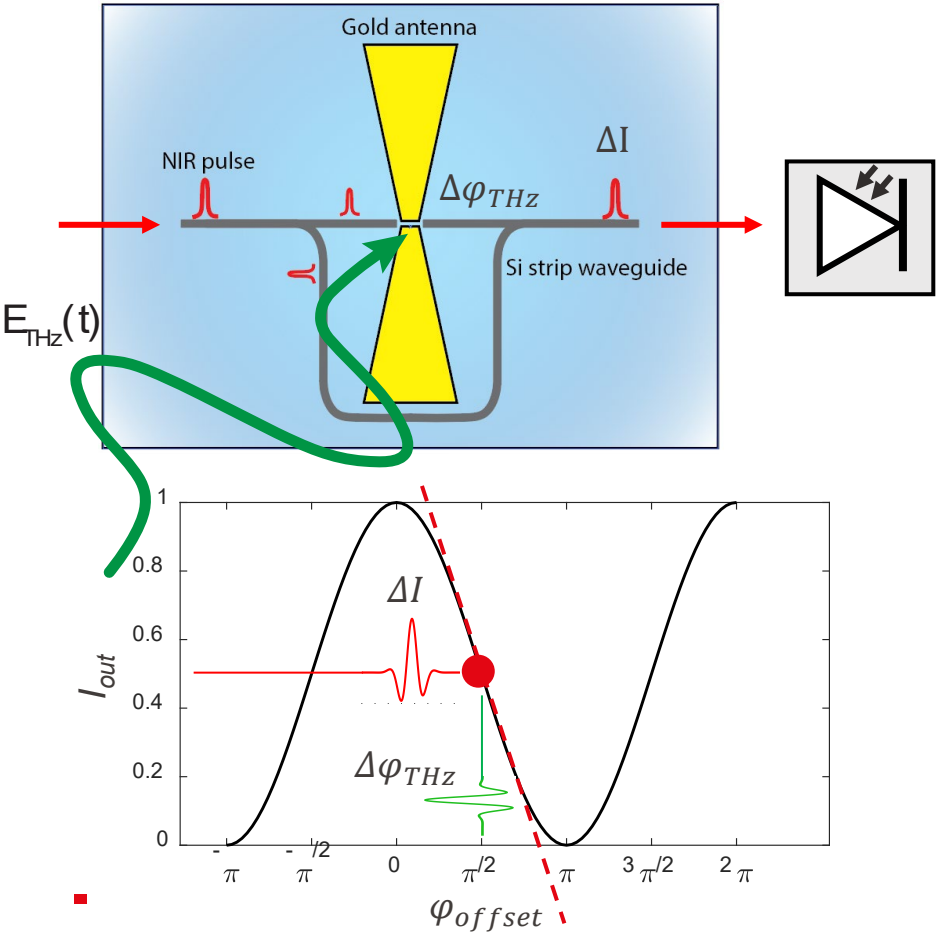






Bertot, Tomasino, Benea-Chelmus, *in preparation* (2024)

Output characteristic: towards balanced detection



- **Mach-Zehnder interferometer (MZI)**: Converts phase in intensity modulation
- Output interference:

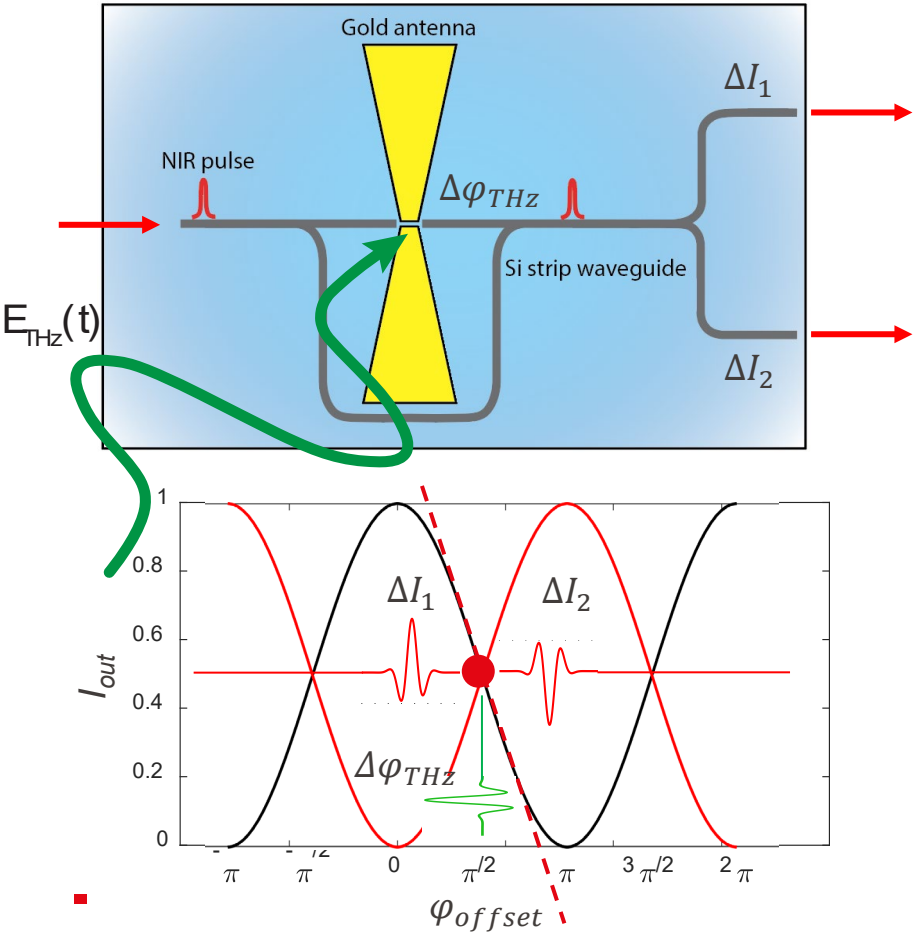
$$I_{out} \propto \frac{I_{in}}{2}[1 + \cos(\varphi_{off} + \Delta\varphi_{THz})]$$

