CHALMERS
UNIVERSITY OF TECHNOLOGY

What nano-technology can do to create efficient and integrated components for THz heterodyne arrays

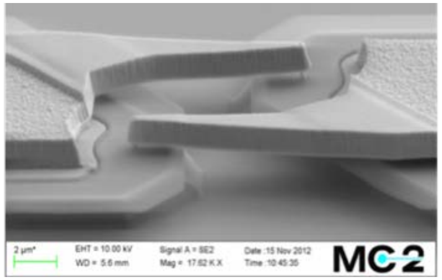
Jan Stake

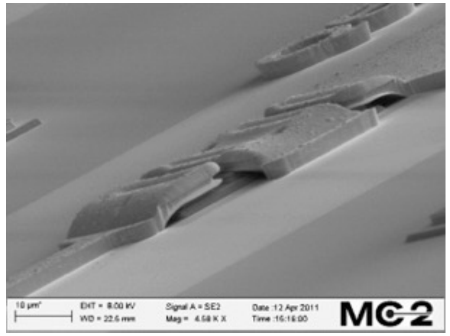
THz heterodyne array workshop

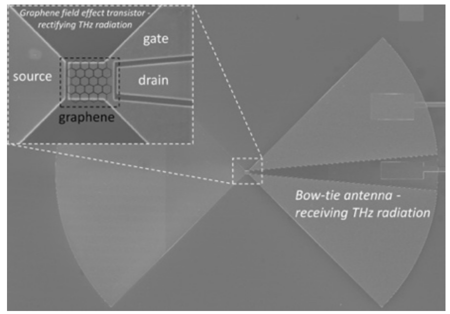
Nunspeet, March 11, 2017

Outline

- **Background and motivation**
  - Challenges
- **Front-end electronics**
- **Frequency multipliers for LO signals**
  - HBV frequency multipliers
  - Single diode triplers and quintuplers
  - Grid multipliers
- **Heterogeneous integration for THz applications**
  - Heterogeneous integration
  - Integration approaches
  - Integrating THz electronics
- **Nano electronics**
  - Graphene

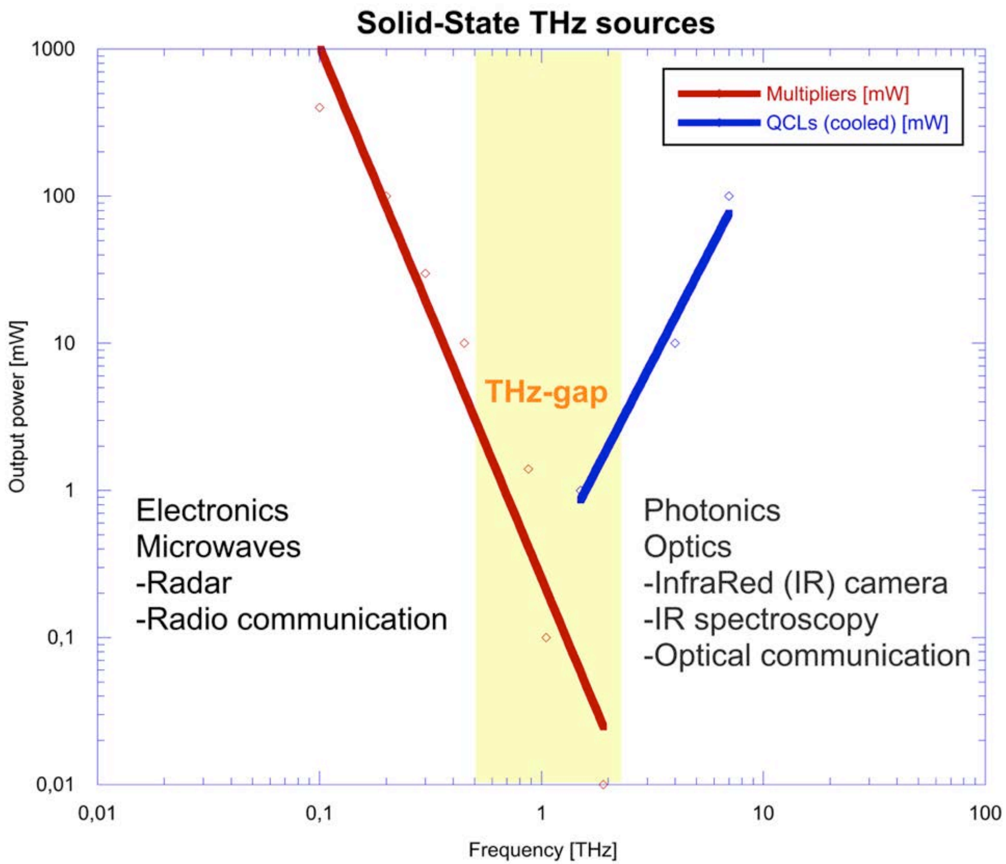




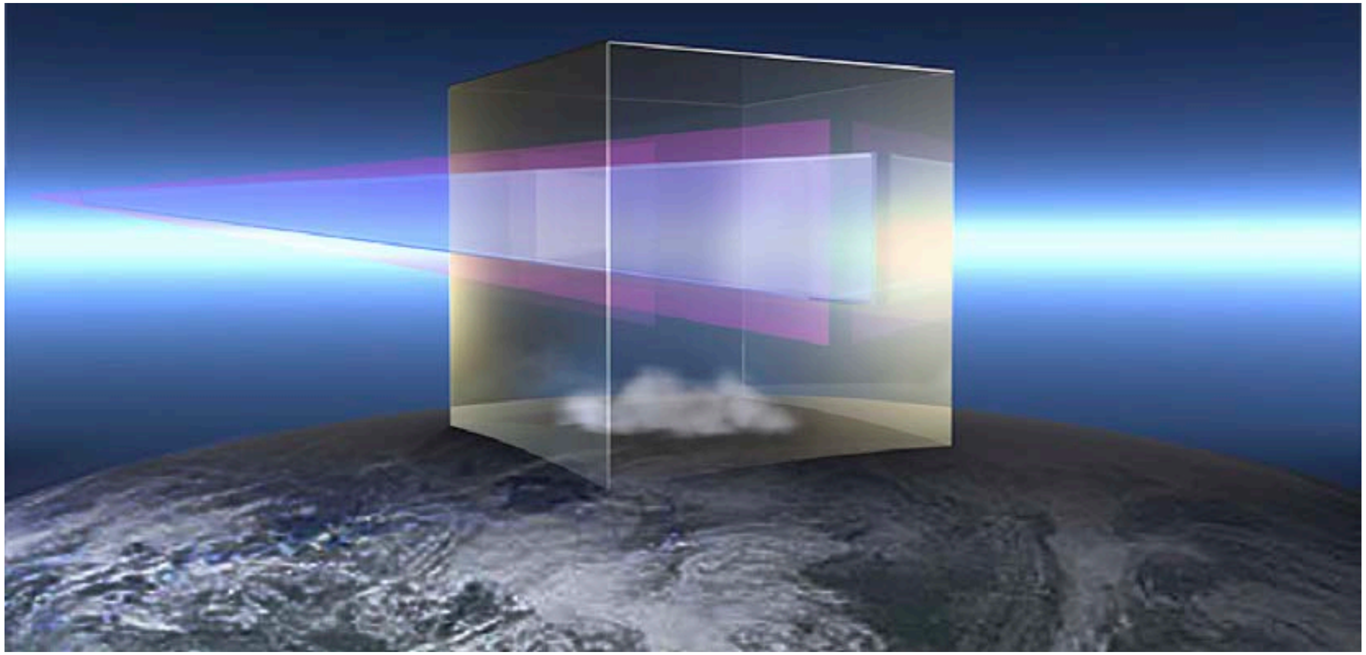


Research challenges

- Multi-pixel and heterodyne arrays
    - Increase in output **power**
    - Reduce total power requirement with better **efficiency**
    - **Integration** and how to build complex circuitry



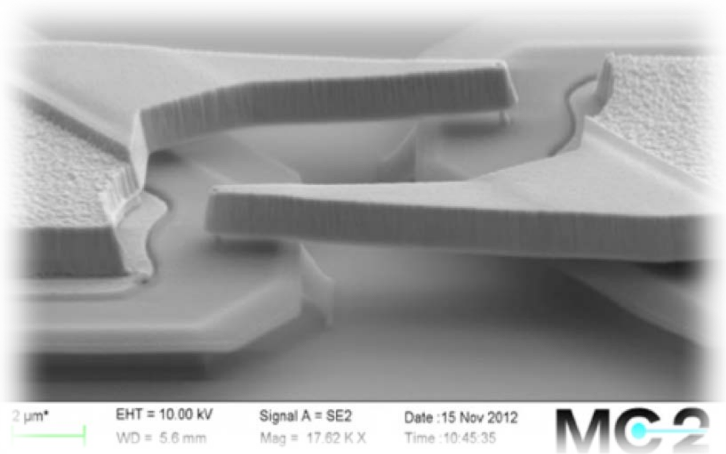
SteamR (Stratosphere Troposphere Exchange And Climate Monitor Radiometer)

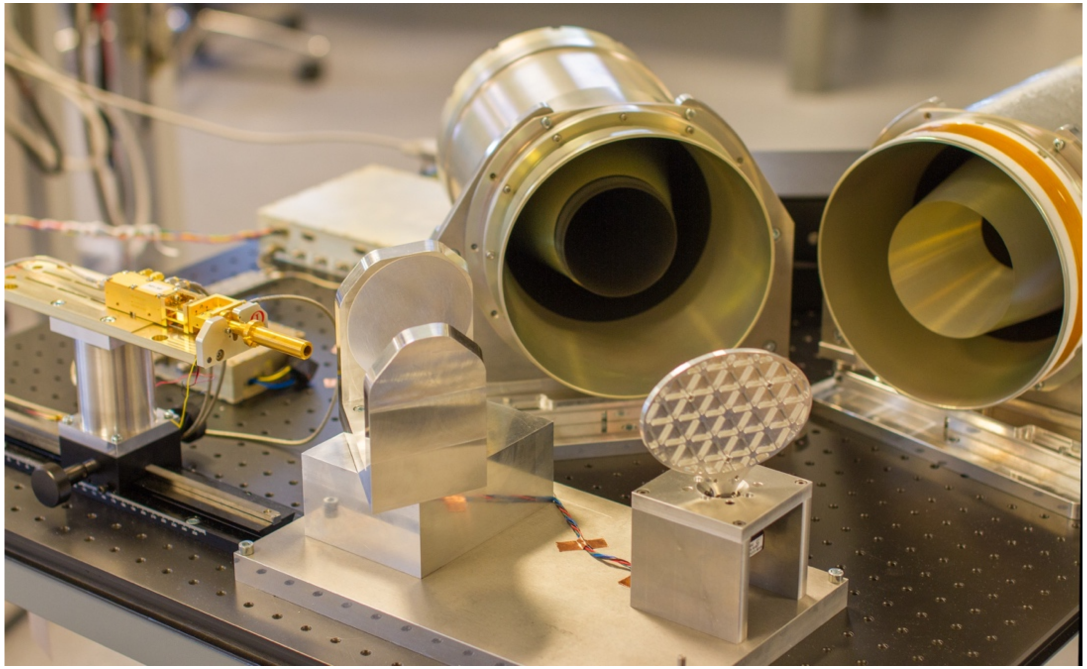


Array of heterodyne Schottky diode receivers

Front-end electronics

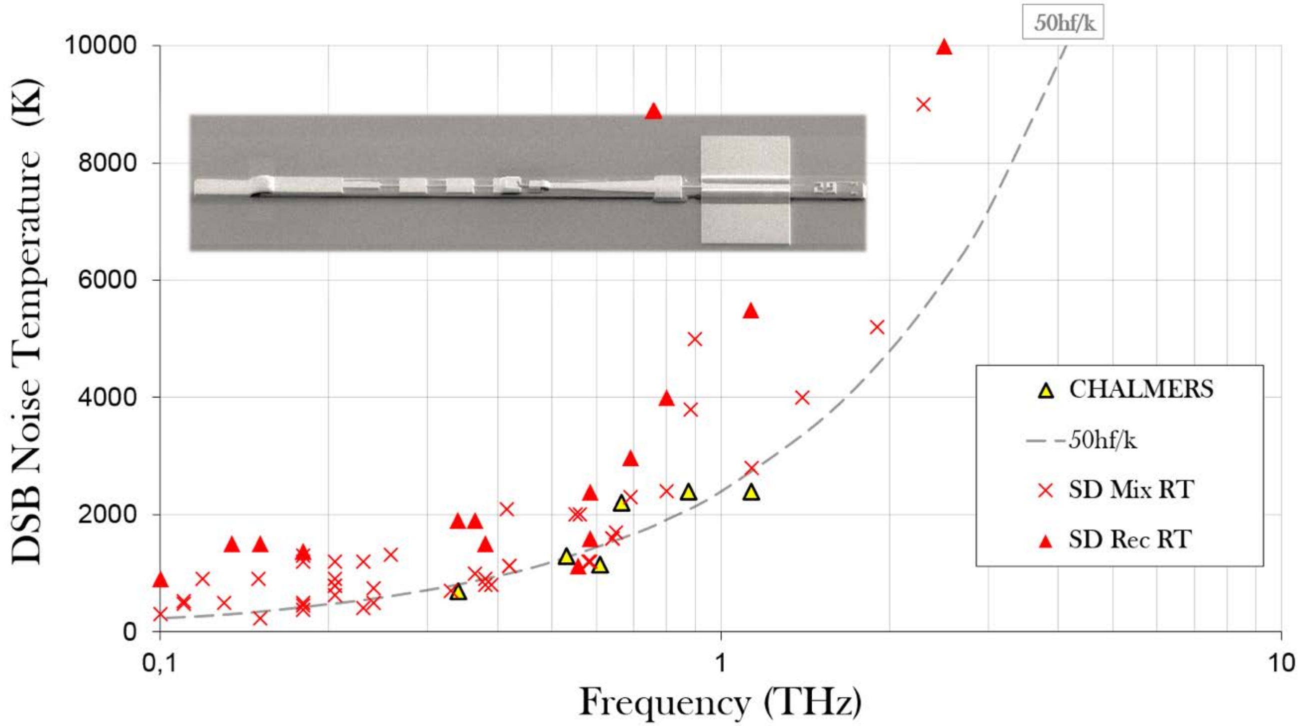
- High efficiency
- Integrate several functions



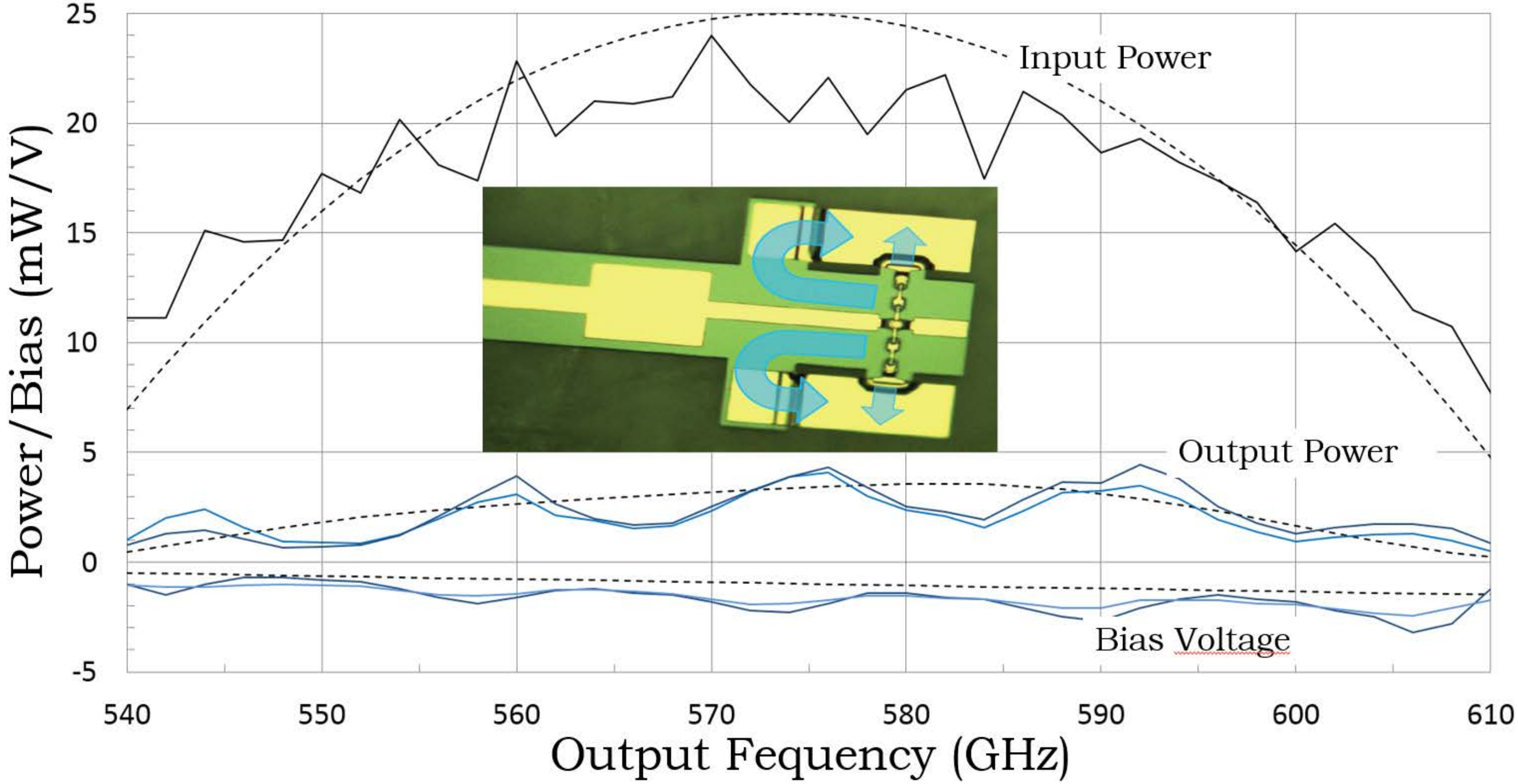


Schottky TMIC process / mixers

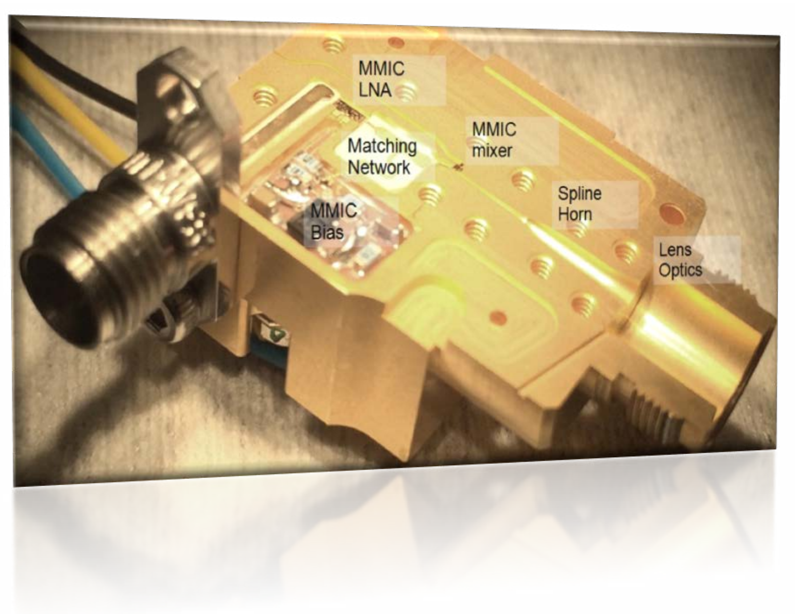
- Integrated on thin GaAs membrane forming a suspended stripline technology
- Devices as small as 0.1 µm^2
- Undergoing LAT for 2nd generation MetOp

