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Micromachining

enabling new solutions at millimeter and submillimeter frequencies

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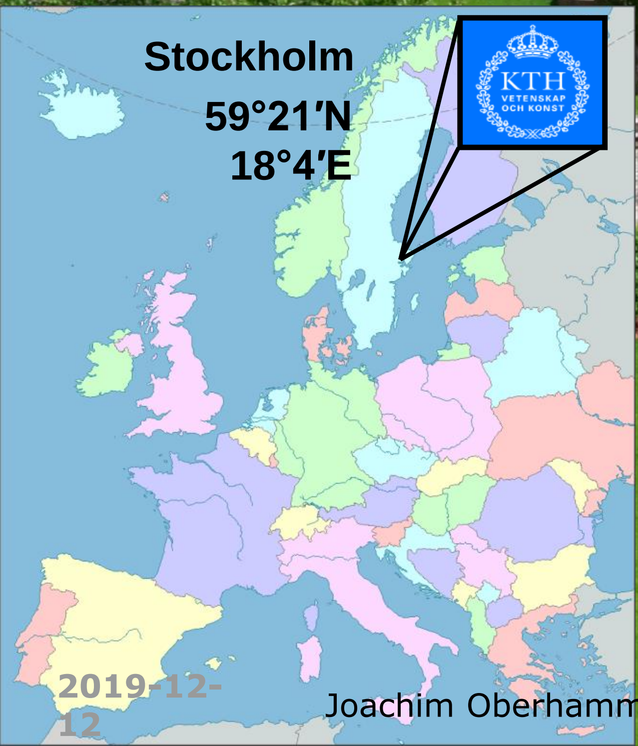


Microwave/THz MEMS@KTH

(School of EE and CS)

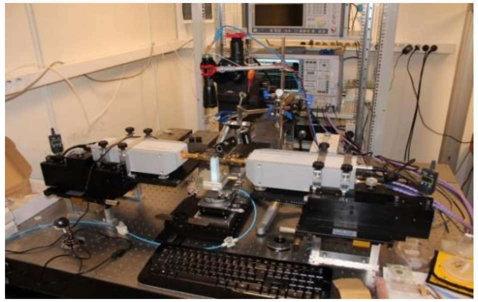
Group size:

- 1 professor
- 3 senior researchers
- 10 PhD students

Average external project funding:

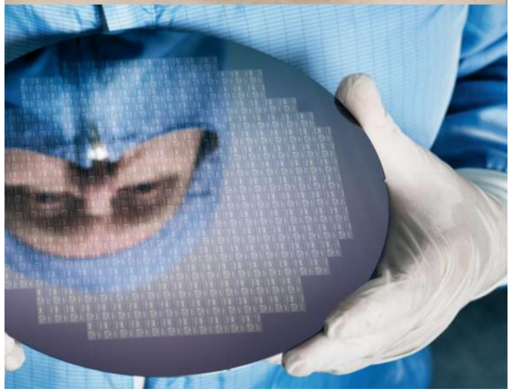
- >EUR 1 million/year

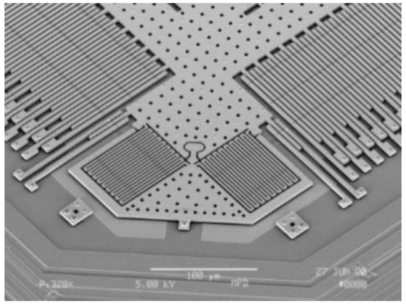
KTH micro&THz resources:



ELECTRUM LAB
KTH & ACREO IN COLLABORATION

- 1300m^2 class 100 clean-room for MEMS, photonics, III-V, SiC
- MW characterization (VNA, antennas) to 500 GHz





Micro-mechanics
MEMS

Micro-ElectroMechanical Systems

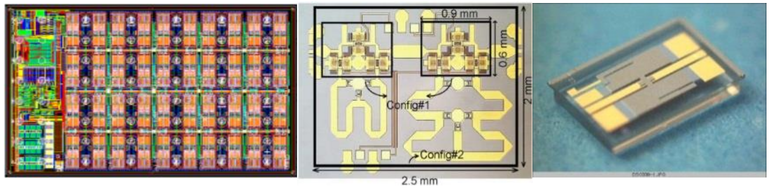
Semiconductor clean-room manufacturing:

- miniaturization
- very high volume
- very low cost

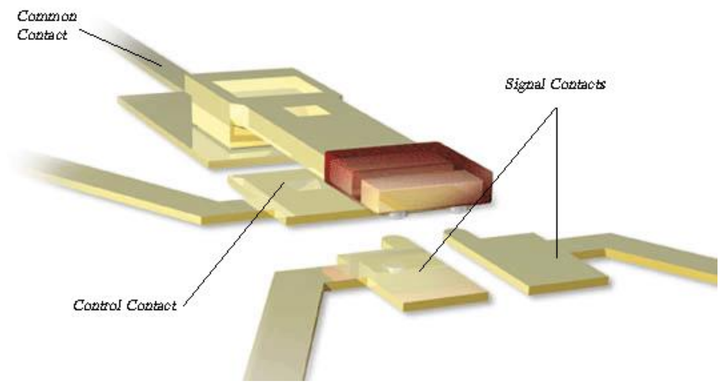
Revolutionized information age

inertial sensors,
microphones, ...
billions devices/year,
<1 EUR/dev

Revolutionized sensors and user interfaces



RF (radio—frequency) MEMS:
mobile phone antenna tuners,...



Typical performance:

- insertion loss<0.5dB@38GHz
- isolation: 23dB@10GHz, 18dB@36GHz
- linearity IIP3>65dBm

MEMS examples ...

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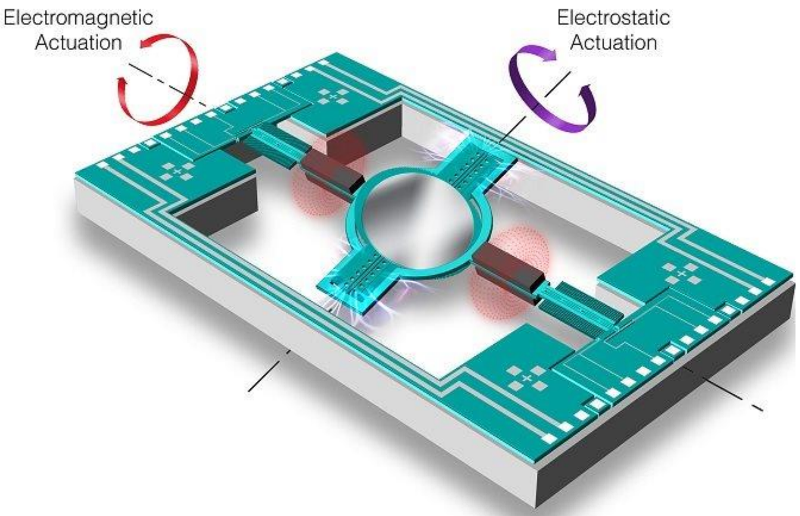
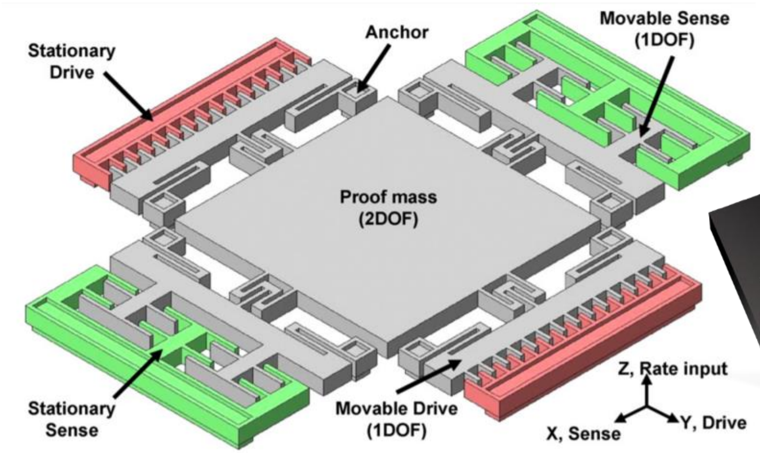
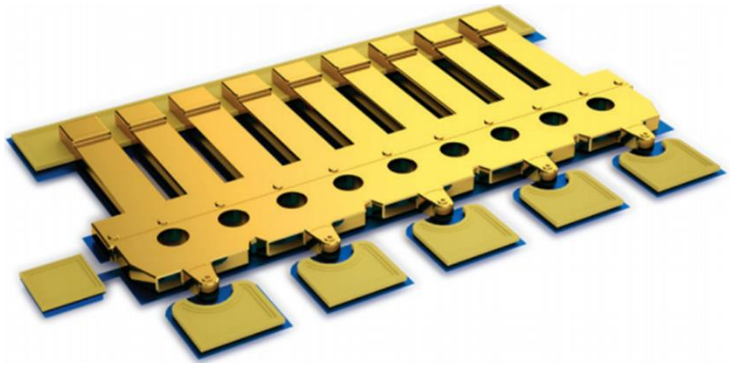
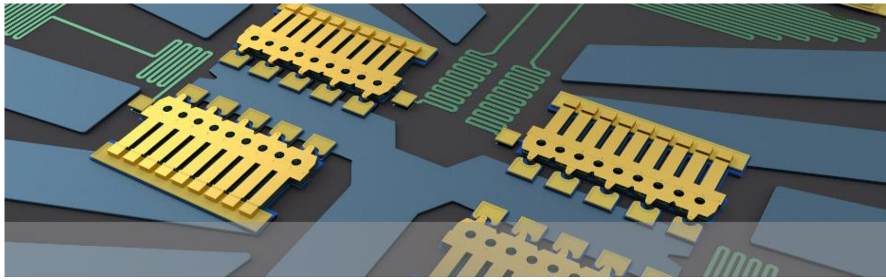


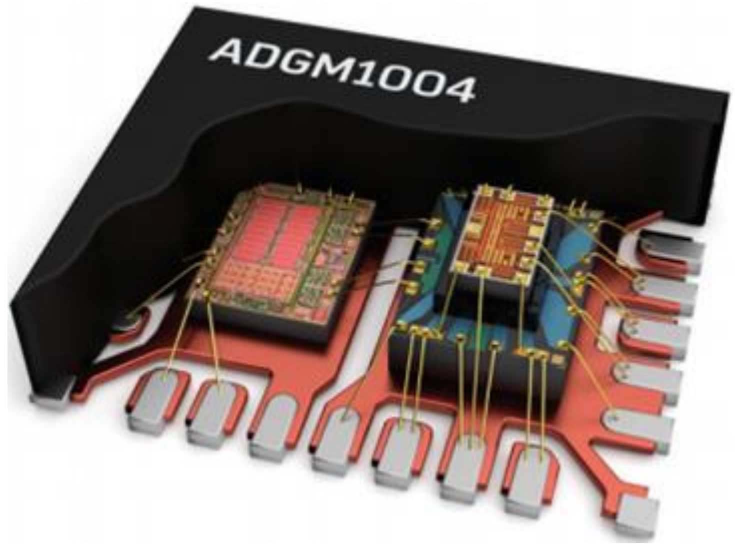
Moveable micromirror for LIDAR



MEMS gyroscope







Analog devices SP4T MEMS switch:
13 GHz BW, IL 0.45 dB (2.5 GHz),
ISO 30 dB (1GHz)
3.4 billion cycles (hot switched, 10 dBm)

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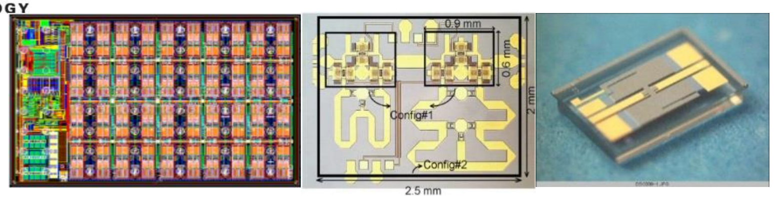
From RF MEMS to THz MEMS ...



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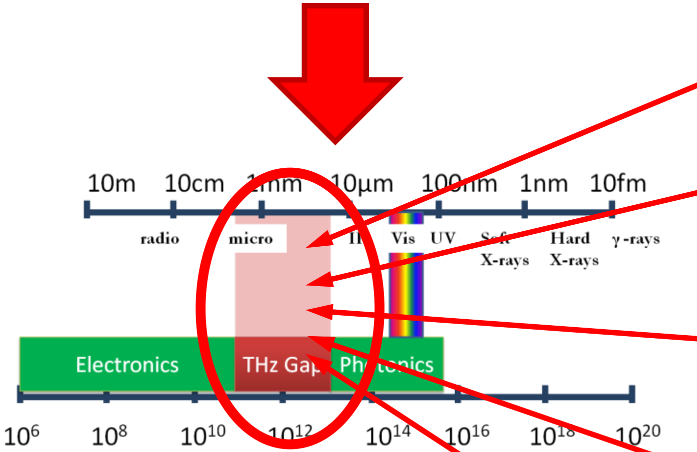
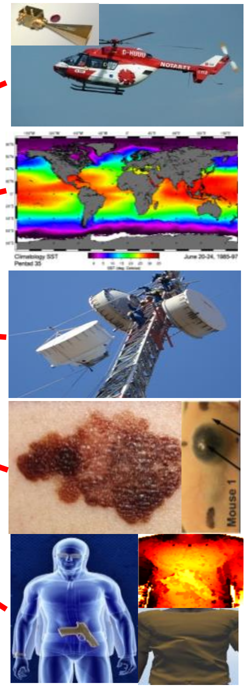
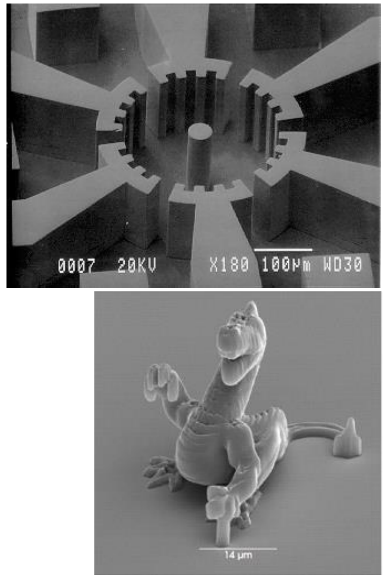




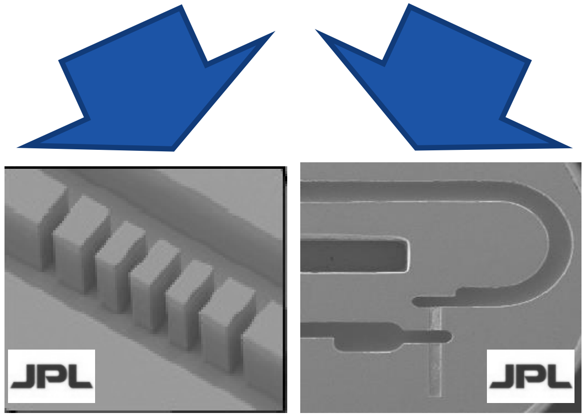
'THz gap': 100 GHz .. 10 THz

? THz MEMS revolutionizing exploitation of THz spectrum ?

microwave geometries are 3D



3D-micromachining



3D micromachined waveguides

Why micromachining?

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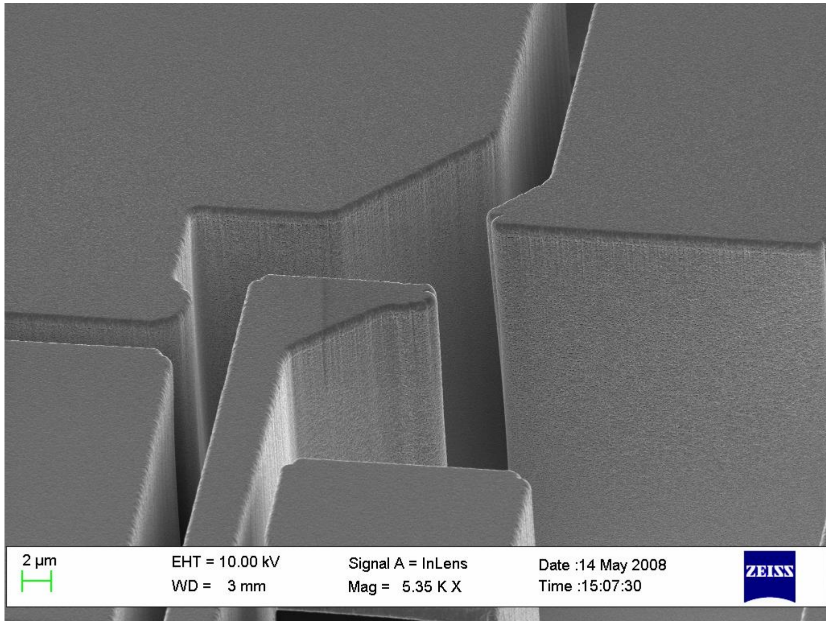
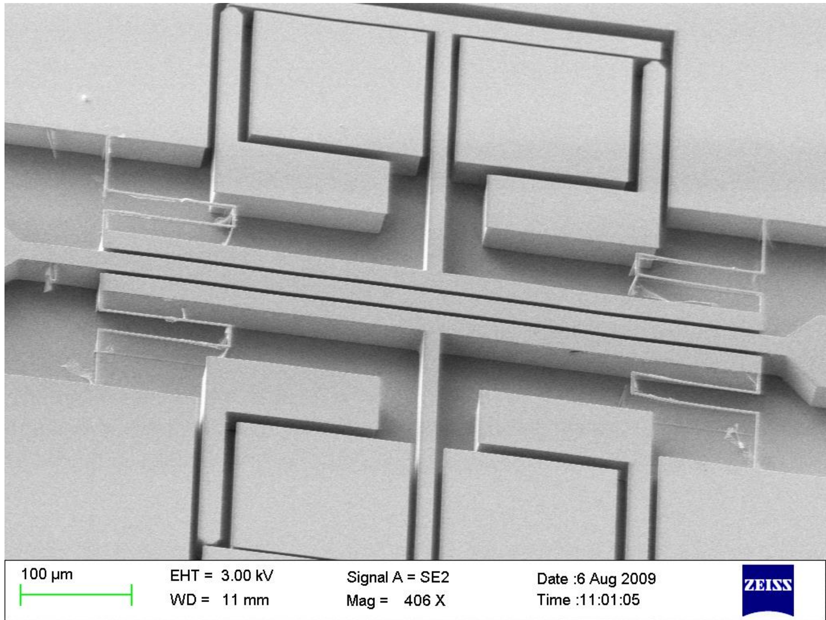
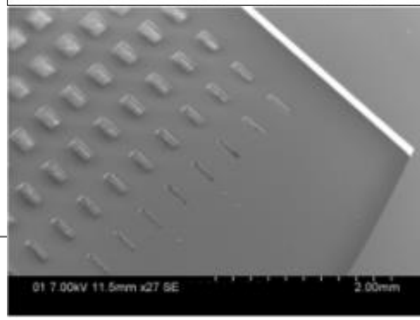
- Feature sizes/tolerances: down to µm
  => accurate geometries for THz-wavelengths
- Surface roughness: down to nm
  => ultra-low insertion loss
- Ultra-high aspect ratio geometries:
  - Vertical features: 110:1
  - Horizontal features: 1000:1
- Alignment accury: <2 µm
- Volume manufacturable
- High product uniformity
- Low cost in high volumes

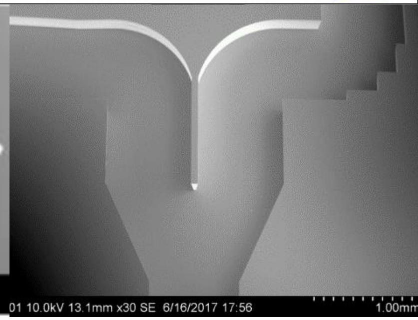
- Integrated MEMS microactuators
  => reconfigurability
  with near-ideal performance

Micro electromechanical systems



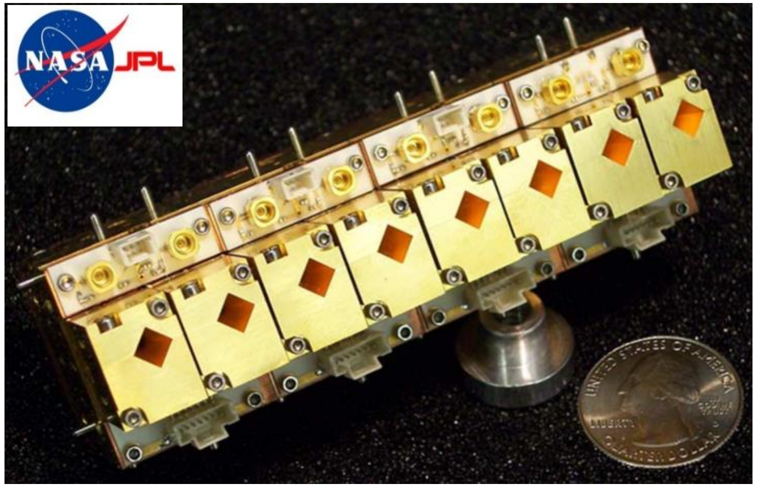


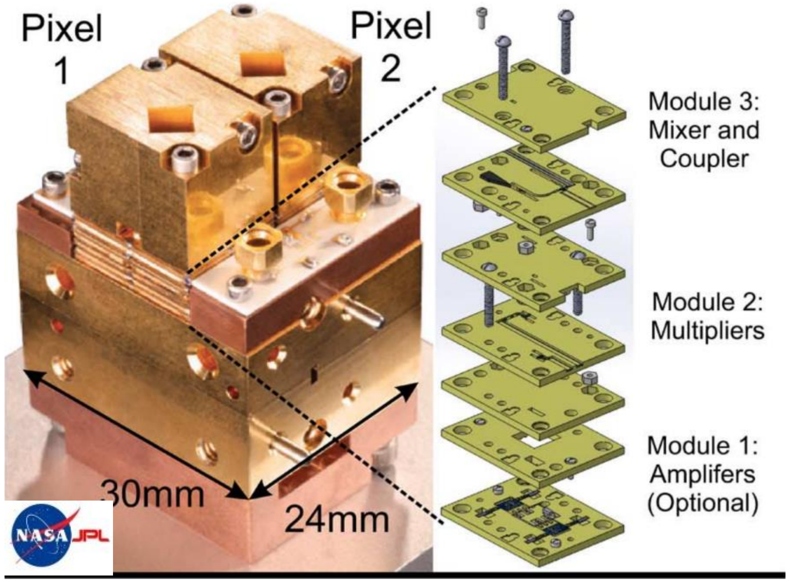


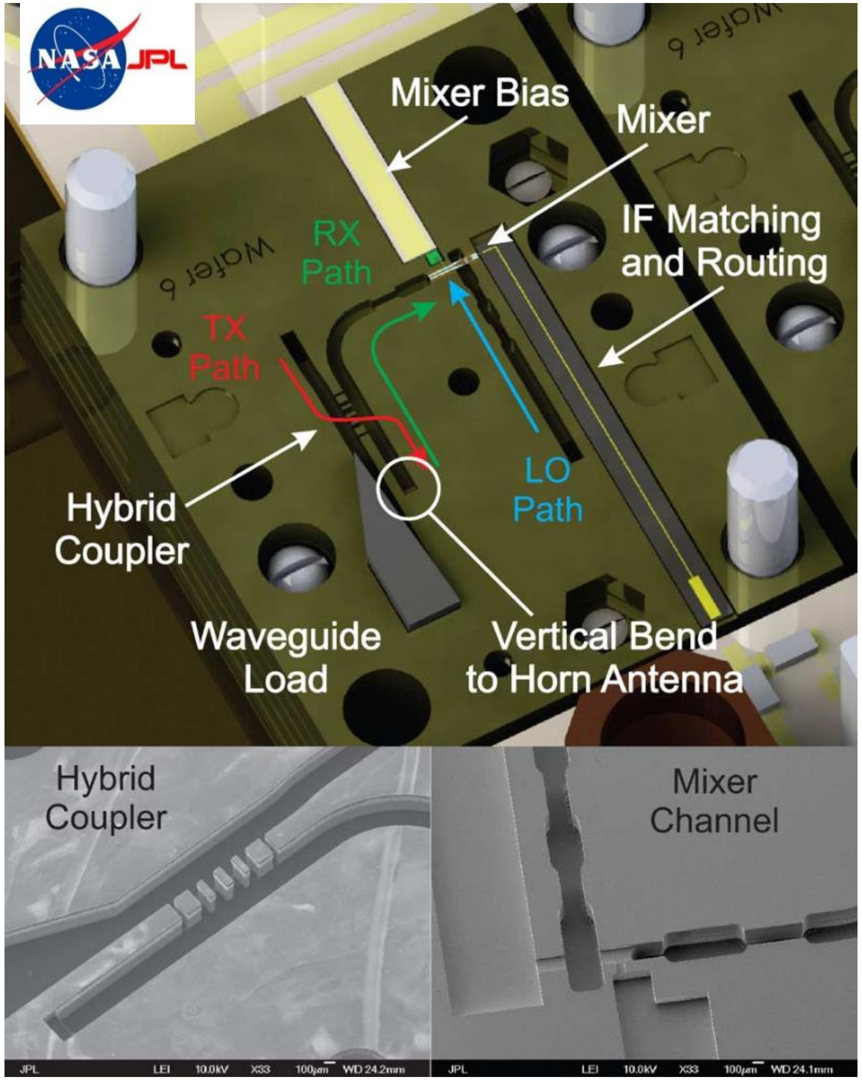


State-of-the-art THz microsystems: 340 GHz 8-pixel transceiver for imaging radar (JPL)

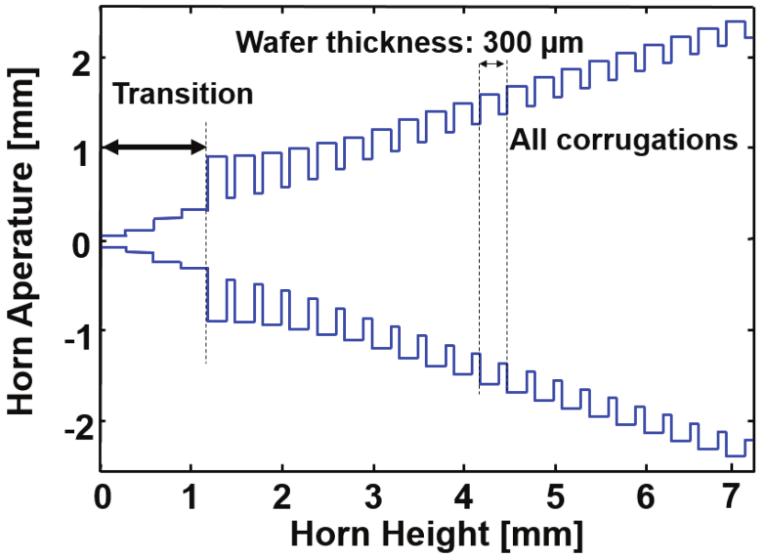
[T-THzSciTec 2015]

