KTH ROYAL INSTITUTE OF TECHNOLOGY

Micromachining for THz Frequencies

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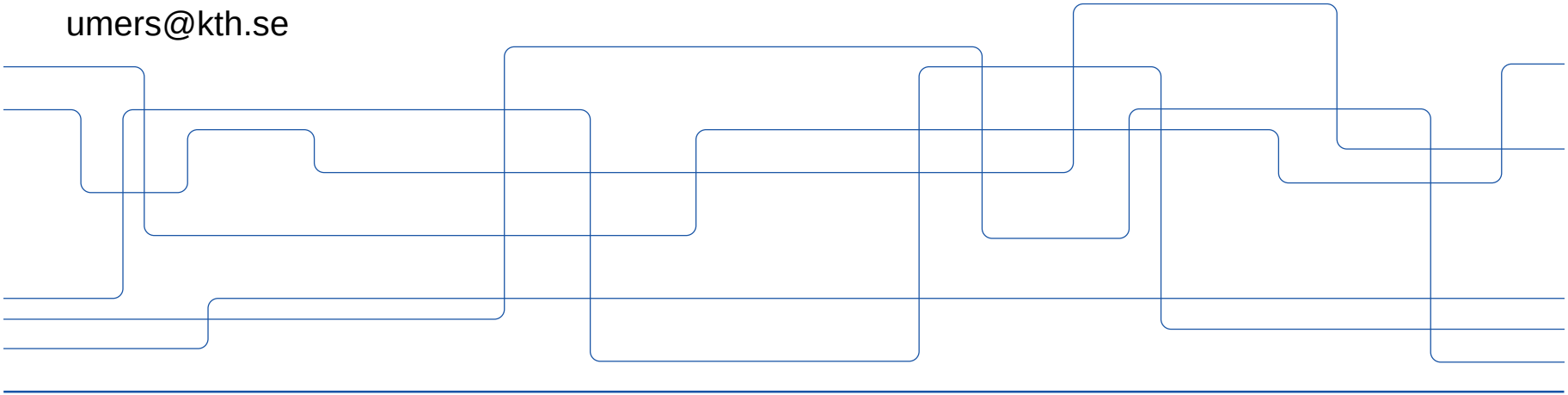


Microwave/THz MEMS@KTH

(School of EE and CS)

Group size (2022):

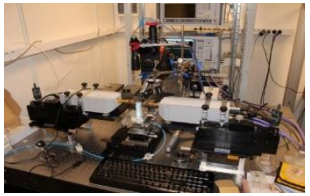
- 1 professor
- 3 senior researchers
- 2 post-docs, 8 PhD students

Average external project funding:

- EUR 1-1.5 million/year

KTH micro & THz resources:

ELECTRUM LAB
KTH & ACREO IN COLLABORATION



- 1300m^2 class 100 clean-room for fabrication
- MW characterization (VNA, antennas) to 750 GHz

Contents

- Why silicon-micromachining?
- Low-loss micromachined waveguides and waveguide cavities
- Complex 3D Geometries and Components
- System Integration
- Conclusion

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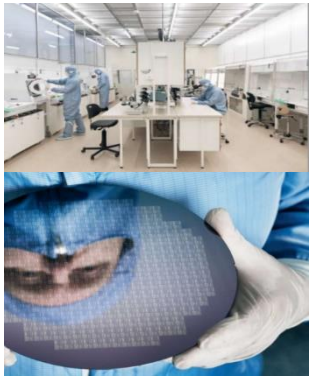
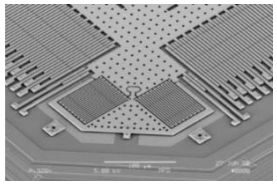
Micromachining for RF/MW/THz



Semiconductor clean-room manufacturing:

- miniaturization
- very high volume
- very low cost

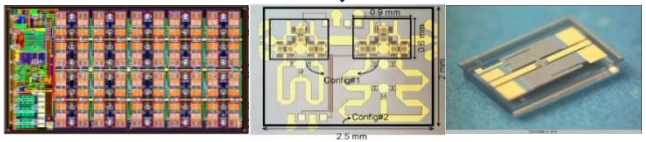
Revolutionized information age



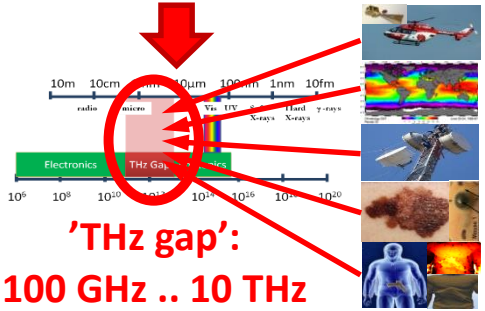
Micro-mechanics
MEMS
Micro-ElectroMechanical Systems