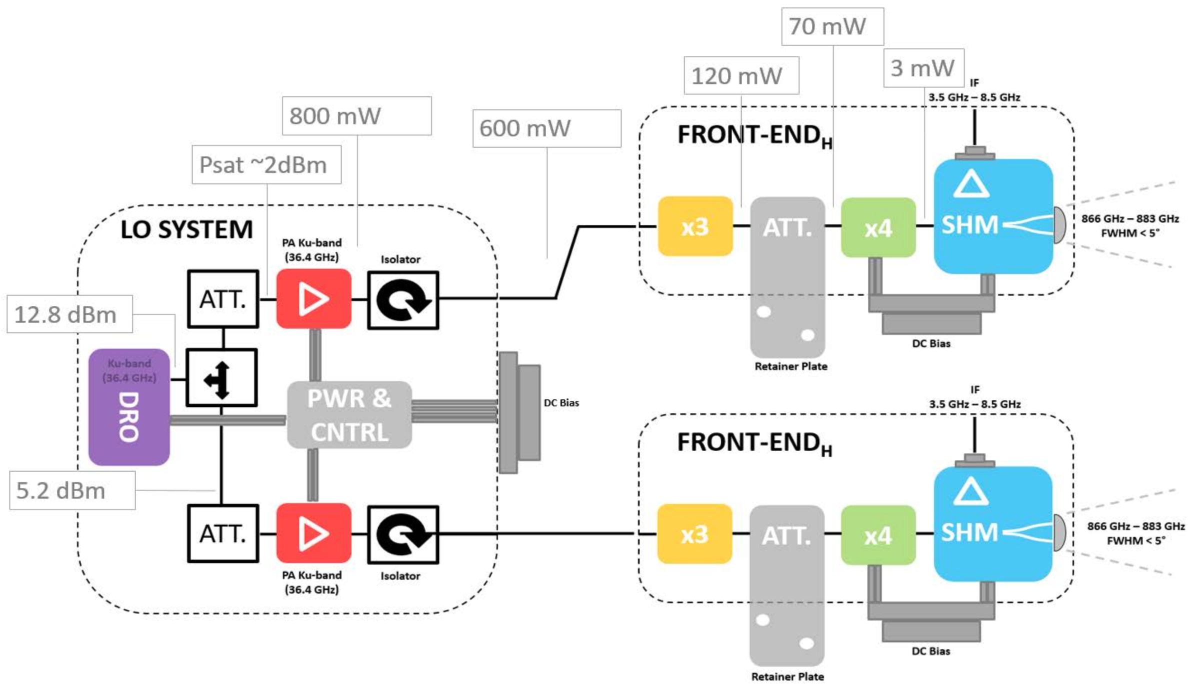


Schottky TMIC process / multipliers



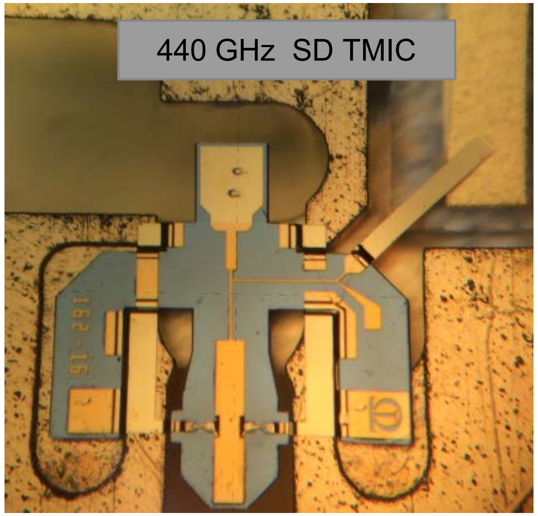
875 GHz Receiver Front-end for an Airborne Icecloud Imager Demonstrator

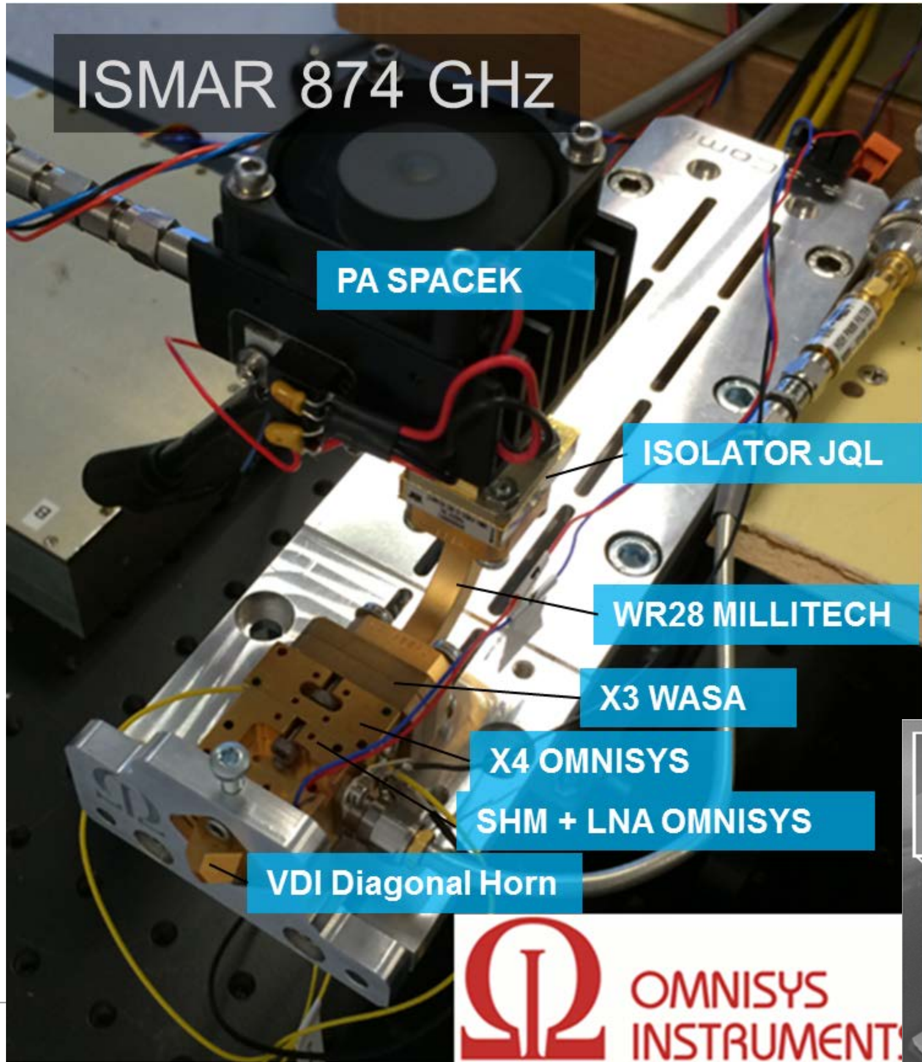


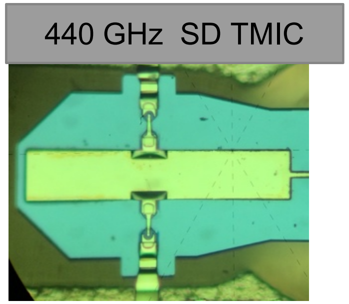


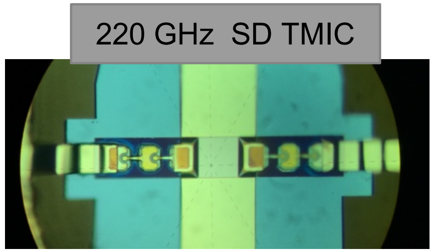
Courtesy of Peter Sobis, Omnisys Instruments.

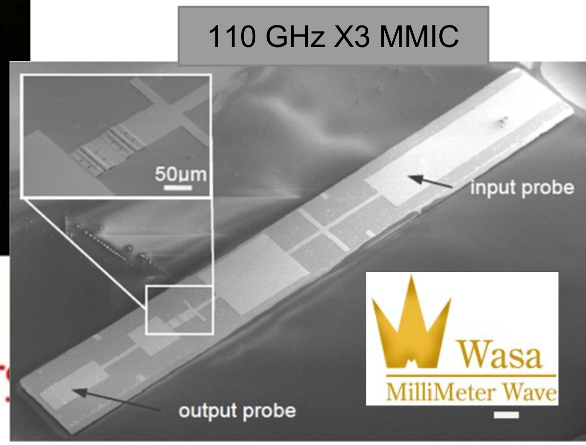
200 mW @ 110 GHz (η~20%)
25 mW @ 220 GHz (η~30%)
5 mW @ 440 GHz (η~20%)
Tr,min ~ 2500 K