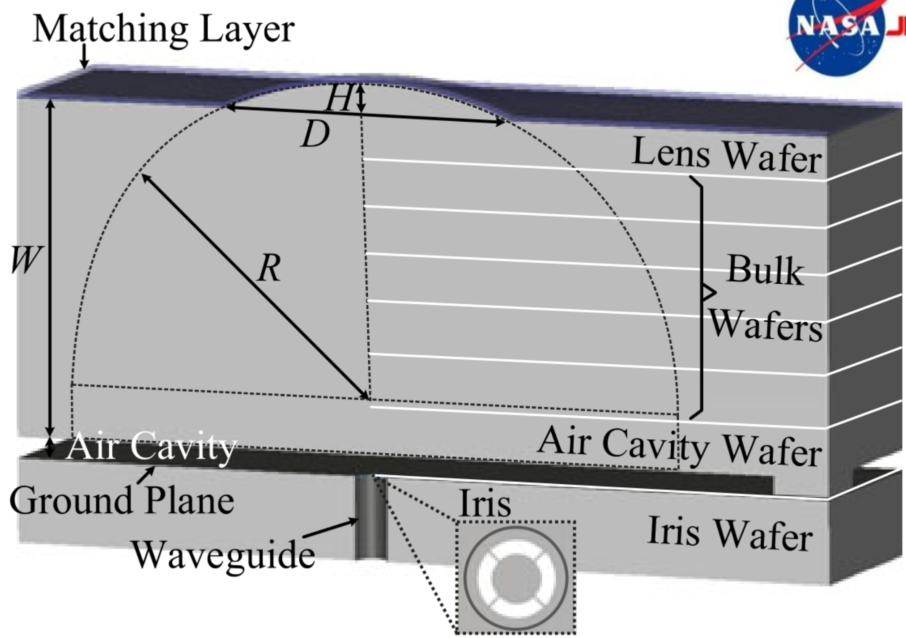


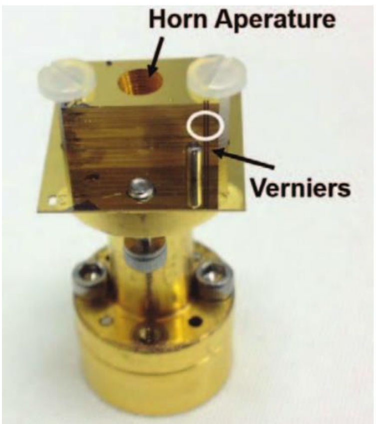


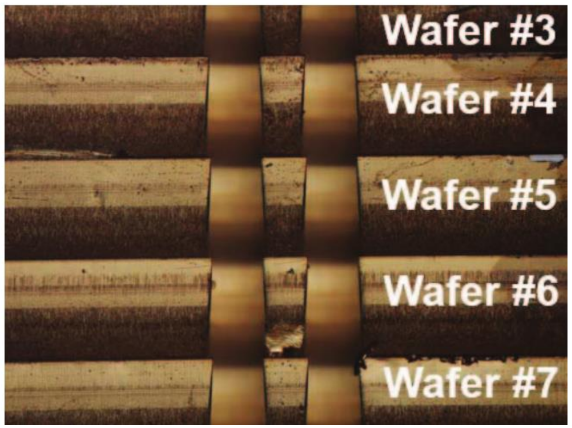


Micromachined THz stacked-chip antennas by JPL





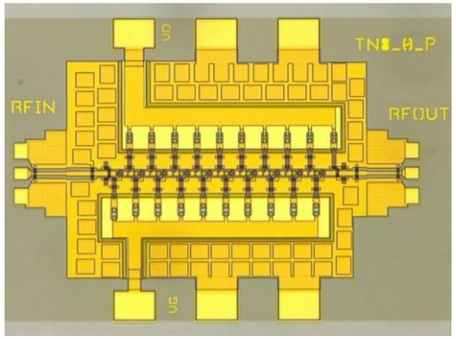


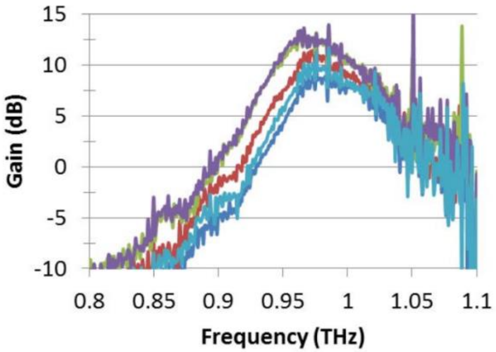


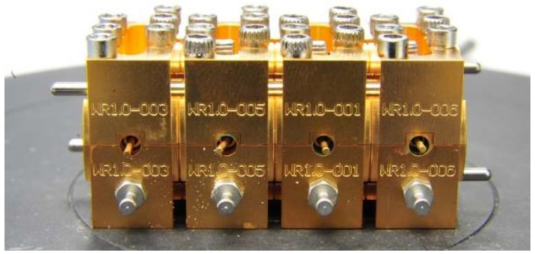
By 24 stacked micromachined silicon chips, 340 GHz, 20 dBi gain [JPL, 2015]

1.9 THz, narrow-band lens antenna [T-THzSciTec 2017]

Power-combining at 1 THz





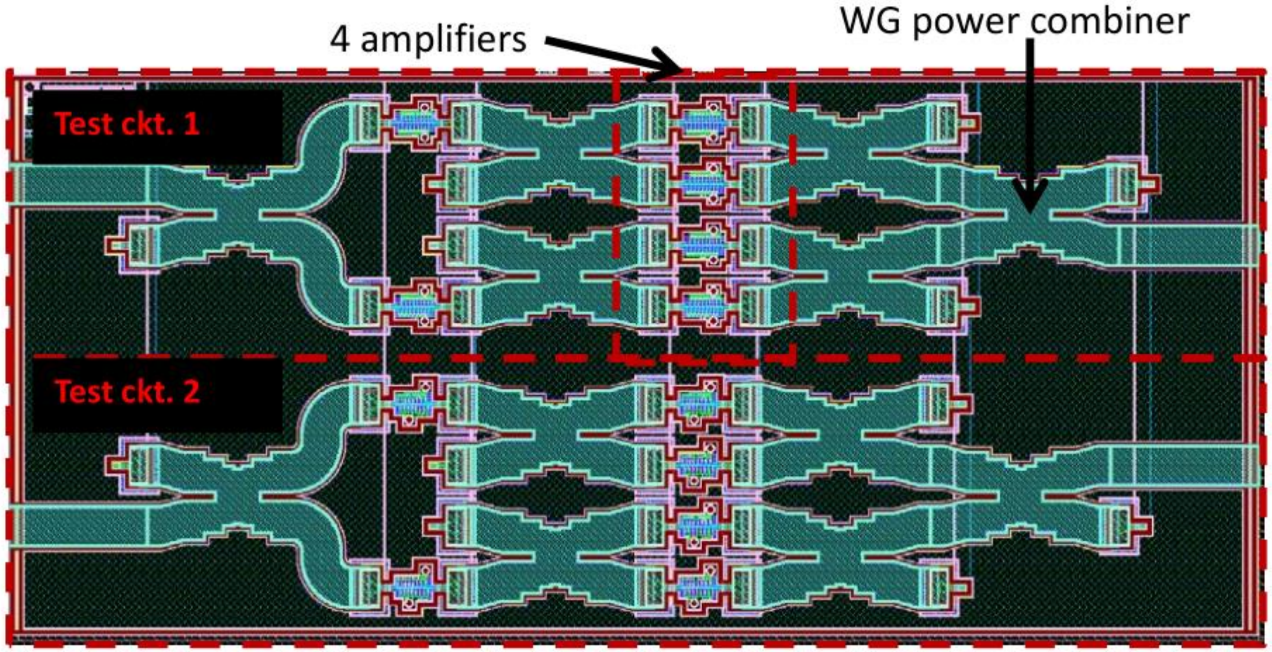


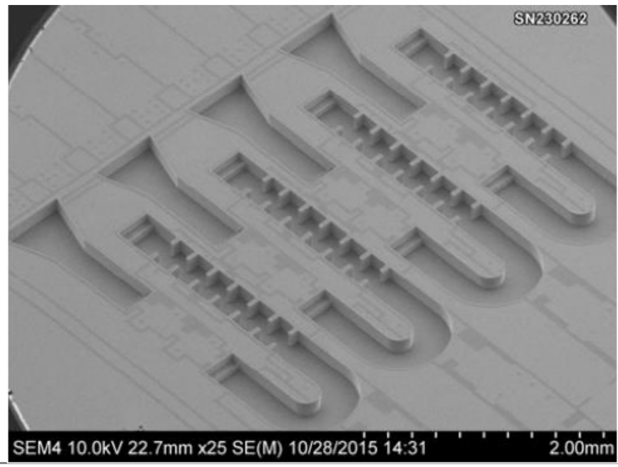
0.4 mW Measured Power at 975 GHz

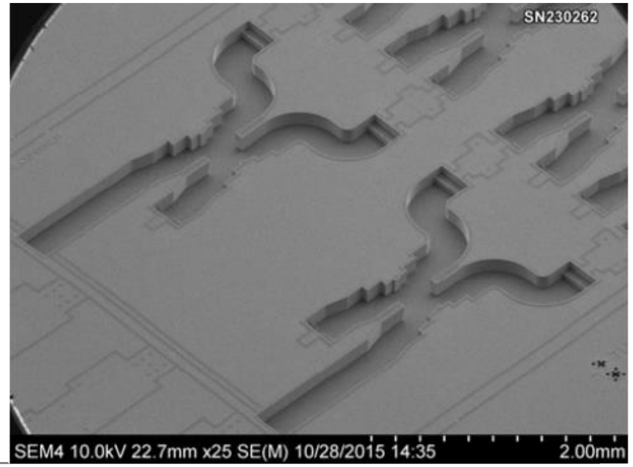
- Split block housings proven effective, *<u>but</u>*
- Expensive and difficult to mass produce

Micro-machining

Integrated 4-way Power Combiner







Micromachining & MEMS enabling new ways of building THz components and systems

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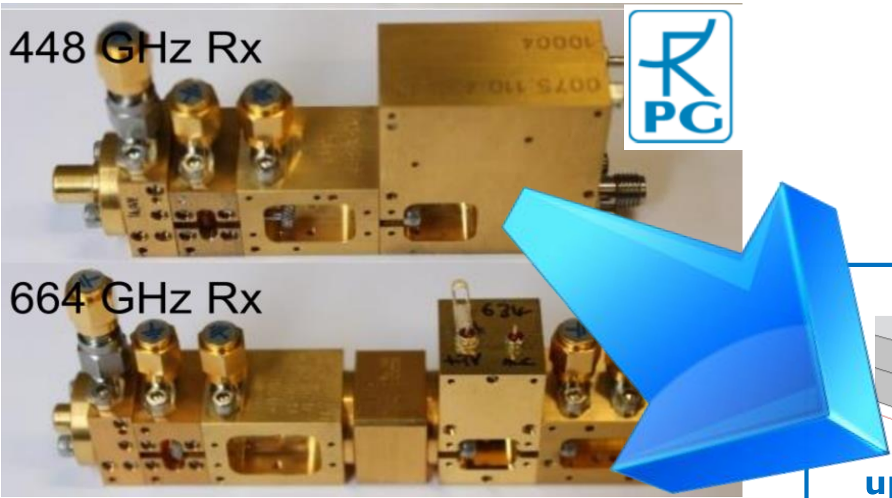
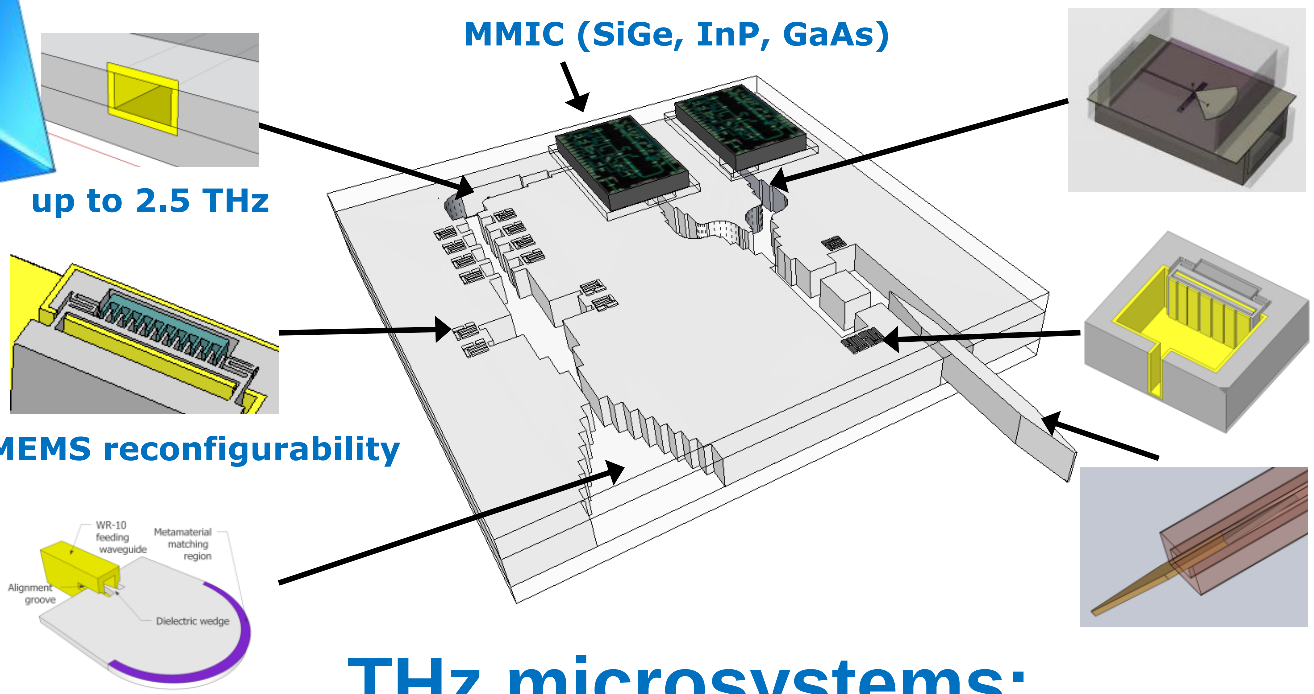


1000x smaller
1000x lighter
100x lower cost
10x less power consumption
reconfigurable
volume-manufacturable

THz technology = stone age

- bulky
- heavy
- manually assembled
- expensive
- only for scientific instruments
- not volume manufacturable



THz microsystems:

Enabling the large-scale exploitation of the THz frequency spectrum

Micromachined THz Systems at KTH

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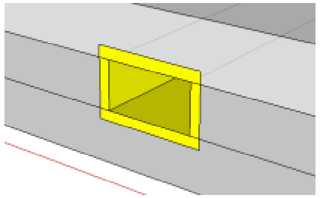
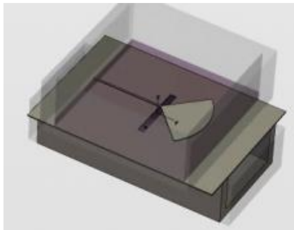
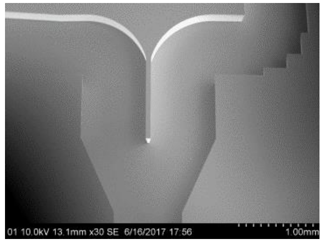
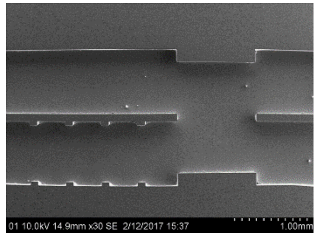


Low loss waveguides:
0.020 dB/mm @ 270 GHz
0.008 dB/mm @ 170 GHz

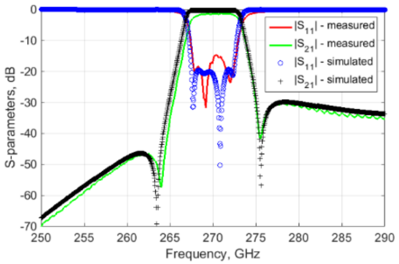
MMICs (SiGe, InP, GaAs) with waveguide interfaces



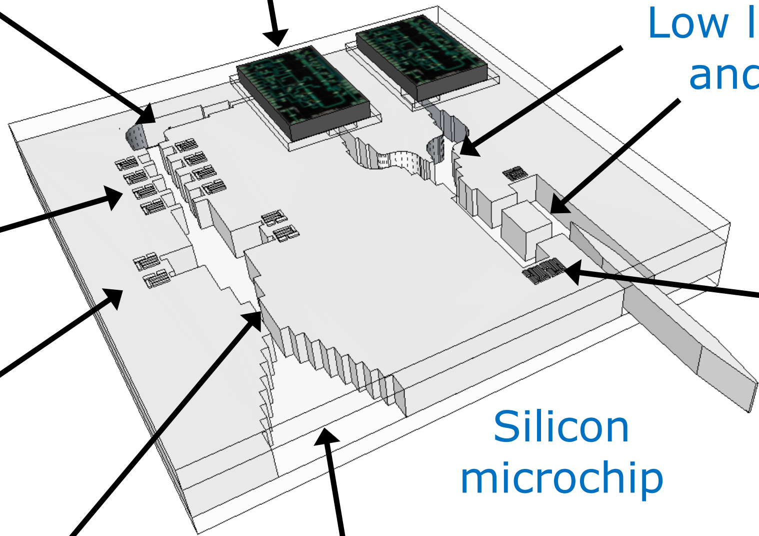




Low loss waveguide power combiners and couplers (0.2dB IL@320GHz)

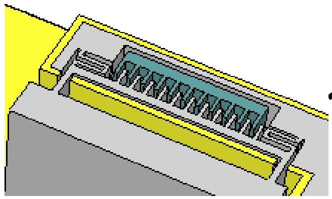


Filters: Q=800@450GHz, Q=1600@170GHz

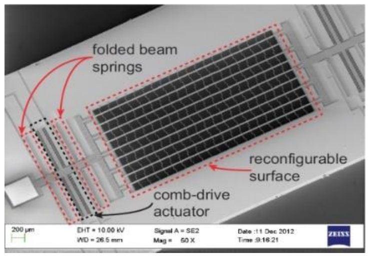


Silicon microchip

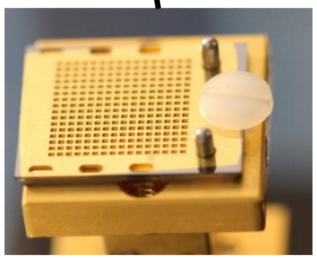
Integrated waveguide absorbers

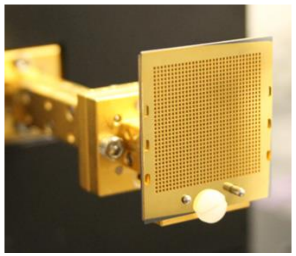


MEMS phase shifters up to 750GHz

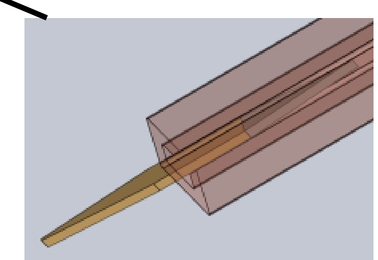


MEMS waveguide switches:
220GHz: 50dB ISO, 0.6dB IL





Antenna arrays, 320-400 GHz:
16x16: 34dBi gain, 0.8dB IL
32x32: 38dBi gain, 1.4dB IL



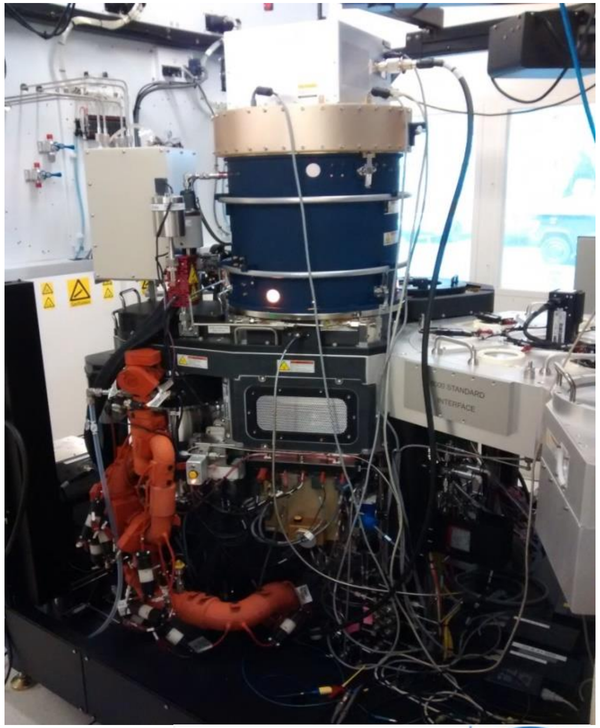
Micromachined medical sensor interfaces

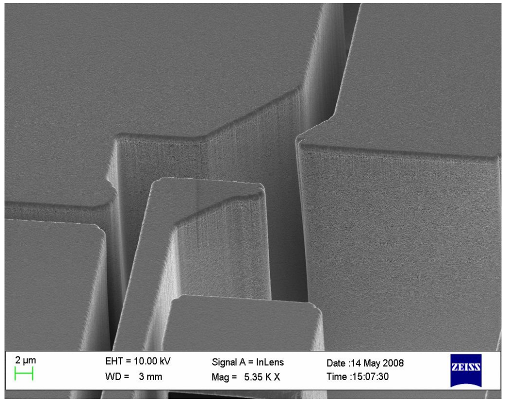
Combining competences in

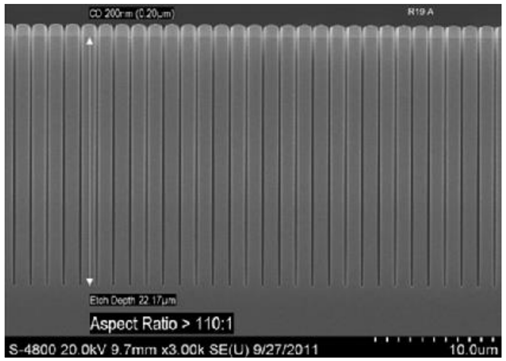
Advanced micro-wave design

Advanced silicon micromachining

Measurements& characterization
- VNA 67-500 GHz
- Antenna robot (4DoF) 67-500 GHz







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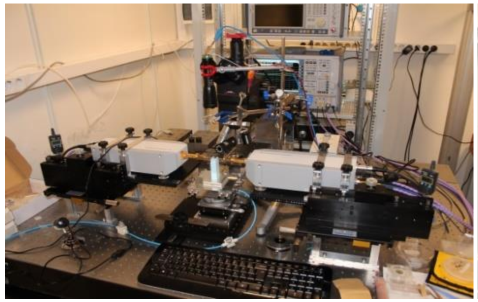

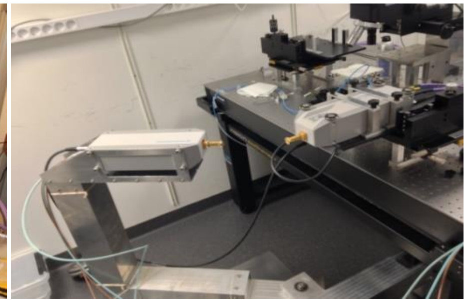

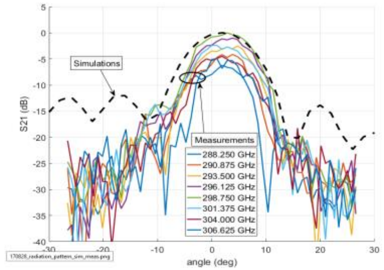

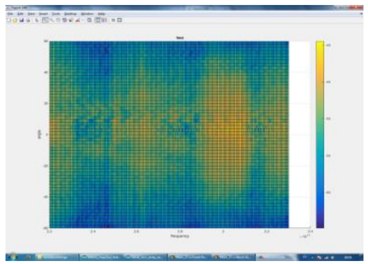

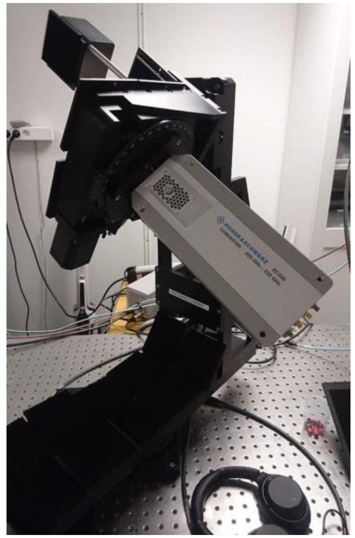

Examples of sub-THz micromachined/MEMS devices recently implemented at KTH (since 2015)

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Basic components:

- Waveguides
- Couplers, splitters, matched loads
- Waveguide switches, phase shifters
- Ultra high-Q filters

Complex components:

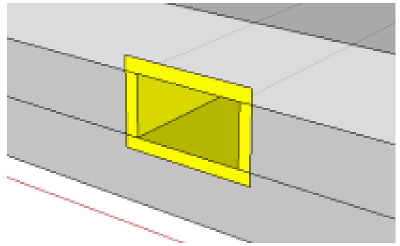
- Orthomode transducers
- Antenna arrays

Systems:

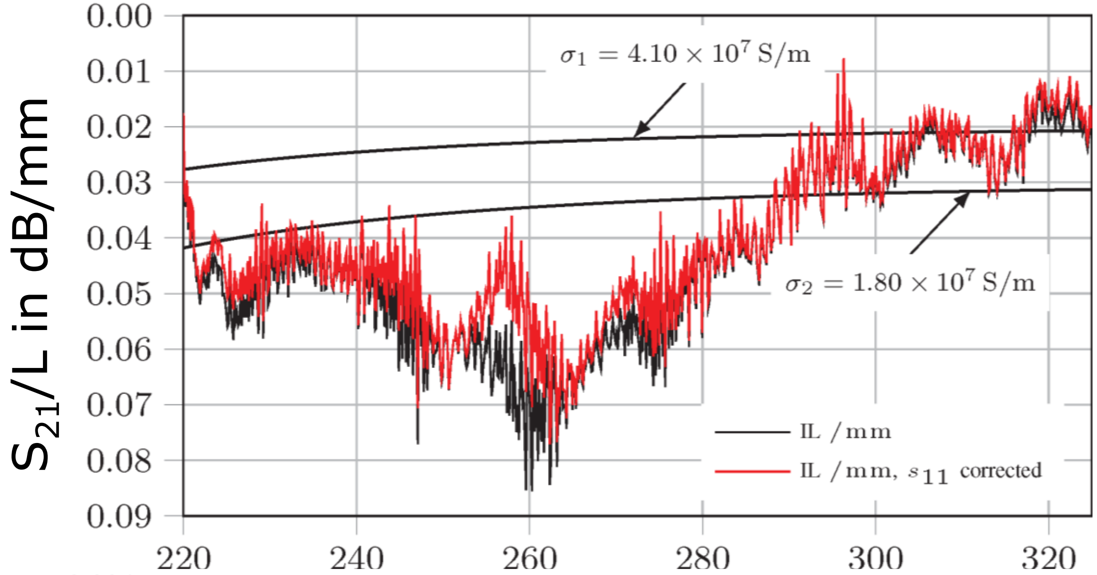
- Telecom front-end integration platform
- Beam-steering/radar demonstrators

Micromachined waveguides

Ultra-low loss micromachined waveguides at 110-330 GHz

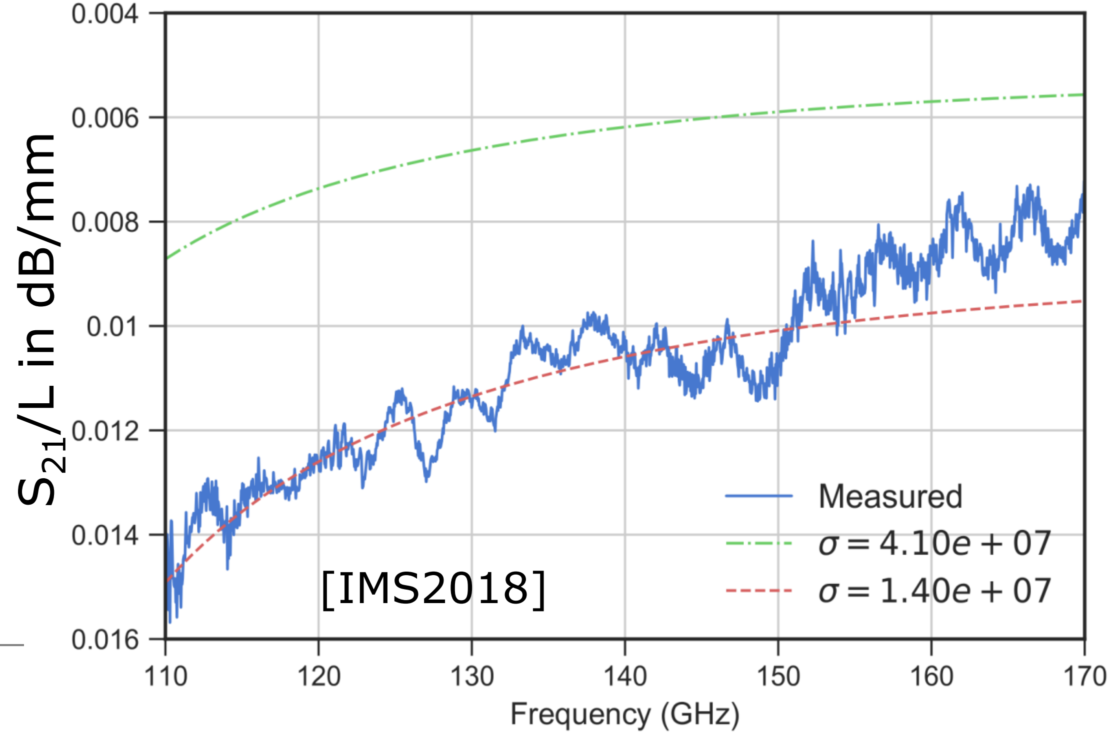


220-330 GHz:
0.020-0.070 dB/mm
Q_{UL}~750-800 (270 GHz)
[IEEE THzSciTec 2018]



Best performance of any waveguide in any technology in these bands!

