CMOS based terahertz instrumentation for imaging and spectroscopy

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Where innovation starts

Overview

Introduction

Terahertz unique properties
Technology evolution
Terahertz roadmap initiative

Miniaturized terahertz systems for imaging and spectroscopy

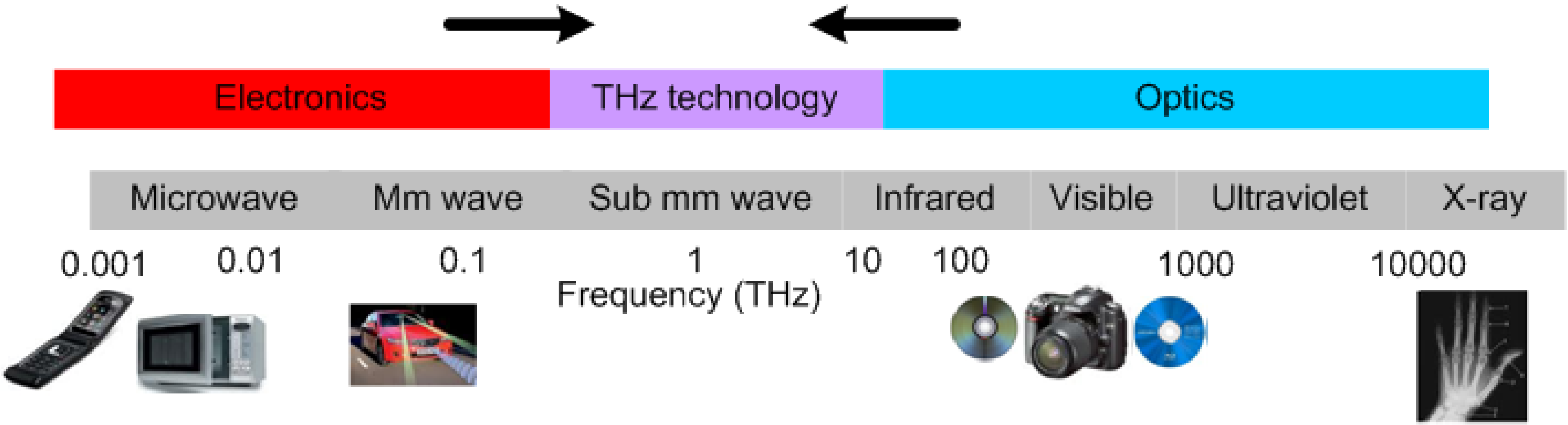
Nonlinear mixing in CMOS technology
Terahertz imaging camera
Spectroscopy system
3D microsystem integration

Free space network analyzer for application testing

Conclusions

THz radiation: Unique properties

1 THz = 1000 GHz

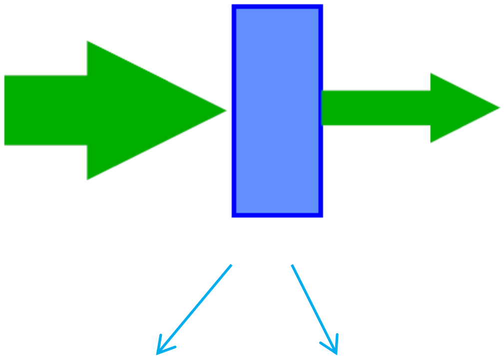


- THz radiation can **penetrate** through non-polar materials (e.g. plastics, wood, clothing)
- THz imaging has sub-mm **resolution**
- THz spectroscopy **identifies** specific materials (e.g. explosives)
- THz radiation is **non-ionizing** (and therefore safer than X-ray)
- THz radiation is **strongly absorbed polar materials** (e.g water)
- Enabler for extreme high data rate communication
- Applications in the THz range continue to increase rapidly

