12th INTERNATIONAL BEAM INSTRUMENTATION CONFERENCE
SASKATOON, CANADA
September 10-14, 2023

Paper ID: WE1C03

THz antenna-coupled Zero-Bias Schottky Diode Detectors for Particle Accelerators

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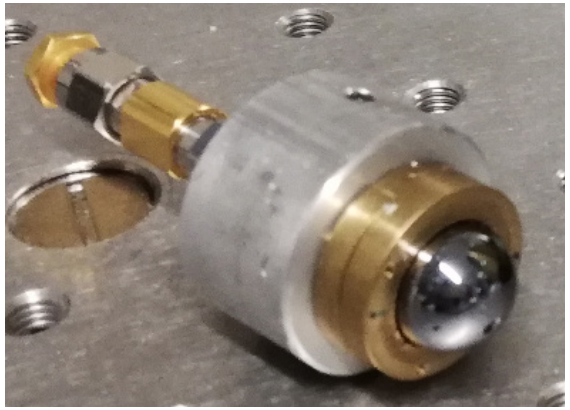
[2] *High Frequency Technology, THM Friedberg*
[3] *Institute of Radiation Physics, HZDR Dresden*

Date: 13th September 2023



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  - Requirement of THz detectors
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  - Antenna analysis
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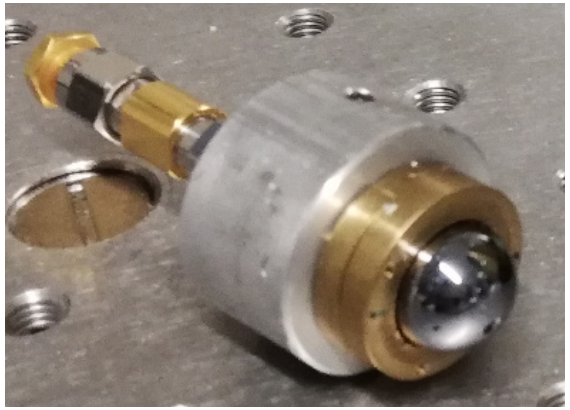
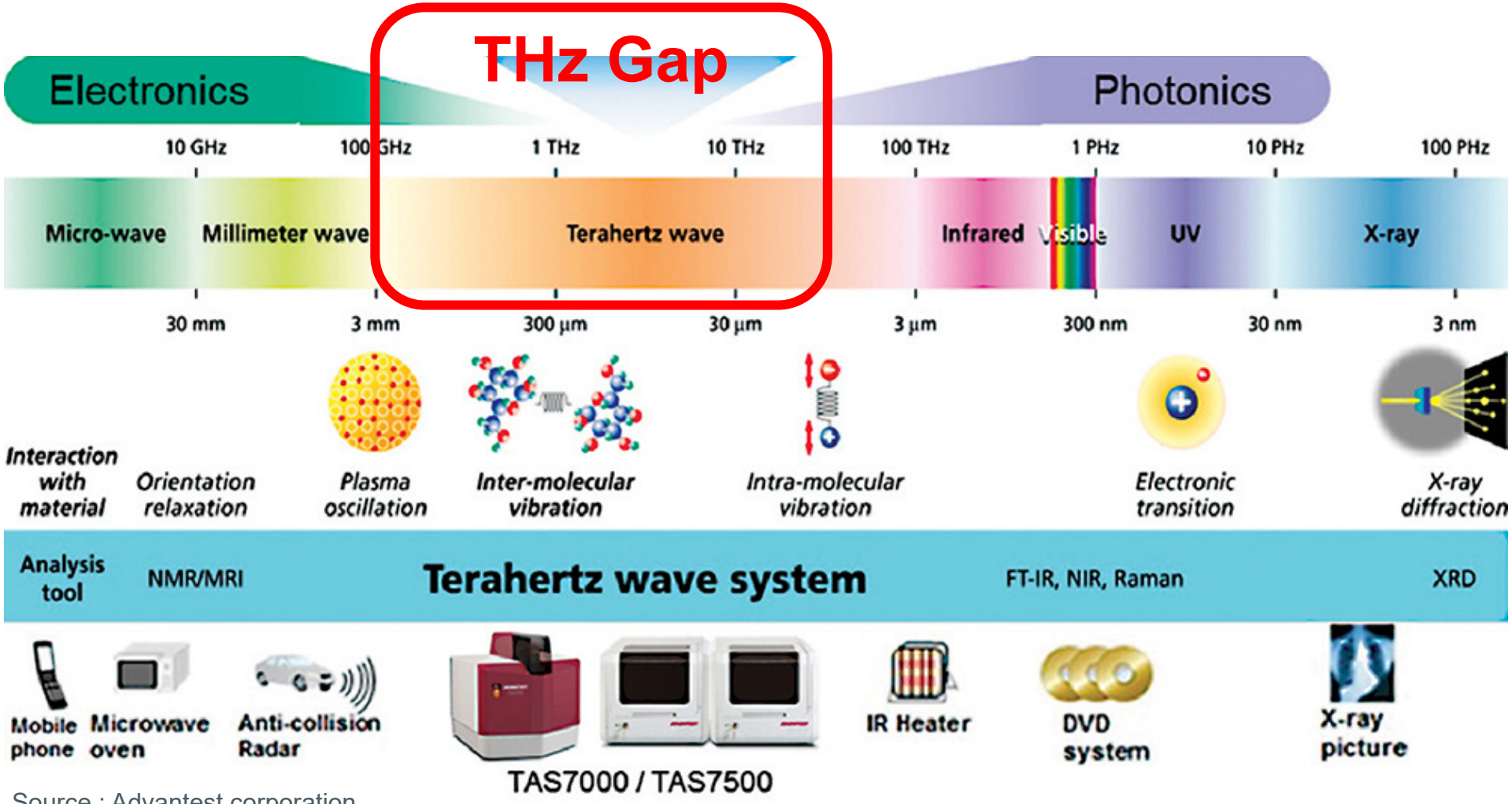


Motivation : what are THz waves ?



Source : Advantest corporation

1 THz
↕
1 ps
↕
33 1/cm
↕
0.3 mm
↕
4.1 meV

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Motivation : development of THz components

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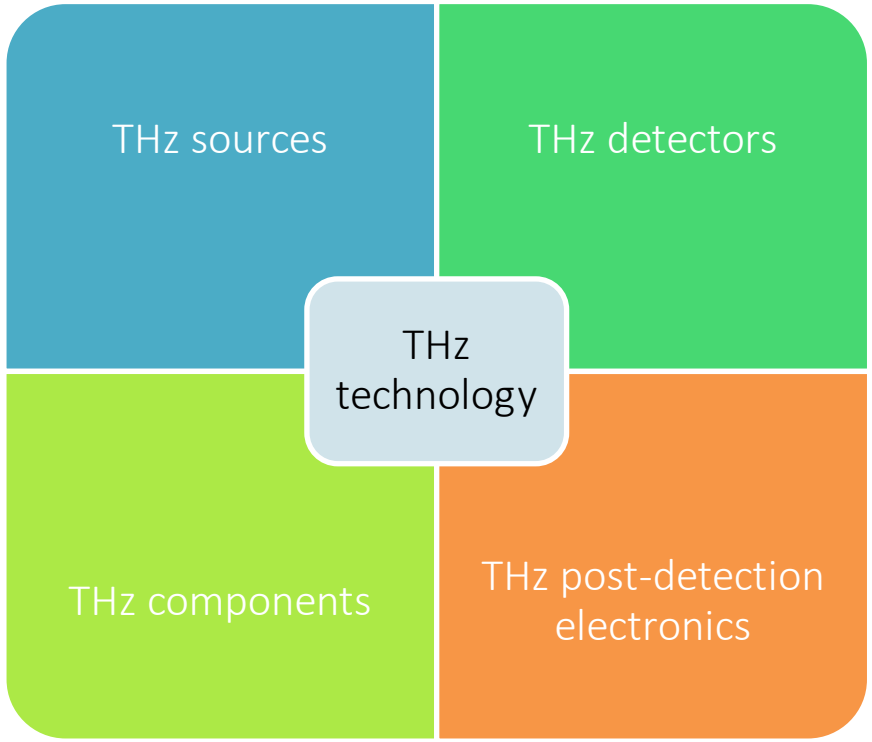
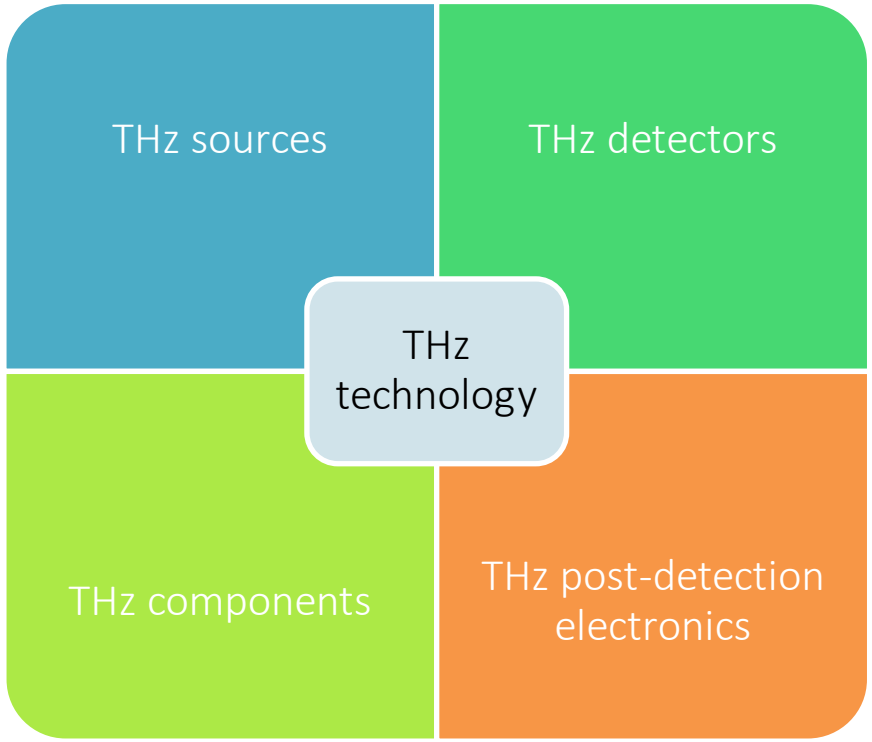
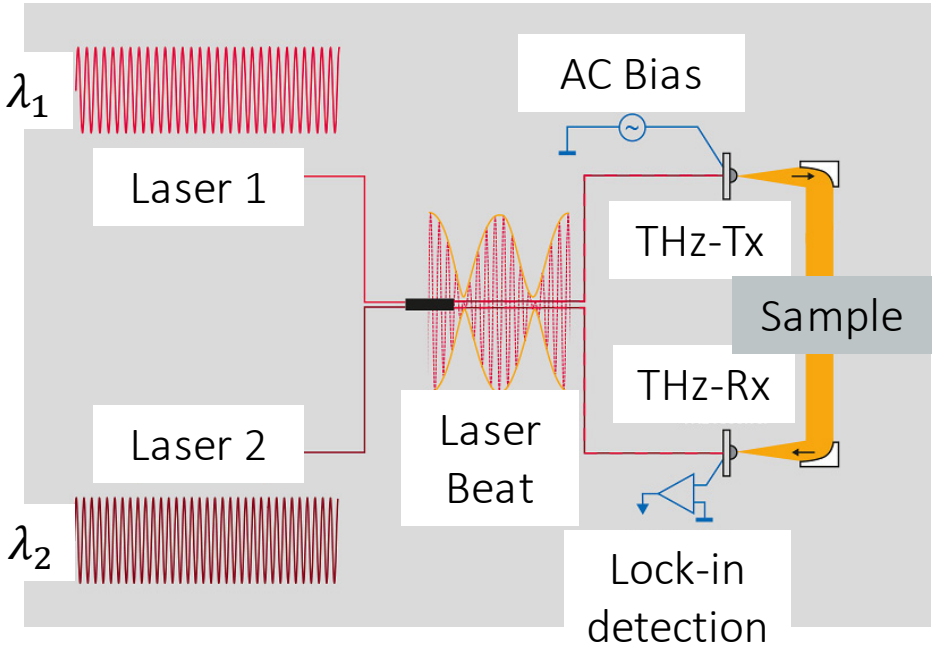


Motivation : development of THz components

Table top system

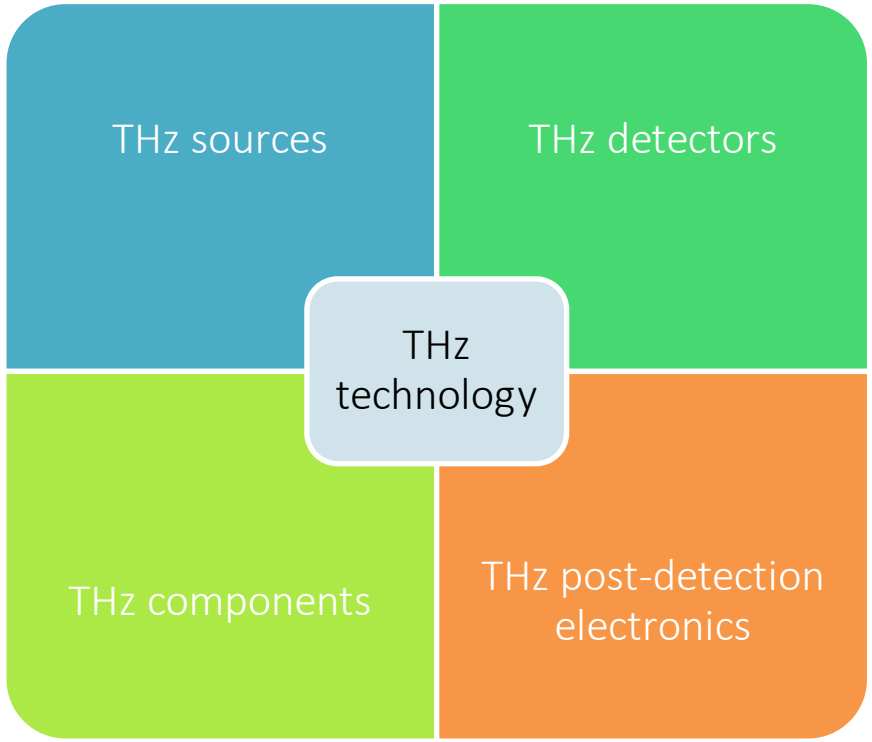




Source : Toptica Photonics AG

THz Power:
100 GHz ~ 100 µW
1 THz ~ 1 µW

Motivation : development of THz components



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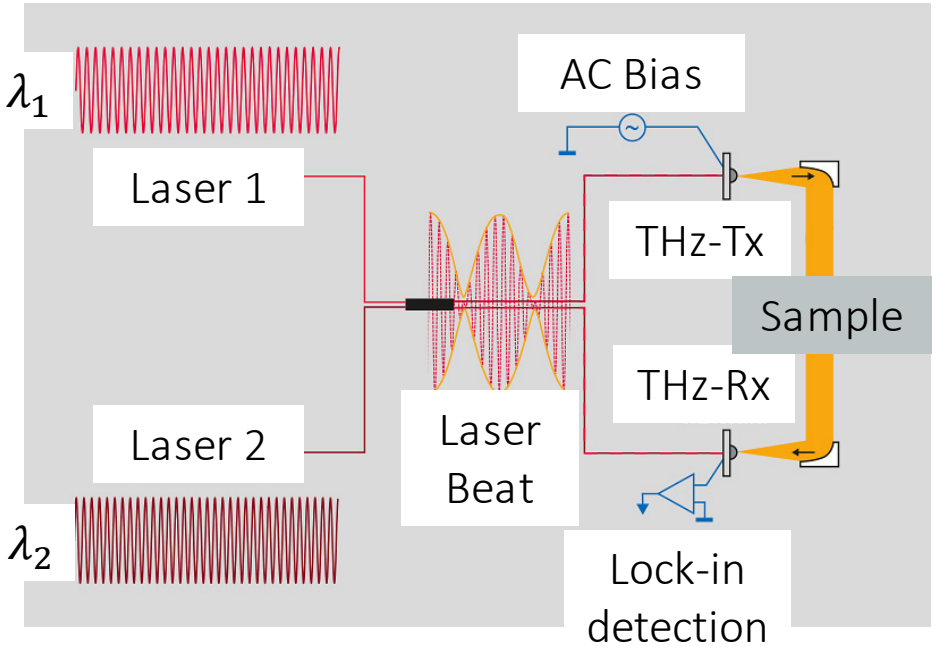

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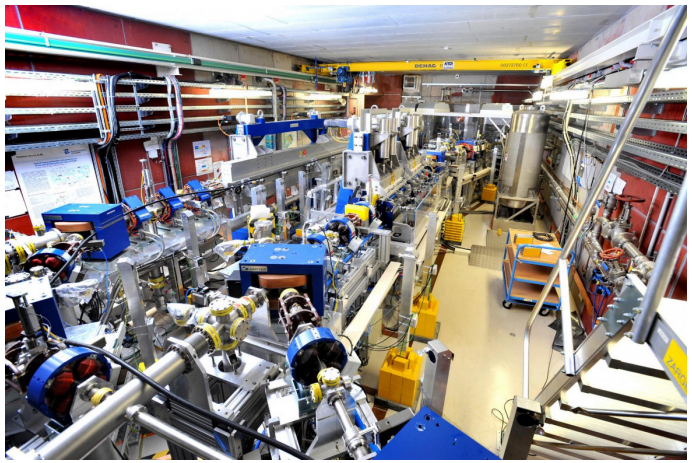
Free electron laser, HZDR, Dresden



