

# CMOS based terahertz instrumentation for imaging and spectroscopy

***Citation for published version (APA):***

Matters - Kammerer, M. (2014). CMOS based terahertz instrumentation for imaging and spectroscopy. In *Proceedings of the International conference on Technology and instrumentation in particle physics (TIPP 2014)*, 02-06 June 2014, Amsterdam, The Netherlands

***Document status and date:***

Published: 01/01/2014

***Document Version:***

Accepted manuscript including changes made at the peer-review stage

***Please check the document version of this publication:***

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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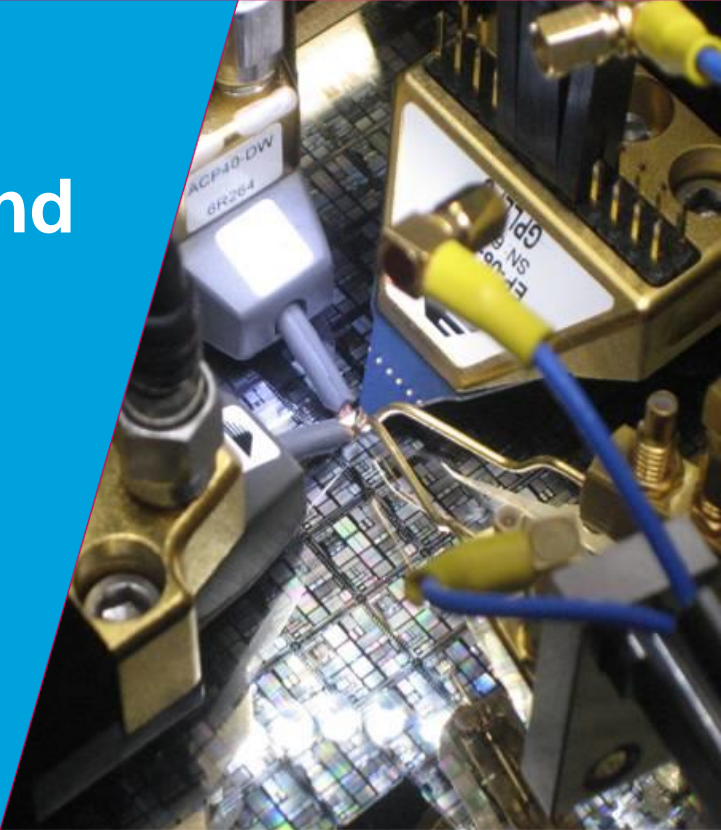
# CMOS based terahertz instrumentation for imaging and spectroscopy

TIPP, 2<sup>nd</sup> of June 2014

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Electrical Engineering

Center of Wireless Technology Eindhoven



**TU** / **e**

Technische Universiteit  
**Eindhoven**  
University of Technology

**Where innovation starts**

## 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

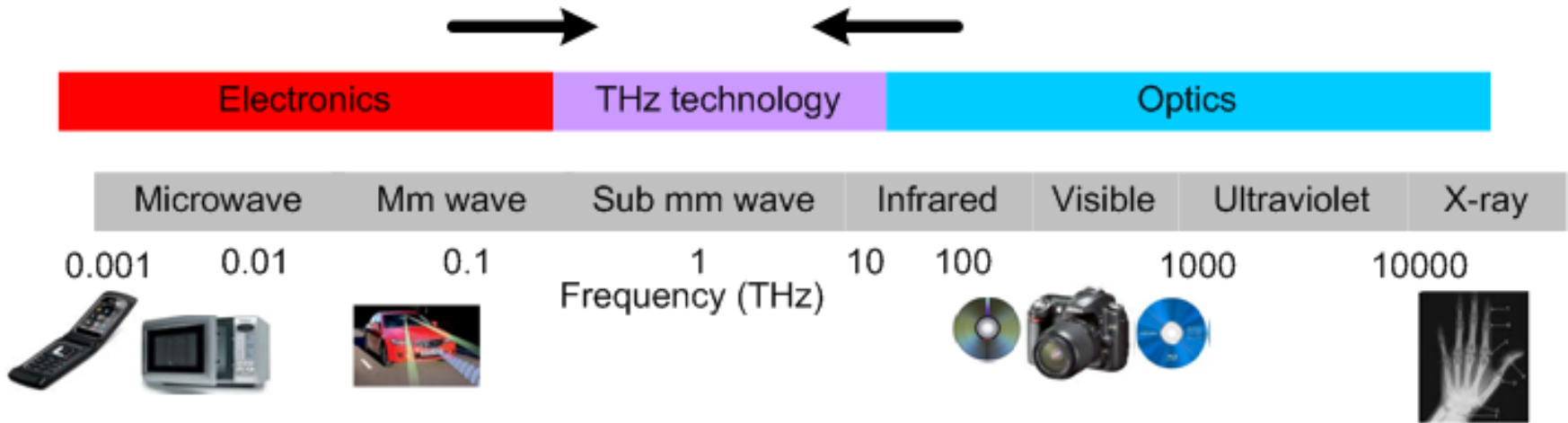
## Free space network analyzer for application testing

## Conclusions

# THz radiation: Unique properties

1 THz = 1000 GHz

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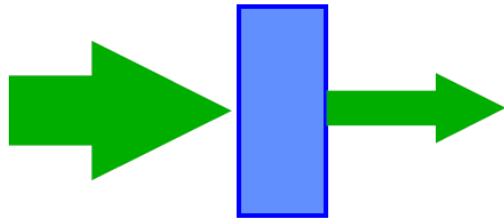
- THz radiation can **penetrate** through non-polar materials (e.g. plastics, wood, clothing)
- THz imaging has sub-mm **resolution**
- THz spectroscopy **identifies** specific materials (e.g. explosives)
- THz radiation is **non-ionizing** (and therefore safer than X-ray)
- THz radiation is **strongly 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

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## Terahertz imaging

CW or pulsed systems



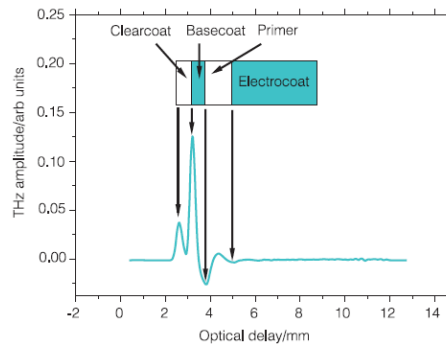
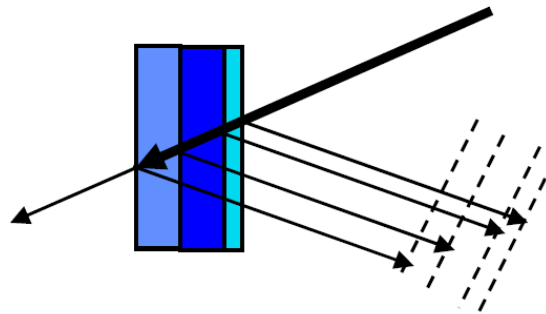
Intensity only

Intensity and phase

Amplitude and phase imaging

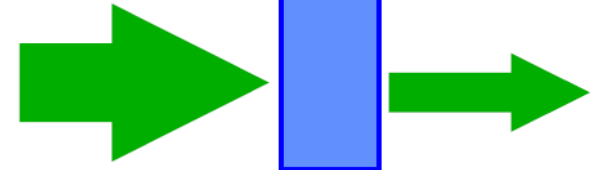
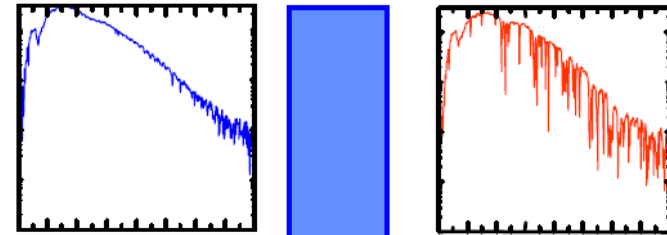
## Terahertz tomography