Terahertz characterization techniques

Terahertz imaging

CW or pulsed systems



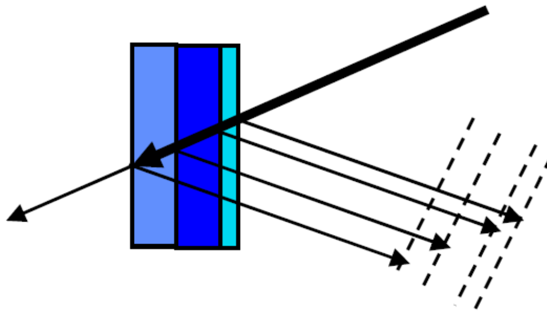
Intensity only

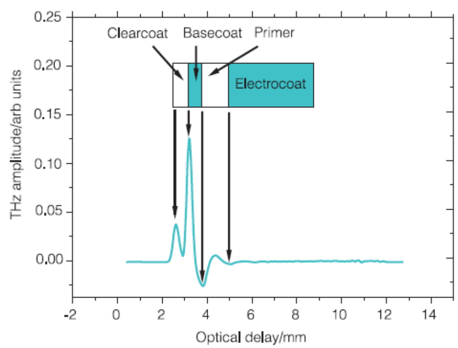
Intensity and phase

Amplitude and phase imaging

Terahertz tomography

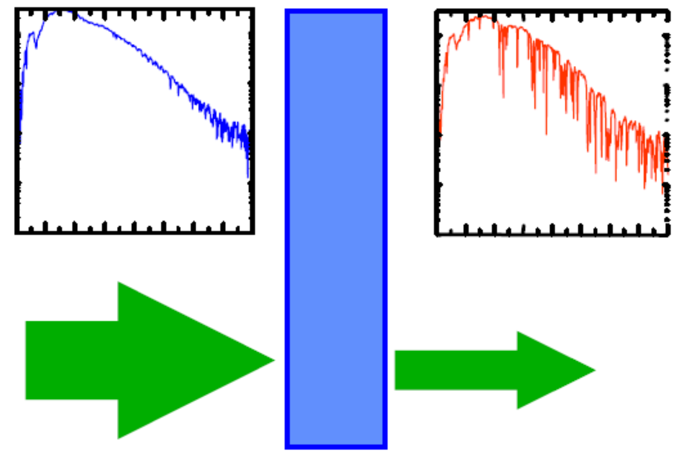
Pulsed systems





Terahertz spectroscopy

CW or pulsed systems



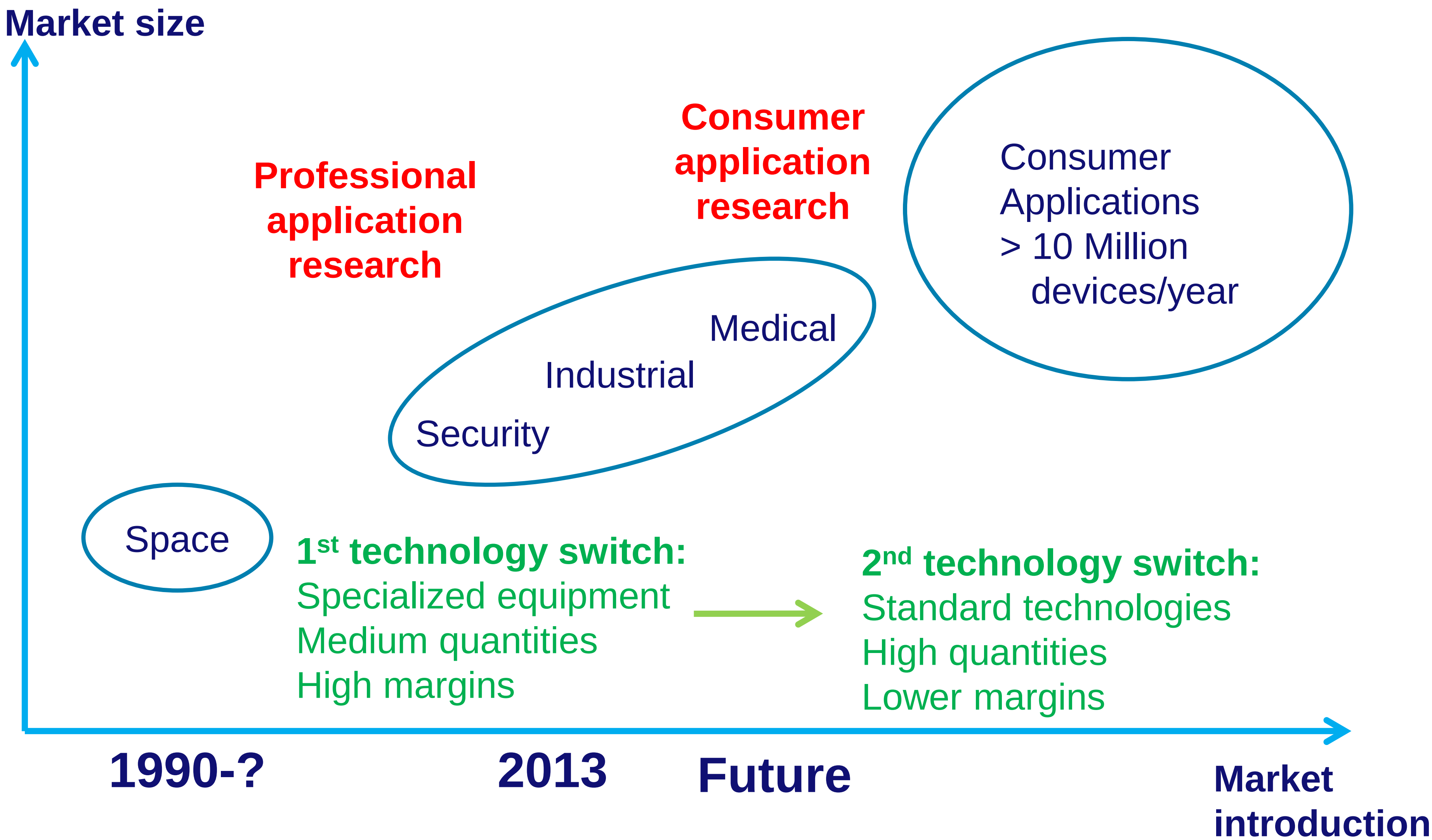
Intensity only

Intensity and phase

Broadband detection

Transmission or reflection measurements are both valuable

Professional and consumer applications



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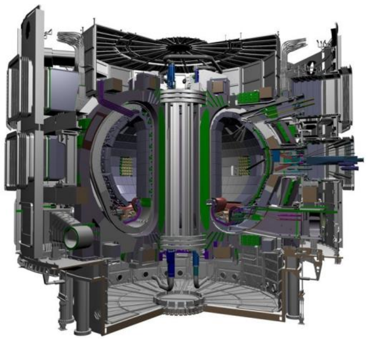
Terahertz for large science

SRON: Dutch space research organization:
Terahertz research group in Groningen
Miniaturized terahertz sensors for space applications

Plasma physics research at TU/e:
Experiments at ITER
Nuclear fusion experiments
Terahertz sensors for fusion control



Tokamak reactor

Terahertz for particle physics:
Let's exchange ideas on this
Non-destructive testing of thin layers?
Radiation sensors in the terahertz domain?

HTSM roadmap "Advanced Instrumentation" mentions Terahertz as one of the key new technologies, potential for funding of research projects.

CWT/e: Short range terahertz observation program

Center of Wireless technology Eindhoven (CWT/e) is an interface between:

1) Users of Terahertz technology
2) Terahertz research within TU/e
3) New research results and industrial partners

Research focus:

1) CMOS integrated transmitter-receiver systems at mm-wave and terahertz
2) Beam steering systems (2D and 3D imaging)
3) Lab-building for mm-wave and terahertz measurements

Terahertz Applications:

1) Industrial process control (non-destructive testing, inline process monitoring)
2) Large volume consumer applications (e.g. mobile phone/tablet, 3D scanners)
3) Medical applications (spectroscopy and imaging, minimal invasive surgery)
4) Growing interest form large science applications (ITER, SRON)

Dutch terahertz roadmap initiative

Goal: Form strong networks on terahertz applications and technologies with research institutes and international companies

TU/e CWT/e is leading the initiative

Involved research organizations (growing):
TU Eindhoven
Dutch Space Research Organization (SRON)
TU Delft

In discussion with many companies (growing):
ABB
Philips
NXP
Canon-Océ
Kippen&Zonen
Food&Agriculture industry
Packaging industry

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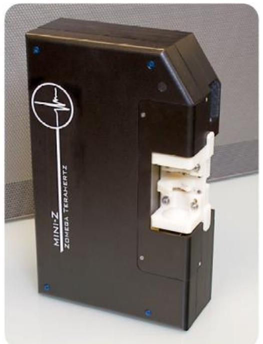
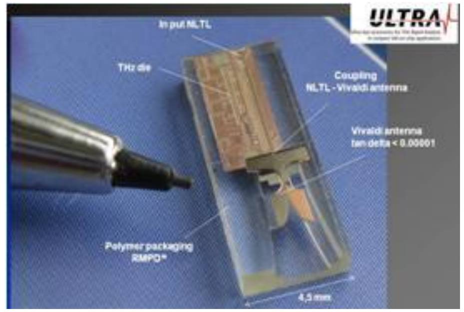
Research on miniaturized THz systems



Optical setups based on femtosecond lasers



All-electronic approach: CMOS based generation and detection of the THz signals

Hybrid approach: miniaturized/integrated opto-electronics sources and receivers

Miniaturized and integrated THz systems

New THz applications

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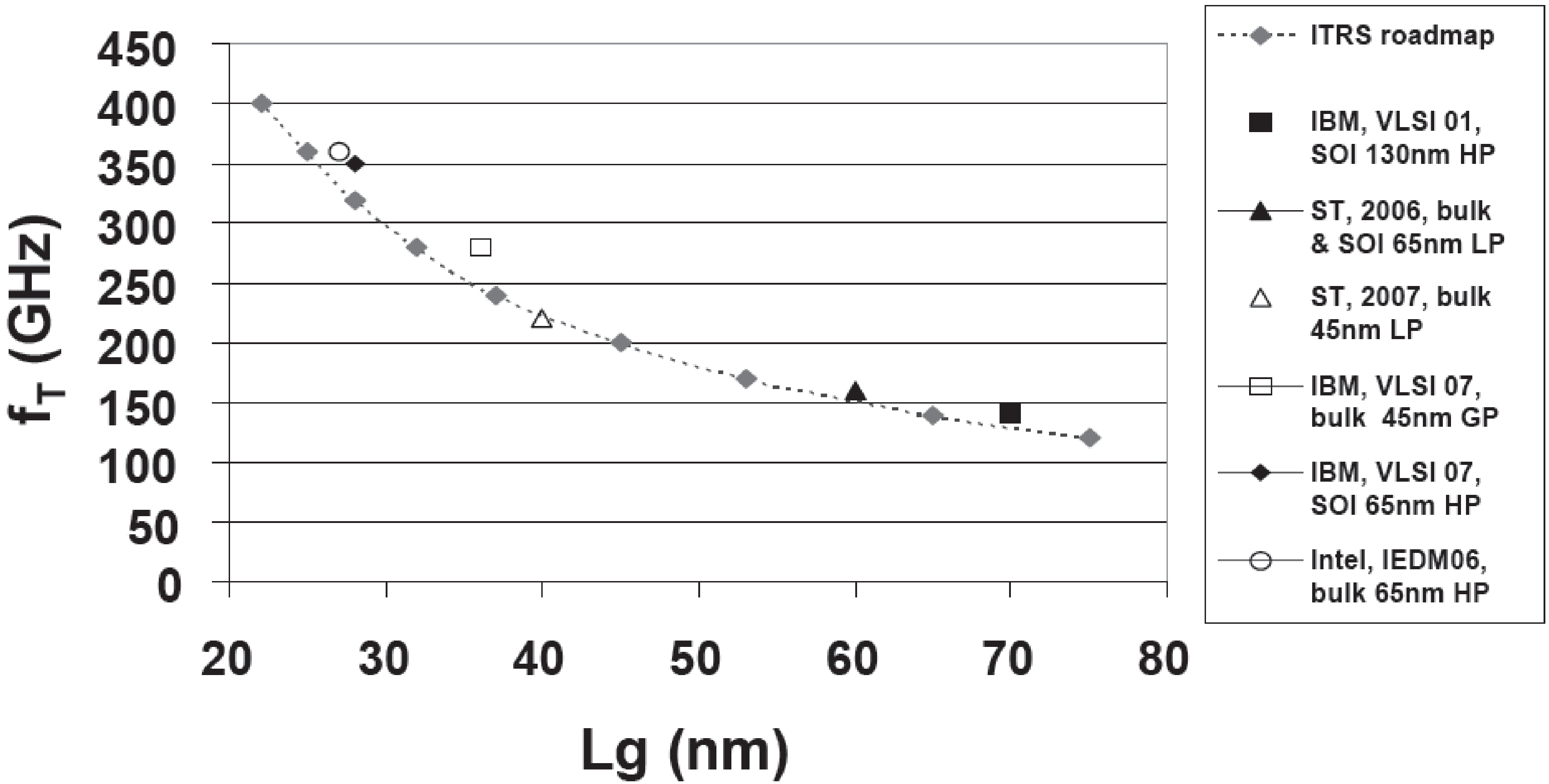
Frequency limits of CMOS transistors



timeline

Terahertz generation and detection

Sources

Oscillator based

fundamental oscillators: limited by f_T and f_{max}

harmonic oscillators: filter out the base frequency and use the harmonics

Multiplier based

Generate harmonics in a nonlinear device

Require a strong input signal

Receivers

"Traditional non-mixing" techniques

limited by f_T and f_{max}

Mixing in **Schottky diode** based detectors

can work beyond the transistor frequency limits

Mixing in **FET detectors**

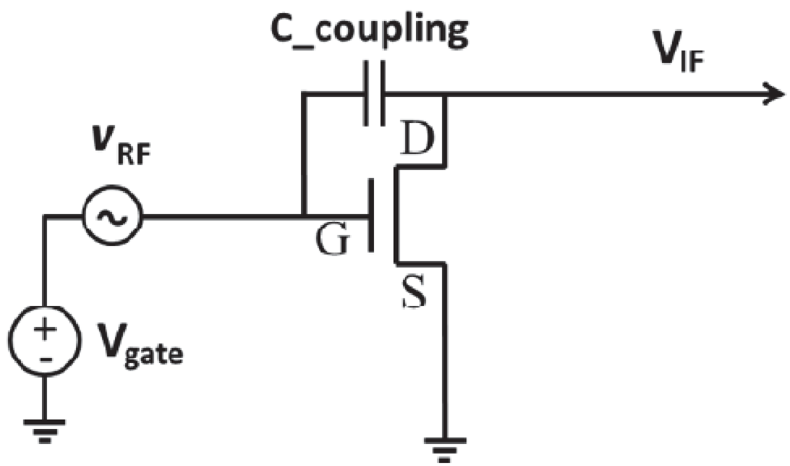
broadband direct conversion demonstrated

passive imaging detectors not sensitive enough

Bolometers integrated into CMOS technology

Require special postprocessing (etching of the Silicon)

Self-mixing in CMOS transistors



$$i_{ds}(t) = g_{ds} \cdot v_{ds}(t)$$

$$= \frac{W}{L}\mu C_{oxide}\left(v_{gs}(t) - V_{Th} - \frac{v_{ds}(t)}{2}\right)v_{ds}(t)$$

$$= \frac{W}{L}\mu C_{oxide}\left(v_{RF}^2 + v_{RF}(V_G - V_{Th})\right)$$

Linear term!