Pulse energy: up to 2 µJ
THz Power ~ 1 to 100 W
(depending on wavelength and beam parameters)

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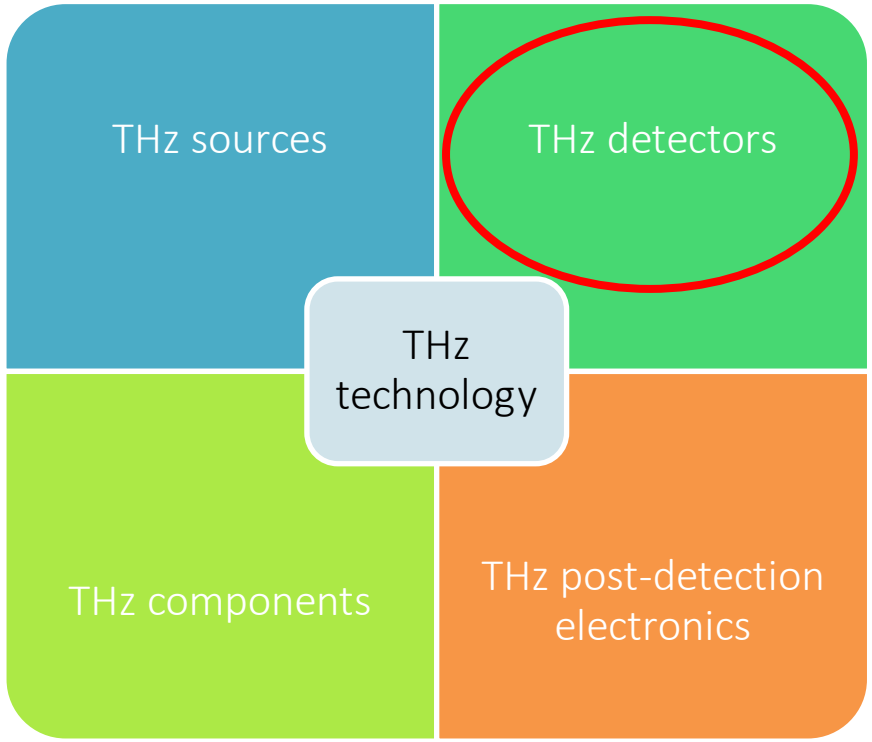

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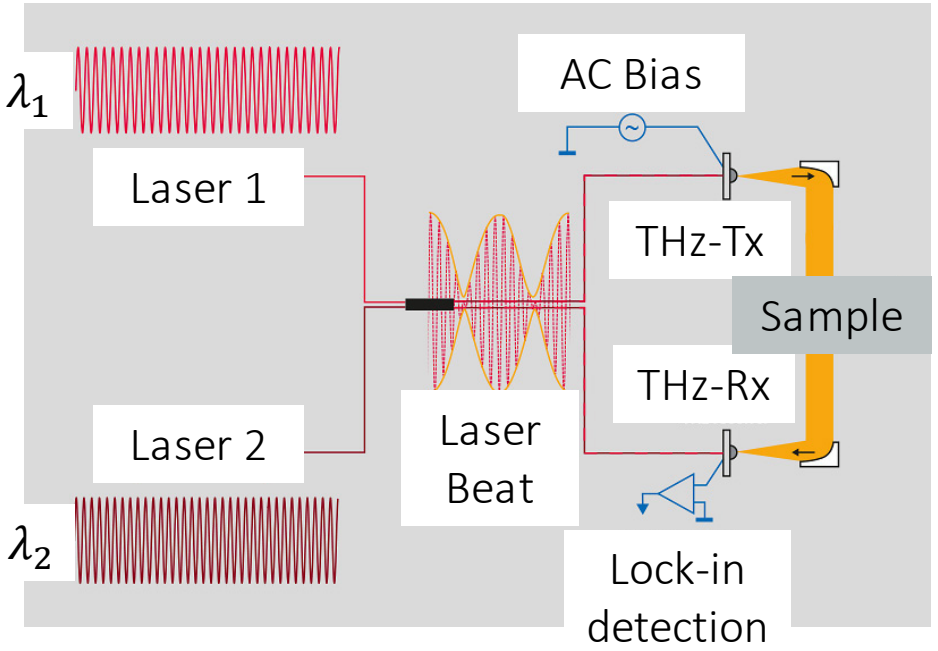

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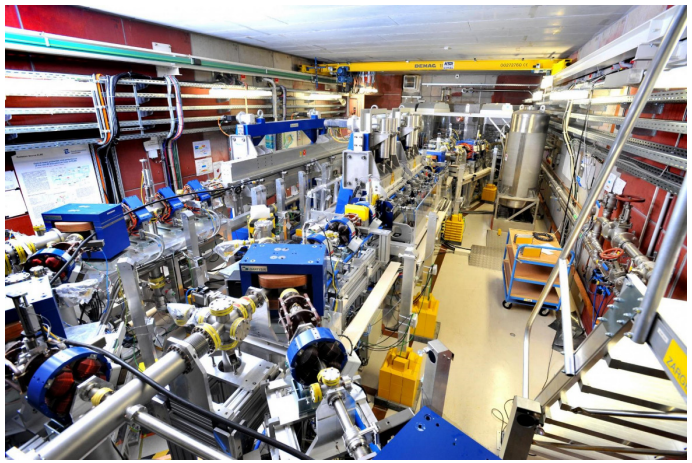

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Suitable for ms scale pulses

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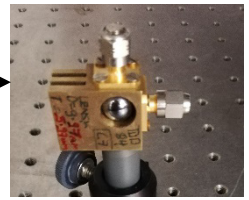

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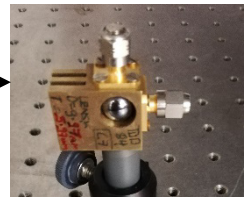
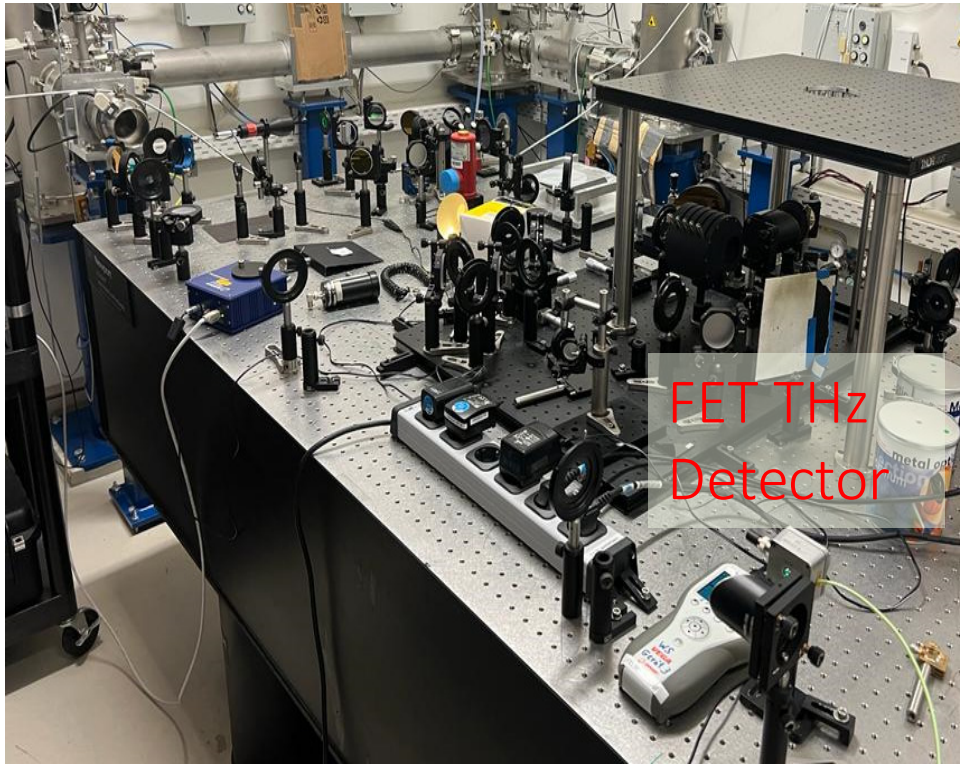


Suitable for higher THz power

Experimental setup at FELBE, HZDR



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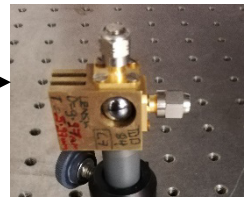

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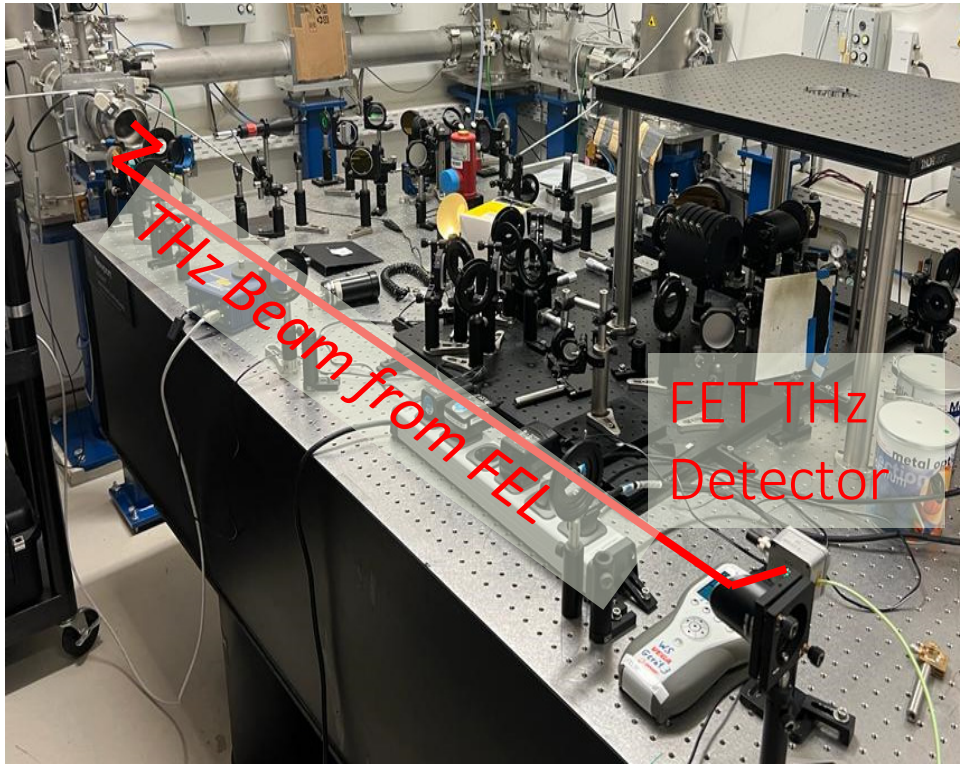

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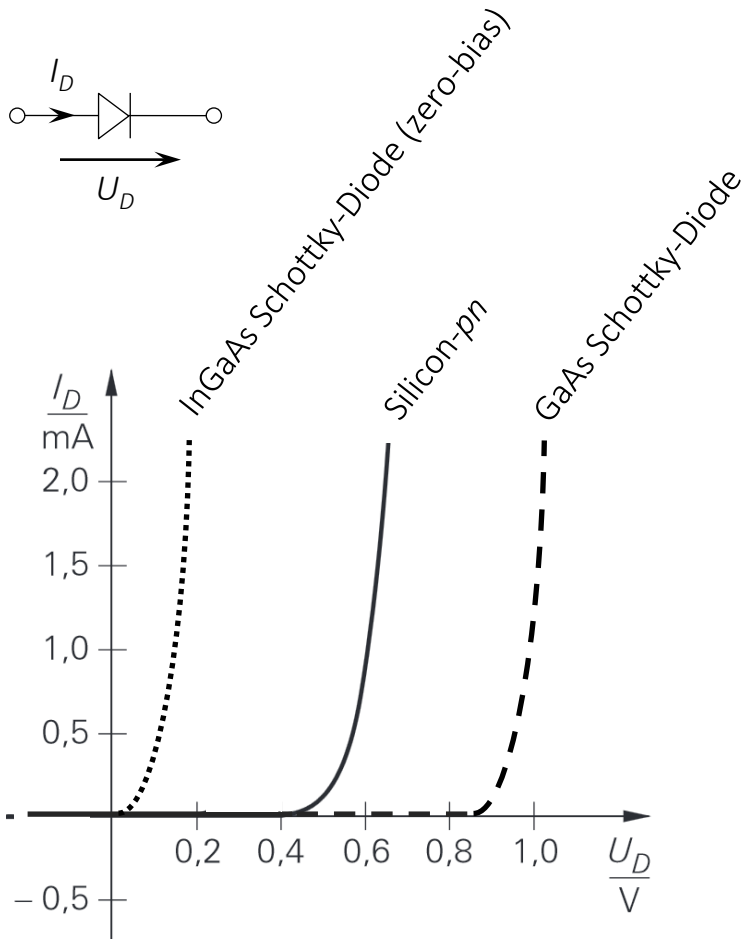
ZBSD based detectors : ZBSD & it's operational principal

- Fast and sensitive room temperature operable THz detectors

- Semiconductor material:
  - GaAs and Silicon: small signal detection with bias voltage, biasing increases noise component.
    Band energy: $\varphi_{\mathrm{GaAs}} = 0.34\ \mathrm{eV}$,
    $\varphi_{\mathrm{Si}} = 1.1\ \mathrm{eV}$
  - InGaAs: zero-bias operation, low noise contribution
    Band energy: $\varphi_{\mathrm{InGaAs}} = 0.75\ \mathrm{eV}$



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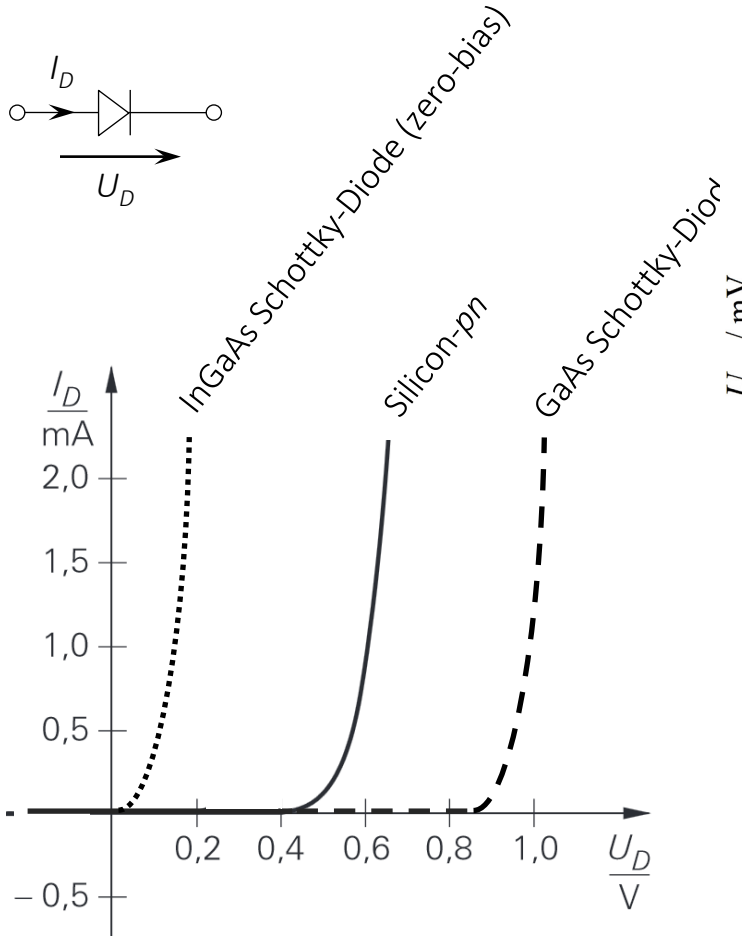