- At quadrature point ($\varphi_{offset} = \pi/2$):

$$\Delta I_{out} \propto I_{in}\, \Delta\varphi_{THz}$$

Bertot, Tomasino, Benea-Chelmus, *in preparation* (2024)

Output characteristic: towards balanced detection



- **Mach-Zehnder interferometer (MZI)**: Converts phase in intensity modulation
- Output interference:

$$I_{out} \propto \frac{I_{in}}{2}[1 + \cos(\varphi_{off} + \Delta\varphi_{THz})]$$

- At quadrature point ($\varphi_{offset} = \pi/2$):

$$\Delta I_{out} \propto I_{in}\, \Delta\varphi_{THz}$$

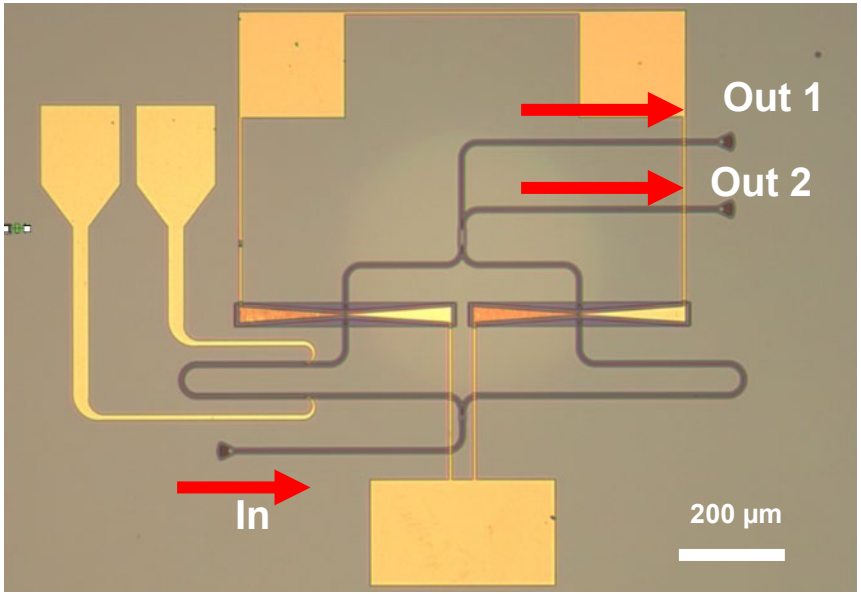
- With two outputs and balanced detection:

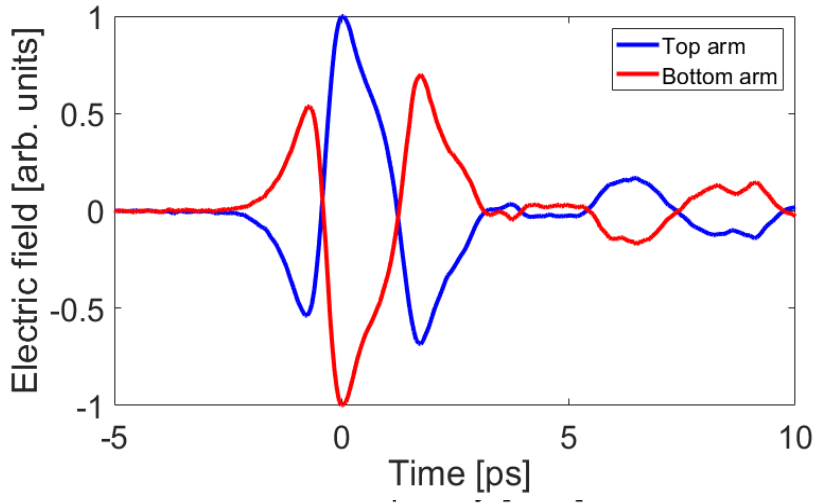
$$\Delta I_{out} \propto 2\, I_{in}\, \Delta\varphi_{THz}$$