Quadratic term!

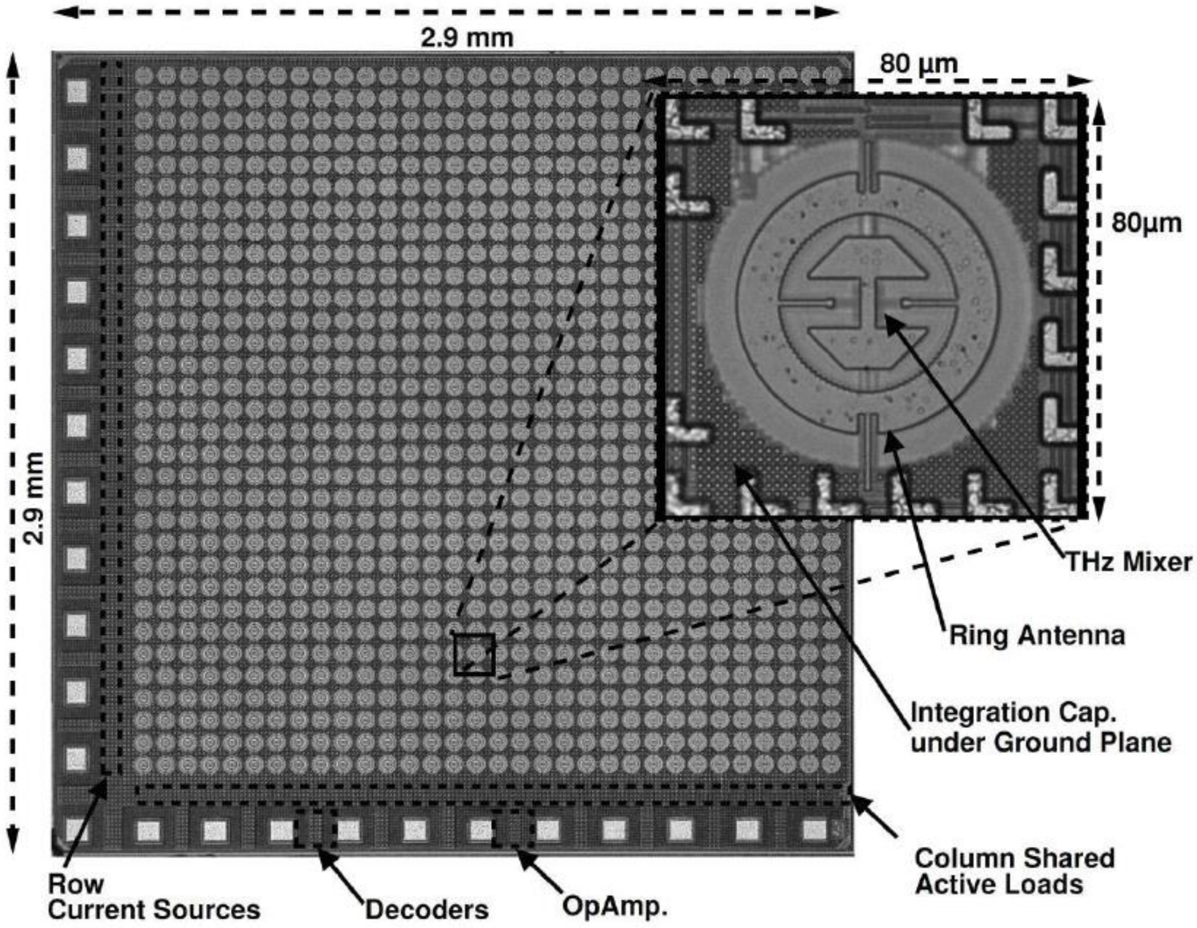
$$v_{ds}(t) = v_{RF}(t)$$

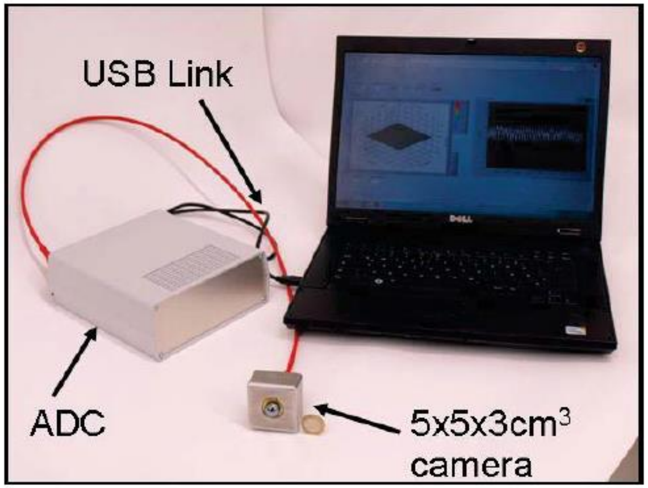
$$v_{gs}(t) = V_g + v_{RF}(t)$$

$$v_{RF}(t) = V_{RF}\sin(2\pi f_{in} t)$$ → I_{ds} contains signals at 0, f_{in} and 2 f_{in} .

2012: World's first CMOS terahertz camera

H. M. Sherry, U. R. Pfeiffer, et al., University of Wuppertal

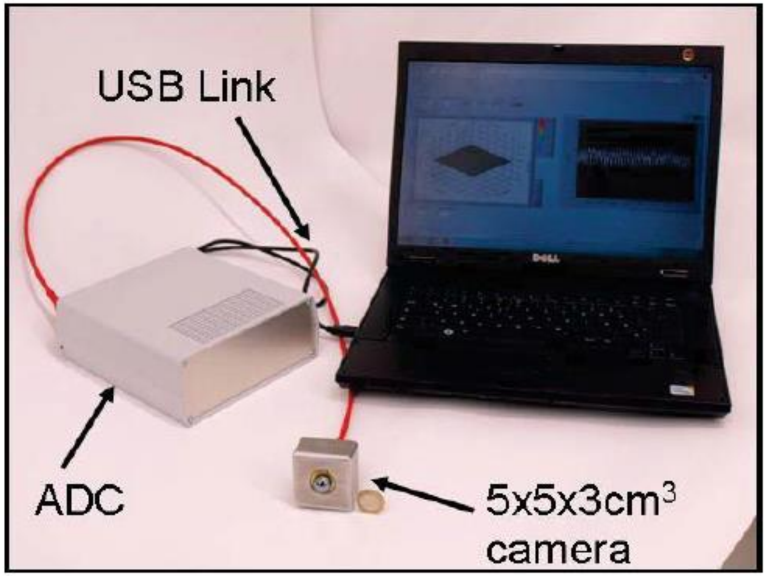




32 by 32 pixels, differential source coupled FET direct conversion

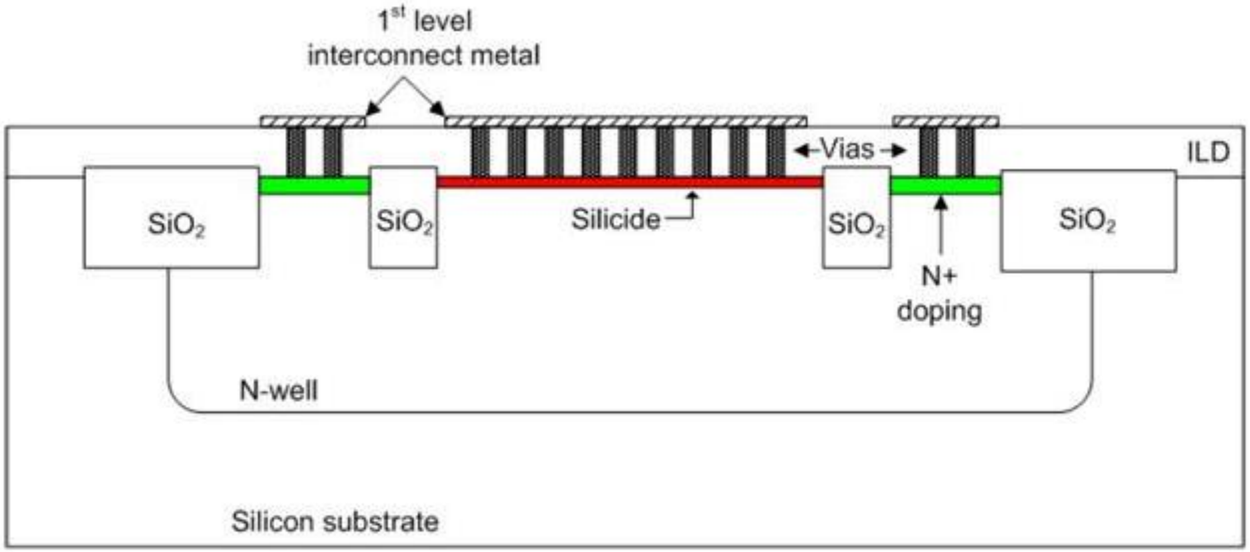
Key specs of the CMOS terahertz camera

Technology	CMOS65nm (ST)
Pixel count	1024pixels
Freq. range	0.75-1THz
Chip size	7.5mm^2
Frame rate	25fps
Camera housing	5x5x3cm^3
Power Consump./pixel	2.5µW
Rvi, max	566MV/W
NEPi, min	47fW/√Hz
Oper. temp	25°C
Lens diameter	15mm^2