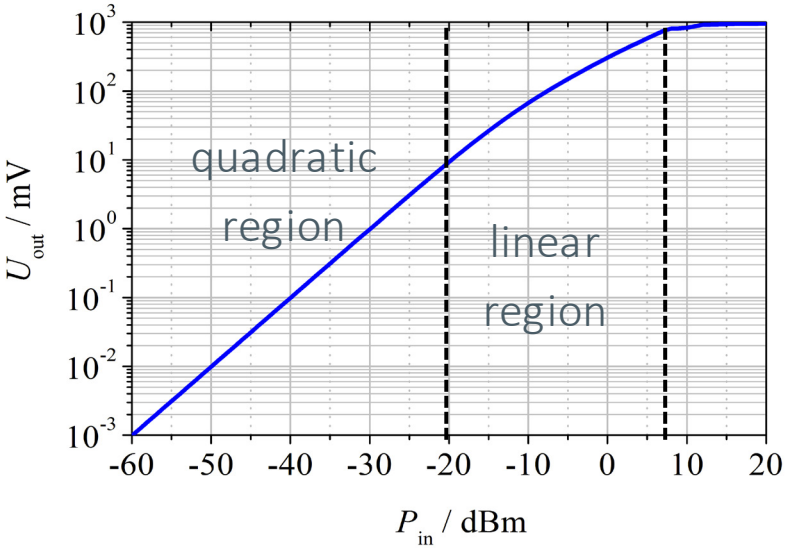

quadratic region

$$U_{\mathrm{out}} \propto U_{\mathrm{in}}^2 \propto P_{\mathrm{in}}$$

linear region

$$U_{\mathrm{out}} \propto U_{\mathrm{in}} \propto \sqrt{P_{\mathrm{in}}}$$

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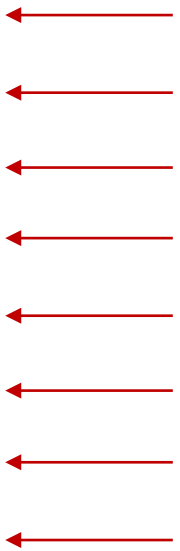

$$U_0(t) = U_0 \cos(\omega t)$$

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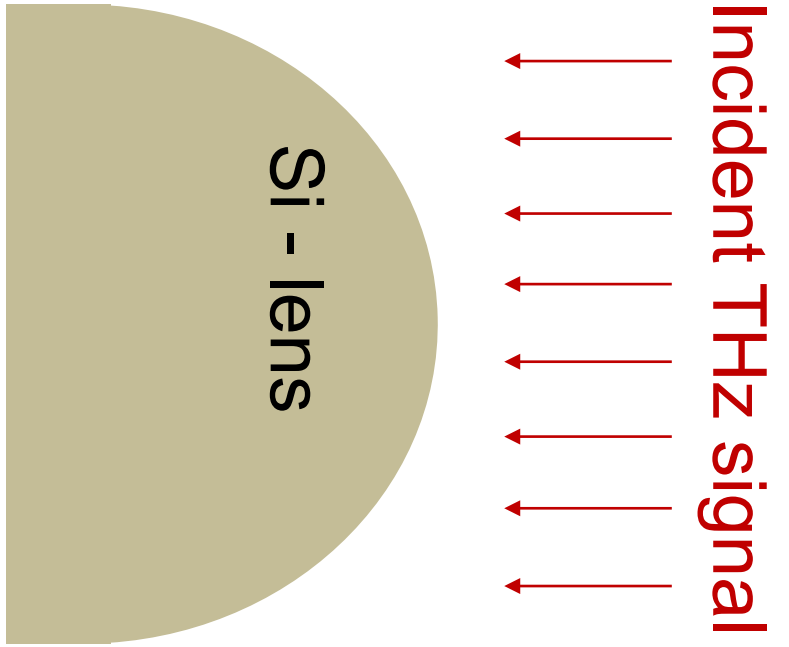

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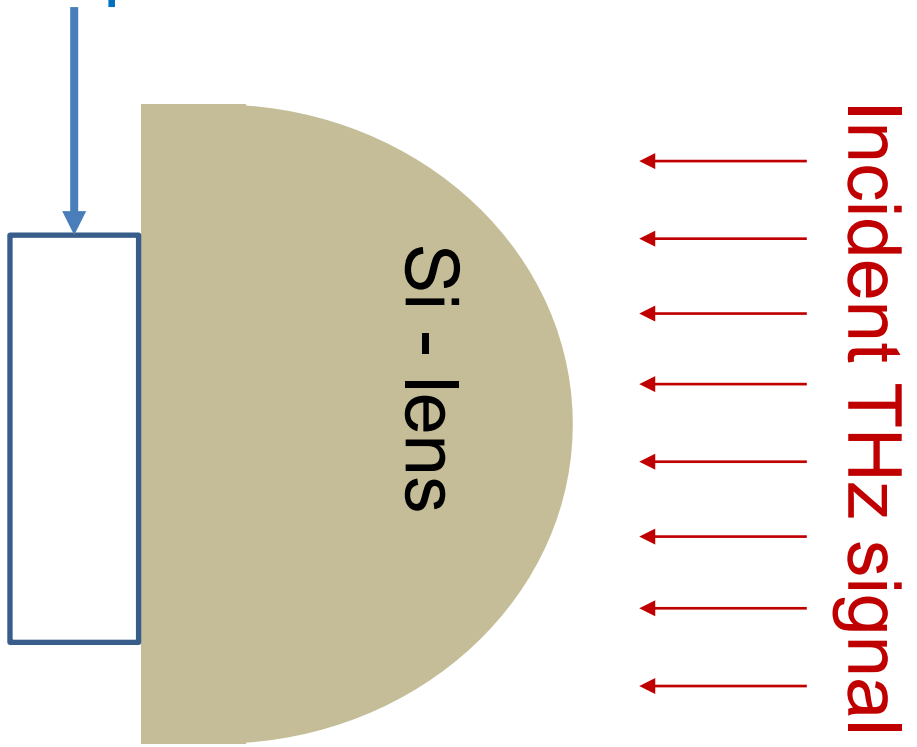
Antenna coupled ZBSD



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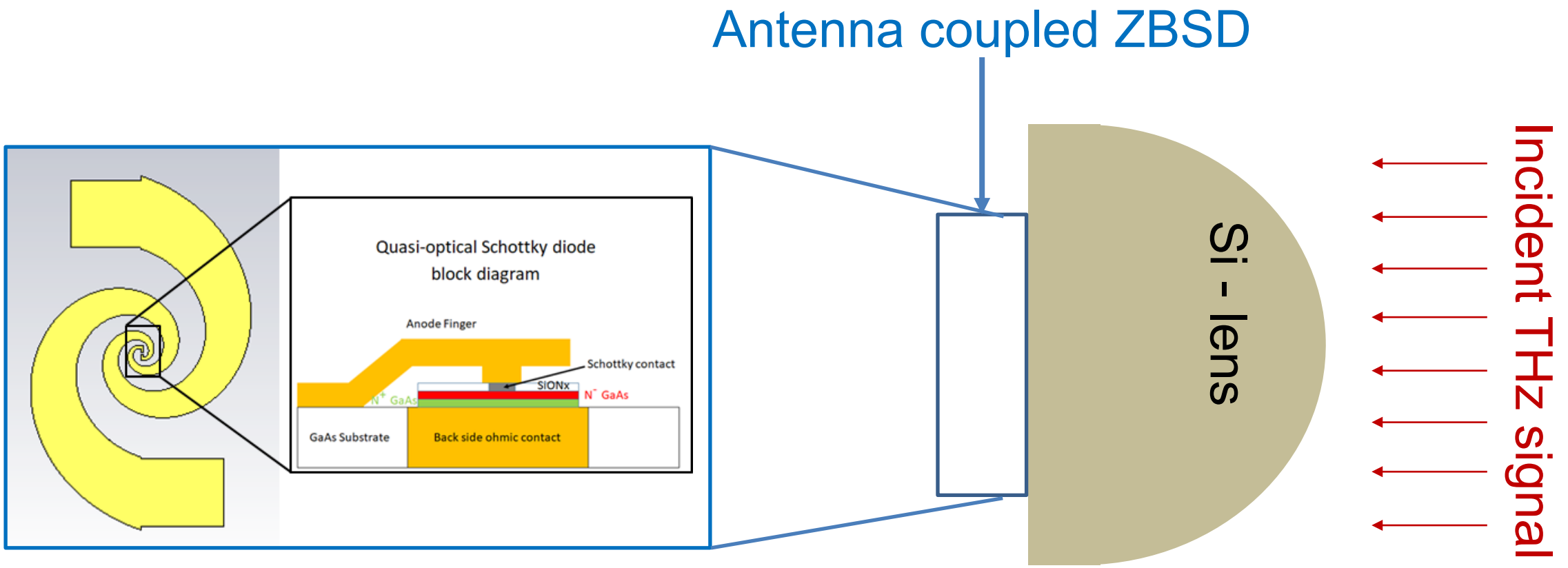

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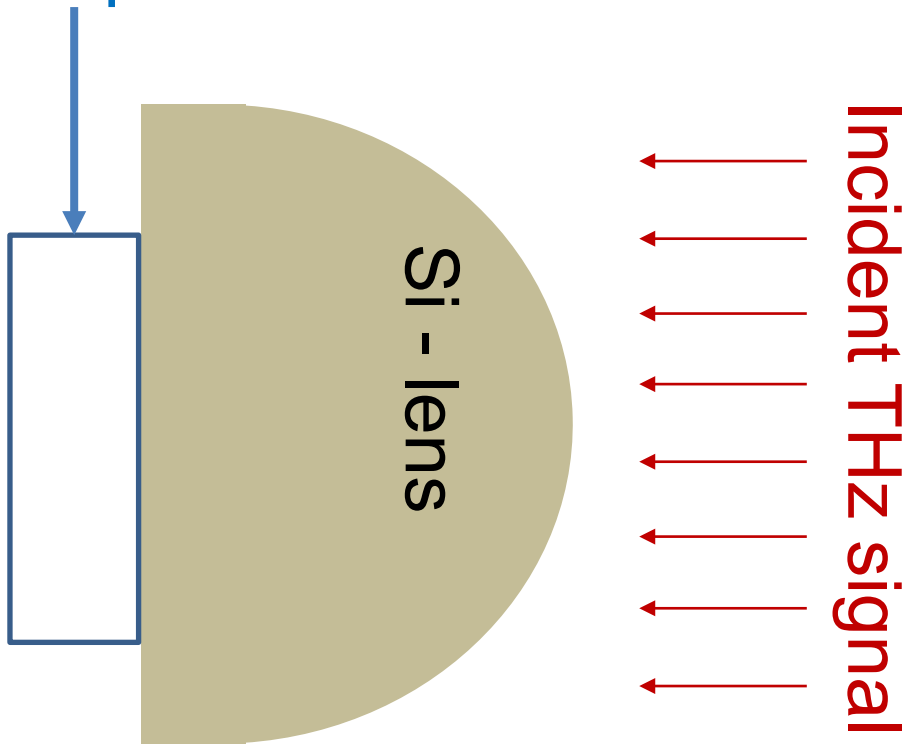

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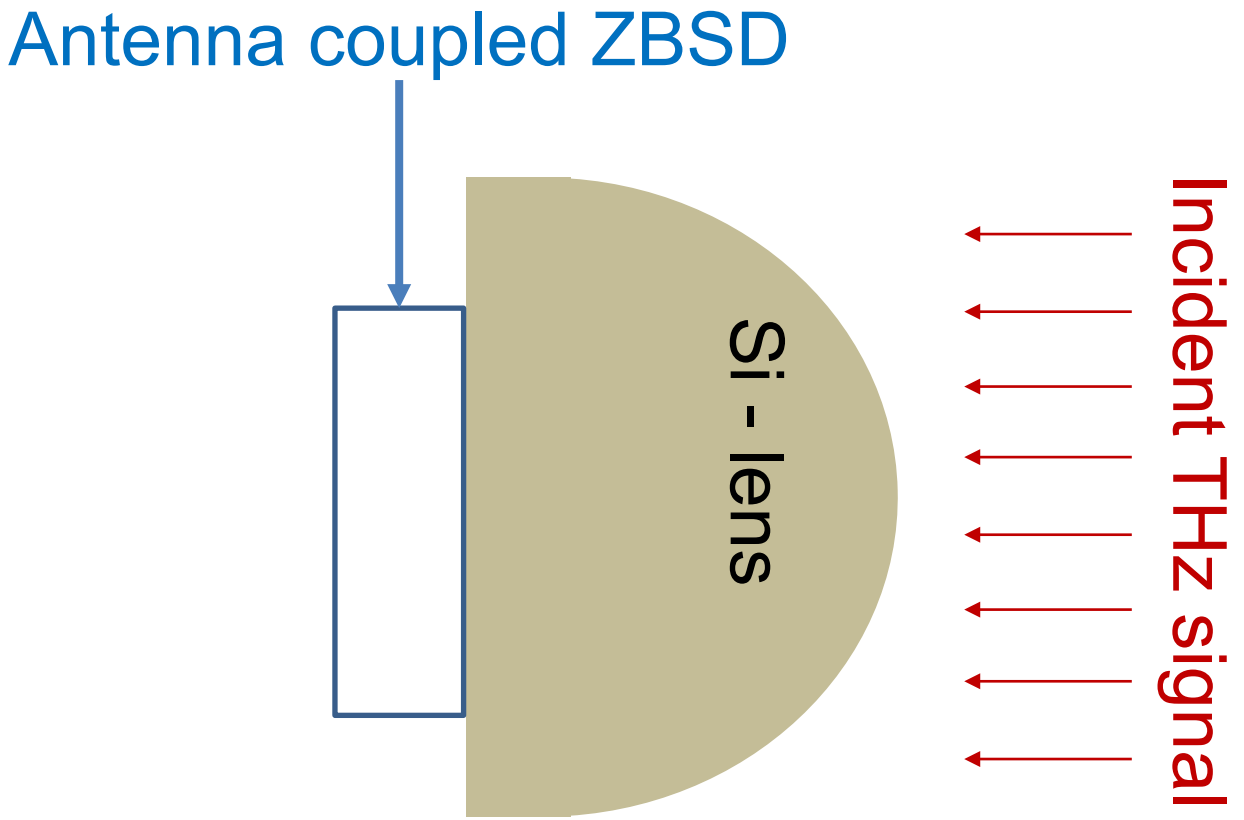
ZBSD based detectors : ZBSD & it's operational principal

- By using Taylor series expansion up-to 2nd order, diode current is given by:



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$$I_0\,(t) = A_1 U_0 \cos(\omega t) + A_2 {U_0}^2 \cos(\omega t) + \cdots$$

$$= A_1 U_0 \cos(\omega t) + \frac{1}{2} A_2 {U_0}^2 + \frac{1}{2} A_2 U_0 \cos(2\omega t)$$

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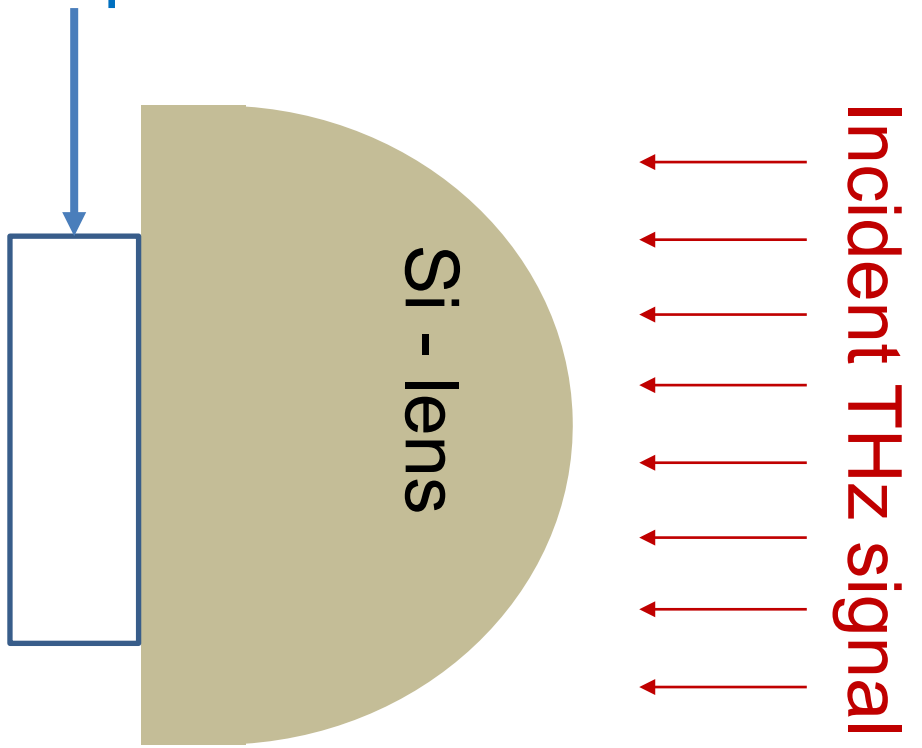

