New electronic components based on GaN for THz applications

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Microwave
& RF

Coworkers

- ✓ University of Montpellier (IES)
  - ✓ P. Nouvel, C. Daher, A. Penot, L. Varani
- ✓ University of Salamanca
  - ✓ I. Iniguez-de-la-Torre, T. Gonzalez, J. Mateos
- ✓ University of Lille (IEMN)
  - ✓ P. Sangare, B. Grimbert, M. Faucher, G. Ducournau, C. Gaquière
- ✓ CRHEA-CNRS UPR20 (Sophia Antipolis)
  - ✓ S. Chenot, M. Chmielowska, Y. Cordier

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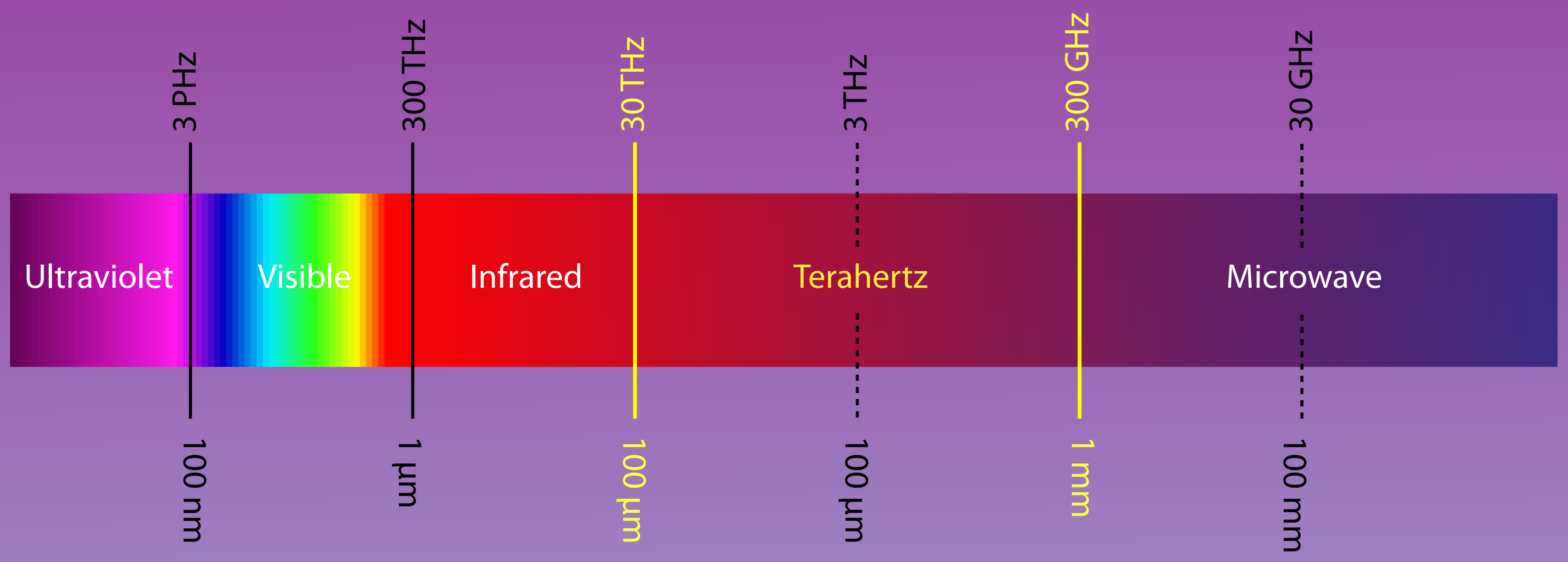
TeraHertz

$$f = 10^{12}\ \text{Hz},\ \ T = 1\ \text{ps},\ \ \lambda = 0.3\ \text{mm},\ E = 4.1\ \text{meV}$$



Why THz ?

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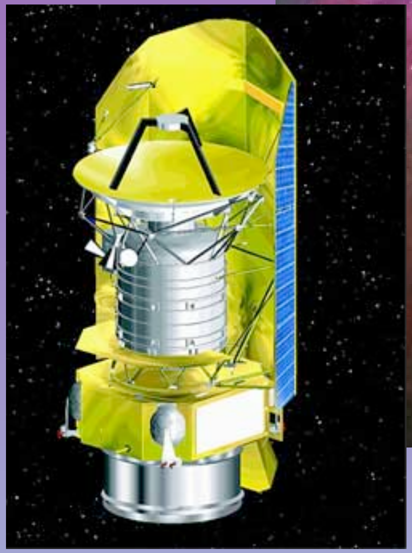
Applications in Spectroscopy

✓ Astronomy: detection of ionized gas, ...

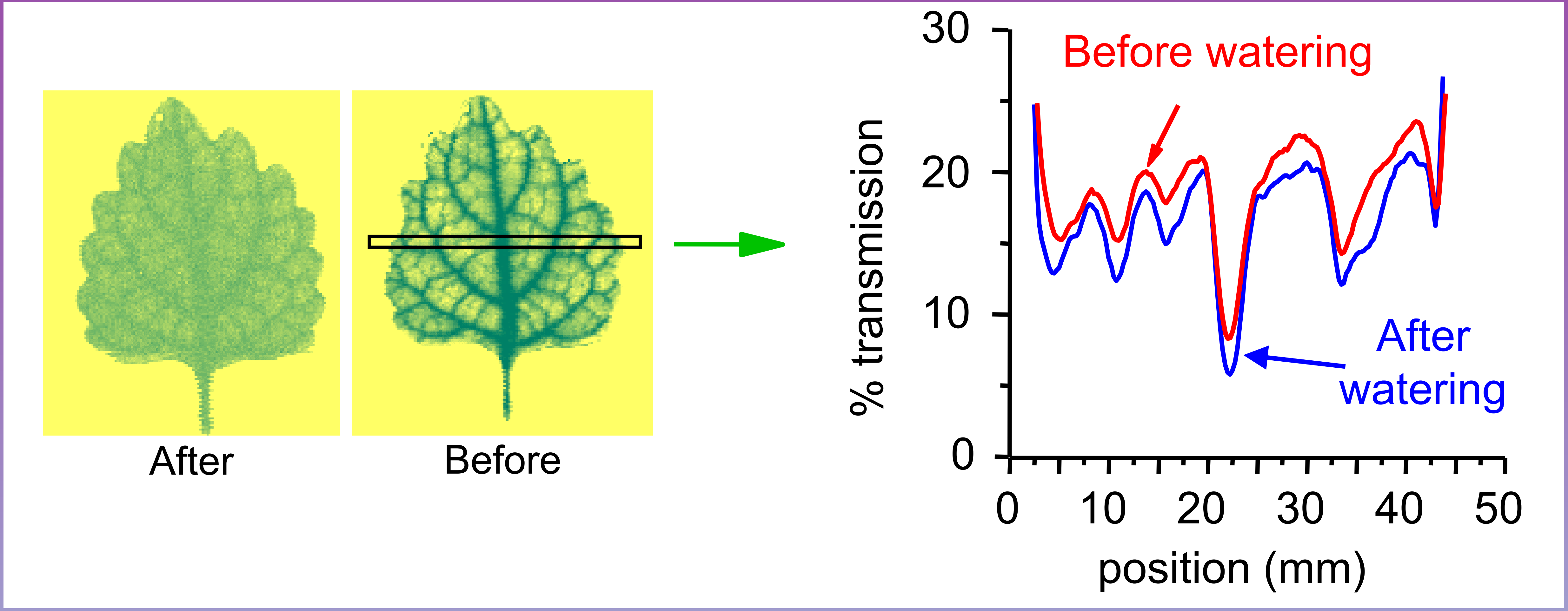


http://hubblesite.org/newscenter/archive/releases/2006/01/

Hershel (Hifi: Heterodyne Instrument for the Far-Infrared)

Applications in Agronomy (T-Ray)

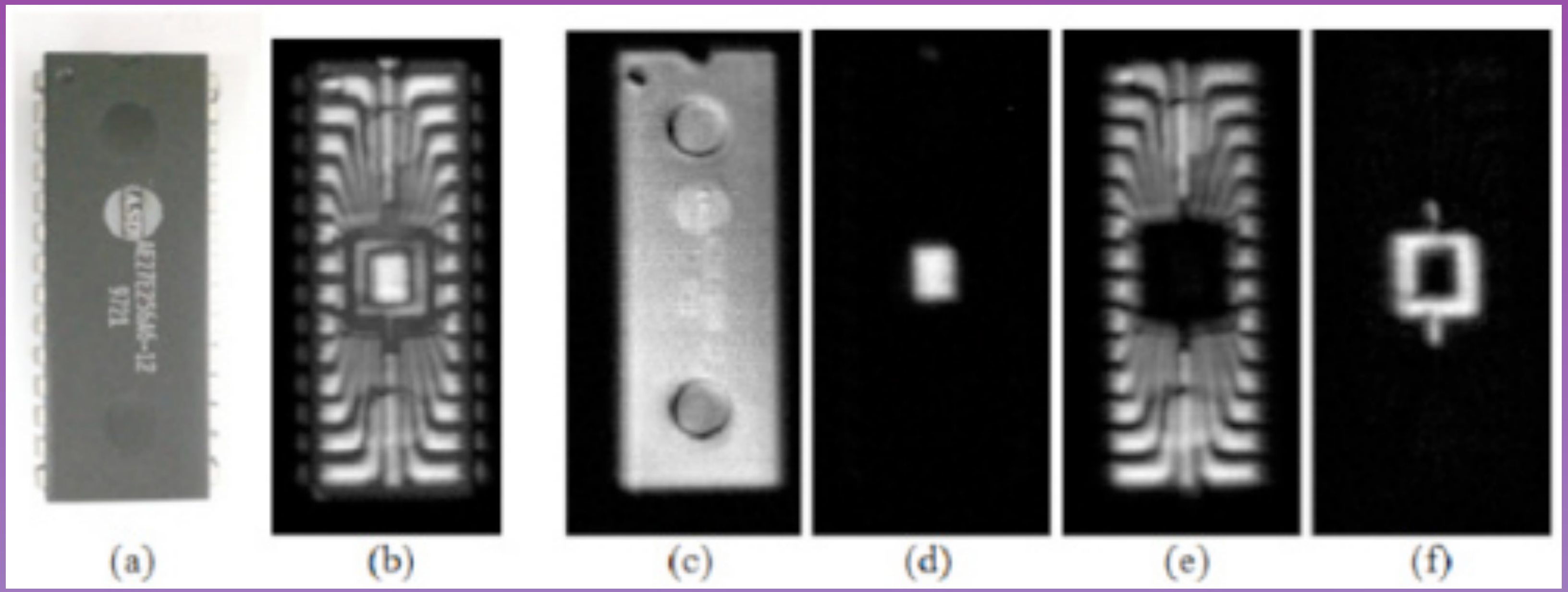
- ✓ Biology
- ✓ "water stress"



(Mittleman, Rice Univ.)

Applications in Imaging (T-Ray)

✓ Nondestructive test of integrated circuits



(a) THz top view, and (b)-(f) at depth of 0.14mm, 2.06mm, 2.44mm, and 3.19mm

Sang-Heum Cho *et al.*, Opt Exp, Vol. 19, Issue 17, 16401(2011)

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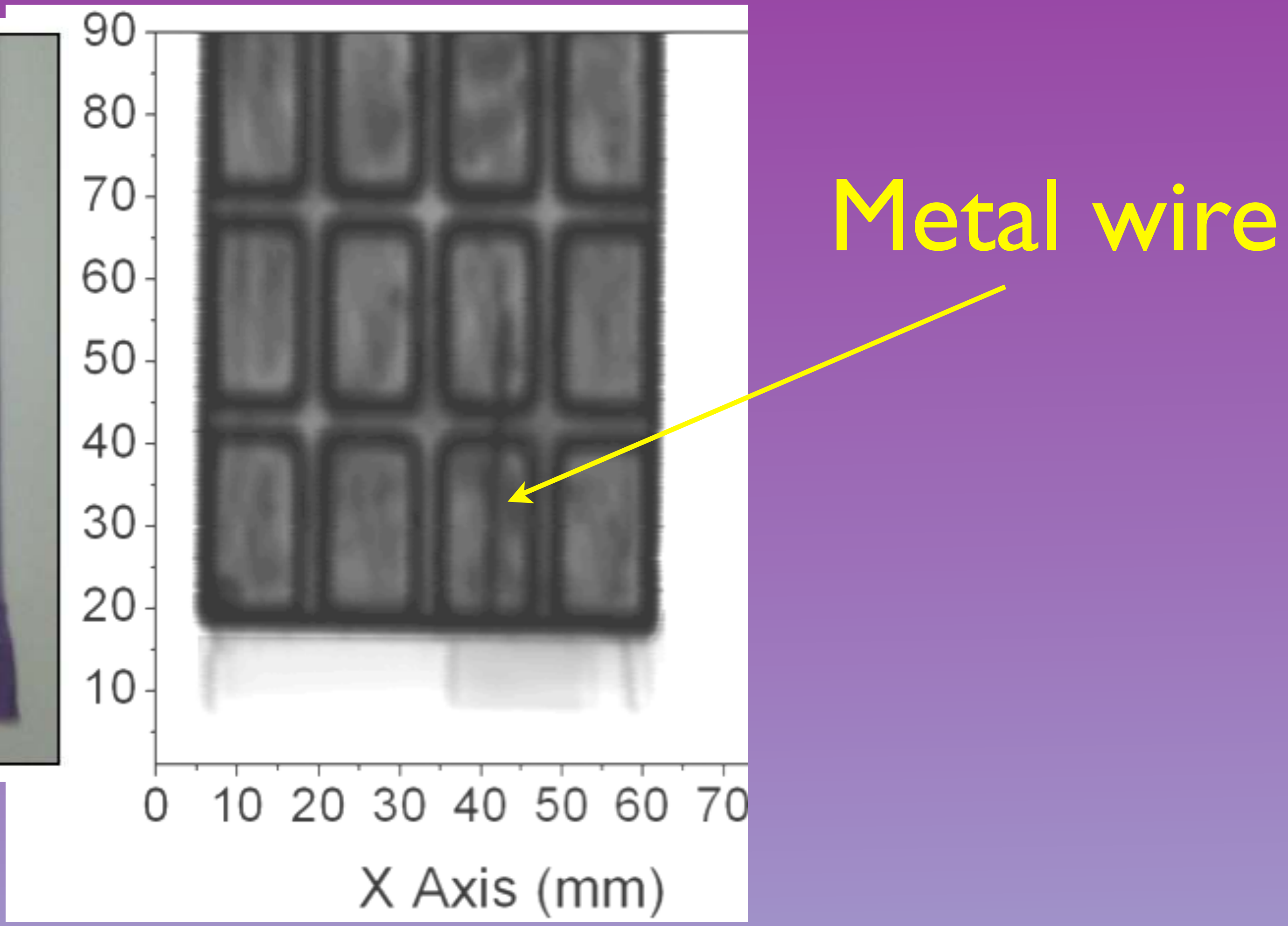
Applications in Imaging (T-Ray)

✓ Non destructive test in food market



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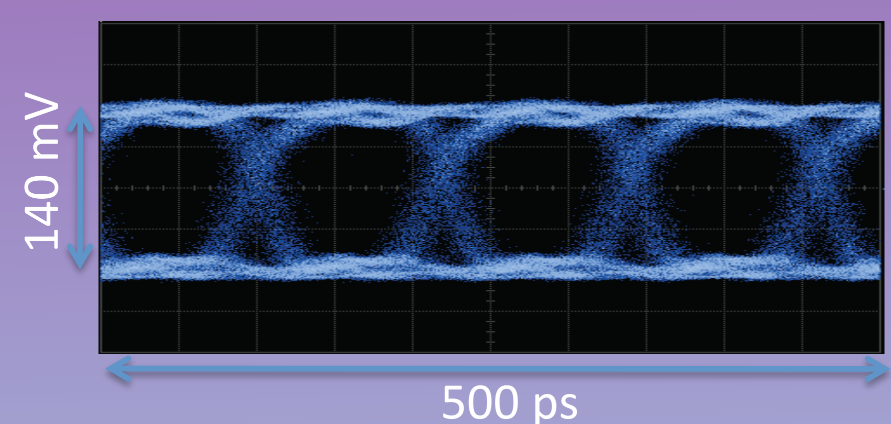
Applications in telecom



Eye diagram at 3 Gbits/s
"error free" (BER < 10^{-11})

S. Blin et al., Journ. of Communications and Networks, Special Edition on THz communications, Dec. 2013.

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THz emitter - detector system

HIGH INPUT POWERS

HIGH MOBILITY

INTEGRATION

PLANAR GEOMETRY

LOW COST

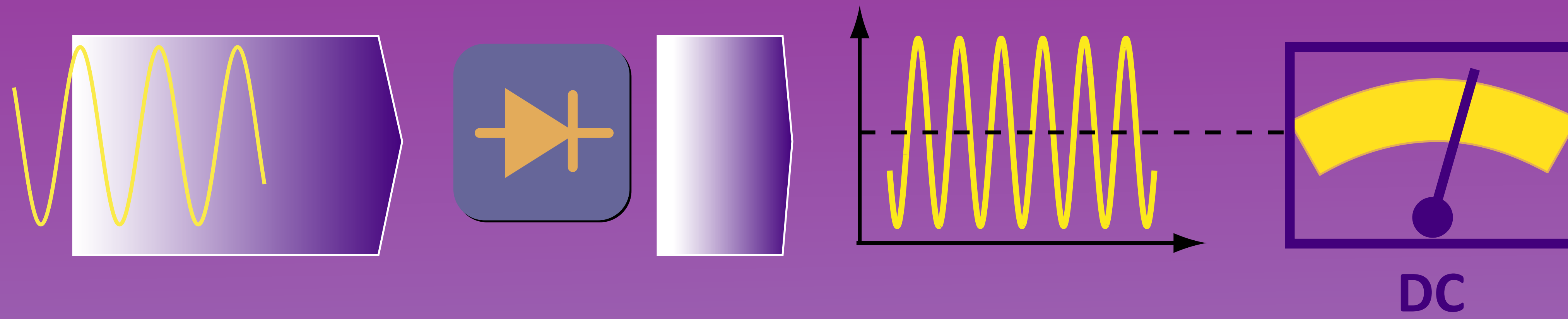
GENERATION OF THz FREQUENCIES

Outline

- ✓ THz detection
- ✓ THz emission
- ✓ THz amplification
- ✓ Conclusion

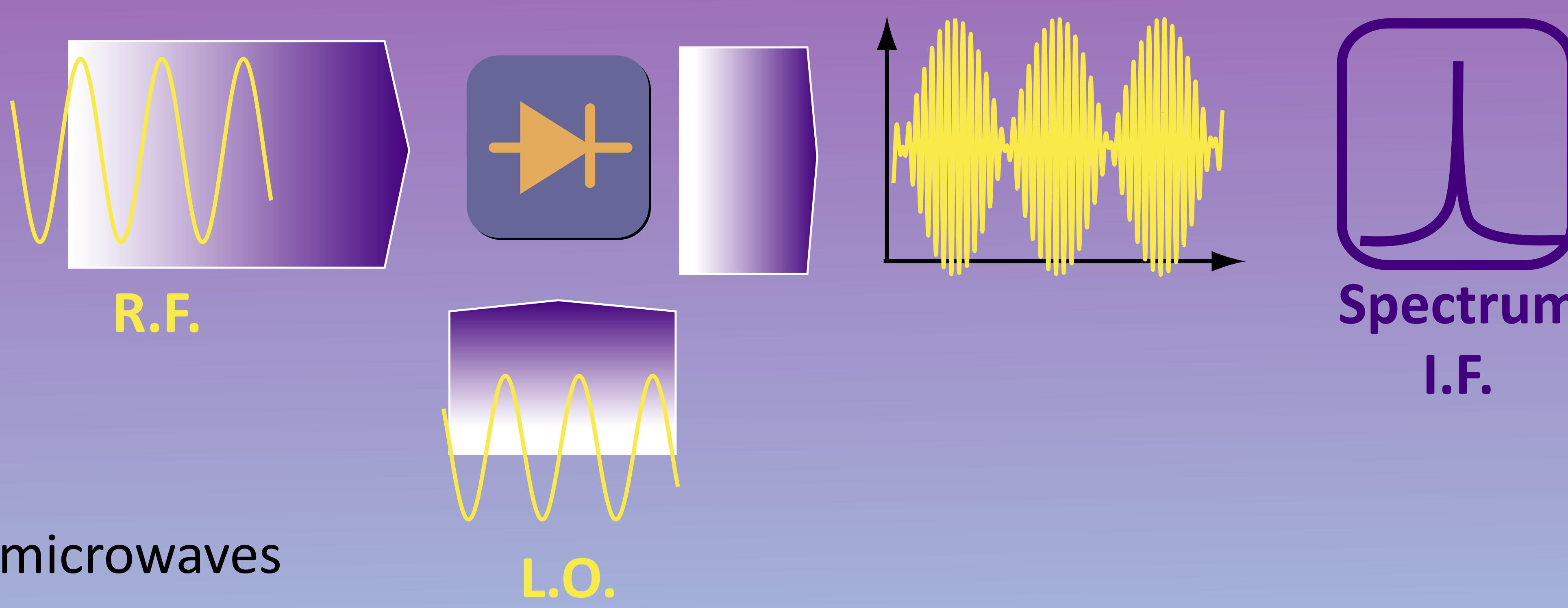
THz detections

Direct detection



- ✓ Responsivity

Heterodyne detection



- ✓ $f_{IF}=f_{RF}-f_{LO} \in$ microwaves
- ✓ frequency and phase of RF radiation