Pulsed systems



## Terahertz spectroscopy

CW or pulsed systems



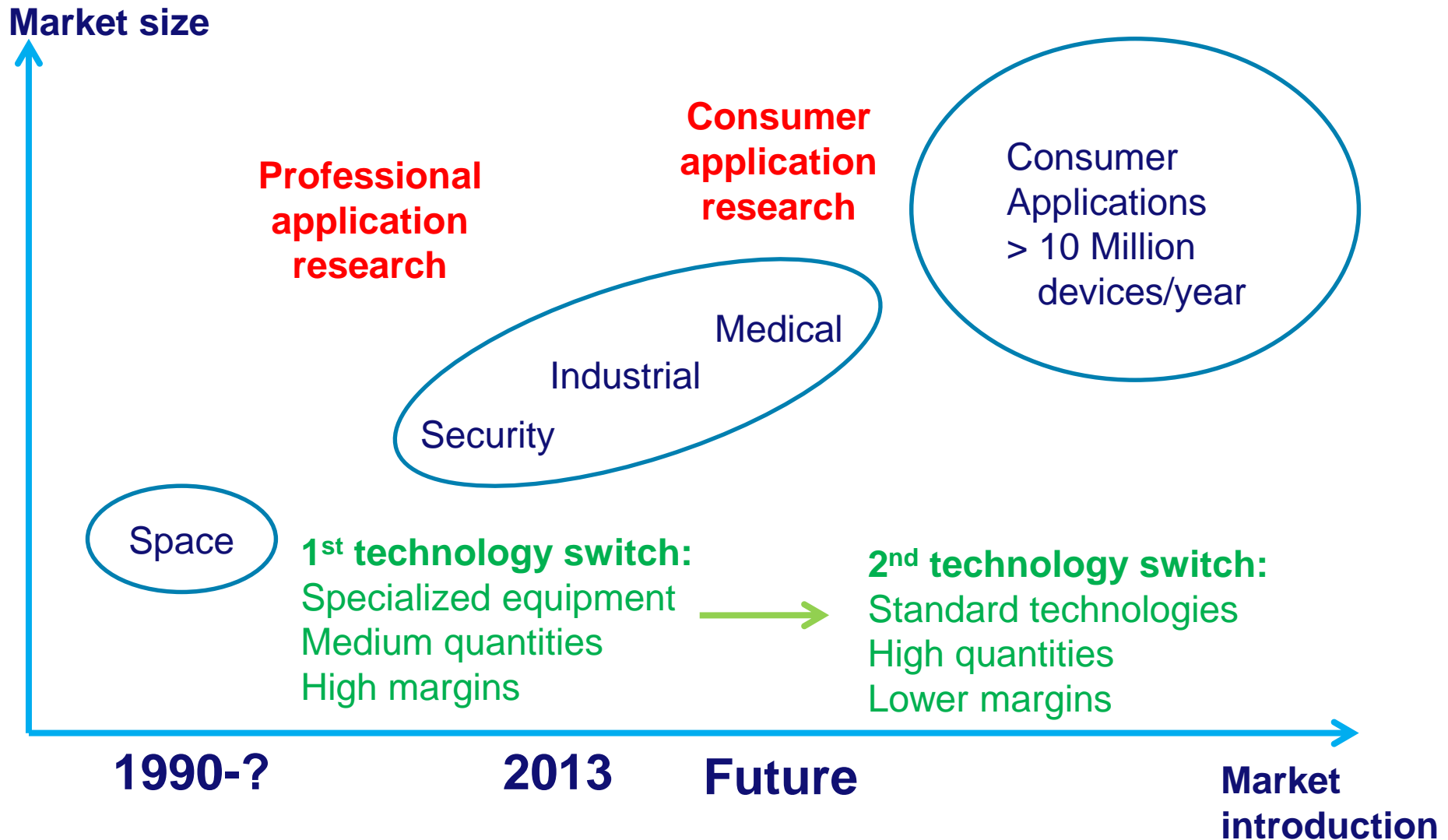
Intensity only

Intensity and phase

Broadband detection

Transmission or reflection measurements are both valuable

# Professional and consumer applications



## **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

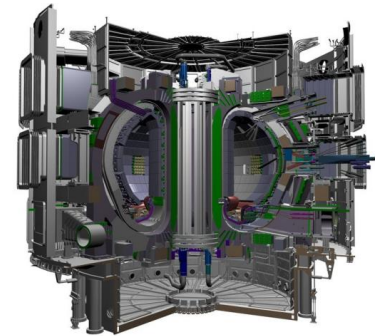
## **Terahertz for particle physics:**

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.



Tokamak reactor

## **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

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**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

## Introduction

- Terahertz unique properties
- Technology evolution
- Terahertz roadmap initiative

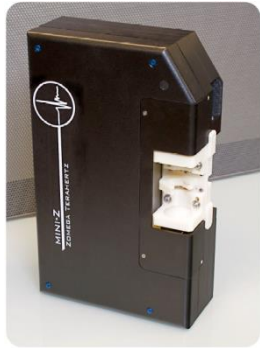
## Miniaturized terahertz systems for imaging and spectroscopy

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

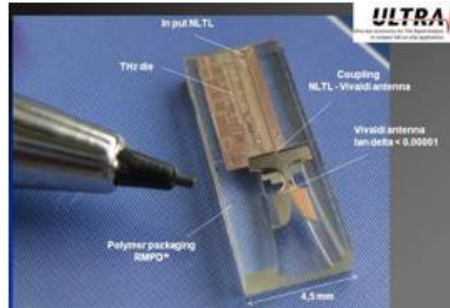
## Free space network analyzer for application testing

## Conclusions

# Research on miniaturized THz systems



Optical setups based on femtosecond lasers



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

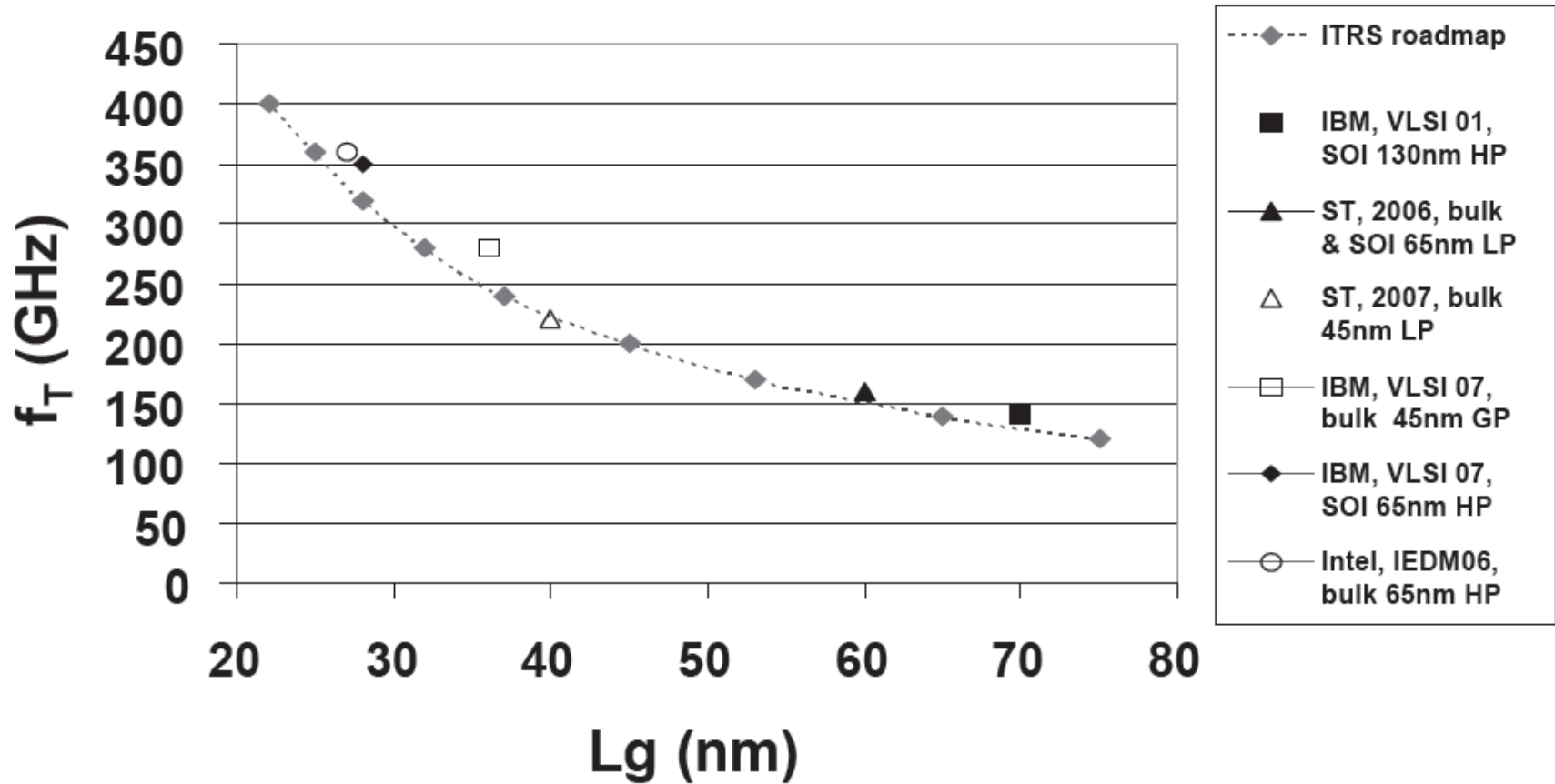
Hybrid approach: miniaturized/integrated opto-electronics sources and receivers