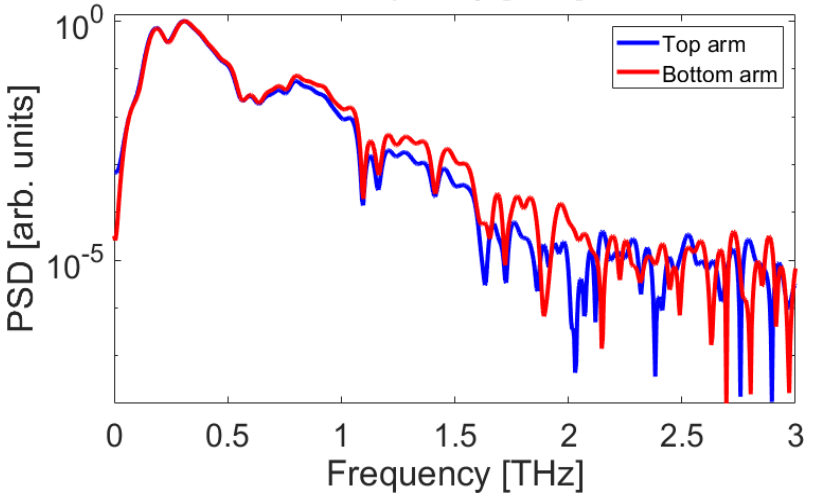
- Obtained adding an output *X-coupler*

Bertot, Tomasino, Benea-Chelmus, *in preparation* (2024)

THz sensor

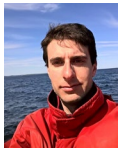






- Bow-tie antenna for broadband operation
- Plasmonic interaction region (L_{int} = 5 µm)