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

Revolutionized sensors and user interfaces



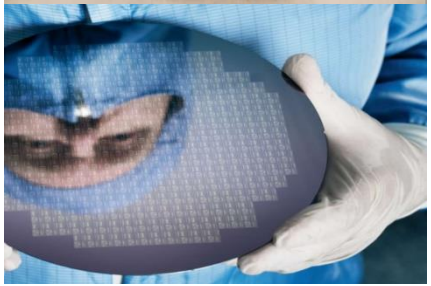
RF (radio—frequency) MEMS:
mobile phone antenna tuners,...



'THz gap':
100 GHz .. 10 THz

Why silicon micromachining?

- Accurate geometries down to 1 µm
- Surface roughness down to nanometers
- Ultra-high aspect ratio geometries: 1000:1
- Volume manufacturable
- High product uniformity, high yield
- Low cost in high volumes
- Integrated MEMS microactuators
  => near-ideal reconfigurability

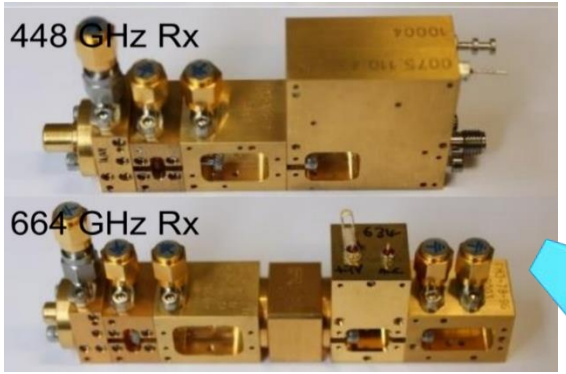


Mm/Sub-mm-wave Fabrication Technologies

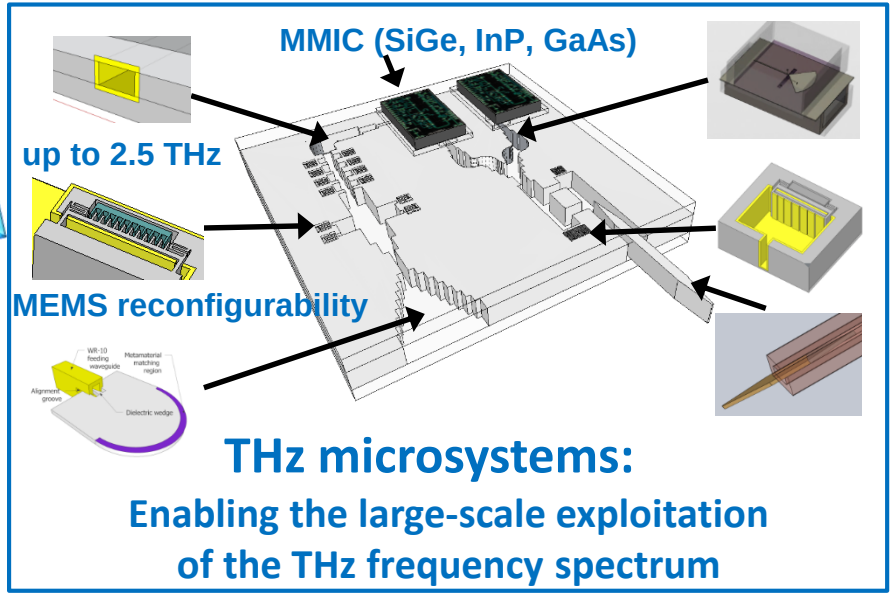
	CNC milling + EDM	*Si. micromachining*	*3D printing plastic/metal*	*SU8/Electroforming*	
min. feature size	> 20µm	1-10µm	50µm	10µm	
positioning tolerance	1-10µm	< 1µm	>10µm	1µm	
aspect ratio	very low	very high	Low	high	
surface roughness	>1µm	1-10nm	>5µm	>10nm	1-10nm
geometrical limitations	average	good	Very good	poor	
volume manufacturability	very poor	very good	poor	very good	
product uniformity	low	very high	low	high	
tool cost	high	very high	low	low	
development cost	low	high	low	medium	
low volume product cost	medium	high	very low	med.	v. low
high volume product cost	high	very low	medium	low	v. low
integration compactness	average	very high	average	high	
integration with MMICs	medium	high	medium	medium	

very good | **good** | **average** | **poor** | **very poor**

Micromachined THz Systems



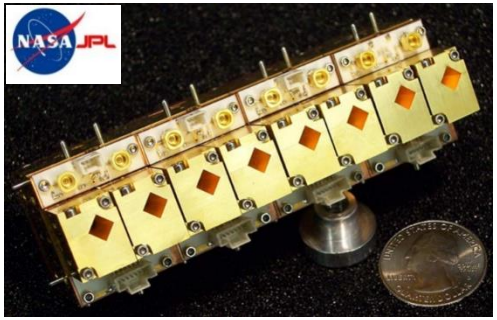
1000x smaller
1000x lighter
100x lower cost
10x less power consumption
reconfigurable
volume-manufacturable