Miniaturized and integrated THz systems

New THz applications



# Frequency limits of CMOS transistors



← timeline

## 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

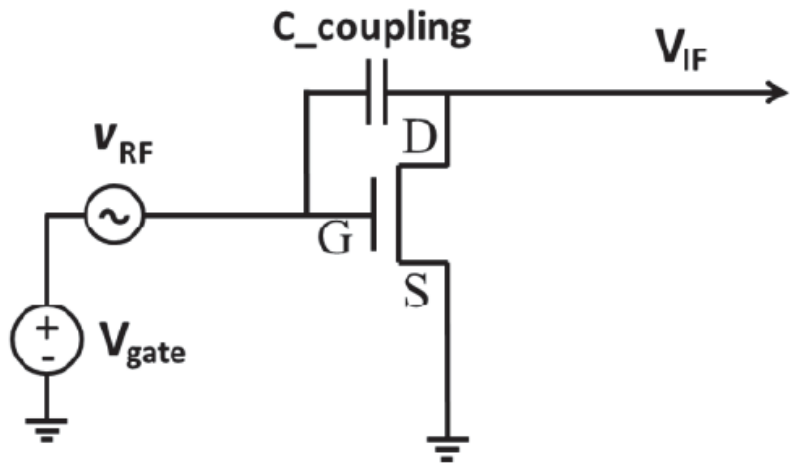
broadband direct conversion demonstrated

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!

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

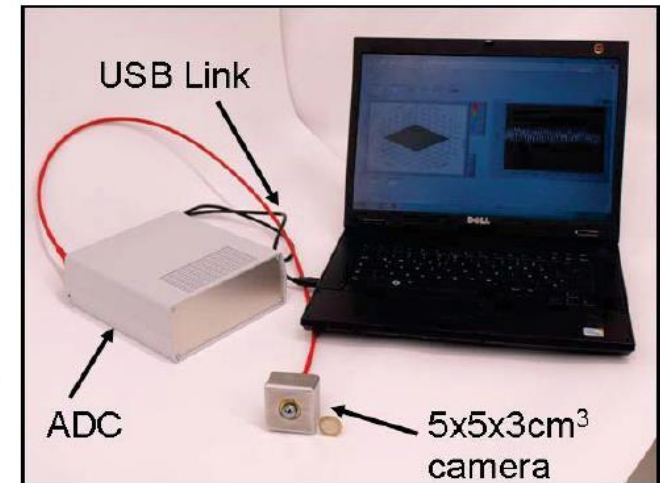
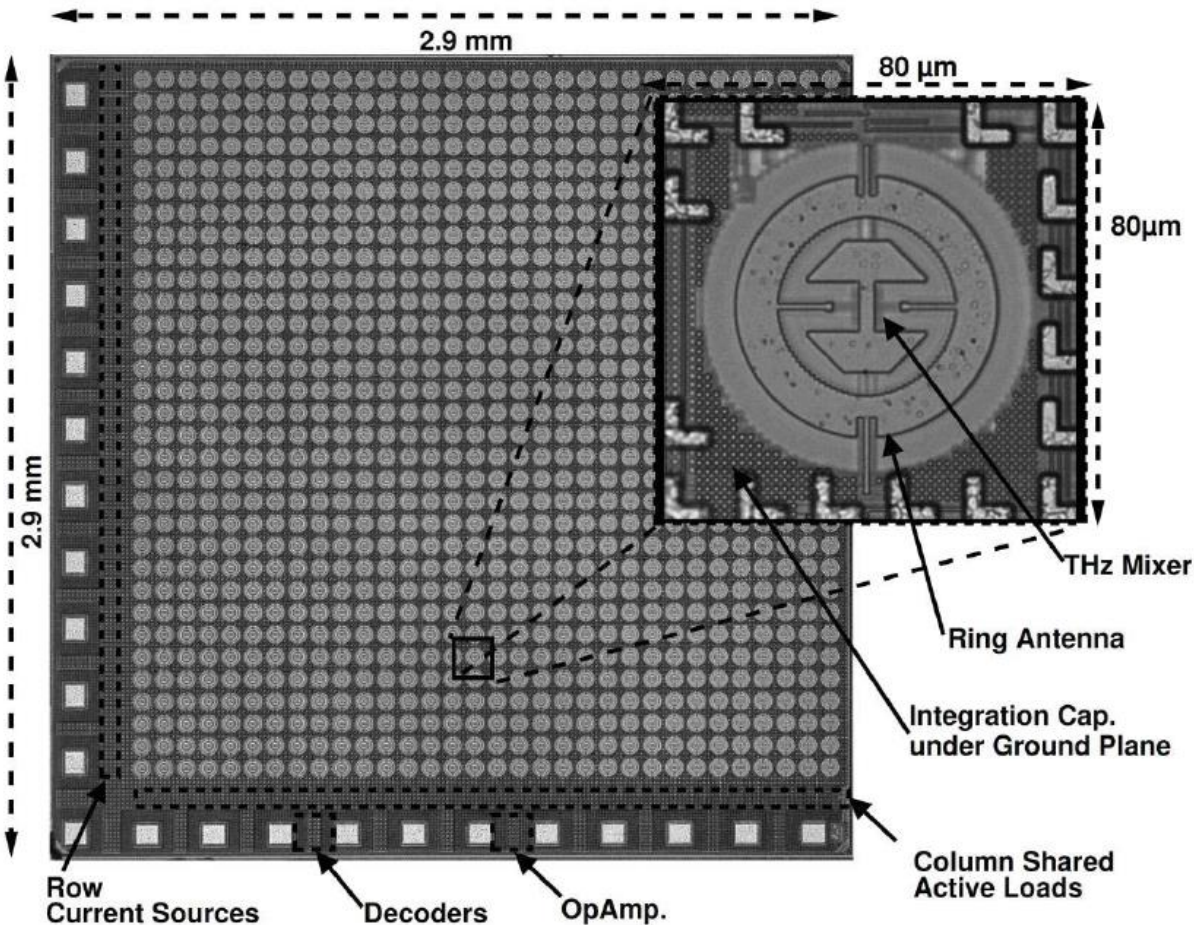
$$v_{gs}(t) = V_g + v_{RF}(t)$$

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

# 2012: World's first CMOS terahertz camera

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



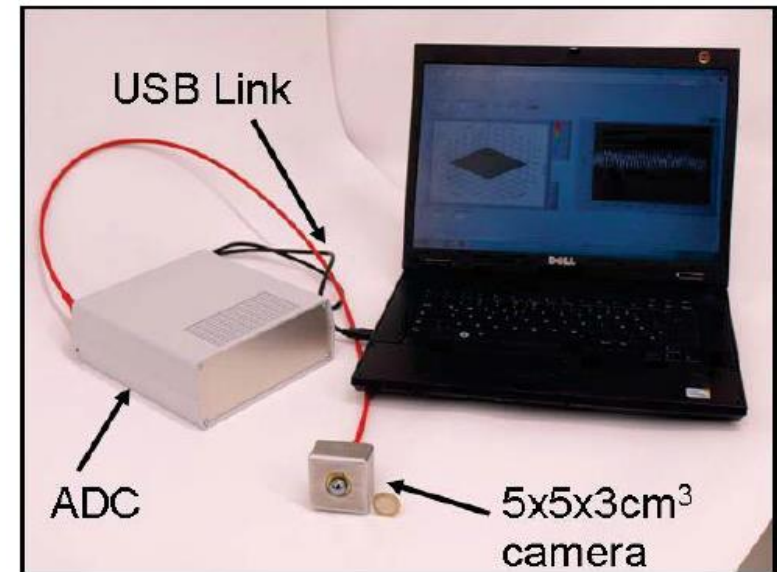
32 by 32 pixels, differential source coupled FET direct conversion