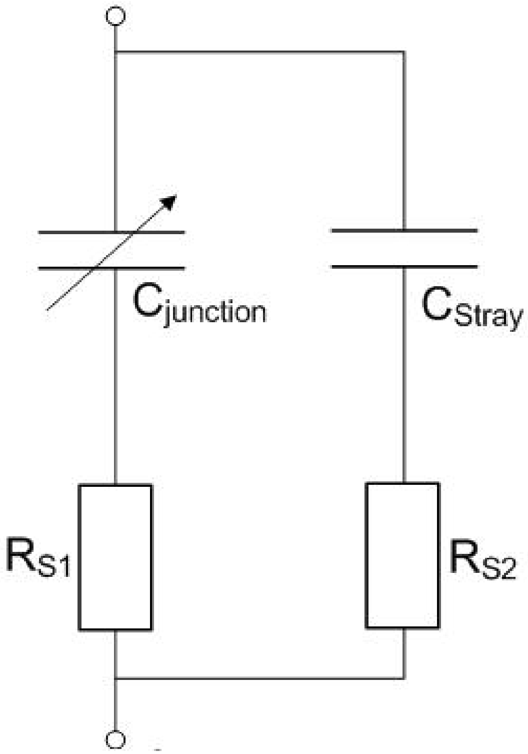
H.M. Sherry, U. R. Pfeiffer, University of Wuppertal, Germany

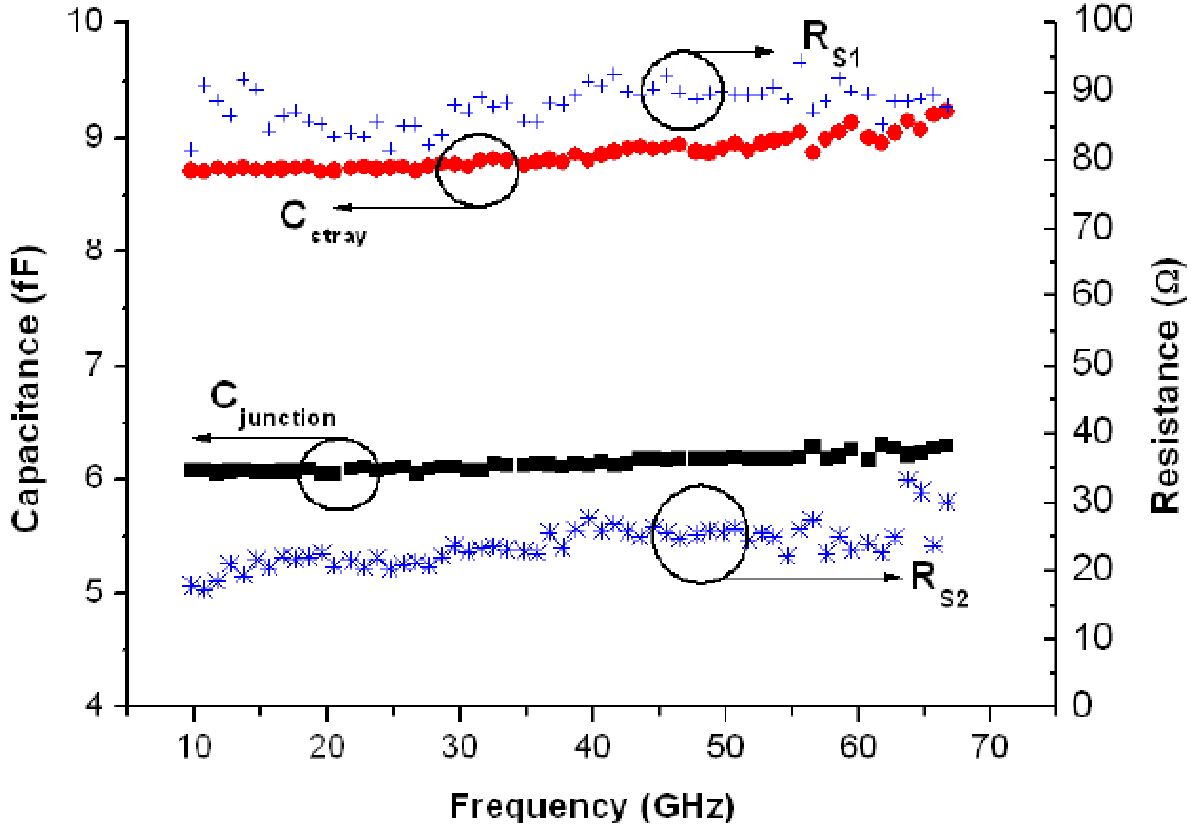
Schottky diodes in CMOS: cross section



- Nonlinearity originates from the I(V) curve of the diode
- Speed of the diode originates from the parasitics and diode size

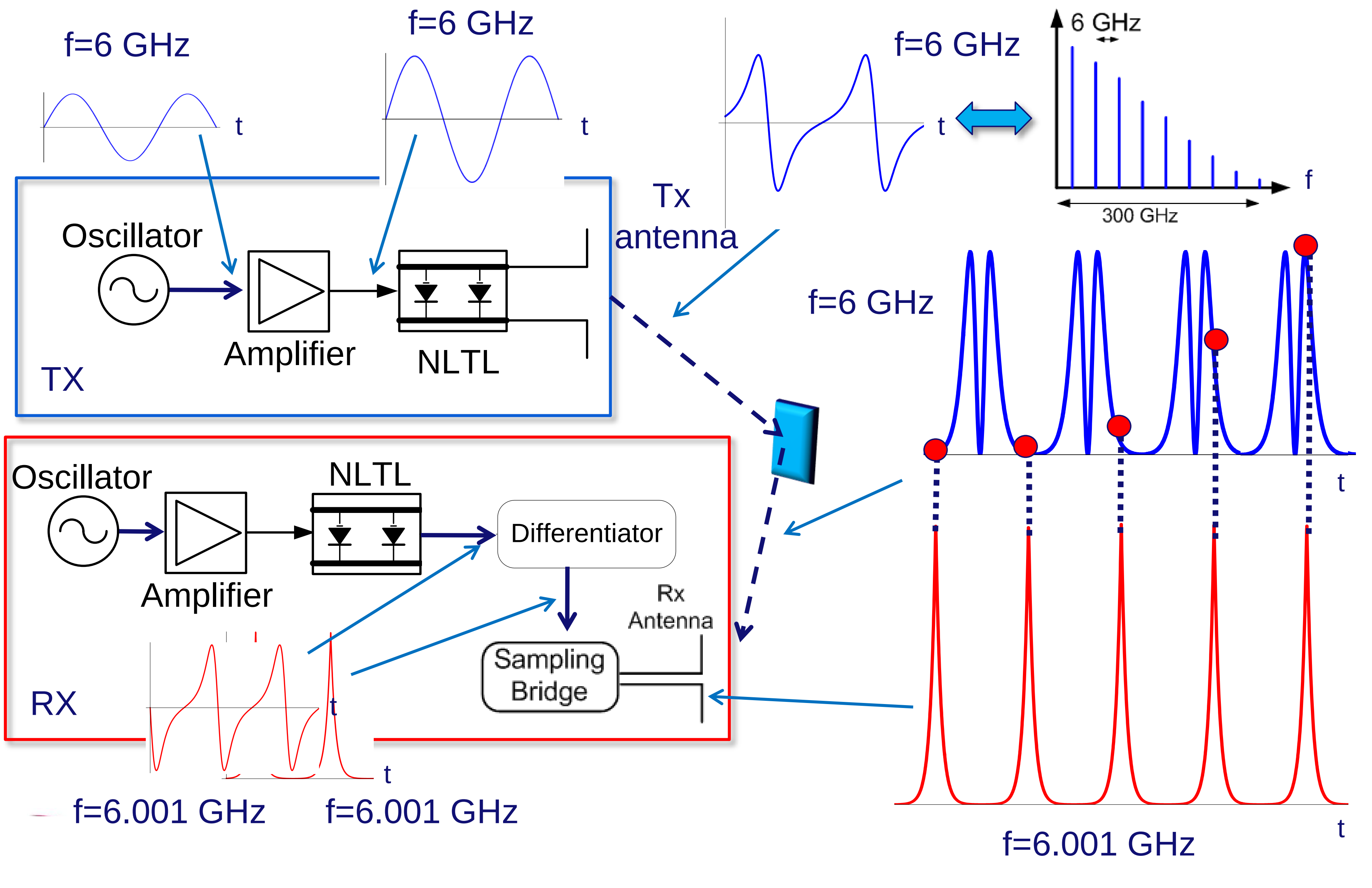
Schottky diodes in CMOS: Reverse bias diode model