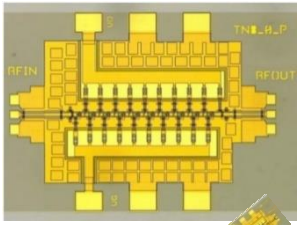
THz technology = stone age

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

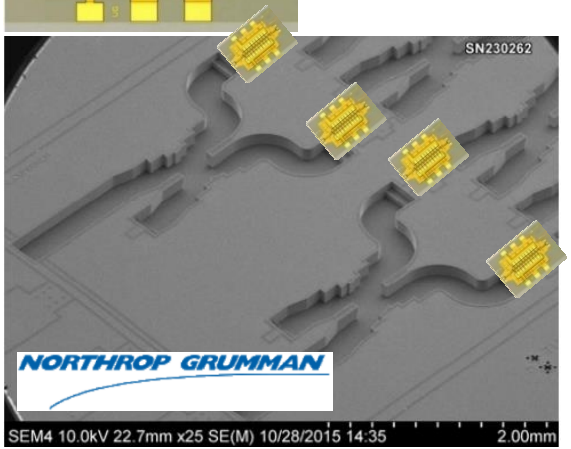
Micromachined THz Systems



340 GHz 8 channel transceiver
[JPL USA, T-THzSciTec 2015]



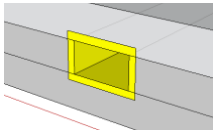
single InP PA



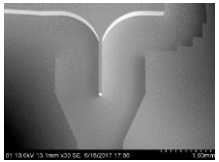
Micromachined, 1.080 THz
4-way power combiner: 1 mW
[NG, USA, IMS 2017]

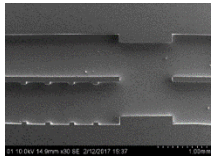
Toolbox at KTH

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

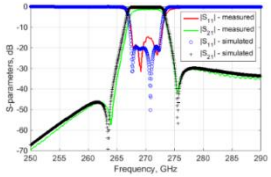


Turnstile ortho-mode transducer 220-330 GHz;
0.5dB IL 36dB x-ISO

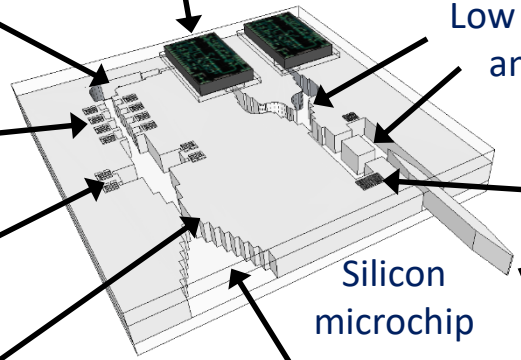




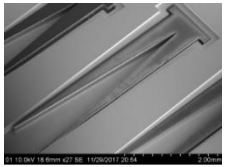
Low loss waveguide power combiners and couplers (0.2dB IL@320GHz)



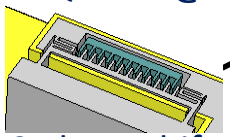
Filters: Q=800@450GHz,
Q=1600@170GHz



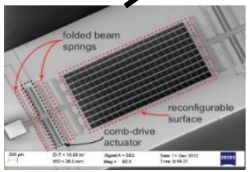
Silicon microchip



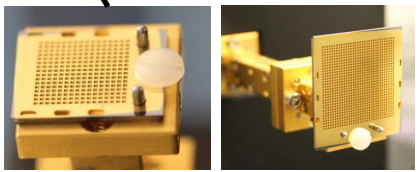
Integrated waveguide absorbers



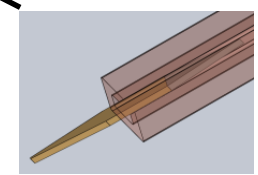
MEMS phase shifters
500-550GHz,
220-330 GHz