# Key specs of the CMOS terahertz camera

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

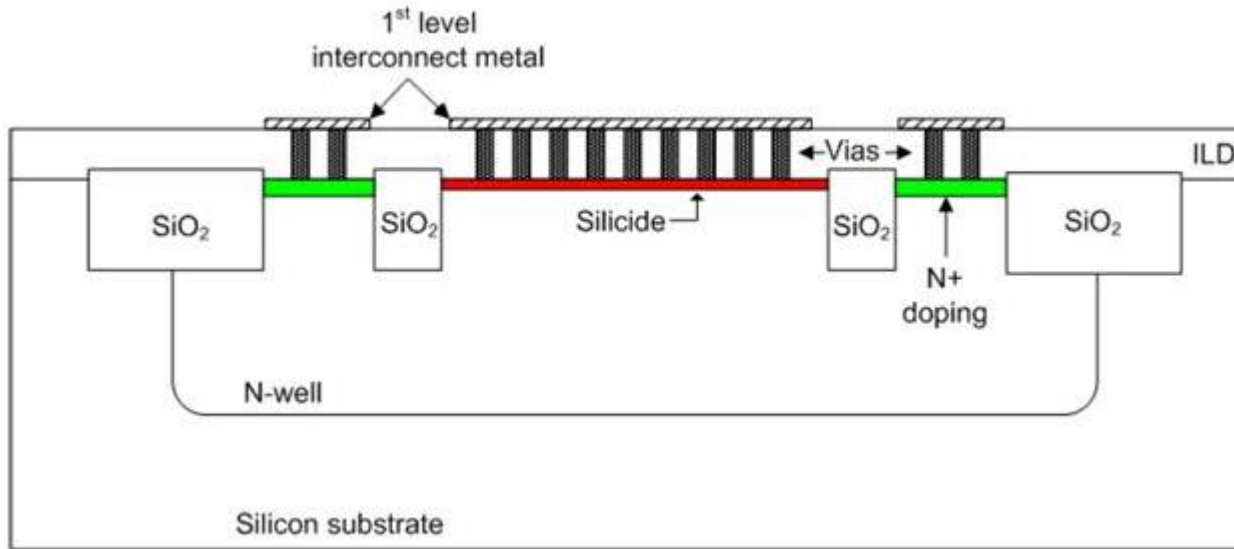


H.M. Sherry, U. R. Pfeiffer, University of Wuppertal, Germany



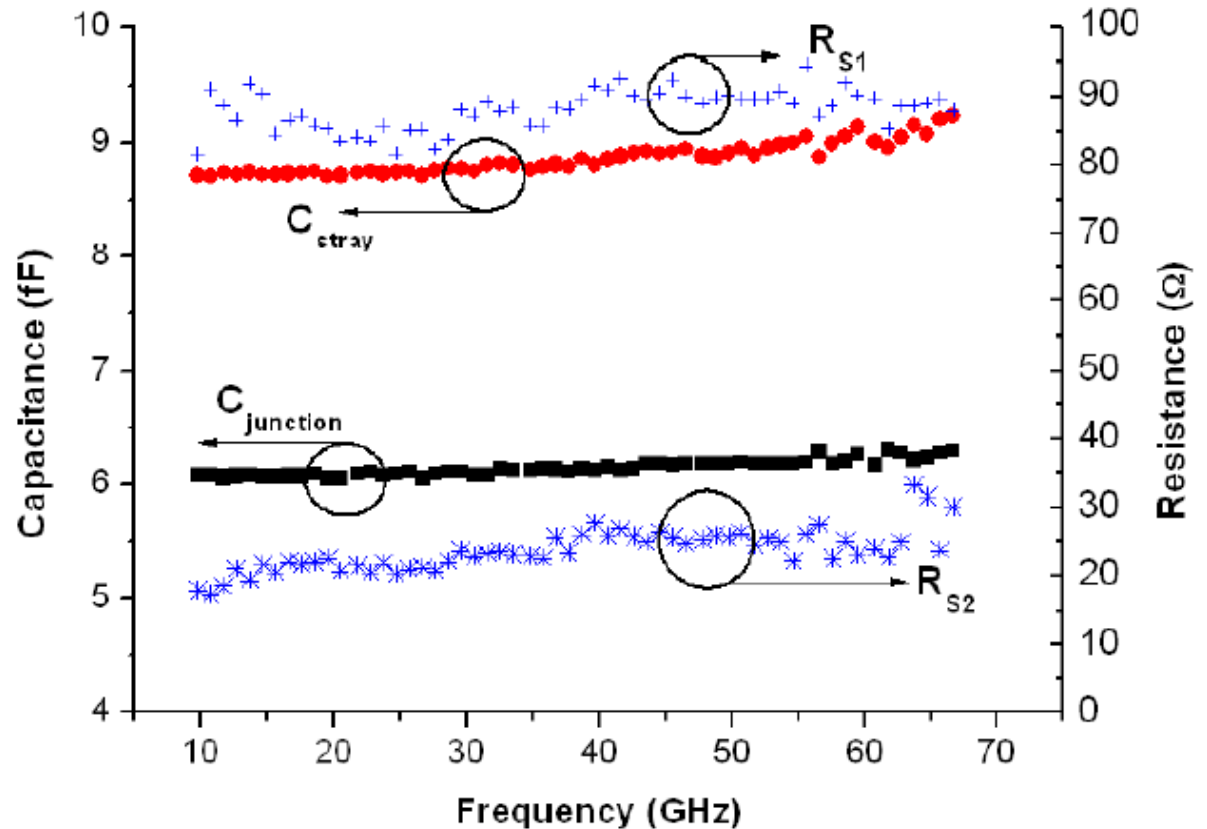
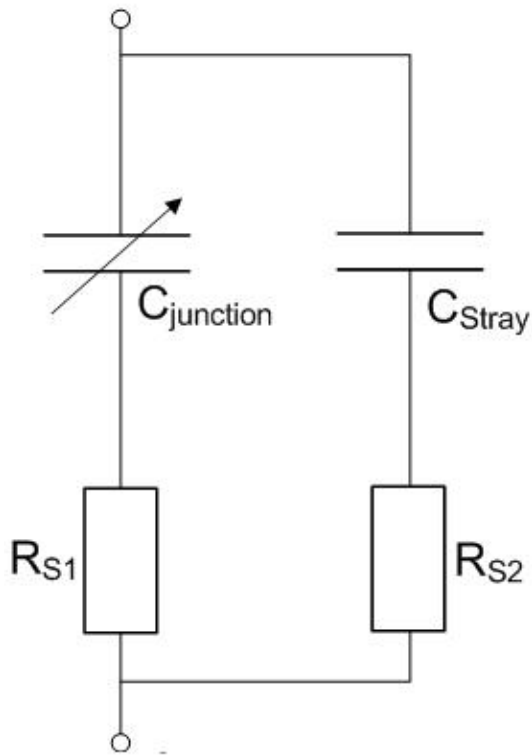
# Schottky diodes in CMOS: cross section