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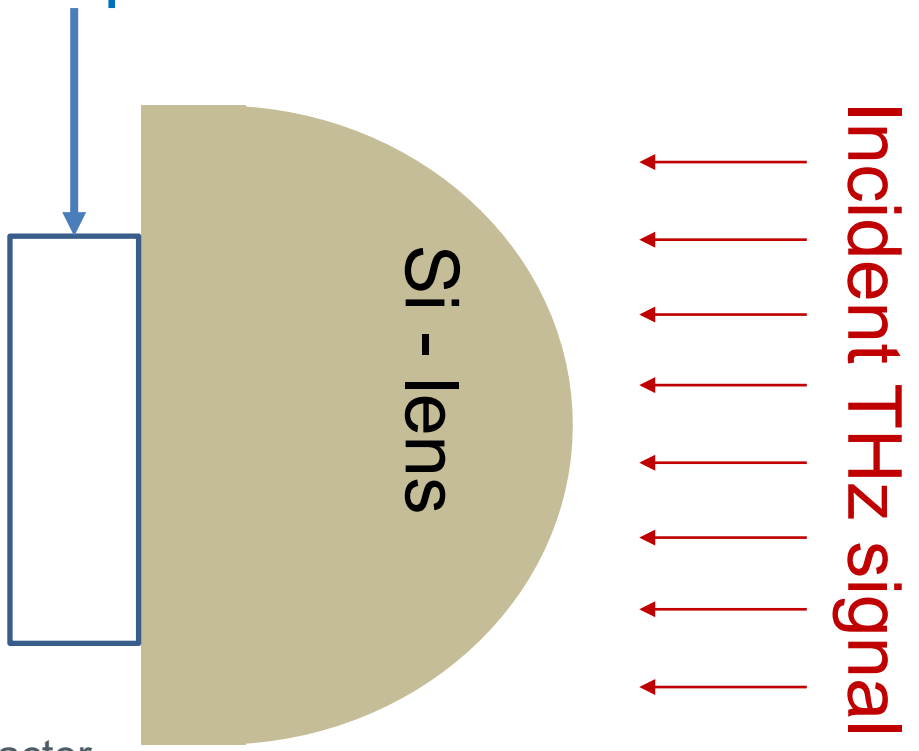
$$where, A_1 = \frac{1}{R_{diff}}$$

$$A_2 = \frac{1}{2 \cdot R_{diff} \cdot \eta \cdot U_T}$$

Antenna coupled ZBSD



η : ZBSD ideality factor
R_{diff} : ZBSD differential resistance
U_T : InGaAs thermal voltage

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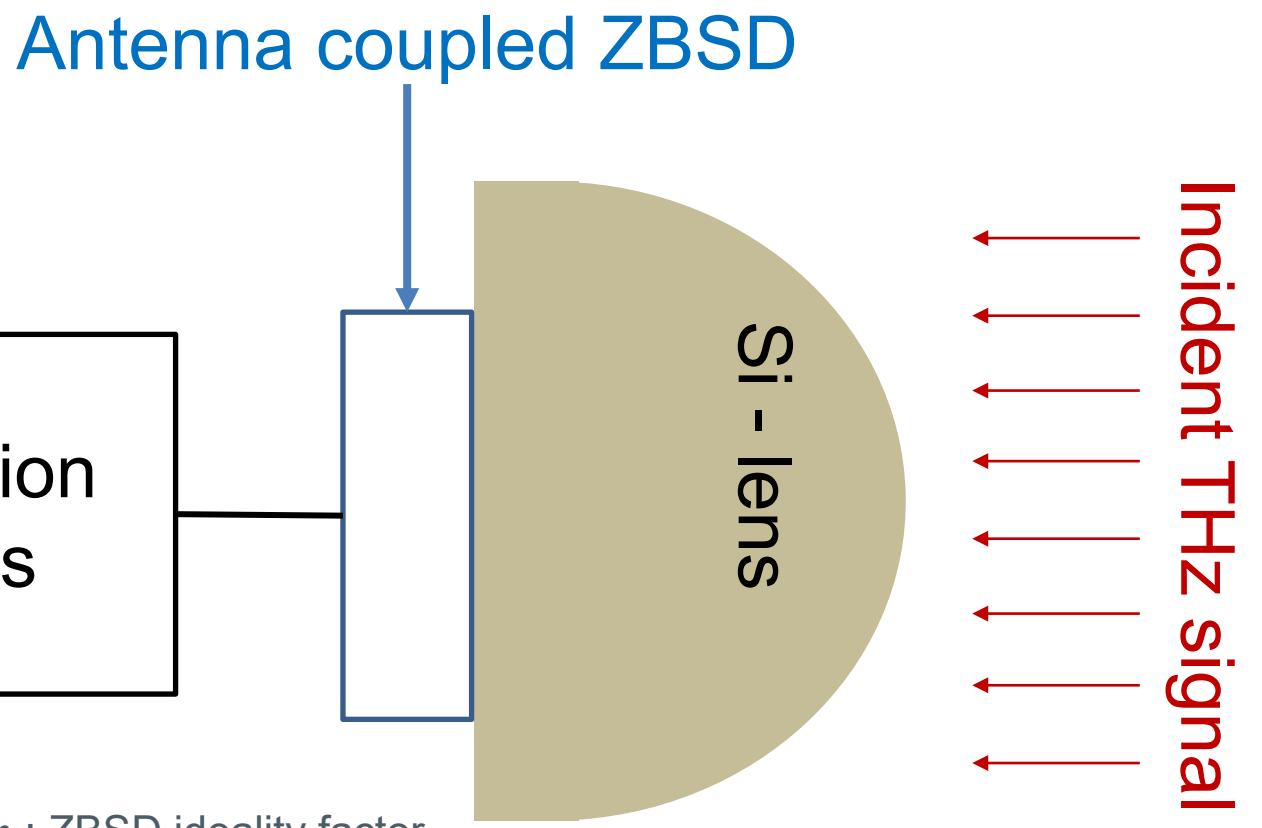
- The rectified signal is read-out by the post-detection electronics
- The term A_2 is directly proportional to detector responsivity because $I_{DC} = A_2 {U_0}^2$



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ZBSD based detectors : antenna analysis

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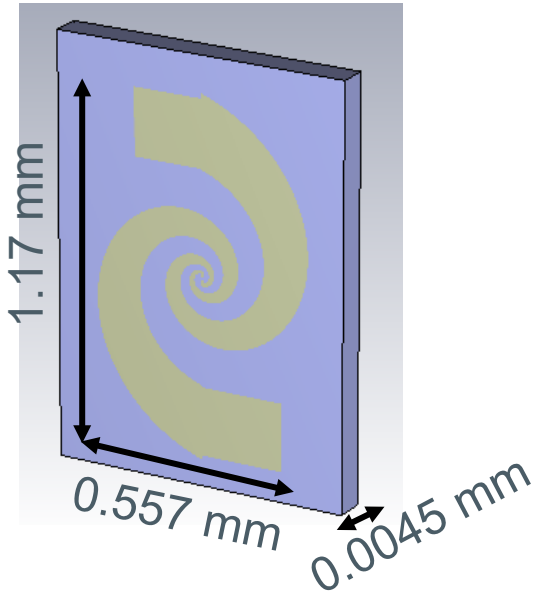
- Investigation on antenna parameters with variable dielectric constant



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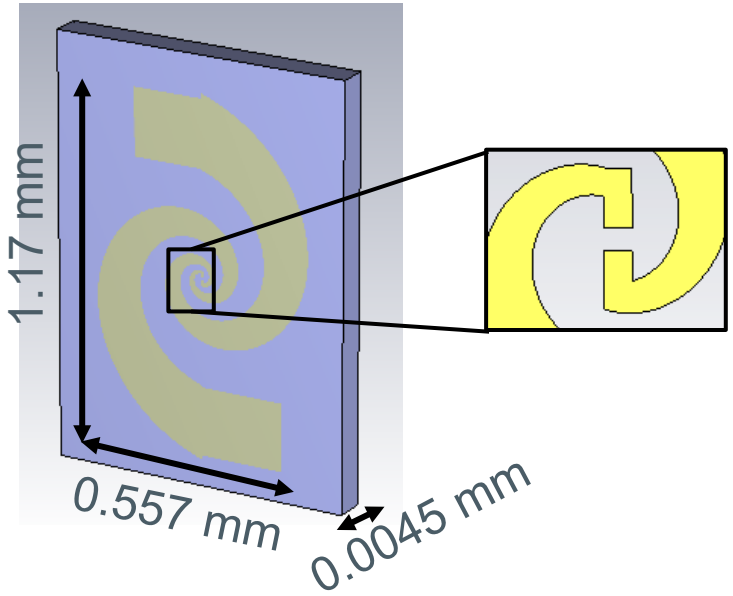

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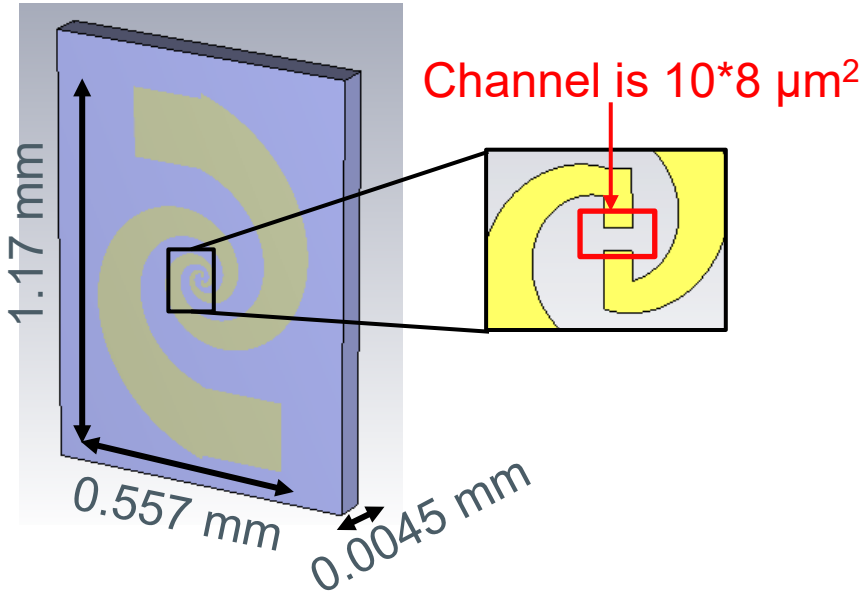
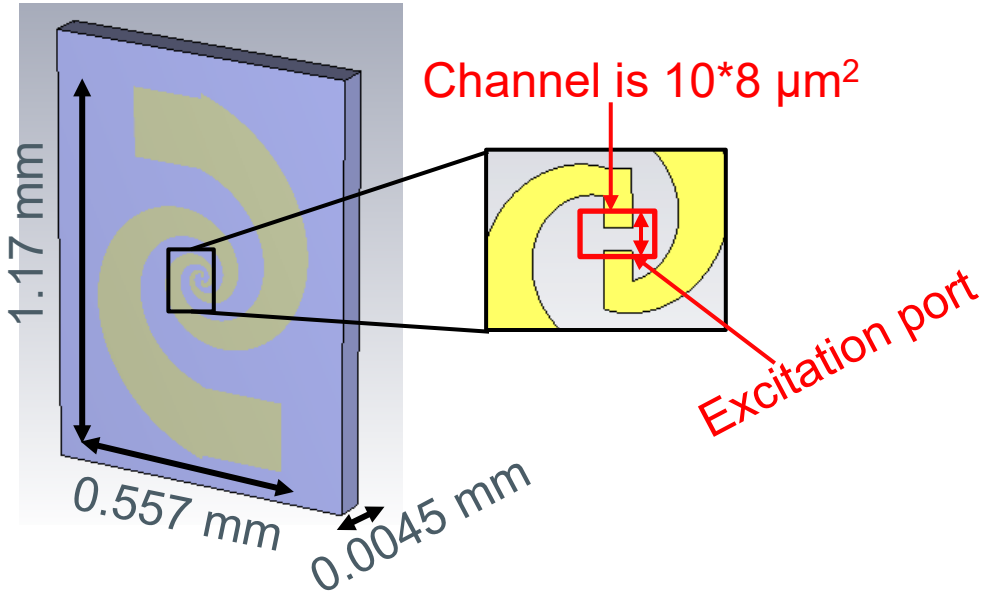


ZBSD based detectors : antenna analysis

Antenna S- parameters

- Investigation on antenna parameters with variable dielectric constant



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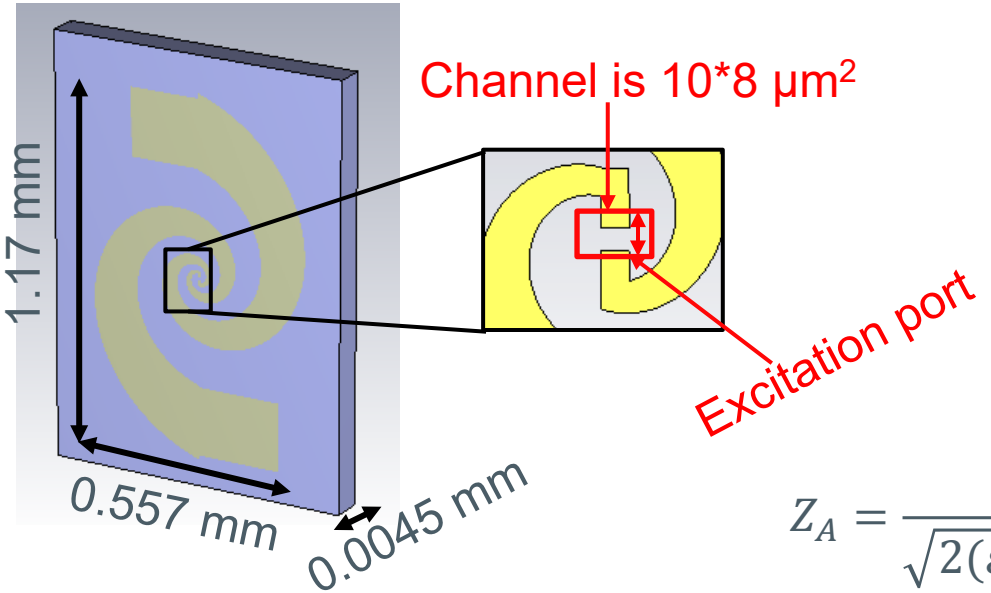

$$Z_A = \frac{Z_0}{\sqrt{2(\varepsilon_1 + \varepsilon_2)}}$$

Z_A : Antenna radiation impedance
Z_0 : Impedance in free space (377 Ohm)
ε_1 : Air dielectric constant
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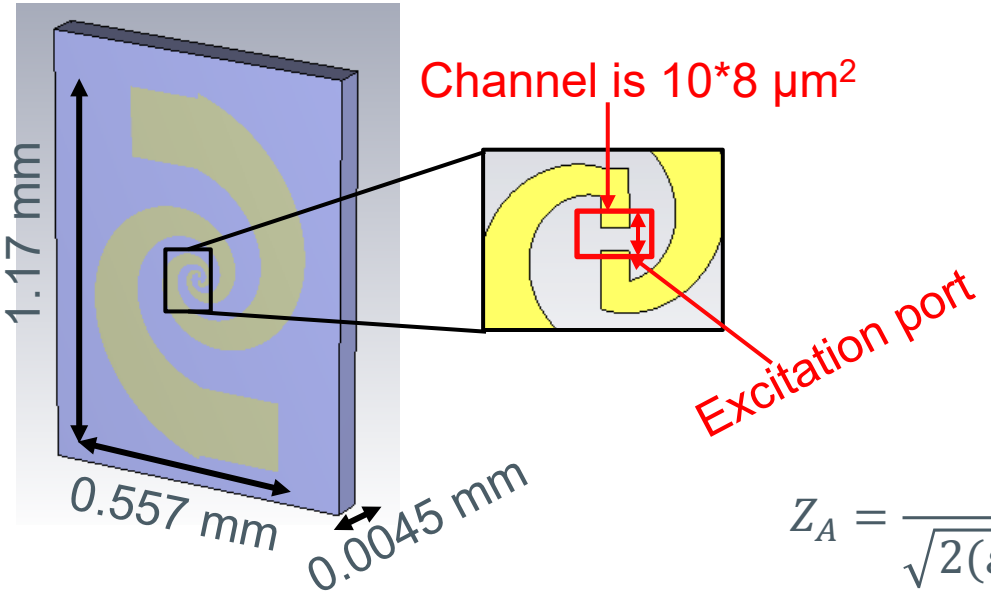

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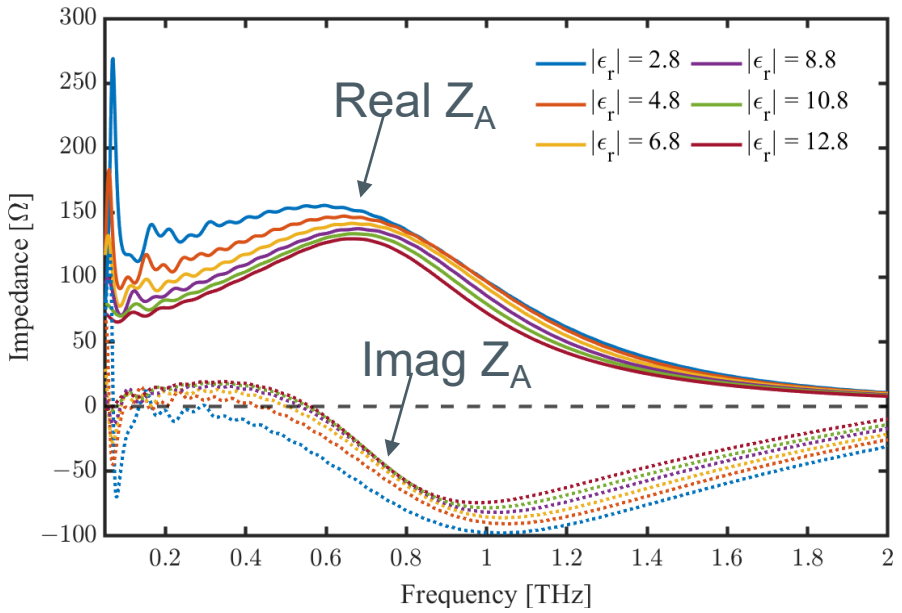