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

Contents

- Why silicon-micromachining?
- Low-loss micromachined waveguides and waveguide cavities
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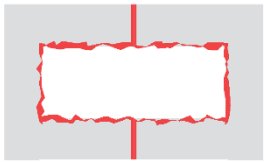
Micromachined Waveguides

$$\alpha_c = \alpha_{c0}\left(1 + K_{rough}\right) \qquad K_{rough} = \frac{2}{\pi}\tan^{-1}\left[1.4\left(\frac{R_a}{\delta}\right)\right] \qquad \alpha_{c0} = 4.58 \times 10^{-8}\sqrt{\frac{f}{\sigma}}\left[\frac{2\frac{b}{a}\left(\frac{f_c}{f}\right)^2 + 1}{b\sqrt{1-\left(\frac{f_c}{f}\right)^2}}\right] dB/mm$$

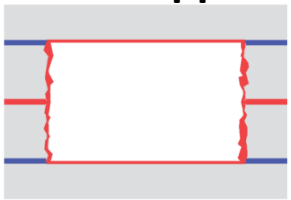
Conventional approaches:



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

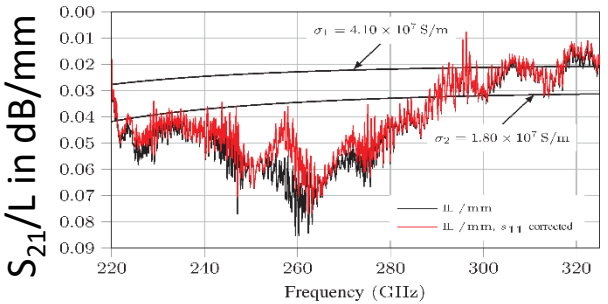
Micromachined Waveguides

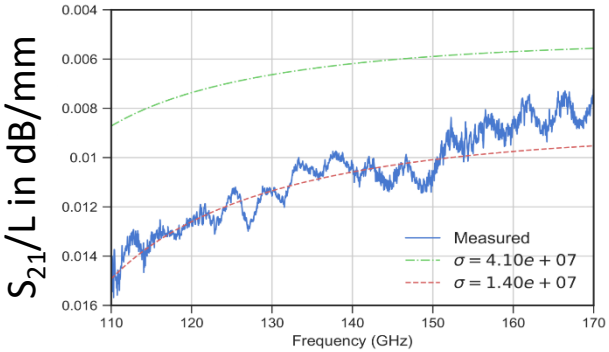
220-330 GHz:
0.020-0.070 dB/mm
Q_{UL}~750-800 (270 GHz)

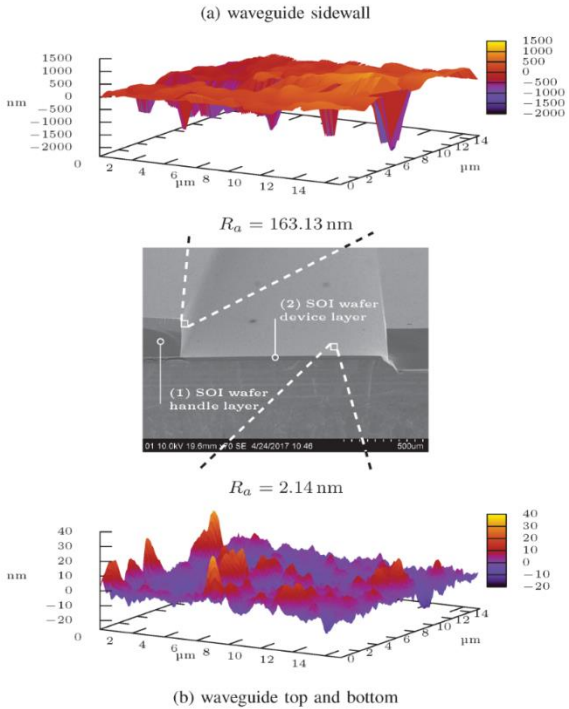
[IEEE THzSciTec 2018]

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

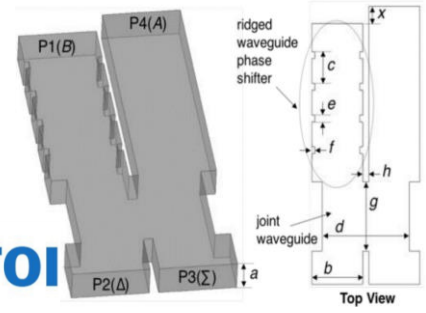
[IEEE IMS 2018]