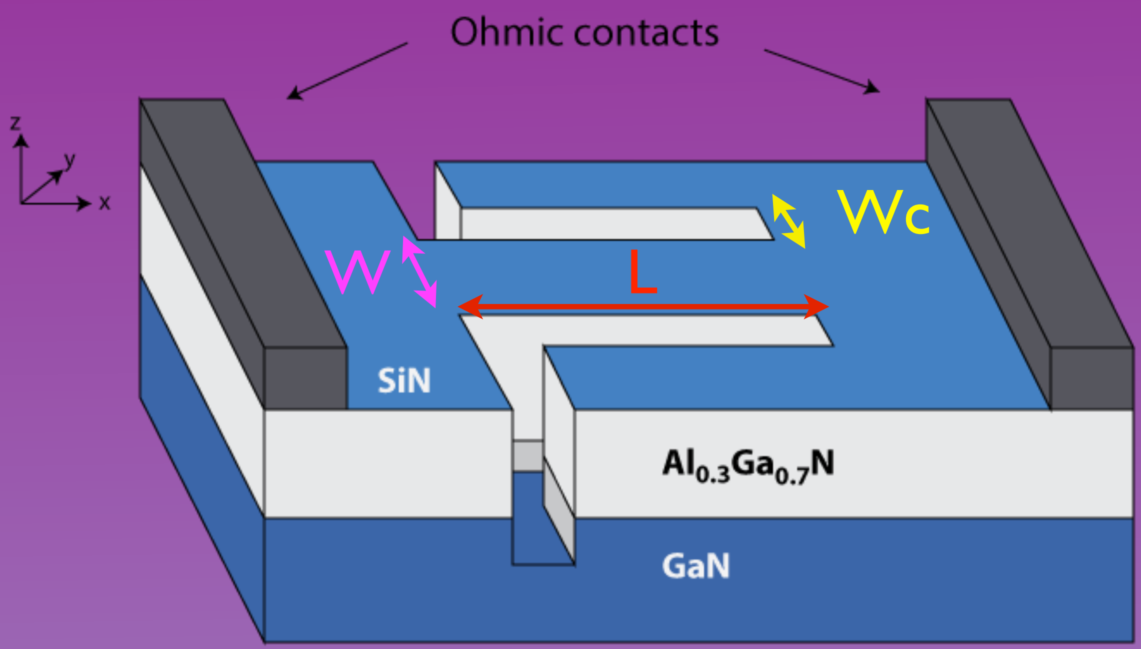
THZ detection

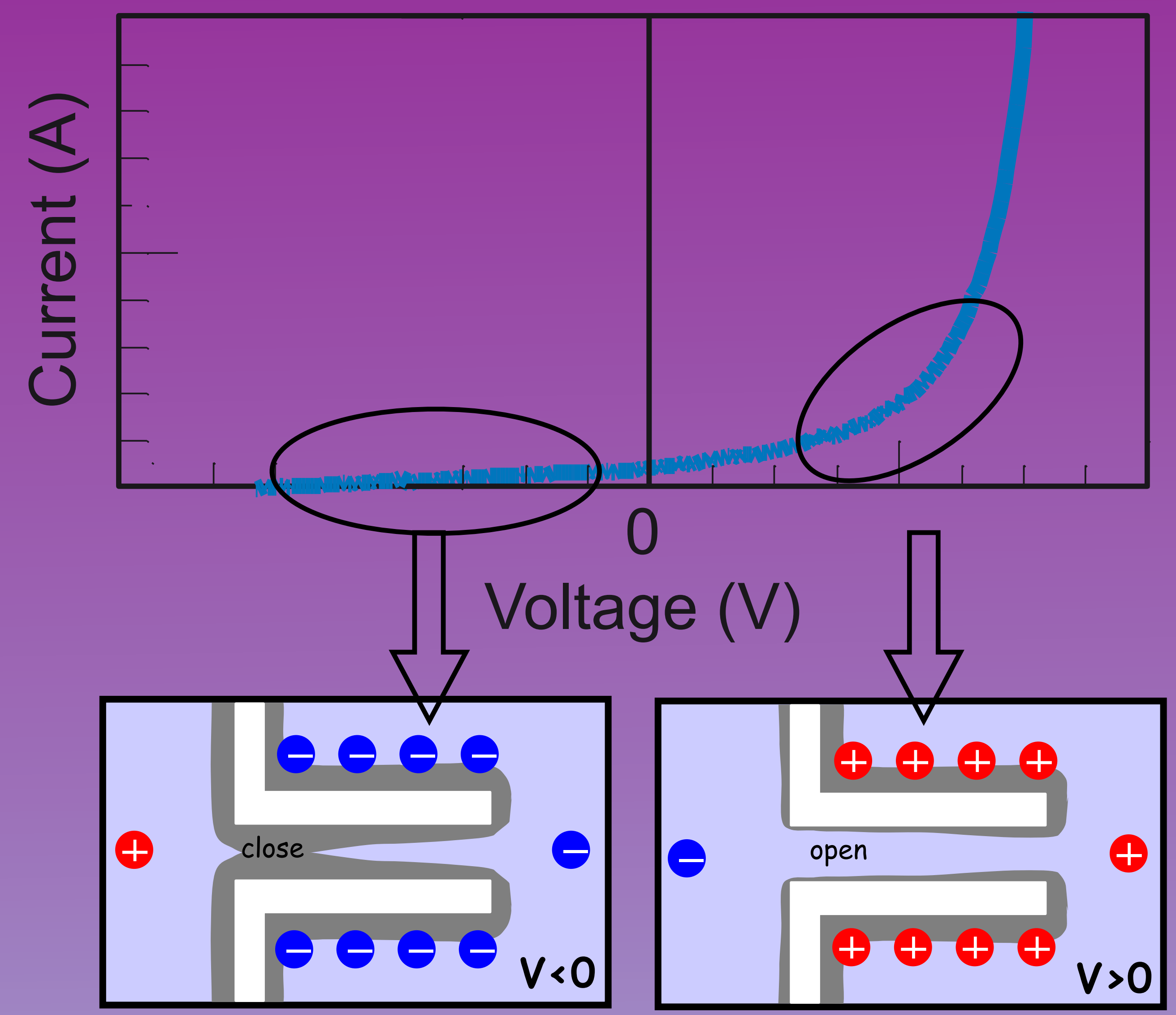
- ✓ Heterodyne detection
  - ✓ Systems working at 300 K: Schottky diode

THz heterodyne detection by SSDs

- ✓ No technological breakthrough
- ✓ Integration to microwaves systems
- ✓ Easy industrialisation

Self-Switching Diodes (SSDs)





- W = 150—>750 nm
- L = 1-2 µm
- Wc = 50 nm

A.M. Song *et al*., Appl. Phys. Lett. 83,1881–1883 (2003)

✓ Planar device; 2 L-shape trenches (one-step technology)

✓ Surface charges --> Channel depletion

✓ Channel opened when V>0, closed when V<0

✓ Downscaling —> THz operation

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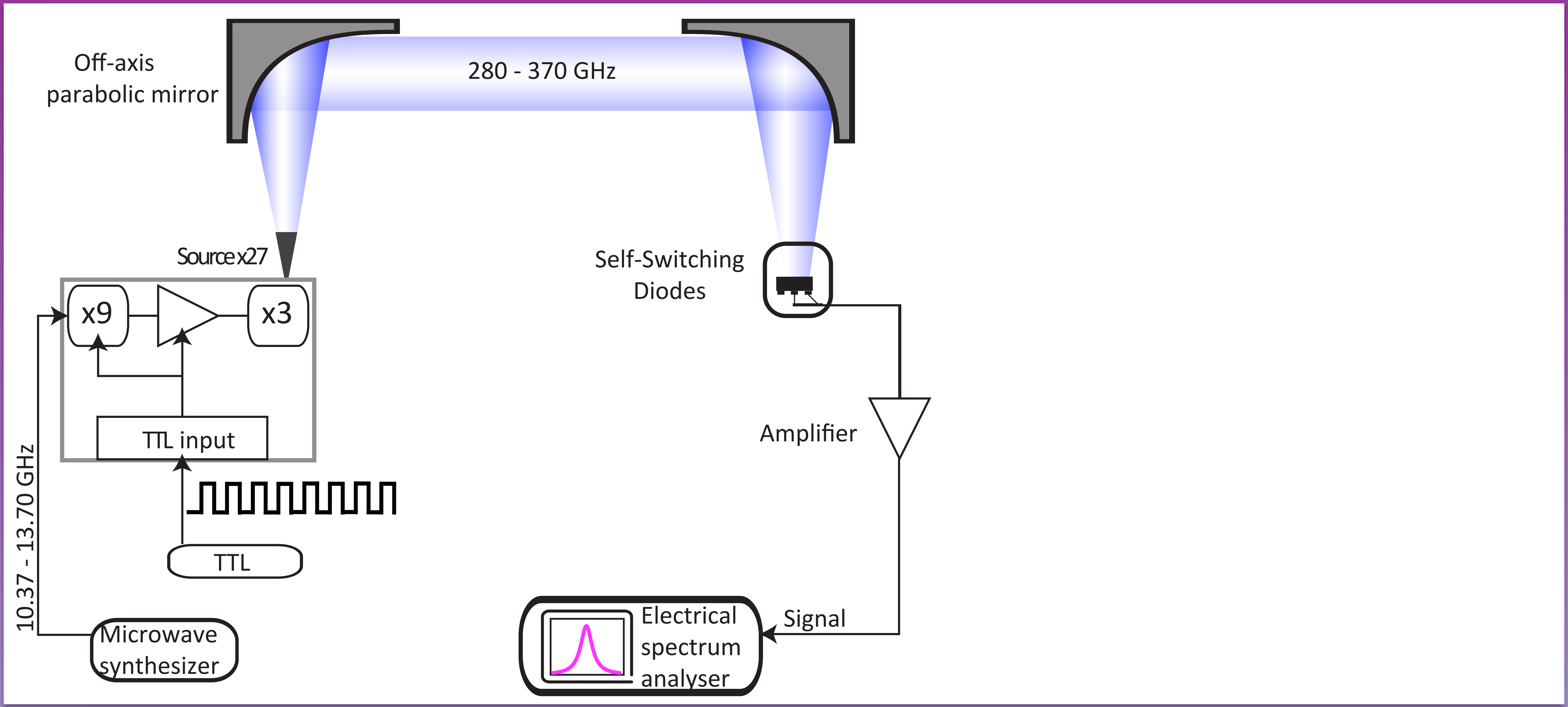
Direct detection : Experimental set-up



- ✓ 16 bow-tie antennae @ f_0=0.26 THz
- ✓ 64 SSDs in paralell in each antenna

- ✓ Amplifier: 40 dB
- ✓ Microwave synthetizer: 20 GHz, 20 dBm
- ✓ TTL modulation: 1kHz

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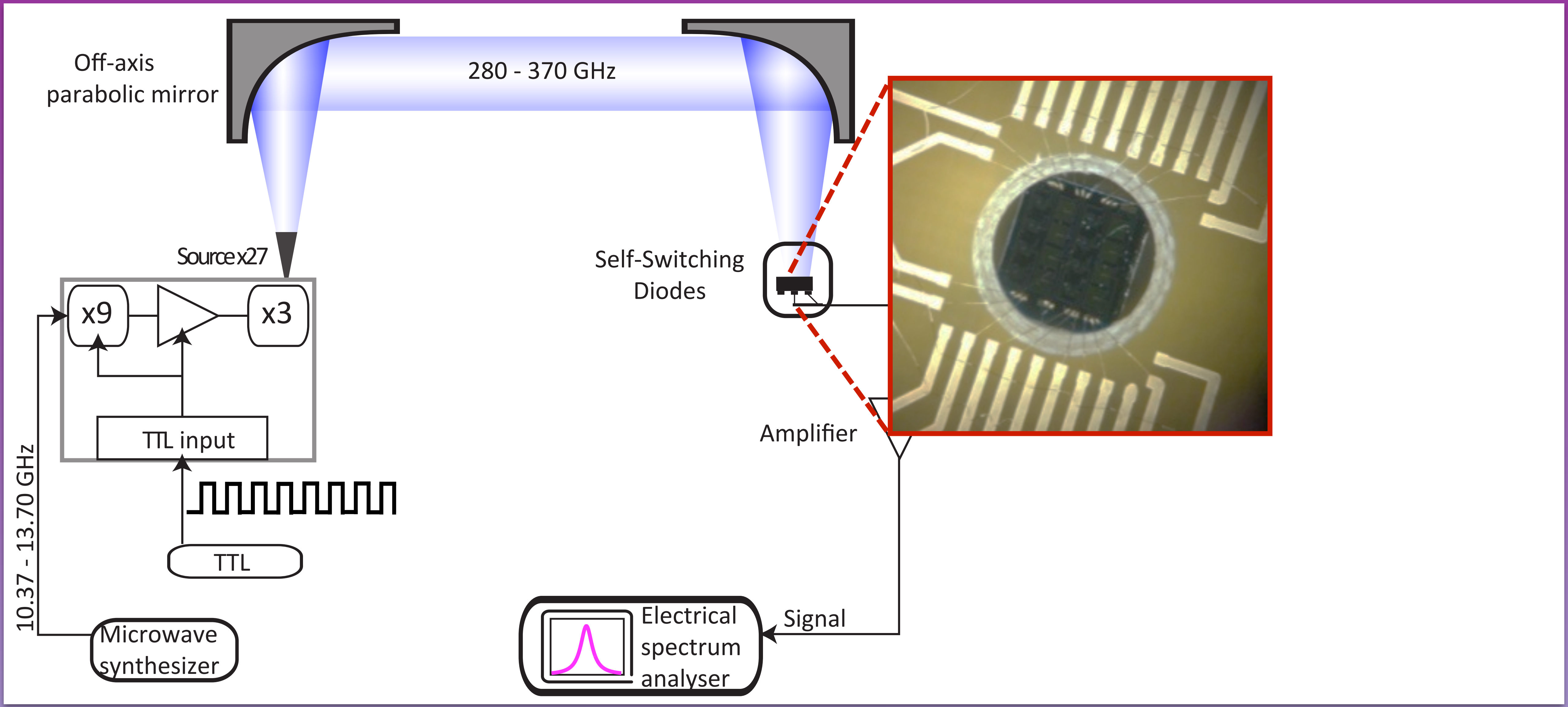

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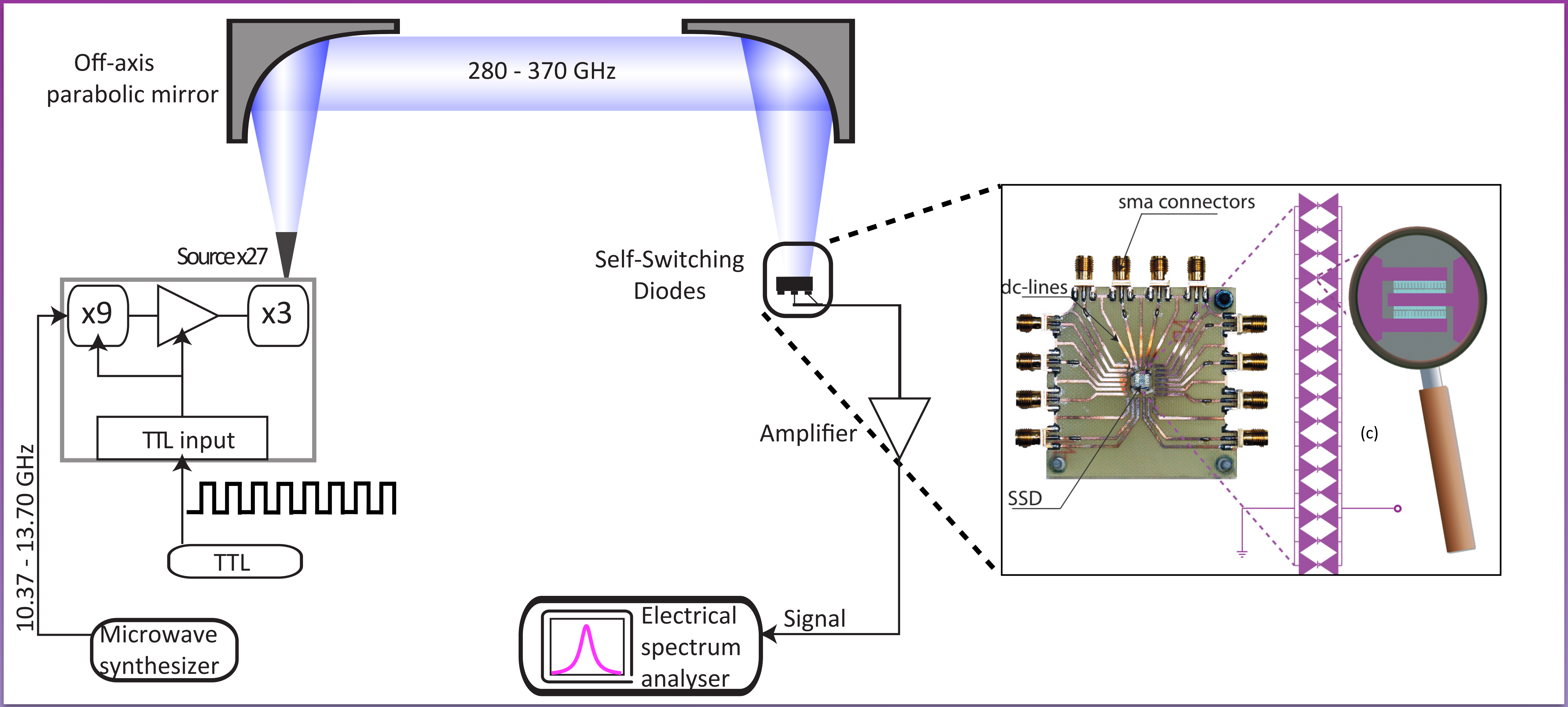

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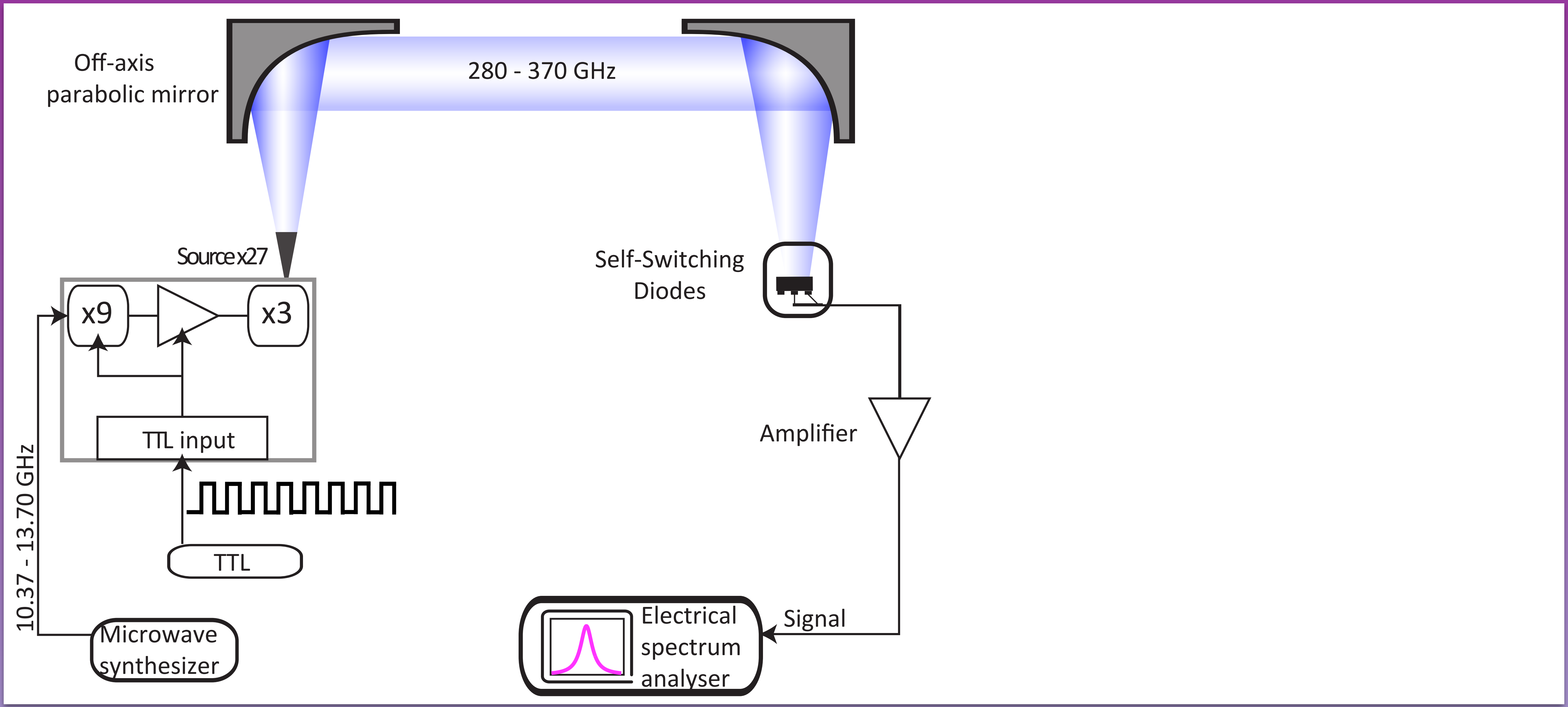