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ZBSD based detectors : detector fabrication

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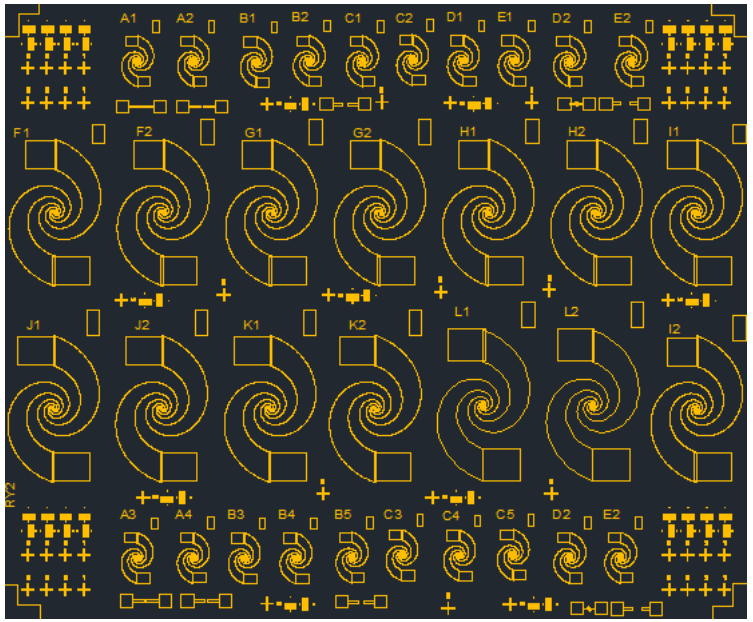
Mask design



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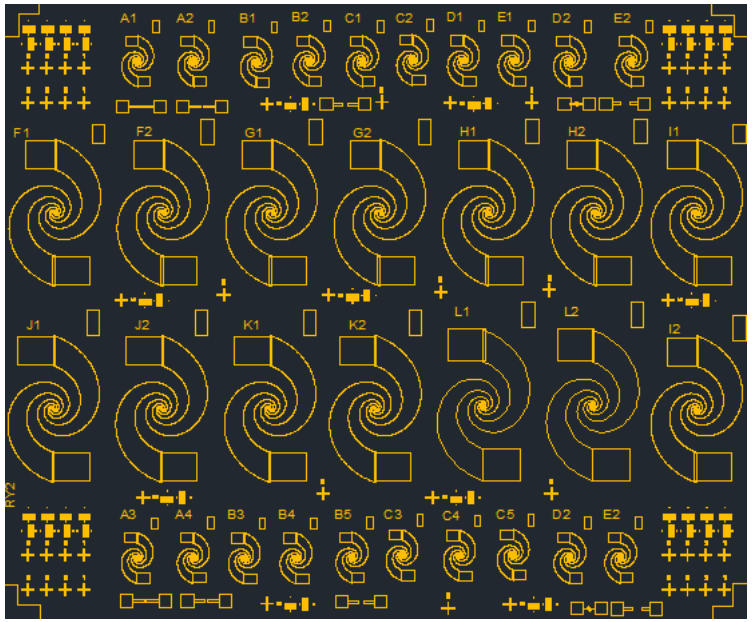
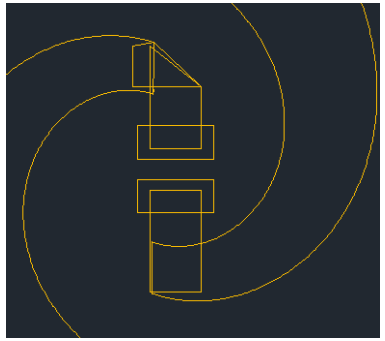


Zoomed



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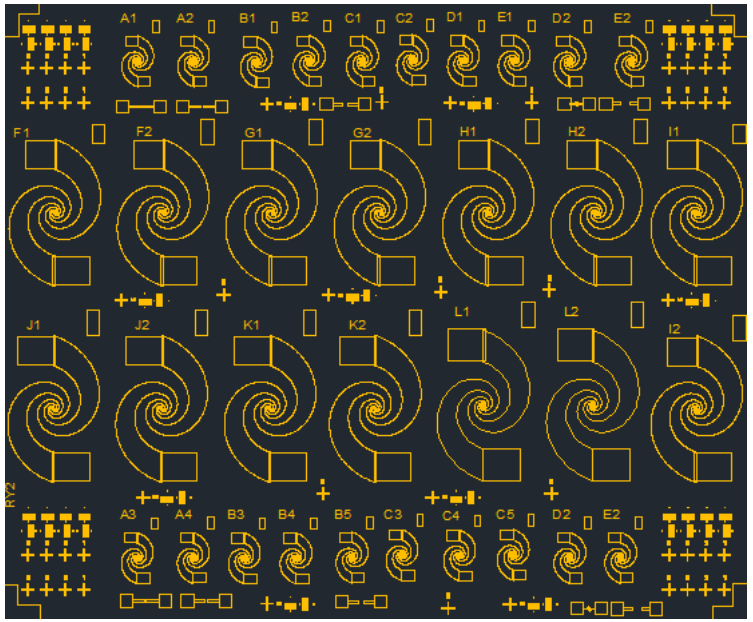
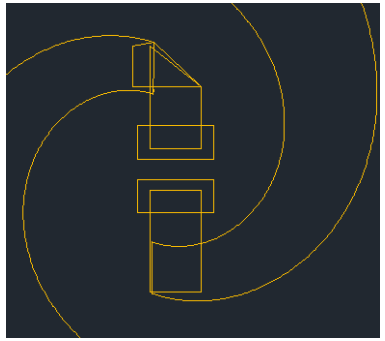
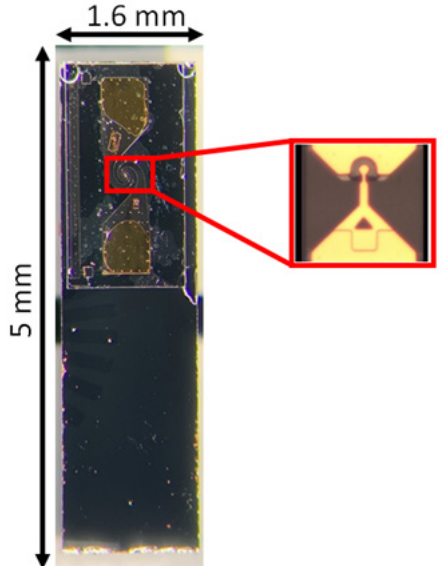


Zoomed

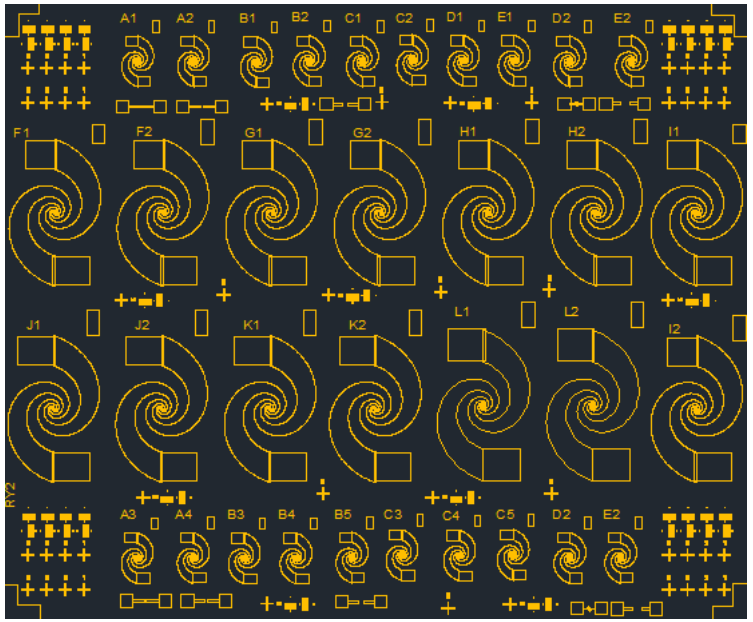


Device fabrication



ZBSD based detectors : detector fabrication

Mask design



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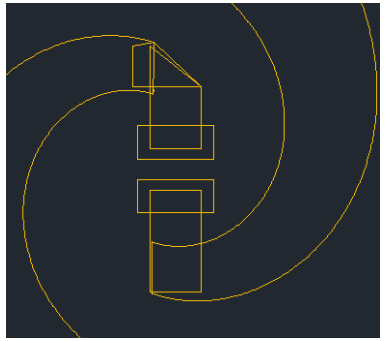

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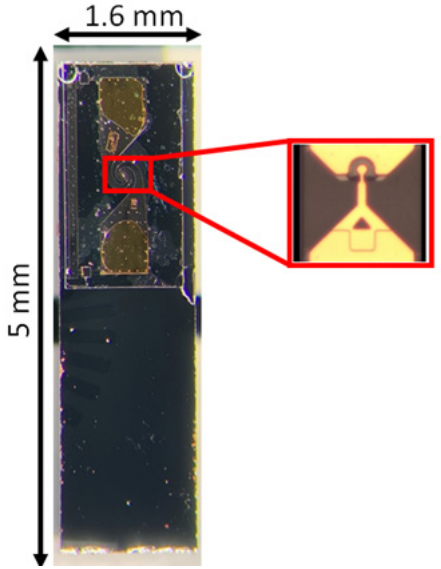
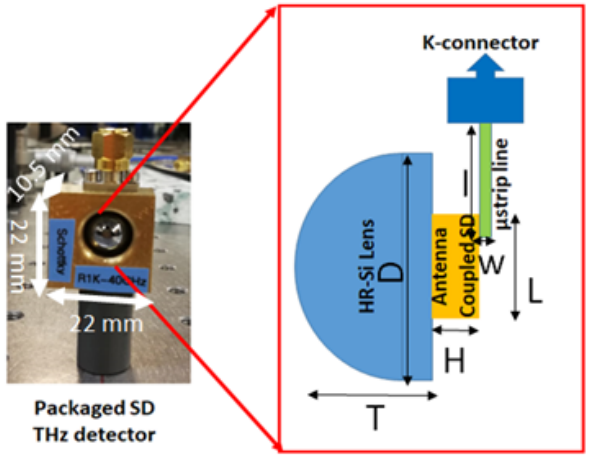


Detector packaging



Abbreviations	Length (mm)
Lens thickness (T)	5.95
Lens diameter (D)	10
Si substrate thickness (H)	0.5
Si substrate length (L)	5
Microstrip line width (w)	0.96
Microstrip line length (l)	15

R. Yadav, et. al, Sensors 2023, *23*, 3469.

Paper ID: WE1C03

ZBSD based detectors : in-house characterization

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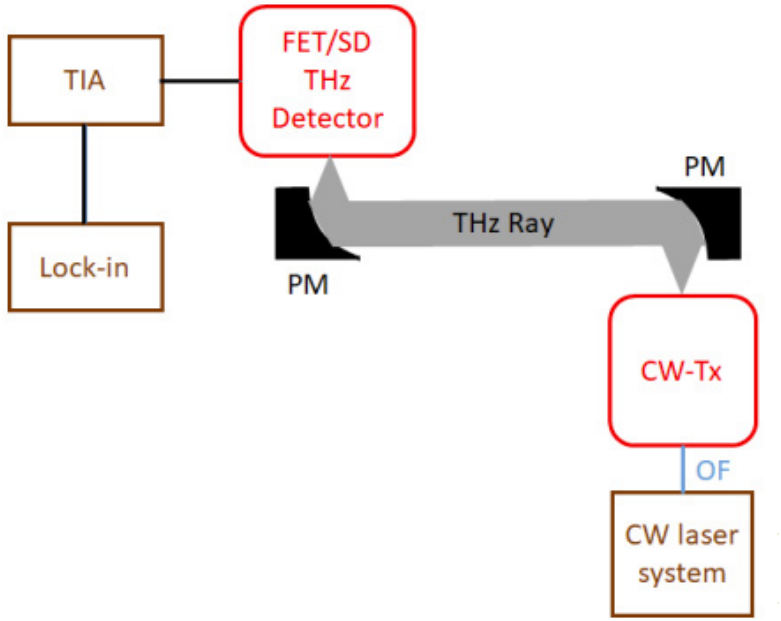
- Experimental set-up



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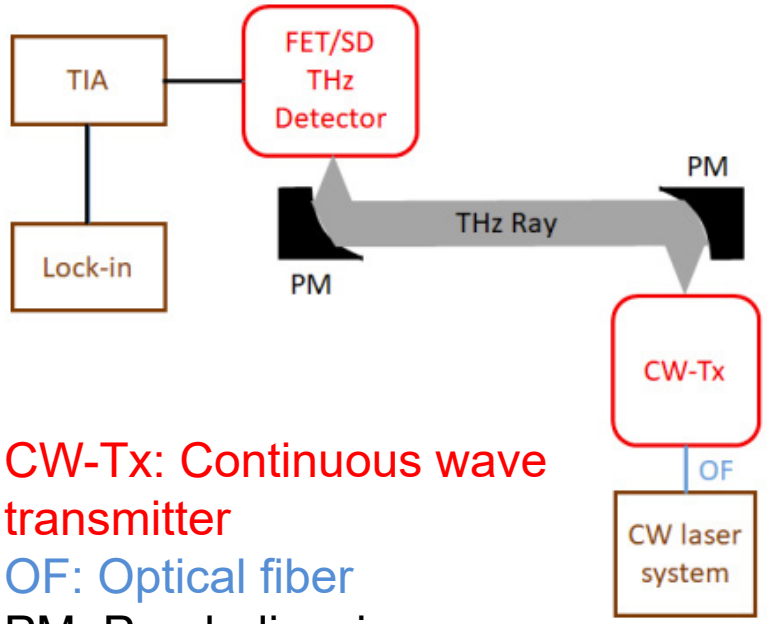

CW-Tx: Continuous wave transmitter
OF: Optical fiber
PM: Parabolic mirror
SD: Schottky diode detector
TIA: Trans-impedance amplifier

- Toptica TeraScan 1550
- THz Power:
  100 GHz ~ 100 µW
  1 THz ~ 1 µW

$$Dynamic\ range\ (dB) = 20 \times log_{10}\left(\frac{Rectified\ signal\ by\ device}{Noise\ floor\ of\ device}\right)$$

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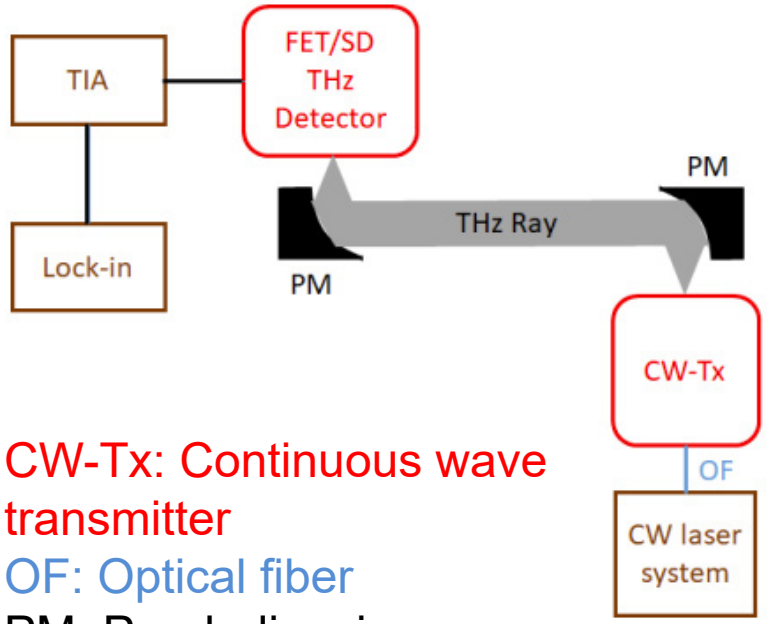