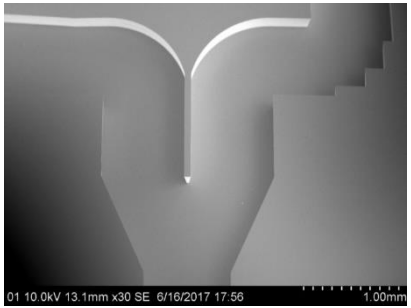


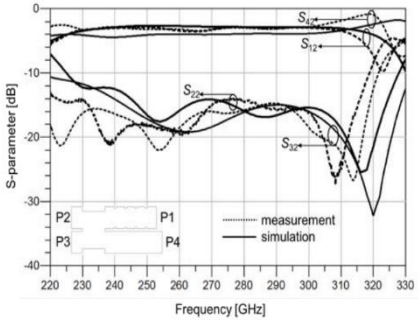




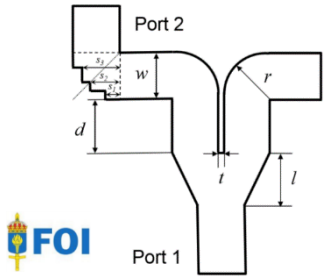
Coupler, Power Splitter and Matched Load



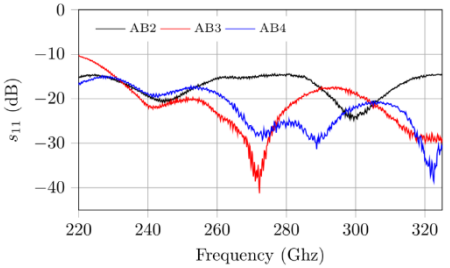




Very low loss, full-band 3-dB coupler [EuMC 2017]

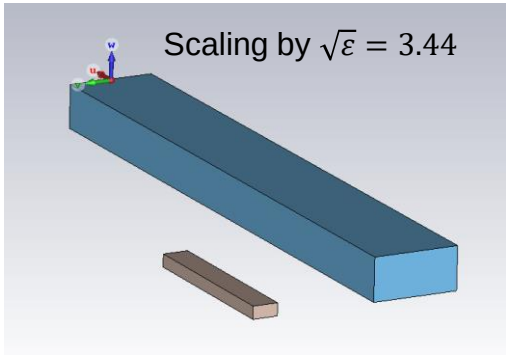


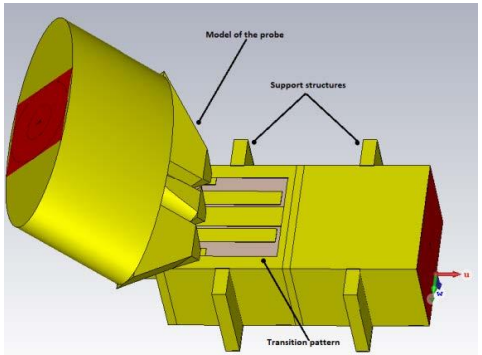
Very low loss power combiner/splitter [APMC 2017]



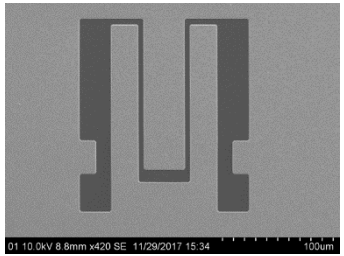
Integrated matched loads, absorbers, attenuators [EuMC 2017, IMS 2018]

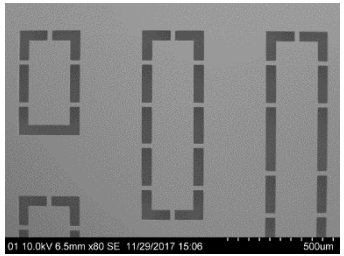
Silicon-Core Waveguide 220 - 330 GHz

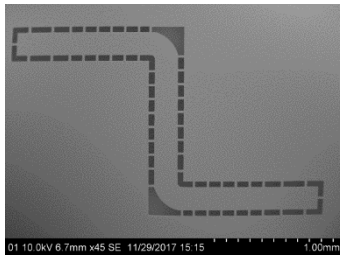


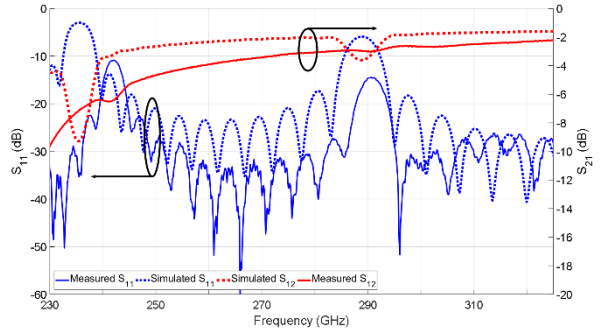


[THzSciTec 2018]