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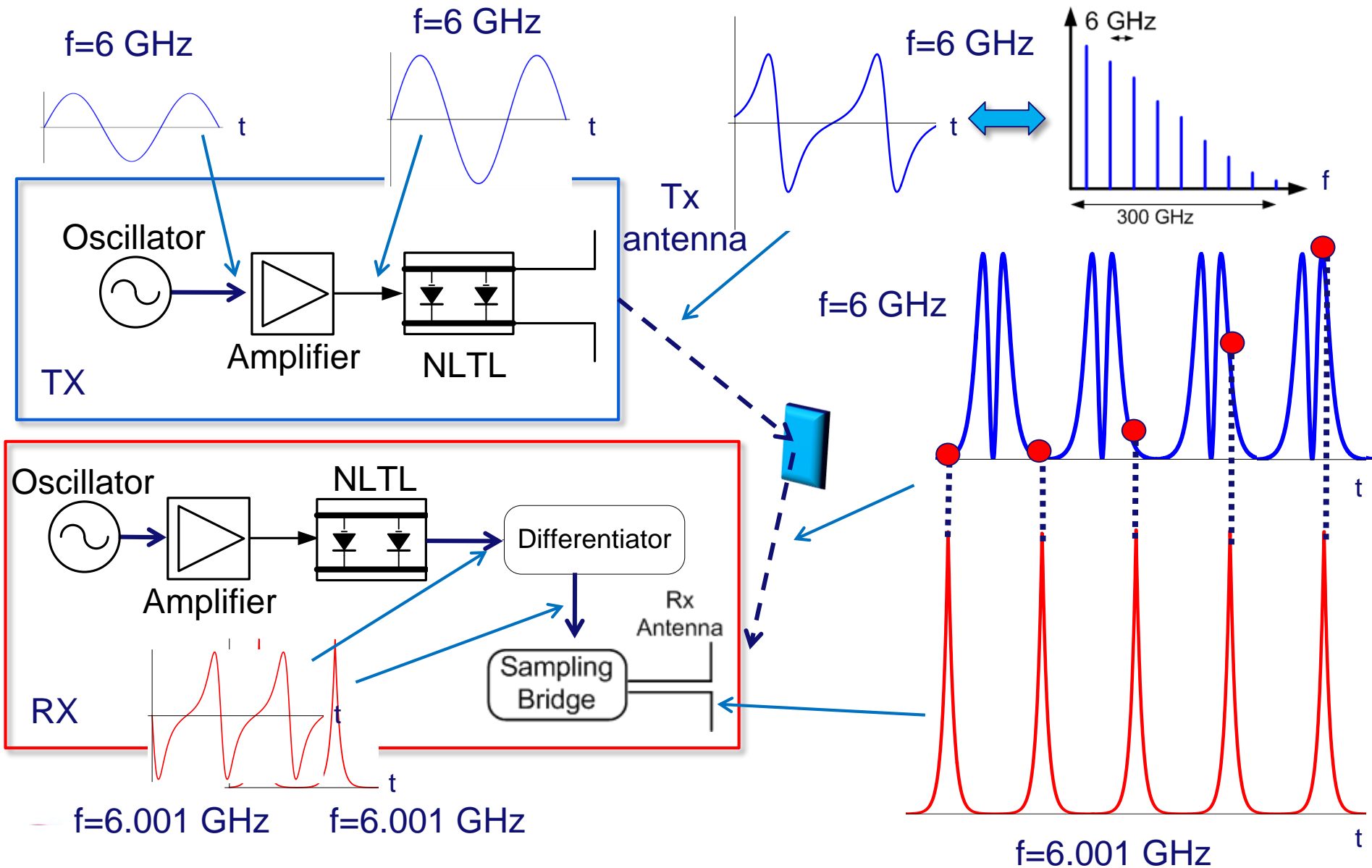
- Nonlinearity originates from the I(V) curve of the diode
- Speed of the diode originates from the parasitics and diode size

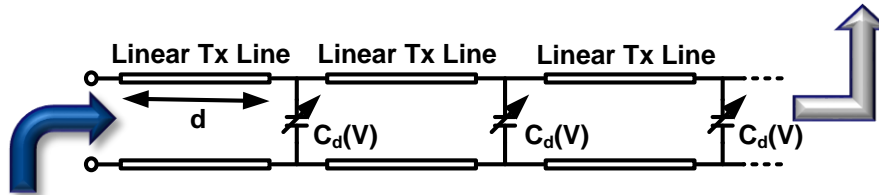
# Schottky diodes in CMOS: Reverse bias diode model



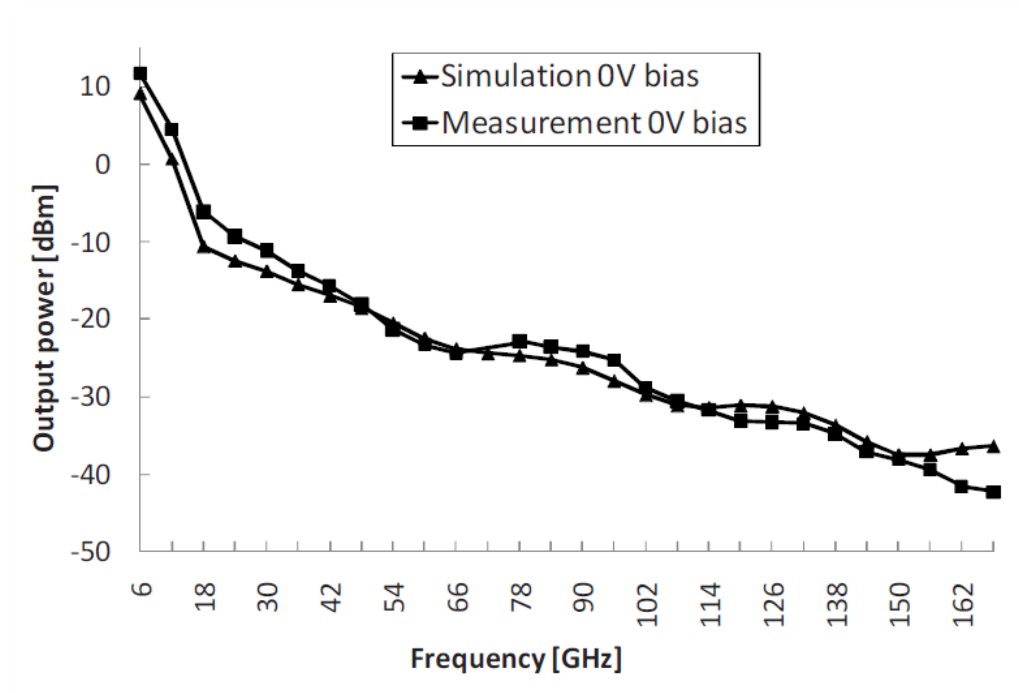
	$C_{\text{junction, 0V}}$ (fF)	$C_{\text{stray}}$ (fF)	$R_{S1}$ ( $\Omega$ )	$R_{S2}$ ( $\Omega$ )	$f_{C_{\text{junction, 0V}}}$ (GHz)
<b>Diode (a)</b>	6.6	1	104	-	231
<b>Diode (b)</b>	6.5	7.8	57	8	430

# System overview



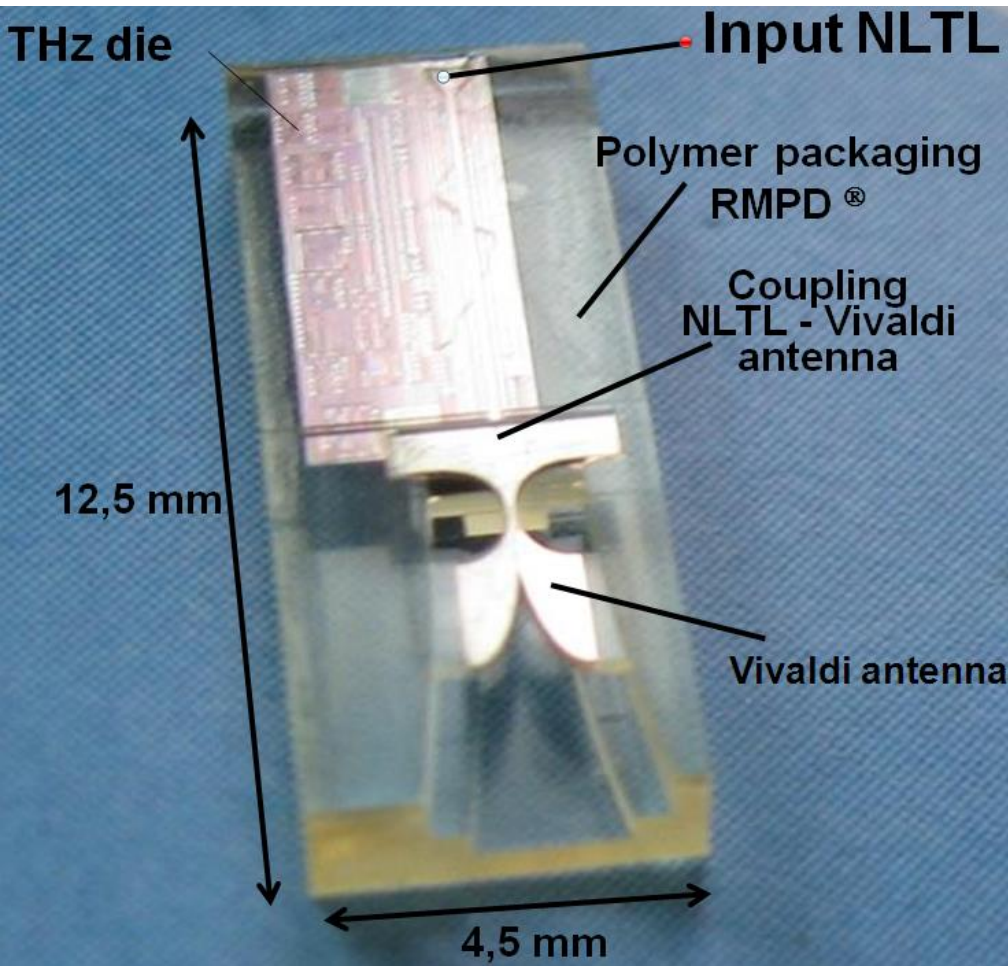


Input: Sinusoid  
 $P_{in} = 18 \text{ dBm}$   
 6 GHz



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

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.