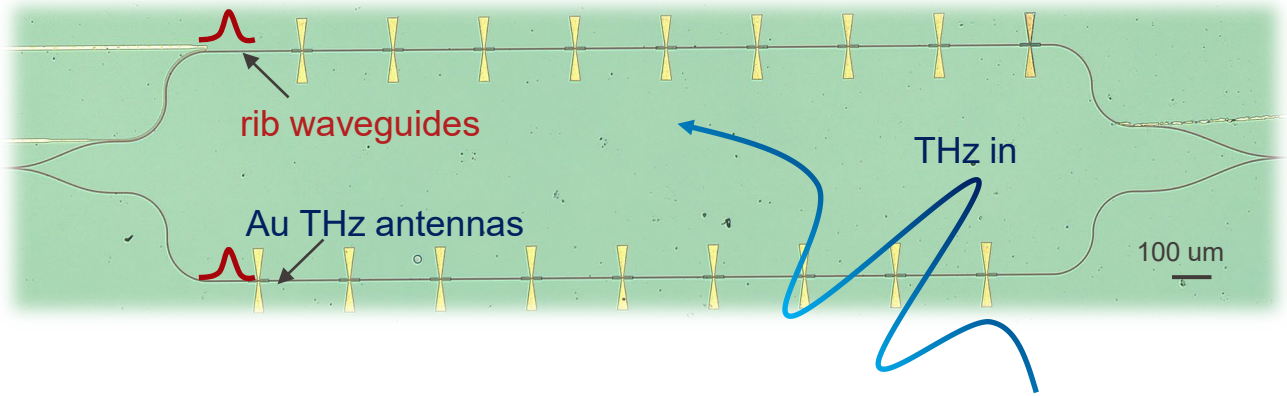
A. Shams-Ansari A. Tomasino

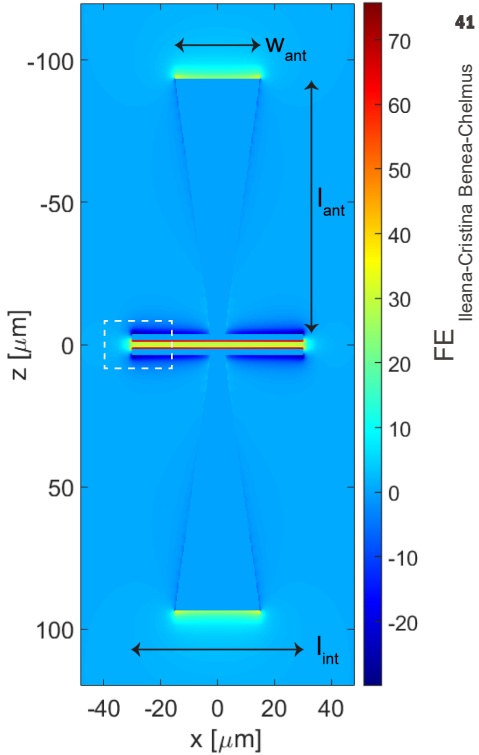


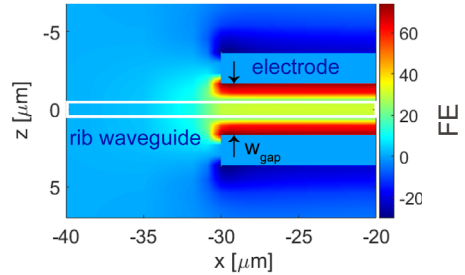
Ileana-Cristina Benea-Chelmus

3. Detection and beam profiling in millimeter-long lithium niobate circuits

Large area terahertz detector







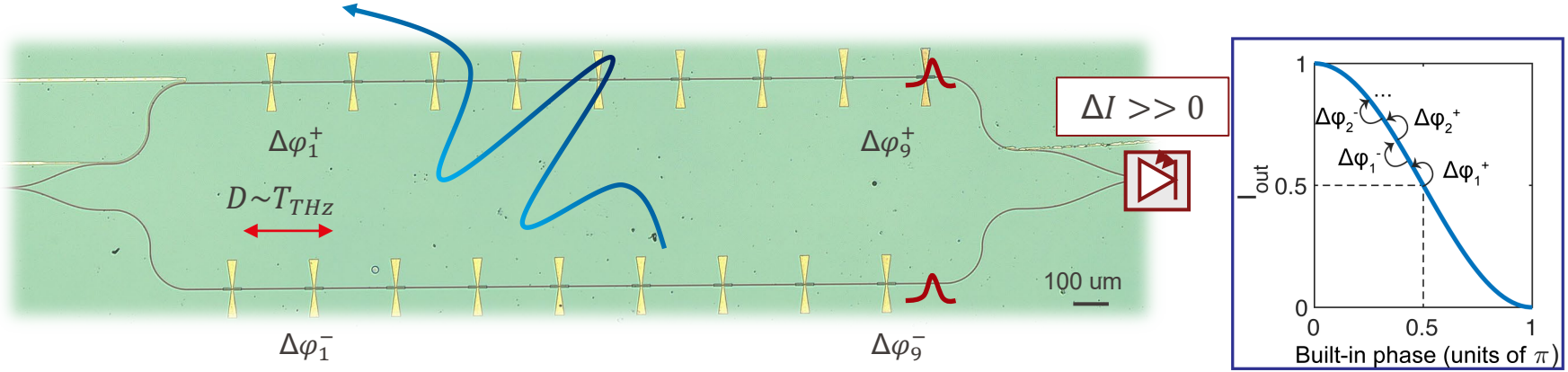
- **Benefits of TFLN:**
  - Low optical loss (< 0.3 dB/cm): 18 antennas
  - High r_{33} = 30.9 pm/V
- **Single antenna: good field enhancement (~70) for l_{int}**

$$\Delta\varphi_{THz}(t) = \frac{1}{2}\, n_{mat}^2 \cdot \Gamma_c \cdot l_{int} \cdot k_0 \cdot n_g \cdot r_{33} \cdot E_{THz,\,gap}\,(t)$$