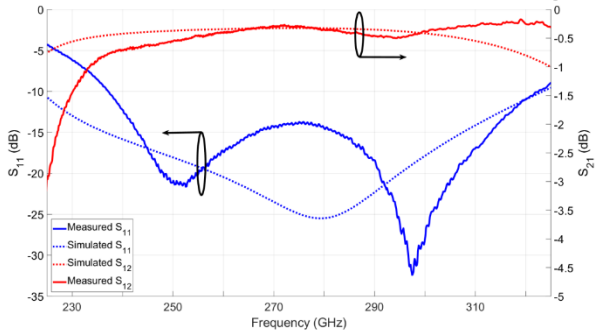








WG line *IL = 0.14 dB/λ_g*



CPW transition *IL < 1 dB*

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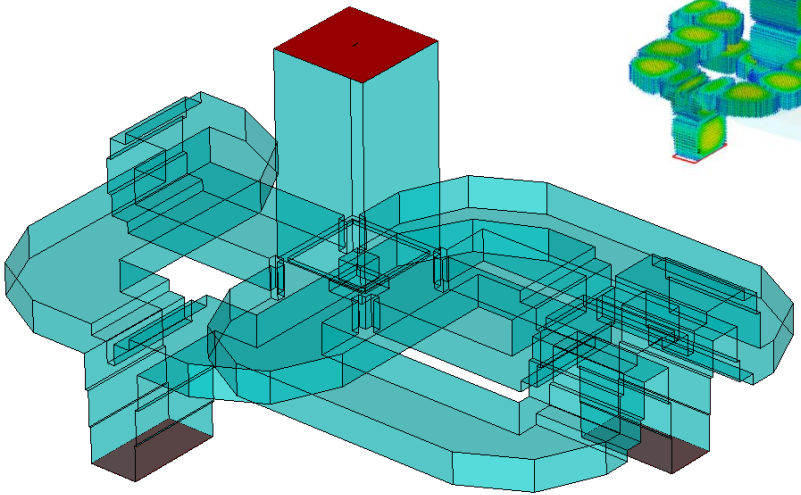
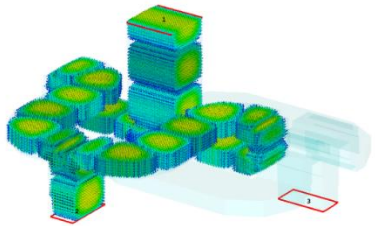
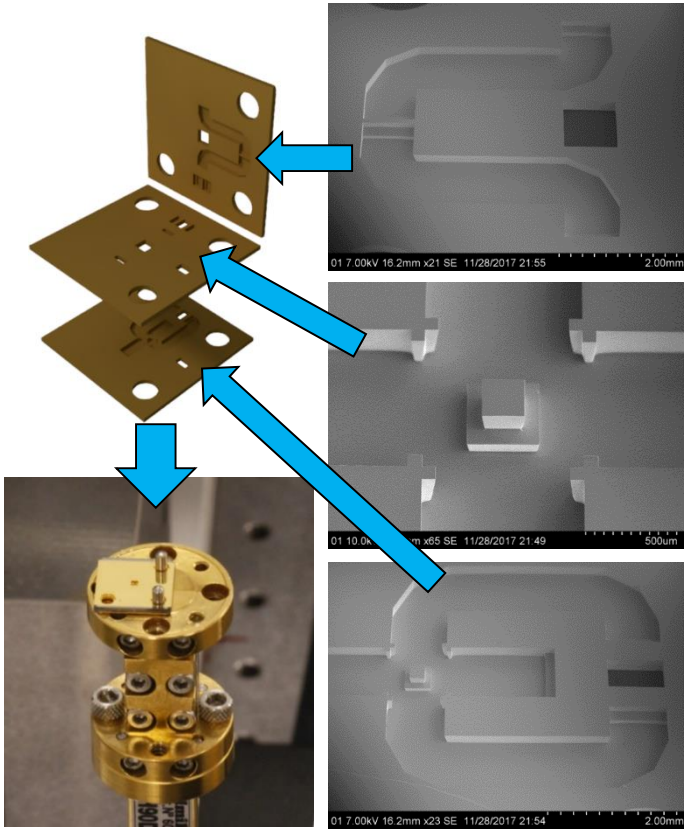
Turnstile Orthomode transducer