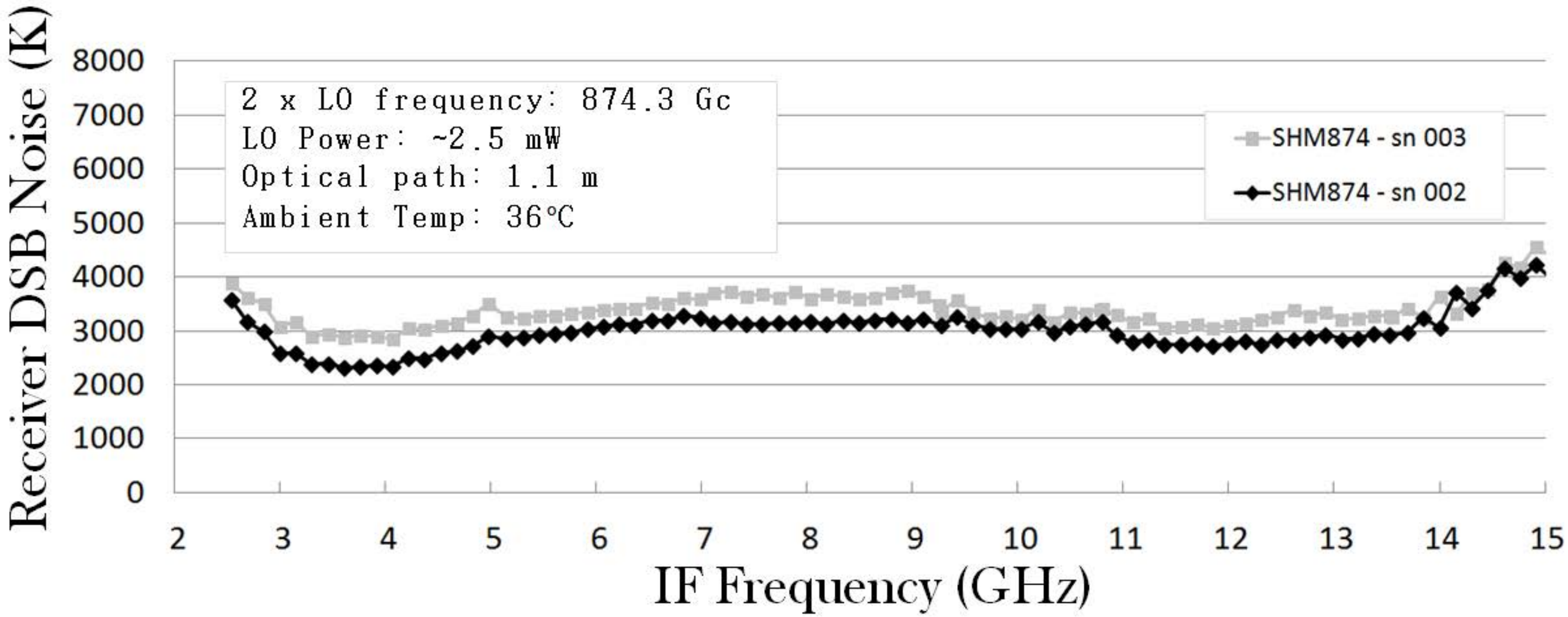






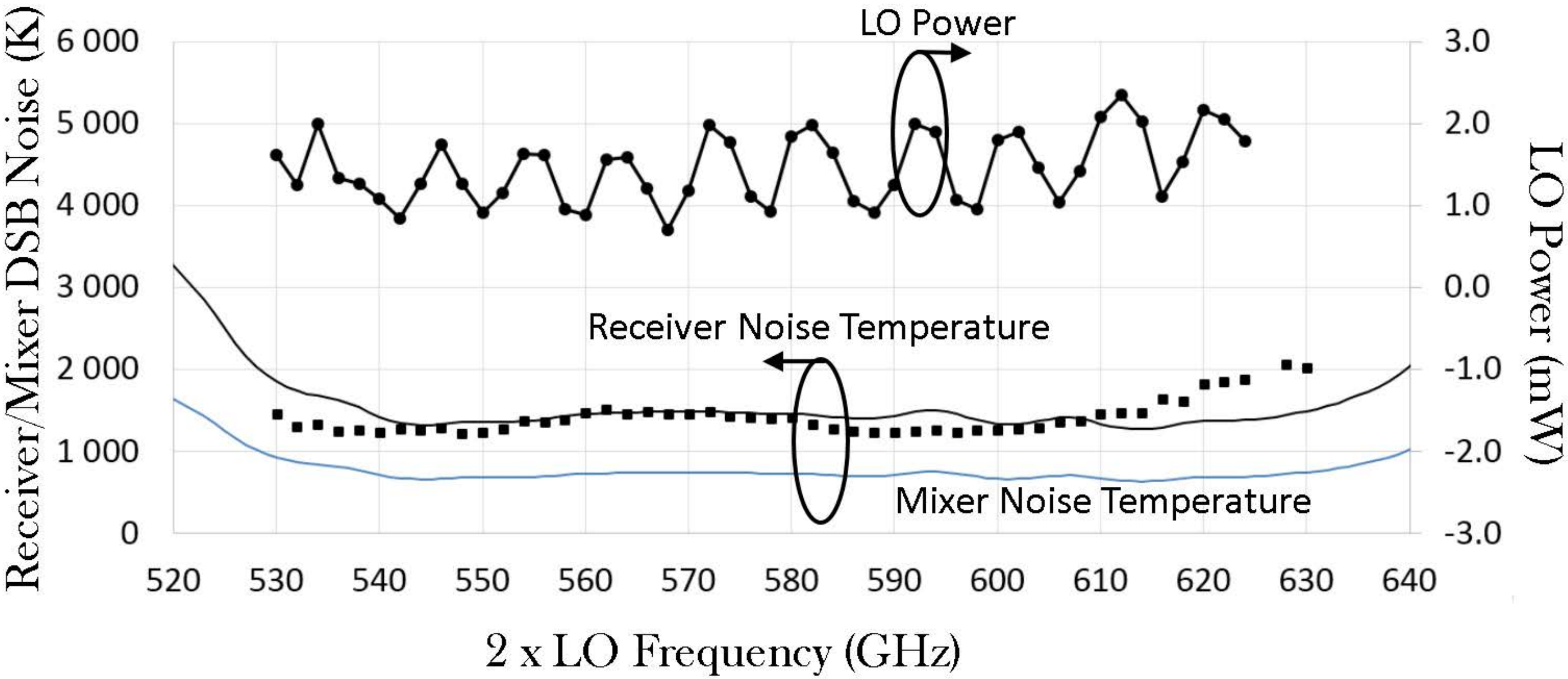


ISMAR receiver performance



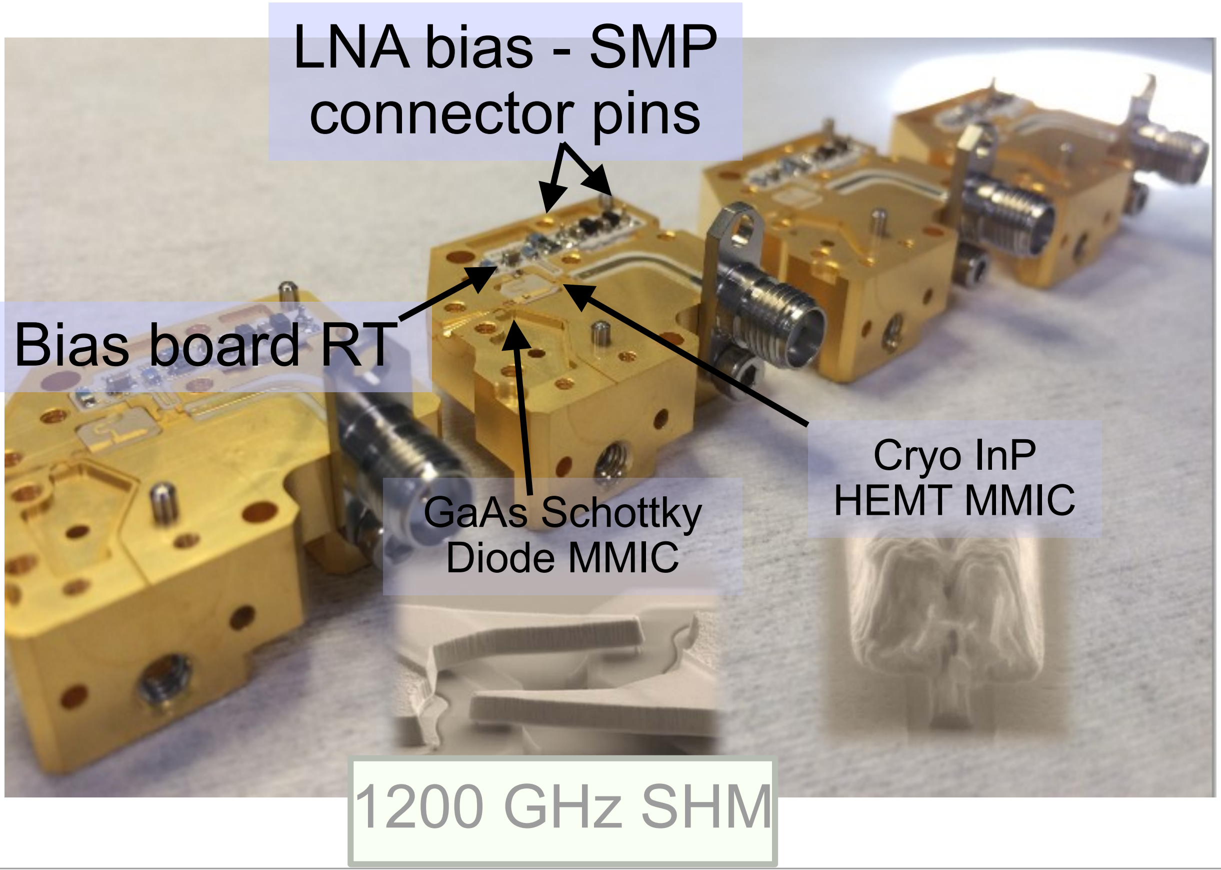
Courtesy of Peter Sobis, Omnisys Instruments.

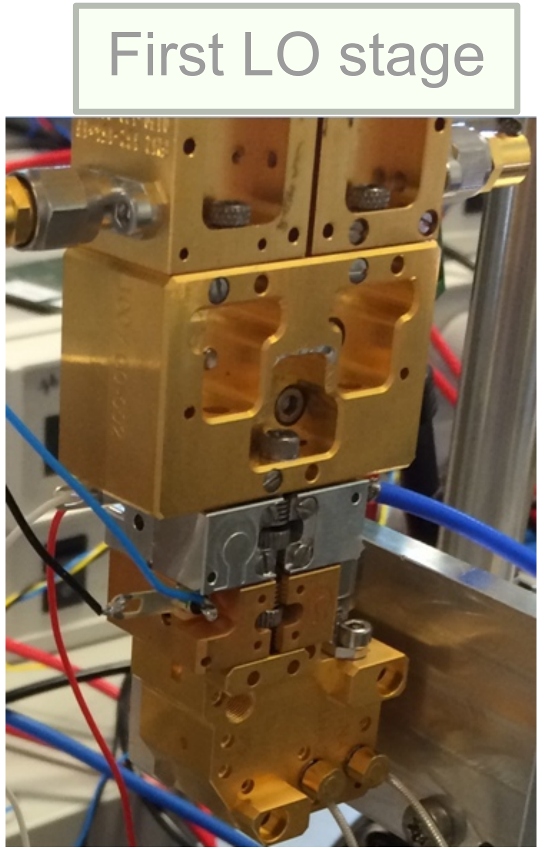
SWI
Submillimetre
Wave Instrument



Courtesy of Peter Sobis, Omnisys Instruments.

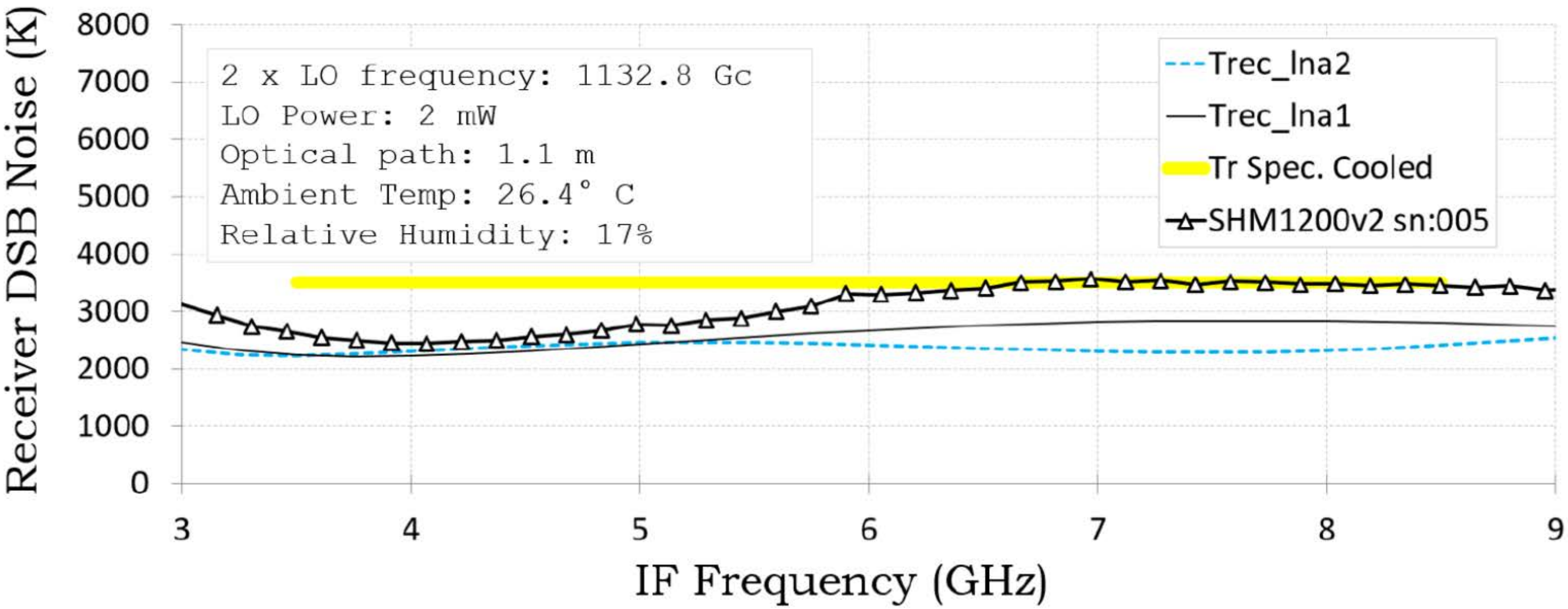
SWI
Submillimetre Wave Instrument





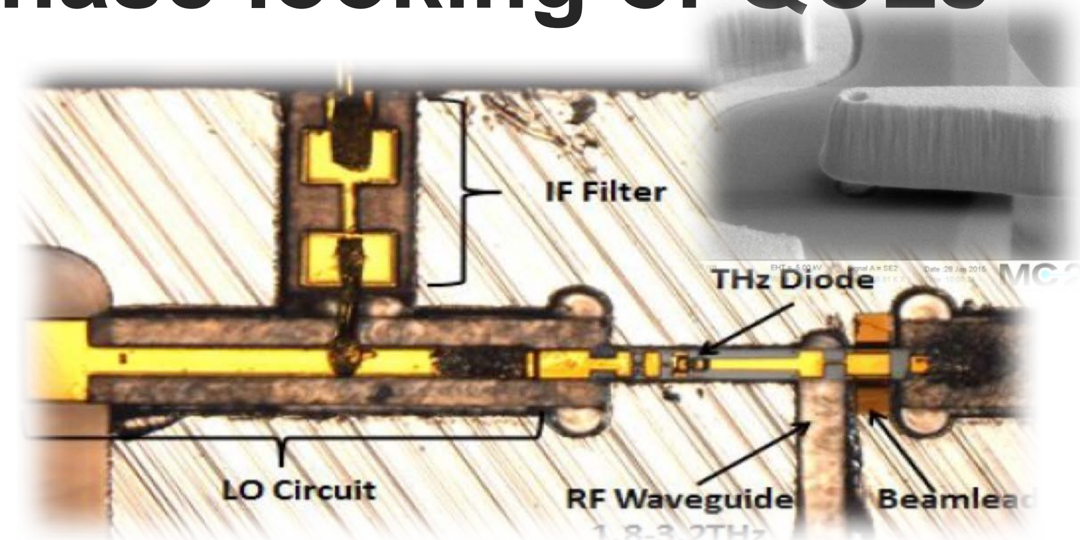
Courtesy of Peter Sobis, Omnisys Instruments.

SWI
Submillimetre Wave Instrument



Courtesy of Peter Sobis, Omnisys Instruments.

1.8-3.2 THz harmonic mixers phase looking of QCLs



Courtesy of Virginia Diodes, Inc.

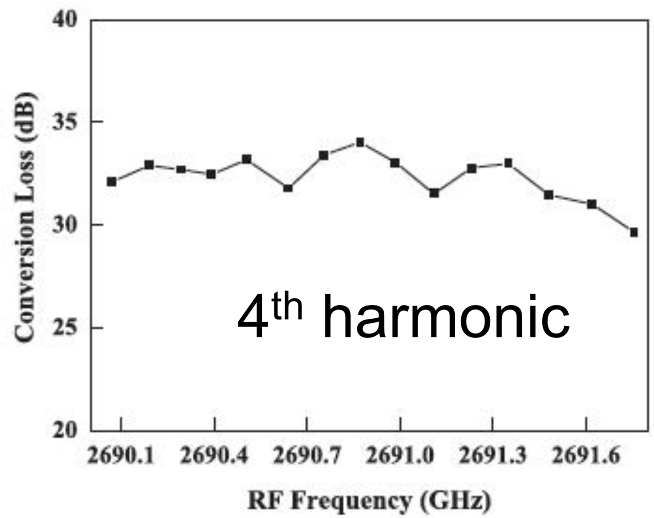
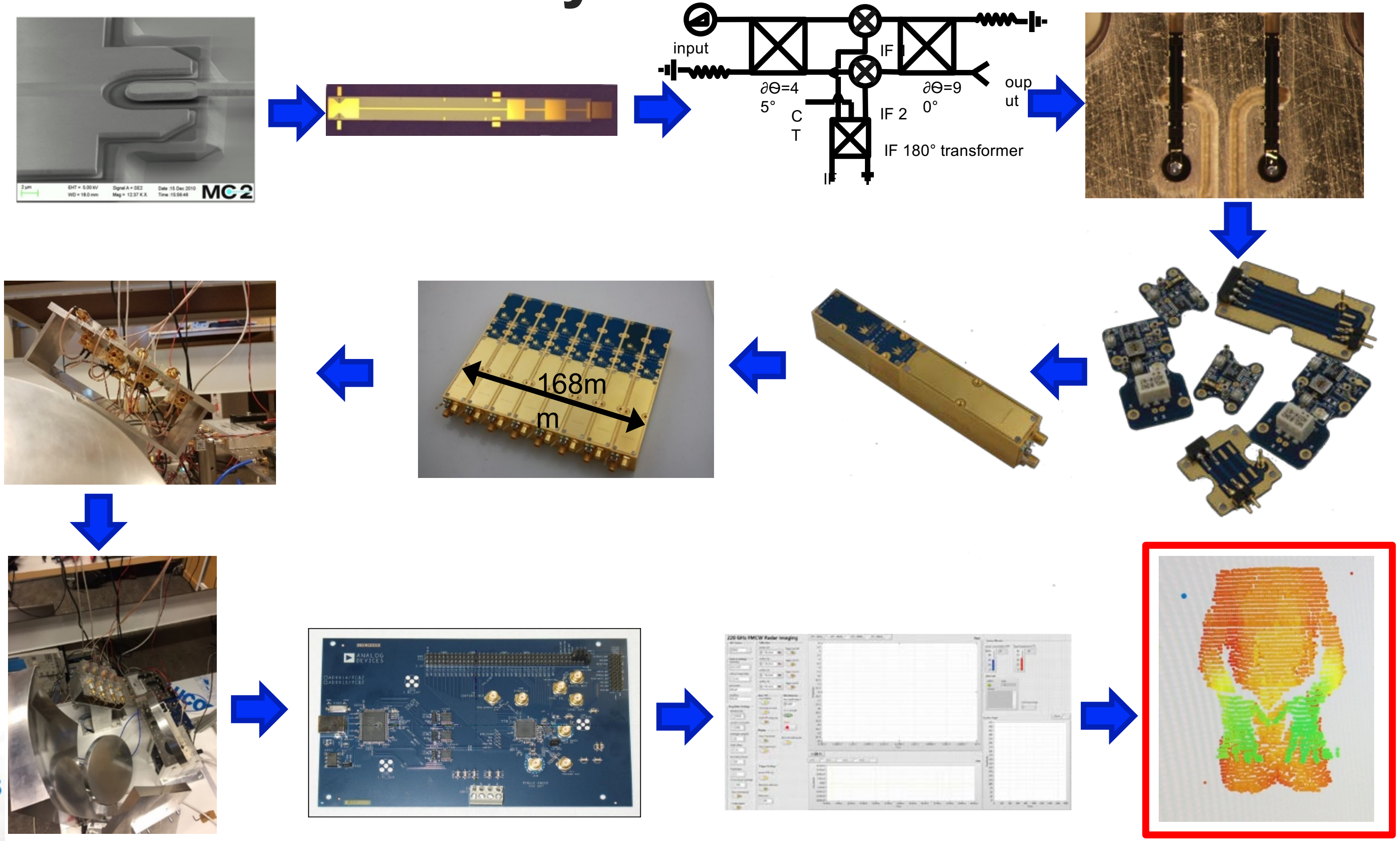


Fig. 20. Conversion loss of the harmonic mixer tested using 2690–2691.8 GHz QCL.

B. T. Bulcha, J. L. Hesler, V. Drakinskiy, J. Stake, A. Valavanis, P. Dean, L. H. Li, and N. S. Barker, “Design and characterization of 1.8–3.2 THz Schottky-based harmonic mixers,” *IEEE Trans. Terahertz Sci. Technol.*, vol. 6, no. 5, pp. 737–746, Aug. 2016.