- **Collective antenna array benefits**

Ileana-Cristina Benea-Chelmus

Large area terahertz detector

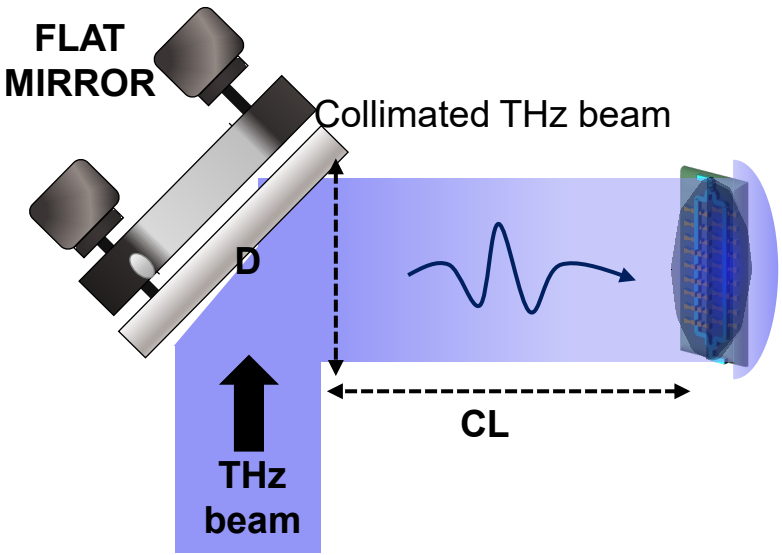


Quasi-phase matching mechanism driven by antenna enhancement

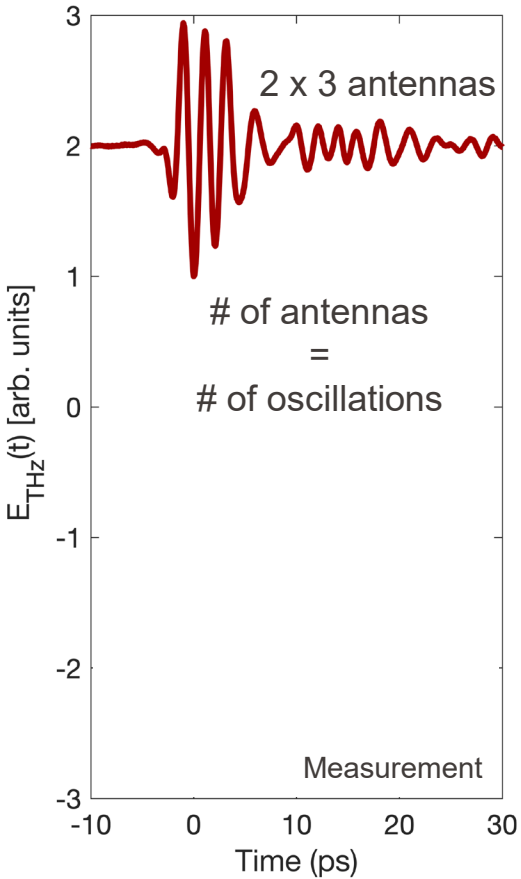
All need same phase to add up

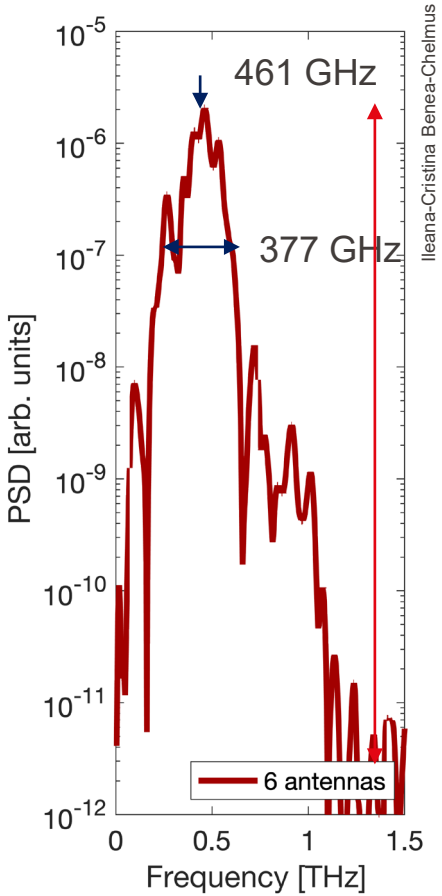
$$\Delta\varphi_{THz}(\mathrm{t}) = \frac{1}{2}\, n_{mat}^2 \cdot \Gamma_c \cdot L \cdot k_0 \cdot n_g \cdot r_{33} \cdot \left(E_{THz}^1(t) + E_{THz}^2(t+\Delta T) + E_{THz}^3(t+2\Delta T)\right) + \cdots$$