# Terahertz imaging with NLTL source

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## Visible



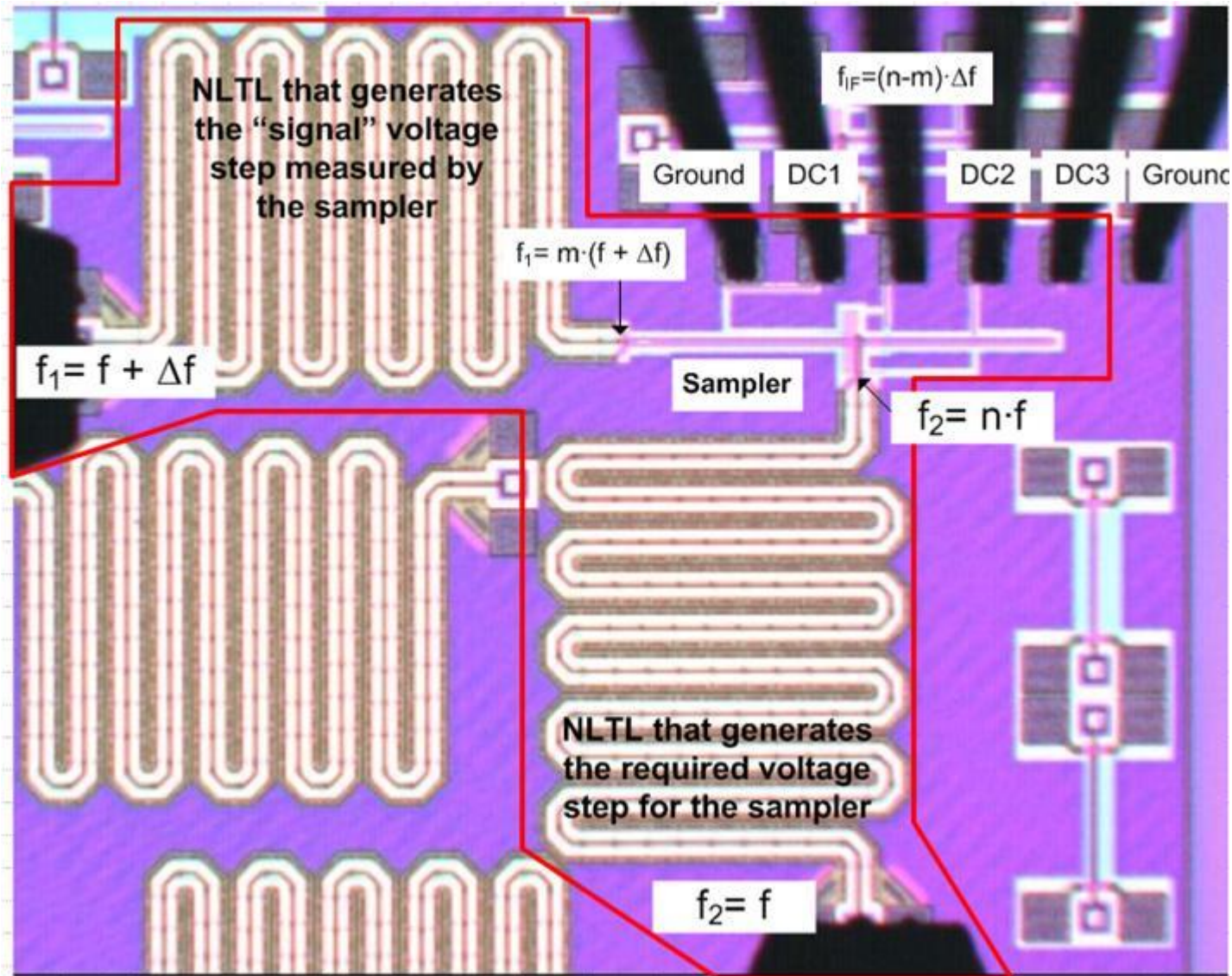
## 200 GHz image



Prof. P. Haring-Bolivar

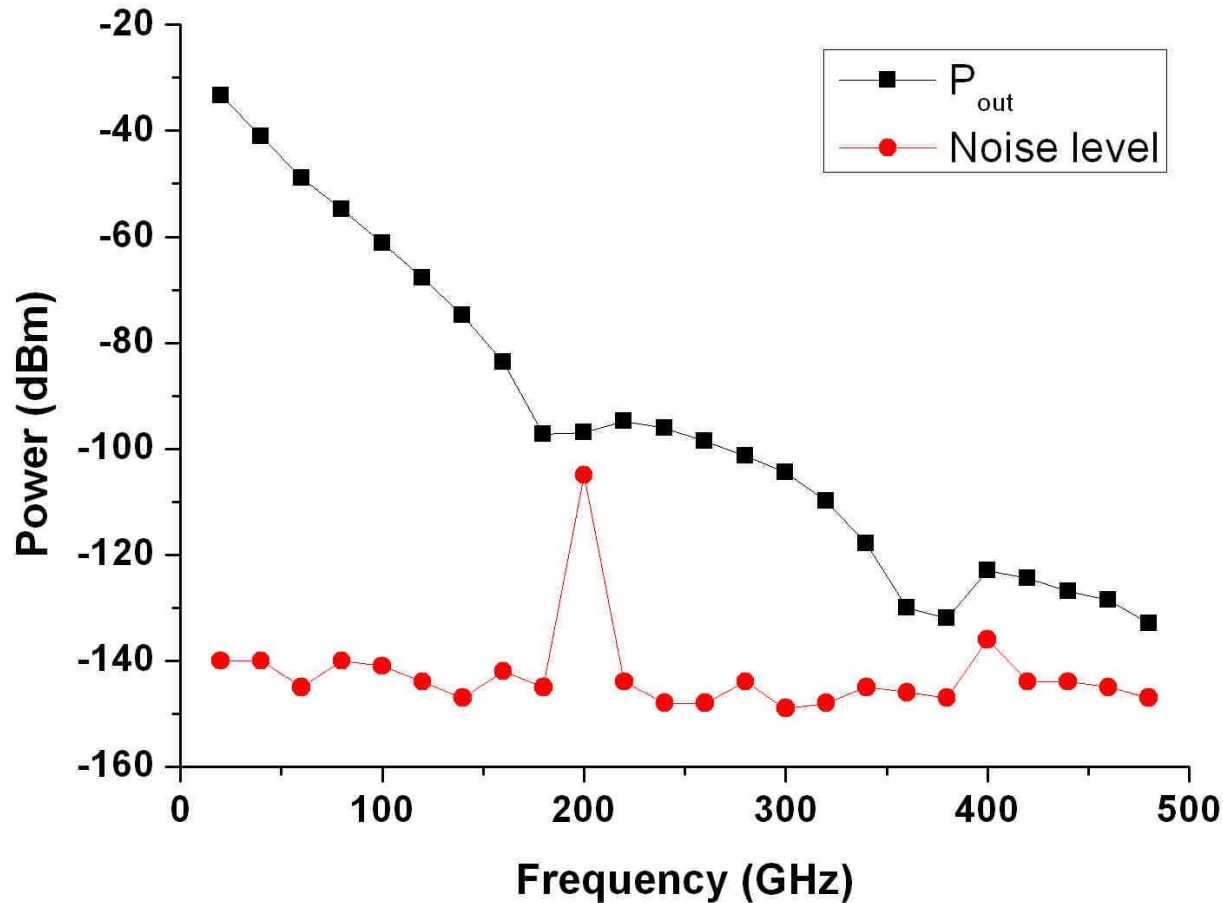


# On-chip sub-THz generator and sampler



# Output spectrum of nonlinear transmission line

Input signal:  $f=20$  GHz, 18 dBm

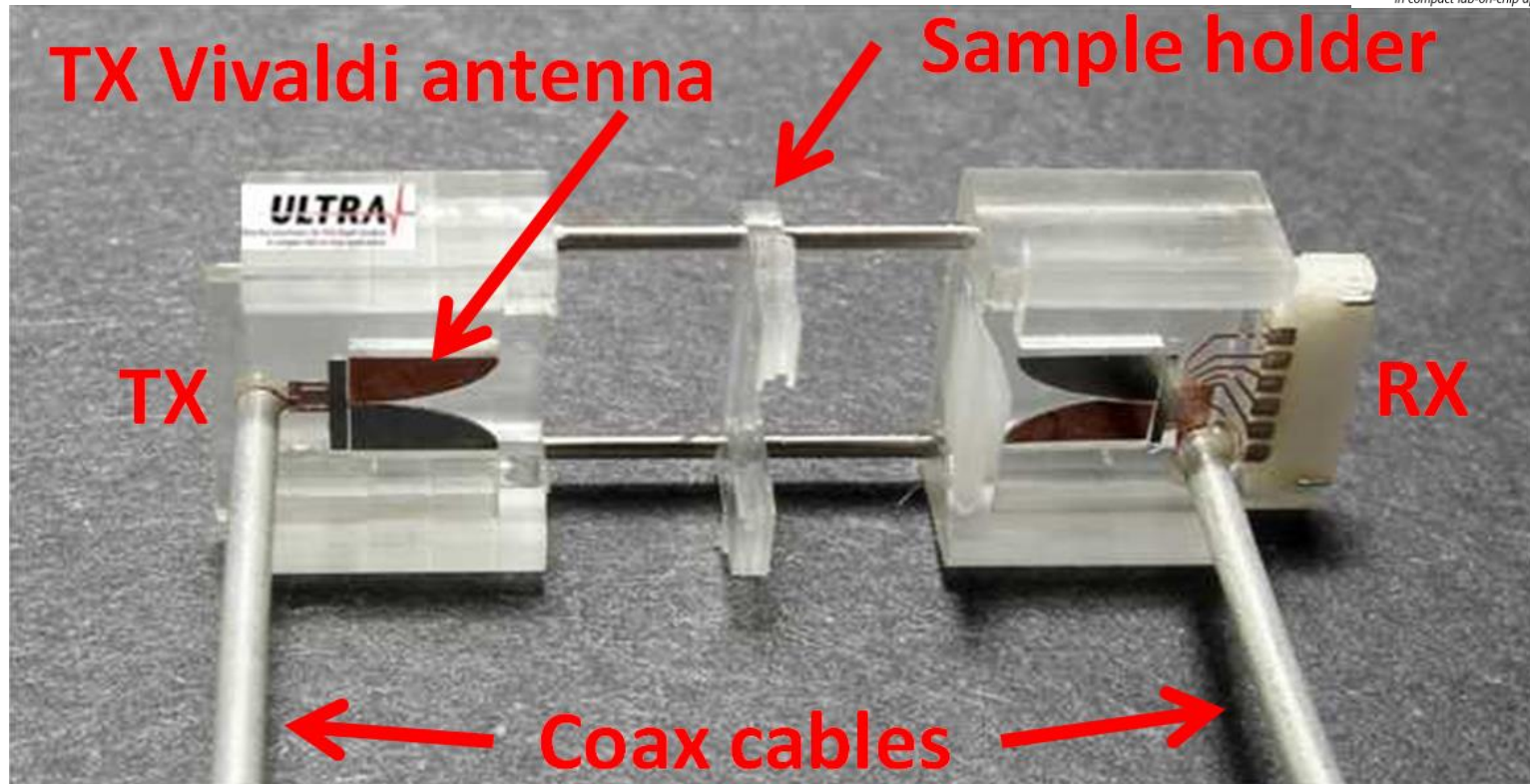




# Hybrid integration concept

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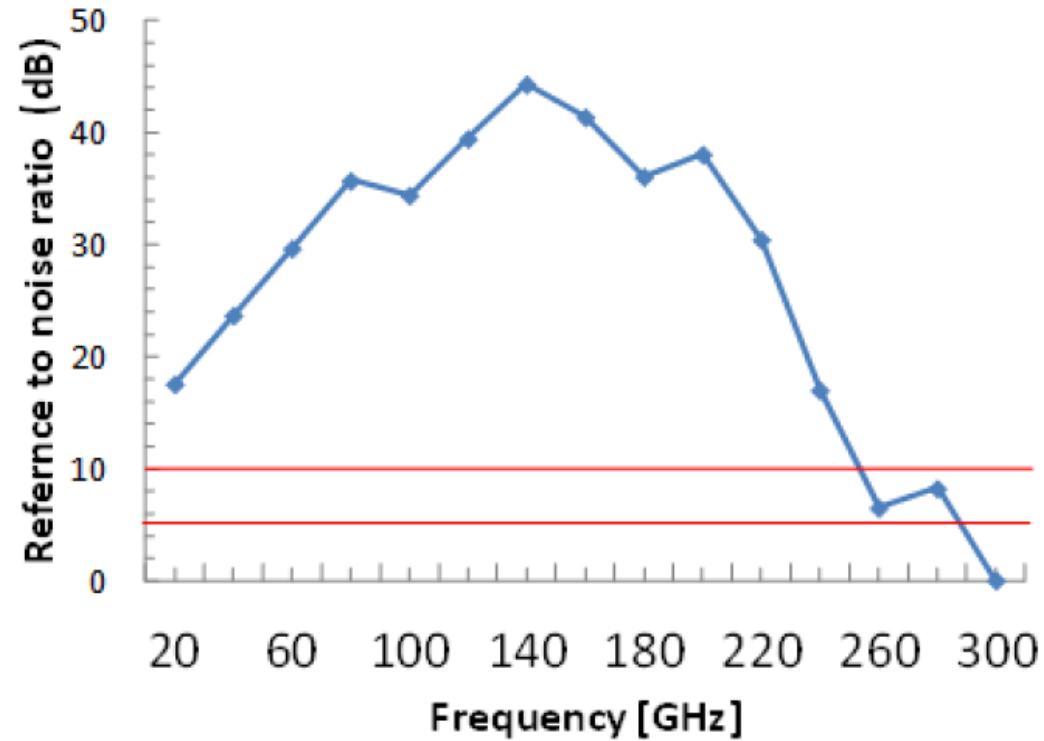