110-170 GHz:
0.008-0.016 dB/mm
Q_{UL}~1600
[IEEE IMS 2018]



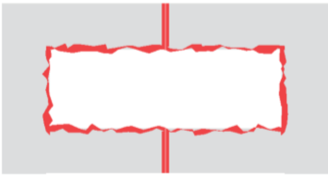
Ultra-low loss micro-machined waveguides

$$\alpha_c = \alpha_{c0}\left(1 + K_{rough}\right)$$

$$K_{rough} = \frac{2}{\pi}\tan^{-1}\left[1.4\left(\frac{R_a}{\delta}\right)\right]$$

$$\alpha_{c0} = 4.58 \times 10^{-8}\sqrt{\frac{f}{\sigma}}\left[\frac{2\frac{b}{a}\left(\frac{f_c}{f}\right)^2 + 1}{b\sqrt{1-\left(\frac{f_c}{f}\right)^2}}\right] dB/mm$$

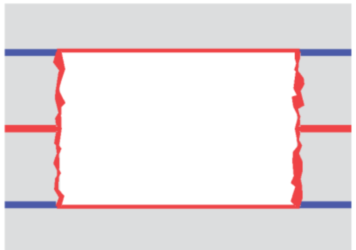
Conventional approaches:



E-plane split

Single H-plane split

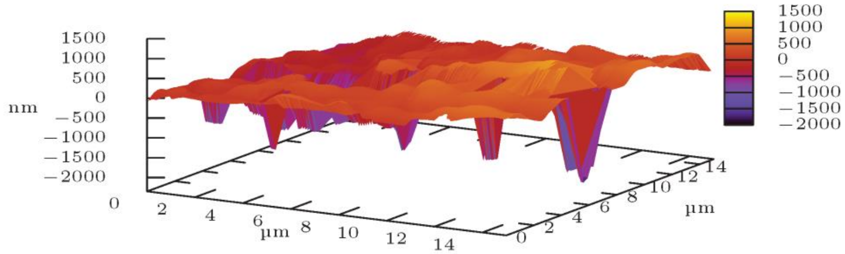
New approach: Double H-plane split



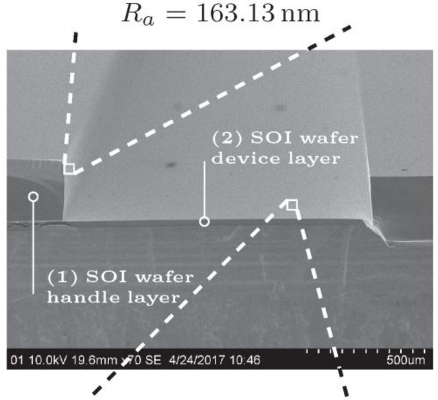
110-170 GHz:
0.008-0.016 dB/mm
Q_{UL}~1600

220-330 GHz:
0.020-0.070 dB/mm
Q_{UL}~750-800

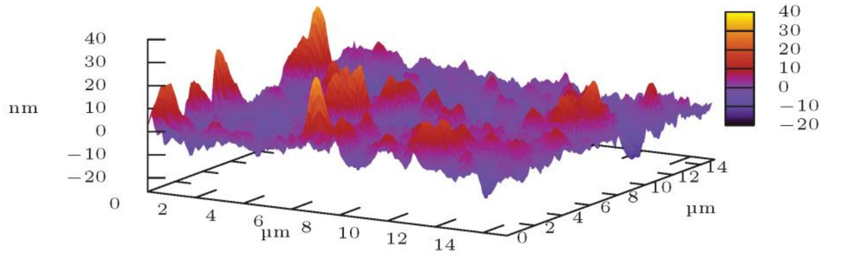
(a) waveguide sidewall



$R_a = 163.13\,\text{nm}$

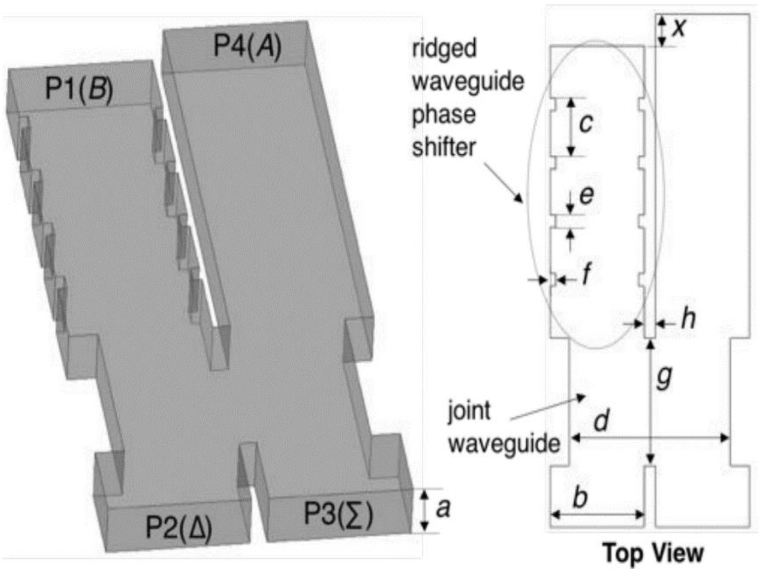


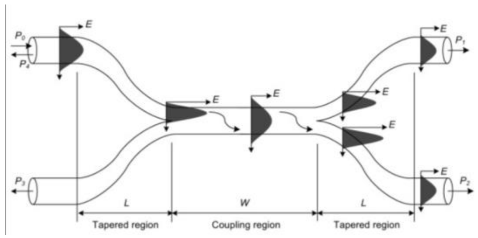
$R_a = 2.14\,\text{nm}$

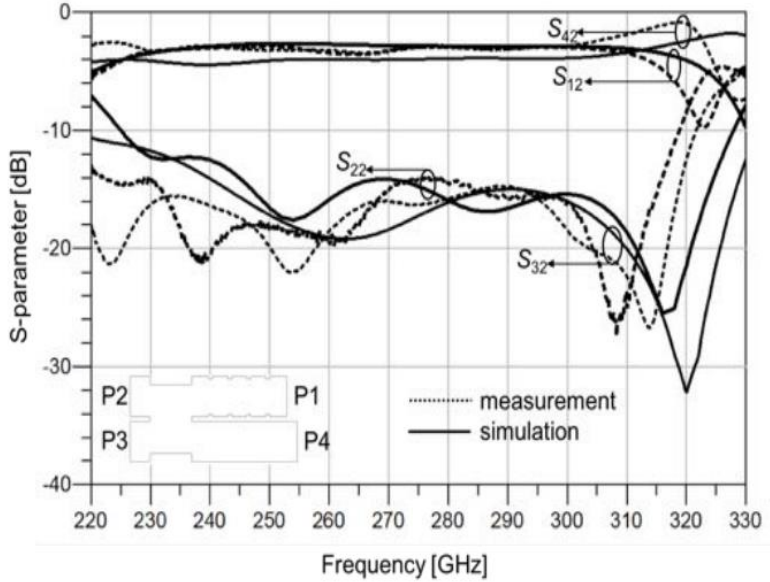


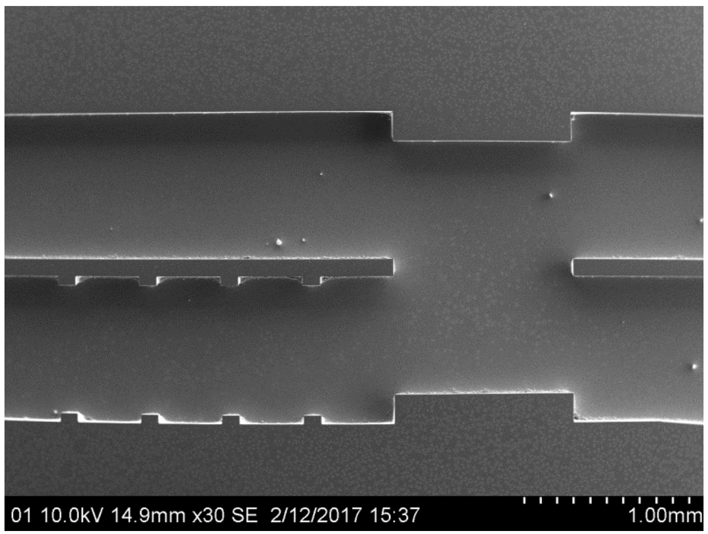
(b) waveguide top and bottom

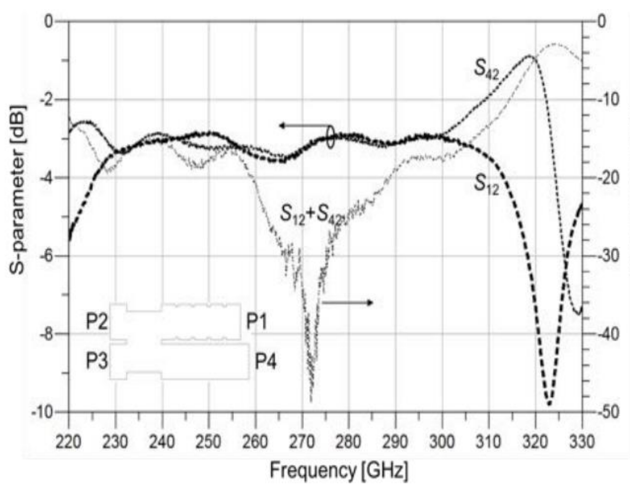
Ultra-low loss micromachined 3-dB coupler at 220-330 GHz

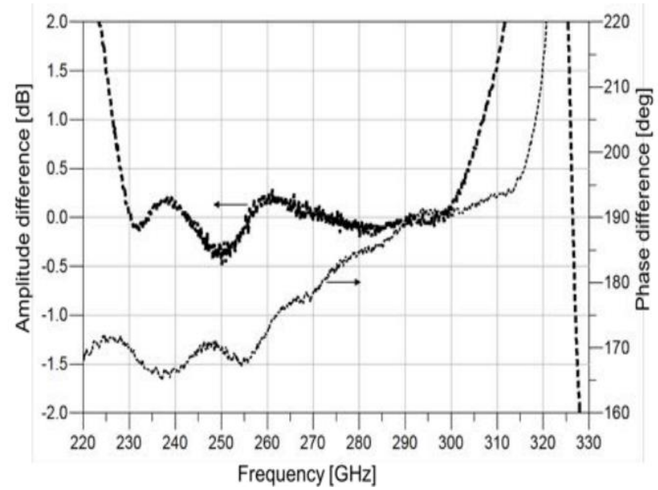




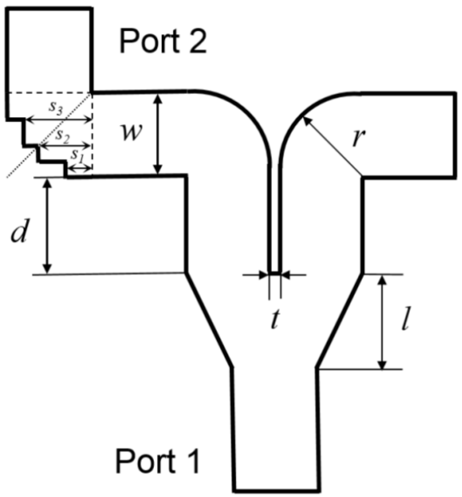


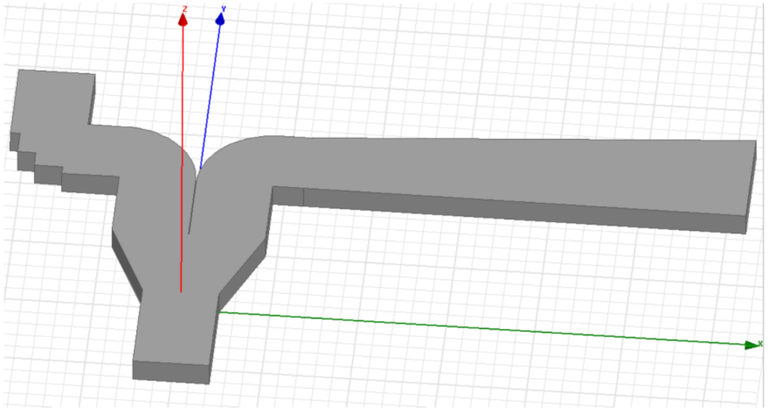


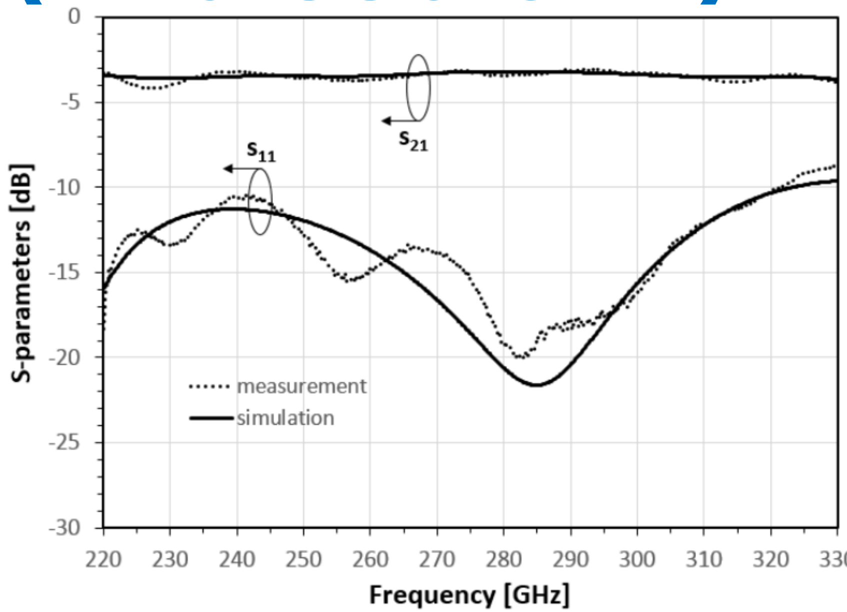




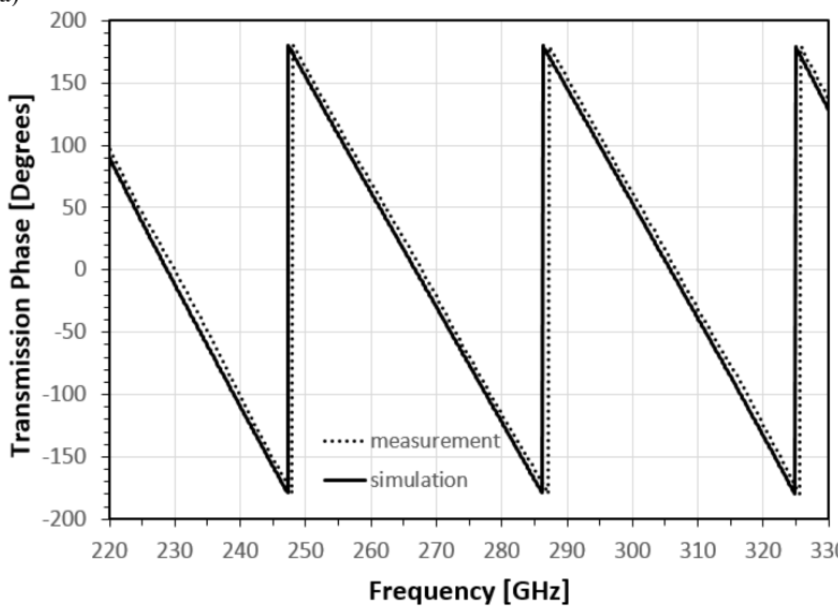
Ultra-low loss micromachined power splitter (220-330 GHz)

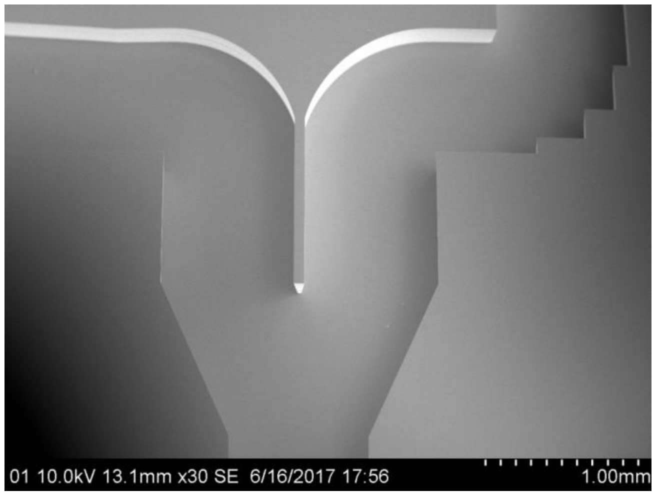


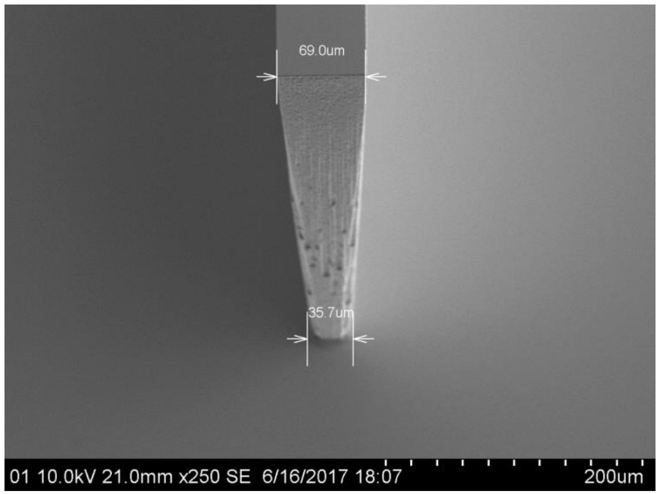




a)

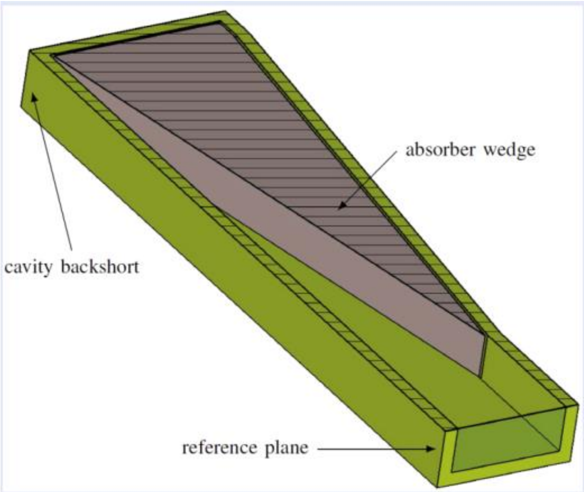


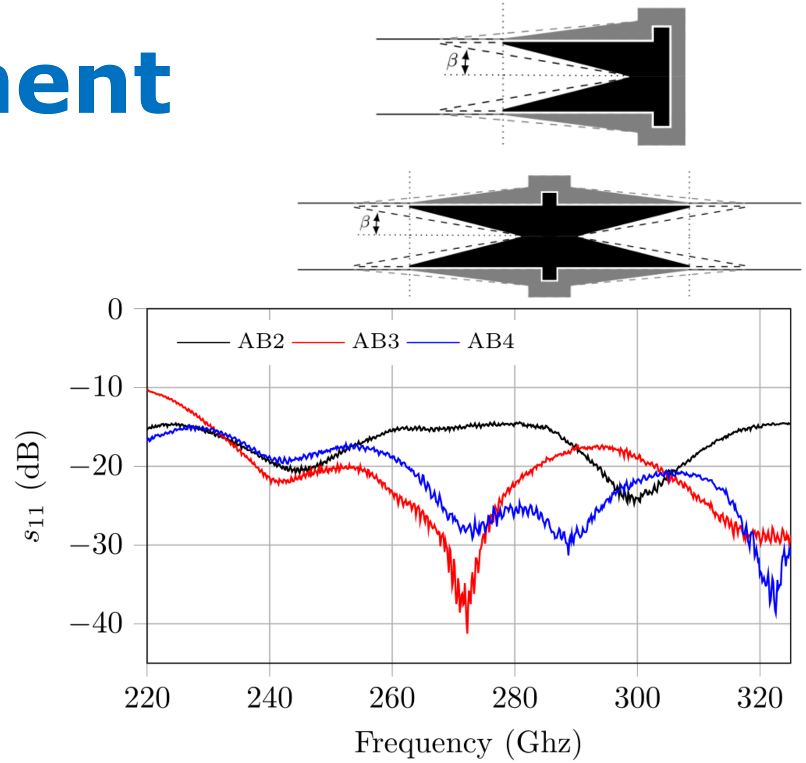




[APMC 2017]

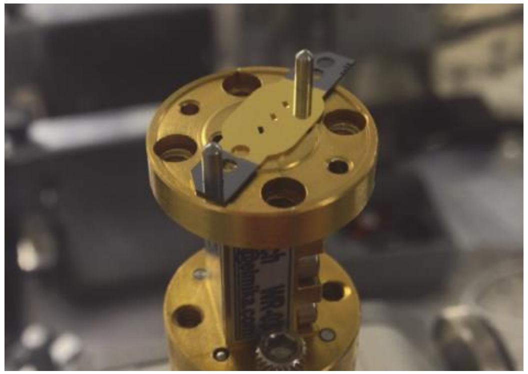
Interfaces & measurement technology

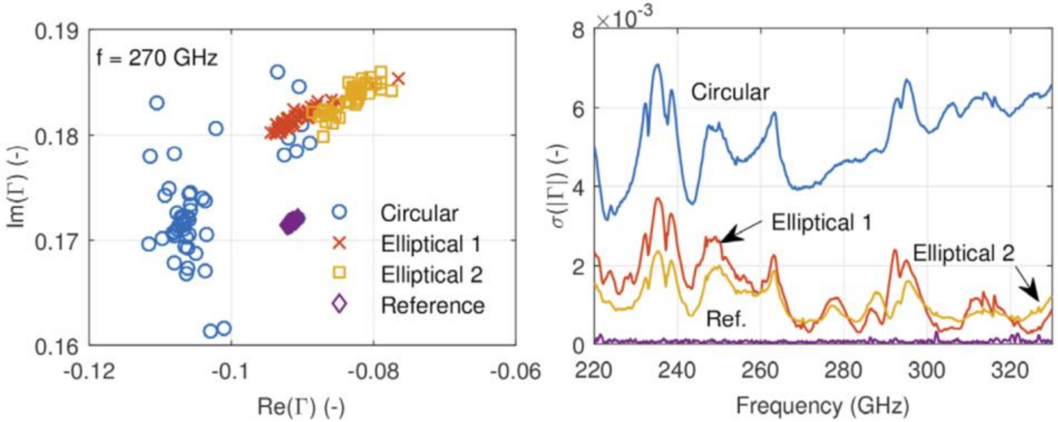




On-chip integrated absorbers, calibration kits

[EuMC 2017, IMS 2018]

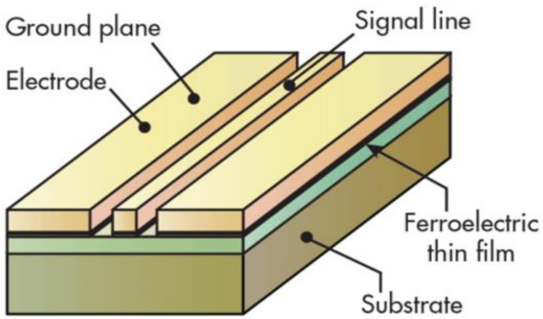




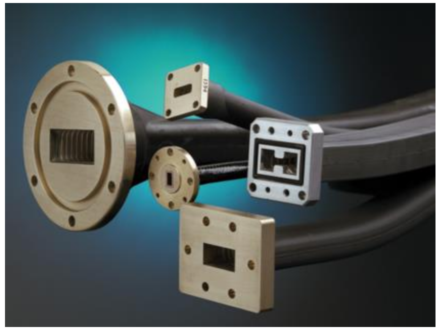
Measurement interfaces:
High-precision flange to microchip alignment method

[IEEE IMS 2017]

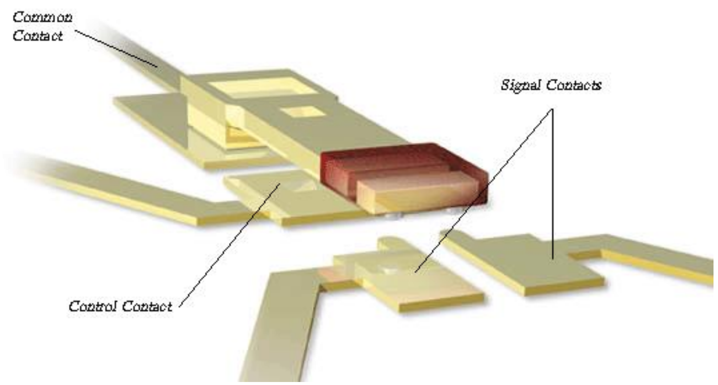
MEMS waveguide switches



Transmission lines



waveguides

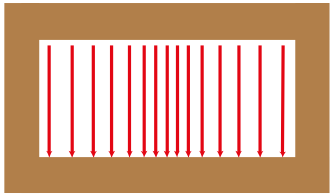


RF MEMS planar switch

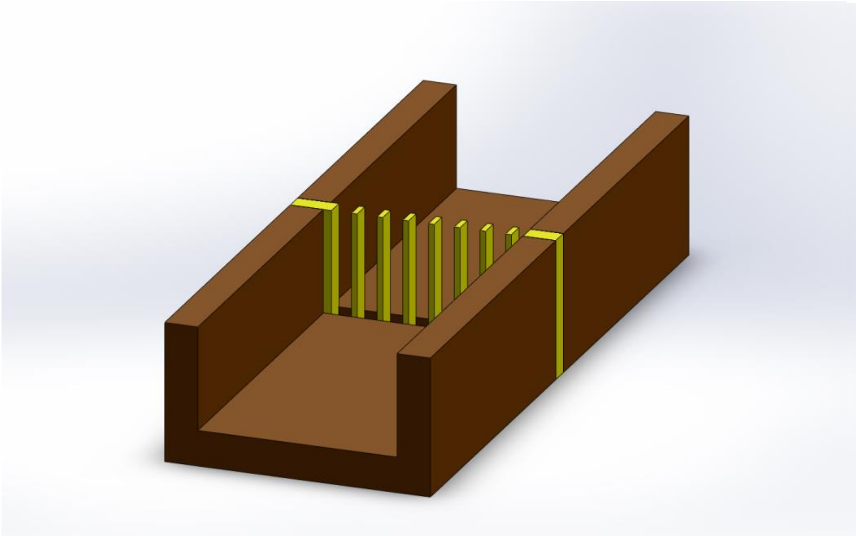
?