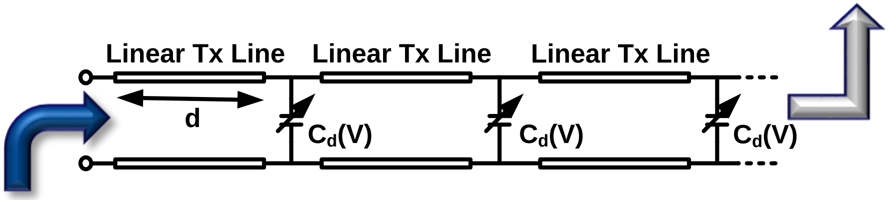


	$C_{junction, 0V}$ (fF)	C_{stray} (fF)	R_{S1} (Ω)	R_{S2} (Ω)	$f_{C,junction, 0V}$ (GHz)
Diode (a)	6.6	1	104	-	231
Diode (b)	6.5	7.8	57	8	430

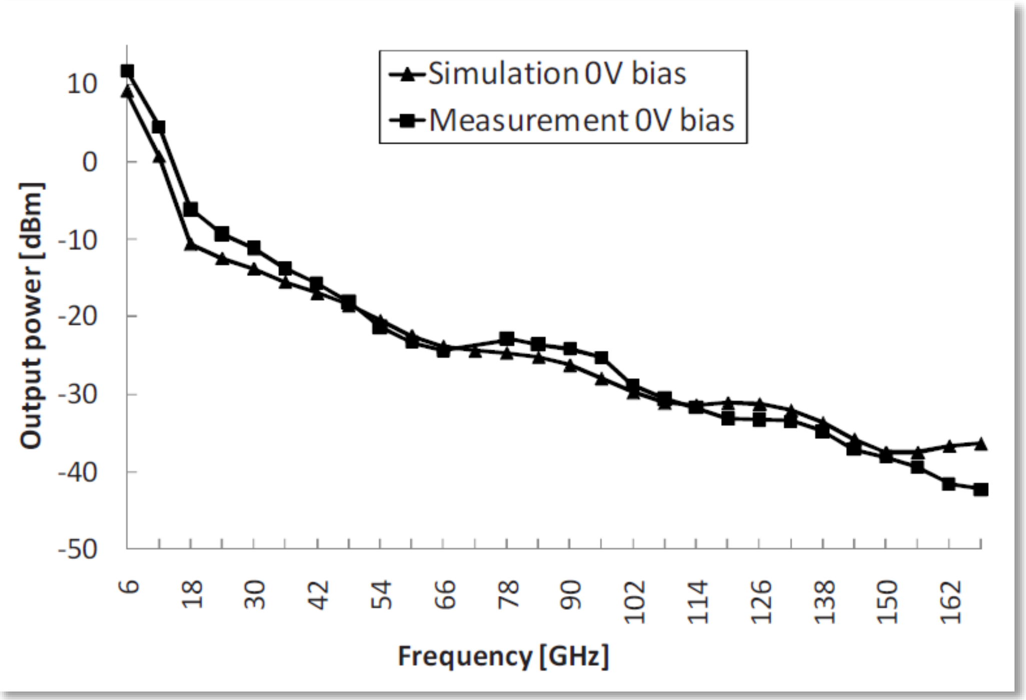
System overview



NLTL: Measurement Results

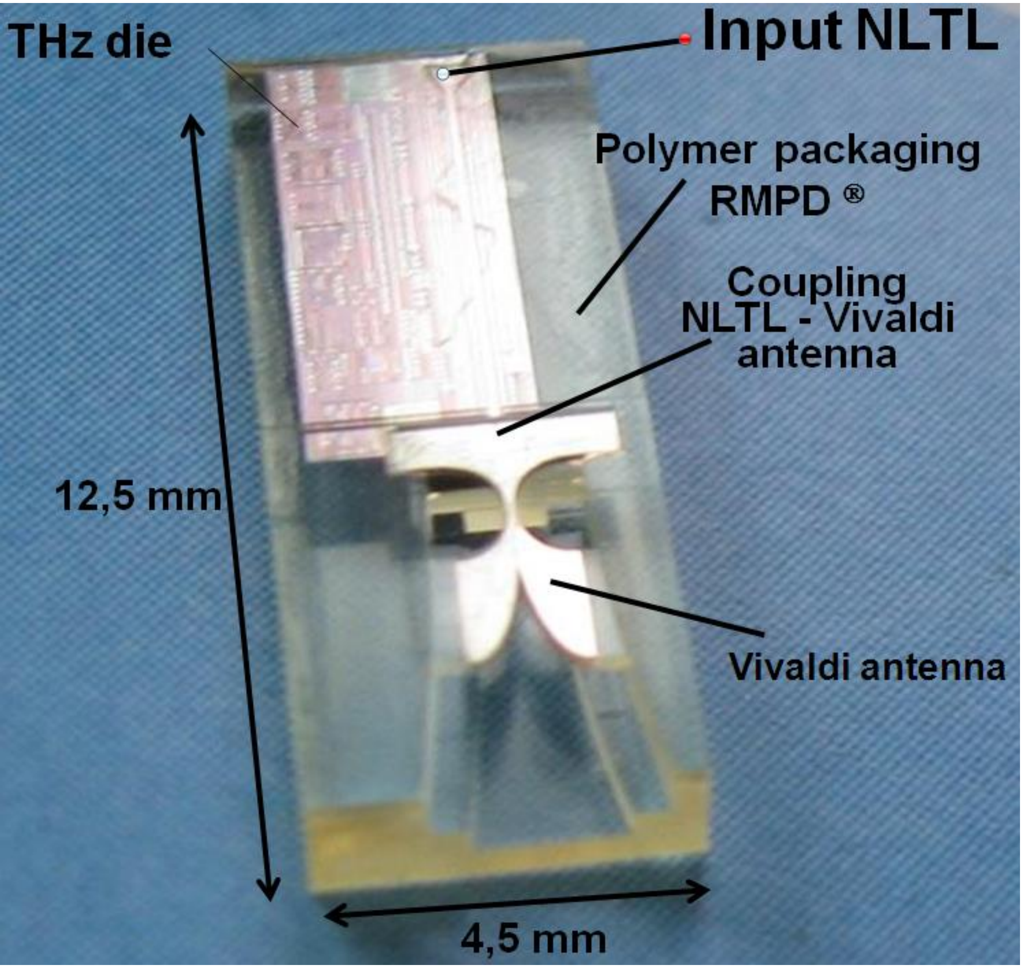


Input: Sinusoid
P_{in}=18 dBm
6 GHz



L. Tripodi, X. Hu, R. Goetzen, M.K. Matters-Kammerer et al., Broadband CMOS Millimeter-Wave Frequency Multiplier with Vivaldi Antenna in 3-D Chip-Scale Packaging, Trans. on MTT, Vol. 60, no. 12, part 1, pp. 3761-3768, 2012

Nonlinear transmission line transmitter



- THz CMOS integrated circuit
- Micro-machined external Vivaldi antenna
- Highly integrated transmitter
- 3D CSP-based THz packaging
- Bandwidth 6 GHz – 300 GHz
- Transmission and Reflection mode solutions

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X. Hu, L. Tripodi, M.K. Matters-Kammerer et al.,
65-nm CMOS Monolithically Integrated Subterahertz Transmitter,
Electron Device Letters, pp. 1182-1184, Vol. 32, issue 9, 2011.