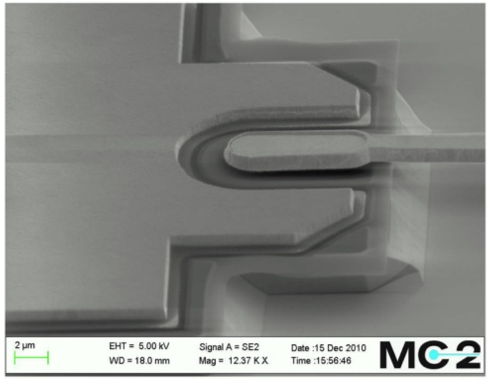
3D radar: from device to system

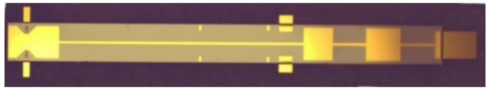


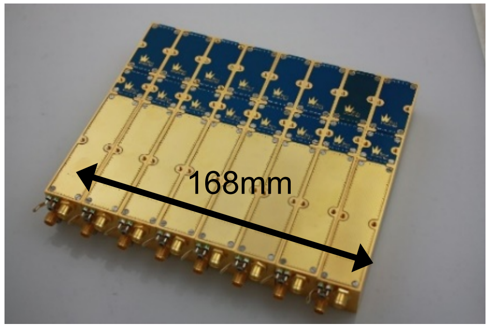
CONSORTIS

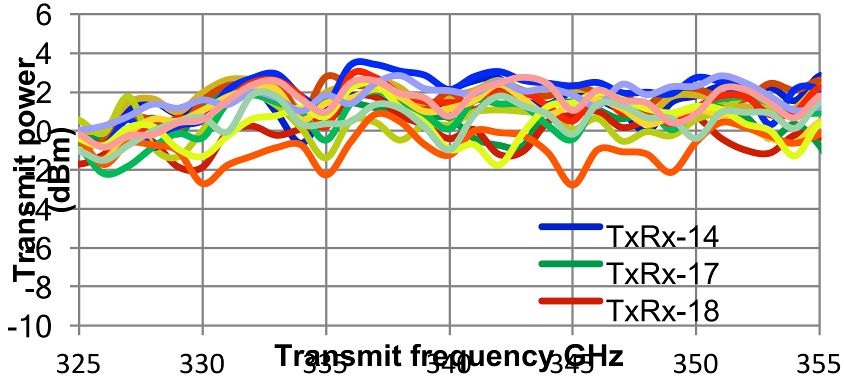
Courtesy of Tomas Bryllert, Chalmers

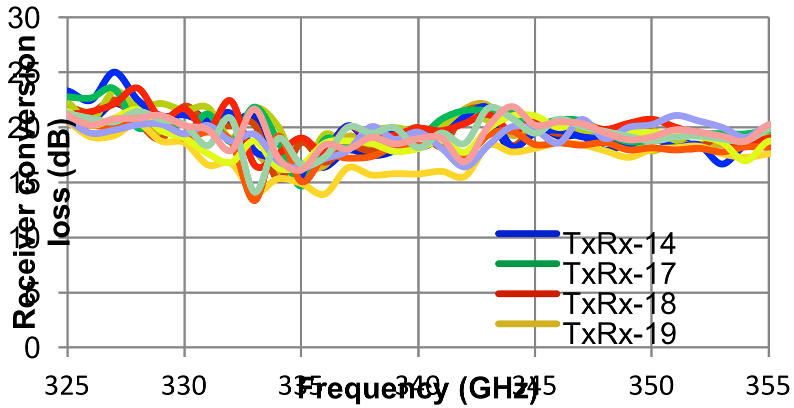
15 TxRx modules at 340 GHz





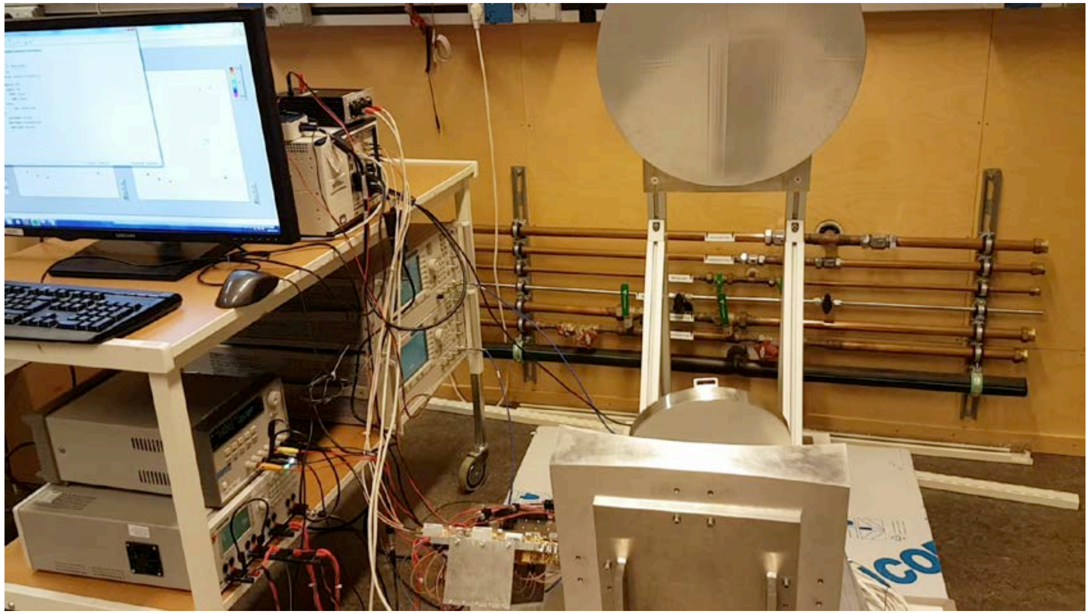






Courtesy of Tomas Bryllert, Chalmers

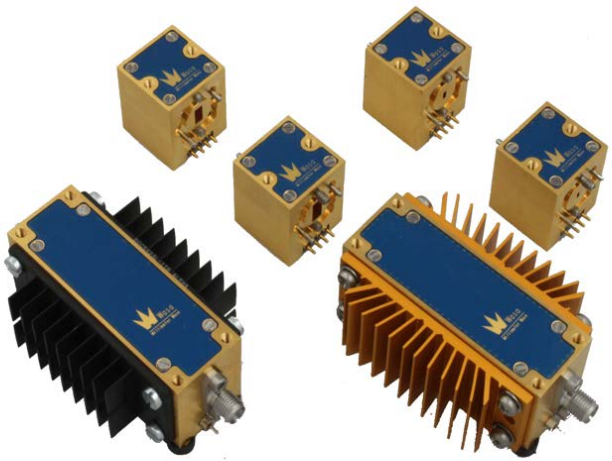
220GHz 3D FMCW THz radar

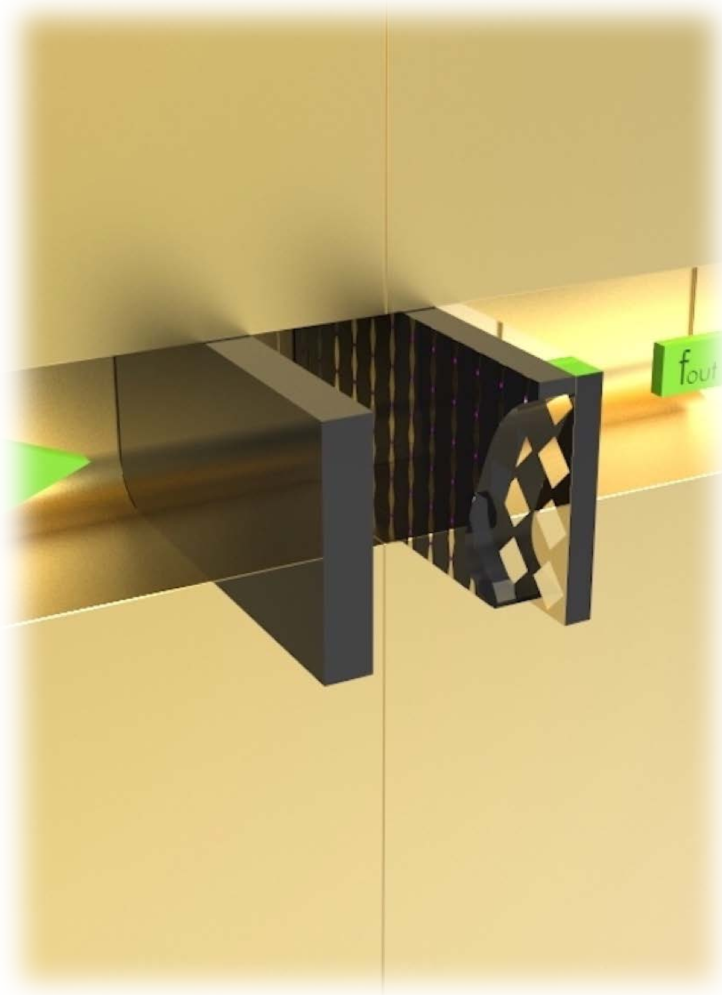


Courtesy of Tomas Bryllert, Chalmers

Solid-state sources

- High efficiency
- Medium power
- Power scaling



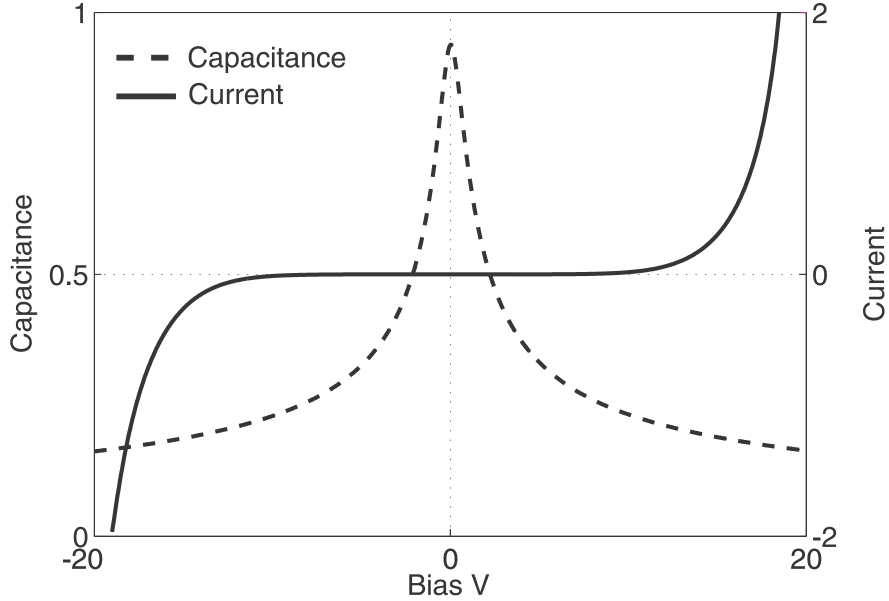


High power amplifiers

- High power GaN technology
- W-band amplifiers

Heterostructure Barrier Varactor (HBVs) frequency multipliers

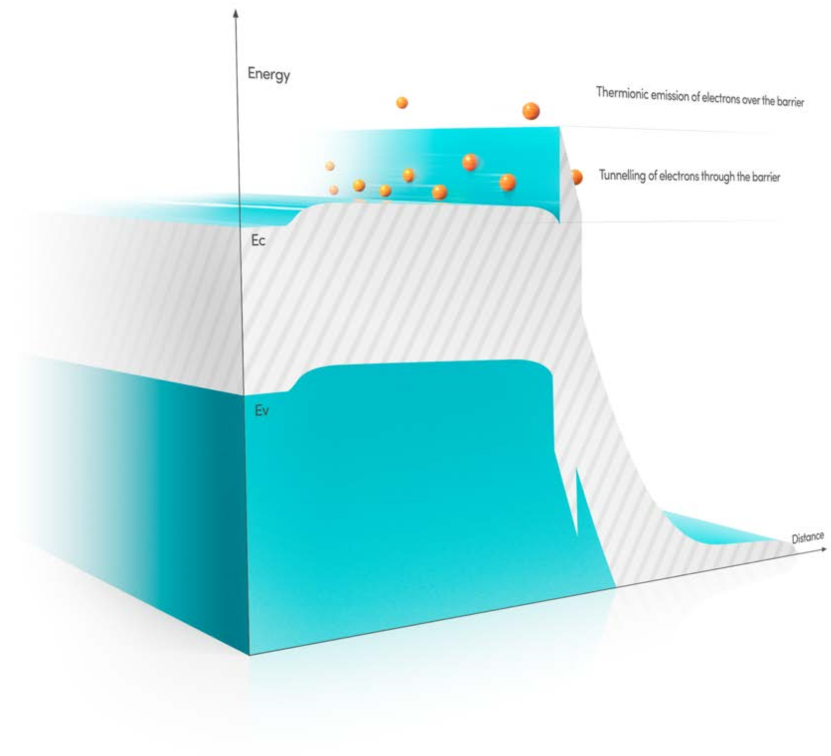
- High output power
- Ultra compact
- No bias circuitry
- High multiplication x3, x5, x7
- Chalmers invention

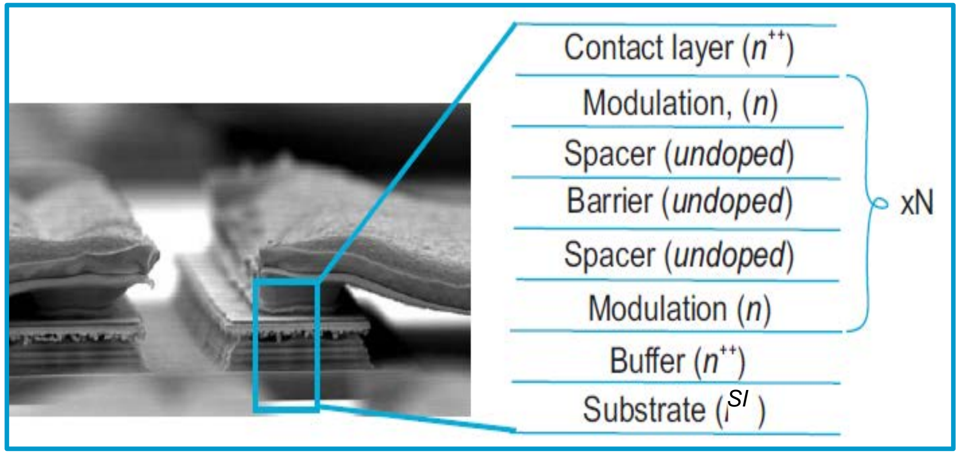


Courtesy of Wasa MilliMeter Wave

Providing more power and reducing system complexity

HBV diodes

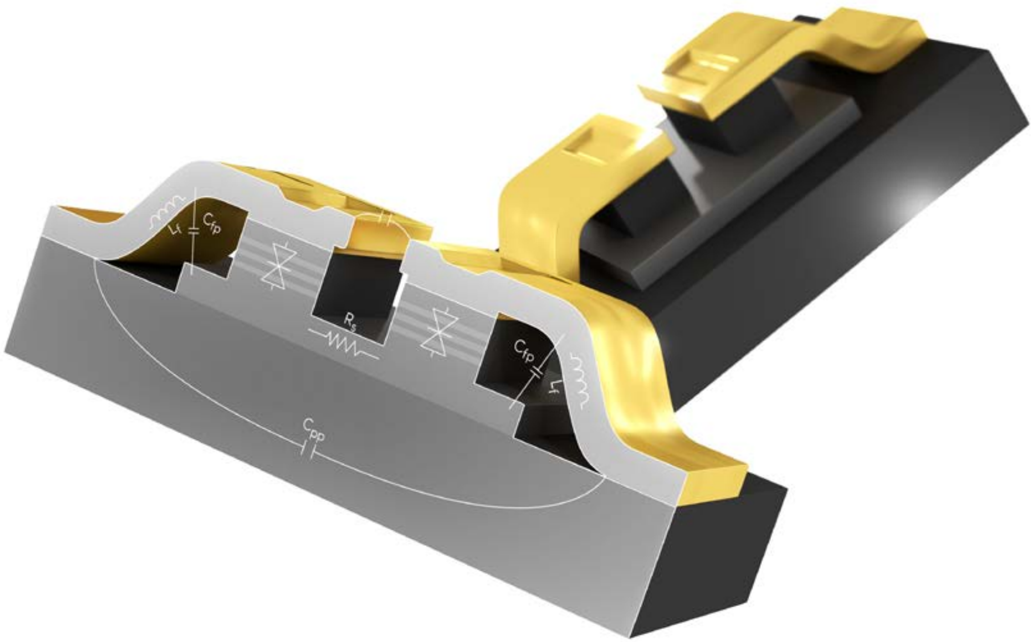


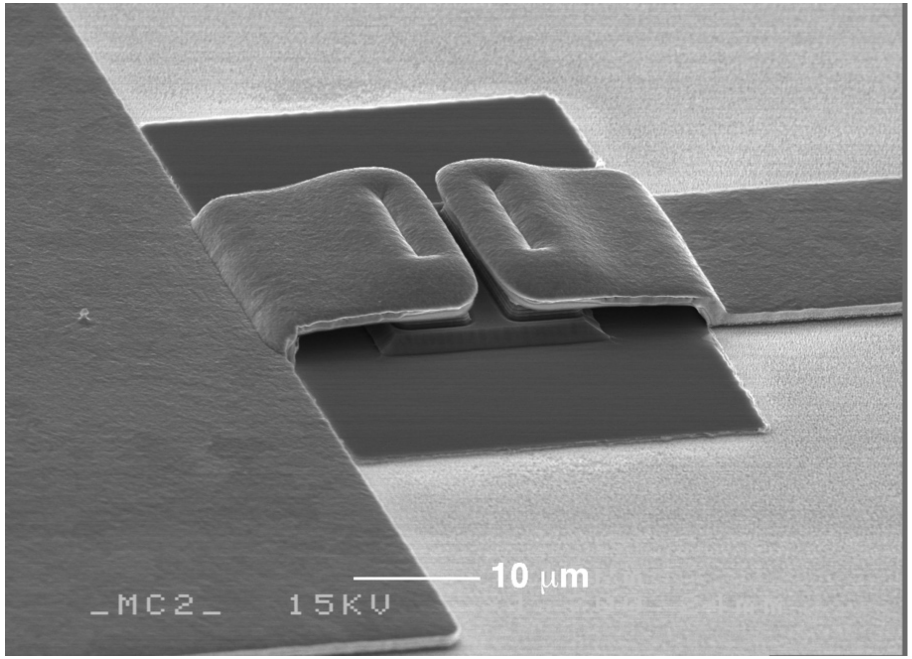


- Epitaxial growth
- $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ on InP or GaAs/AlGaAs on GaAs
- Low – high – low bandgap material
- Symmetric capacitance modulation

J. Stake, A. Aleksandra, T. Bryllert, and J. Vukusic, “Status and Prospects of High-Power Heterostructure Barrier Varactor Frequency Multipliers,” *Proc. IEEE*, 2017.