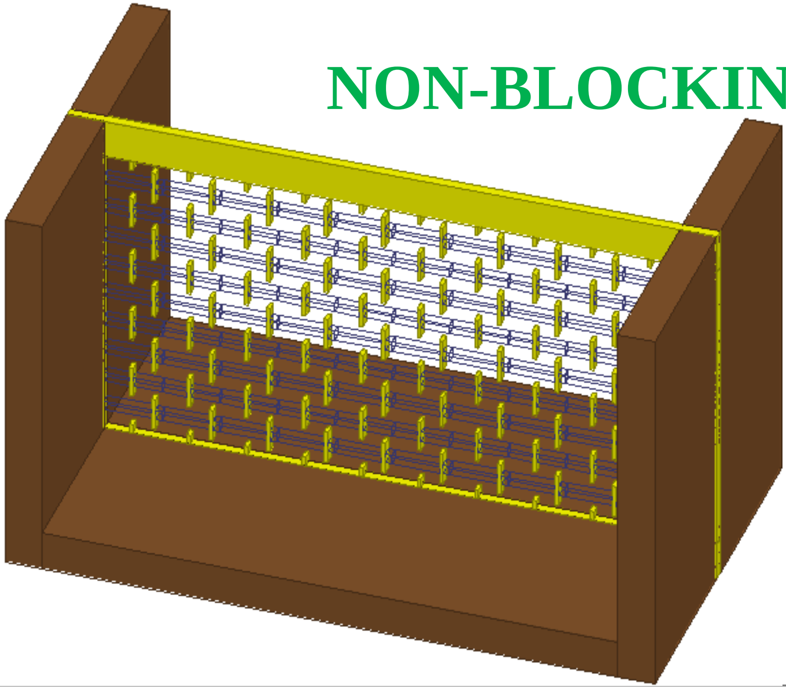
MEMS waveguide switch

How to build a MEMS waveguide switch?



TE10 mode

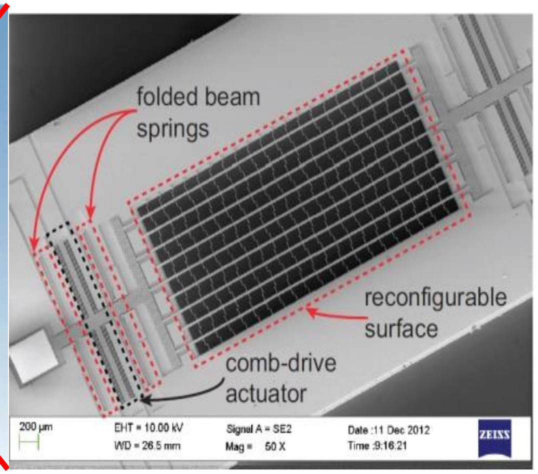




NON-BLOCKING

MEMS:

- 100 000 x smaller
- 100 000 x lighter
- 10 000 x faster
- equal performance



30 µm thick!
thinner than a hair

KTH VETENSKAP OCH KONST
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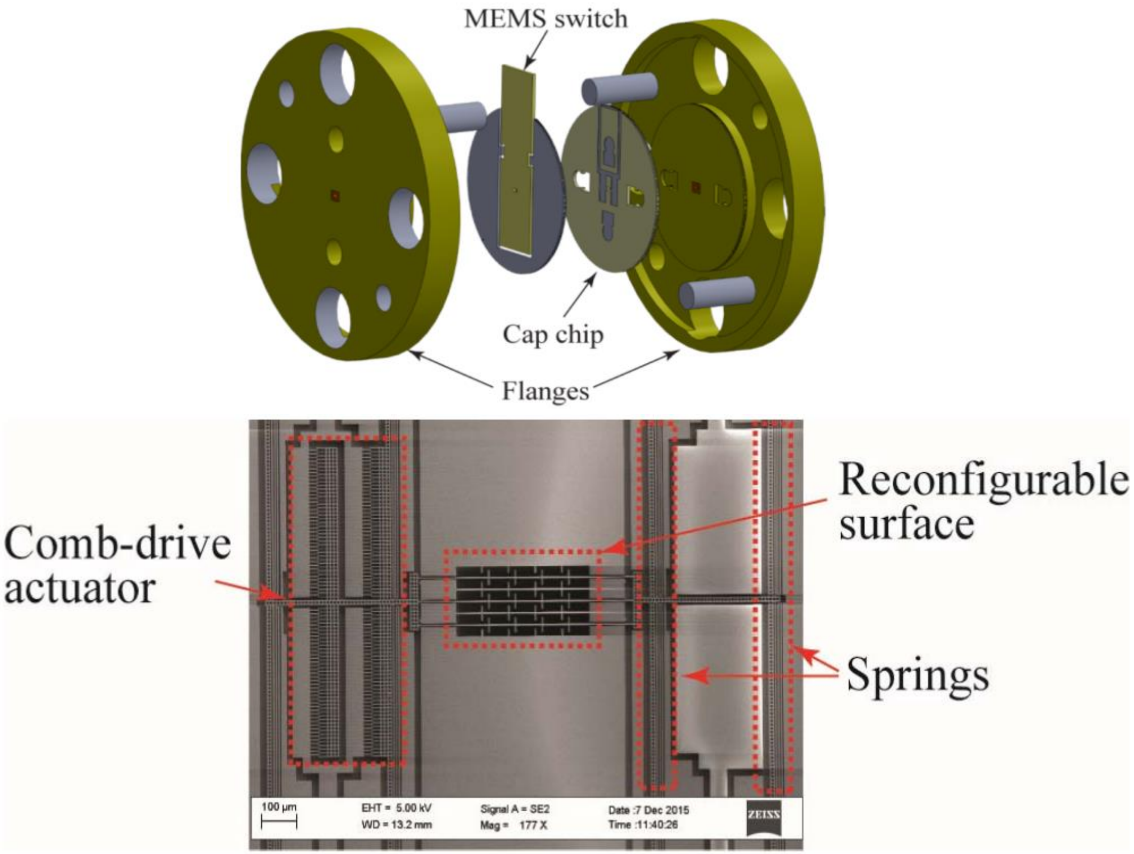
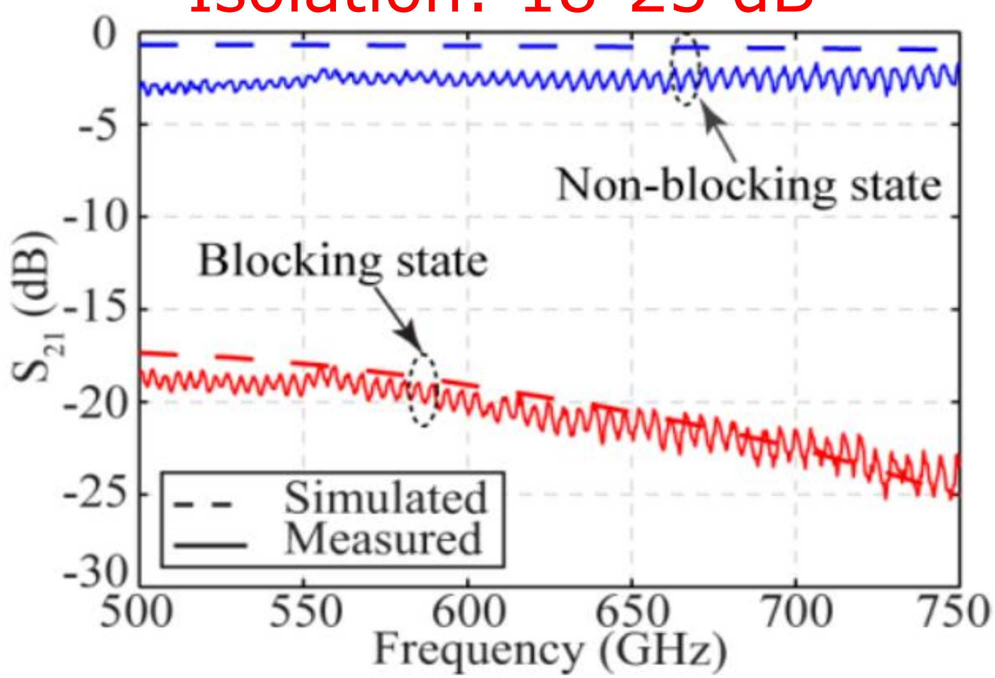
NASA JPL

500-750 GHz
MEMS waveguide switch

- First MEMS waveguide switch above 70 GHz
- First sub-mm-wave MEMS switch
- First MEMS switch above 220 GHz



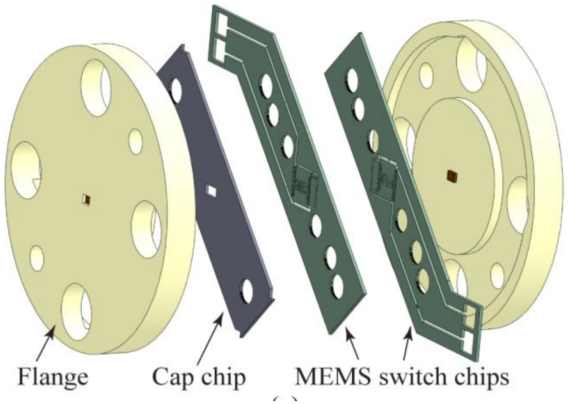
- Insertion loss: 2.5 dB
- Isolation: 18-25 dB

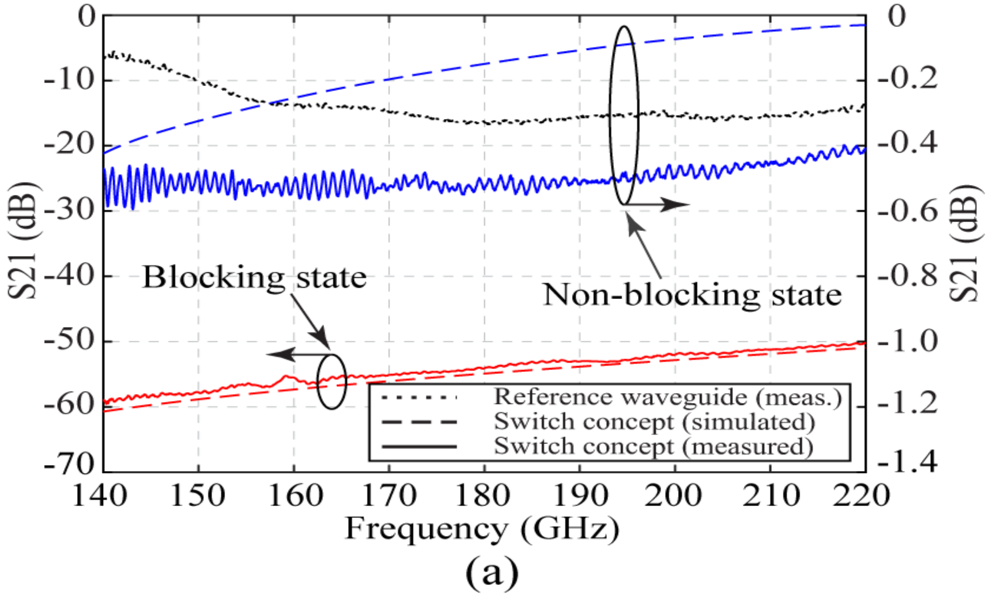


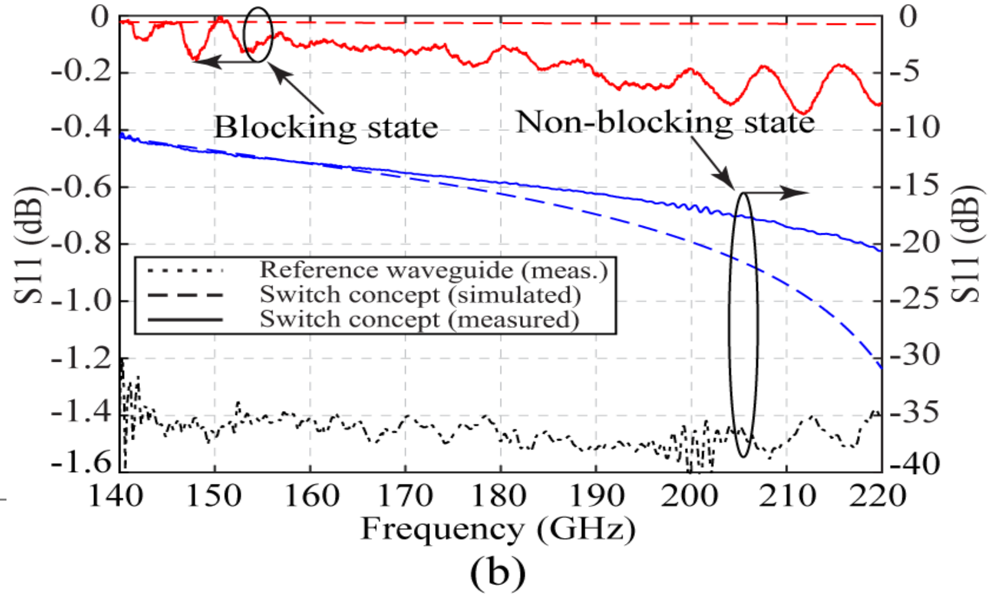
[IEEE IMS 2016, IEEE THzSciTec 2017]

High on/off ratio 183 GHz switch for radiometer calibration

Prototype measurements:







Measured performance flange-to-flange:

Insertion loss:
<0.6dB

Isolation:
>50 dB

For whole band 140-220 GHz

MEMS waveguide switches by KTH

(micro electro mechanical systems)

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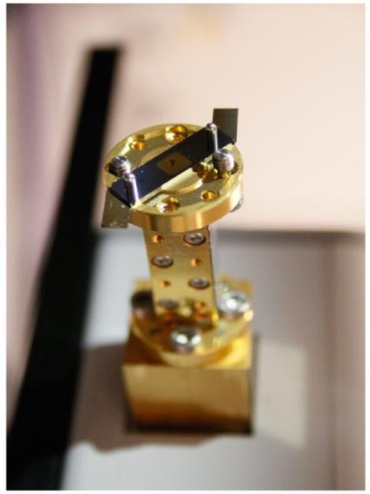
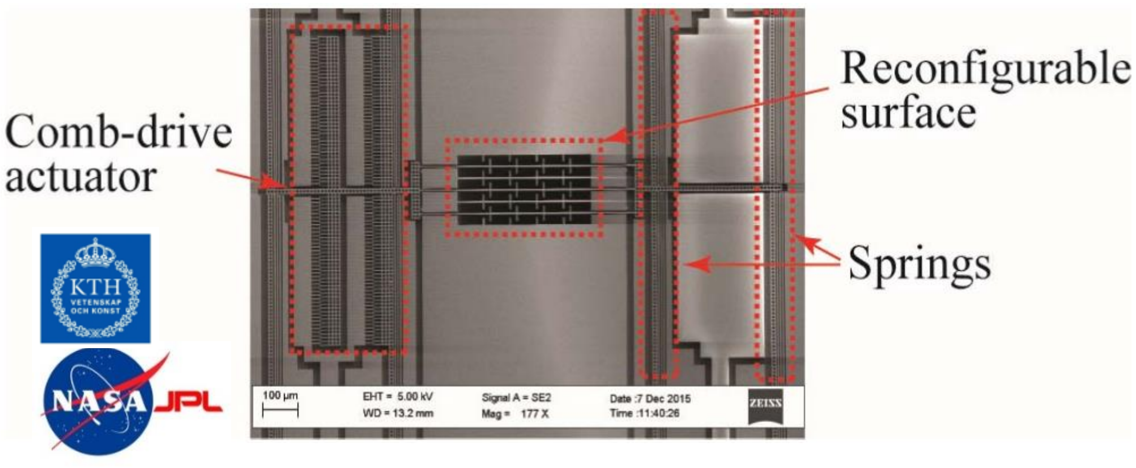
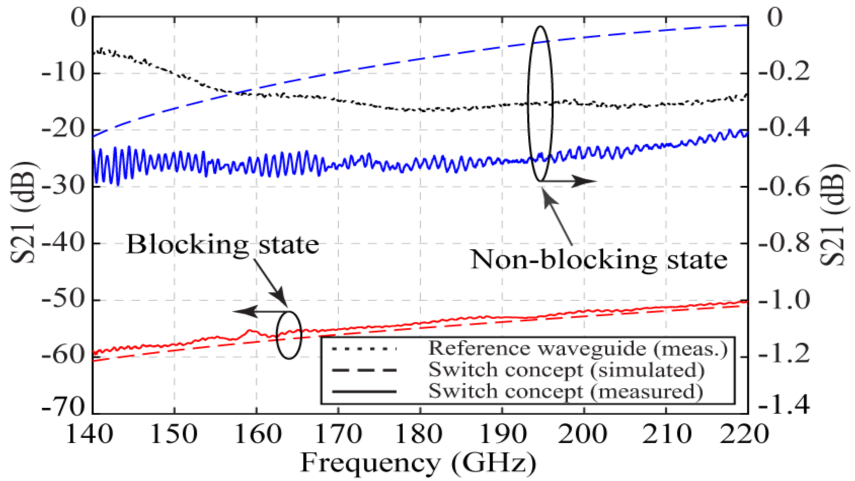
	Generation 1 60-70 GHz	Generation 2 500-750 GHz	Generation 3 140-220 GHz
Insertion loss	0.3-0.4 dB	2.5 dB	<0.6 dB
Isolation	30-40 dB	18-25 dB	>50 dB
On/off ratio	54	9	295





500-750 GHz switch



140-220 GHz switch

500-600 GHz 3.3 bit MEMS phase shifter

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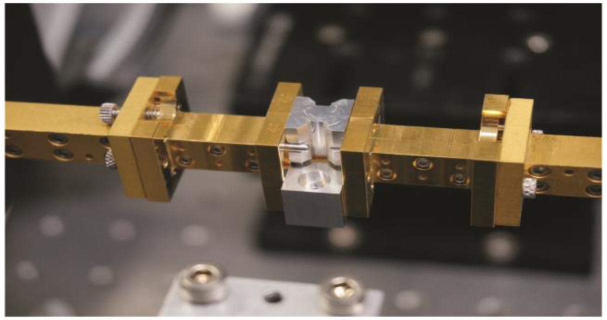

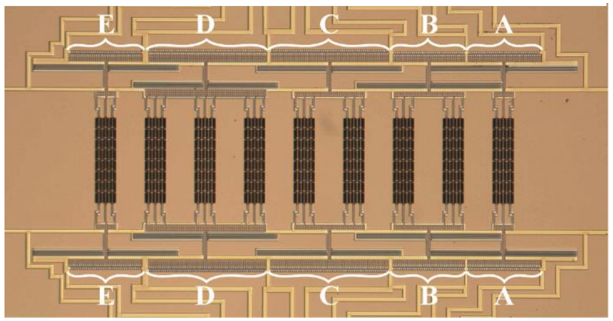

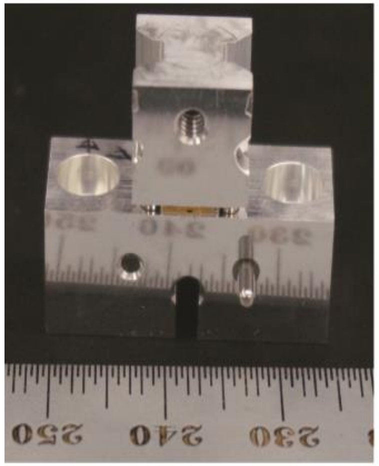

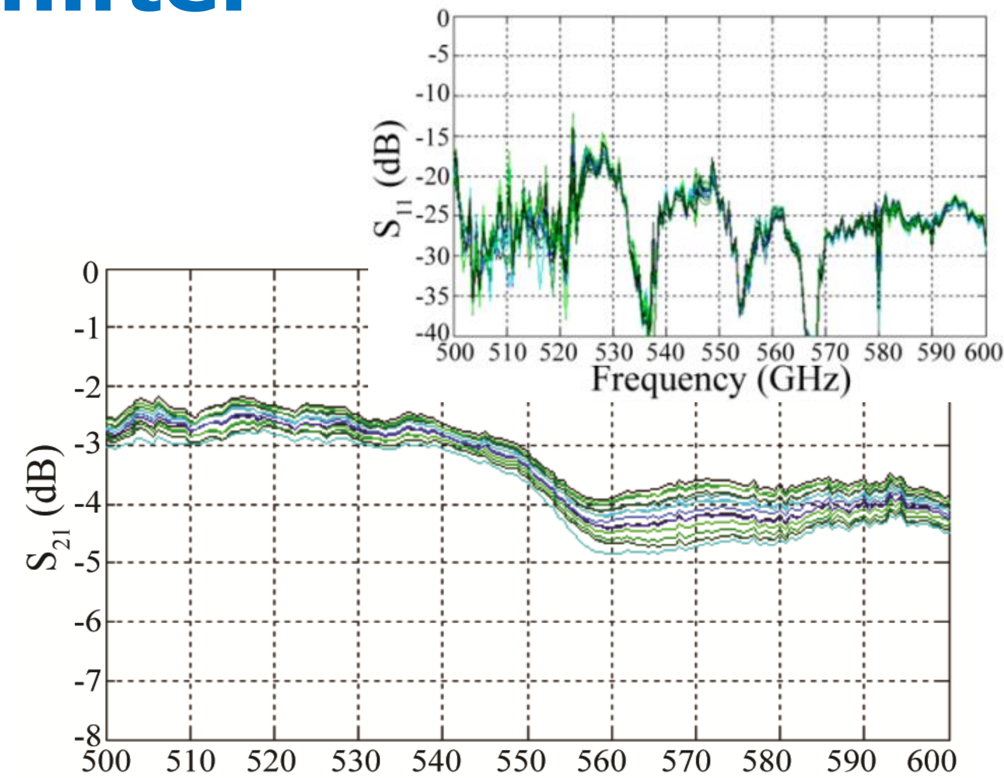

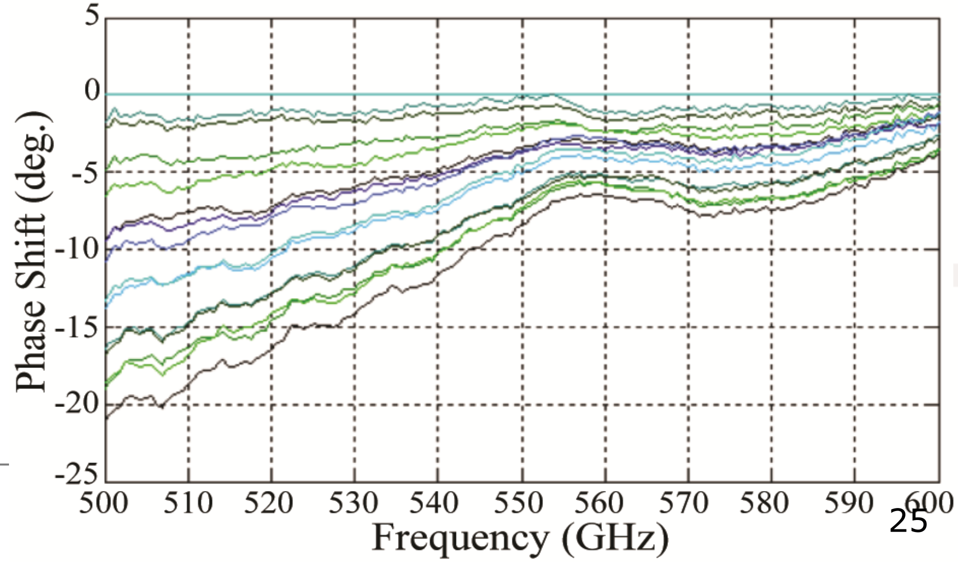

- First sub-mm-wave MEMS circuit
- First RF MEMS above 200 GHz
- First MEMS phase shifter above 110 GHz
- First MEMS waveguide component above 70 GHz

[IEEE IMS 2015; IEEE THzSciTec 2016]