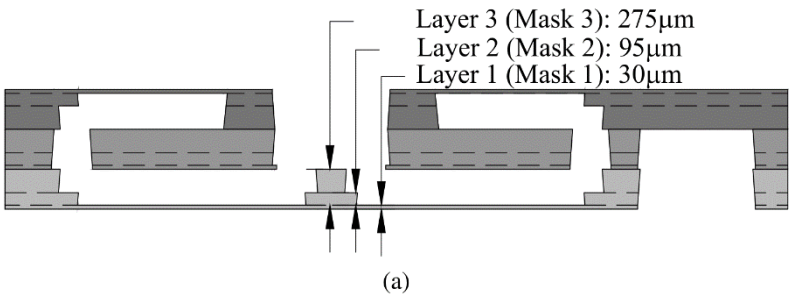
- First turnstile OMT above 110 GHz
- Micromachining enables devices at so far unreachable frequencies!
- Size only 5x5x0.9 mm^3

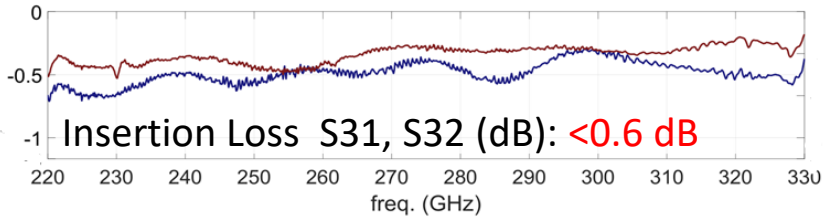


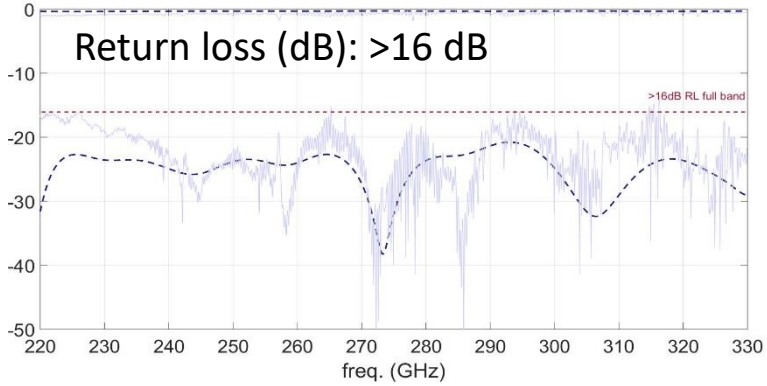


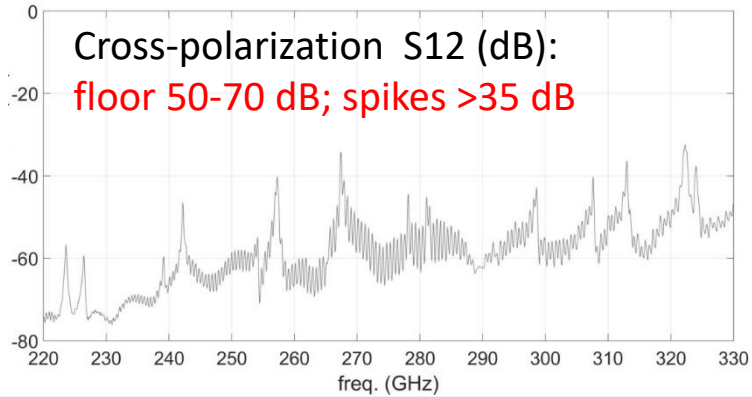


Turnstile Orthomode transducer

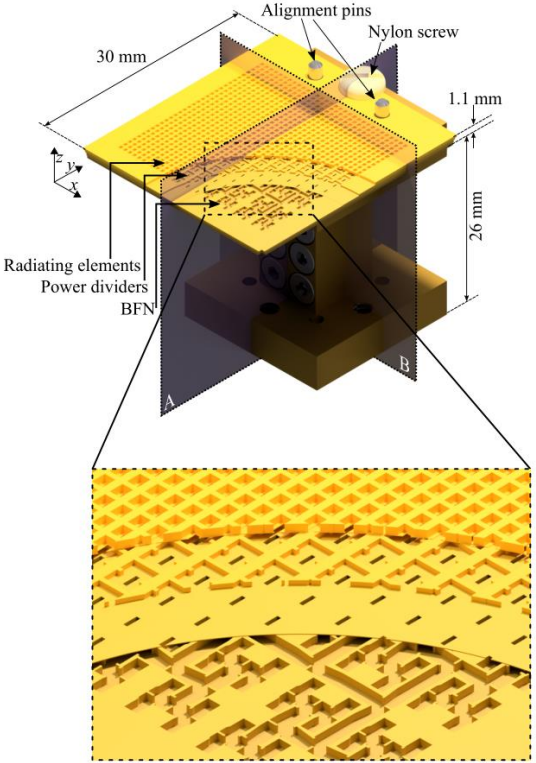


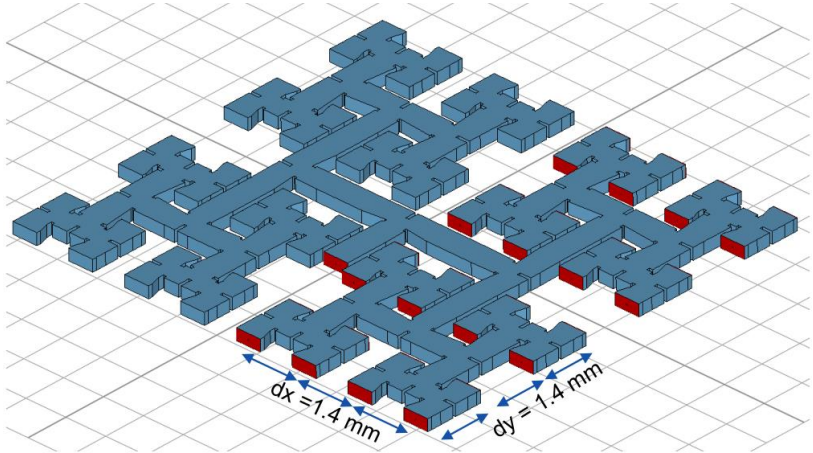