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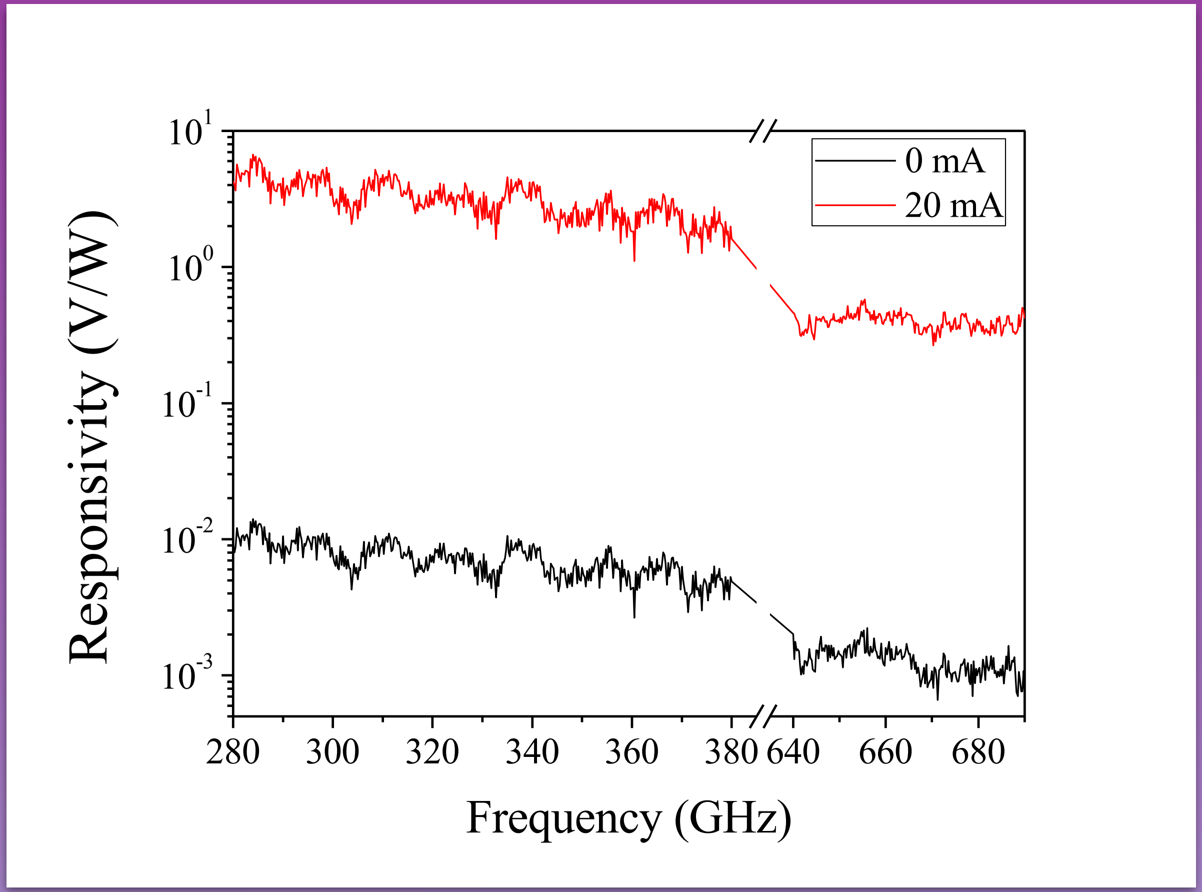
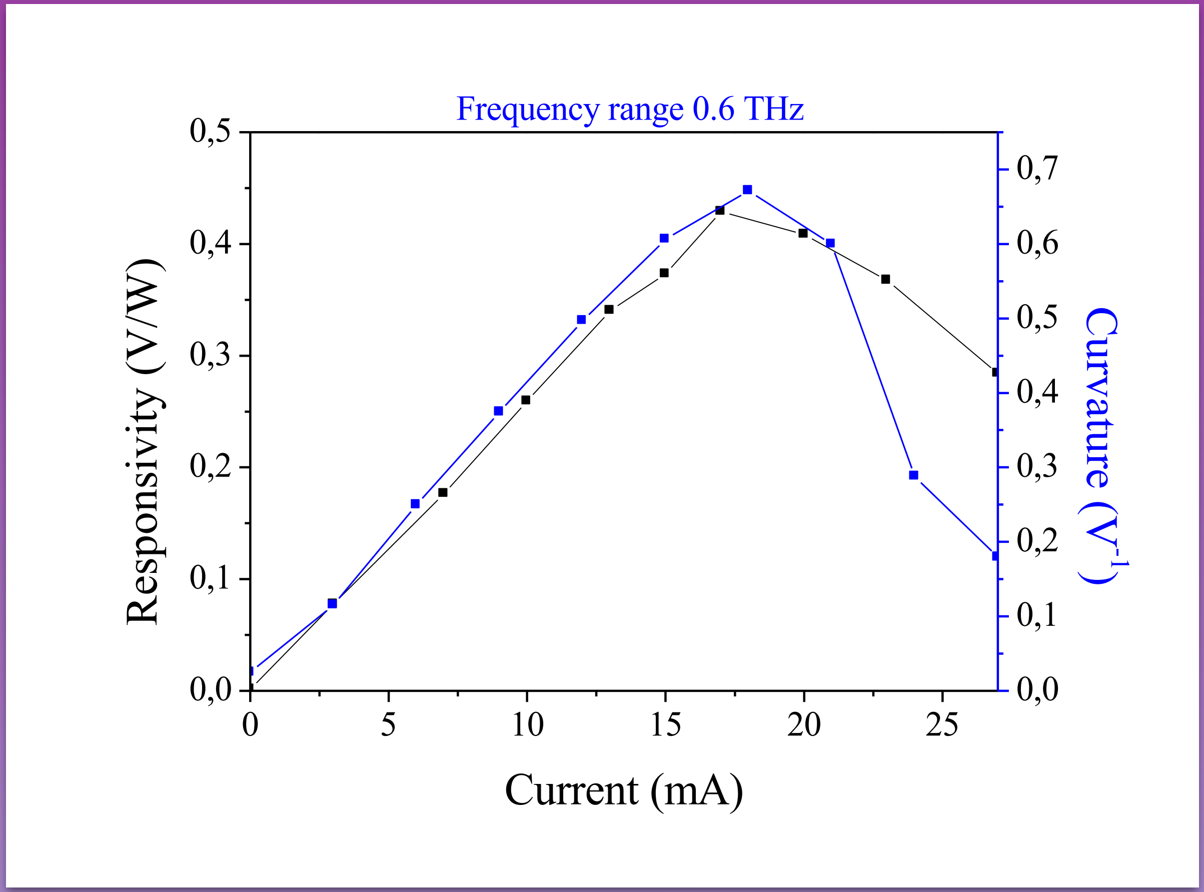
Free space responsivity





- ✓ Full band responsivity from 0.3 to 0.7 THz !!!
- ✓ Follows curvature coefficient
- ✓ R increases since non-linearity increases

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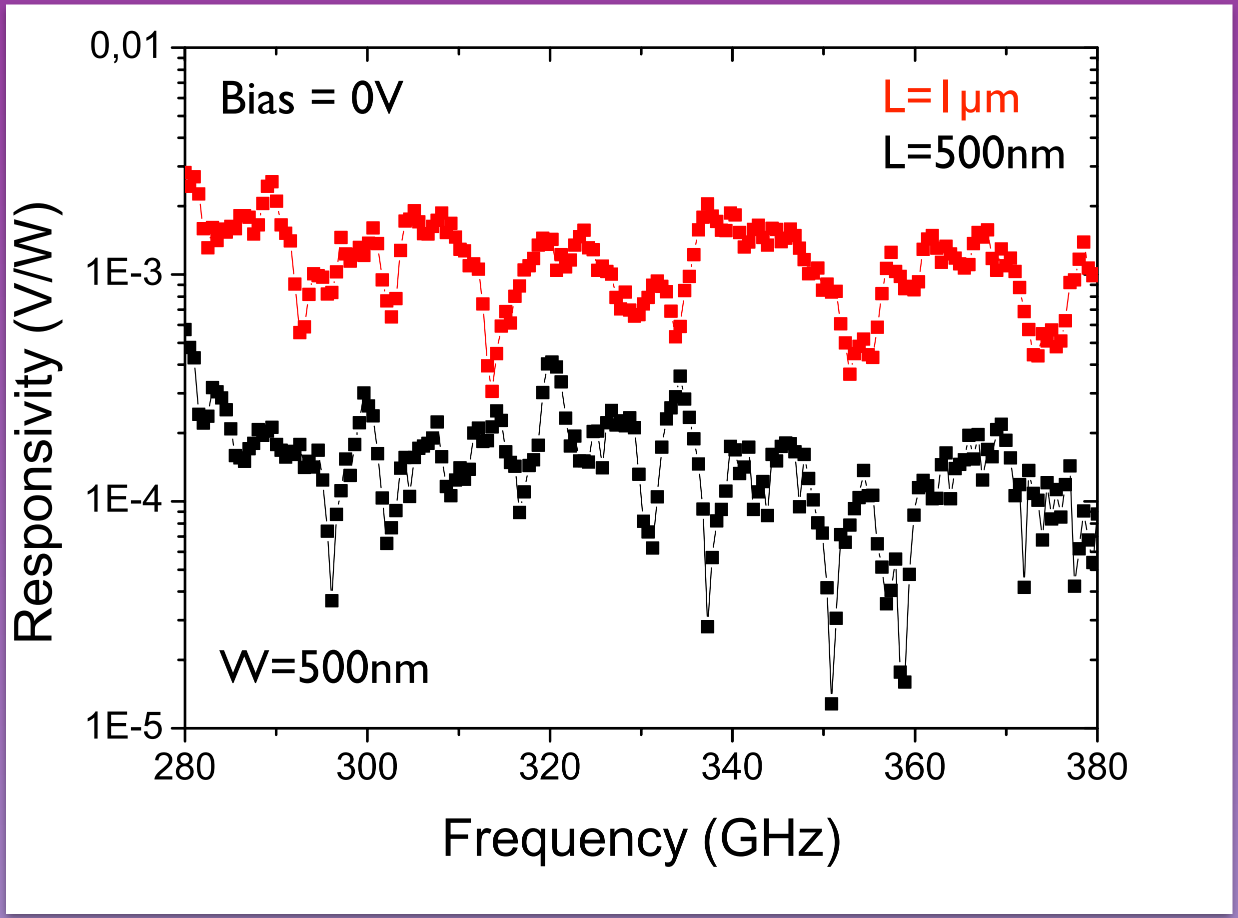
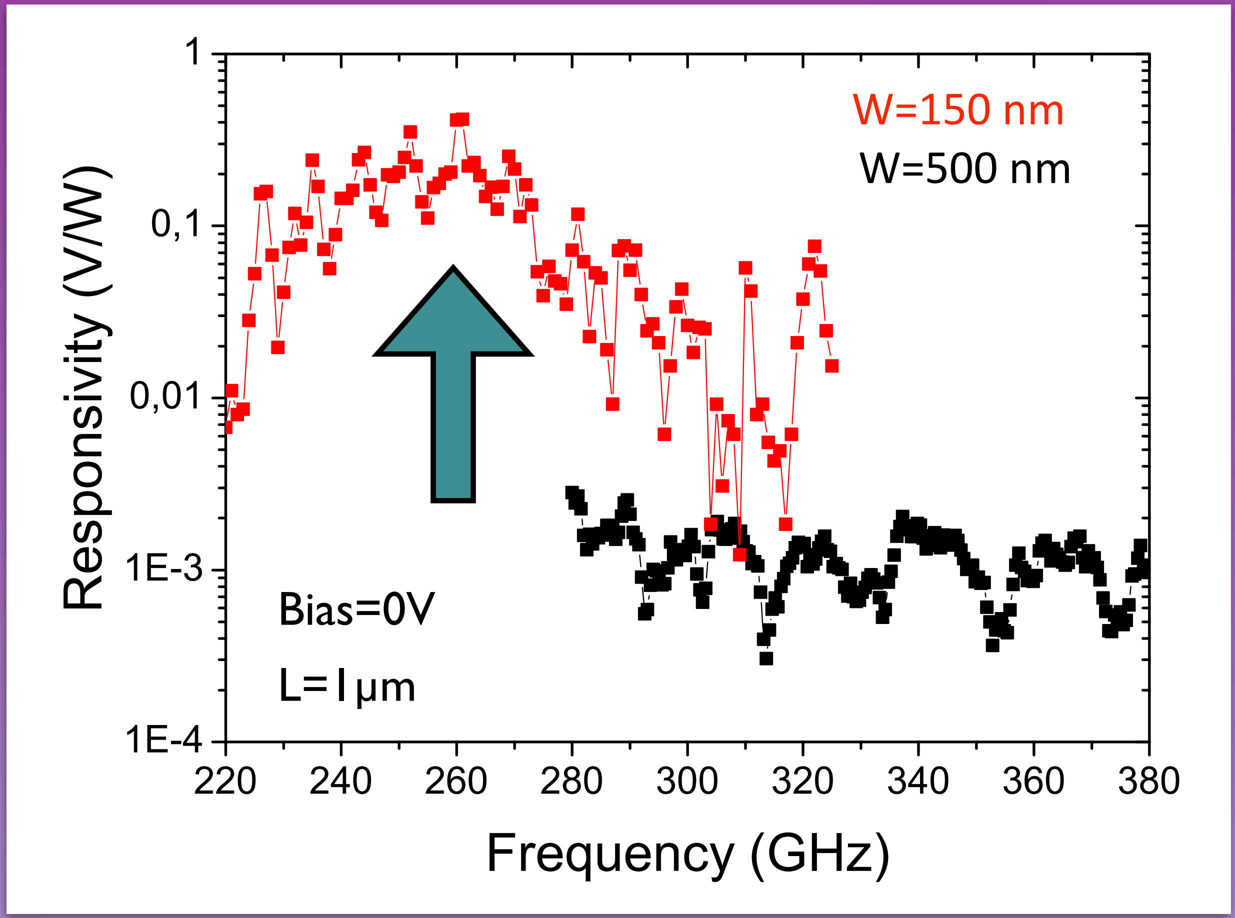
Geometry dependence

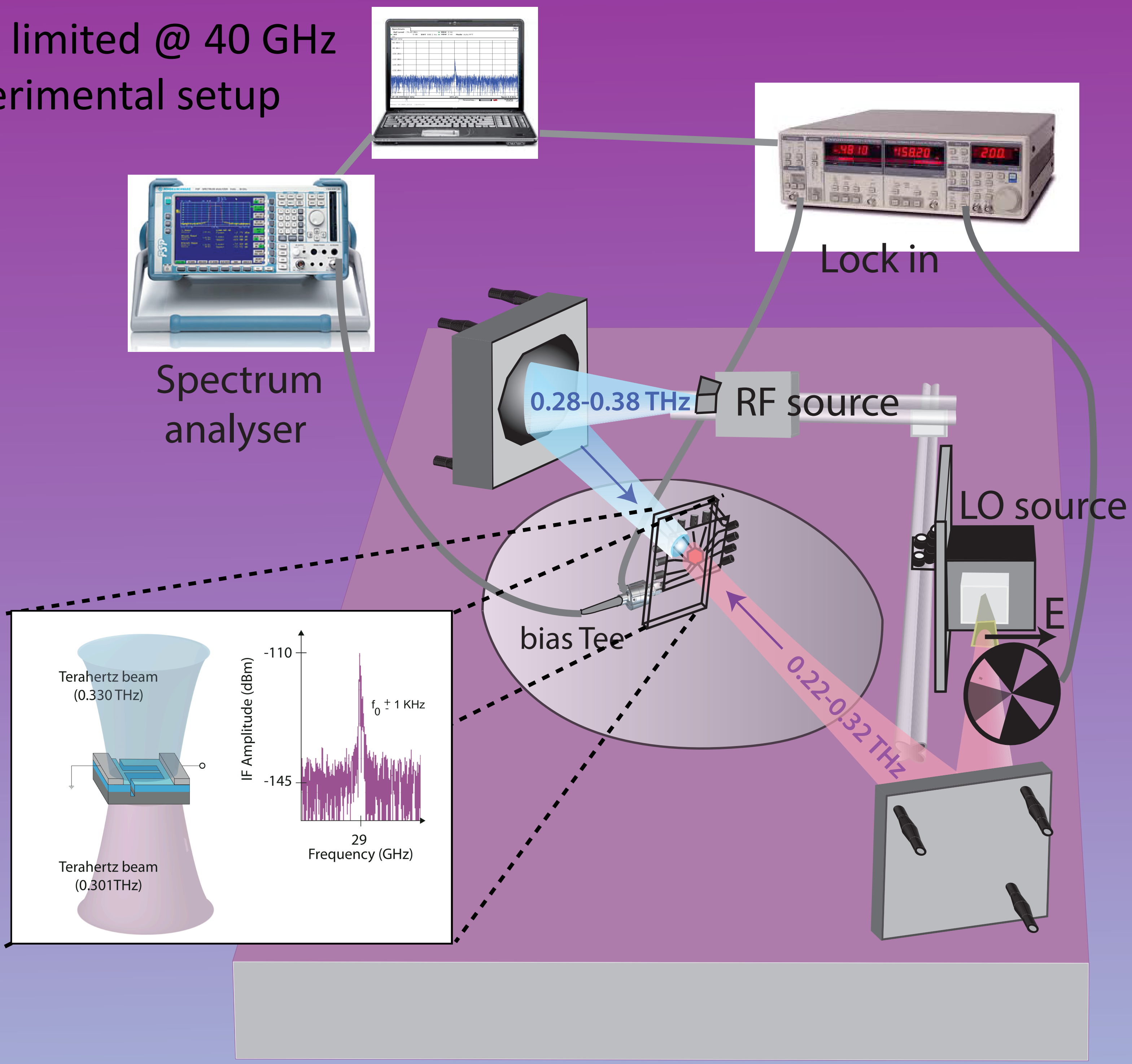




- ✓ Resp. slightly increases when L ↑
- ✓ Resp. strongly increases when W ↓,
  - ✓ surface charges effect ↑, Channel non-linearity ↑, Responsivity ↑

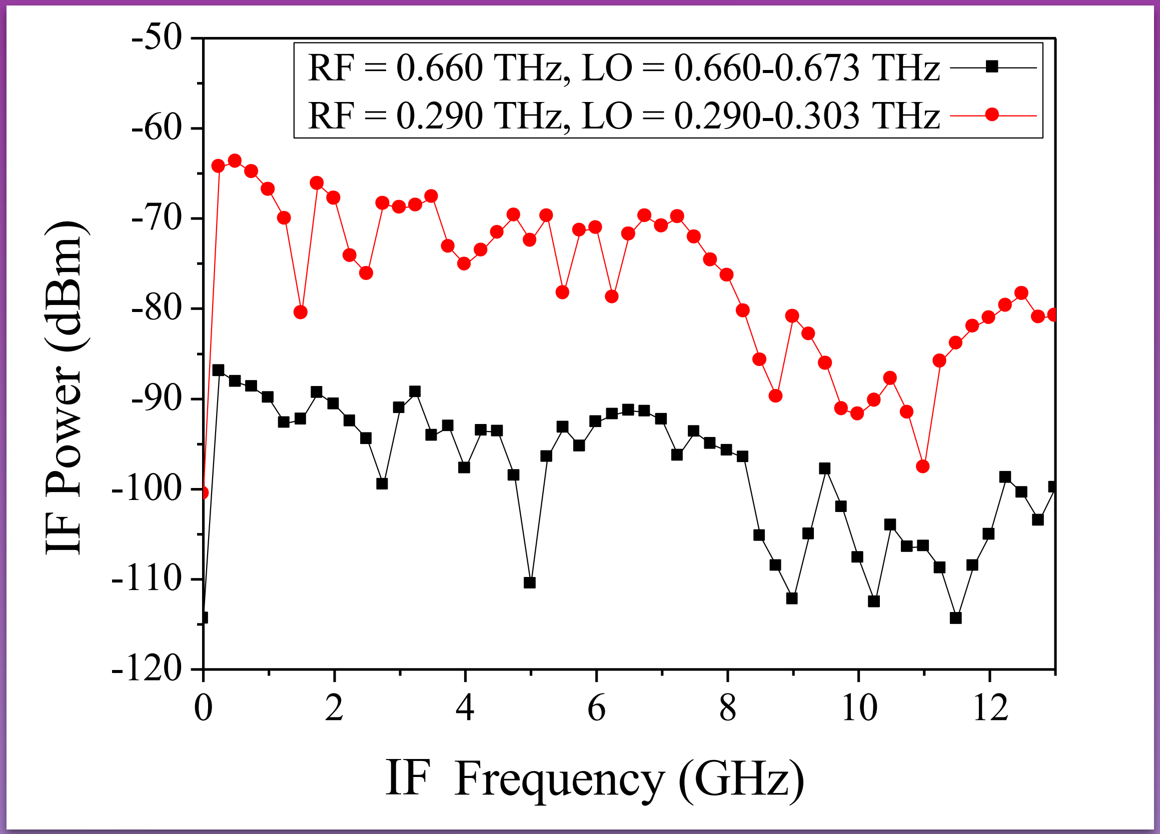
Heterodyne detection : Experimental set-up