Quasi-phase matching



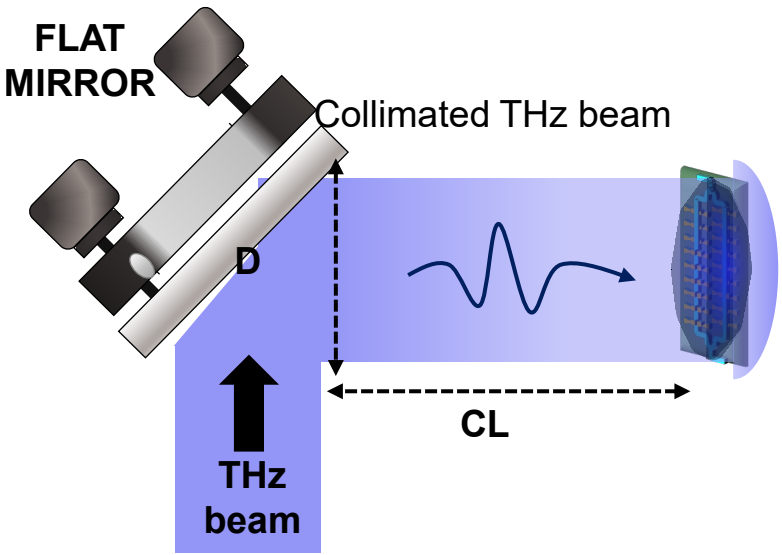
@ 100 uW probe power



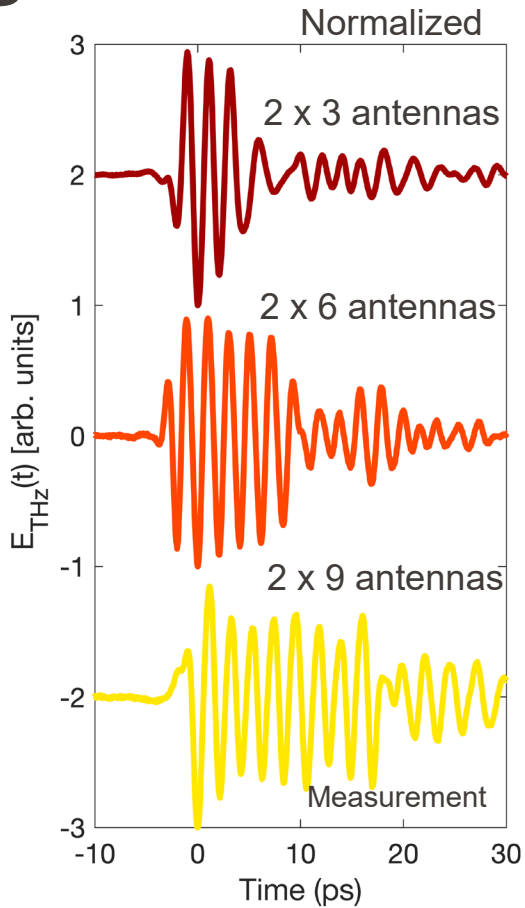


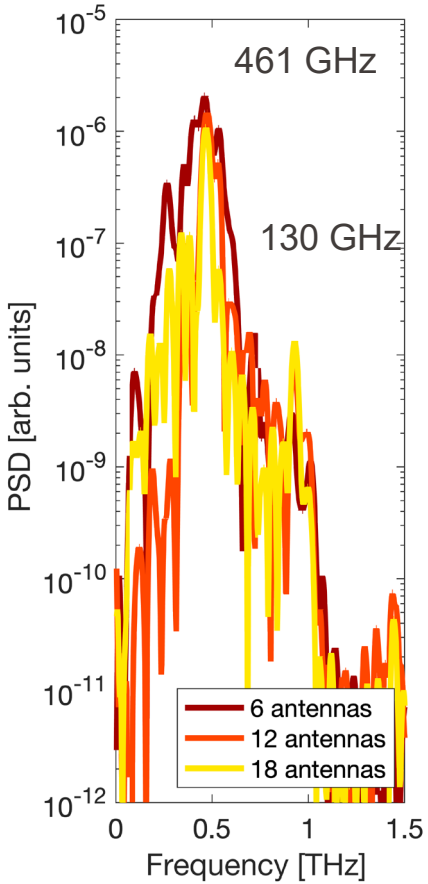
[1] A. Tomasino, A. Shams-Ansari, M. Loncar and I.-C. Benea-Chelmus., *in preparation*.

Quasi-phase matching



- Narrowing spectrum:
  - Insensitive to out-of band signals



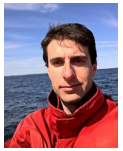


[1] A. Tomasino, A. Shams-Ansari, M. Loncar and I.-C. Benea-Chelmus., *in preparation*.

Use in dynamic scenarios

A. Shams-Ansari

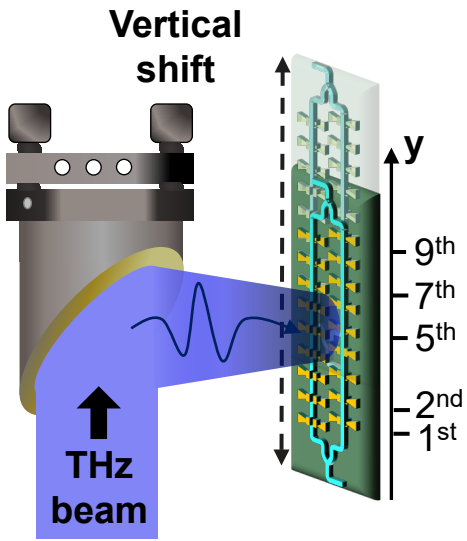
A. Tomasino

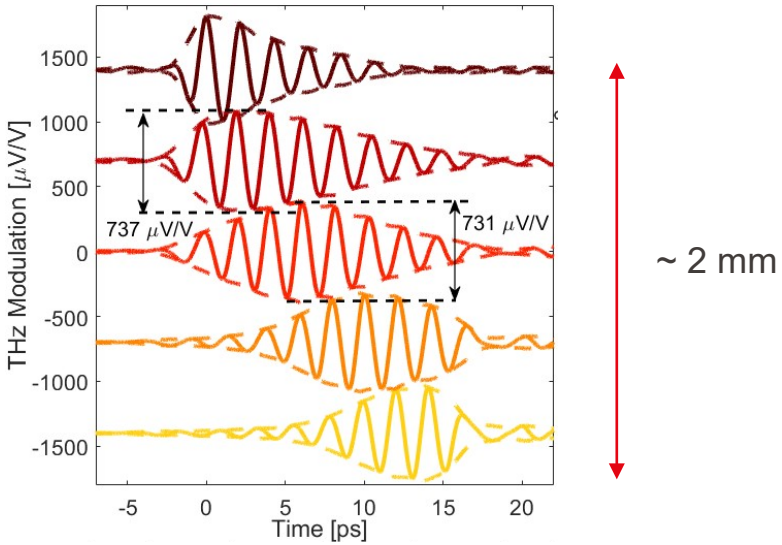


Ileana-Cristina Benea-Chelmus

- Large area can help collect signals that are not perfectly focussed
- Beam profiling of the terahertz at the detector possible?