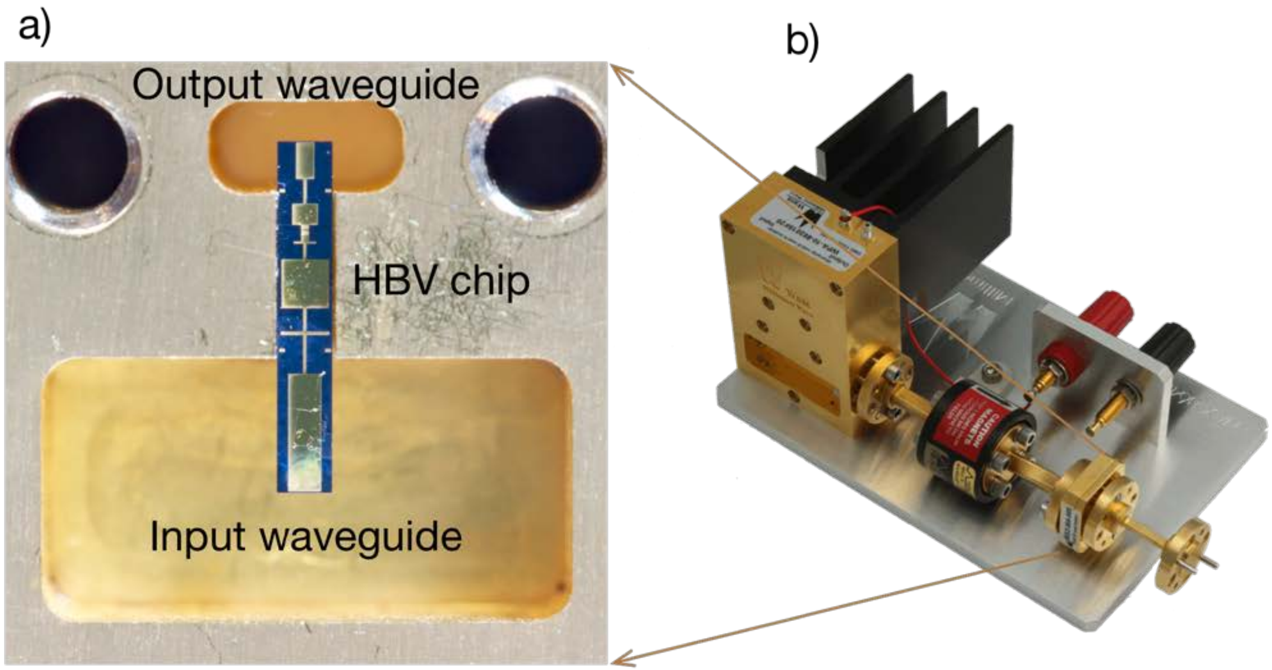
HBV diodes





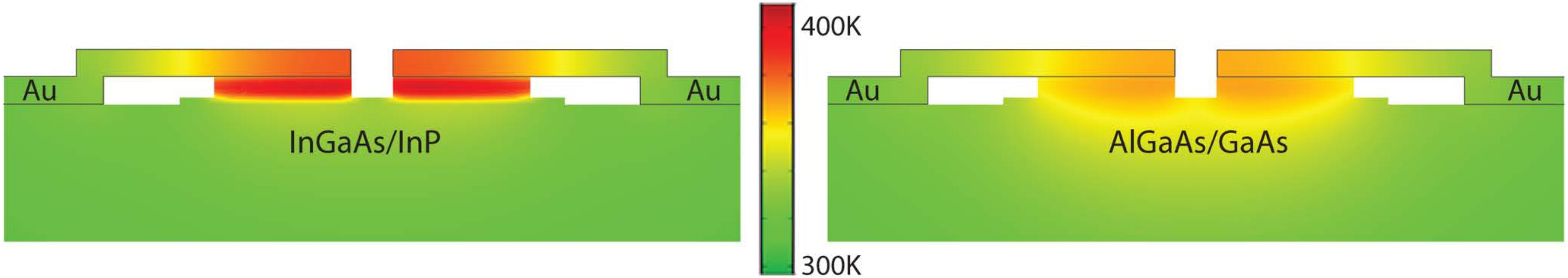
J. Stake, A. Aleksandra, T. Bryllert, and J. Vukusic, “Status and Prospects of High-Power Heterostructure Barrier Varactor Frequency Multipliers,” *Proc. IEEE*, 2017.

HBV multipliers



J. Stake, A. Aleksandra, T. Bryllert, and J. Vukusic, “Status and Prospects of High-Power Heterostructure Barrier Varactor Frequency Multipliers,” *Proc. IEEE*, 2017.

Electrothermal optimisation

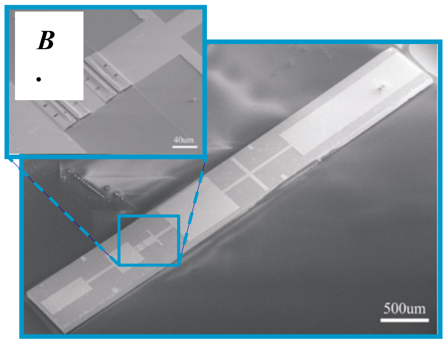


Best material for THz applications?

Diode – Circuit Integration Methods

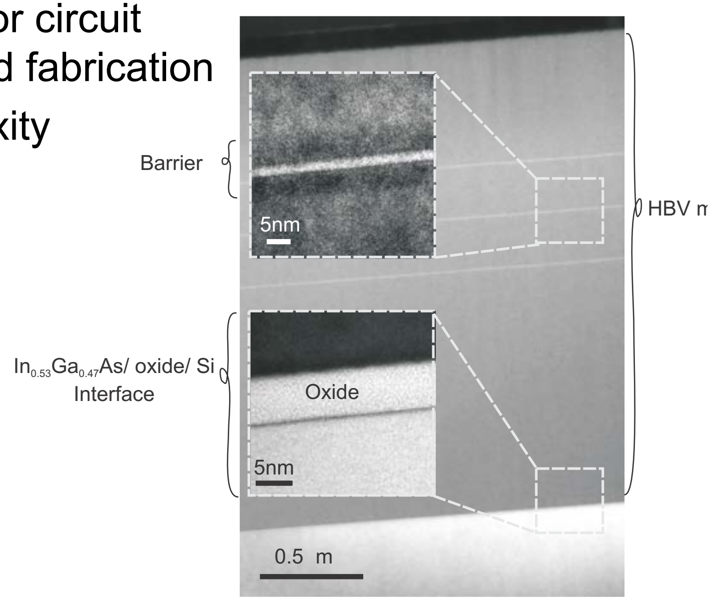
Monolithic

+ Passive and active components processed on the same substrate
+ Repeatability and reproducibility
– Limited choice of substrates



Heterogeneous

+ Materials with dissimilar physical properties
+ Increased performance and functionality
+ Additional degree of freedom for circuit design and fabrication
   – Complexity



Heterogeneous Integration

Combining optimum active material with optimum substrate
- “*no single technology will do it all*”

Substrate material

- Low RF losses
- Mechanically robust/machinable
- Thermal conductivity
- High/low relative permittivity
- Compatible with low freq/digital electronics CMOS compatibility
- Material cost/ availability

Si, Diamond….

Active/device material

- High mobility
- Versatile bandgap engineering
- Ohmic contact formation
- Thermal conductivity

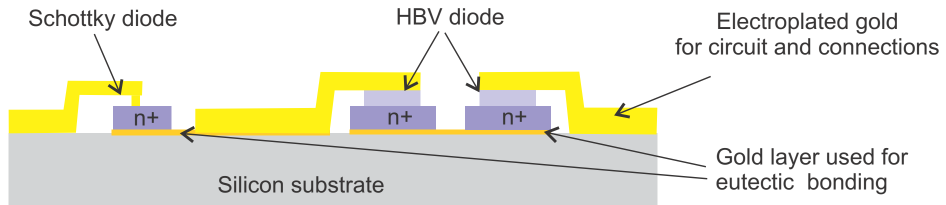
III-Vs, Graphene?

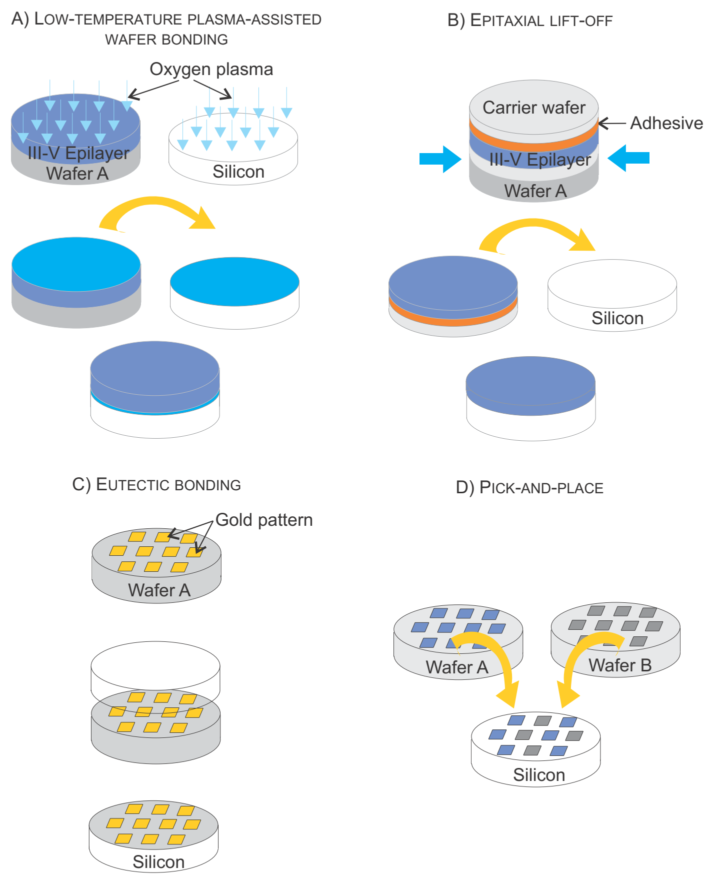
Heterogeneous Integration

Heterogeneous integration

Lattice mismatched materials

- **Epitaxial growth**
  - Intermediate buffer layer
- **Epitaxial transfer**
  - Indirect: adhesive, eutectic
  - Direct: anodic, fusion, *plasma activated*
- **Multi-technology integration**

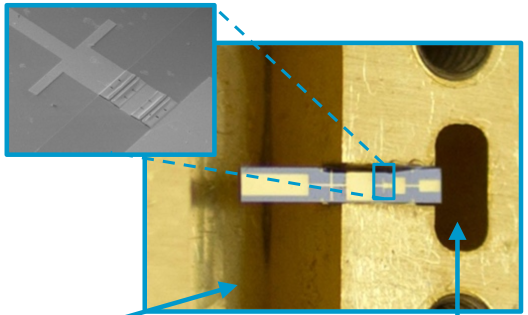




HBV multipliers: III-V on Silicon

	Si	InGaAs	InP as substrate
Mobility [cm^2/Vs]	500	12 000	5000
Thermal conductivity [$Wm^{-1}K^{-1}$]	150	≈4	68
Mechanical rigidity	Rigid/bendable when thin	brittle	brittle
Maturity	MEMS/CMOS		
Bandgap engineering		InGaAs/InAlAs/InP	InGaAs/InAlAs/InP
ε_r	≈12	≈12	≈12

Reference: 100 GHz multiplier (MMIC)
Monolithically integrated multiplier



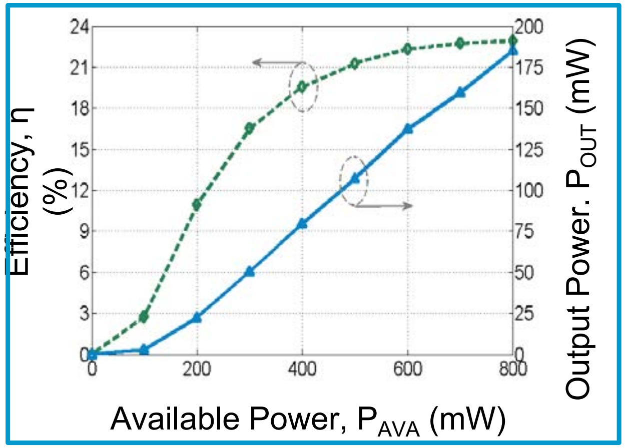
Input waveguide WR-22 (33 – 50 GHz)

Output waveguide WR-10 (75 – 110 GHz)

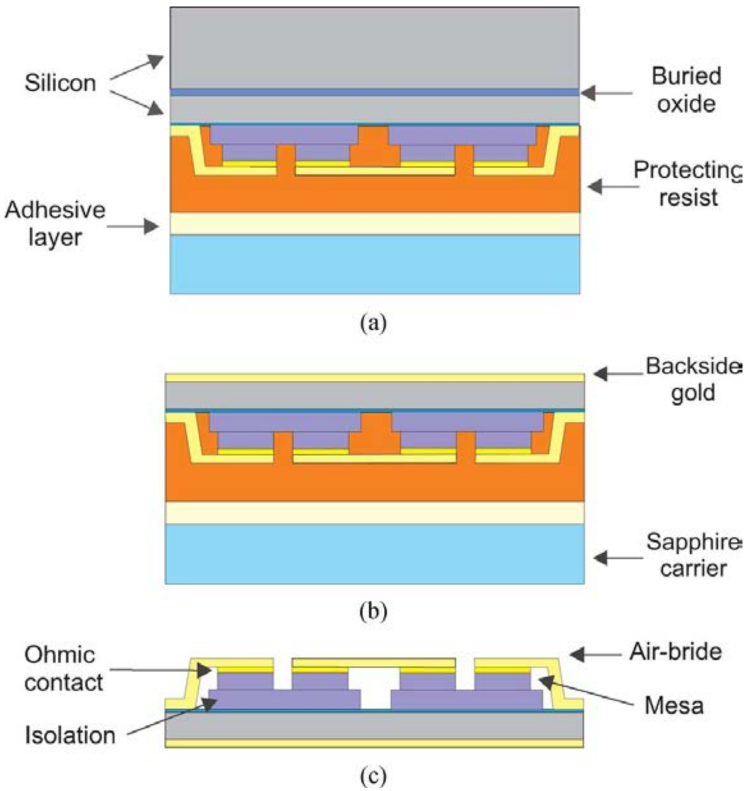
Frequency tripler (×3)

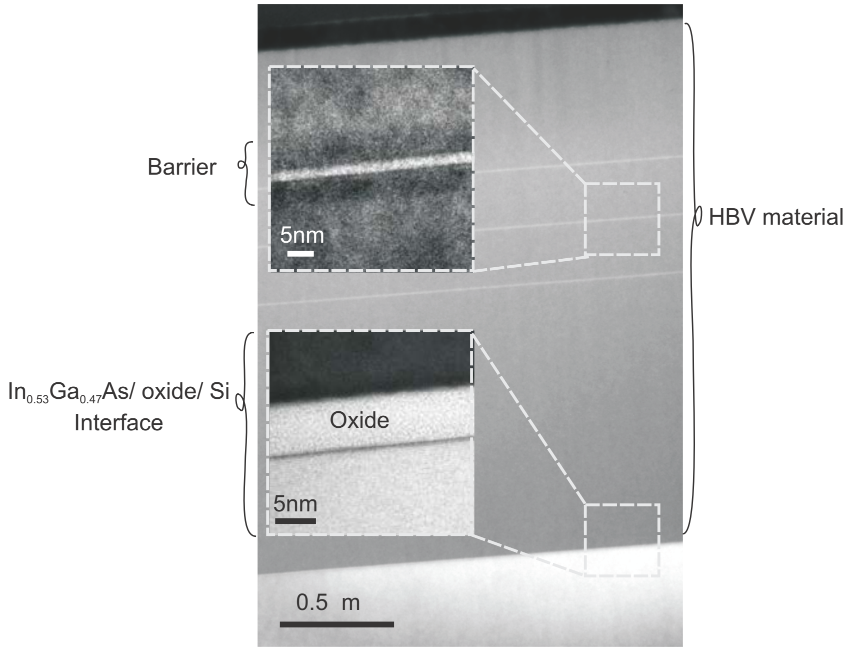
- $In_{0.53}Ga_{0.47}As/\ In_{0.52}Al_{0.48}As$
- InP substrate

- Input Q-band (33 – 50 GHz)
- Output W-band (70 – 110 GHz)
- f_{CENTRE} = 107 GHz
- < 0.2 W ouput power



Heterogeneously integrated multiplier



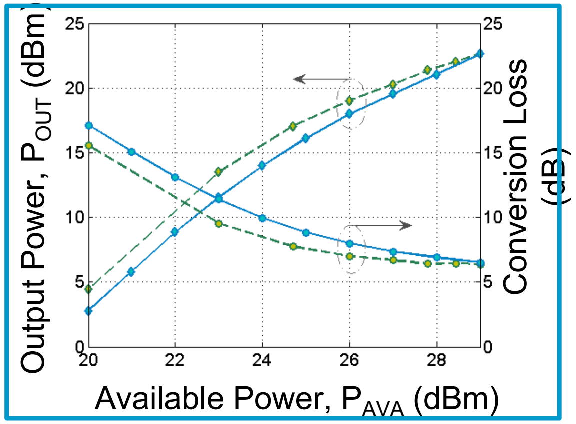


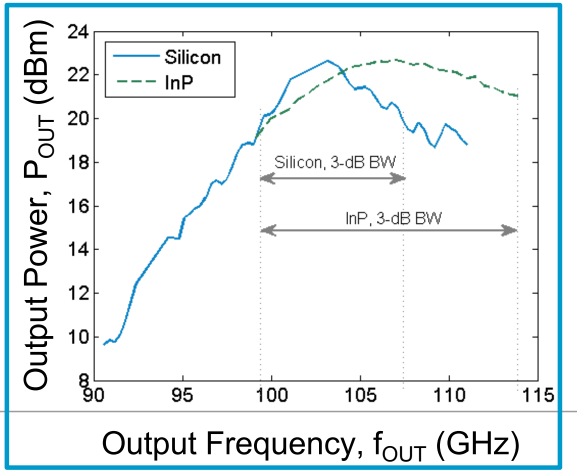
100 GHz multiplier

Heterogeneously integrated multiplier

Frequency tripler (×3)

- Silicon substrate
- Original design on InP
- First demonstration
- Robust circuits