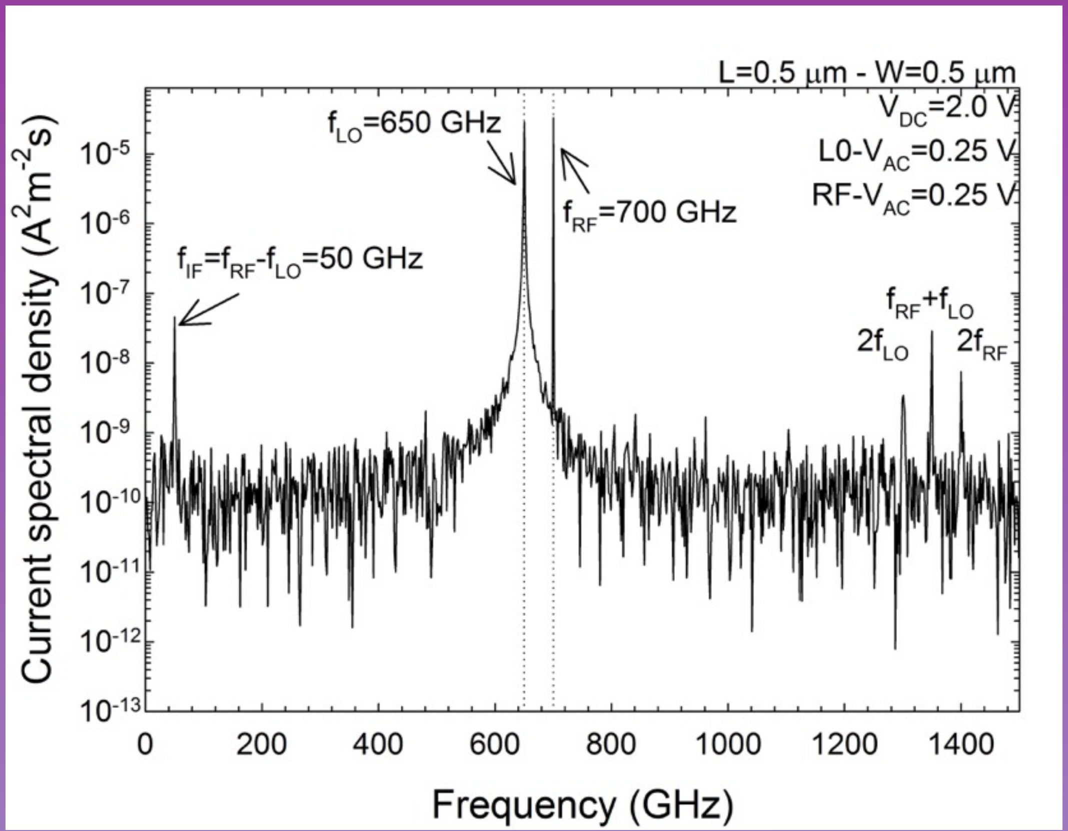
Detection limited @ 40 GHz
by experimental setup



J. Torres *et al.*, Sem Sc Tech 28, 125024 (2013)

Bandwidth





- ✓ Experiments :
- ✓ works at 0.3 THz and 0.67 THz
- ✓ BW : limited by the experimental setup
- ✓ Dynamic range > 50 dB @ 0.3 THz and > 30 dB @ 0.6 THz
- ✓ Conv. Loss: 70 dB but ...

- ✓ Modelling:
- ✓ W= 0.5 µm, L= 0.5µm
- ✓ Bandwidth > 50 GHz

I. Iñiguez-de-la-torre et al, IEEE trans. THz Sc. and Tech. 4, no. 6, 670 (2014)

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Losses characterisation @ 0.3 THz

Frequency (GHz)	Loss (dB)
3	-1.13
10	-2.17
20	-2.3
29	-3.24
40	-4.18

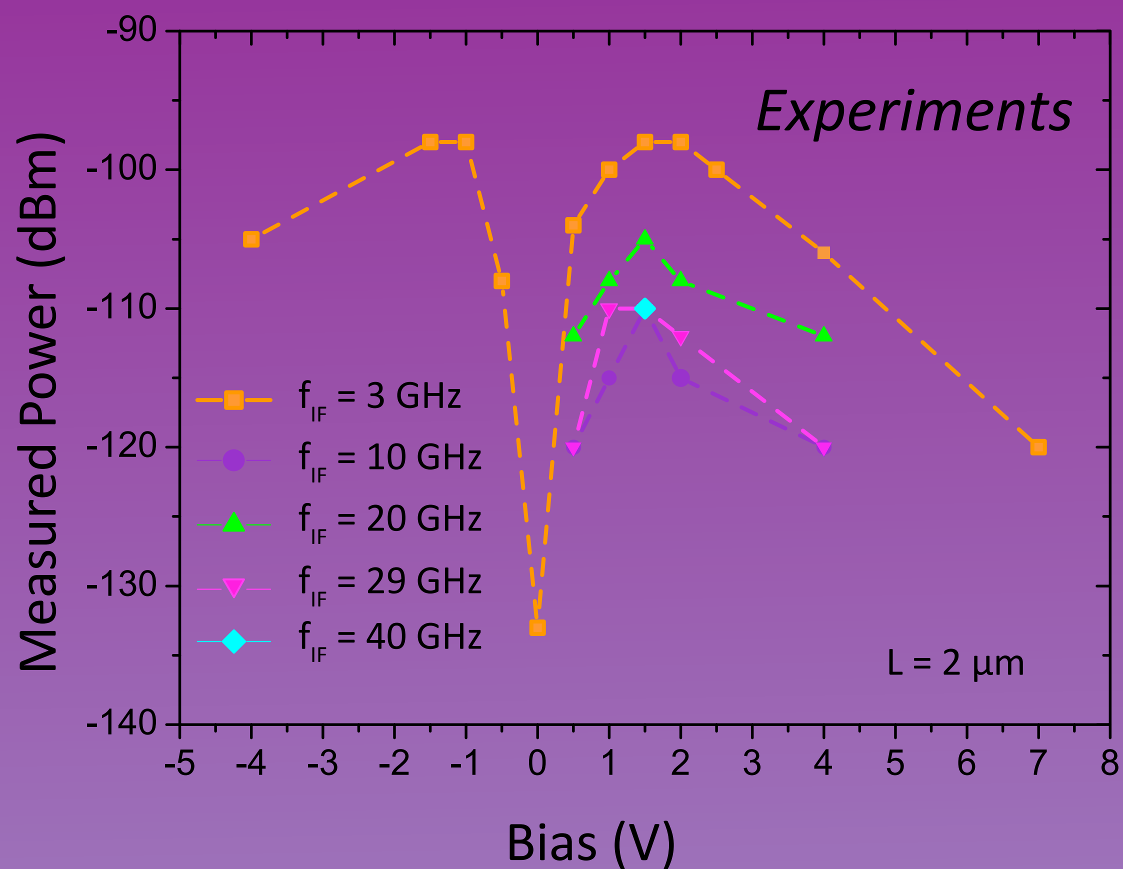
Frequency (GHz)	Loss (dB)
3	-5
10	-7.3
20	-9.8
29	-13
40	-17
50	-33

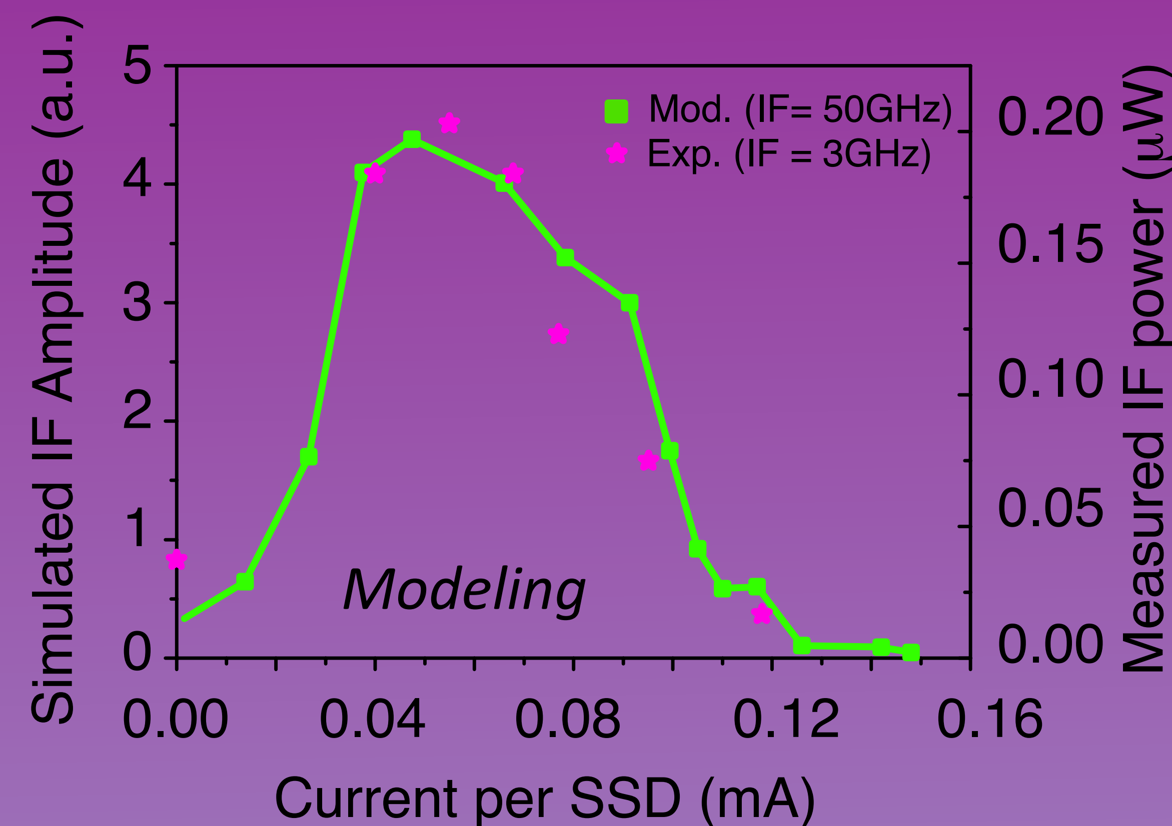
- ✓ RF wires and bias-Tee connection (VNA measurements)
- ✓ Limited bandwidth of the antenna (f0 ~ 0.26 THz ± 40 GHz) between 0.28 and 0.32 THz : ~ 15 dB.
- ✓ SMA connectors and DC lines on the dielectric holder (CST-Microwave Studio)

Total Losses ~ 35 dB @ 40 GHz

Conversion Loss ~ 35 dB !

Frequency limitation

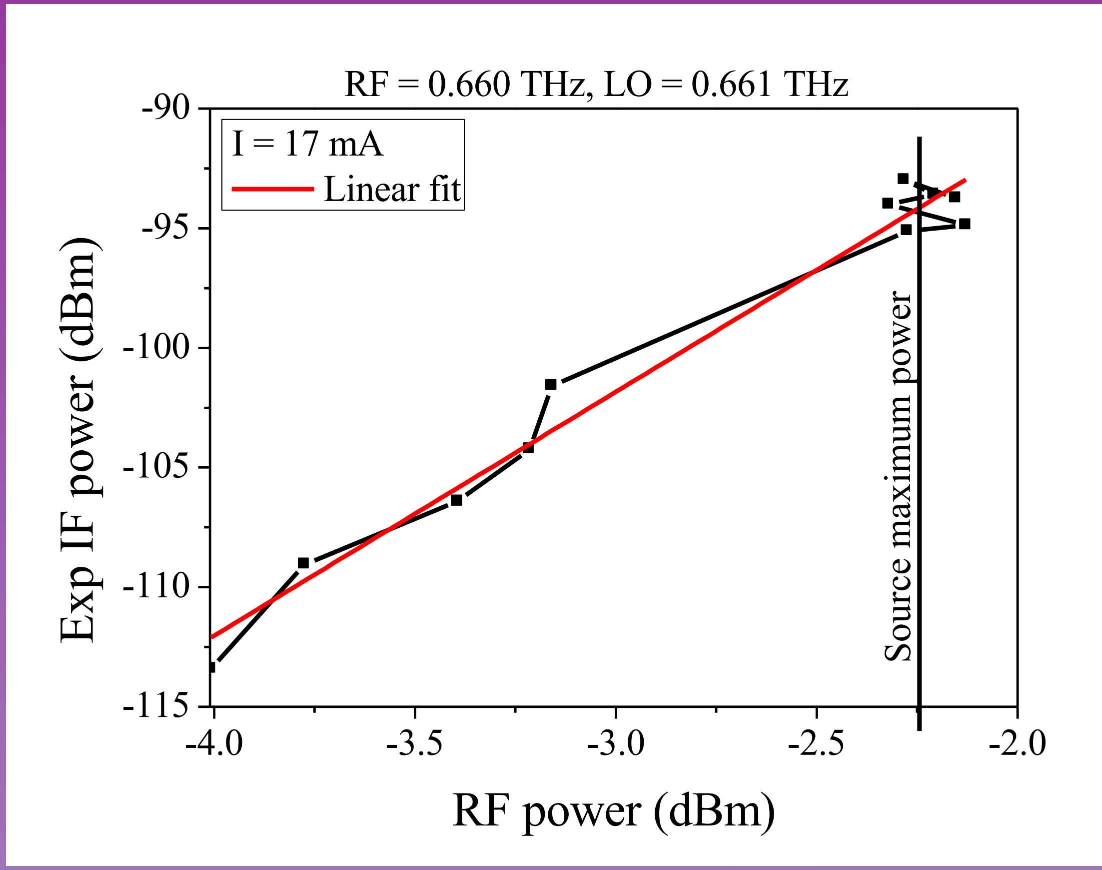


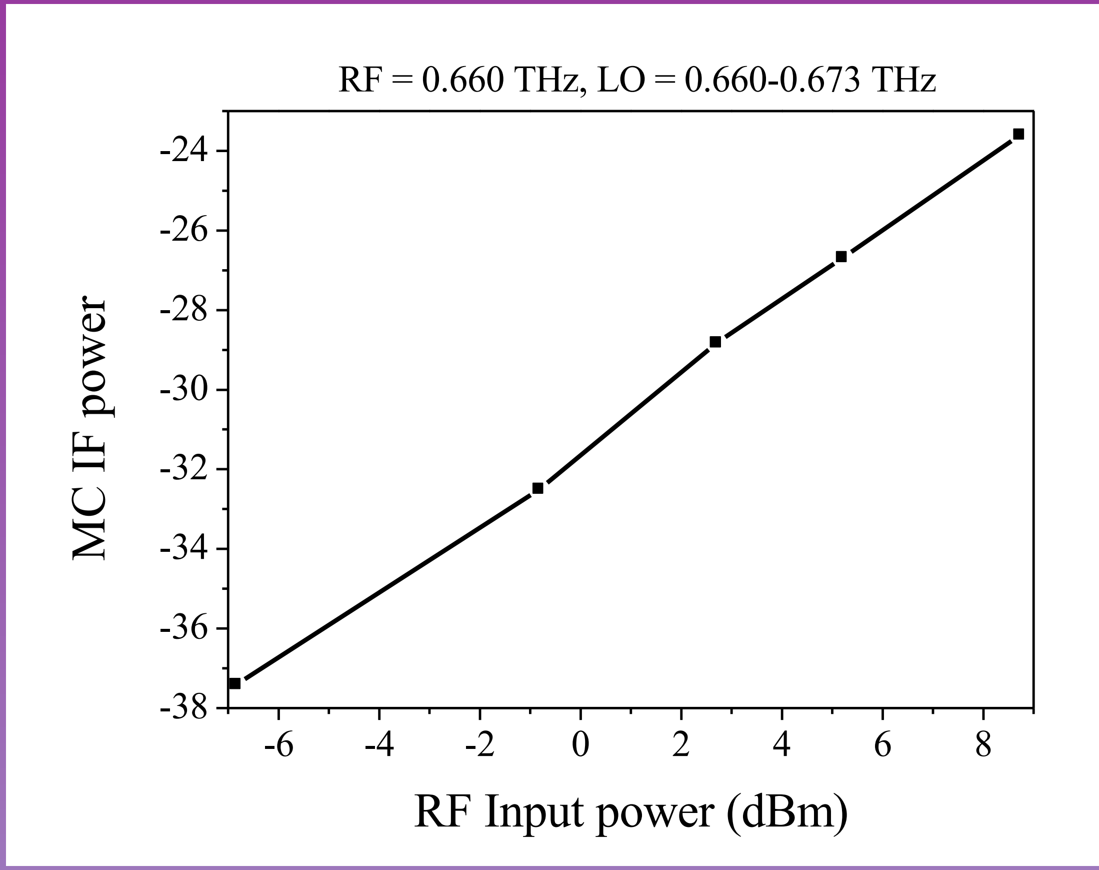


- ✓ IF measured up to 40 GHz !!!
- ✓ IF @ 3GHz (experiments) similar to IF @ 50 GHz (modeling)
- ✓ Frequency limit. : GaN with f_{RF} —> 0.8 THz

J. Torres *et al.*, Sem Scienc Tech 28, 125024 (2013)

Mixer saturation





- ✓ Absence of deviation from linearity between the IF output and the RF input power
- ✓ GaN supports high electric fields
- ✓ Avoid intermodulation

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Conclusion

- Self-Switching diodes work as 0.69-THz heterodyne detectors @ 300 K

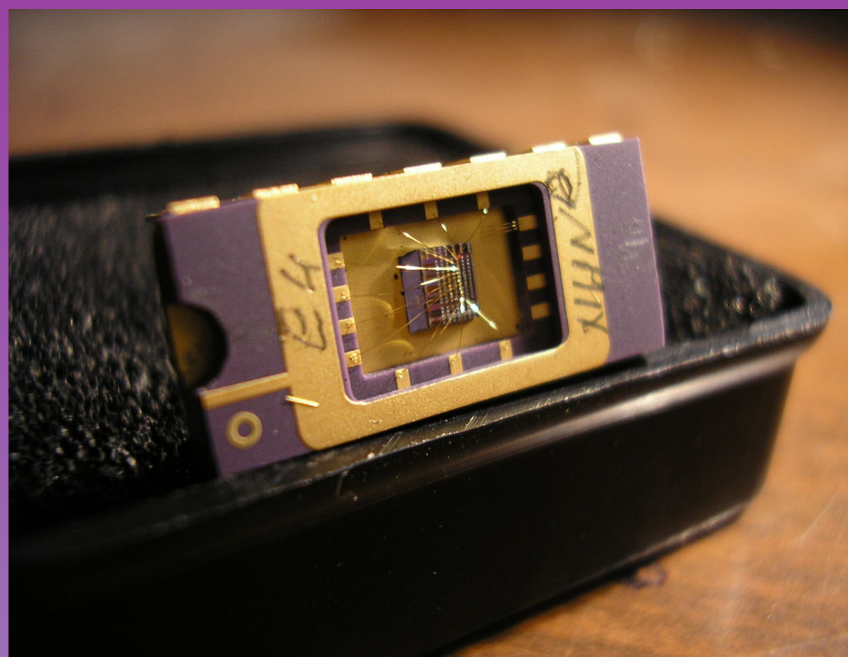
	Schottky diode (guided configuration)	SSD (free space configuration)
Conversion loss	< 9 dB @ 350 GHz	~ 35 dB @ 350 GHz
Bandwidth	40 GHz @ 350 GHz	> 40 GHz @ 350 GHz
Compactness	Low (vertical transport)	High (planar)
Cost	Medium	Low