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Terahertz imaging with NLTL source

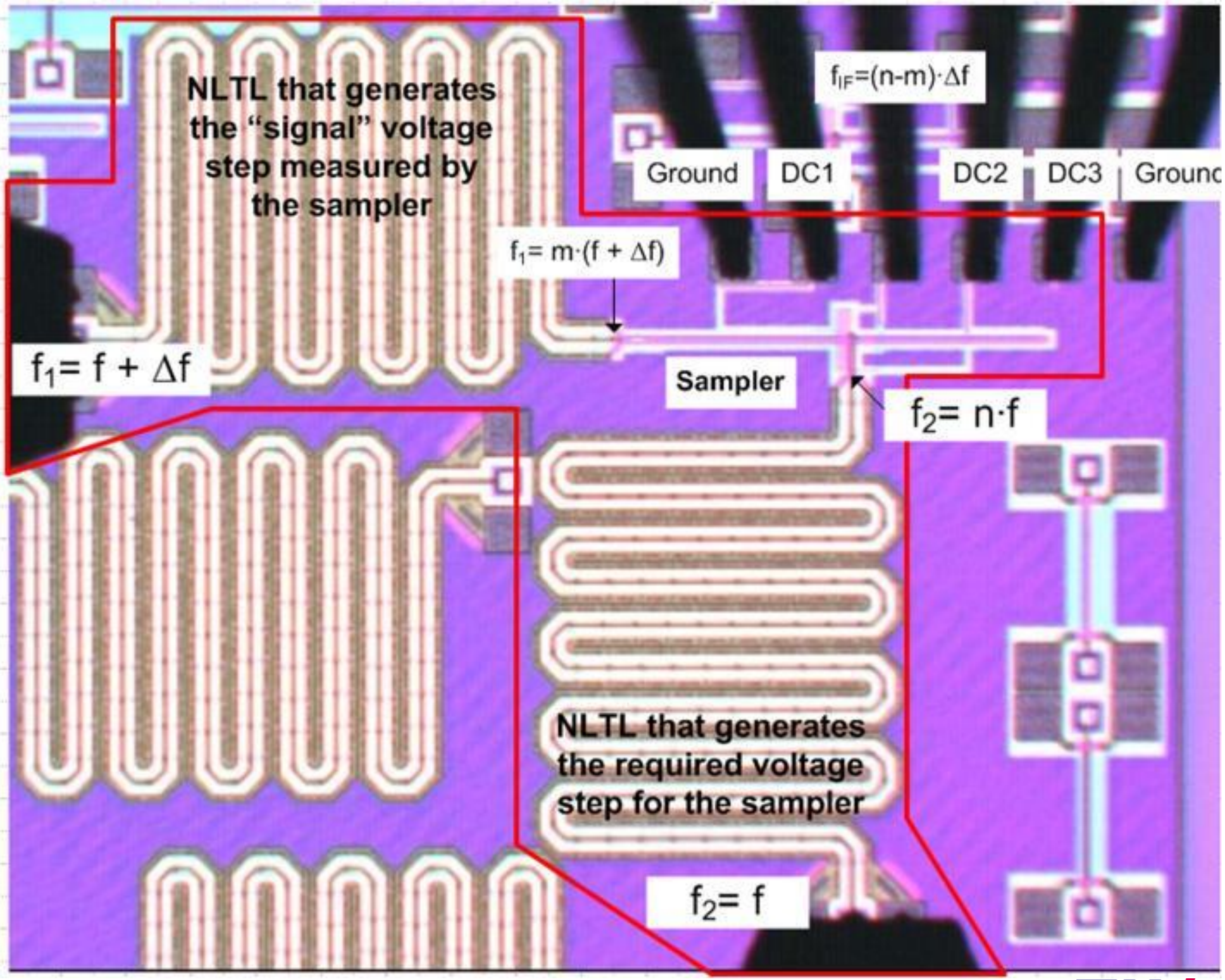
Visible

200 GHz image

UNIVERSITÄT SIEGEN

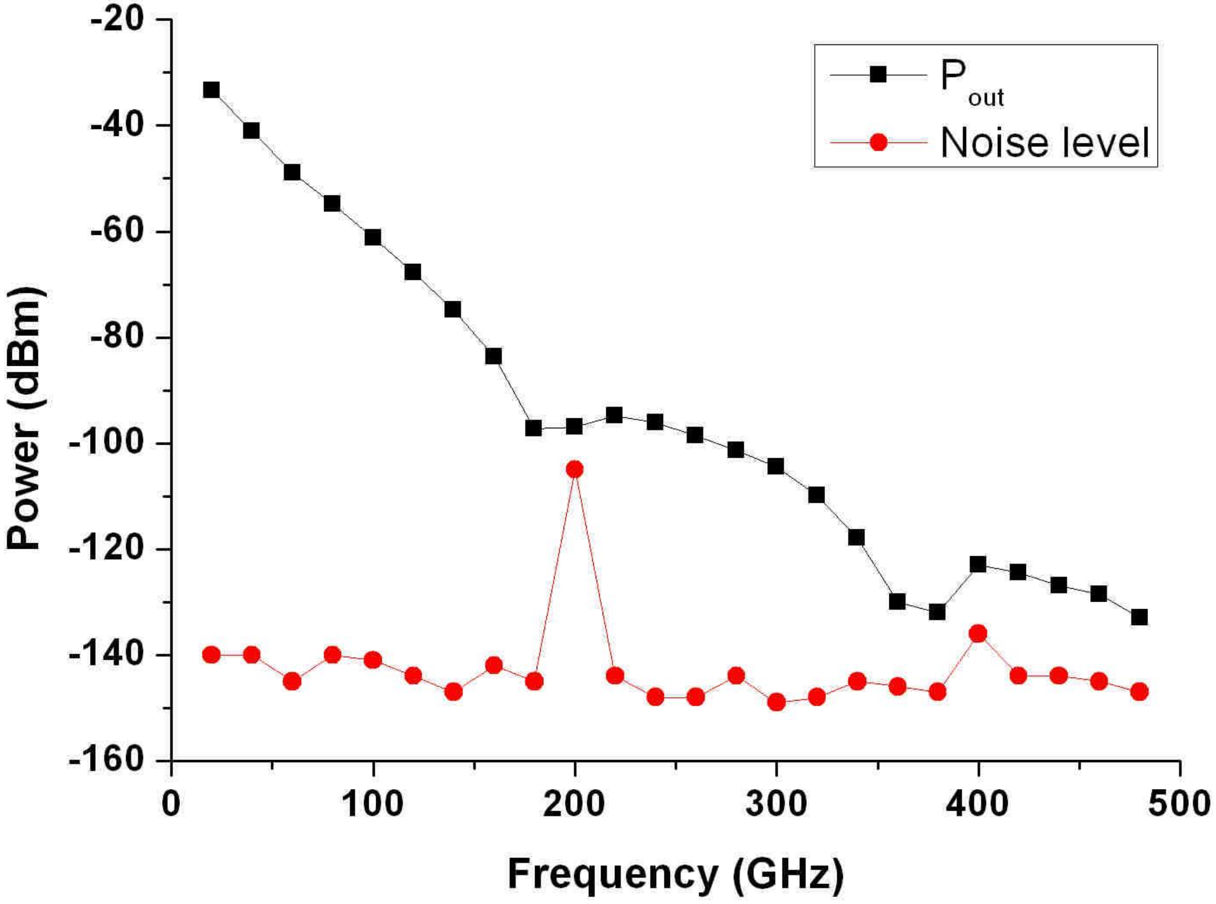
Prof. P. Haring-Bolivar

On-chip sub-THz generator and sampler

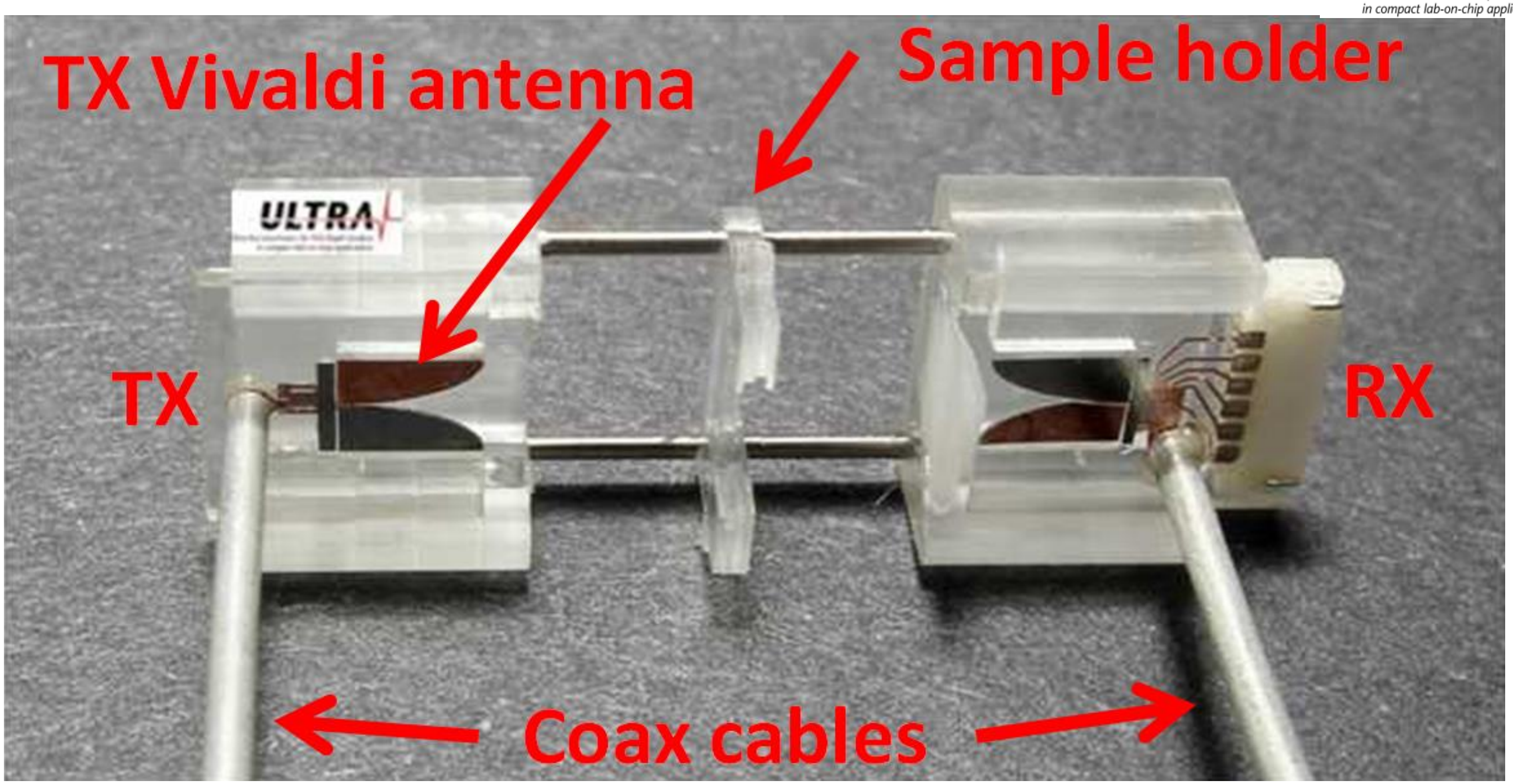


Output spectrum of nonlinear transmission line