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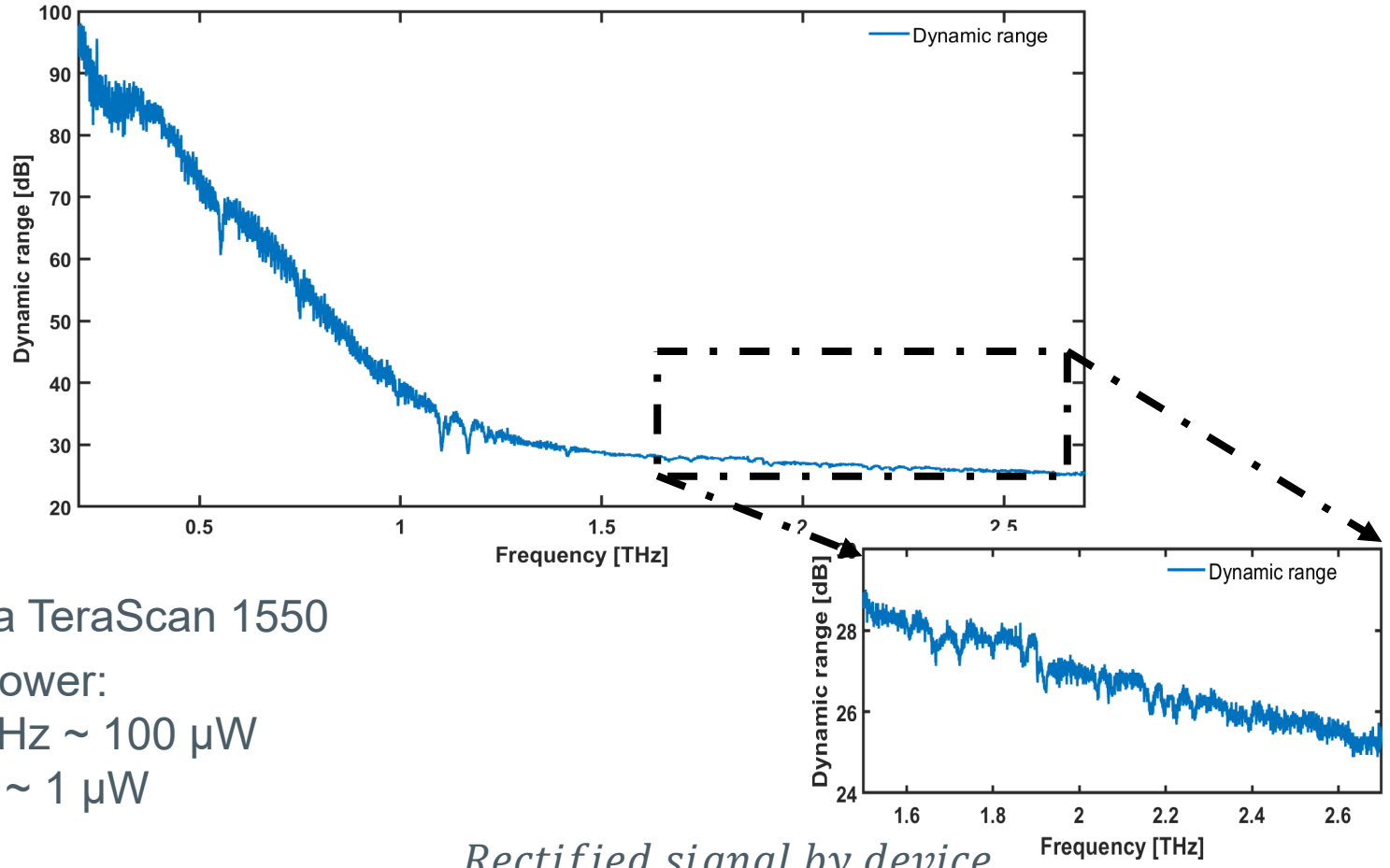

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R. Yadav, et. al, Sensors 2023, ***23***, 3469.

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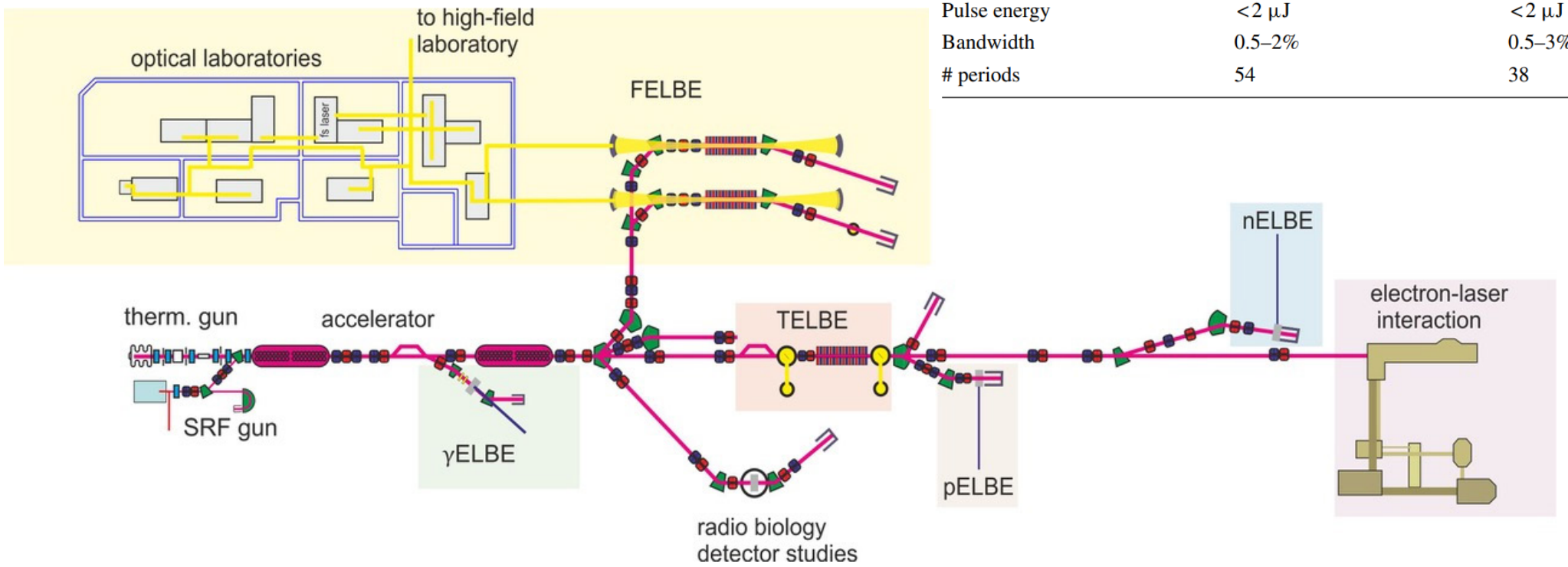
ZBSD based detectors : FEL at ELBE, HZDR, Germany

	FELBE U37	FELBE U100	TELBE U300
Wavelength	5–40 μm	18–250 μm	120–3000 μm
Frequency	7.5–60 THz	1.2–17 THz	0.1–2.5 THz
Repetition rate	13 MHz	13 MHz	0–500 kHz
Pulse energy	<2 μJ	<2 μJ	<10 μJ
Bandwidth	0.5–2%	0.5–3%	10–20%
# periods	54	38	8



M. Helm, et. al, Eur. Phys. J. Plus **138**, 158 (2023).

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ZBSD based detectors : with FELBE characterization

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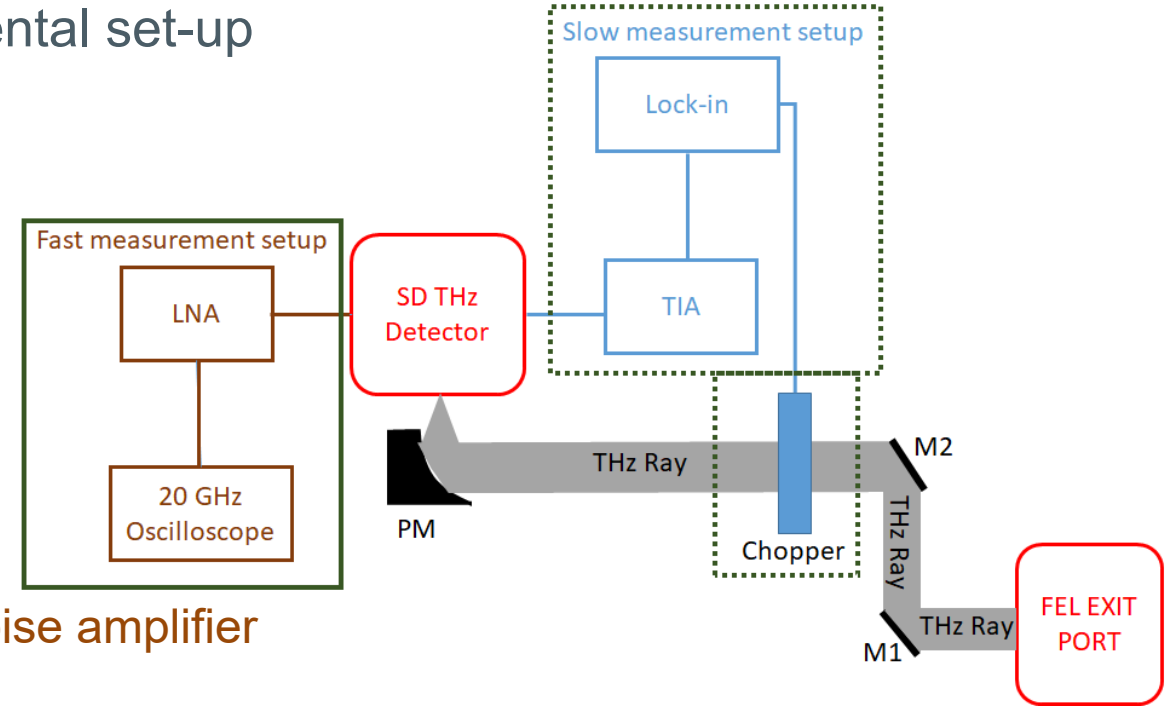

LNA: Low noise amplifier
M: Mirror
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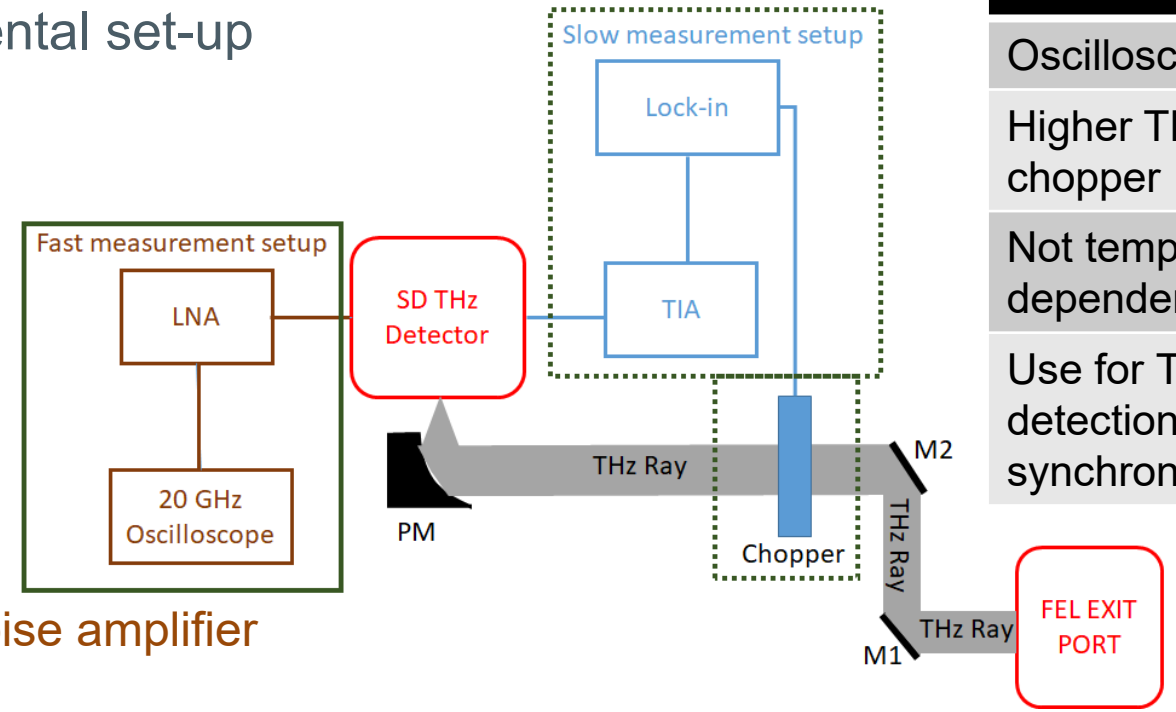

Fast measurements	Slow measurements
Oscilloscope	Lock-in amplifier with chopper
Higher THz power as no chopper	Lower THz power due to chopper
Not temperature dependent	Temperature dependent (Bolometric effects)
Use for THz pulse detection and synchronization	Use to investigate detectors working principle and developments

LNA: Low noise amplifier
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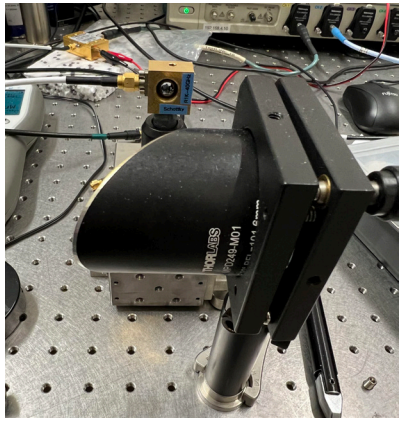

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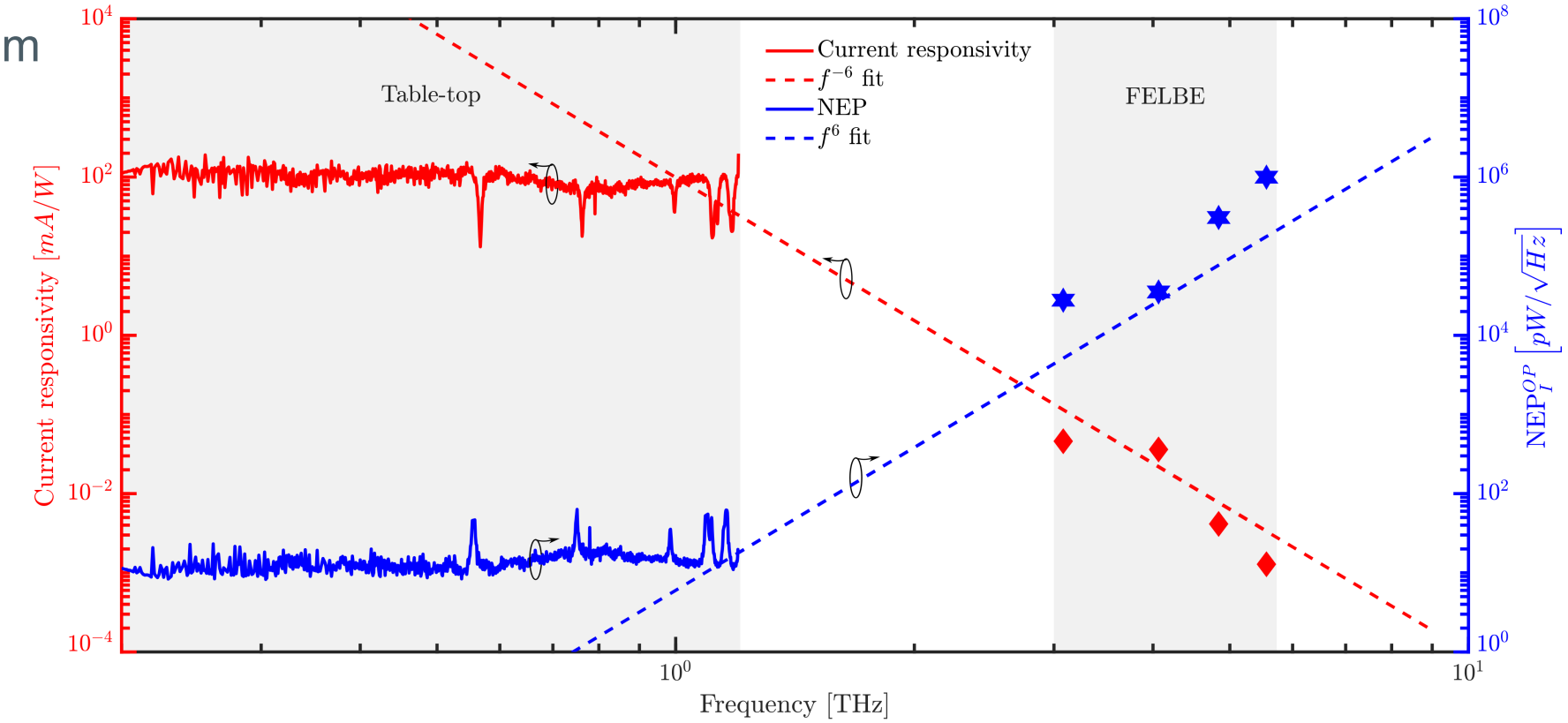
ZBSD based detectors : with FELBE characterization

- Slow measurements
- Responsivity of $10^2 \frac{\mathrm{mA}}{\mathrm{W}}$ from 0.2 to 0.6 THz
- NEP of $10 \frac{\mathrm{pW}}{\sqrt{\mathrm{Hz}}}$ from 0.2 to 0.6 THz
- Responsivity roll-off f^{-6}