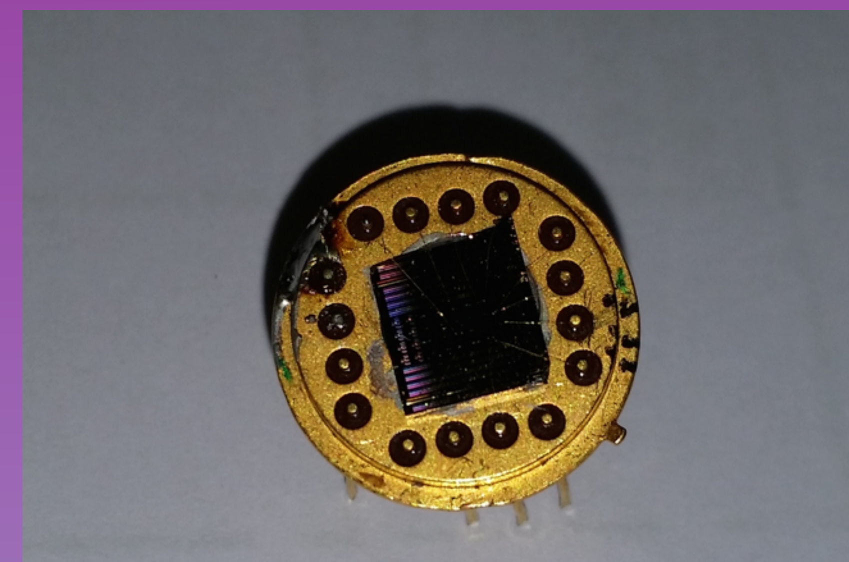
- Not actually competitive with Schottky diodes but first implementation
- Large margin for improvement (geometry, connective elements, proper integration,…)

THz emission

- ✓ Devices
- ✓ Physical mechanism
- ✓ Results

Devices





Nanoscale FET

Lg = 0.15 and 0.25 μm
Lsd = 3 μm
Vth ~ - 4 V
Ns ~ 10^{13} cm^{-2}

Ungated devices

Lc = 2 μm
La= 6 μm
L = 500 μm
Ns ~ 10^{13} cm^{-2}

TeraLab
Montpellier

Physical Mechanism

✓ plasma oscillations = surface waves

✓ boundary conditions : λ/4

⇨ THz emission

M. Dyakonov and M. Shur, Phys. Rev. Lett. 71, 2465 (1993)
J. Torres et al., Appl. Phys. Lett. 89, 201101 (2006)

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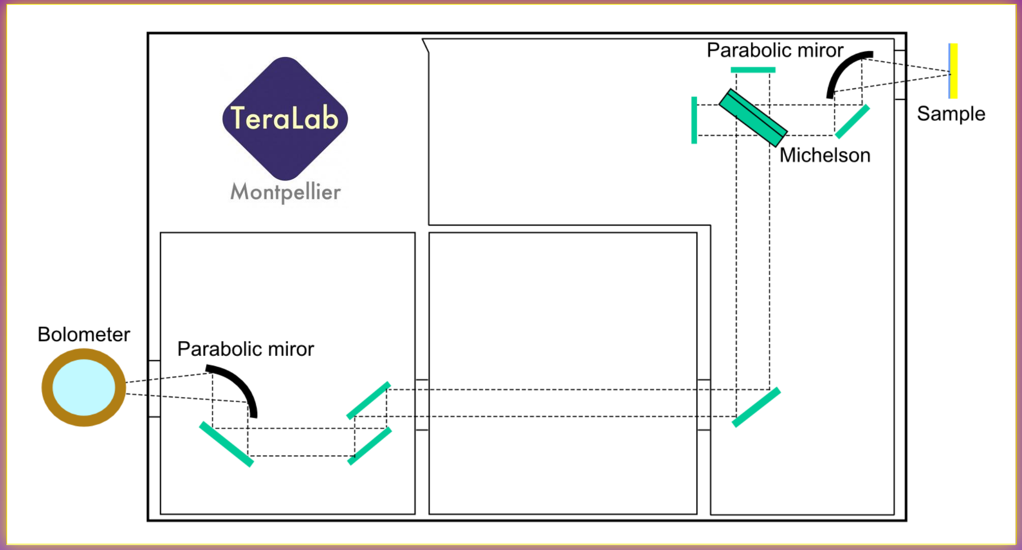
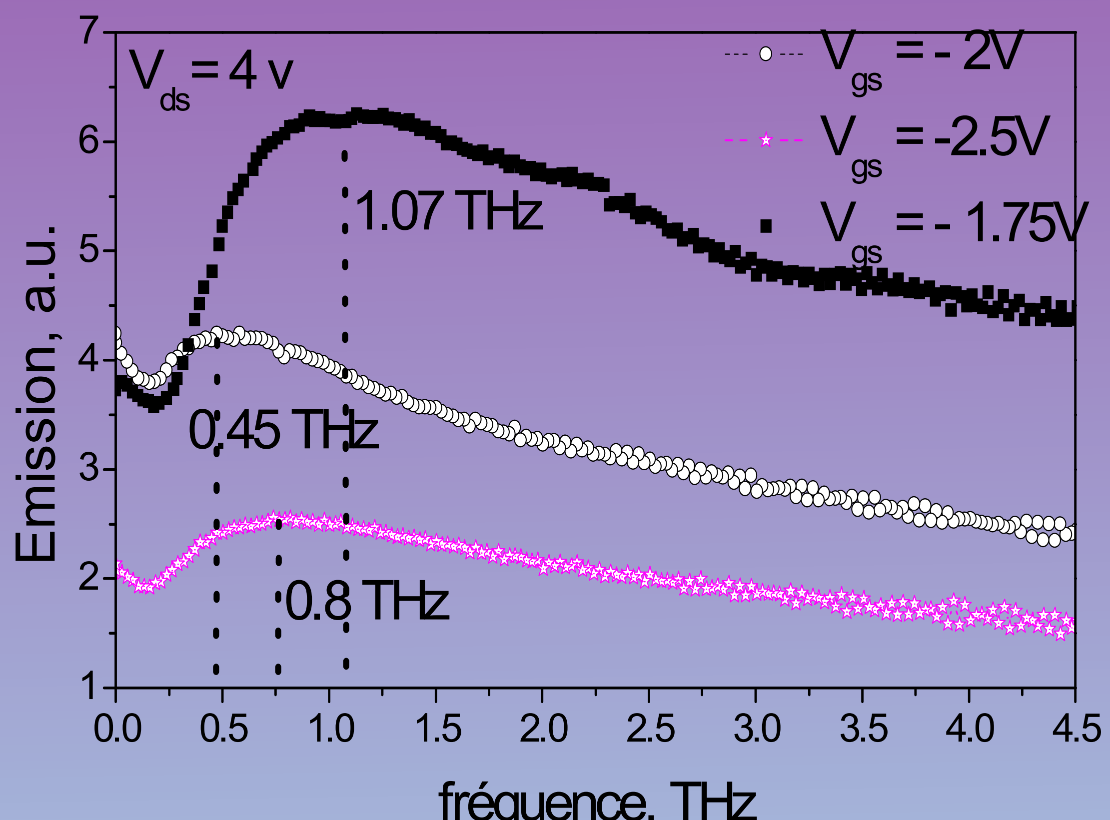
Emission : results

- ✓ FTIR-THz @ 300, 77 and 4 K
- ✓ GaN-based devices

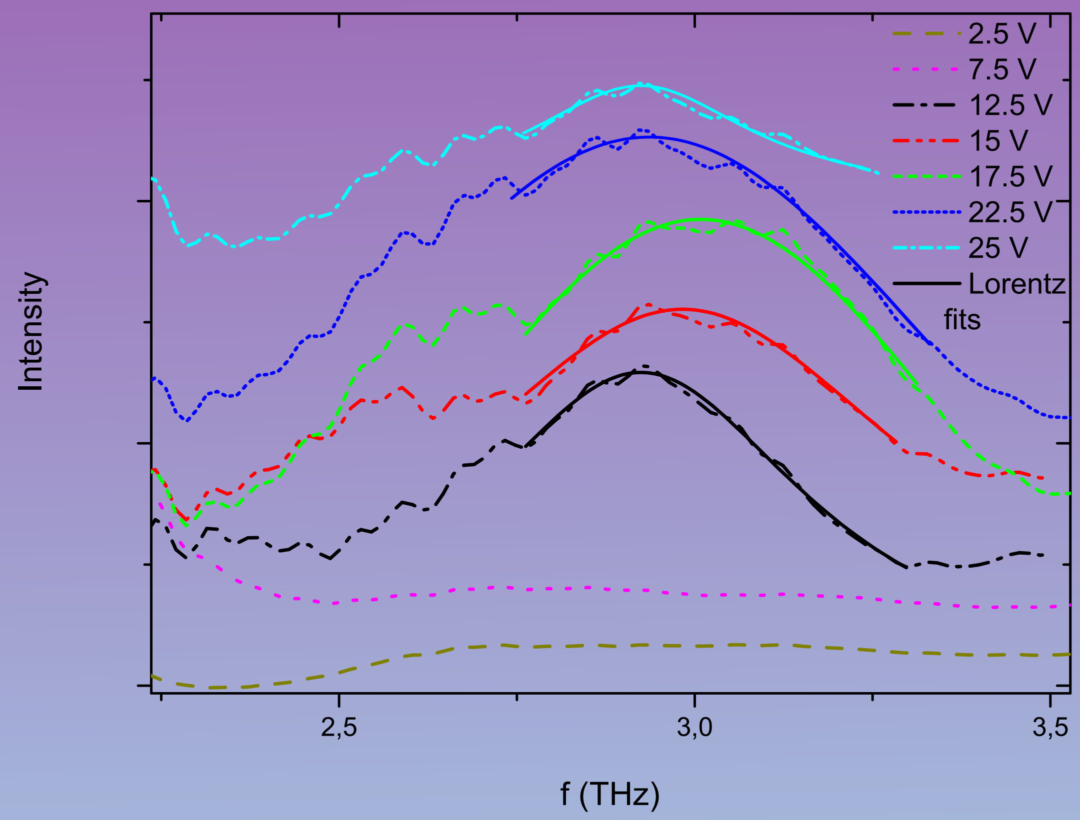


Nanoscale FET (4K)



A. El Fatimy *et al.*, J. Appl Phys 107, 024504 (2010)

Large area Ungated devices (300 K)



A. Penot *et al.*, Lithuanian Journal of Physics 04/2014; 54(1).

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Conclusion

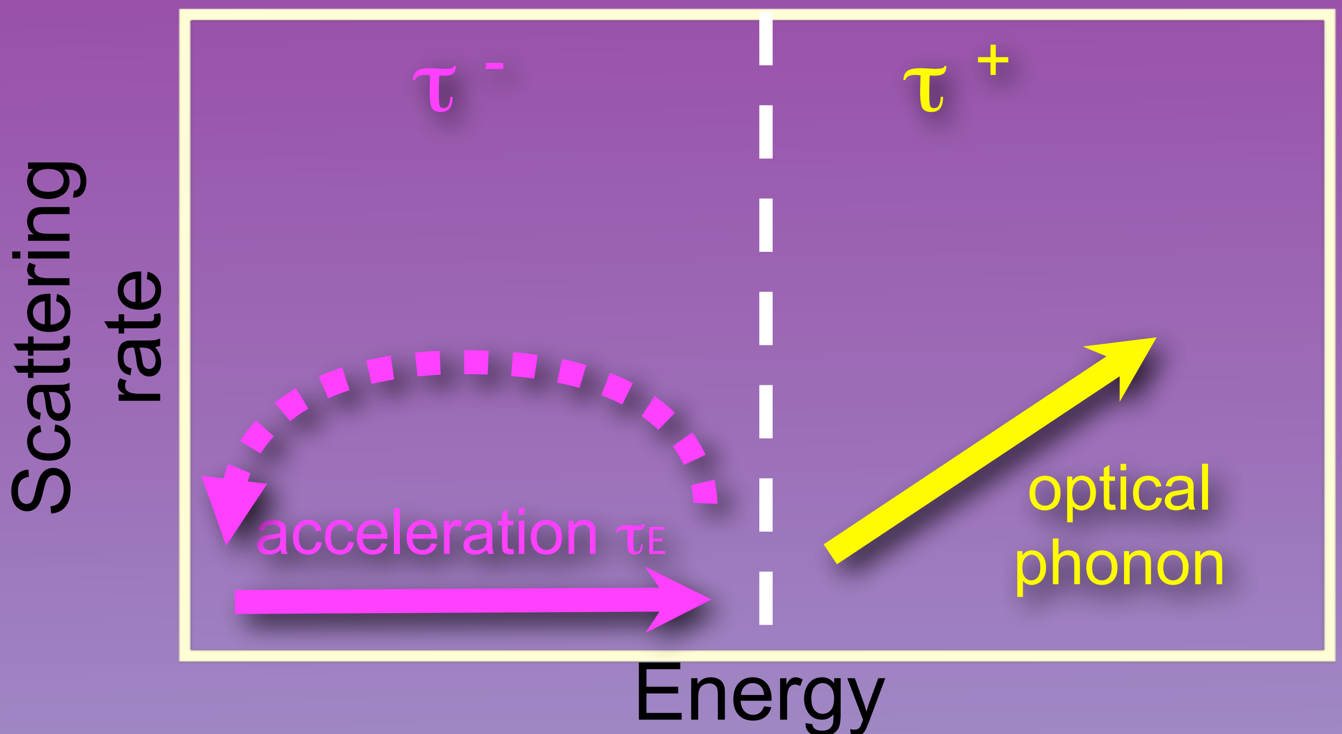
- ✓ Efficient THz emission
- ✓ Need high electric fields
- ✓ Low and room temperature measurements

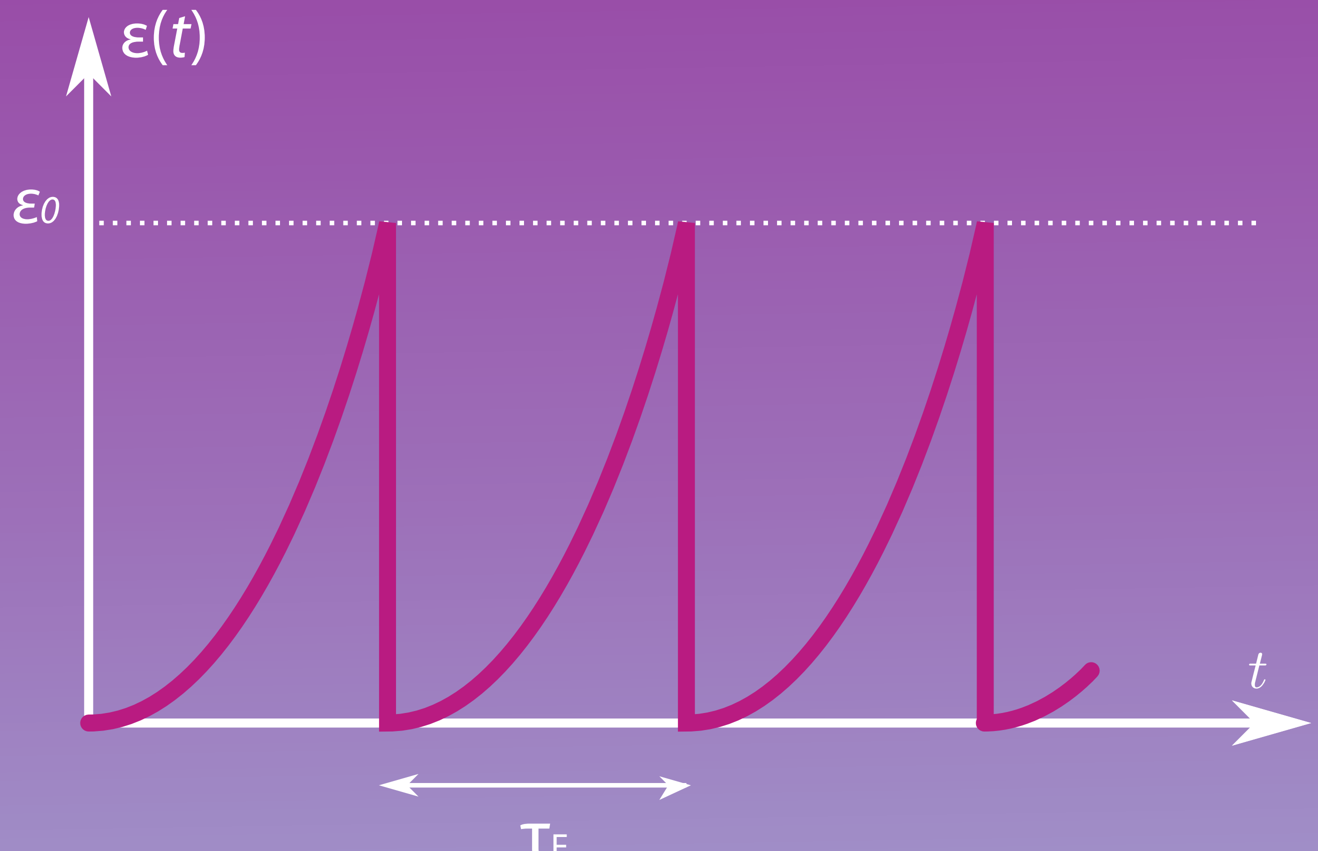
THz amplification

- ✓ Devices
- ✓ Experimental setup
- ✓ Results

Principle

- Perfect semiconductor material



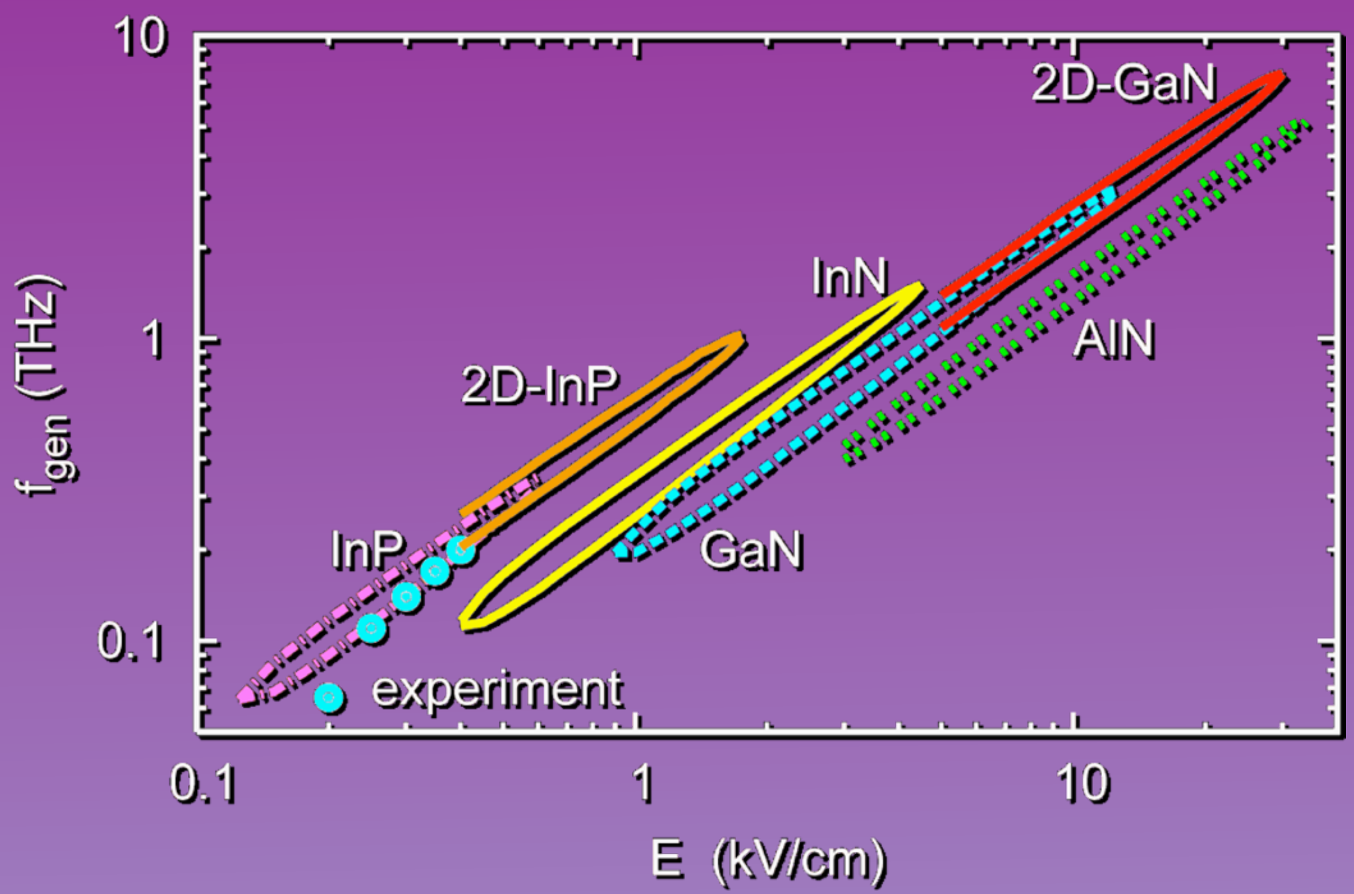


$$\tau^{-} \gg \tau_E = \frac{p_0}{eE} \gg \tau^{+}$$

τ^{-} : Average relaxation time, τ_{E} : Carrier transit time in energy space,
τ^{+} : Time of optical phonon emission