Sensitivity to exact illumination

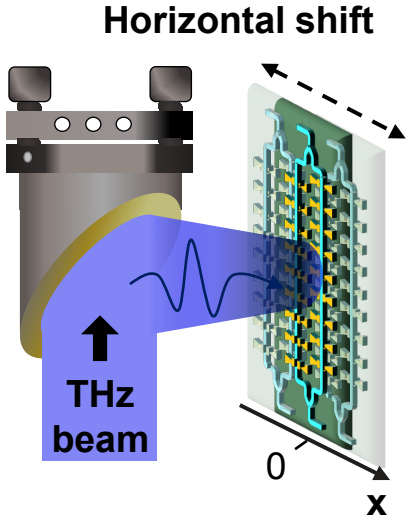


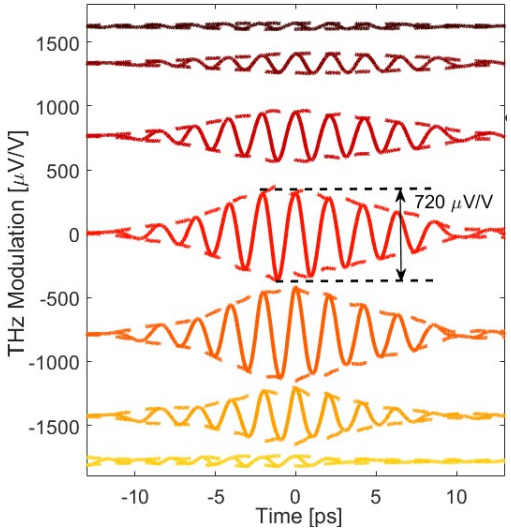


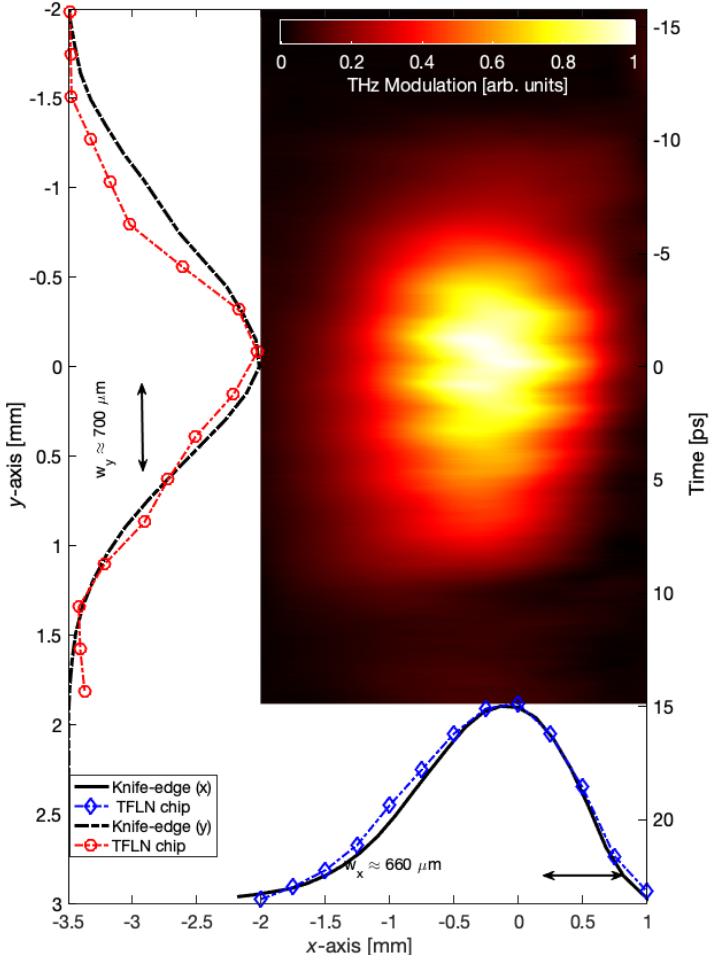
- **Modulation strength** ($\eta = 0.7\ mV/V$)
- One can clearly tell which part of the detector is illuminated (-> hints at spot shape at detector)

[1] A. Tomasino, A. Shams-Ansari, M. Loncar and I.-C. Benea-Chelmus., *in preparation*.