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Ultra-high Q filters

KTH micromachined mm/sub-mm wave filter technology

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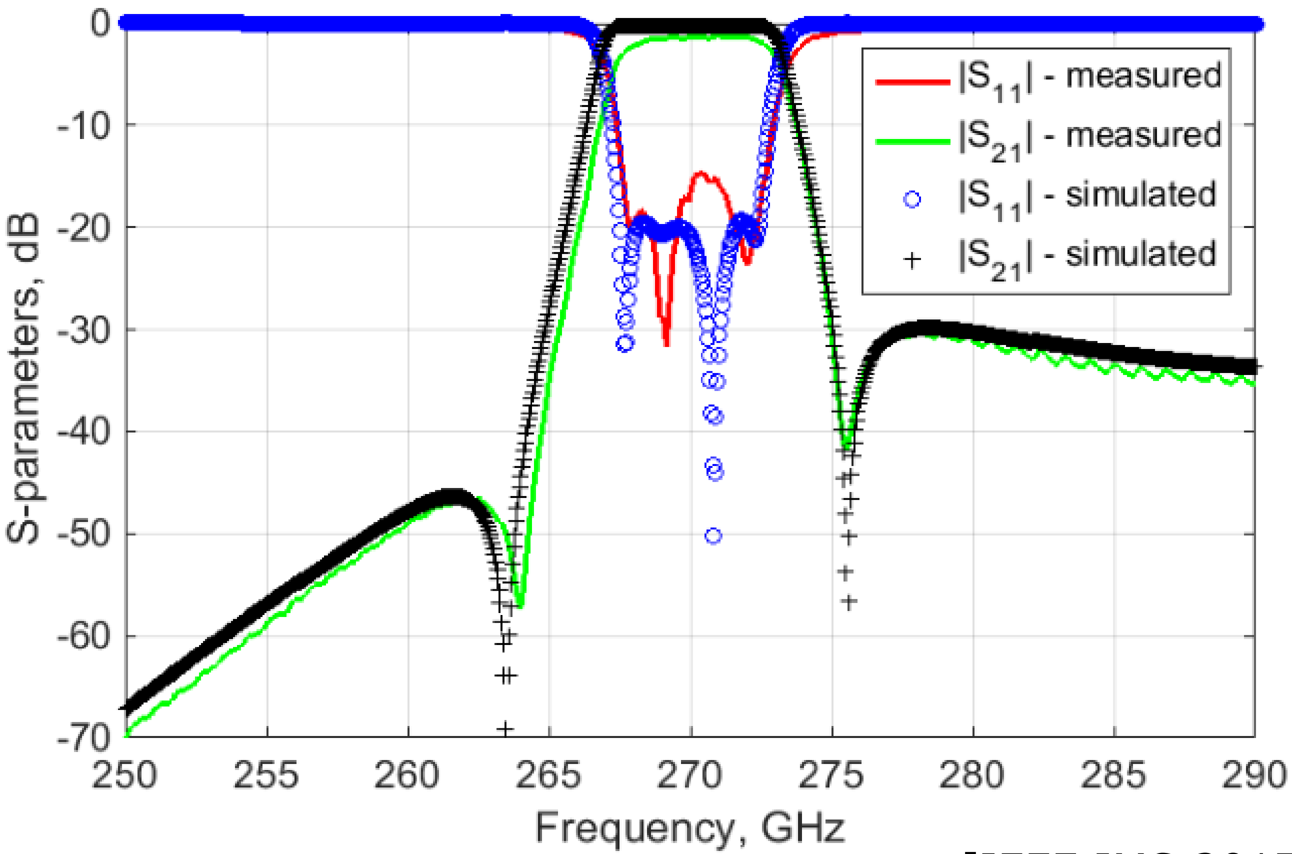
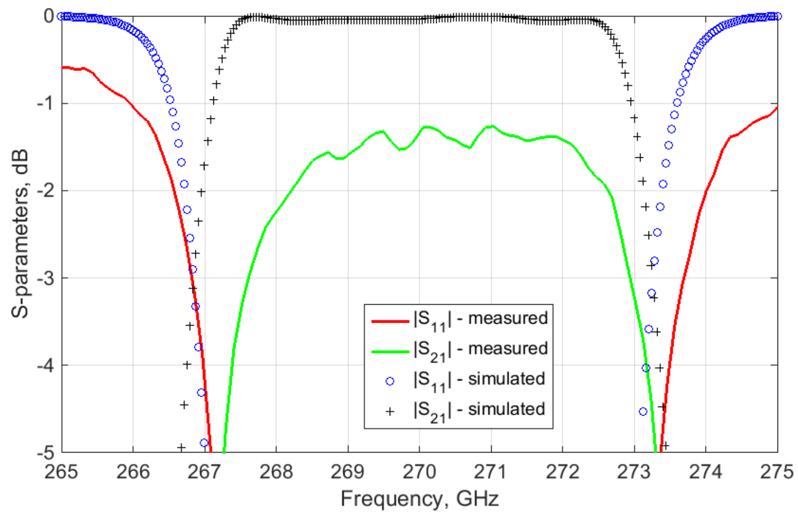
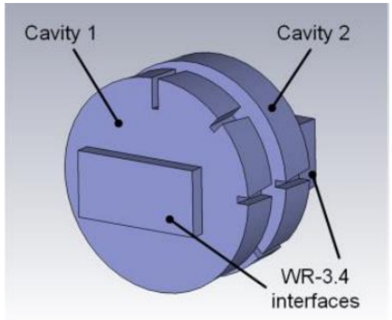
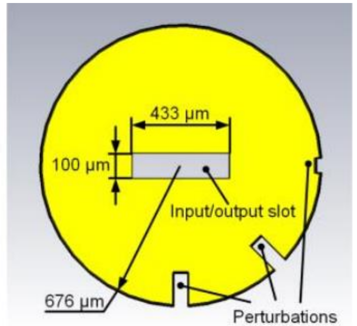


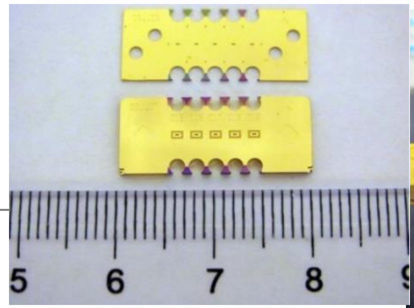
[IEEE IMS 2017]

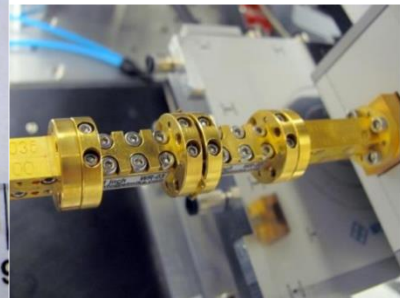


- f_0 = 270 GHz, 1.85% frac. BW (267.5…272.5 GHz)
- avg. IL=1.5dB (best IL=1.25dB)
- avg. RL=-18dB (worst = 16dB)
- rejection: >30 dB (<264, >276 GHz)









- Best performance for any comparable filter design in any technology in this frequency band

KTH micromachined sub-THz filters: best Q-factors in any technology

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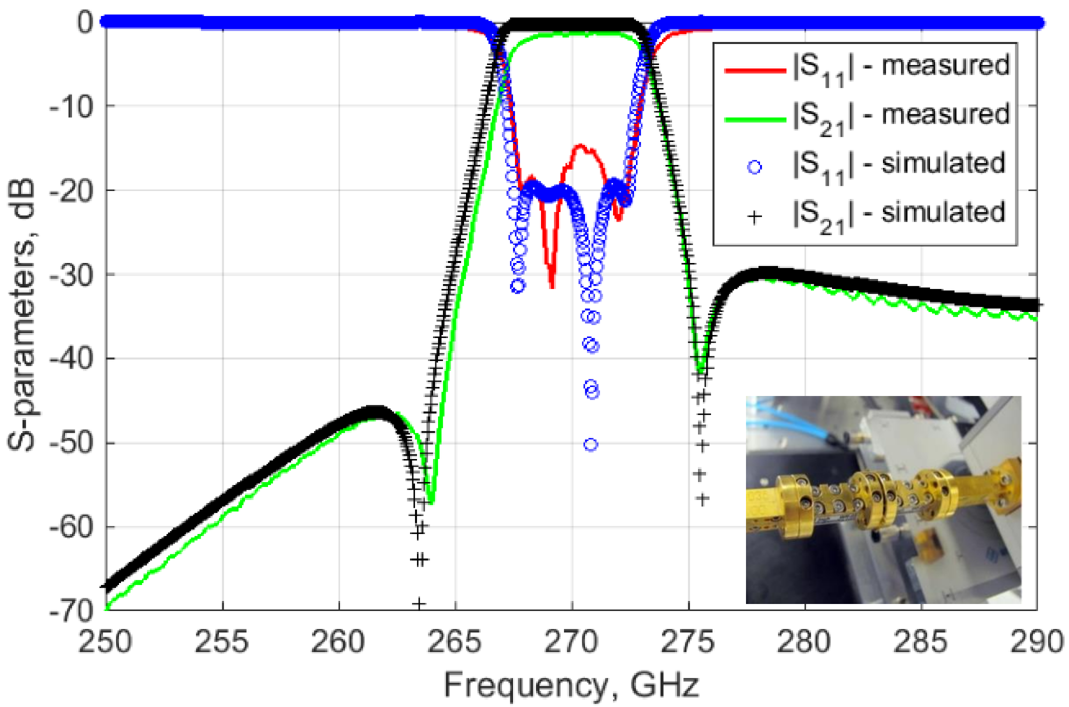
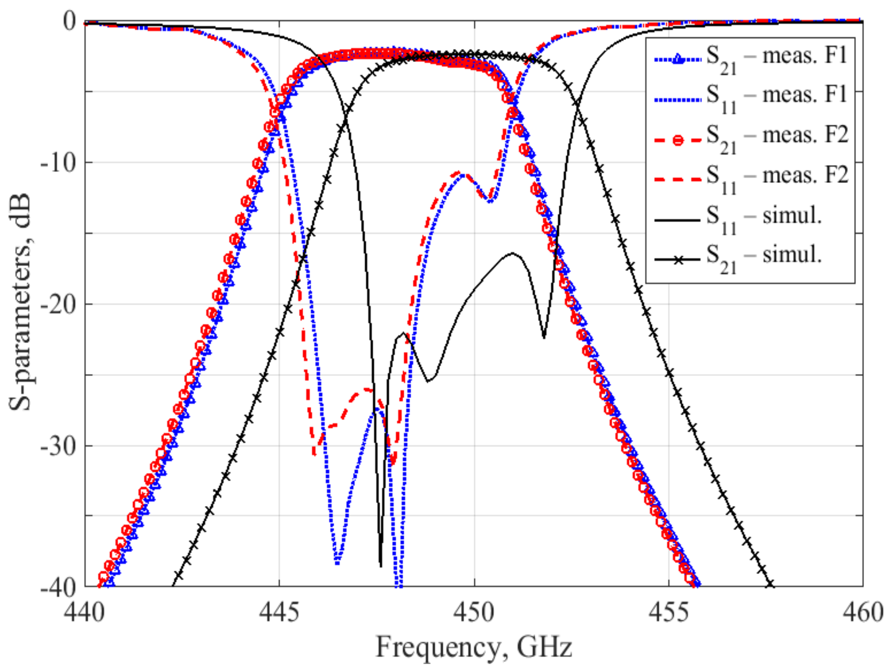
270 GHz, narrow-band:



- f_0=270 GHz, 4p2z
- 1.85% FBW
- IL=1.5dB, RL=-18dB
- $Q_{unloaded}$=800

[IEEE IMS 2017, IEEE TMTT 2019]

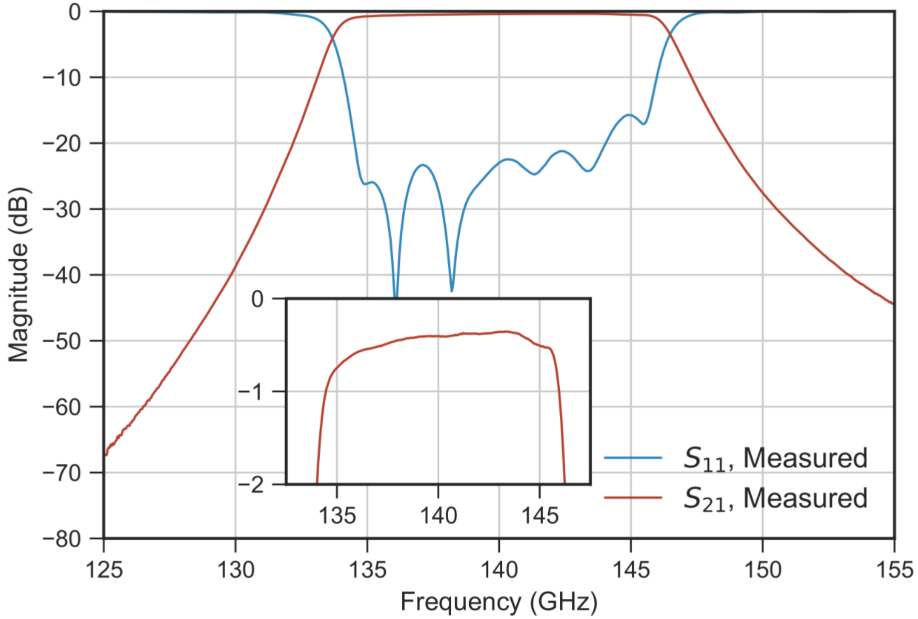
450 GHz, ultra narrow-band:



- f_0=450 GHz, 4p
- 1.00% FBW, IL=2.5dB
- $Q_{unloaded}$=790
- first 1%-BW filter at sub-mm wave frequencies! [IEEE TSTT,2019]

KTH micromachined sub-THz filters: best Q-factors in any technology

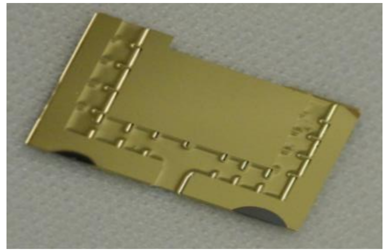
Wide-band example:
5.2% FBW, 141-148.5 GHz

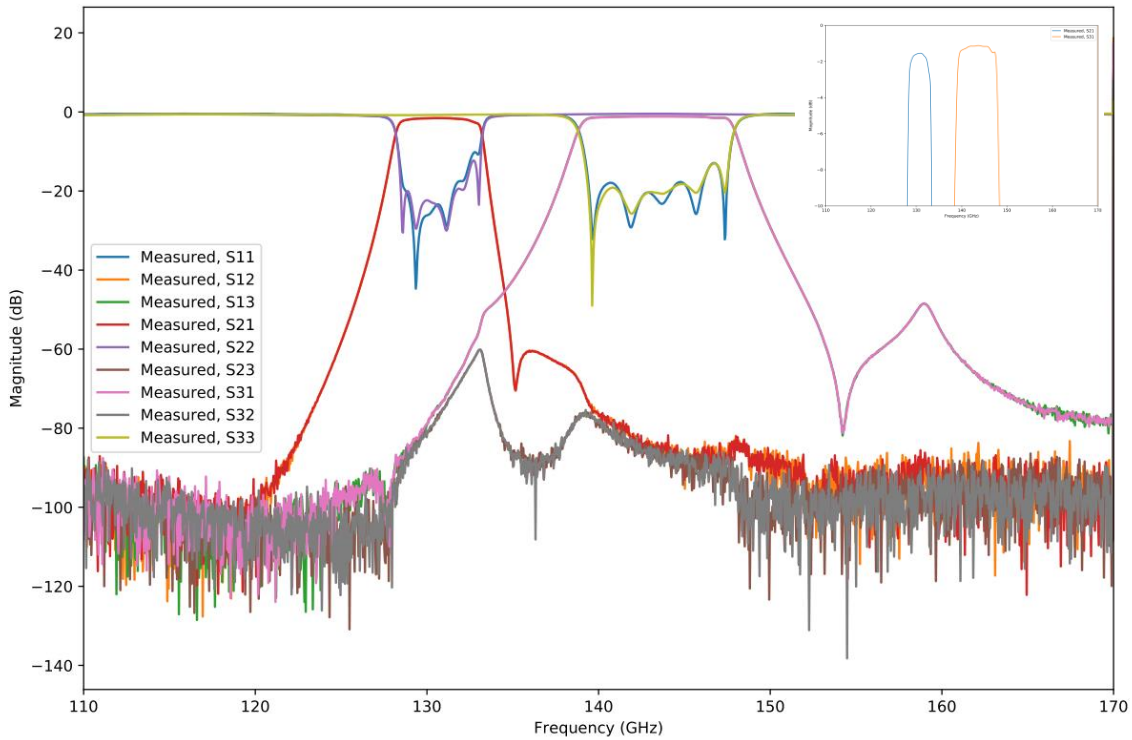


<0.5dB IL, Q_{UL}~1600

[IEEE IMS 2018]

Telecom diplexer:
141-148.5,
129-134 GHz





<1.5dB IL, >60 dB isolation

What is next? Current micromachined filter development activities

Pushing current technology:

- 700 GHz filters with 1% fractional bandwidths

New generation technologies:

- W-band (75-110 GHz) filters with Q factors >5000
- 183 GHz narrow-band filter banks with Q factors of 5000
- Fabrication-tolerance insensitive filter geometries

Micromachined ortho-mode transducer (OMT)

Micromachined orthogonal mode transducer (OMT) at 220-330 GHz

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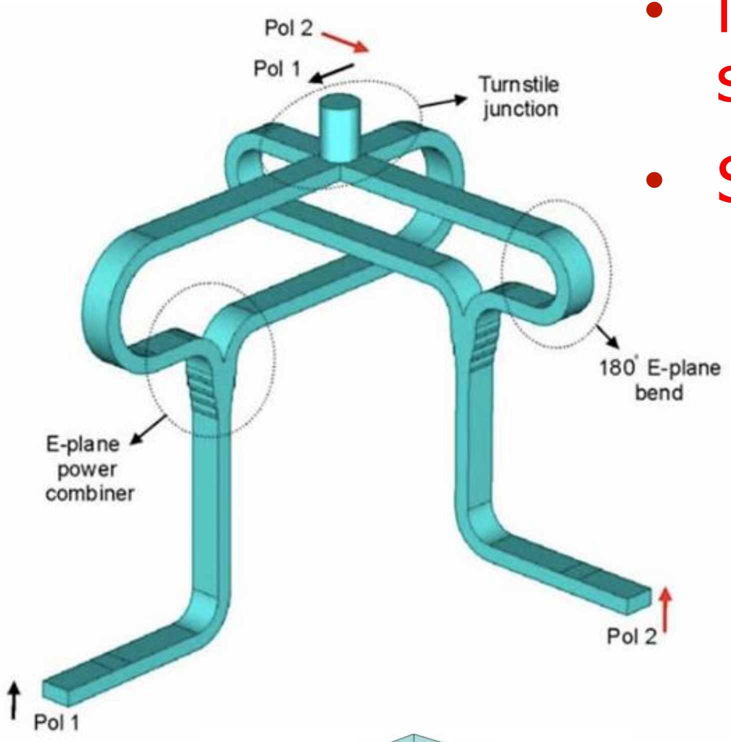
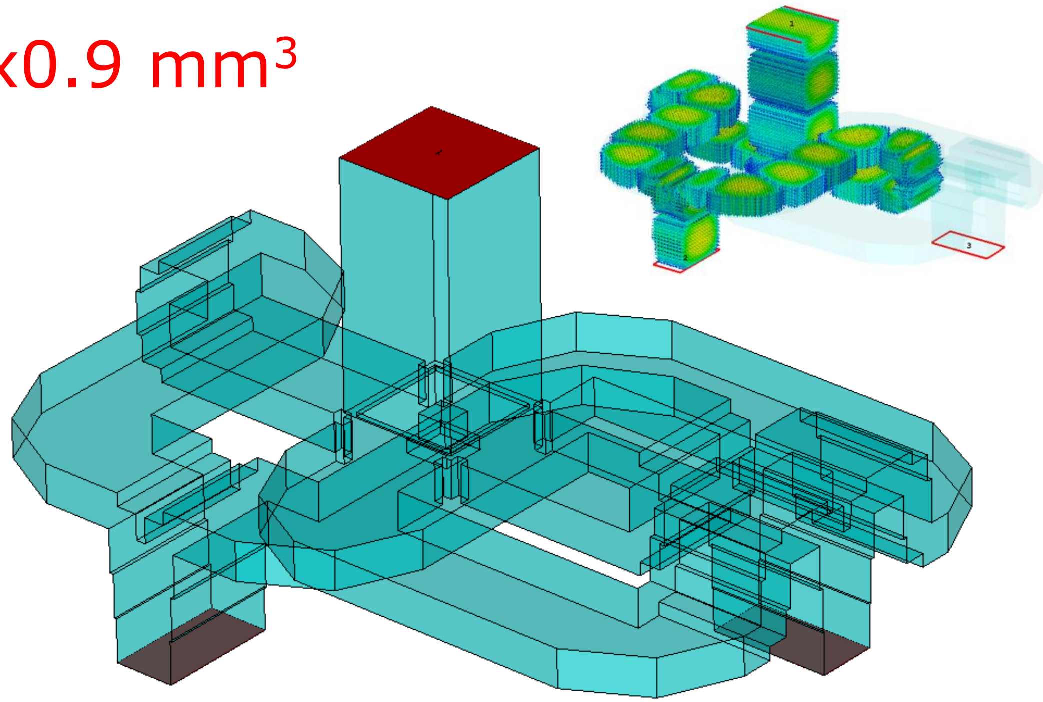
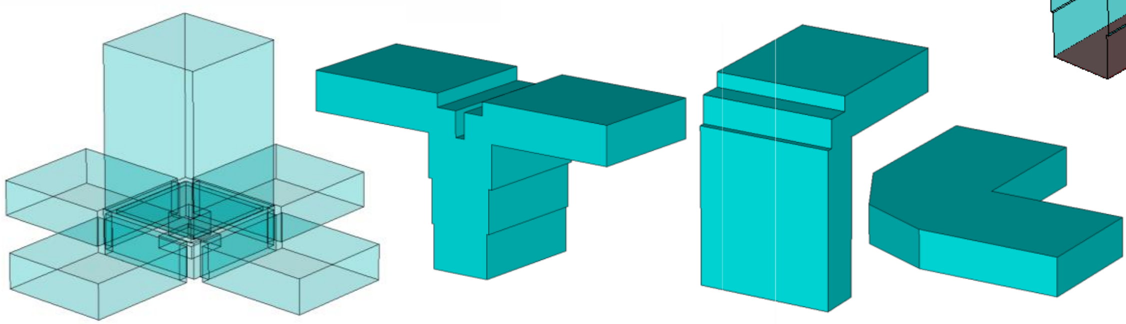
- First turnstile OMT above 110 GHz
- Micromachining enables microwave devices at so far unreachable frequencies!
- Size only 5x5x0.9 mm^3







Combining very complex 3D geometries (9 etched Si layers)

Micromachined orthogonal mode transducer (OMT) at 220-330 GHz

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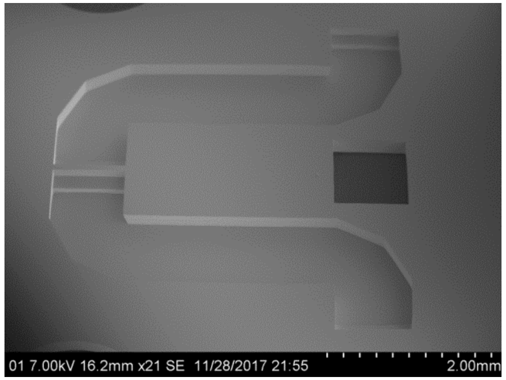
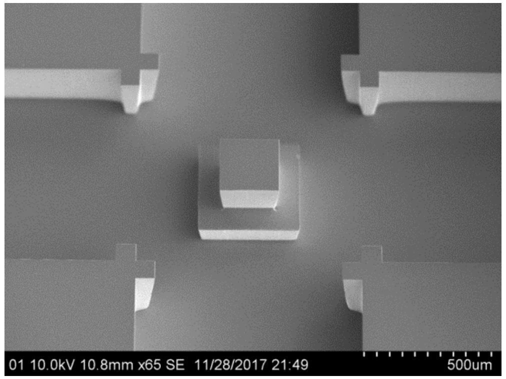
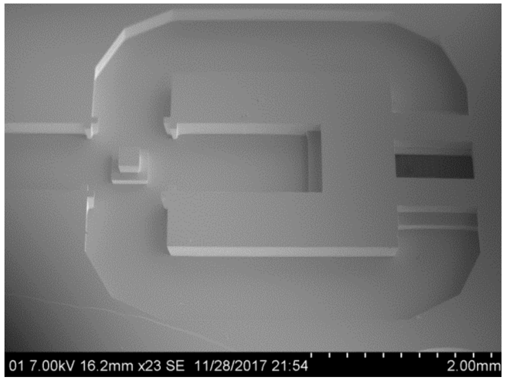
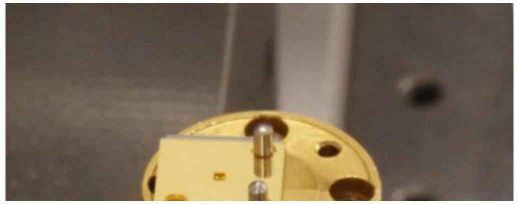
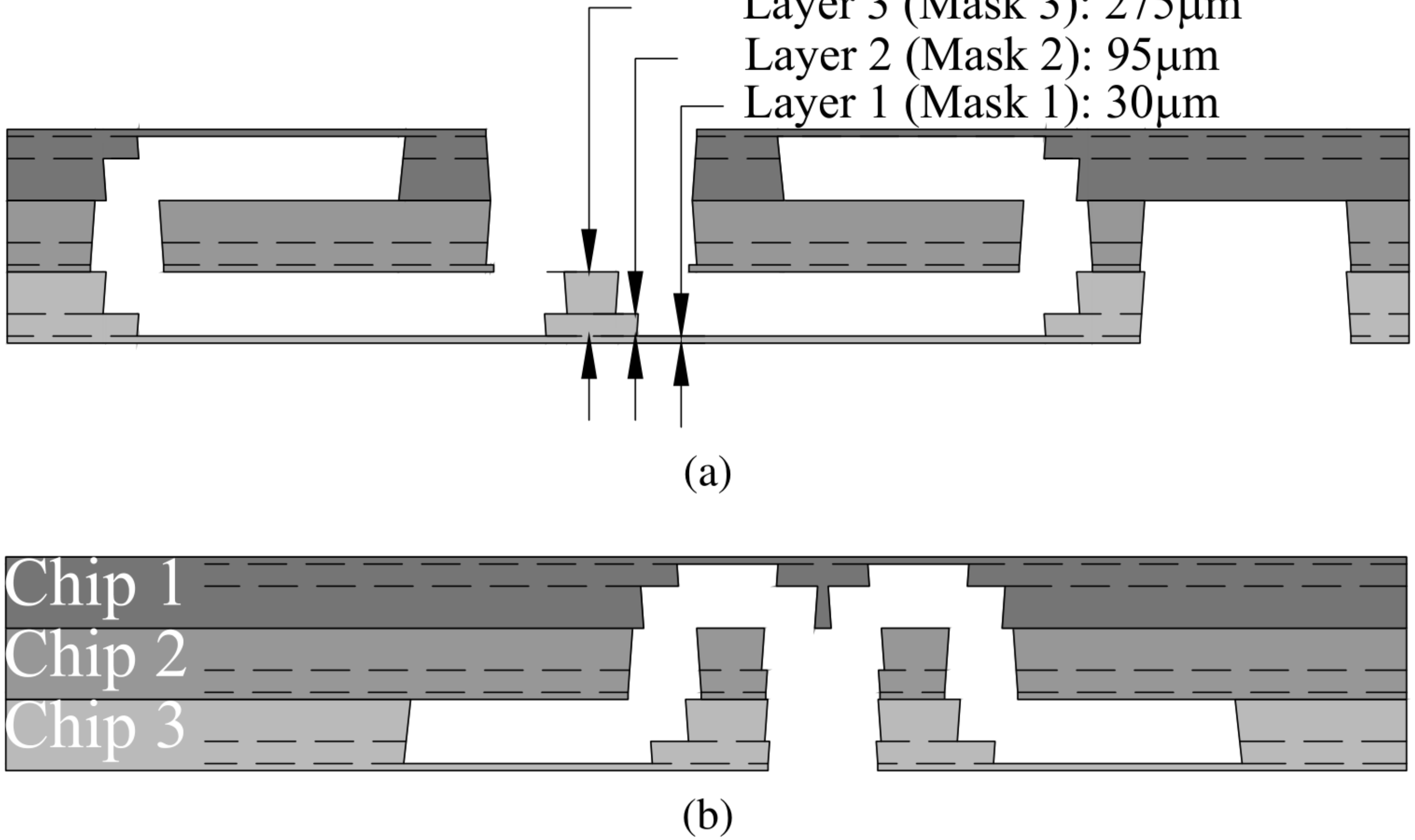
- First turnstile OMT above 110 GHz
- Enabled by micromachining
- 2um alignment needed