E. Starikov et al, J. Appl. Phys. **89**, 1161 (2001)

Amplification bands



E. Starikov *et al.*, J. Nanoelectron. Optoelectron., *2 1-25 (2007)*

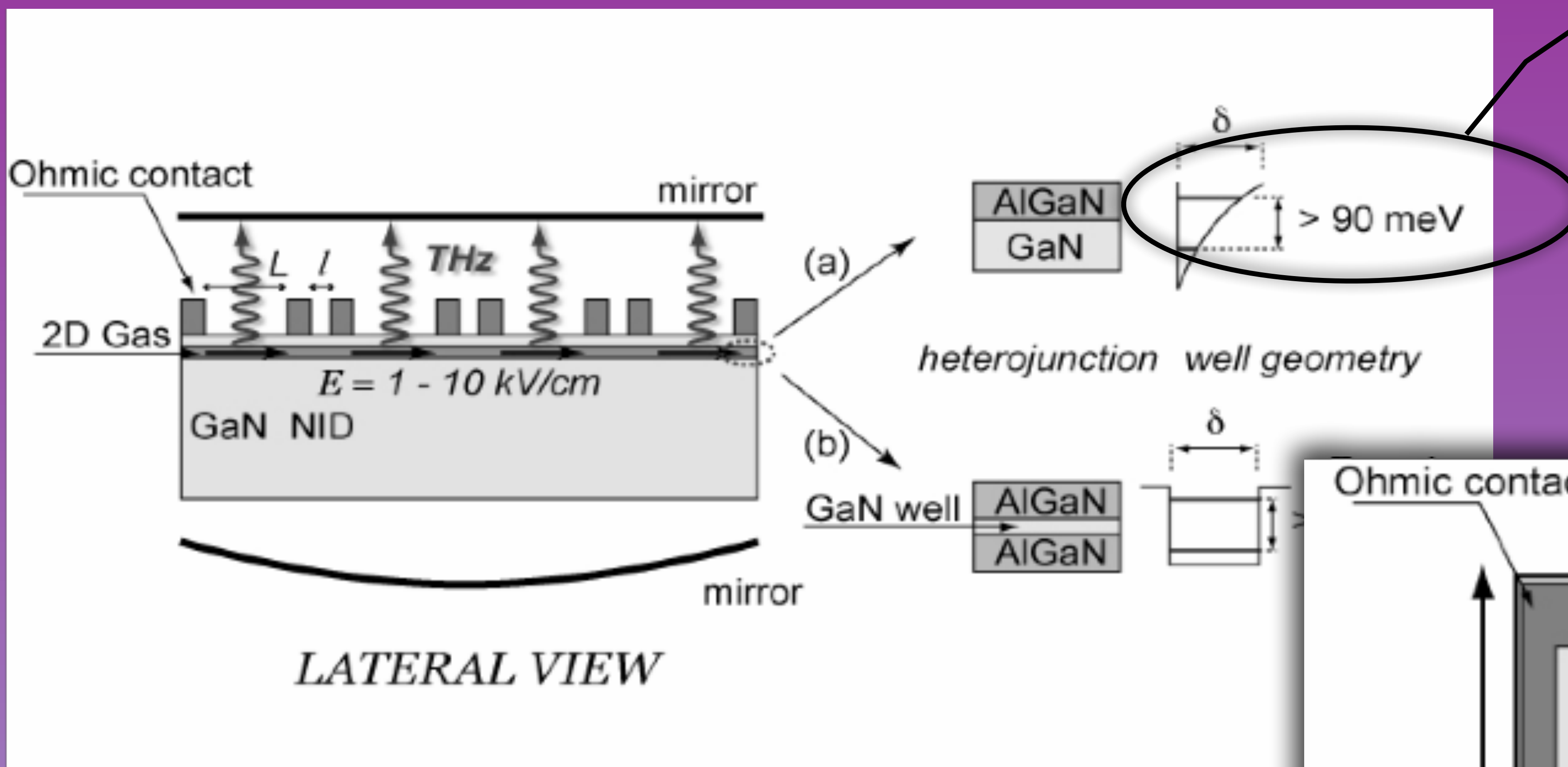
3D *Vs* 2D:

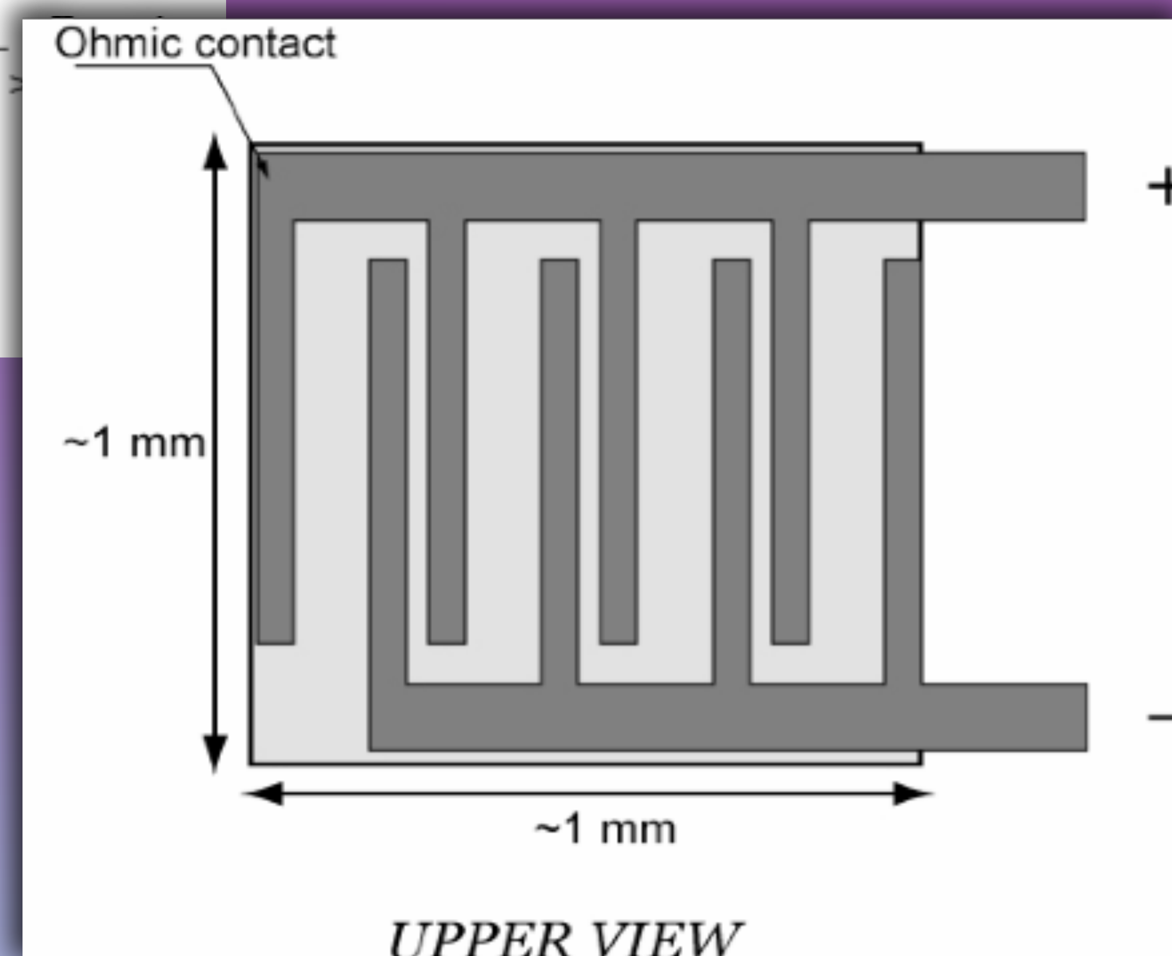
- favourable conditions
- technological choice

} ⇒ 2D-GaN devices

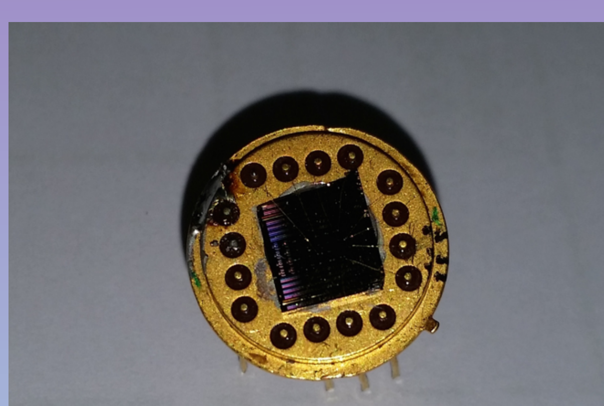
Devices technology and geometry

greater than $\hbar\omega_0$





E ~ 2 kV/cm over 1mm



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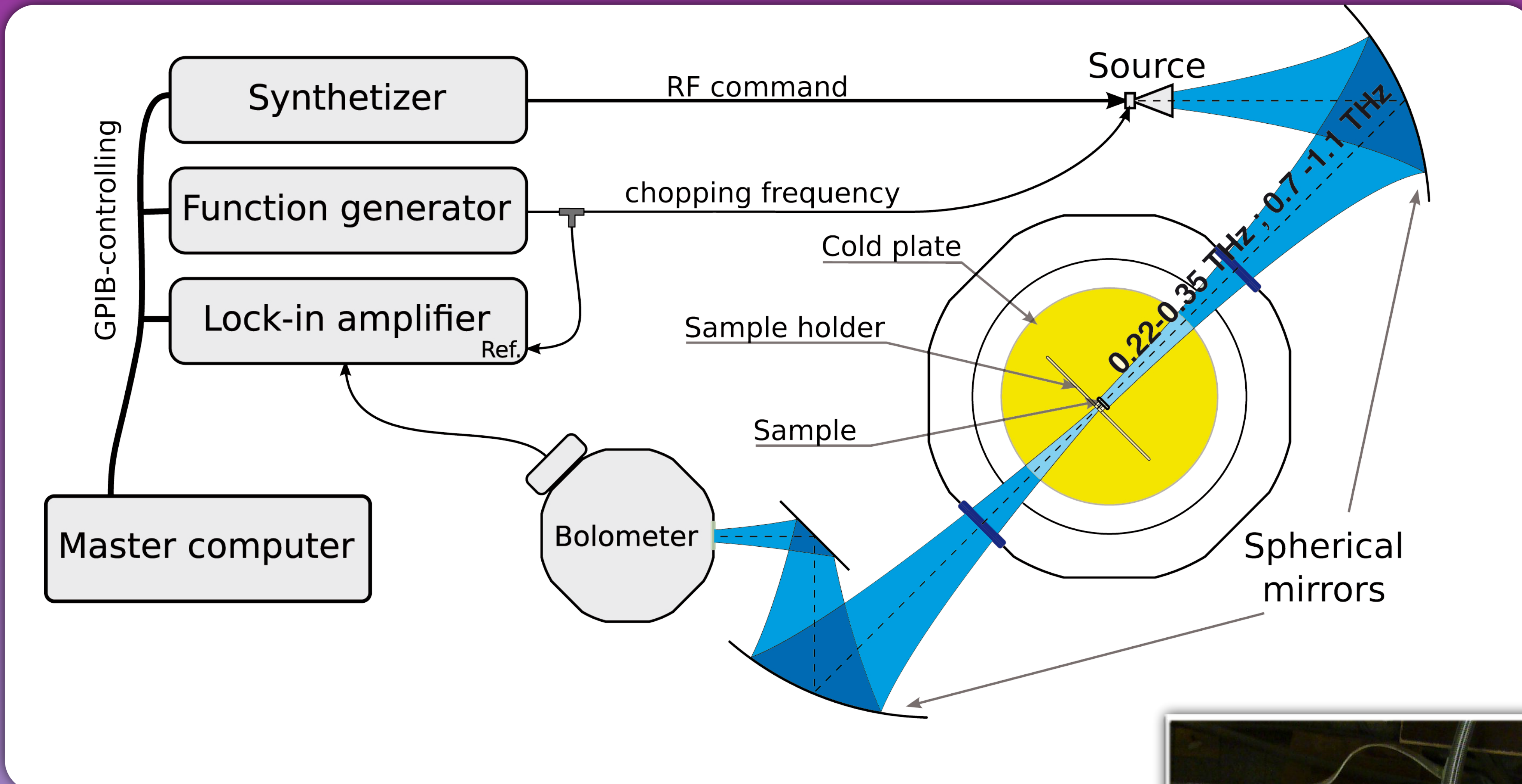
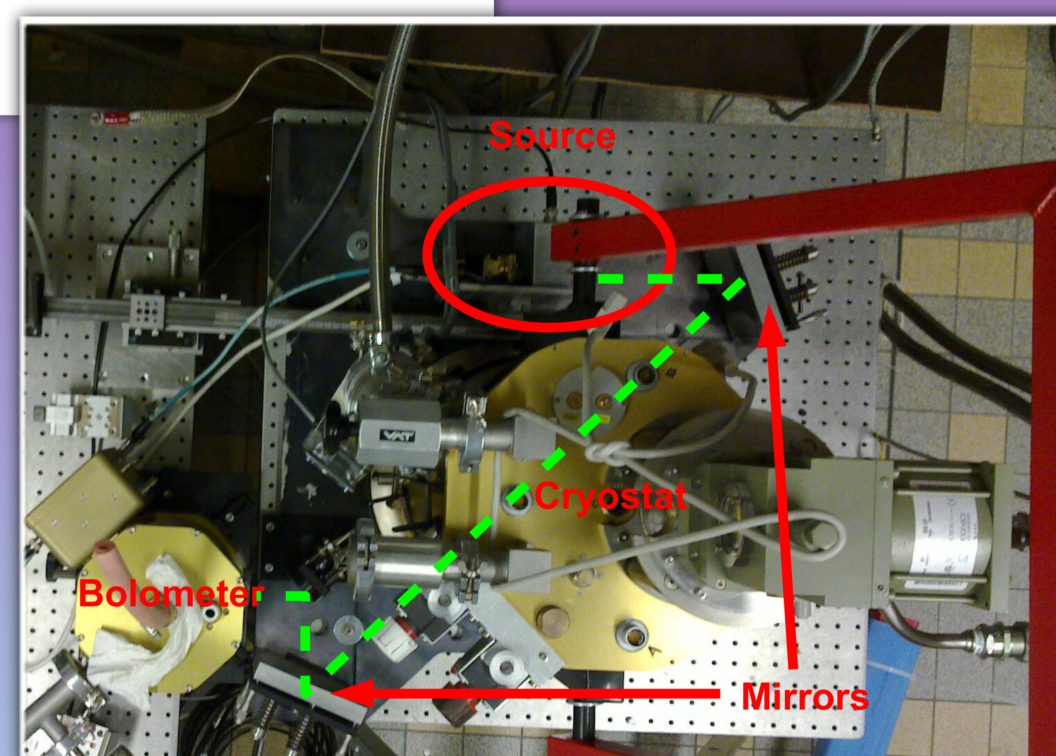
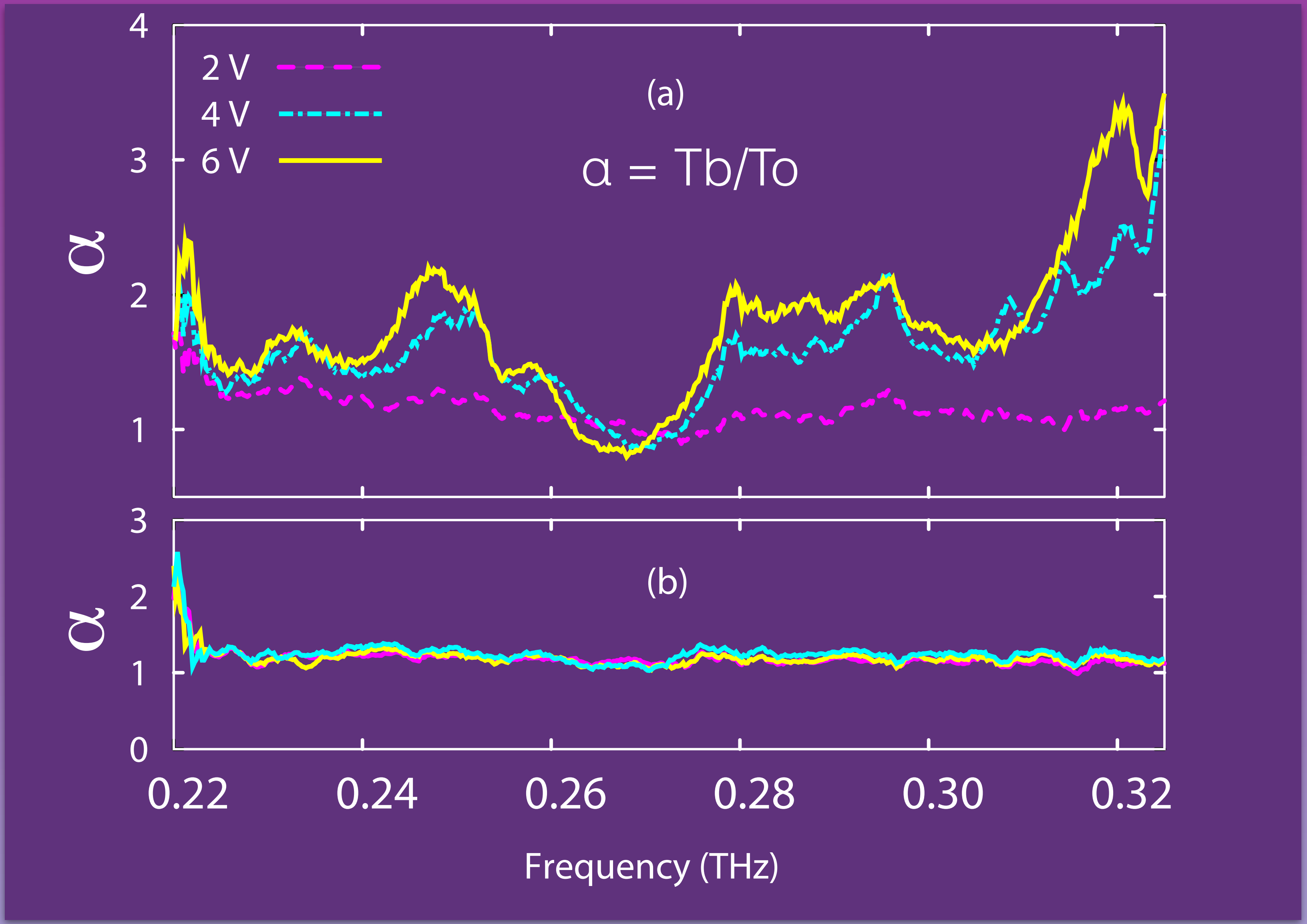
Experimental set-up





- ✓ Low temp experiments,
- ✓ Invisible beam, alignement,
- ✓ low intensity.