Comparison of in-house (table-top) and FELBE measurements



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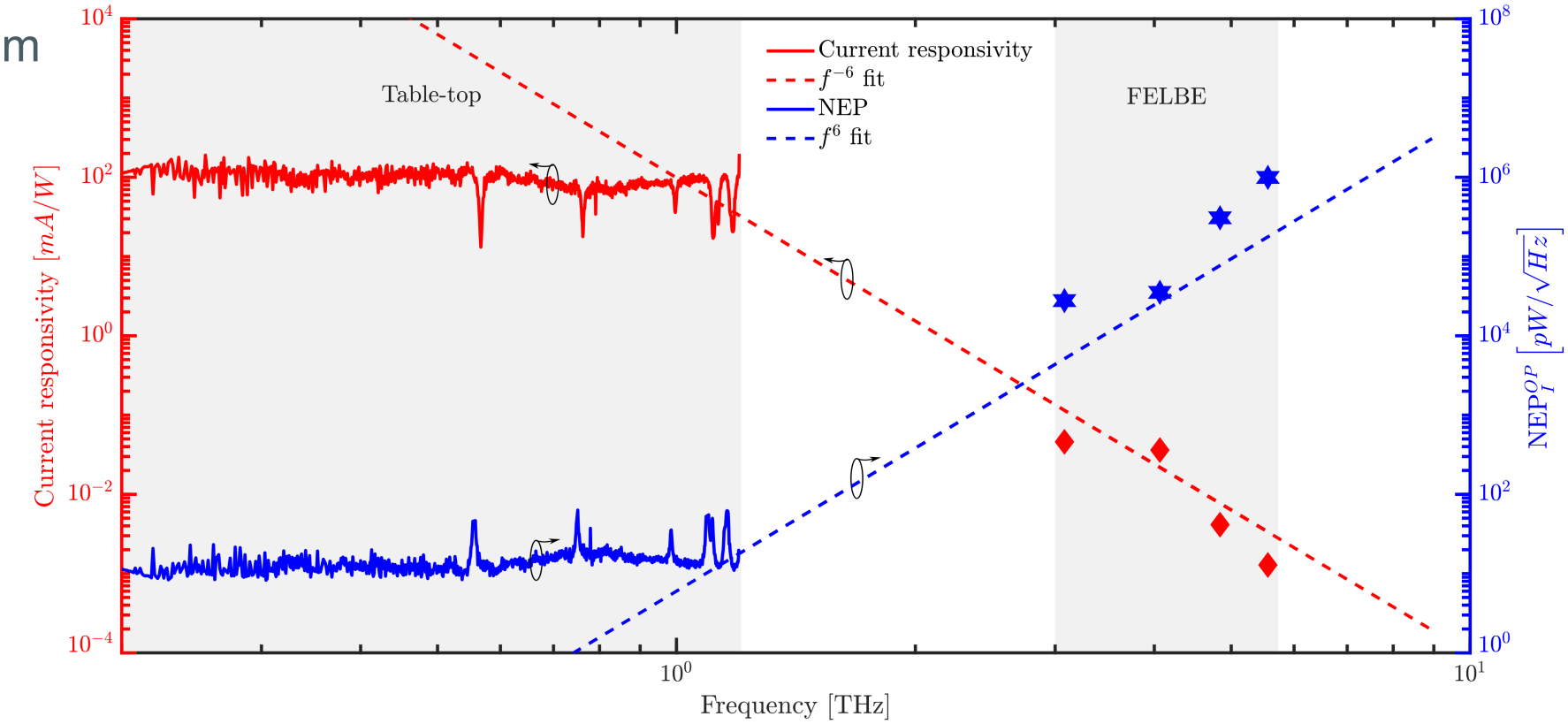

Note: Table-top (in-house results here are not with same device as in slide 10)

R. Yadav, et. al, Sensors 2023, ***23***, 3469.

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ZBSD based detectors : with FELBE characterization

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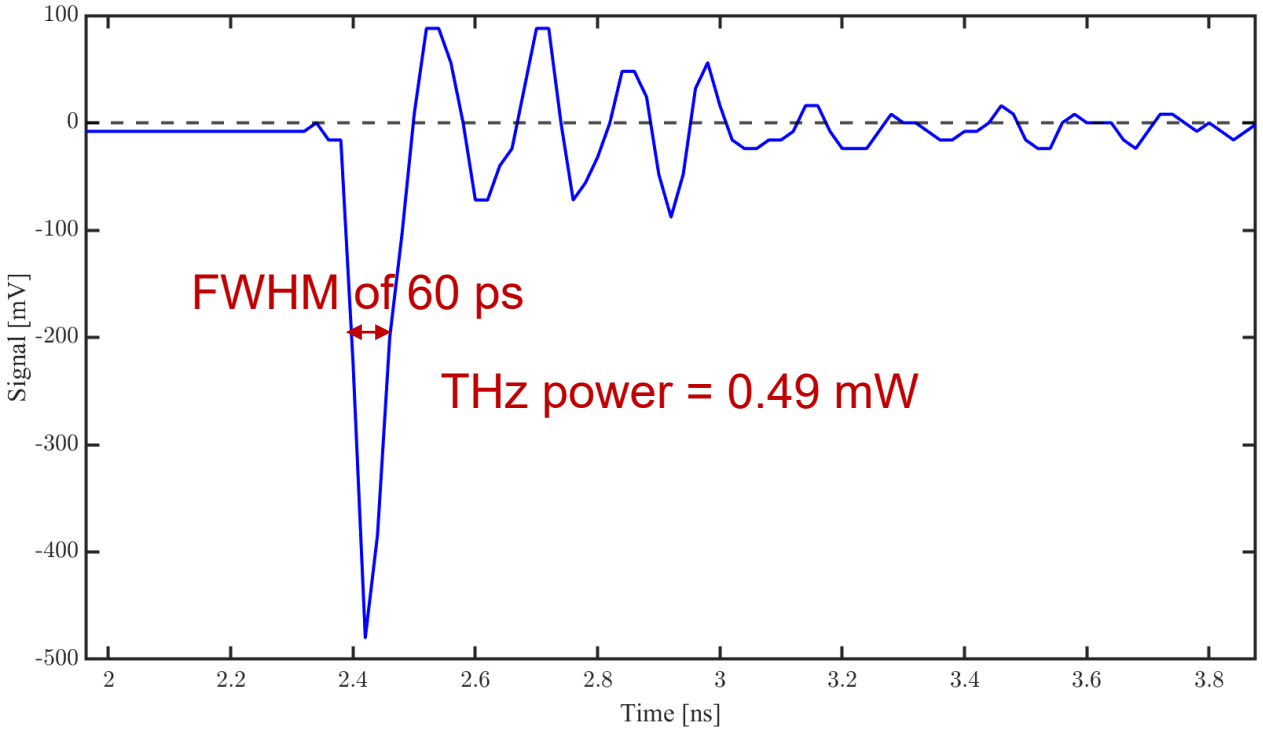
ZBSD based detectors : with FELBE characterization

Fast measurement at 1.99 THz with FEL



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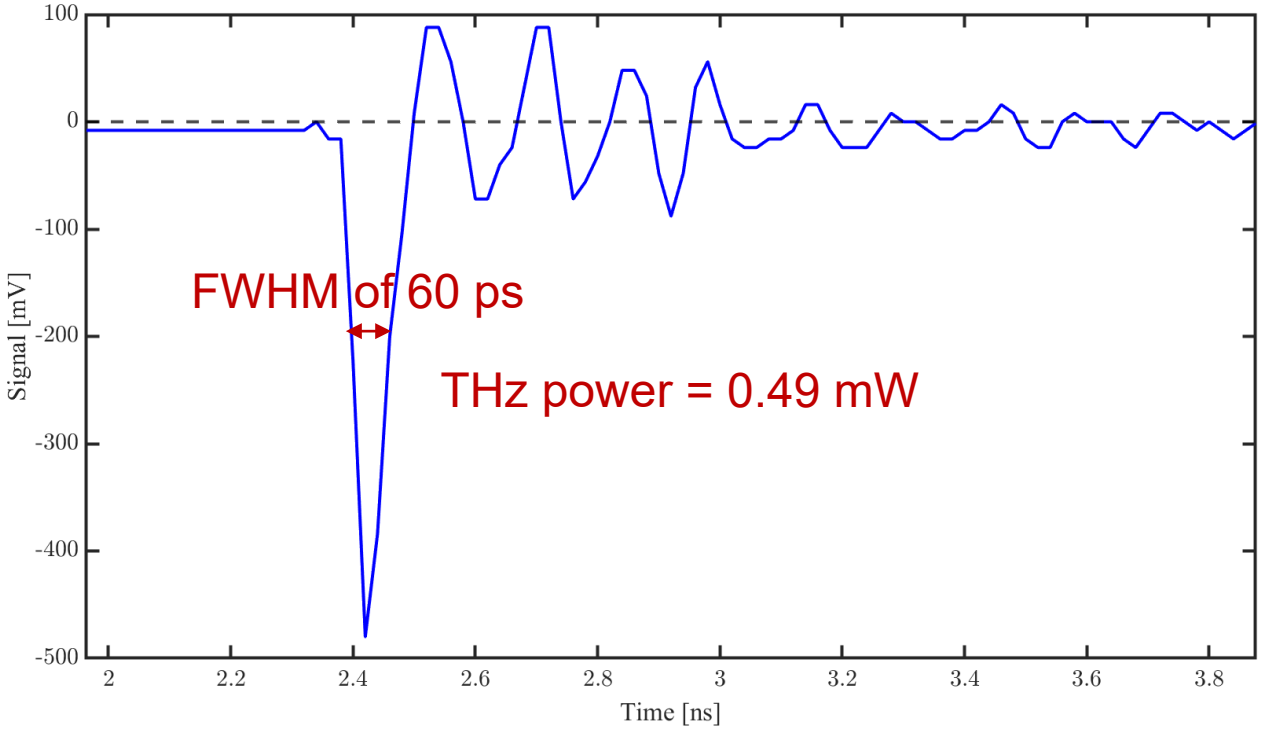
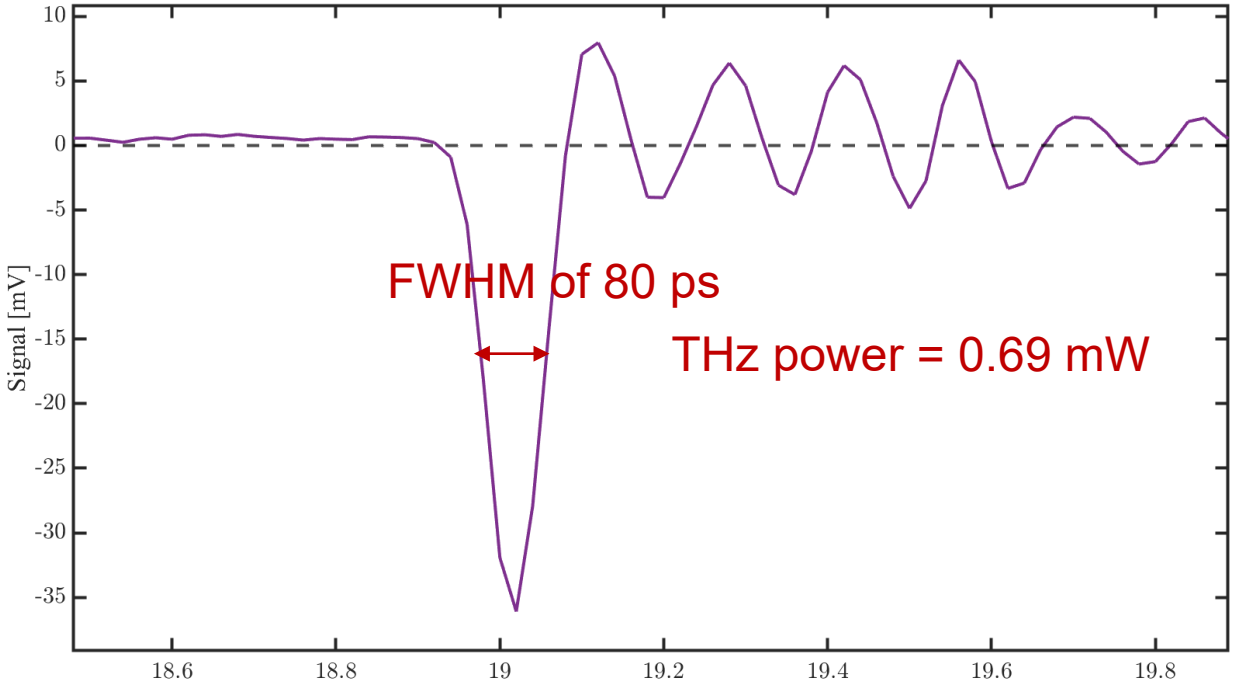


Fast measurement at 4.84 THz with FEL



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ZBSD based detectors : with FELBE characterization

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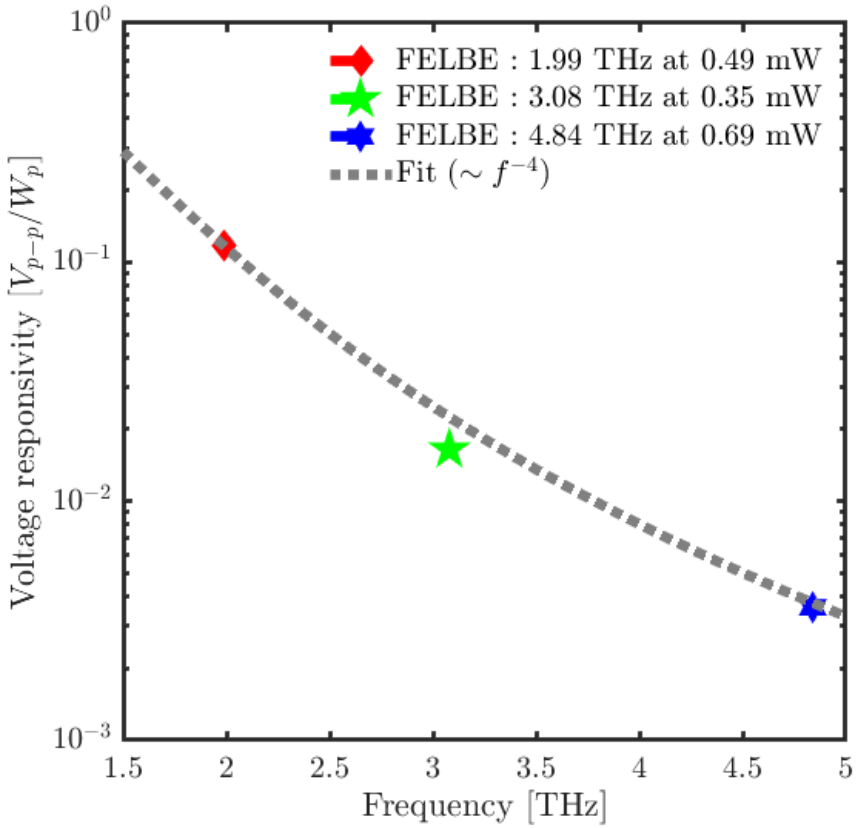