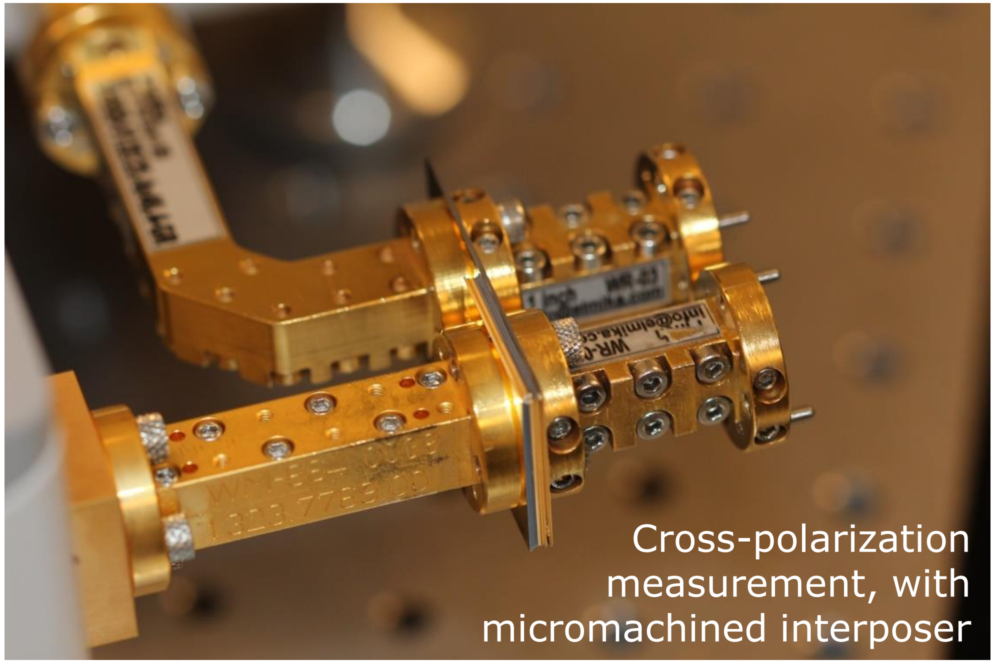


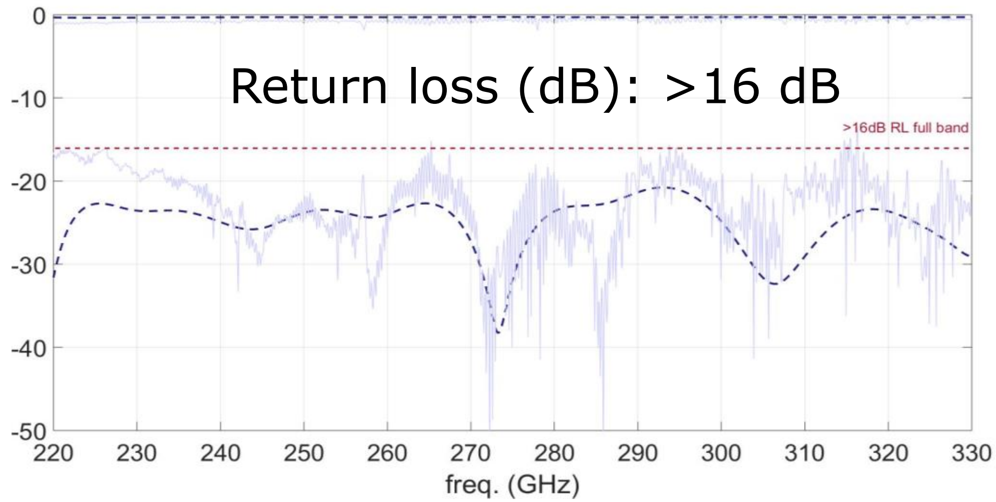


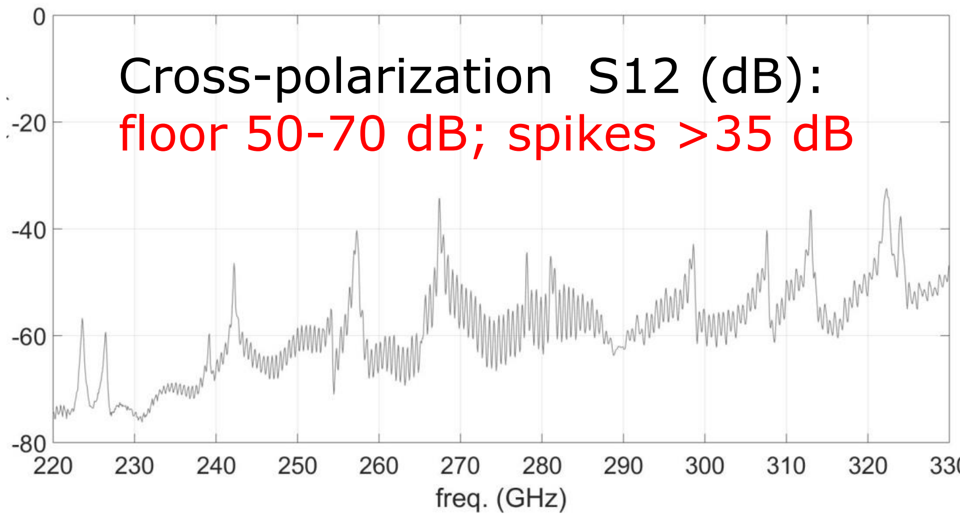


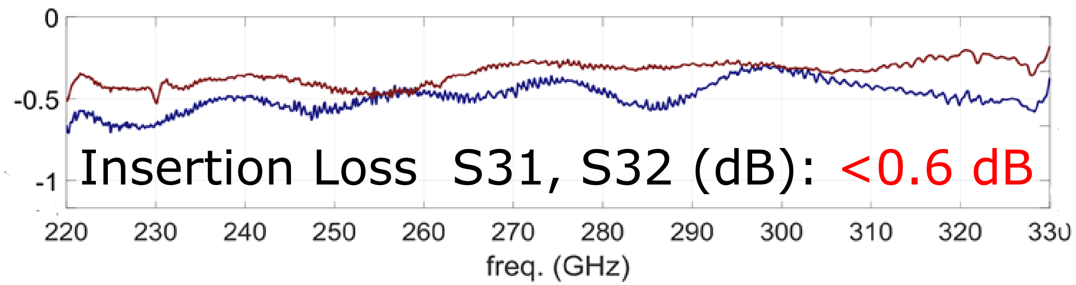
[IEEE IMS 2018]

Micromachined orthogonal mode transducer (OMT) at 220-330 GHz









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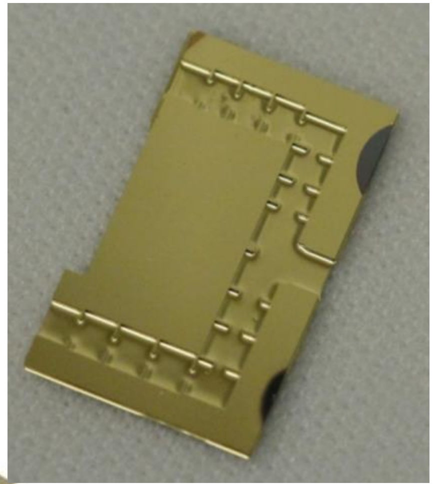
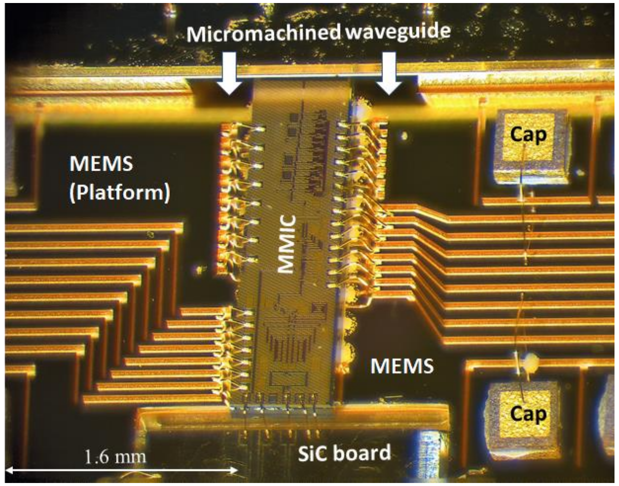
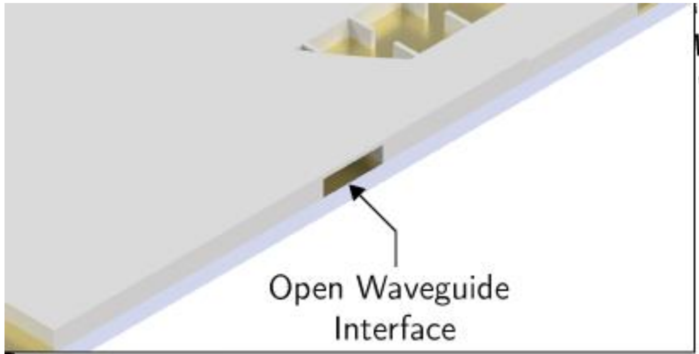
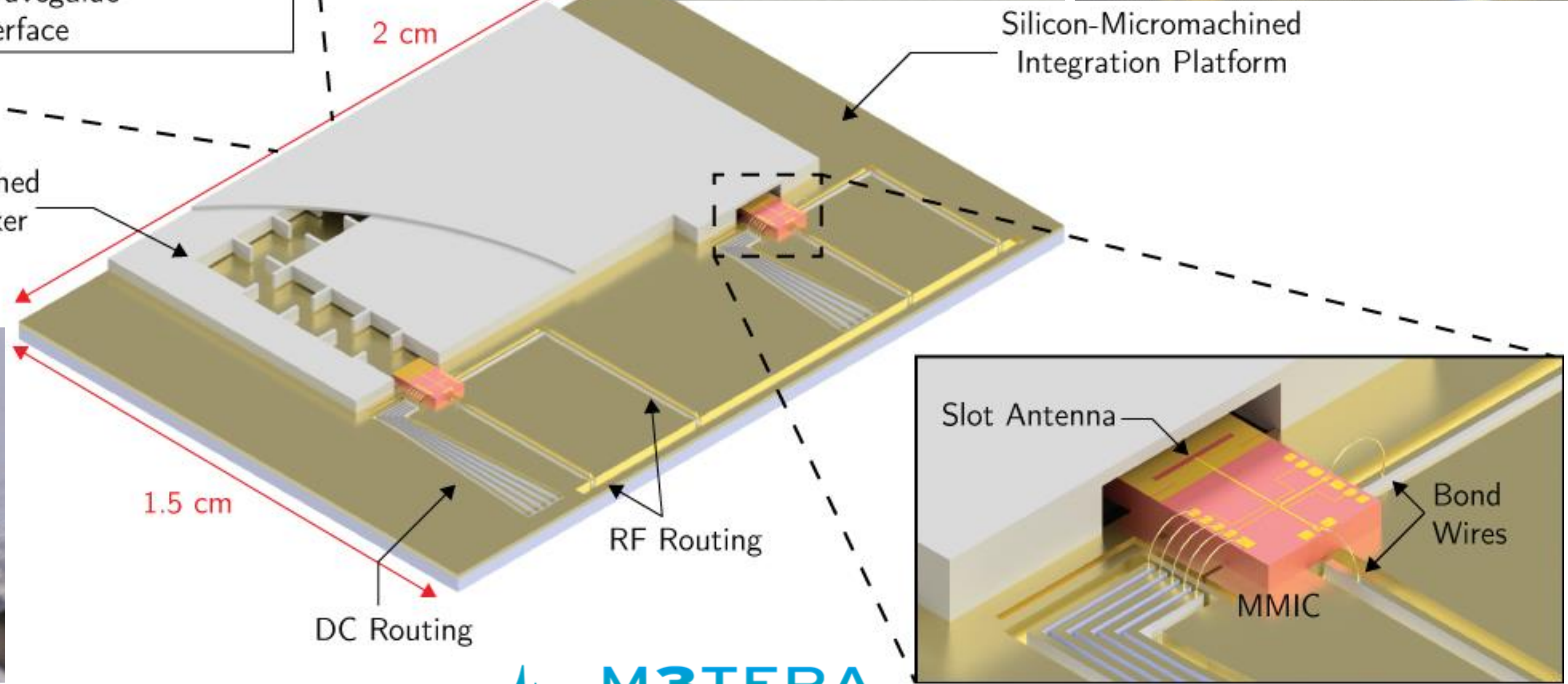
More complex systems: A micromachined TxRx integration platform for D-band point-to-point communication links

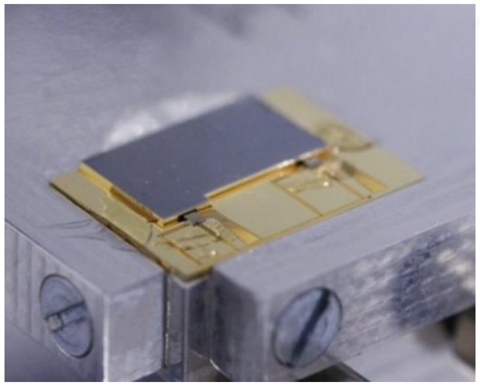
Highly-integrated, micromachined D-band communication link









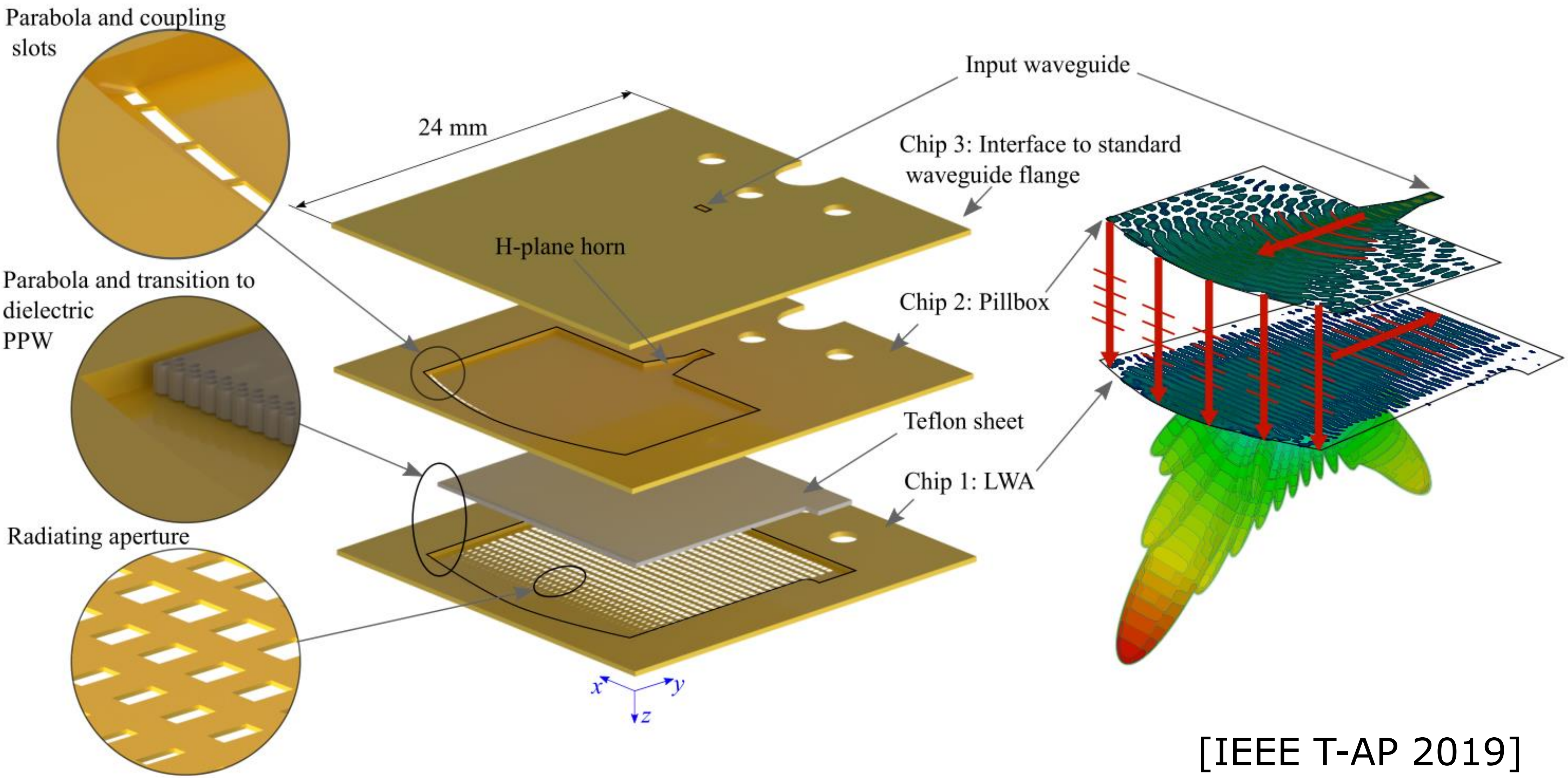


[IEEE THz Sci Tech 2019]

ROYAL INSTITUTE OF TECHNOLOGY

A micromachined high-gain leaky-wave antenna for beam steering at 220-300 GHz

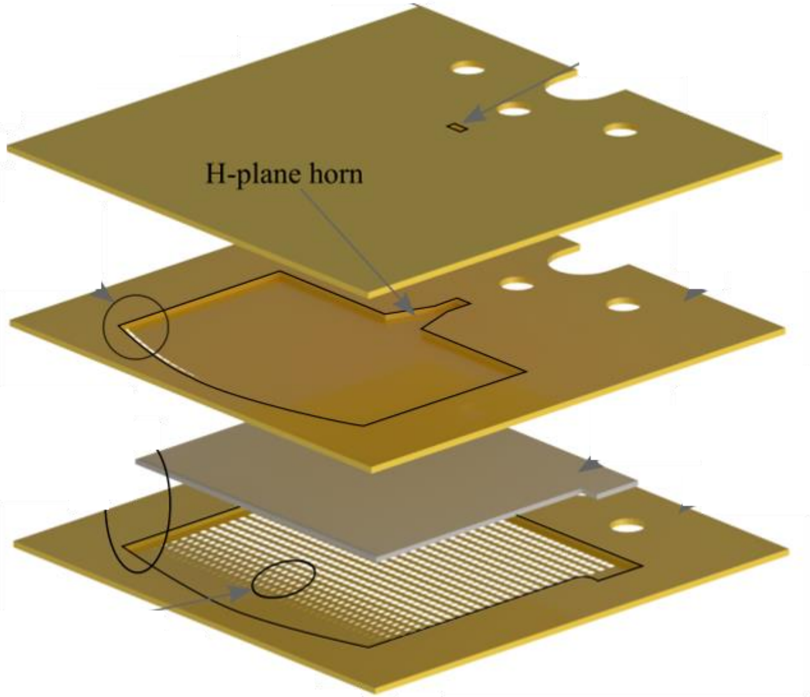
Micromachined “pill-box” beam-steering antenna

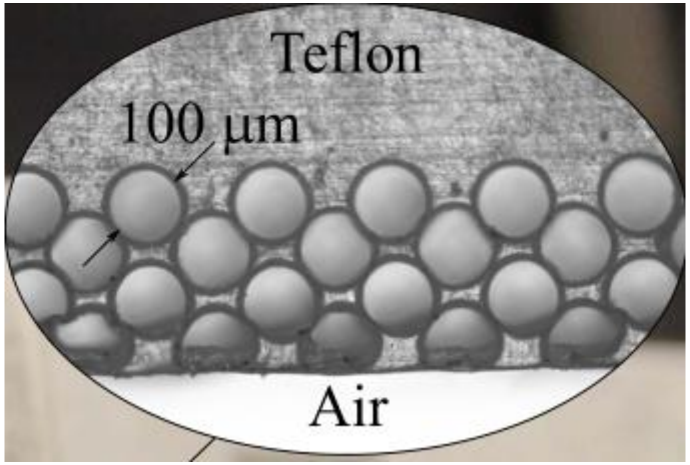


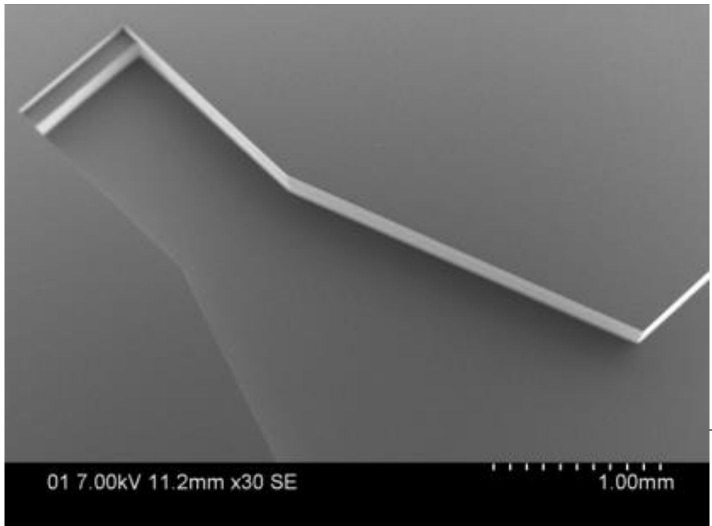
[IEEE T-AP 2019]

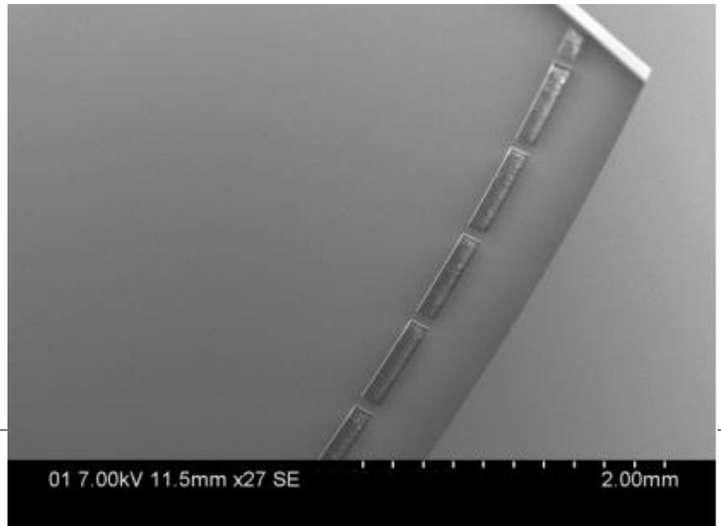
Micromachined "pill-box" Leaky-wave antenna

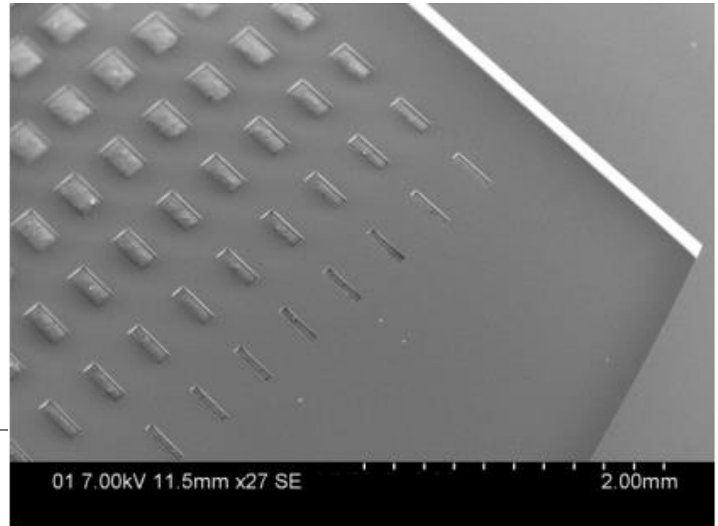
[IEEE T-AP 2019]