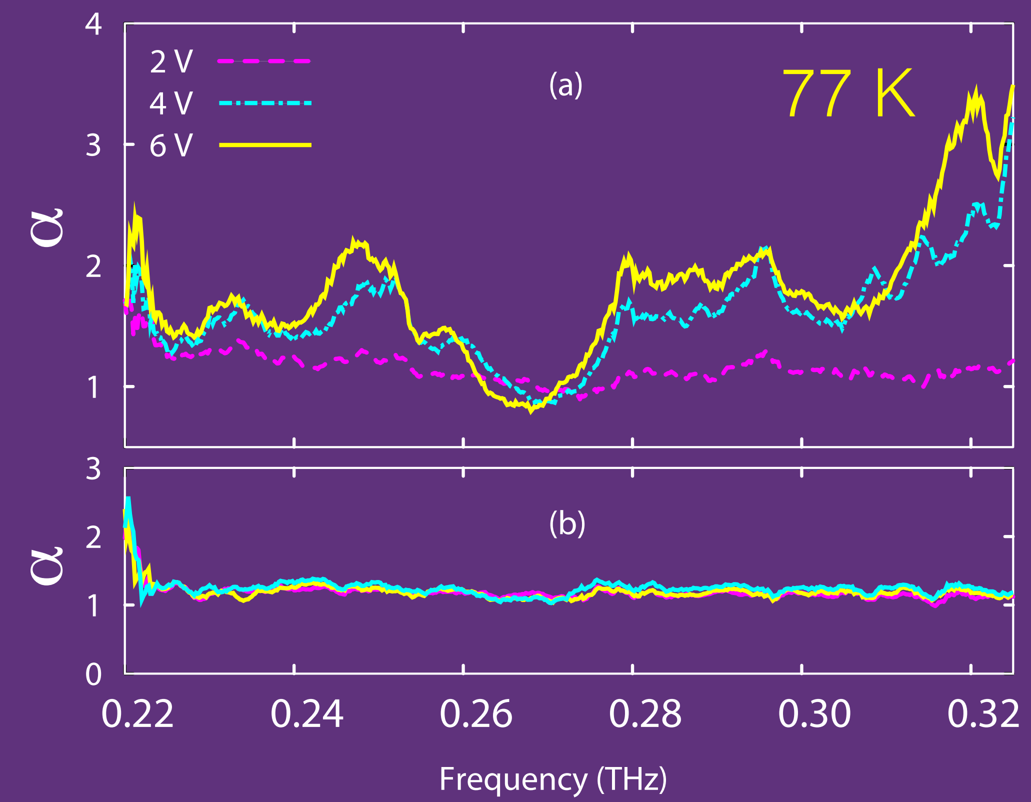
Effects of temperature/bias

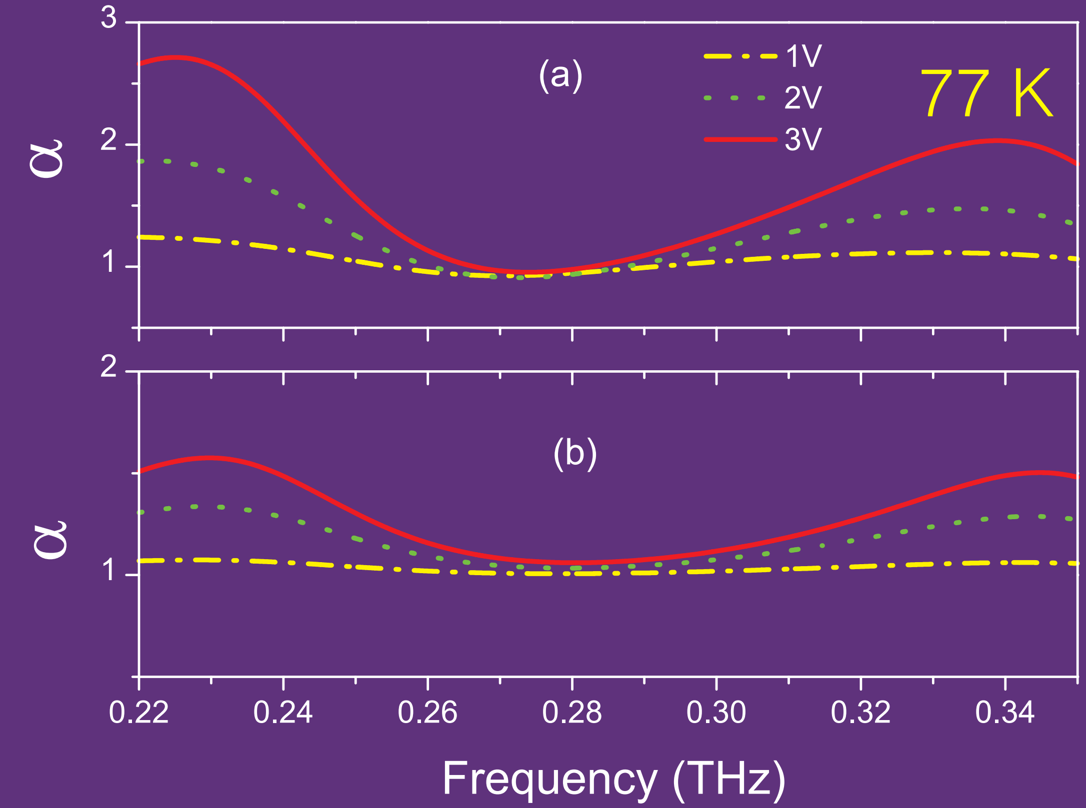


✓ Modulation of THz radiation by dc-voltage

T. Laurent *et al.*, Appl. Phys. Lett., 99, 8082101 (2011)

Experiments Vs Modelling





- ✓ Drude - Lorentz Model
- ✓ radiation interference on the substrate ~ 0.27 THz
- ✓ differential mobility changes with V due to heating effect

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Conclusion

- ✓ Modulation of THz radiation @ 77K
- ✓ No effect at room temperature
- ✓ Need integration into THz cavity —> effect increases

Conclusion

- ✓ GaN, a promising materials:
  - ✓ Robust & linear: high electric fields, high power THz
  - ✓ Detection at 0.3 and 0.7 THz frequencies @ 300 K
    - ✓ No technological breakthrough —> industrialisation
  - ✓ Amplification and emission more prospective
- ✓ Industrial turning point
  - ✓ start-up growth
  - ✓ real-life applications (imaging, spectroscopy, security,…)

Thank you

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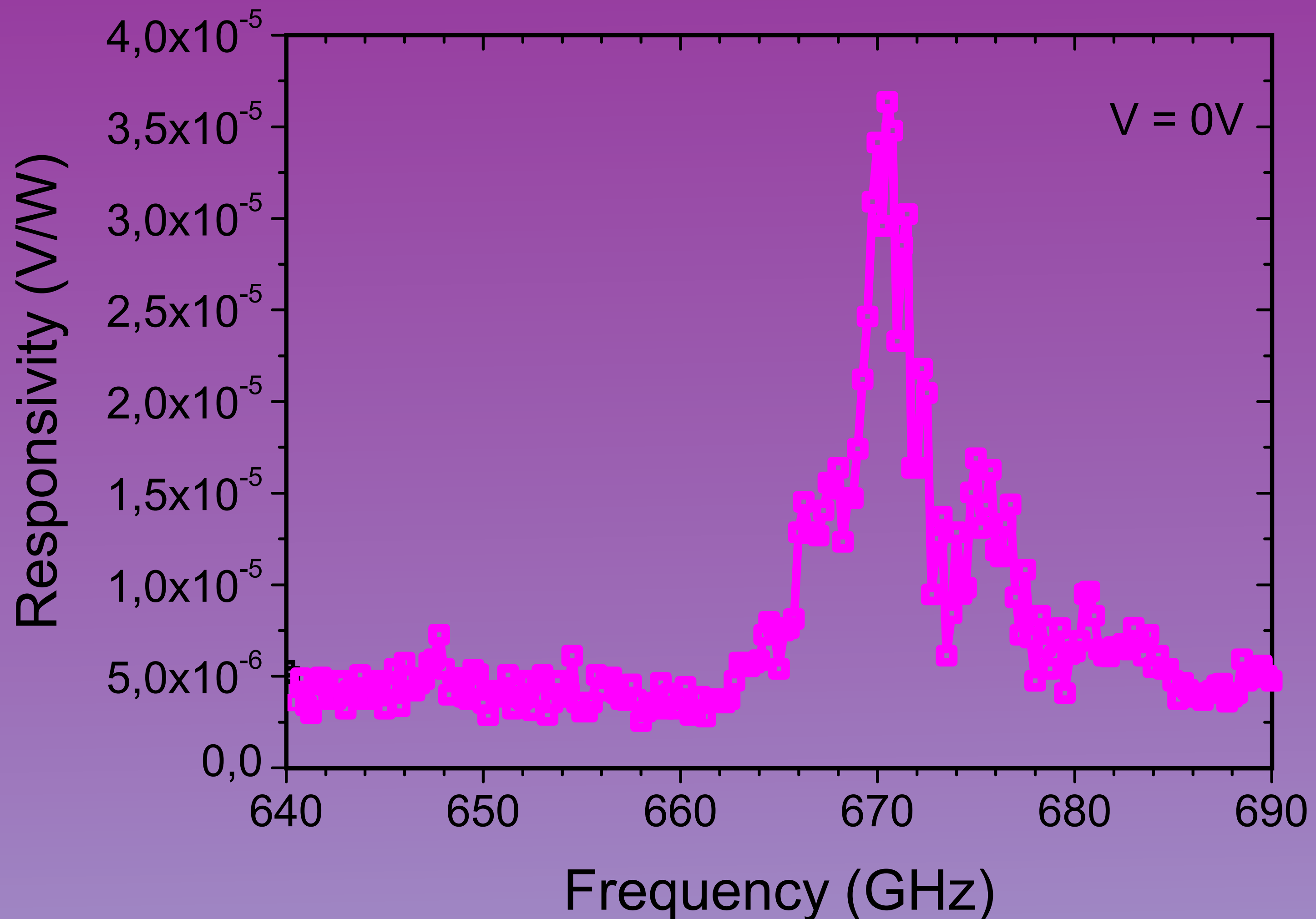
THz detection



- ✓ Detection @ 670 GHz in GaN SSD
- ✓ No bias
- ✓ FWHM ~10 GHz

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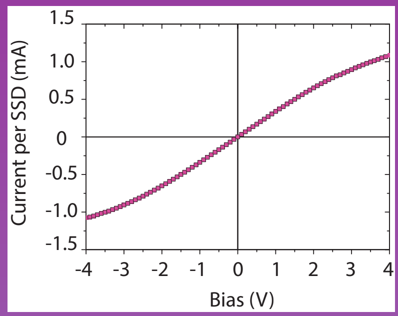
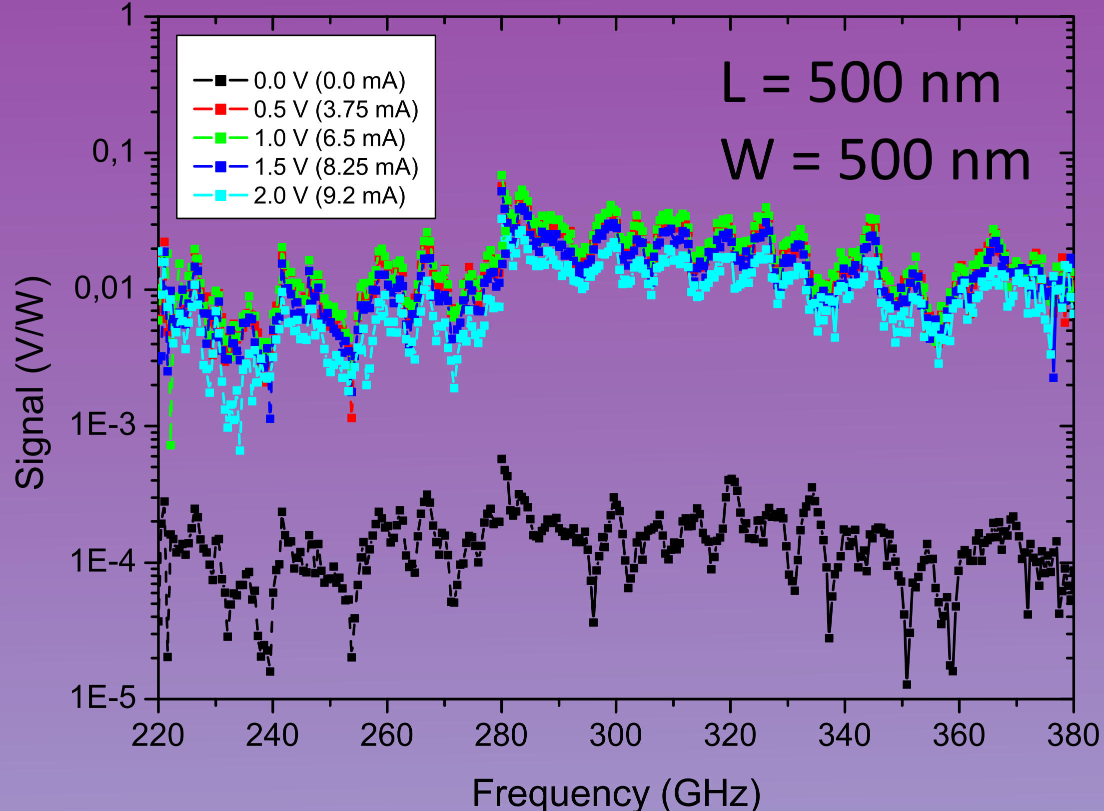
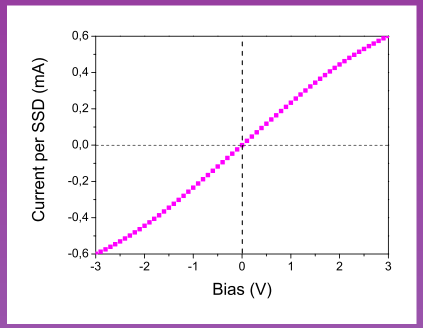
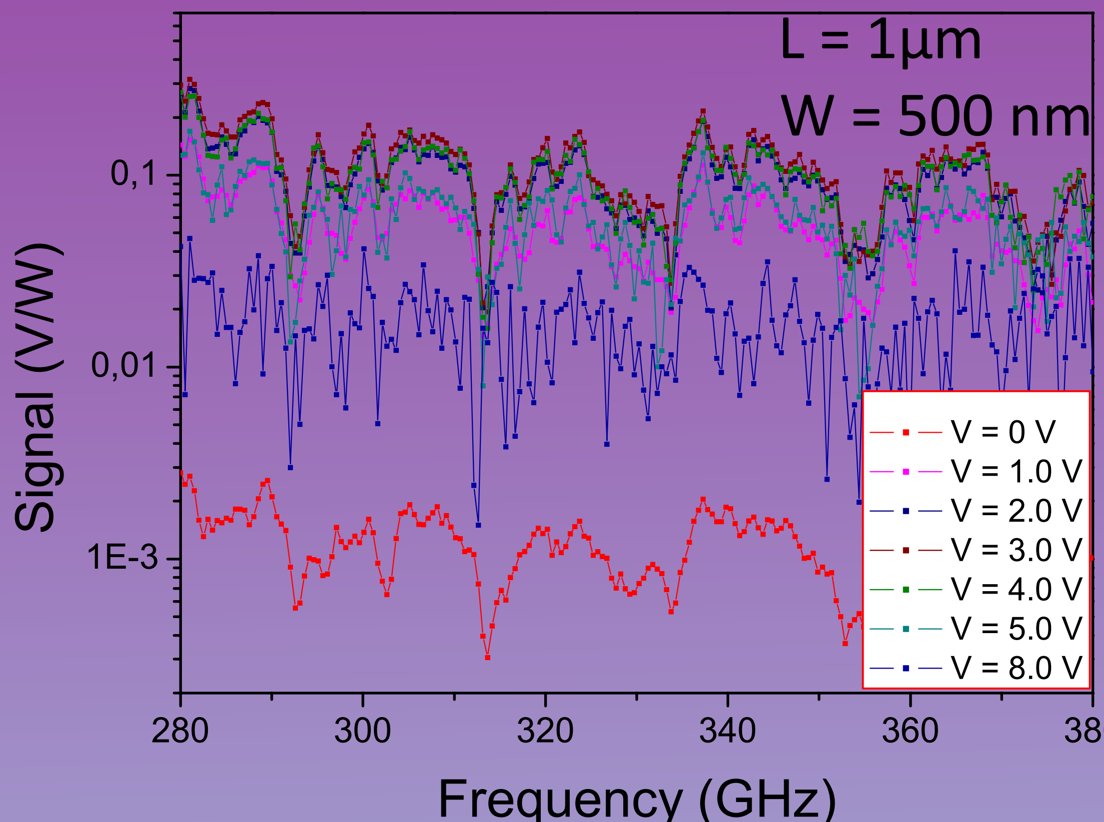
THz homodyne detection:









- Responsivity ↑ when L ↑

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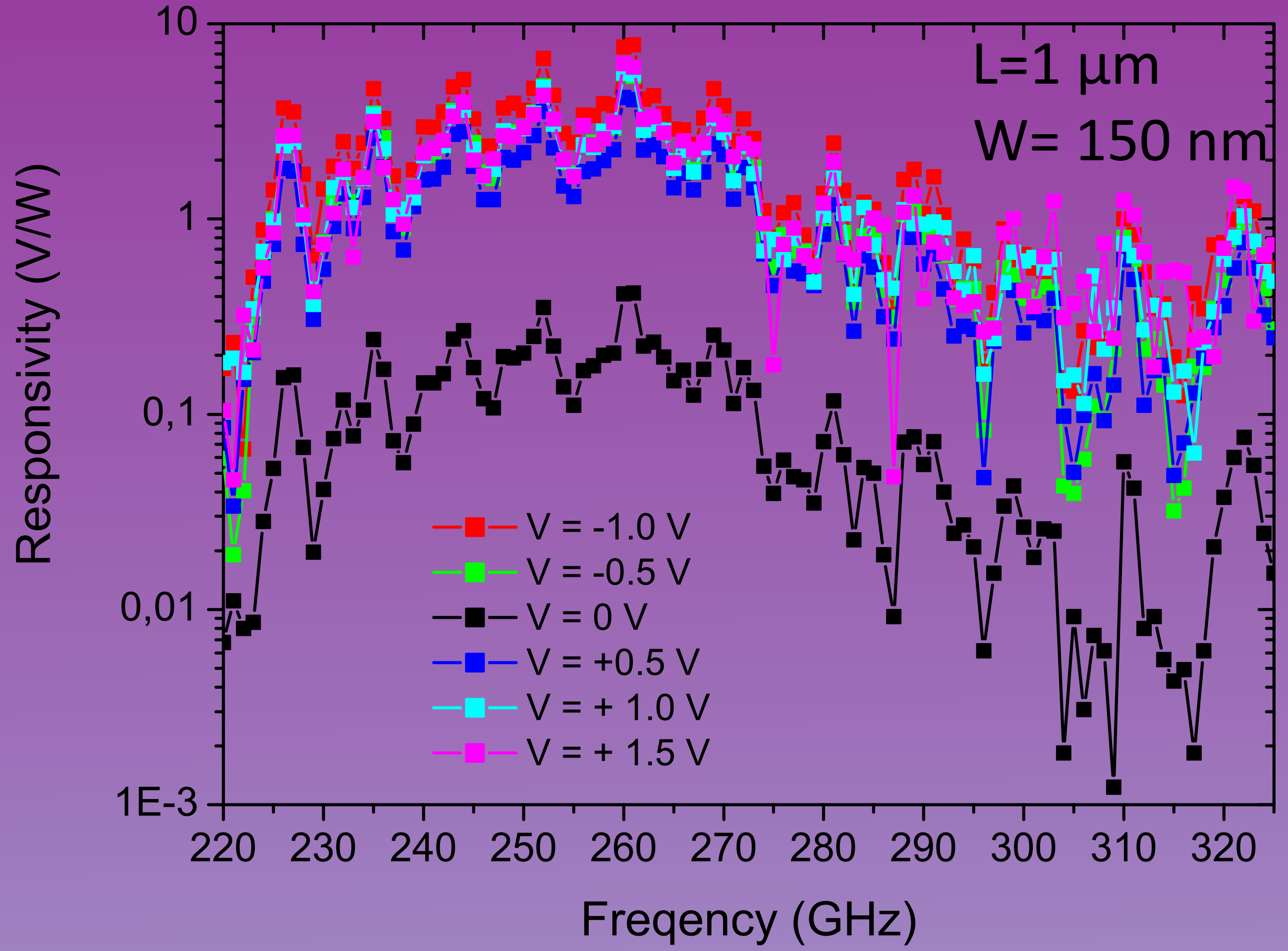
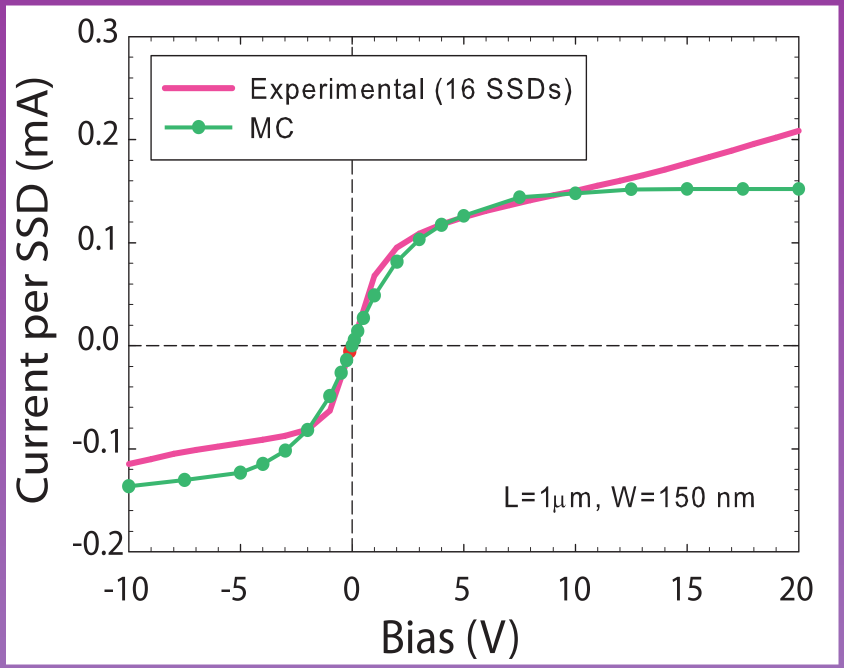
THz homodyne detection