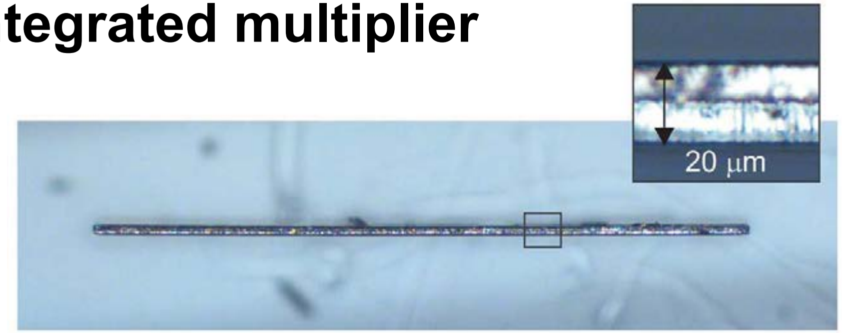


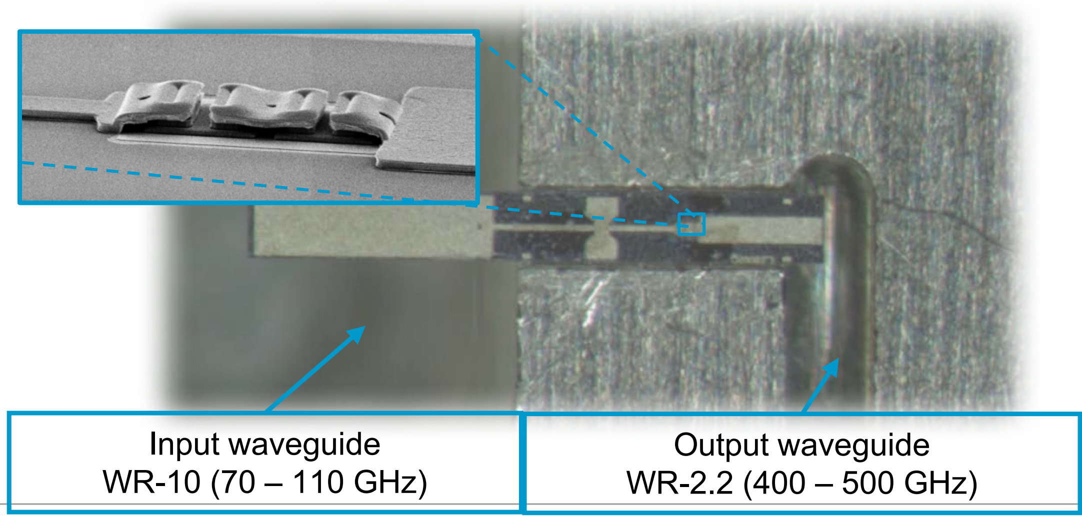
- Similar RF performance
- $f_{CENTRE,\ Si}$ = 103 GHz
- $f_{CENTRE,\ InP}$ = 107 GHz
- < 0.2 W output power (input power limited)

480 GHz quintupler / SOI technology

Heterogeneously integrated multiplier

SOI process / 20µm
thick Si-substrate





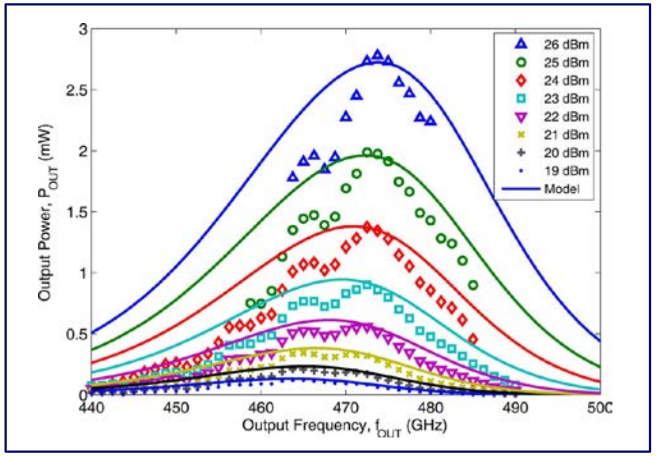
480 GHz quintupler / SOI technology

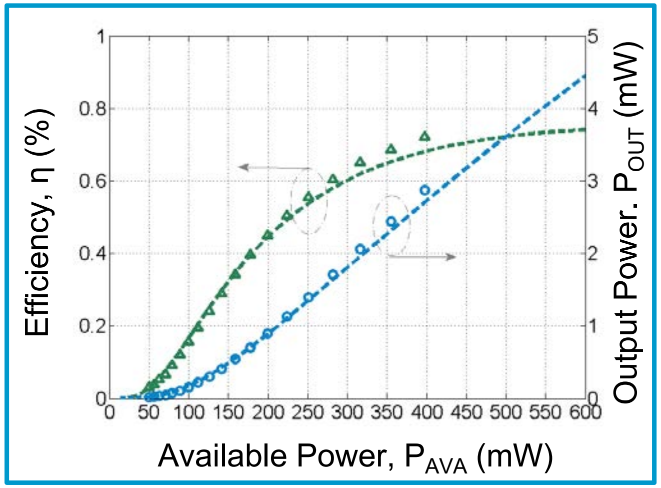
Heterogeneously integrated multiplier

Frequency quintupler (×5)

- Silicon-on-insulator (SOI)
- Predefined thickness 20 μm

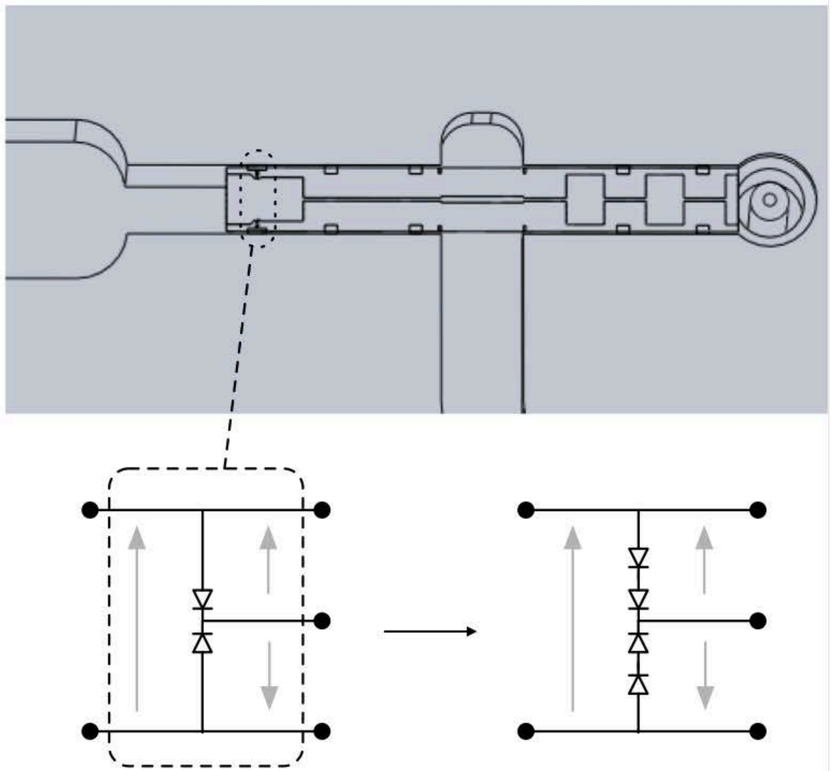
- Input W-band (75 – 110 GHz)
- Output WR – 2.2 (400 – 500 GHz)
- Highest frequency of operation
- < 3 mW output
- Limited by available input power (> 5 mW) measured

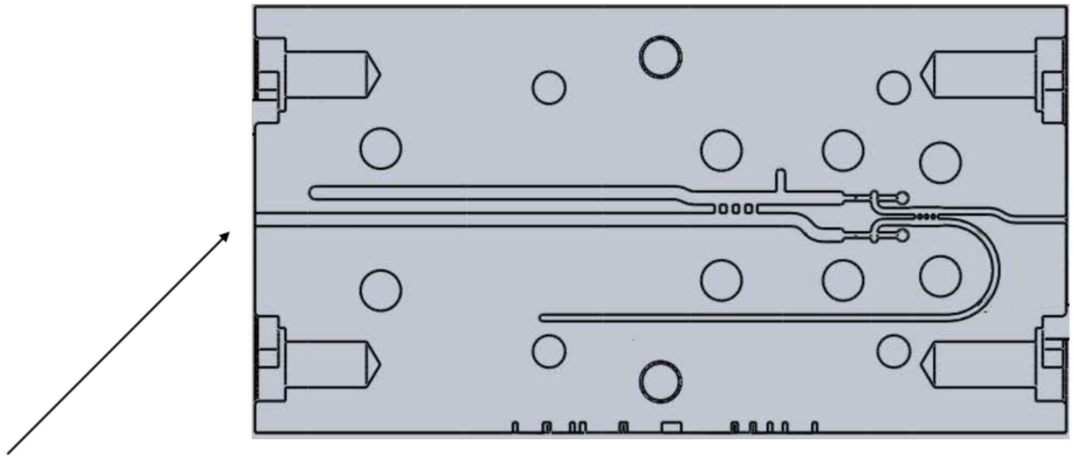




A. Malko, T. Bryllert, J. Vukusic, and J. Stake, “A 474 GHz HBV Frequency Quintupler Integrated on a 20 μm Thick Silicon Substrate,” *IEEE Trans. Terahertz Sci. Technol.*, vol. 5, no. 1, pp. 85–91, 2015.

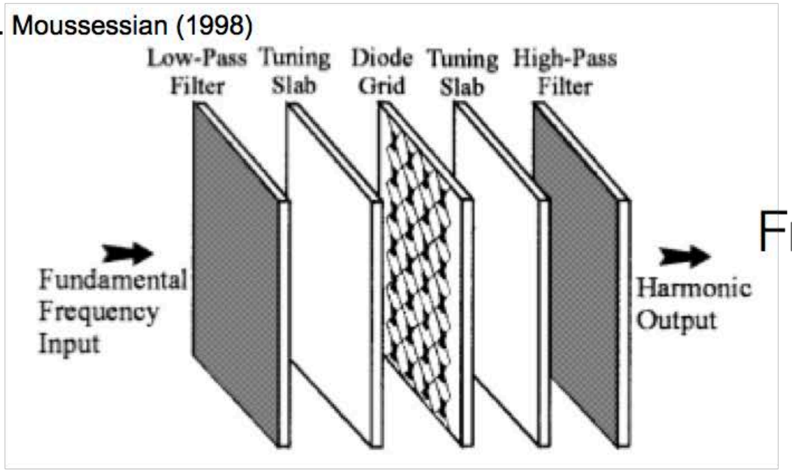
Classical power combining





Concept of grid power combining

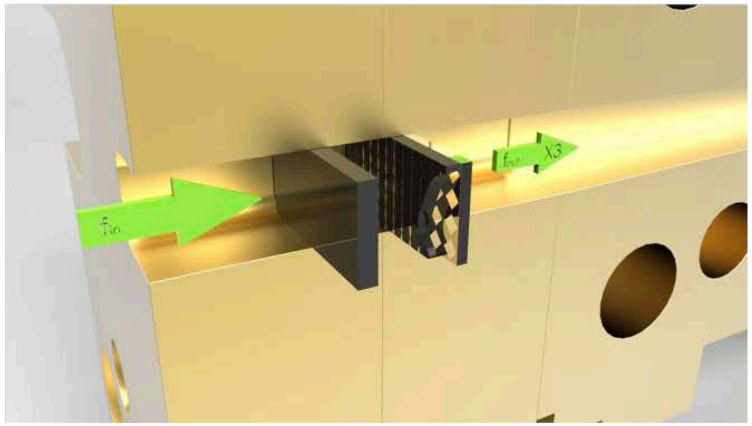
A. Moussessian (1998)