**ULTRA**  
Ultra fast eElectronics for THz Rapid Analysis  
in compact lab-on-chip applications



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

# Terahertz microsystem: Dynamic range

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## Introduction

- Terahertz unique properties
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- Terahertz roadmap initiative

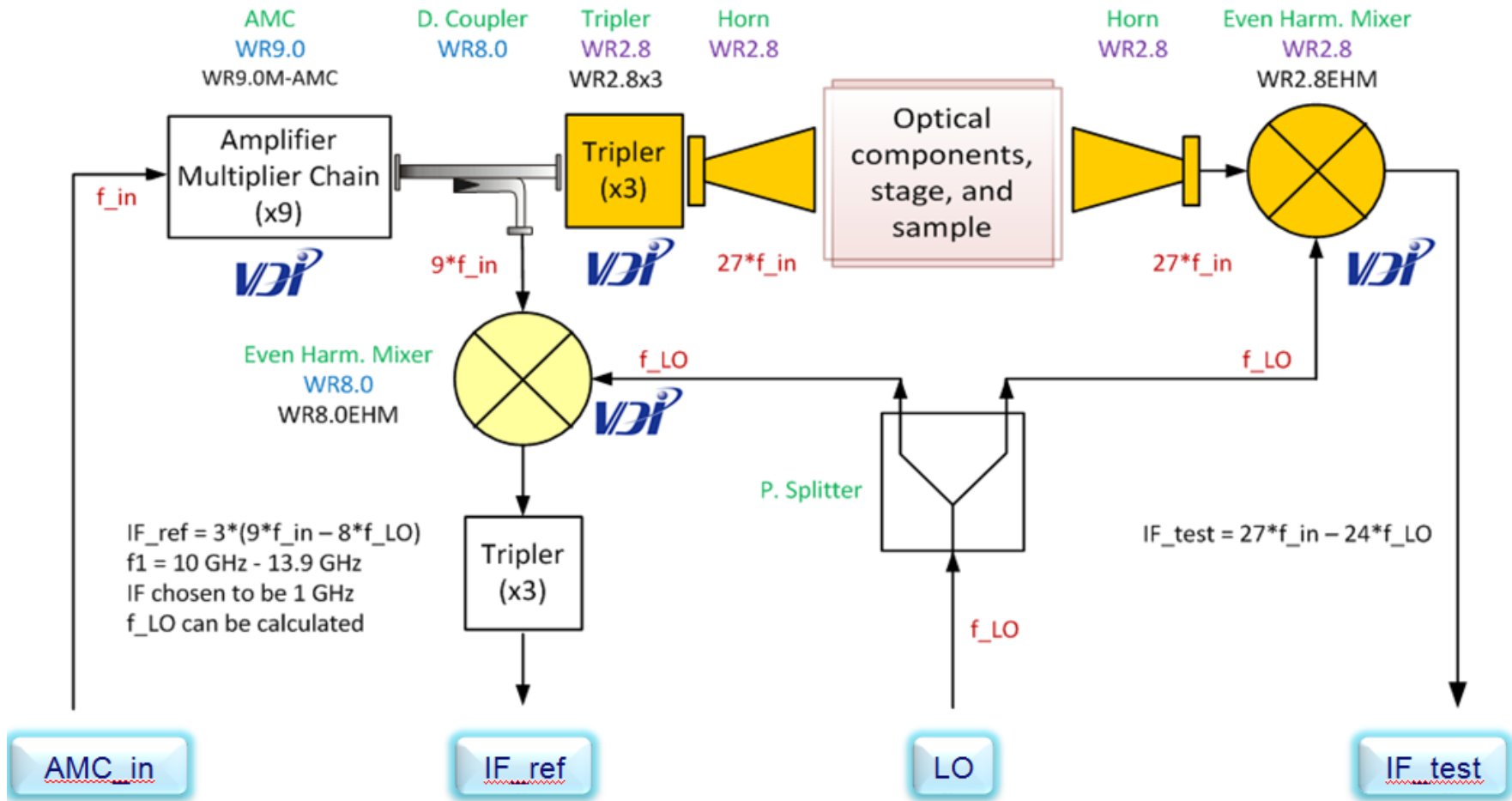
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**Free space network analyzer for application testing**