- ✓ W ↓, surface effect ↑, Channel non-linearity ↑, responsivity ↑

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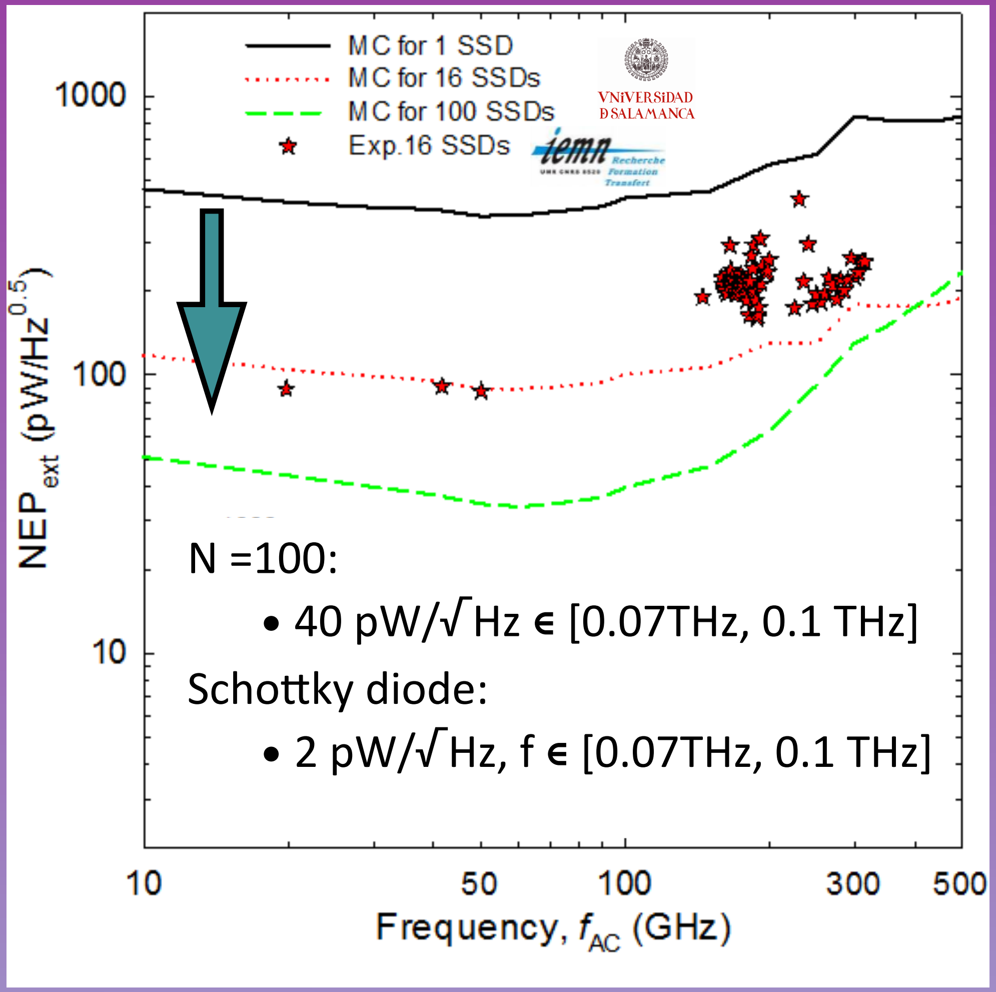
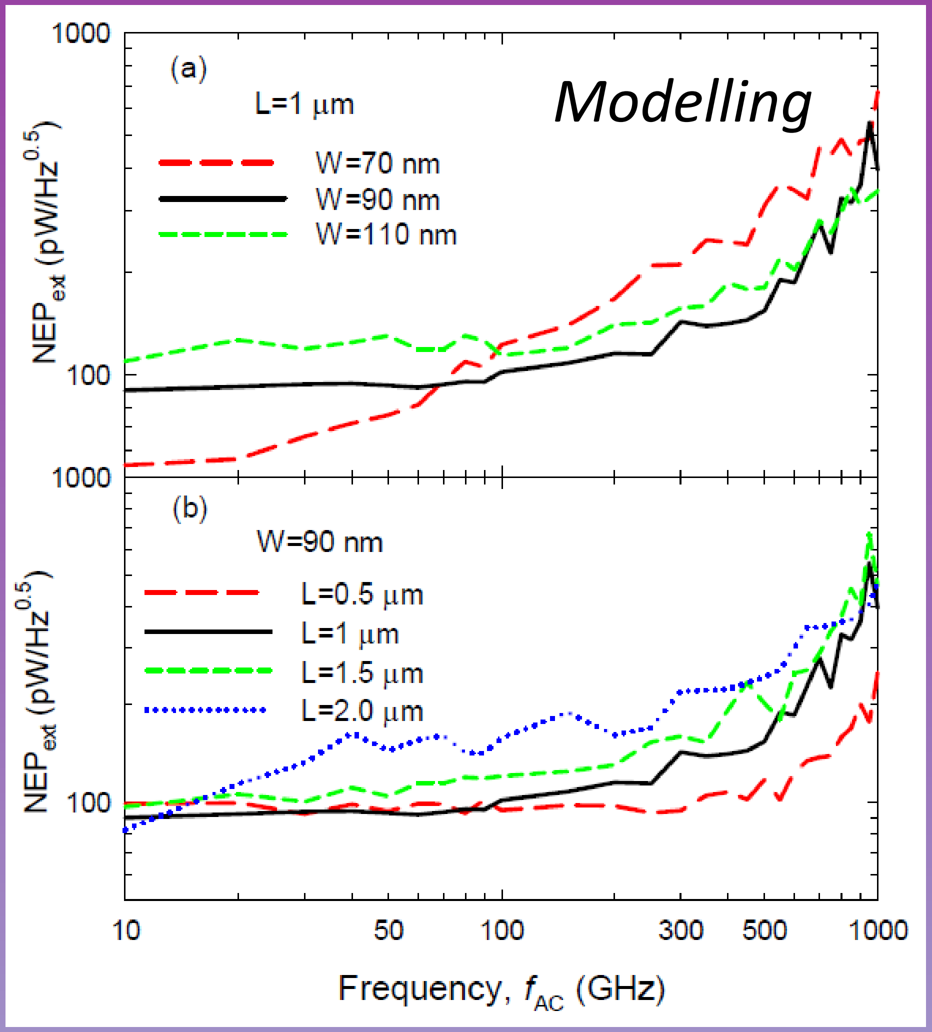
NEP in SSDs





J. Millithaler *et al.*, Proc. ICNF to be published (2013)

✓ Good overall agreement

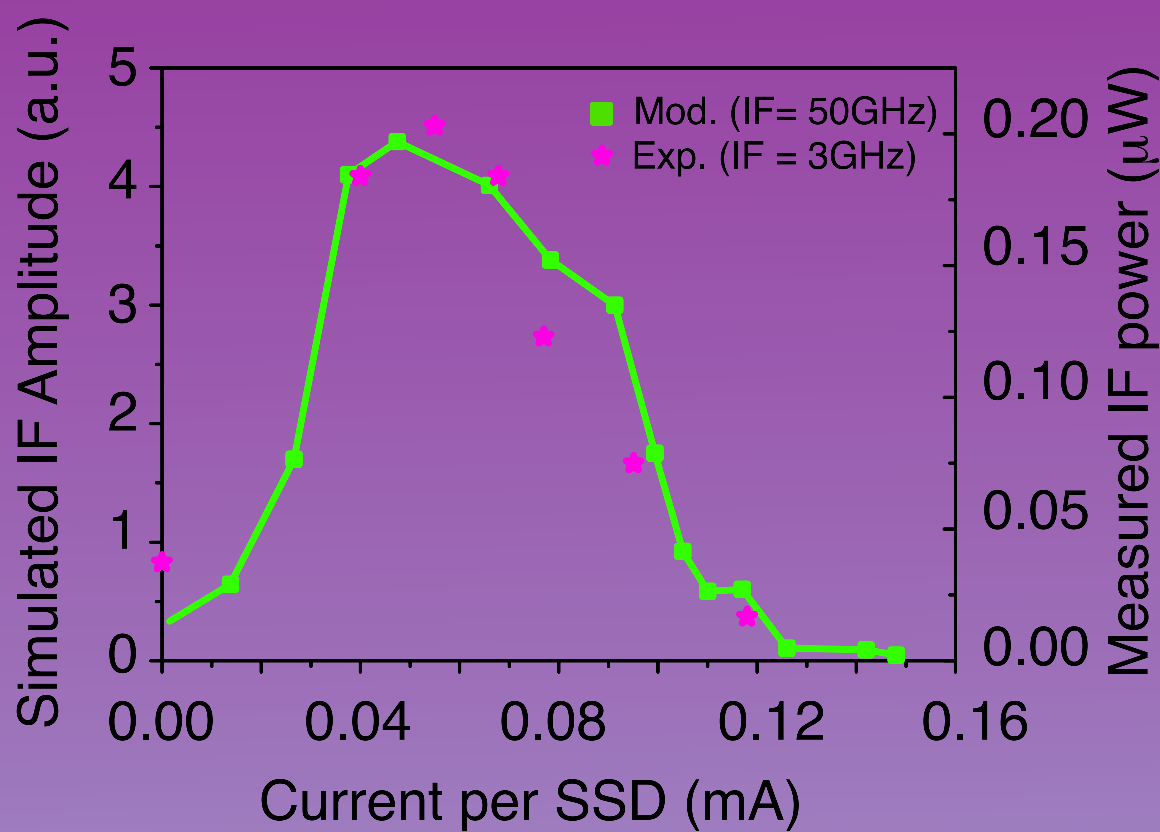
✓ Important reduction in the NEP for N↑

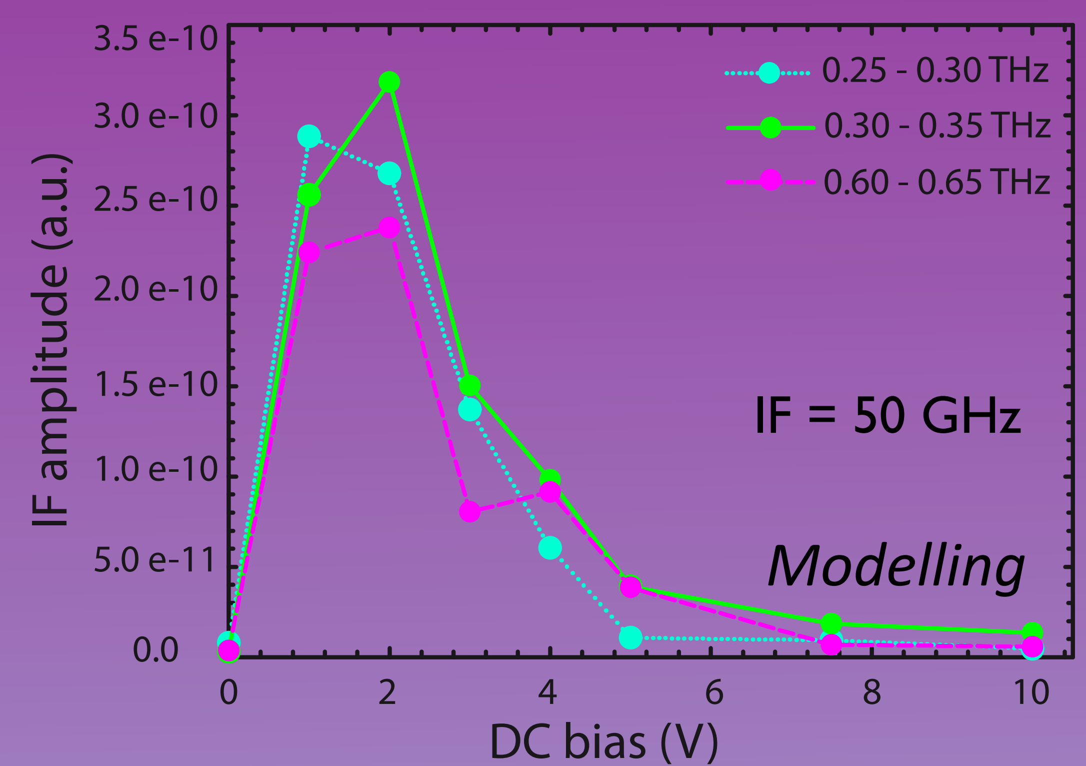
- NEP decrease reducing W, but R↑: poorer freq. response
- L↓ → ↑ cut-off frequency (0.5 μm: constant up to 500 GHz)

Microwave

& RF

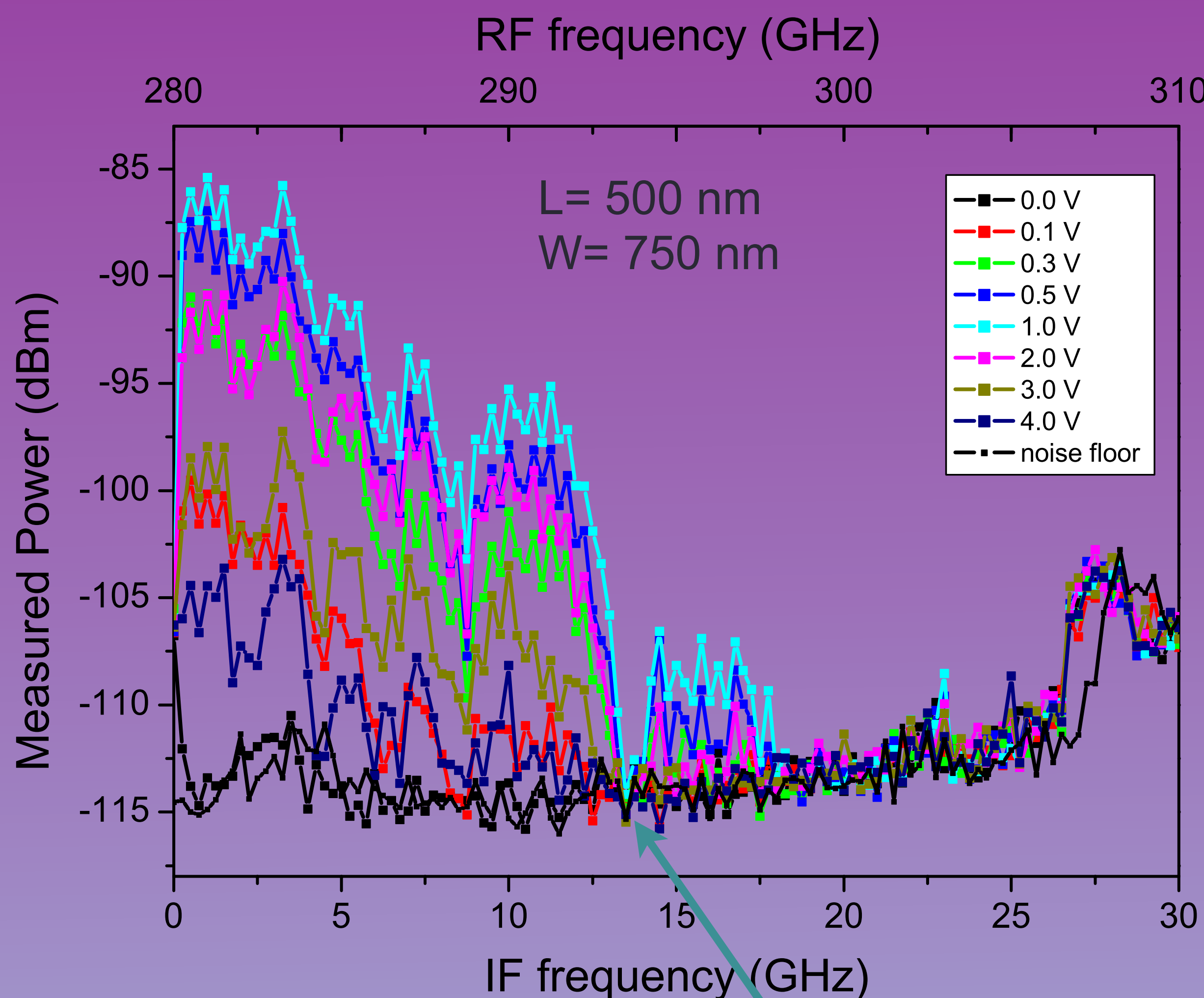
Frequency limitation

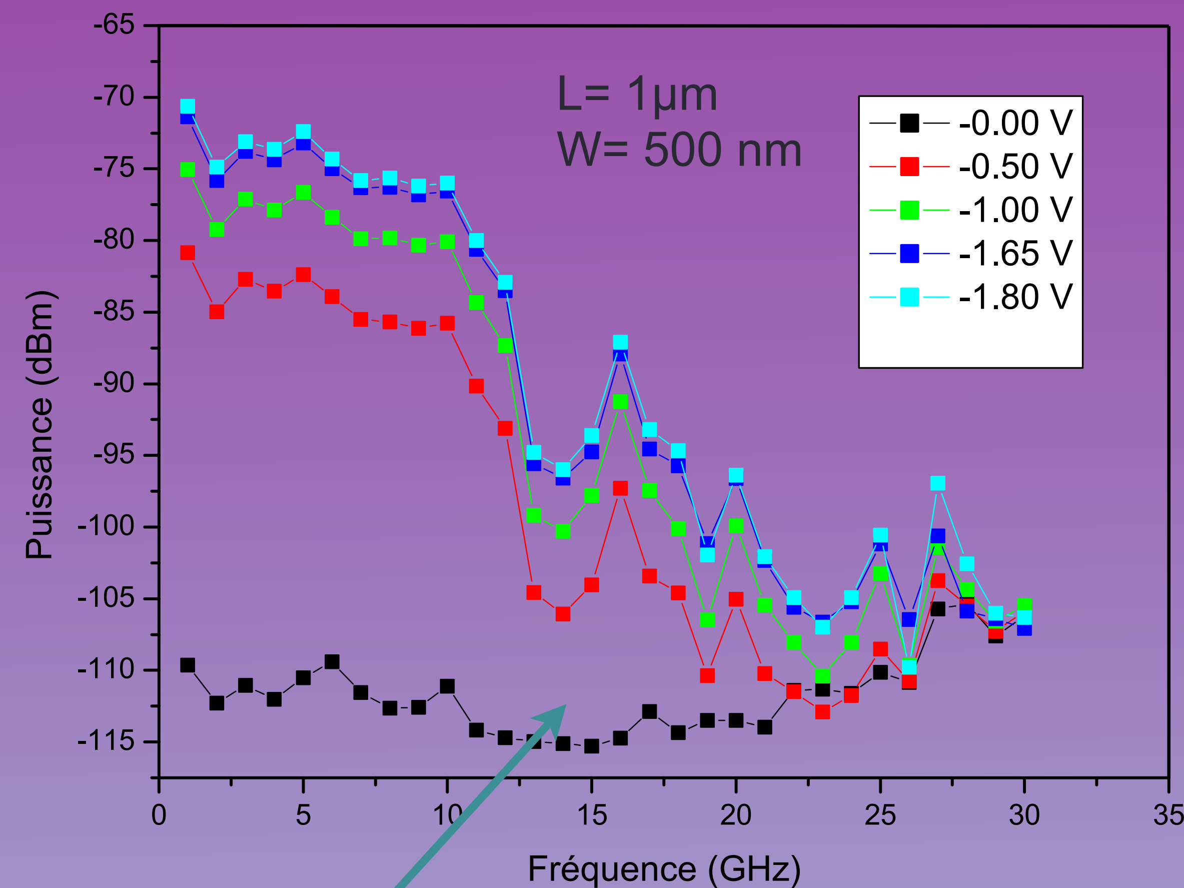




- ✓ f_{RF} ~ 300 GHz
- ✓ GaN should works with f_{RF} up to 0.65 THz
- ✓ Conversion losses : 80 dB but ...

Bandwidth





Limitation @ 13 GHz: micro-wires cut-off

Microwave & RF

SSD *Vs* Schottky

	Schottky diode (guided configuration)	SSD (free space configuration)
Conversion loss	< 7 dB @ 100 GHz < 9 dB @ 350 GHz	~ 45 dB @ 350 GHz [(a)]
Bandwidth	20 GHz @ 100GHz 40 GHz @ 350 GHz	> 40 GHz @ 350 GHz [(a)]
NEP (zero-bias detector)	1.5 $pW/Hz^{1/2}$ @ 150 GHz* 10 $pW/Hz^{1/2}$ @ 800 GHz**	40 $pW/Hz^{1/2}$ @ 100 GHz [(b)] 200 $pW/Hz^{1/2}$ @ 350GHz [(c)]
Compactness	Low (vertical transport)	High (planar)
Cost	Medium	Low

(a) no HF wires, first implementation, (b) Monte Carlo simulations, (c) Measurements

* Hesler, J.L., Crowe, T.W. "NEP and responsivity of THz zero-bias Schottky diode detectors" IRMMW-THz,844-845 (2007); ** Semenov, A. et al. "Application of Zero-Bias Quasi-Optical Schottky-Diode Detectors for Monitoring Short-Pulse and Weak Terahertz Radiation" IEEE Electron Device Letters, 674 - 676, 31 (2010).