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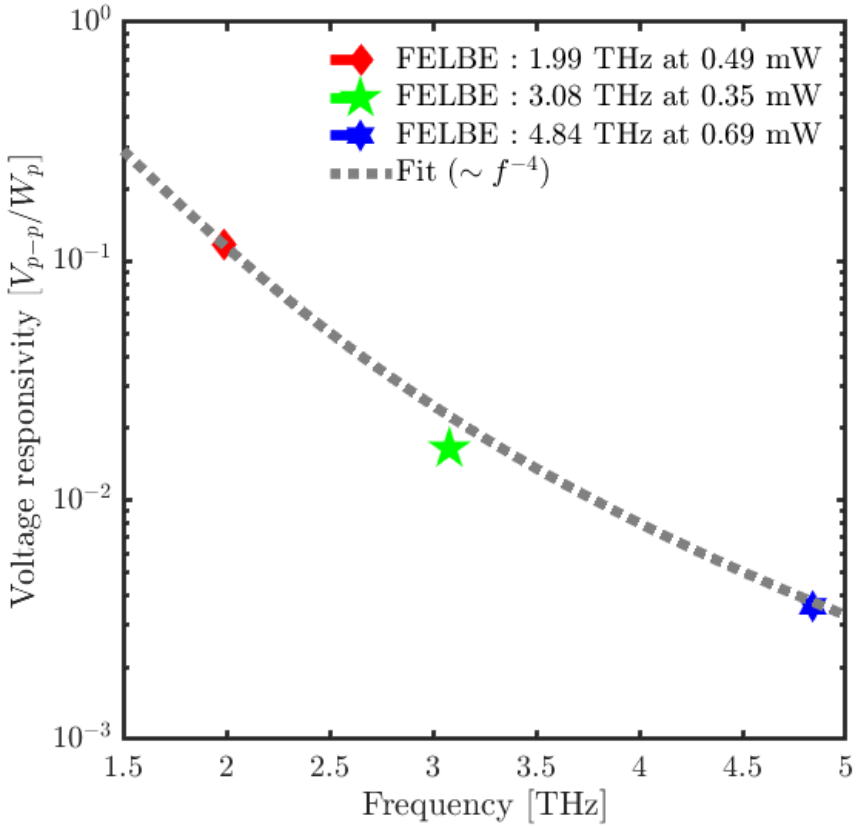
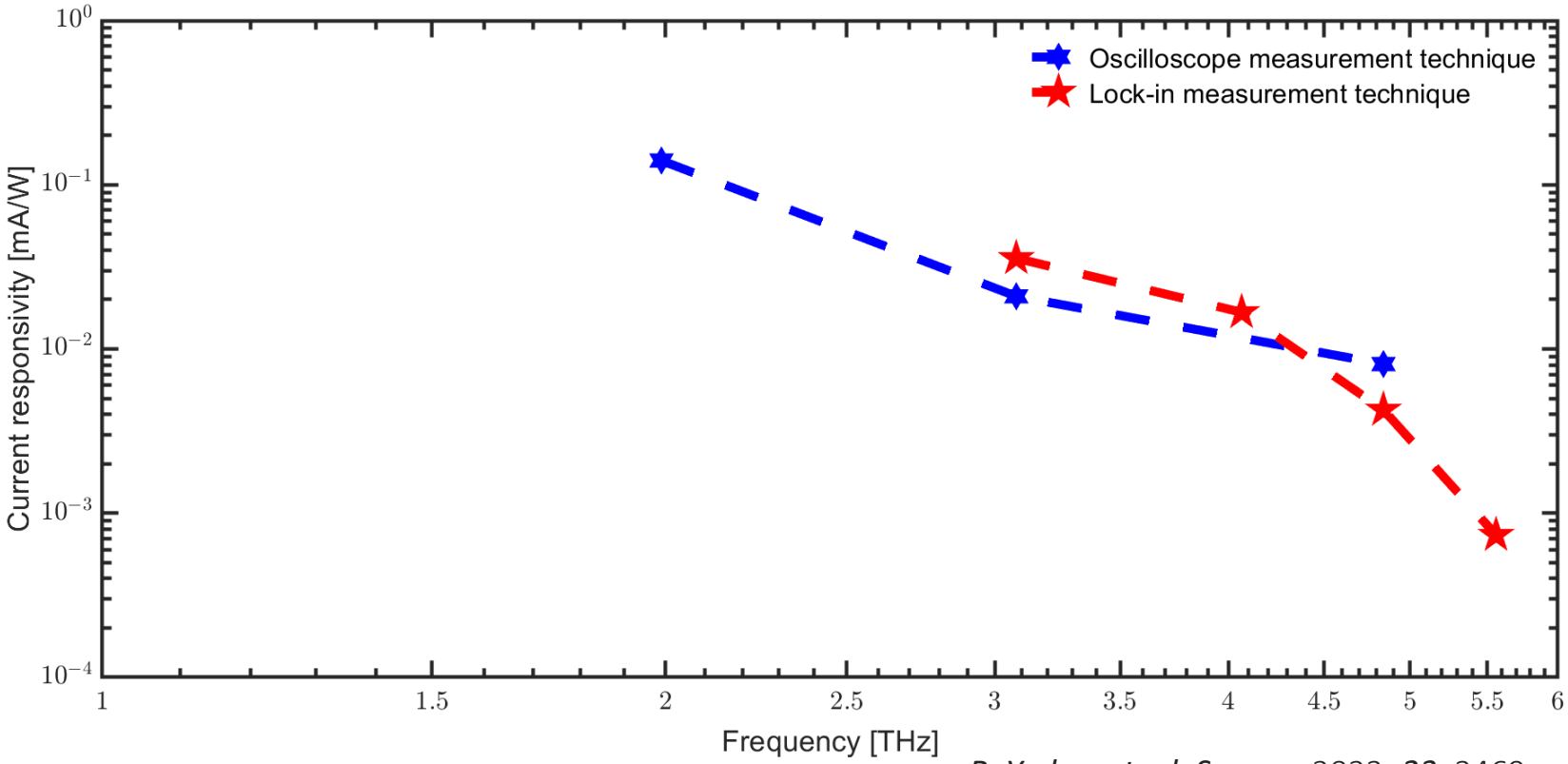


Slow and fast measurement comparison



R. Yadav, et. al, Sensors 2023, ***23***, 3469.

Summary

- Requirement of having direct THz detectors
- Working principle of ZBSD based THz detectors
- Si-lens coupling for broadband THz detectors
- Analysis of antenna performance for ZBSD THz detectors
- Responsivity of $10^2 \frac{\mathrm{mA}}{\mathrm{W}}$ and NEP of $10 \frac{\mathrm{pW}}{\sqrt{\mathrm{Hz}}}$ from 0.2 to 0.6 THz
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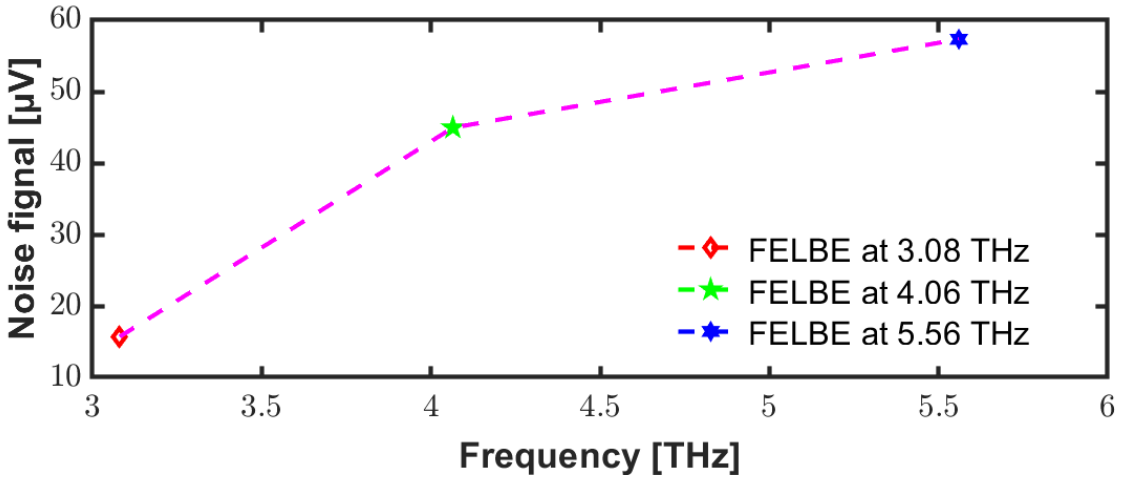

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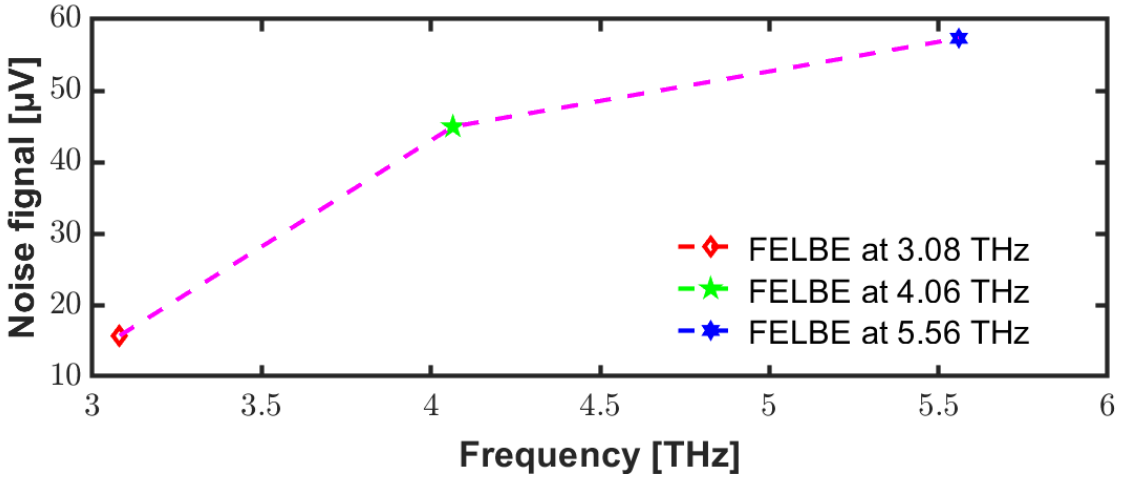

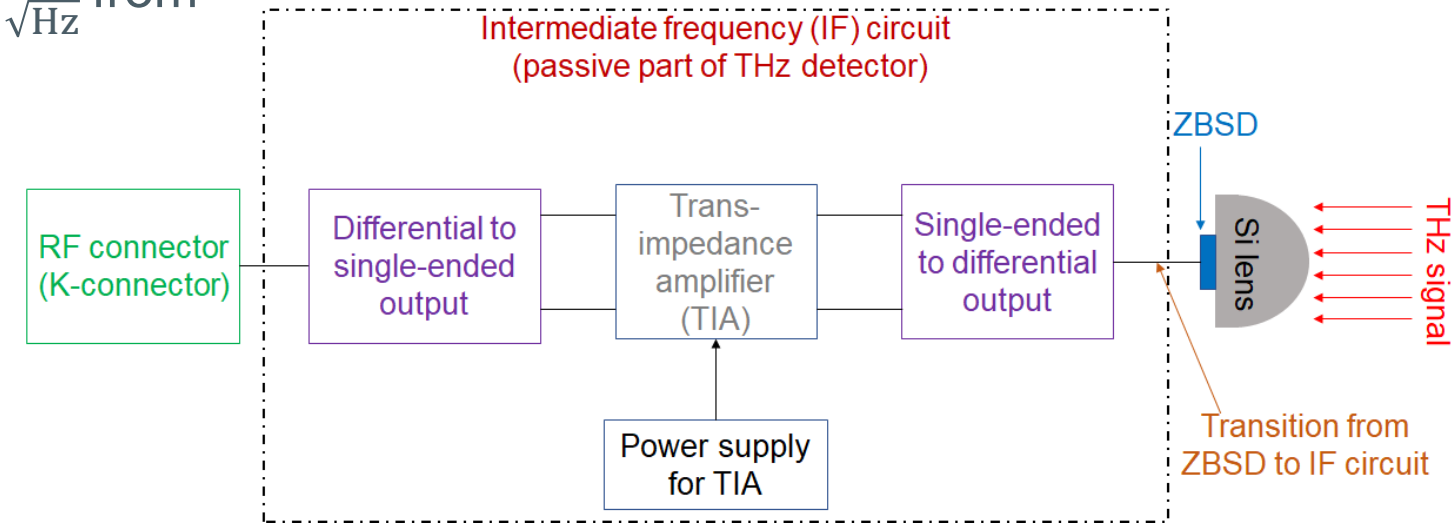

Outlook

- Investigation on broadband and narrow-band planar antennas for future ZBSD THz detectors and their fabrication

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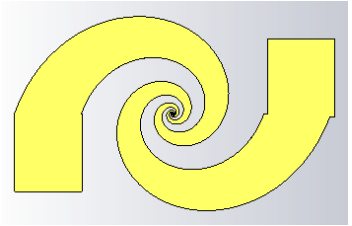
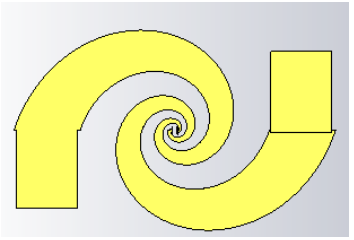
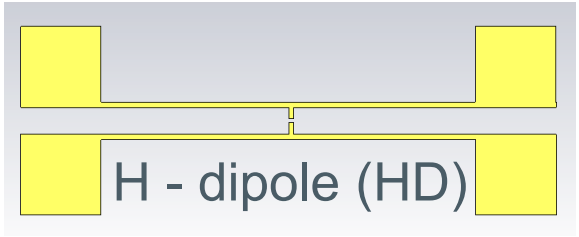
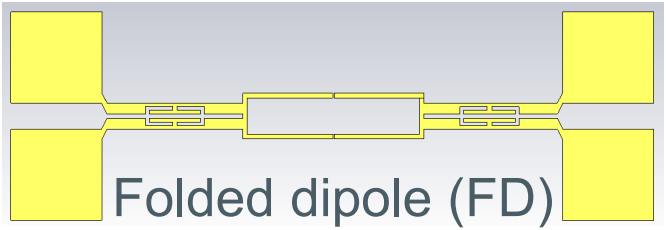


Log-spiral antenna (LSA)



Smaller log-spiral antenna (SLSA)





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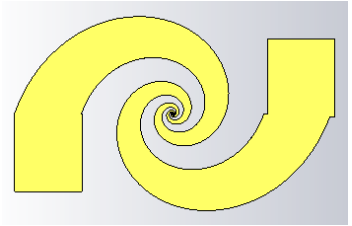
- Selection of optimum flexible transition between active device (ZBSD) and intermediate frequency (IF) circuit



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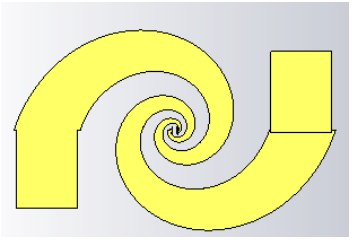

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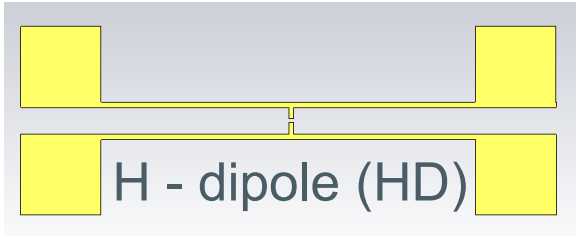

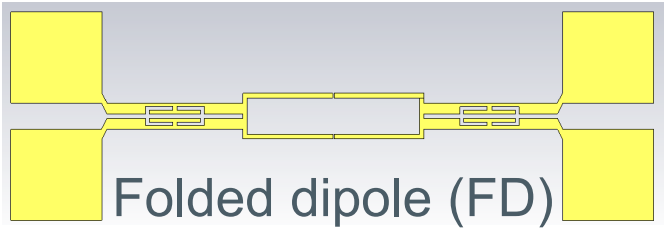

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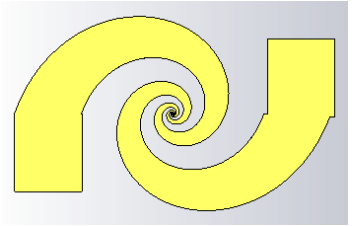
- Selection of optimum flexible transition between active device (ZBSD) and intermediate frequency (IF) circuit
- Investigation and fabrication of IF circuit components



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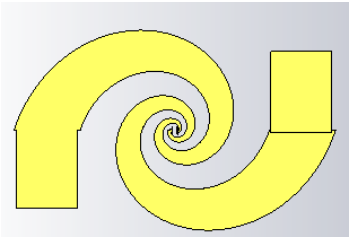

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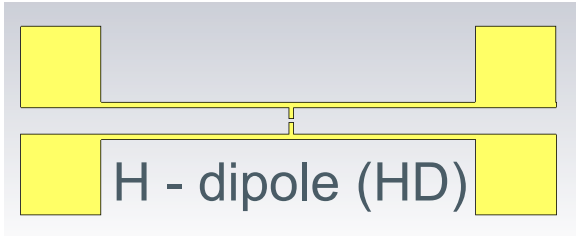
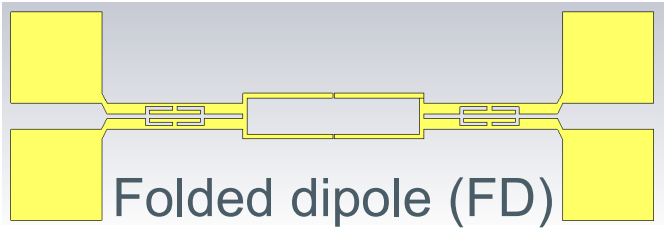
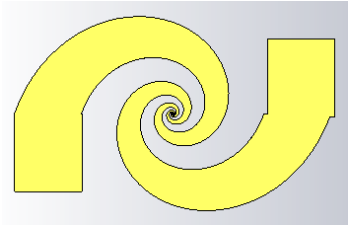




Outlook

- Investigation on broadband and narrow-band planar antennas for future ZBSD THz detectors and their fabrication
- Selection of optimum flexible transition between active device (ZBSD) and intermediate frequency (IF) circuit
- Investigation and fabrication of IF circuit components
- Integration of amplifier inside the same housing as THz detector



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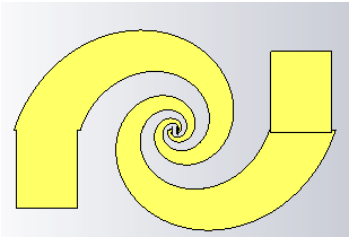

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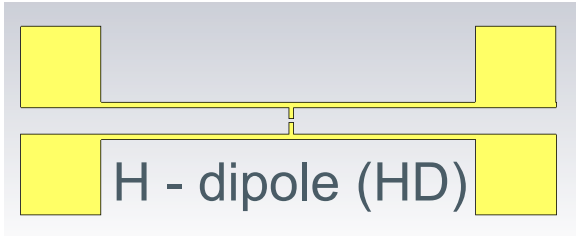
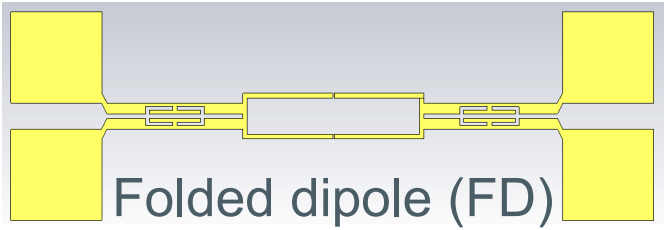


H - dipole (HD)



Folded dipole (FD)

Paper ID: WE1C03

Thank you for your attention and questions are welcome

Team @ THM

Team @ TU Darmstadt

This work is supported by the German Federal Ministry of Education and Research (BMBF) under contract no. 05K22RO1 and Hesse ministry of science and culture.