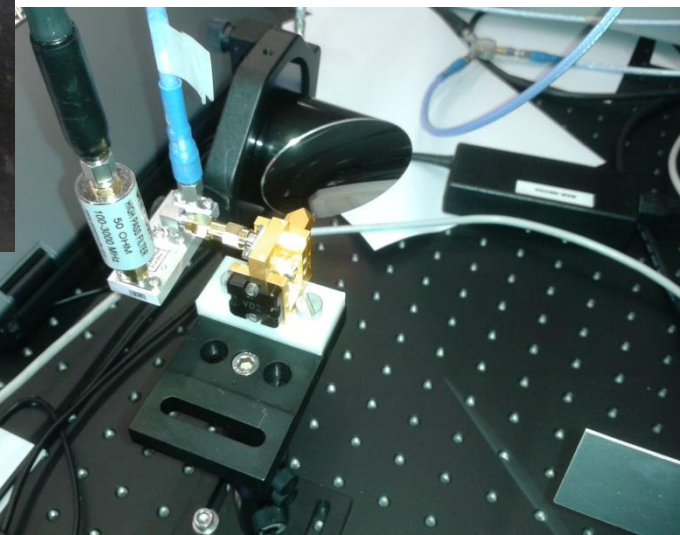
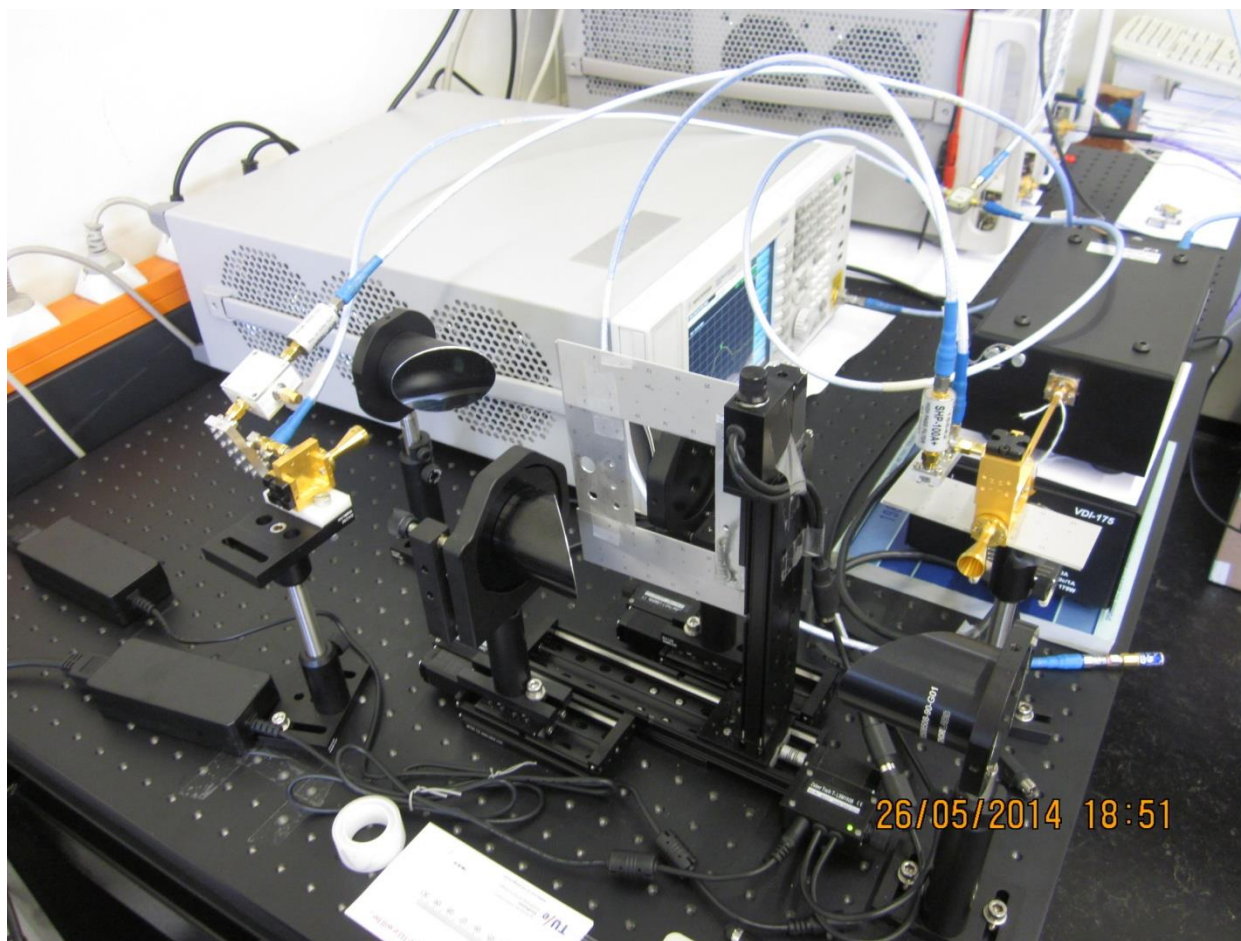
## Conclusions

# 270 GHz to 370 GHz free space network analyzer





# Free space Network analyzer

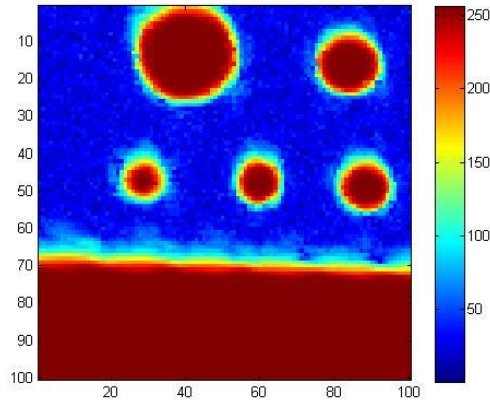


**90 GHz to 120 GHz setup**

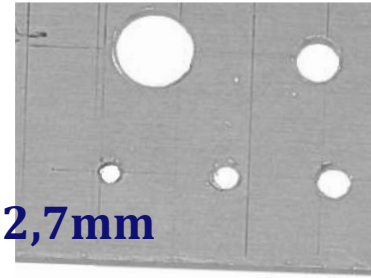
**Up: Tripler+antenna  
Down: downconversion  
for operation in WR 2.8**

# Amplitude images at 345 GHz

**Metal plate  
with  
holes**



**D=10,05mm**



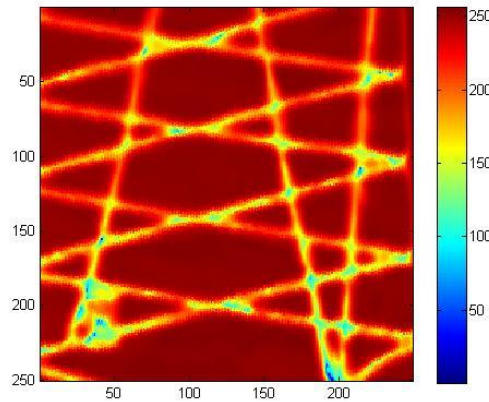
**D=6mm**

**D=4,5mm**

**D=2,7mm**

**D=3,5mm**

**Plastic card  
with  
metal  
ribbon**



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 (Euroensors), [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.

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