Input signal: f=20 GHz, 18 dBm

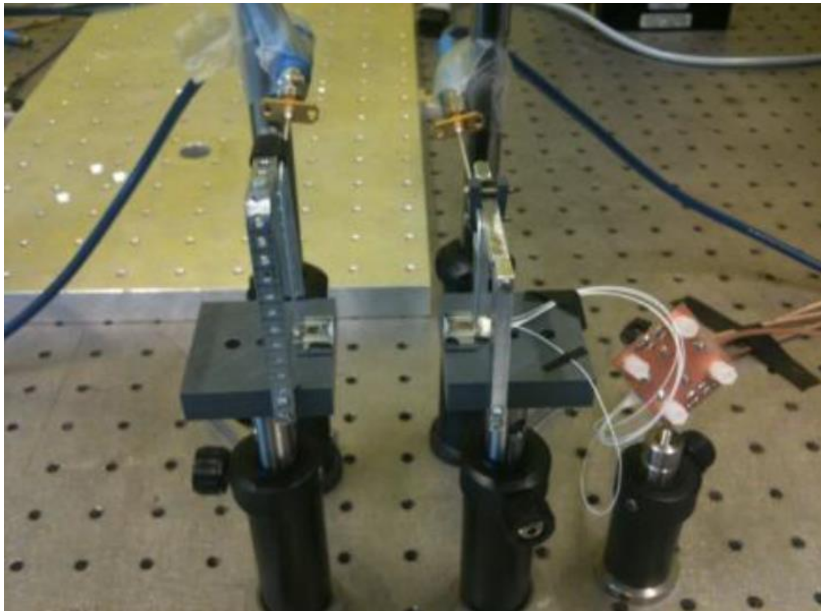


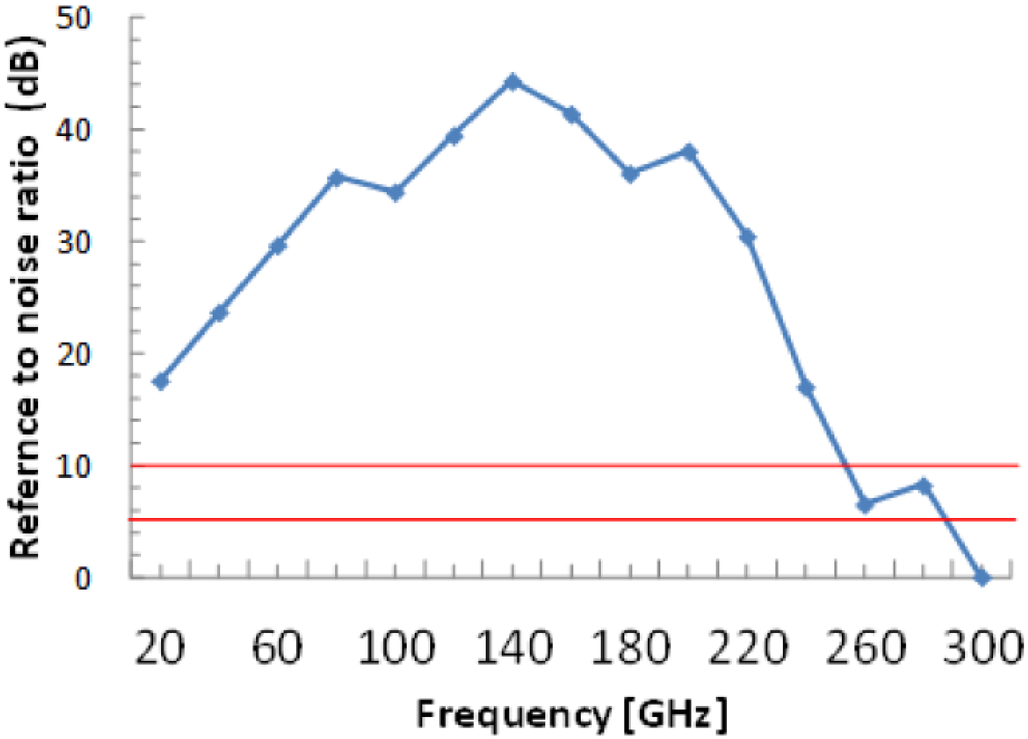
Hybrid integration concept



L. Tripodi , M. Matters-Kammerer, et al. Eurosensor 2012

Terahertz microsystem: Dynamic range





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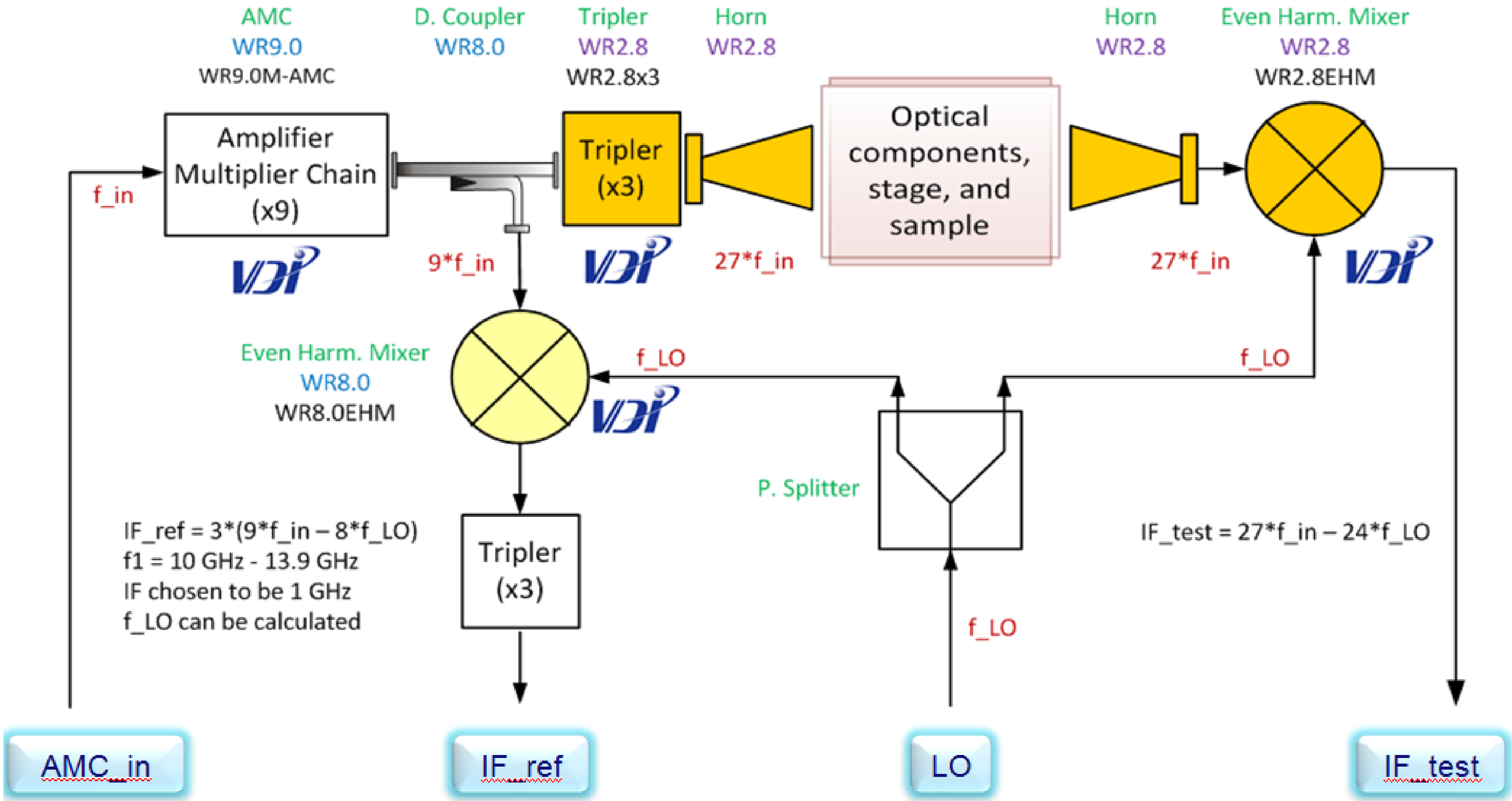
Free space network analyzer for application testing