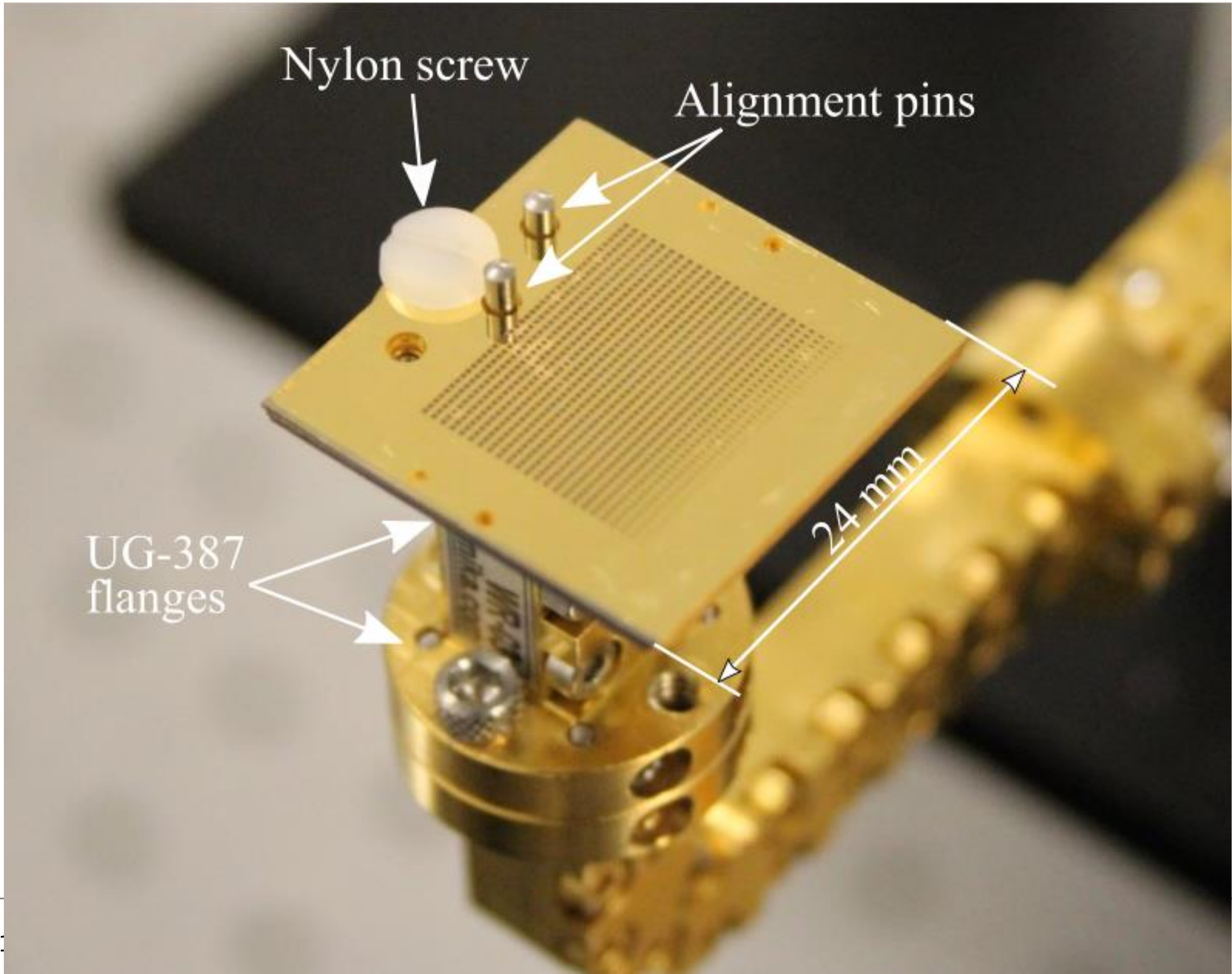






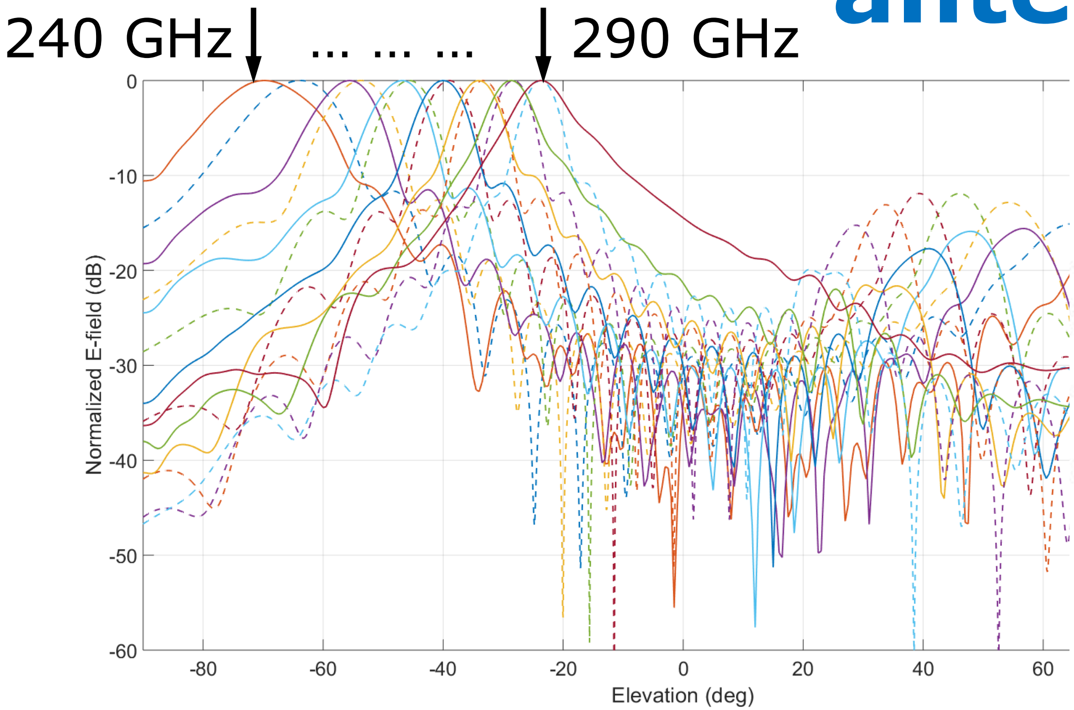


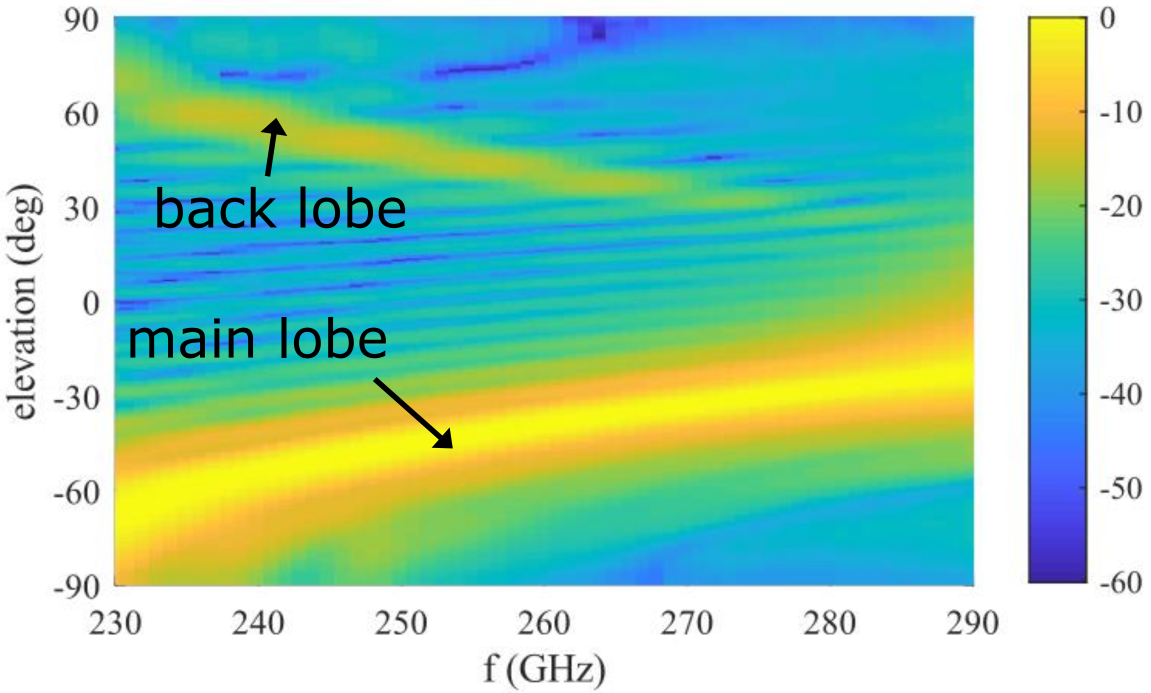
Micromachined “pill-box” beam-steering antenna



[IEEE T-AP 2019]

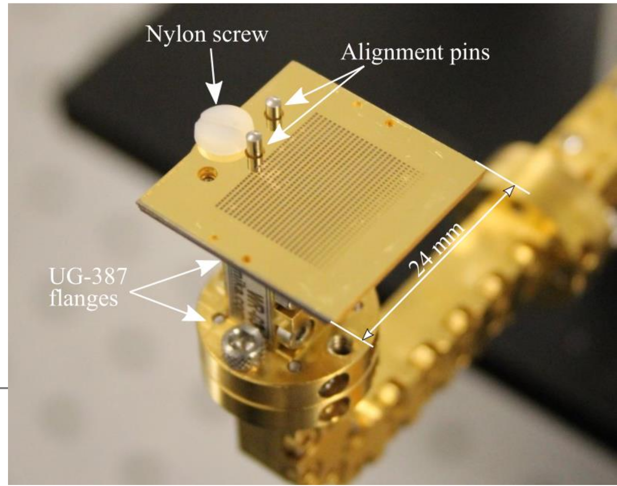
Micromachined high-gain beam-steering leaky-wave antenna 220-290 GHz





- size: 24x24x0.9 mm^3
- 220-300 GHz frequency sweeping
  => 20˚-75˚ scanning (55˚ field of view)
- measured gain: 28.5 dBi
- measured average HPBW: 7˚

[IEEE T-AP 2019]

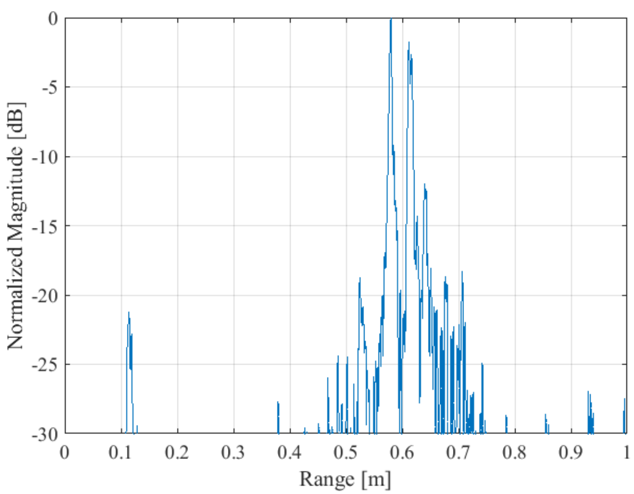


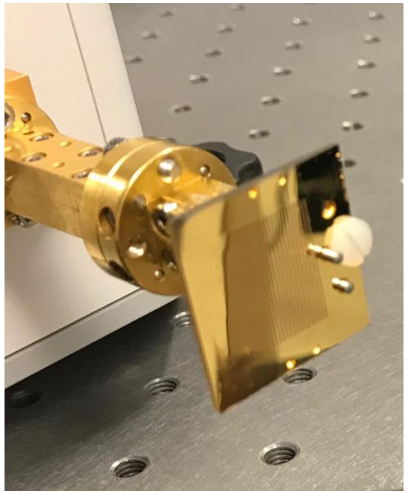
Radar demonstrator based on micromachined beam-steering antenna at 220-300 GHz

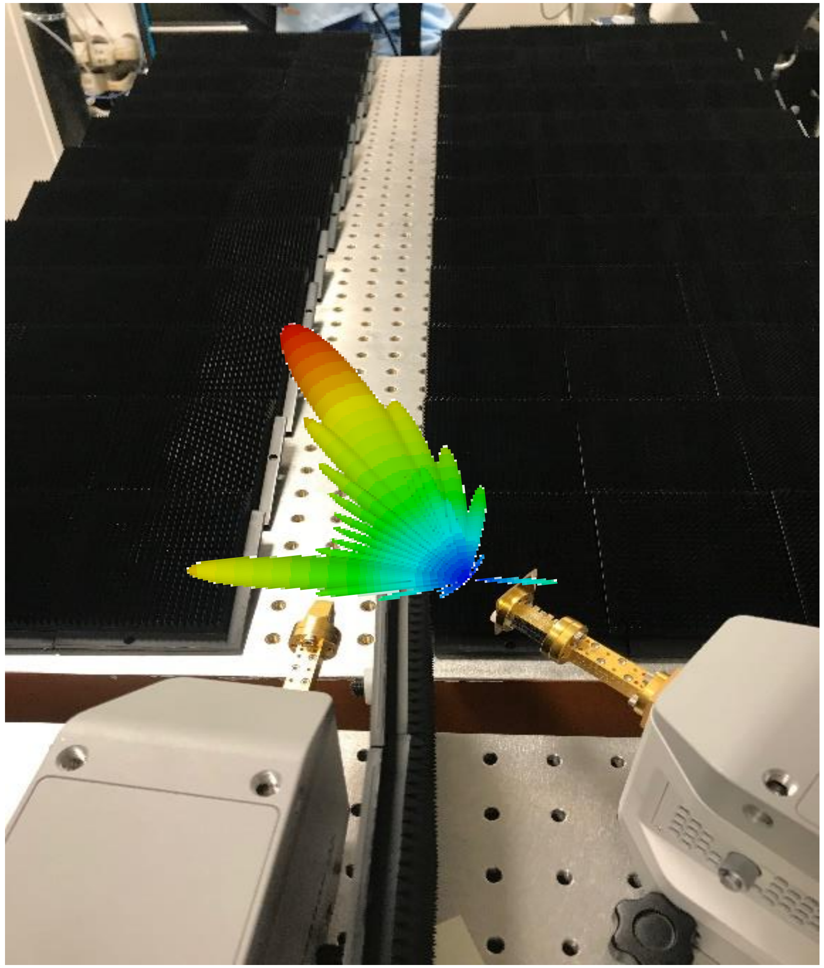
KTH VETENSKAP OCH KONST
ROYAL INSTITUTE OF TECHNOLOGY

Micromachined radar front-end:

- $20 \times 20 \times 0.9$ mm^3
- 220..300 GHz freq. sweep,
  20..75° scanning (55° FoV)
  3.5-10° HPBW
- <0.5 cm range resolution *at* <10° angular resolution





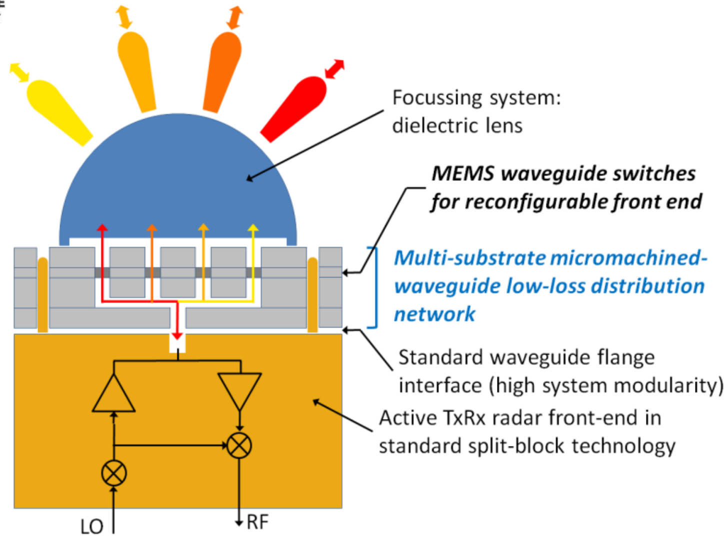


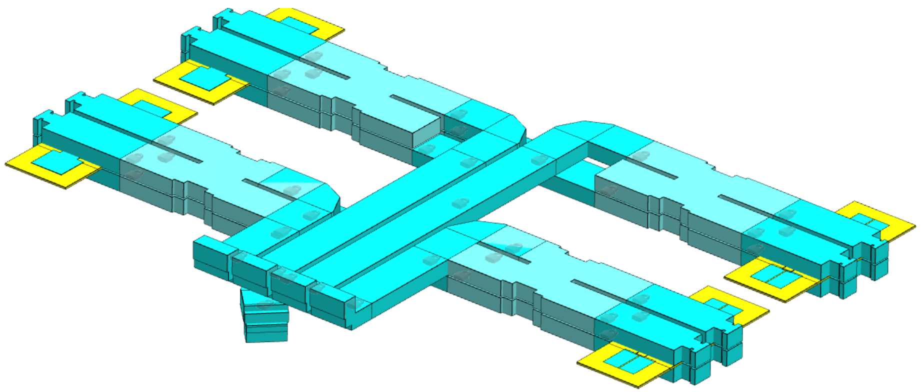
[IEEE IrMMWTHz 2019]

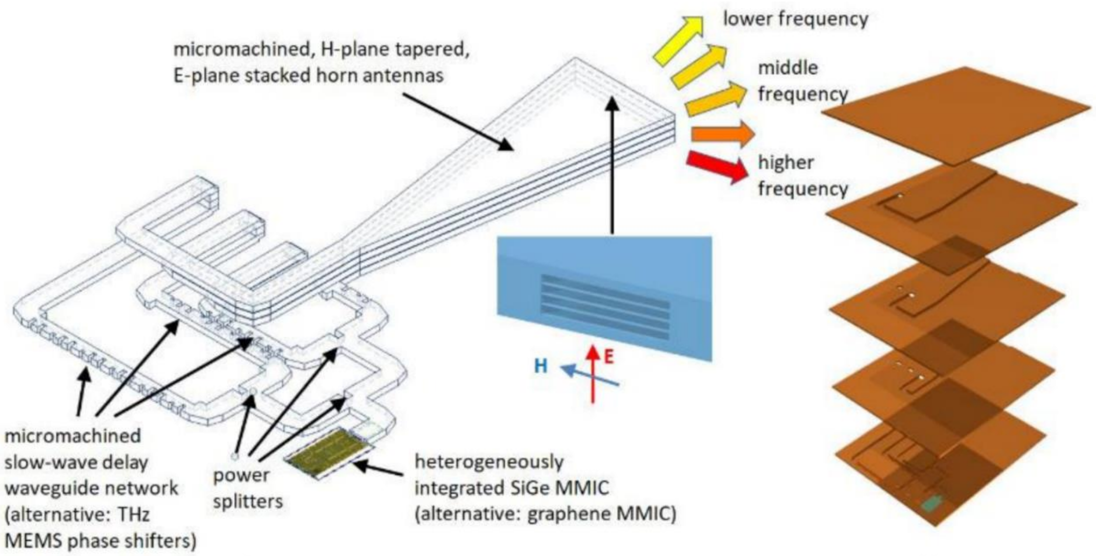
-60 -80 -60 -40 -20 0 20 40 60 80
Elevation (deg)

Beam-switching using MEMS waveguide switches

THz MEMS for radar beam steering







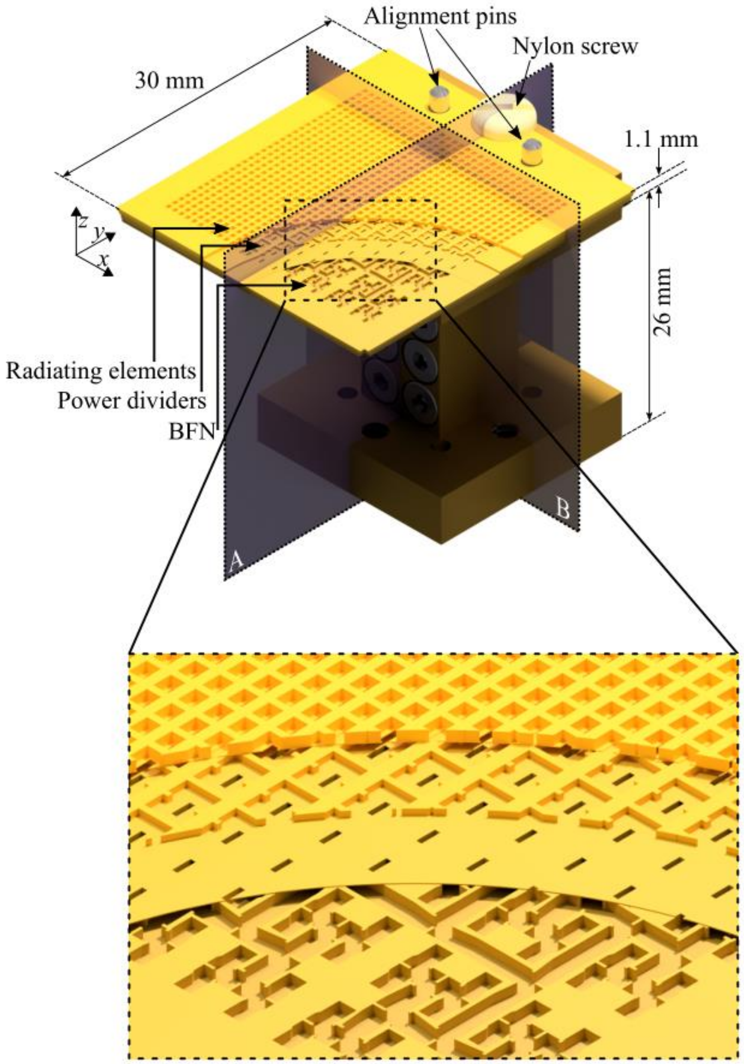
238-248 GHz car radar
- micromachined beam-steering front-end
- intelligent beam-shaping

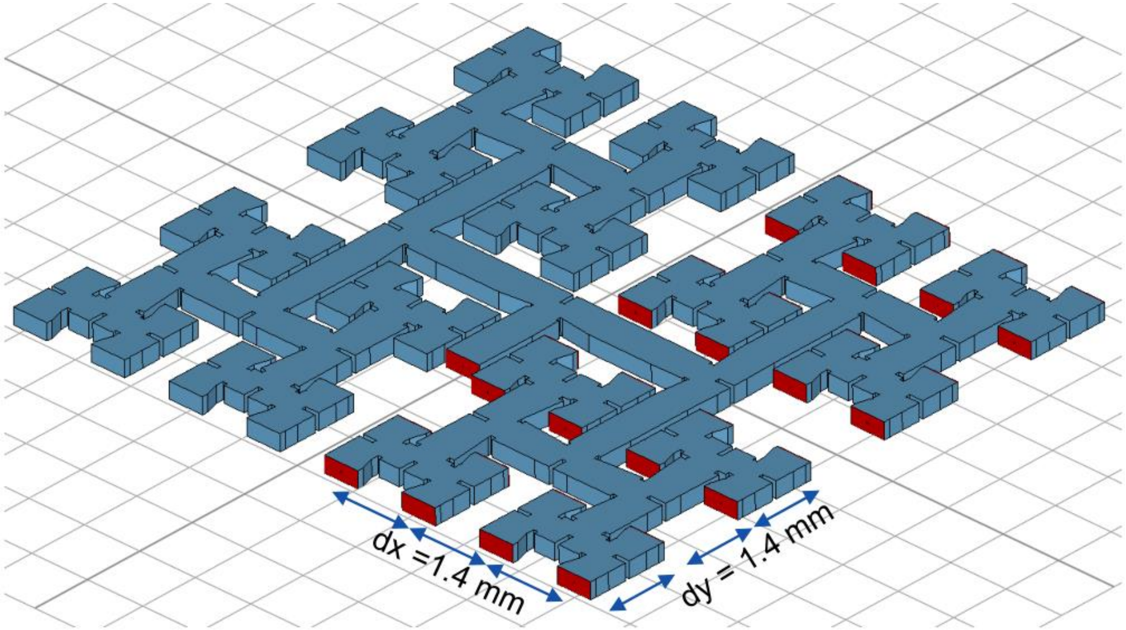
MEMS-switched 340 GHz industrial radar:
- 340 GHz, 30 GHz BW, 4x1 and 4x2 arrays
- using MEMS Waveguide switches:
  <0.6dB IL, >50 dB ISO

ROYAL INSTITUTE OF TECHNOLOGY

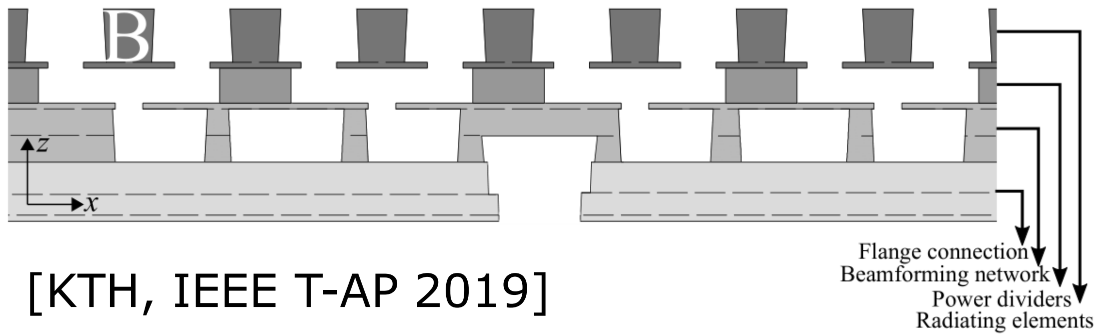
Ultra-compact, corporate-fed, large-scale antenna arrays at 300-400 GHz

Micromachined super-compact, super high-gain antennas



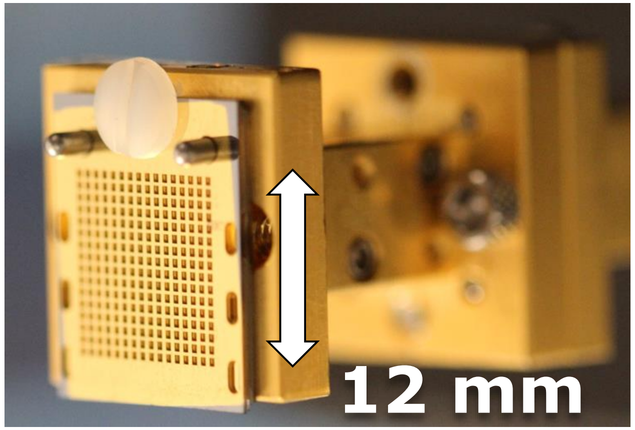


Single-layer feeding network to 2x2 sub-arrays => 16x16 antenna array



[KTH, IEEE T-AP 2019]

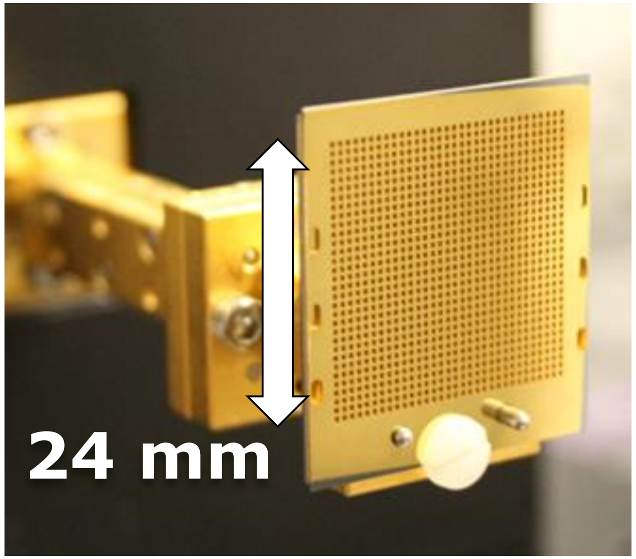
Micromachined super-compact, super high-gain antennas



16x16 antenna array: 256 elements
320-400 GHz, 80 GHz BW

Directivity:	33.5 dBi
Gain:	32.8 dBi
Loss:	<0.8 dB
HPBW:	<4.2°
Radiation efficiency:	>82%
Avg. RL in band:	15 dB

Size:
$12x12x1.1mm^3$

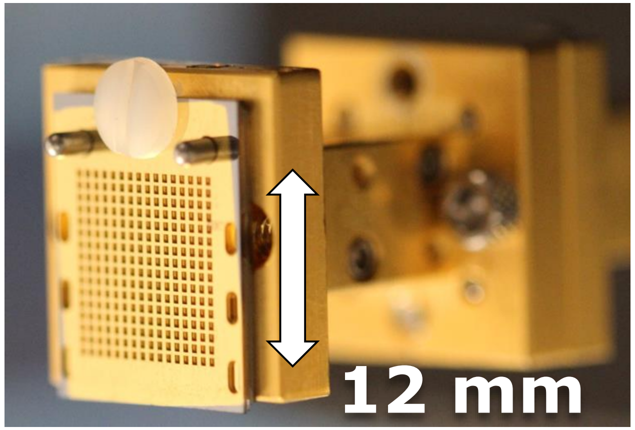


32x32 antenna array: 1024 elements
320-400 GHz, 80 GHz BW

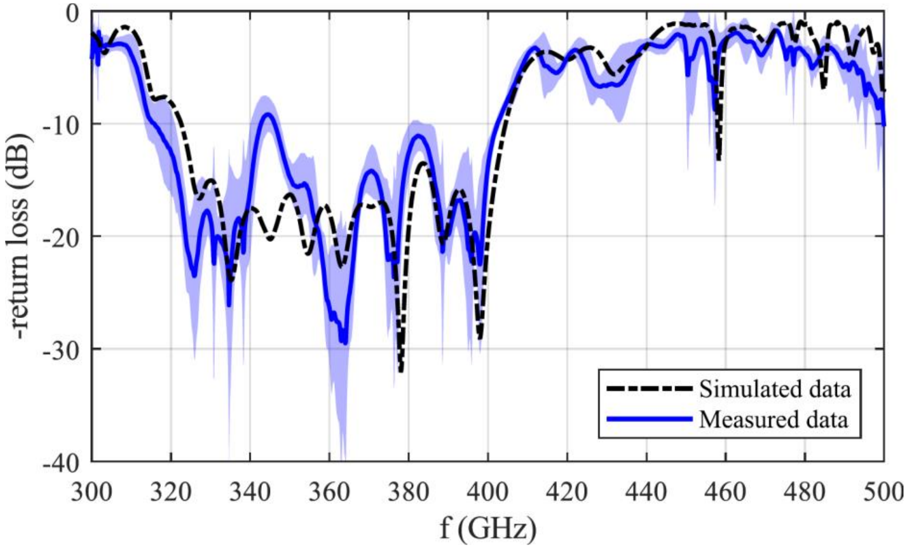
Directivity:	39.7 dBi
Gain:	38.2 dBi
Loss:	<1.6 dB
HPBW:	<2°
Radiation efficiency:	>60%
Avg. RL in band:	15 dB

Size:
$24x24x1.1mm^3$

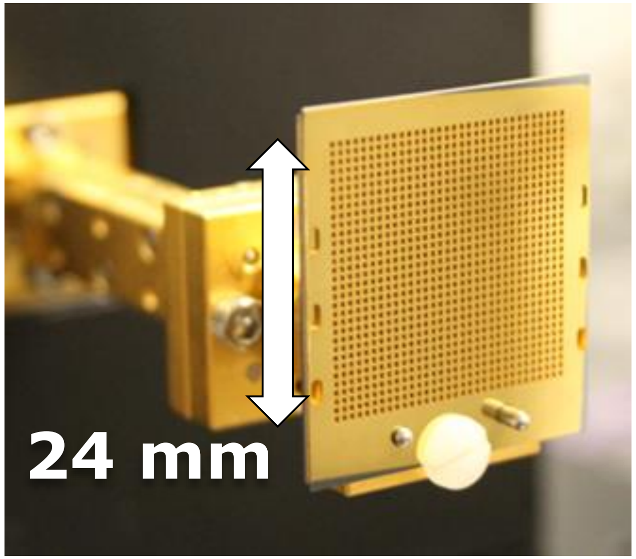
Micromachined super-compact, super high-gain antennas