Terahertz beam profiling in TFLN

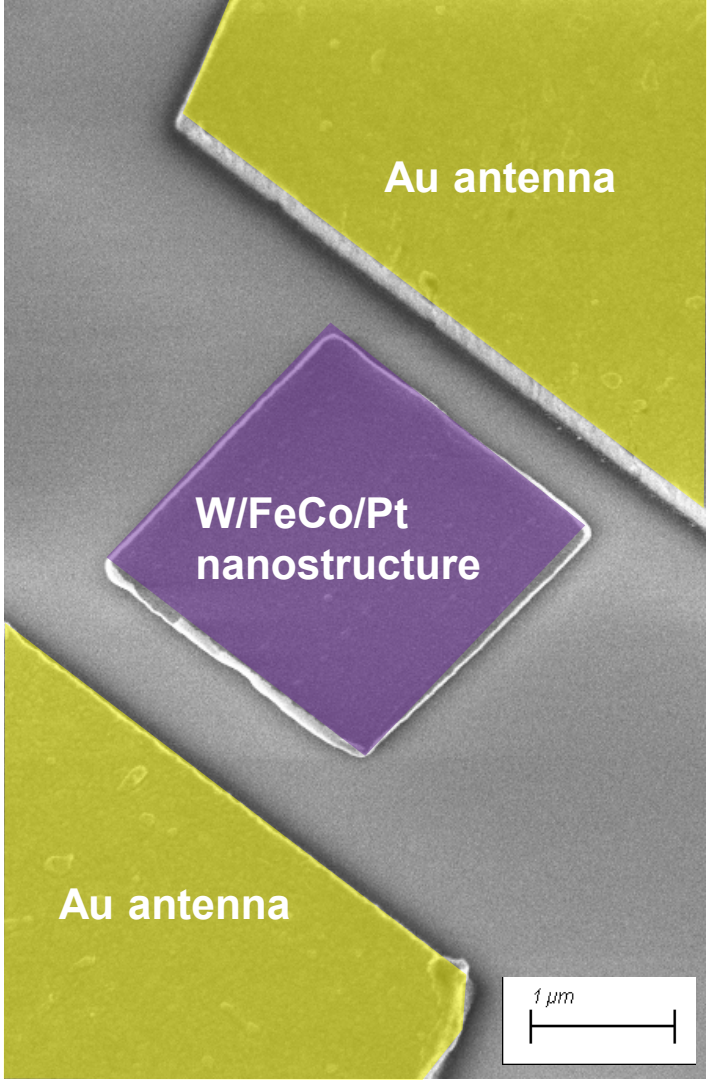


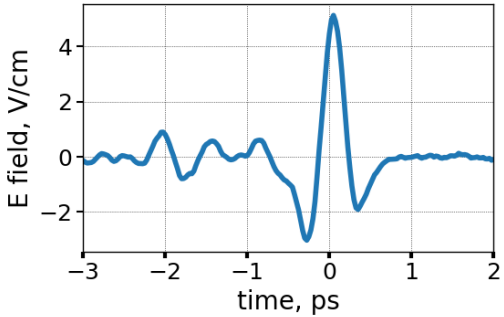


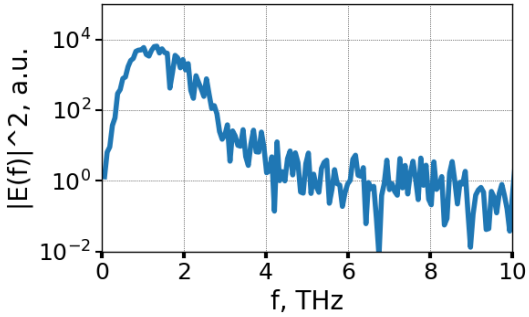


- Reconstructed spot size confirmed by knife-edge
- Not yet imaging but very exciting!

4. Terahertz generation in using spintronic layers







J_{pump} = 10 nJ

$$\eta = 60 \frac{V/m}{nJ}$$

Collaborators

Present

SCHWEIZERISCHER NATIONALFONDS
FONDS NATIONAL SUISSE
SWISS NATIONAL SCIENCE FOUNDATION

HANS-EGGENBERGER-STIFTUNG

Past

QSIT Quantum Science and Technology
National Centre of Competence in Research

erc
European Research Council
Established by the European Commission

Harvard Loncar group (SEAS)

M. Loncar

A. Shams-Ansari

S. Rajabali

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Mathias Vanwolleghem

Nicolas Tiercelin

Geoffrey Lezier

ENS

Sukhdeep Dhillon

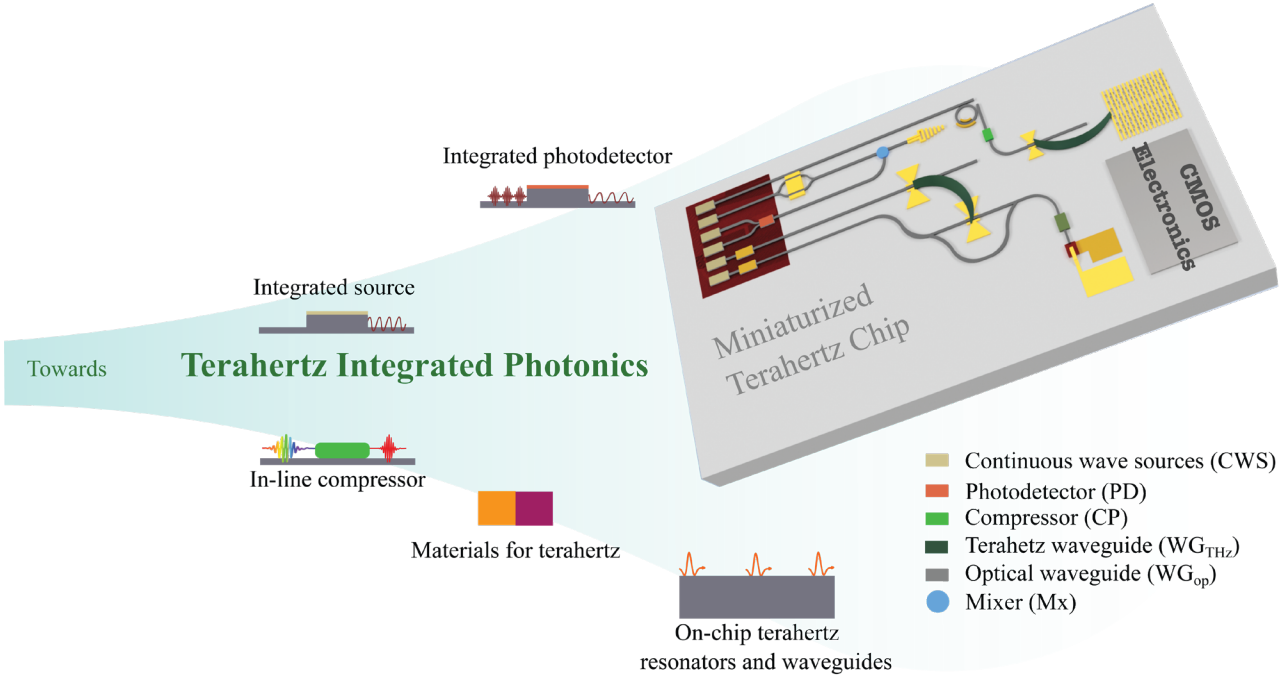
ETHZ Faist group (PHYS)

J. Faist

A. Herter

F. Settembrini

Thank you for your kind attention!



S. Rajabali & I.C.B.C.,"Present and future of terahertz integrated photonic devices", *APL Photonics* **8**, 8 (2023)

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