Conclusions

270 GHz to 370 GHz free space network analyzer



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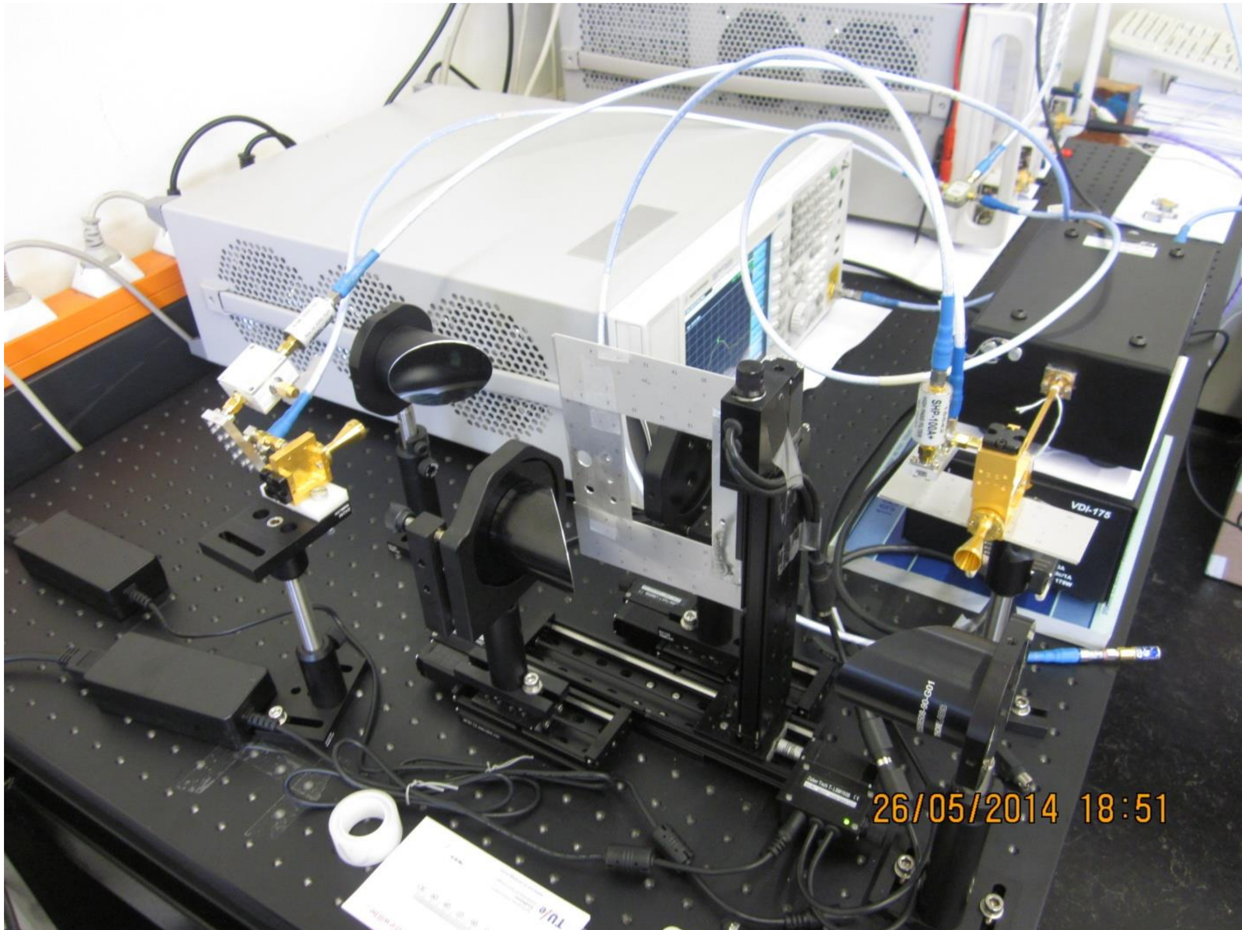
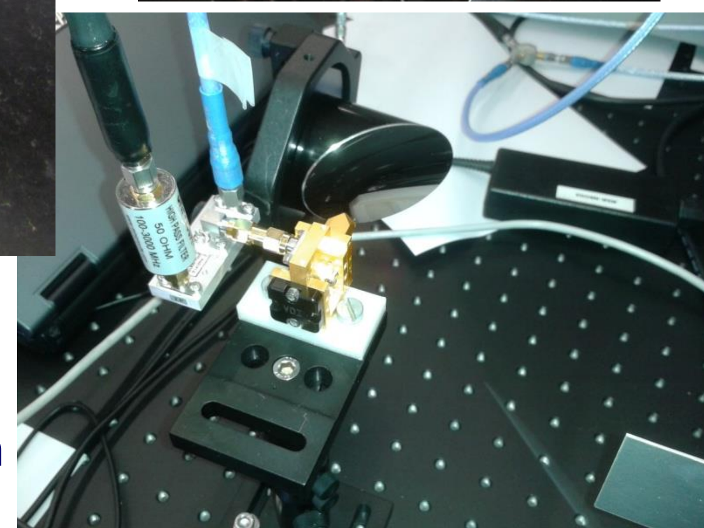
Free space Network analyzer





90 GHz to 120 GHz setup

Up:Tripler+antenna
Down: downconcersion
for operation in WR 2.8

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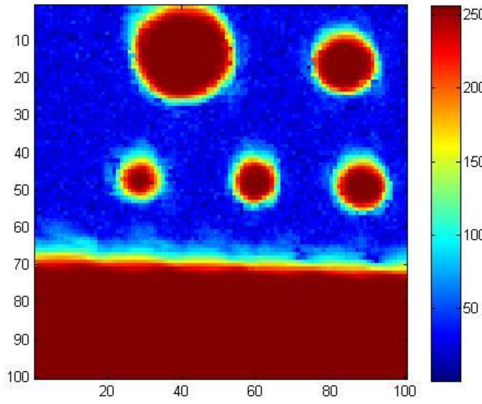
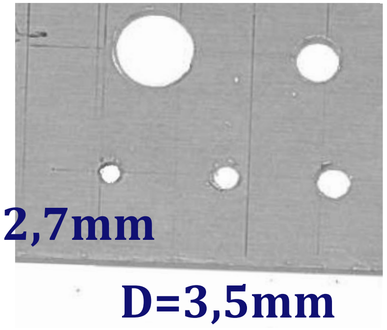
Amplitude images at 345 GHz

Metal plate with holes



D=10,05mm



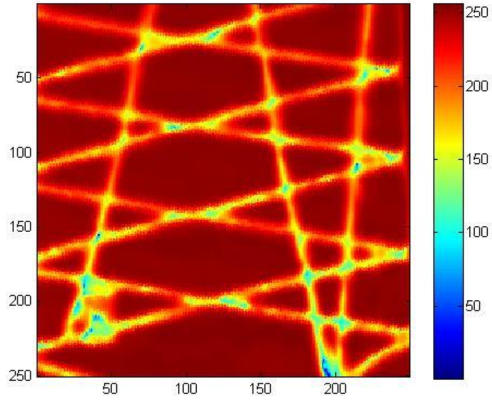
D=6mm

D=4,5mm

D=2,7mm

D=3,5mm

Plastic card with metal ribbon



Publications

M. K. Matters-Kammerer et al., RF Characterization of Schottky Diodes in 65-nm CMOS, IEEE TRANSACTIONS ON ELECTRON DEVICES, Volume: 57 Issue: 5 Pages: 1063-1068 , May 2010.

X. Hu, L. Tripodi, M.K. Matters-Kammerer, et al., 65-nm CMOS Monolithically Integrated Subterahertz Transmitter , IEEE ELECTRON DEVICE LETTERS Volume: 32 Issue: 9 Pages: 1182-1184 , Published: SEP 2011.

L. Tripodi, X. Hu, R. Goetzen, et al., Broadband CMOS Millimeter-Wave Frequency Multiplier with Vivaldi Antenna in 3-D Chip-Scale Packaging, Trans. MTT, Vol. 60, no. 12, part 1, pp. 3761-3768, 2012.

L. Tripodi, M.K. Matters-Kammerer, 26th European Conference on Solid-State Transducers (Eurosensors), Broadband terahertz and sub-terahertz CMOS modules for imaging and spectroscopy applications, Volume: 47 Pages: 1491-1497, Sep. 2012.

L. Tripodi, M.K. Matters-Kammerer, et al., Extremely wideband CMOS circuits for future THz applications, Analog Circuit Design, ISBN 978-94-007-1926-2, Springer, 2012.

Conclusions

Focus on CMOS integration of terahertz circuits

Excellent contacts to companies in the Brainport area and abroad

Leading the Dutch terahertz roadmap initiative

Long term view on terahertz integration in CMOS technology

Cooperation opportunities

Joint lab building and demonstrations

Joint research project proposals (Dutch and European)

PhD and master projects/exchanges

Joint professional educational program