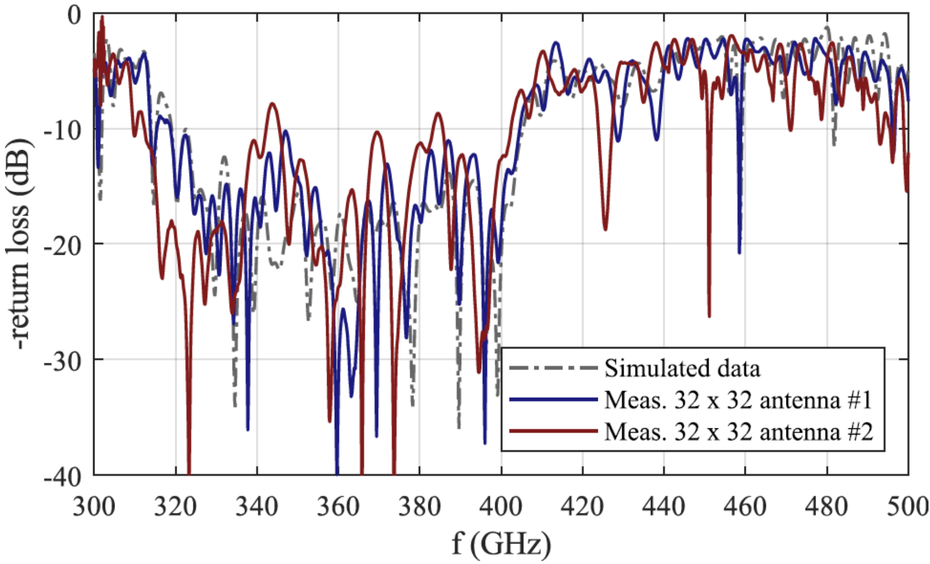
16x16 antenna array
320-400 GHz



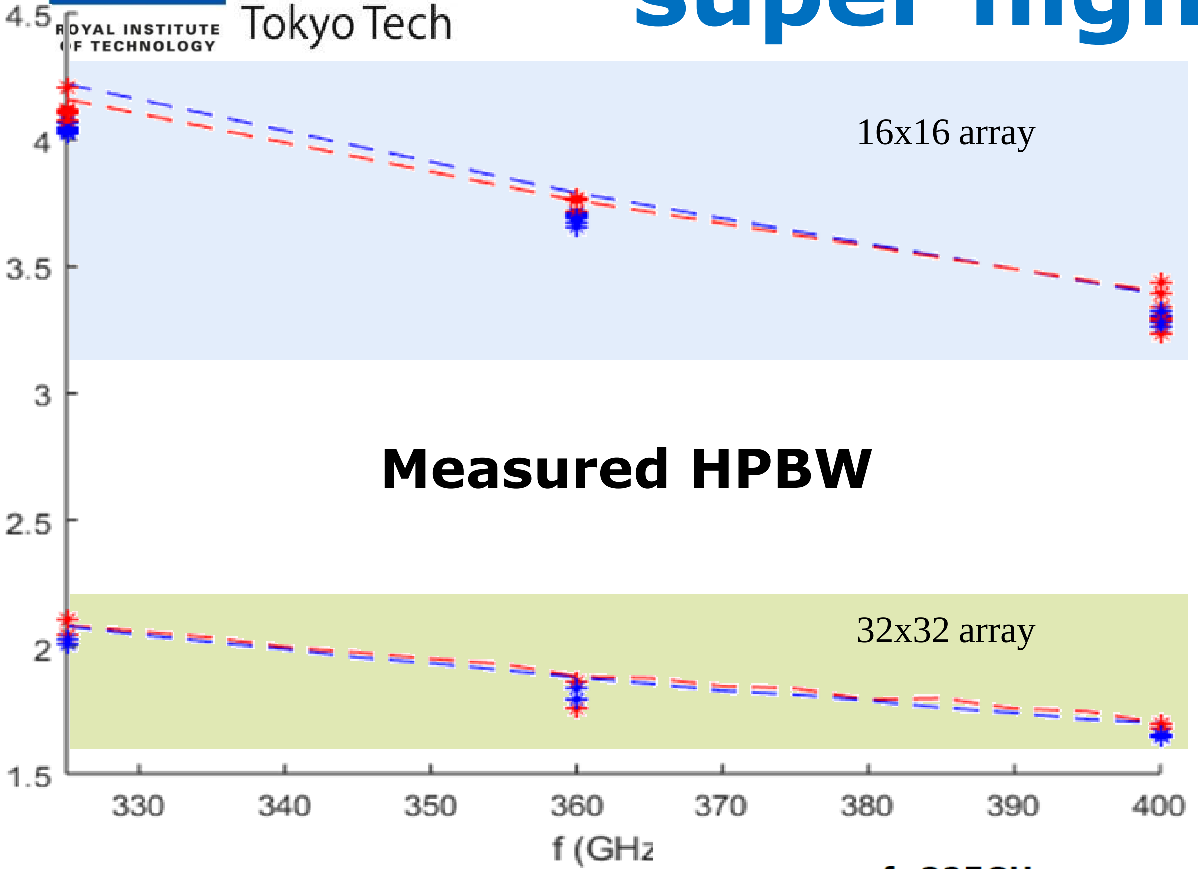
Measured RL: 80 GHz BW

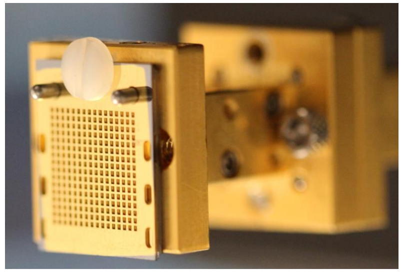


32x32 antenna array
320-400 GHz

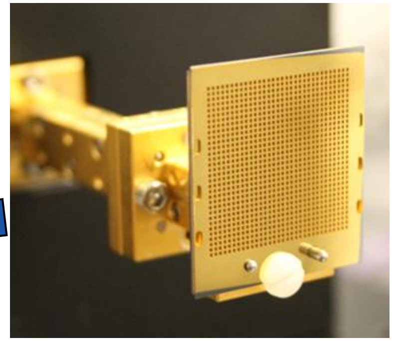


Micromachined super-compact, super high-gain antennas

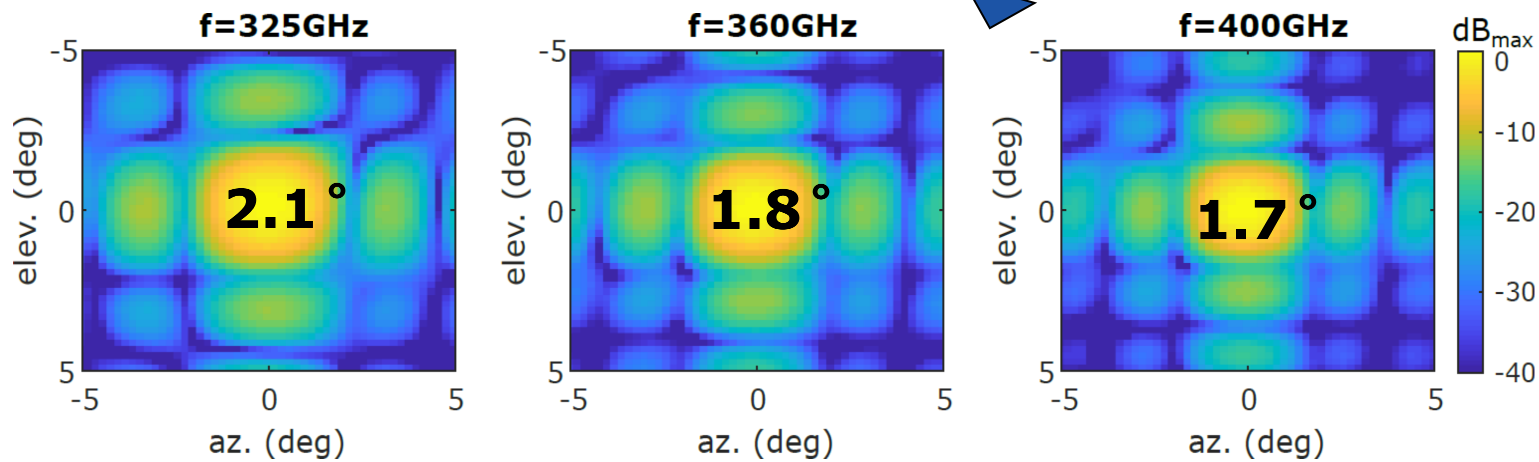




16x16 antenna array



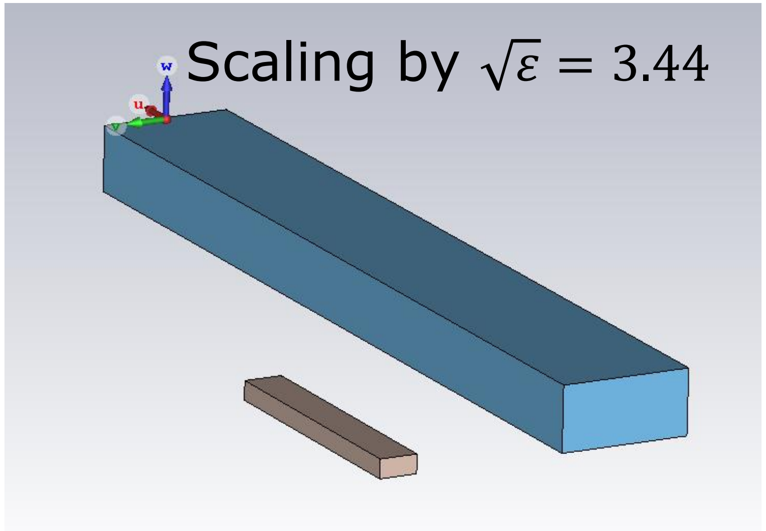
32x32 antenna array

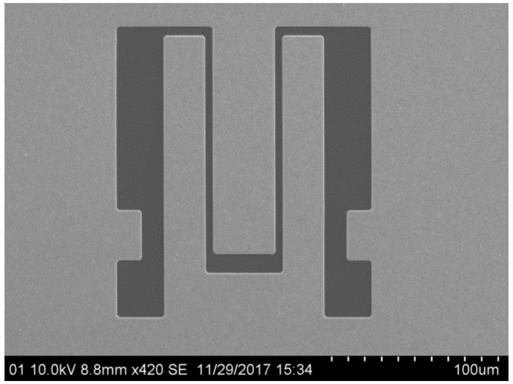


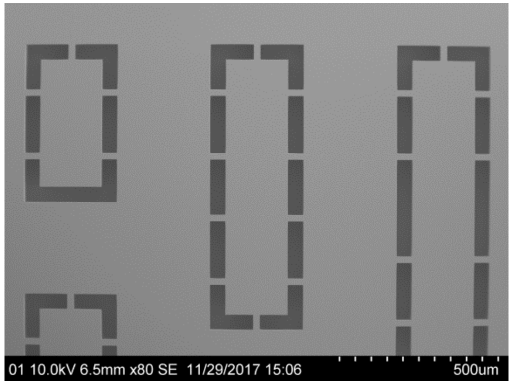
ROYAL INSTITUTE OF TECHNOLOGY

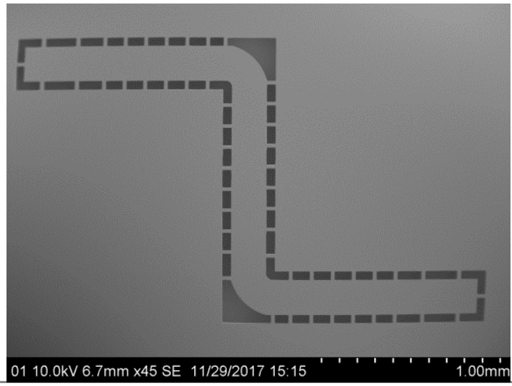
Dielectric waveguides

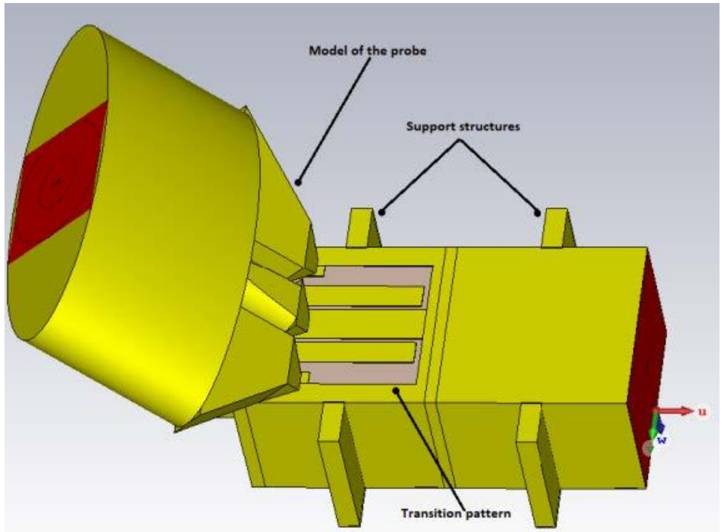
Silicon-core metal-WG 220-330 GHz

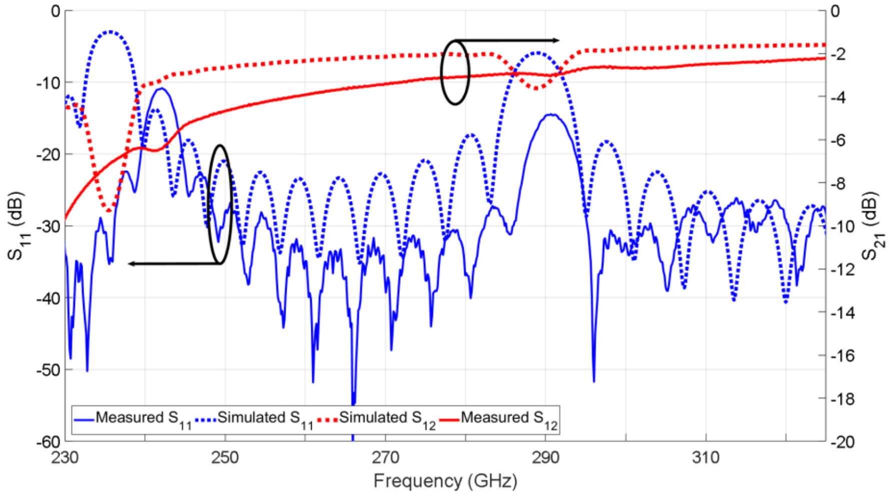




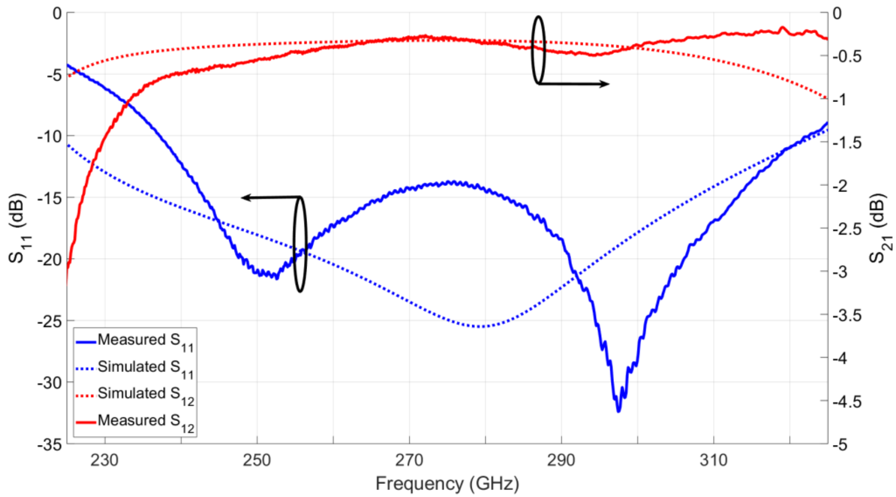








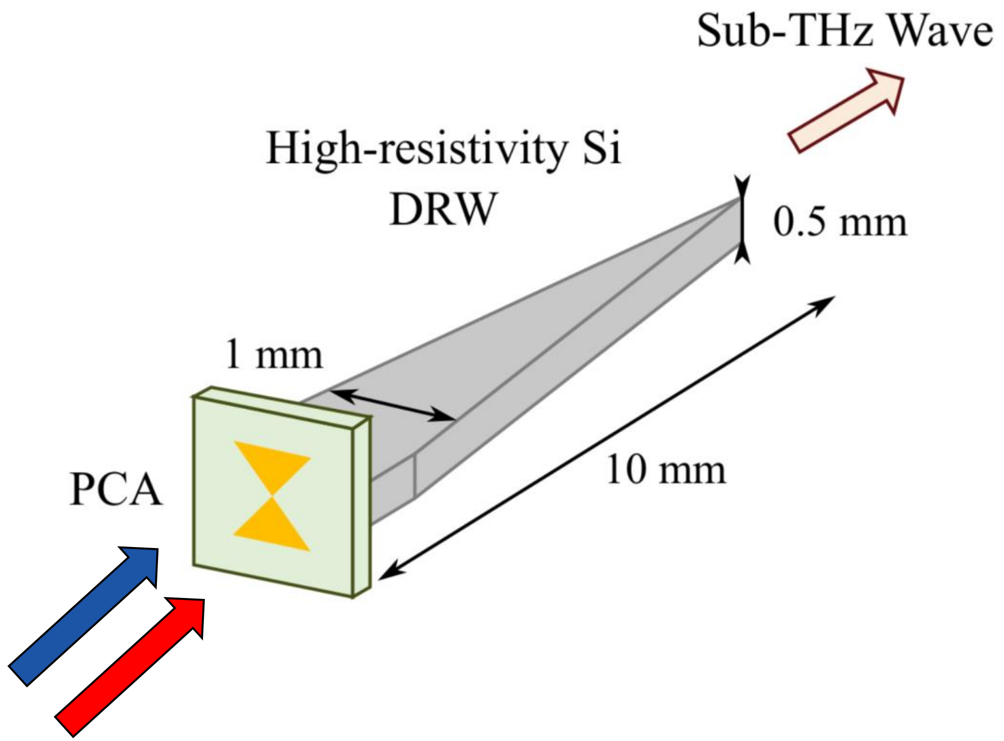
WG line $IL = 0.14\ dB/\lambda_g$



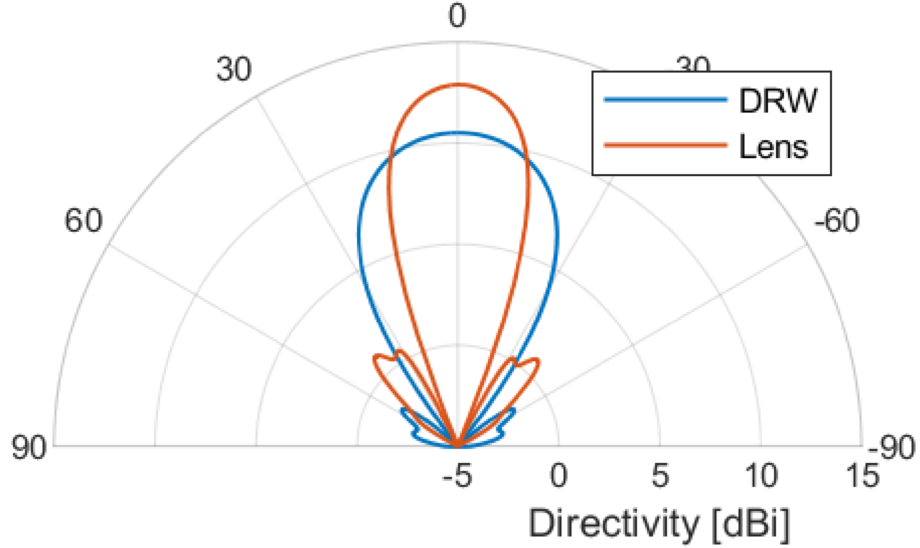
CPW transition $IL < 1\ dB$

[THzSciTec 2018]

Dielectric rod waveguides (DRW) antenna with integrated photonics/microwave converter



Dual-line photonic signal, 1.5 µm

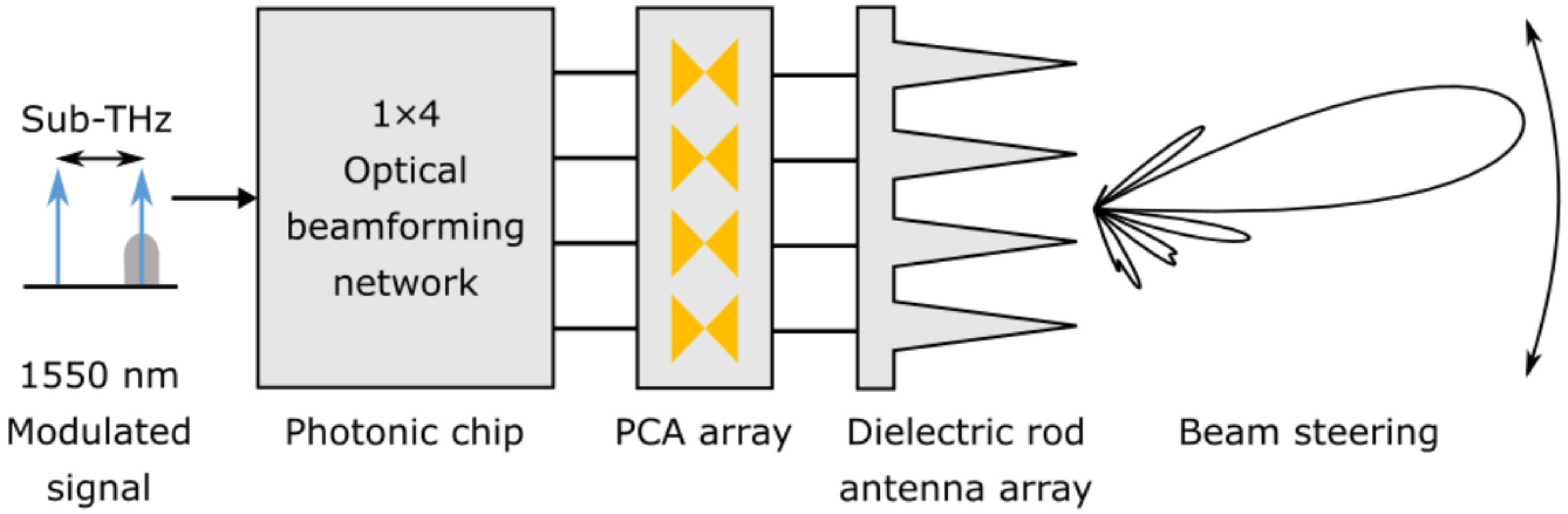


DRW antenna (14.7 dBi directivity) compared to lens

PCA … photoconductive antenna: bow-tie antenna with InGaAs photodiode

[KTH, unpublished]

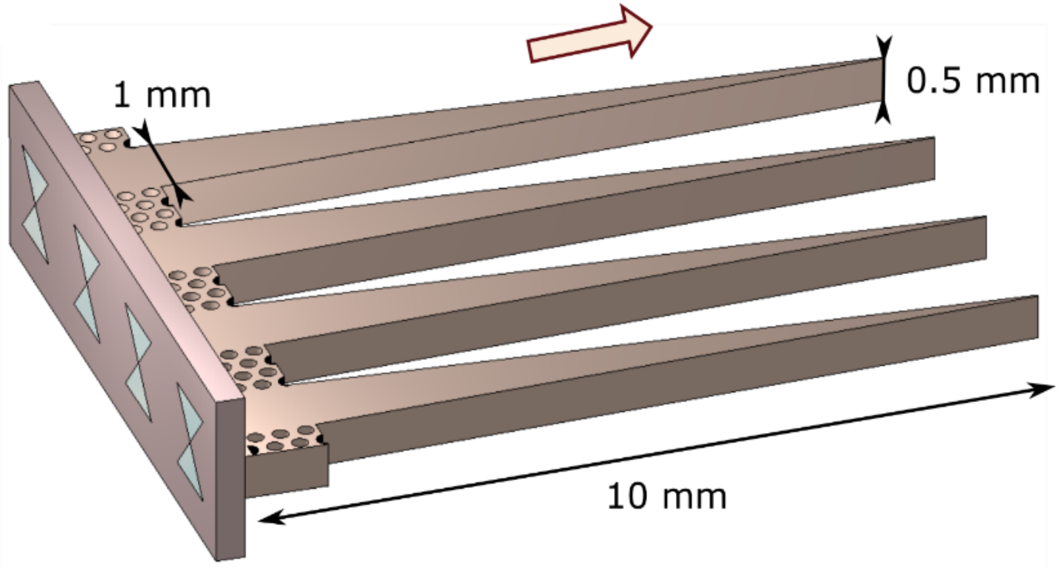
Dielectric rod waveguides (DRW) antenna arrays with integrated PCAs for beam steering

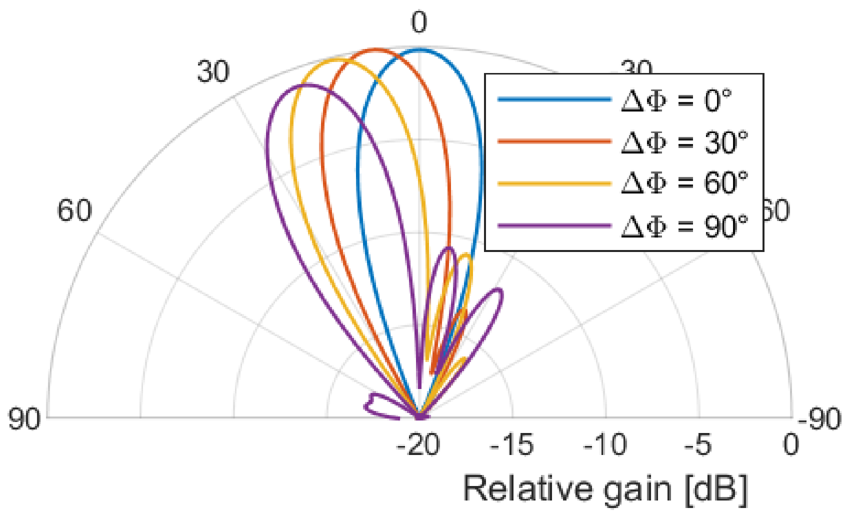


PCA … photoconductive antenna: bow-tie antenna with InGaAs photodiode

[KTH, unpublished]

Dielectric rod waveguides (DRW) antenna arrays with integrated PCAs for beam steering





Silicon-micromachined prototype for 85 GHz 4x1 array

[KTH, unpublished]

Conclusions

- micromachining: an enabling technology for high performance, miniaturized mmW and sub-mmW systems:
  - Very small and accurate feature size and surface roughness
  - High product uniformity, volume manufacturable
  - Integrated micromechanics => near-ideal reconfigurability
- KTH has shown many high-perfonance devices: filters, diplexers, phase shifters, switches, couplers, OMT

Acknowledgements:
- ERC CoG no. 616846
- Swed. Foundation for Strat. Research Synergy Grant Electronics SE13-007
- H2020 “M3TERA” GA no. 644039
- H2020 “Car2TERA” GA no. 824962
- H2020 ITN “CELTA” GA no. 675683
- H2020 ITN “TESLA” GA no. 764321
- KAW Foundation
- VINNOVA Smartare Elektroniksystem

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