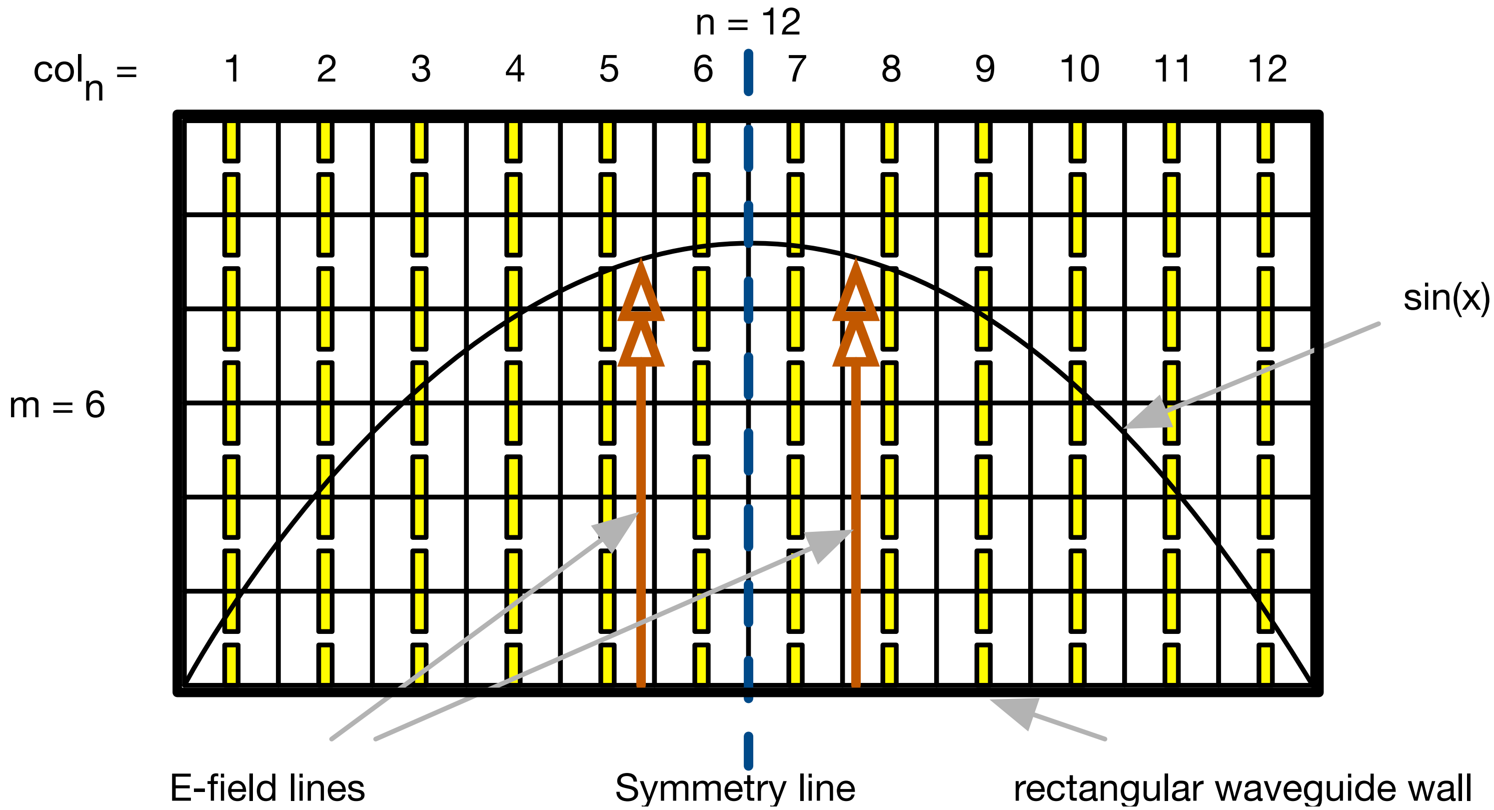
Free space

P~mxn devices

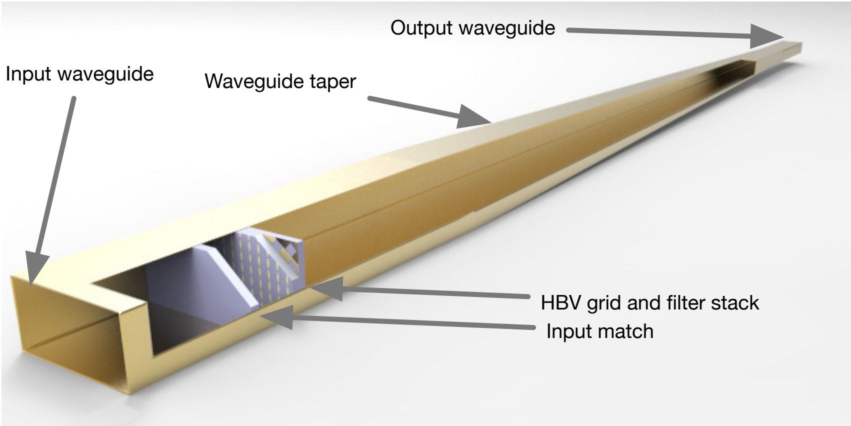
Waveguide enclosed

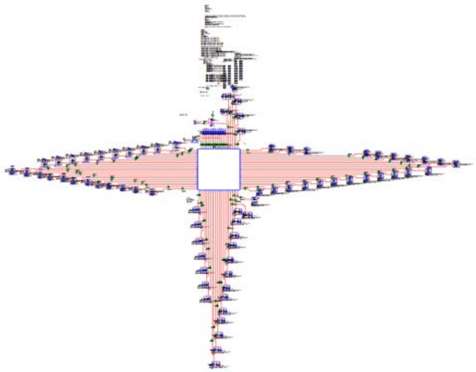


Waveguide enclosed diode array

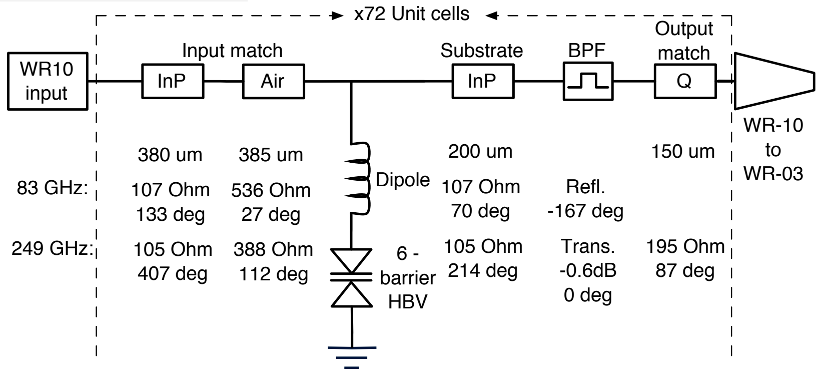


Simulation and design challenge

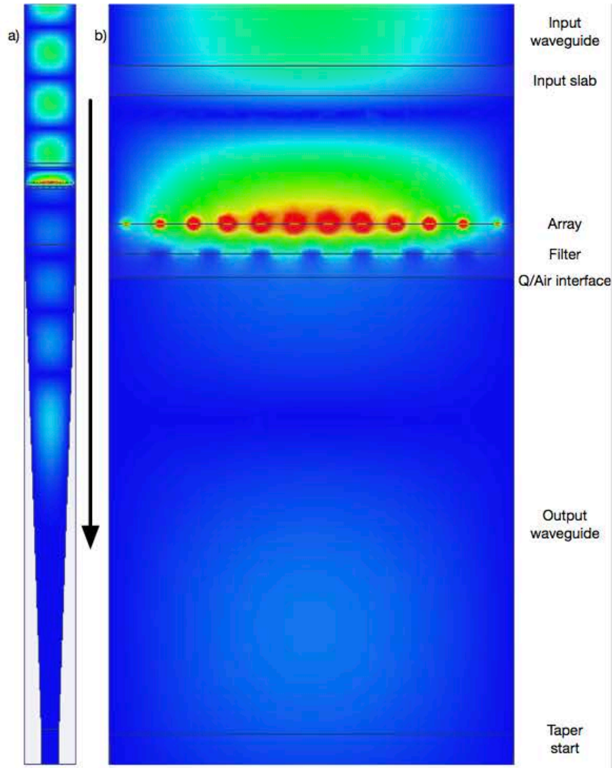


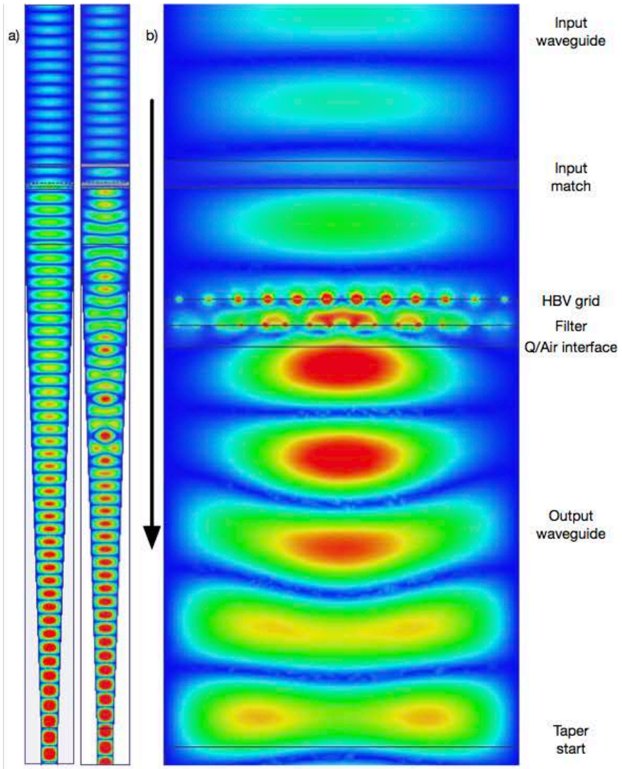


versus

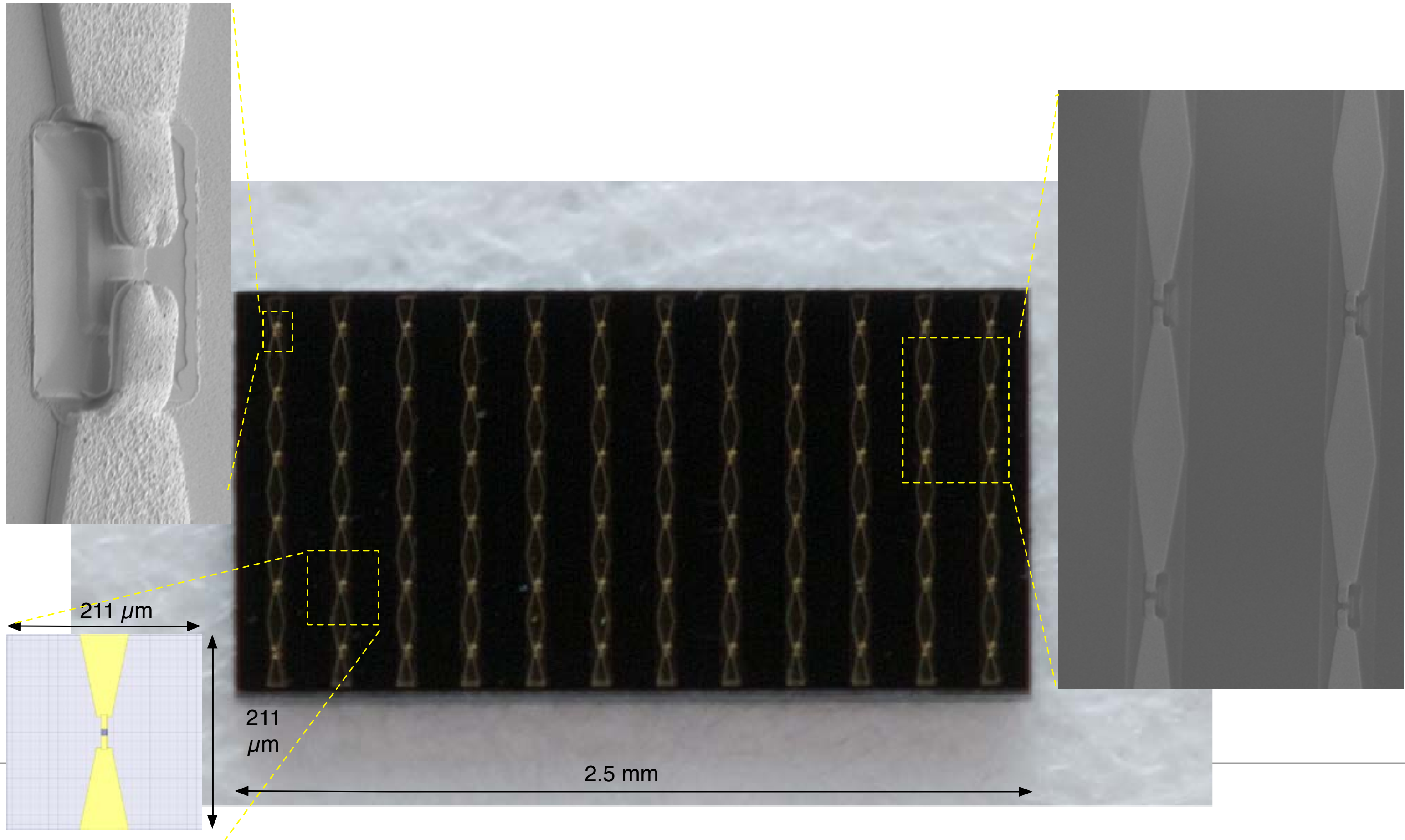


Simulation and design challenge

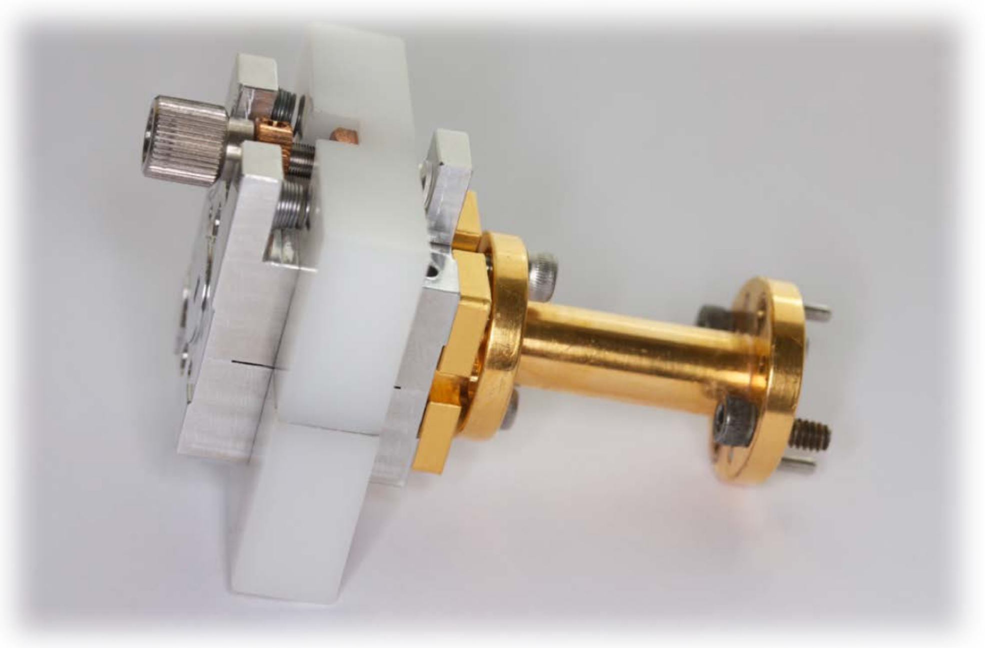


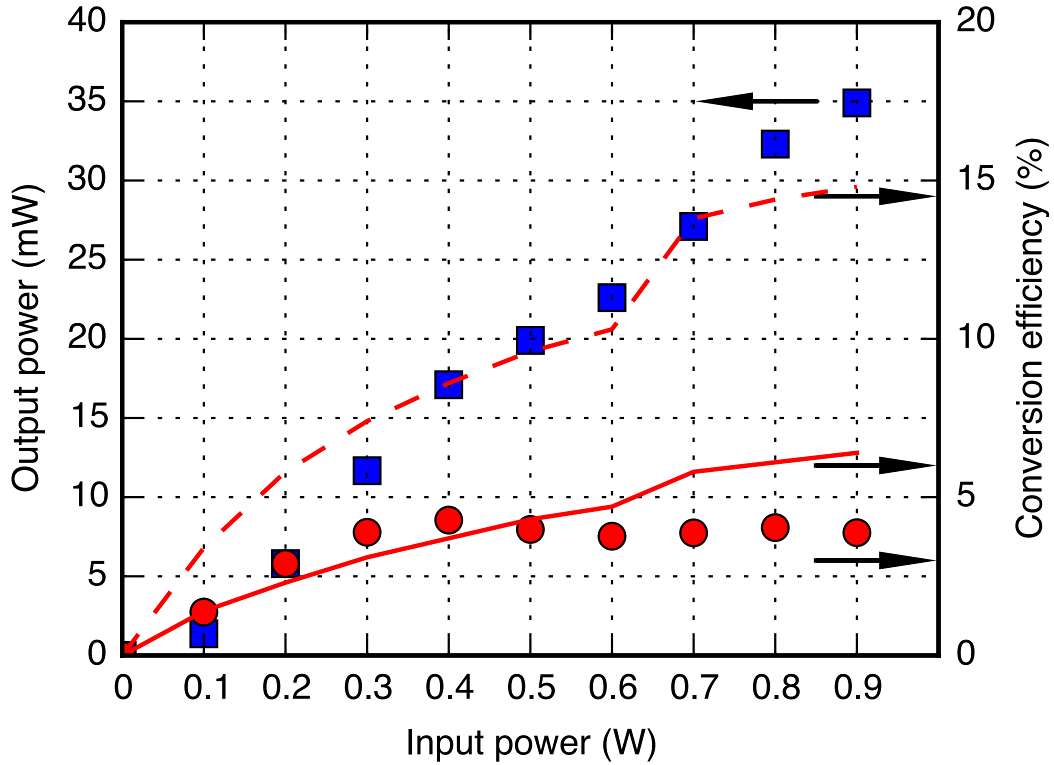


HBV grid tripler



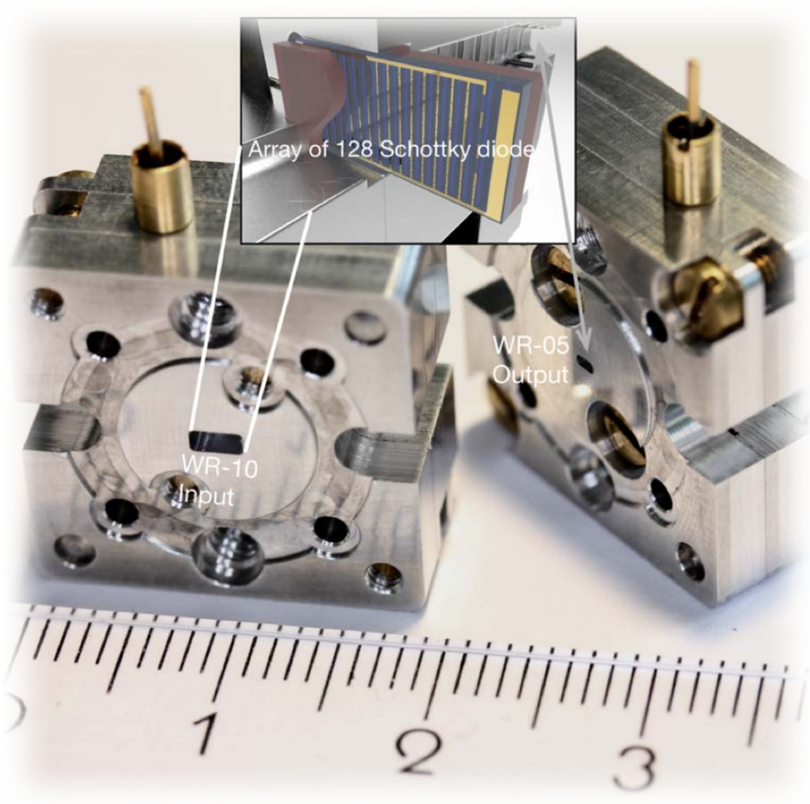
247 GHz HBV grid tripler

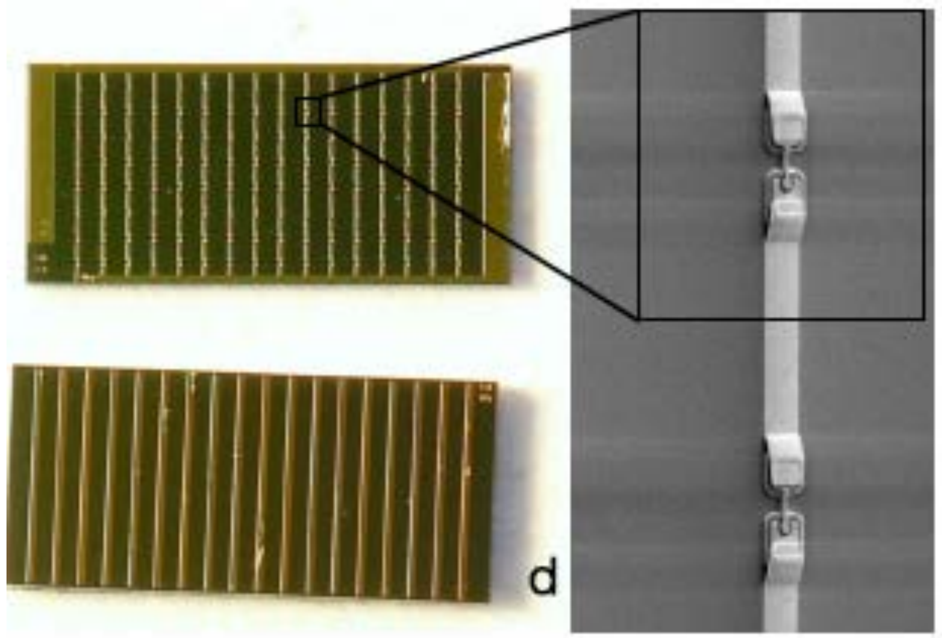




R. Dahlbäck, J. Vukusic, R. M. Weikle II, and J. Stake, “A tunable 240–290 GHz waveguide enclosed 2-D grid HBV frequency tripler,” *IEEE Trans. Terahertz Sci. Technol.*, vol. 6, no. 3, pp. 503–509, Apr. 2016.

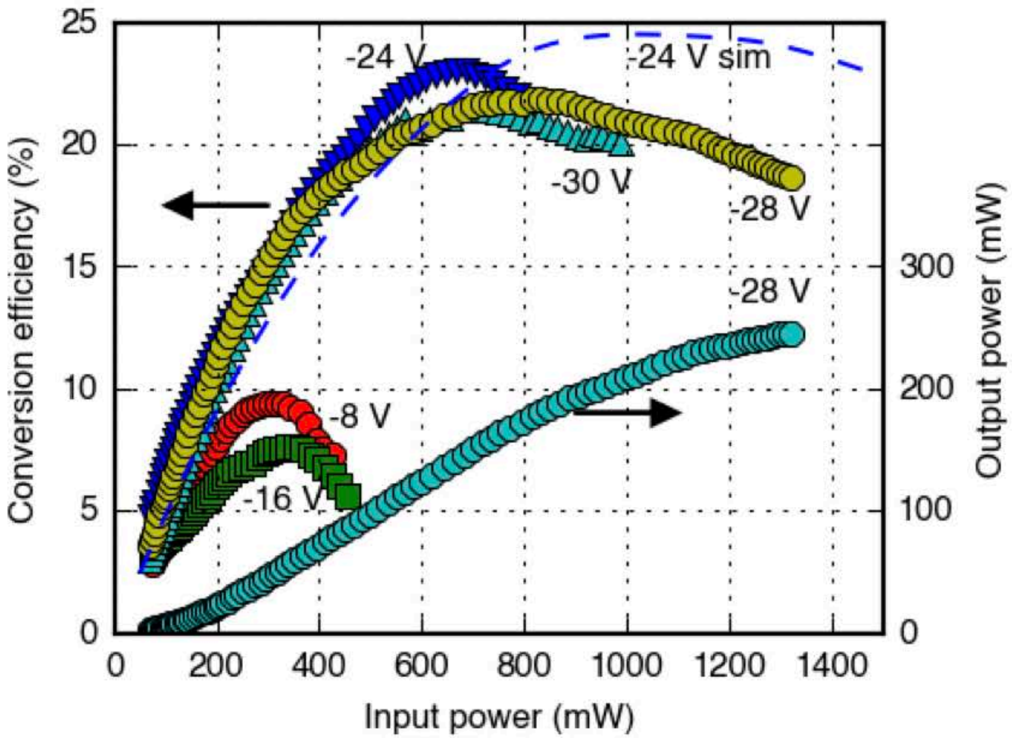
128-element Schottky diode doubler

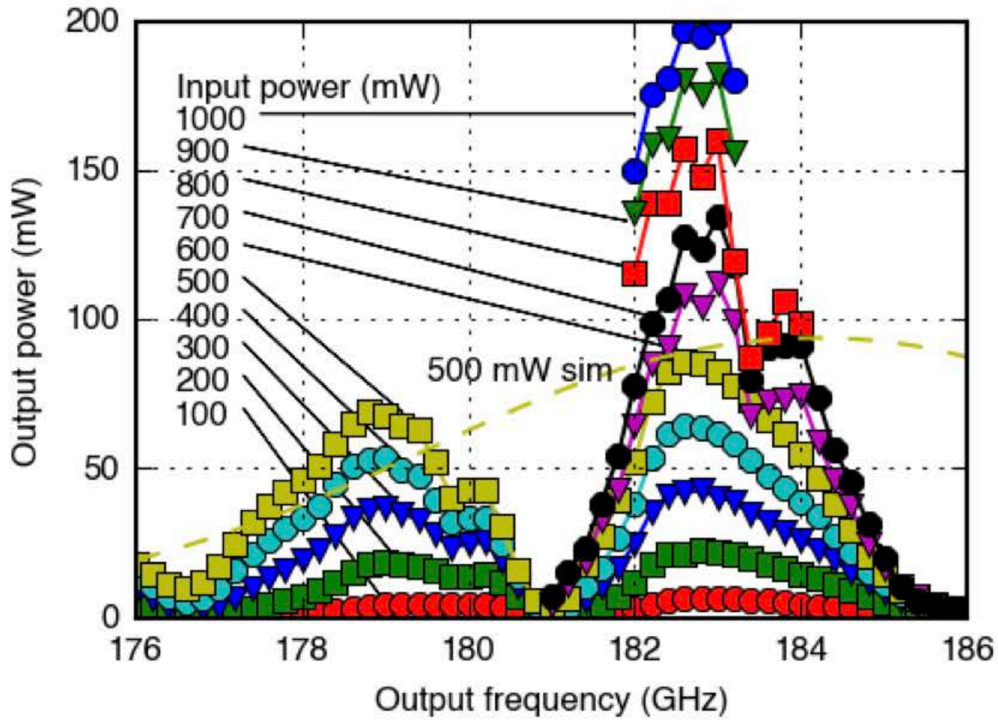




R. Dahlbäck, V. Drakinskiy, J. Vukusic, and J. Stake, “A compact 128-element Schottky diode grid frequency doubler generating 0.25 W of output power at 183 GHz,” *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 2, Feb. 2017.

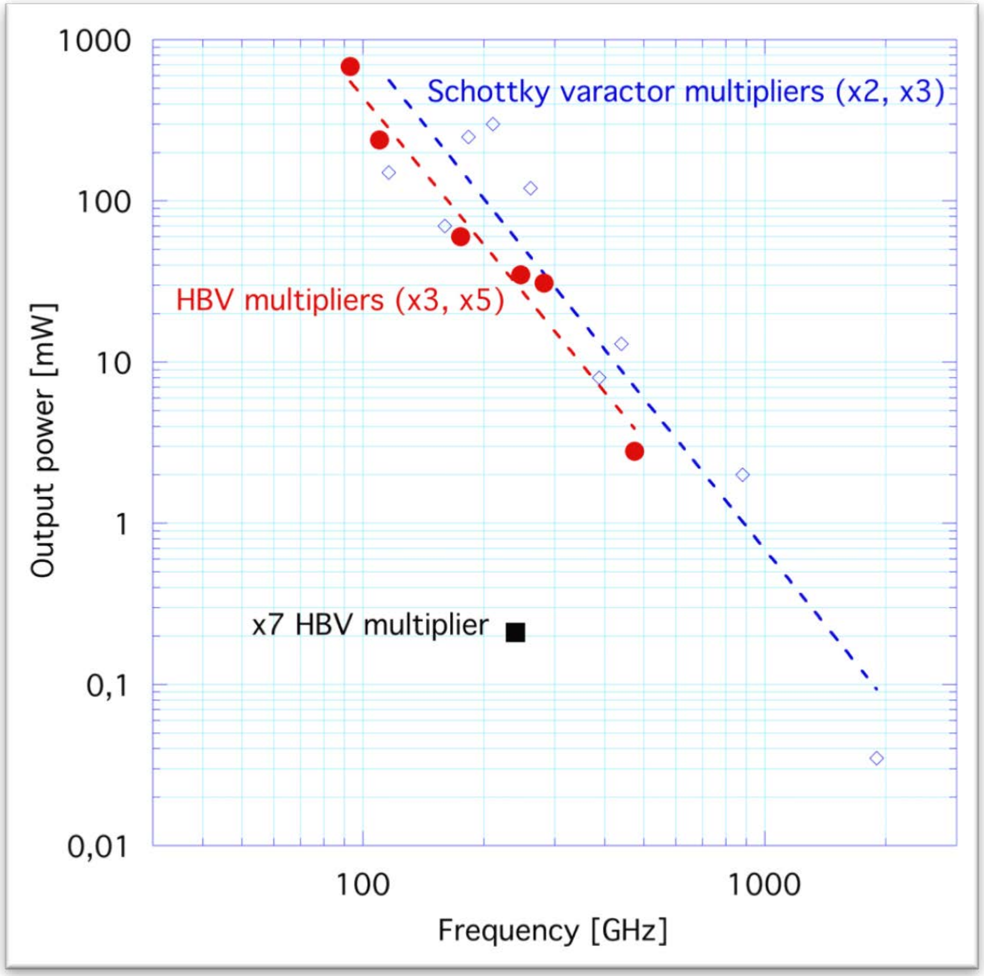
128-element Schottky diode doubler



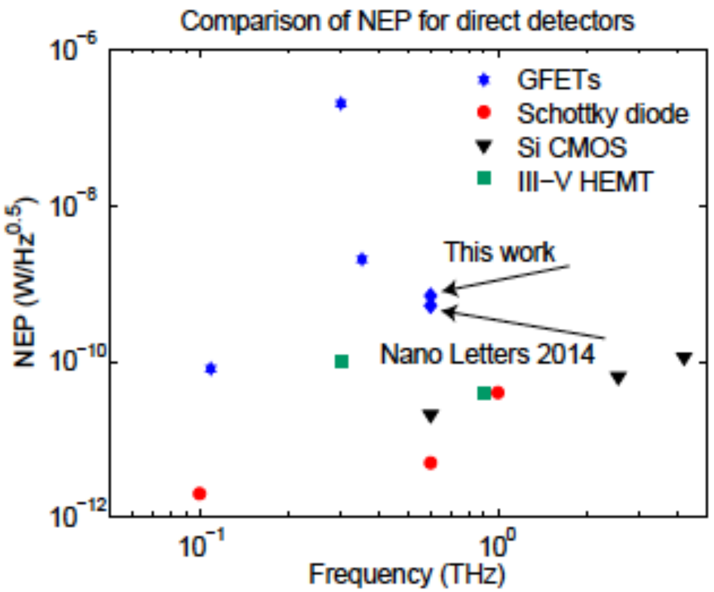


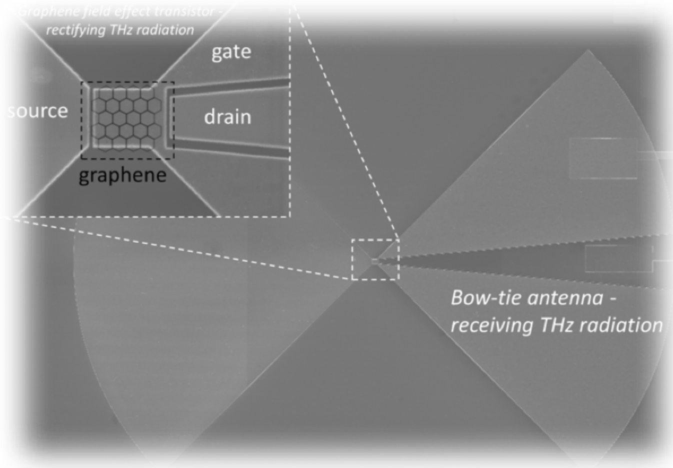
R. Dahlbäck, V. Drakinskiy, J. Vukusic, and J. Stake, “A compact 128-element Schottky diode grid frequency doubler generating 0.25 W of output power at 183 GHz,” *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 2, Feb. 2017.

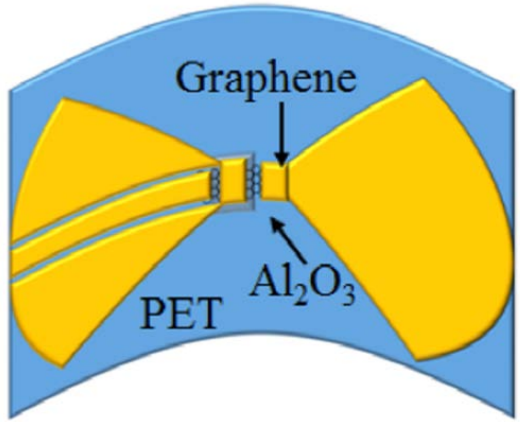
State-of-the-art frequency multipliers



THz Graphene detectors





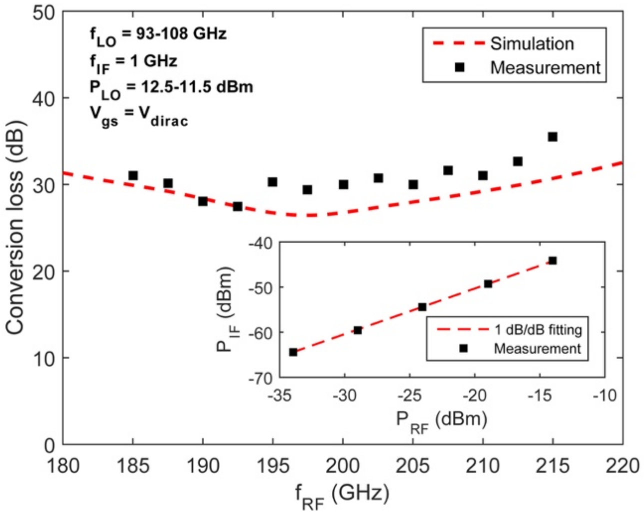


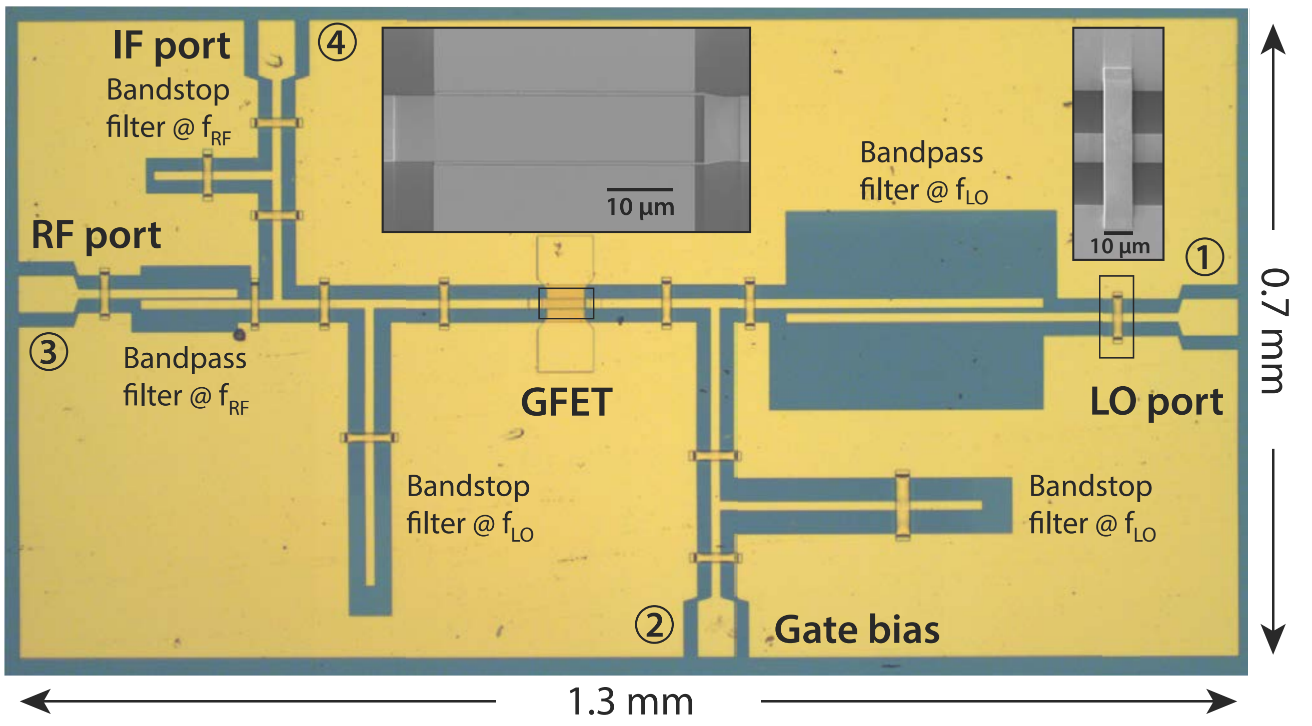
Flexible THz Technology?

"Antenna-Integrated 0.6 THz FET Direct Detectors Based on CVD Graphene," Nano Letters, Oct. 2014.

Graphene heterodyne FET mixers

- New type of subharmonic FET mixer





Knut och Alice Wallenbergs Stiftelse

Nanofabrication Laboratory

Part of Swedish micro and nano fabrication network

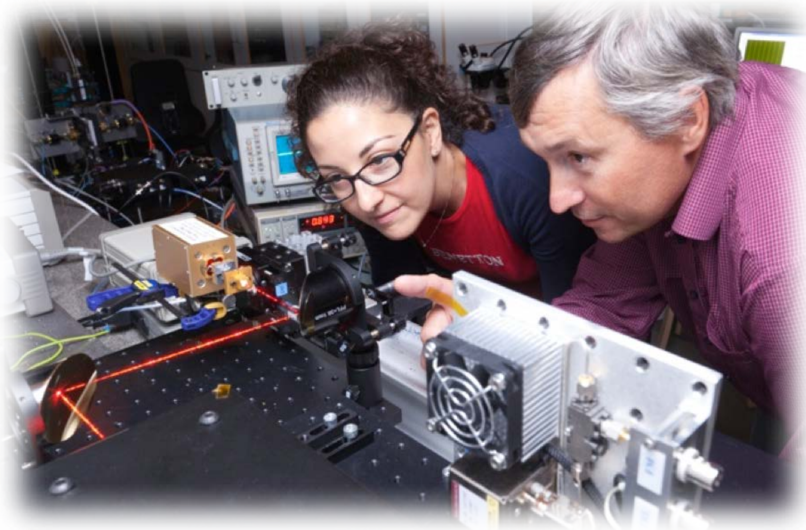
- **Dedicated process lines**
- **Deposition and etching tools**
- **Electron beam lithography**
- **Stepper, Laser writers**
- **Molecular Beam Epitaxy**

Kollberg Laboratory

Knut och Alice Wallenbergs Stiftelse

Chalmers national facility for terahertz characterisation

- **Open facility – unique capability**
- **2-port S-parameters up to 1.5 THz**
- **FTS, TDS**
- **Sources**
- **Antenna set-up**
- **Precision machining facility**



Conclusions

- Nanotechnology and new materials can bring new device concepts such as fundamental oscillators and harmonic generators

- Develop an integration platform, or heterogeneous integration, is a necessity for future THz arrays

THz and millimetre wave lab

AVANCEZ

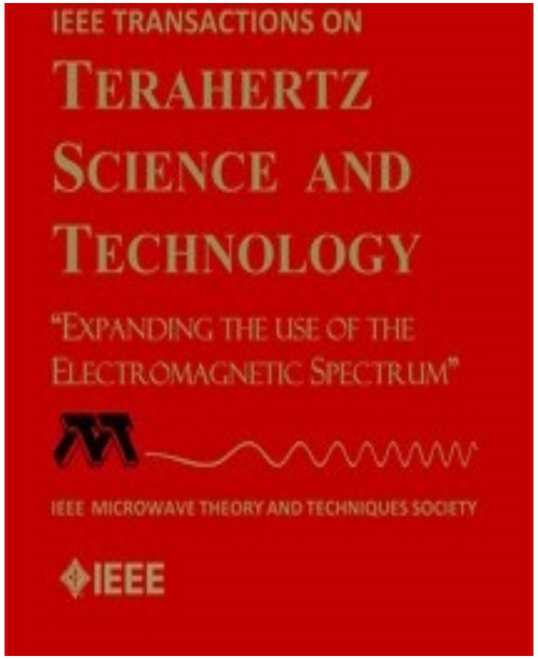
1829

CHALMERS

UNIVERSITY OF TECHNOLOGY

CHALMERS
UNIVERSITY OF TECHNOLOGY

IEEE Transactions on Terahertz Science and Technology














Expanding the use of the electromagnetic spectrum