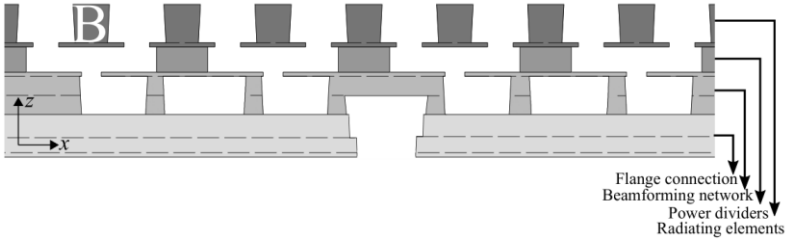


Corporate-fed Antenna Array

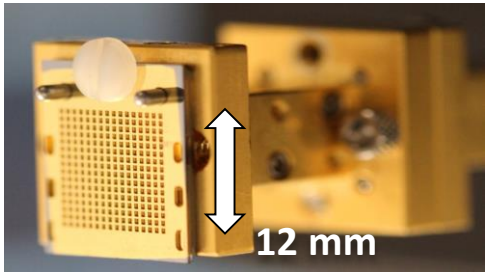




Single-layer feeding network to 2x2 sub-arrays => 16x16 antenna array



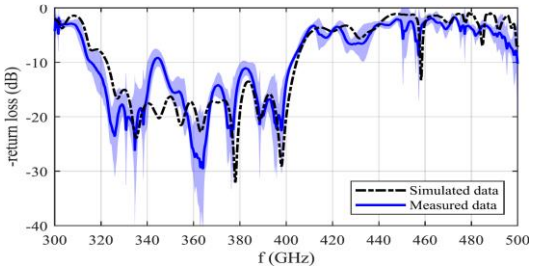
Corporate-fed Antenna Array

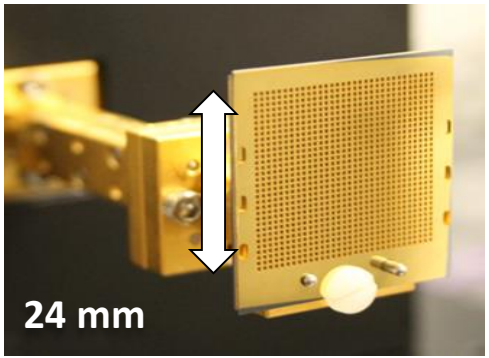


16x16 antenna array: 256 elements
320-400 GHz, 80 GHz BW

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

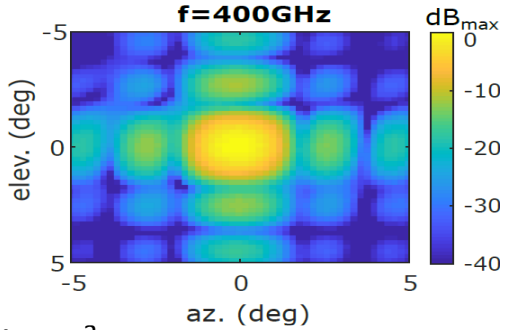




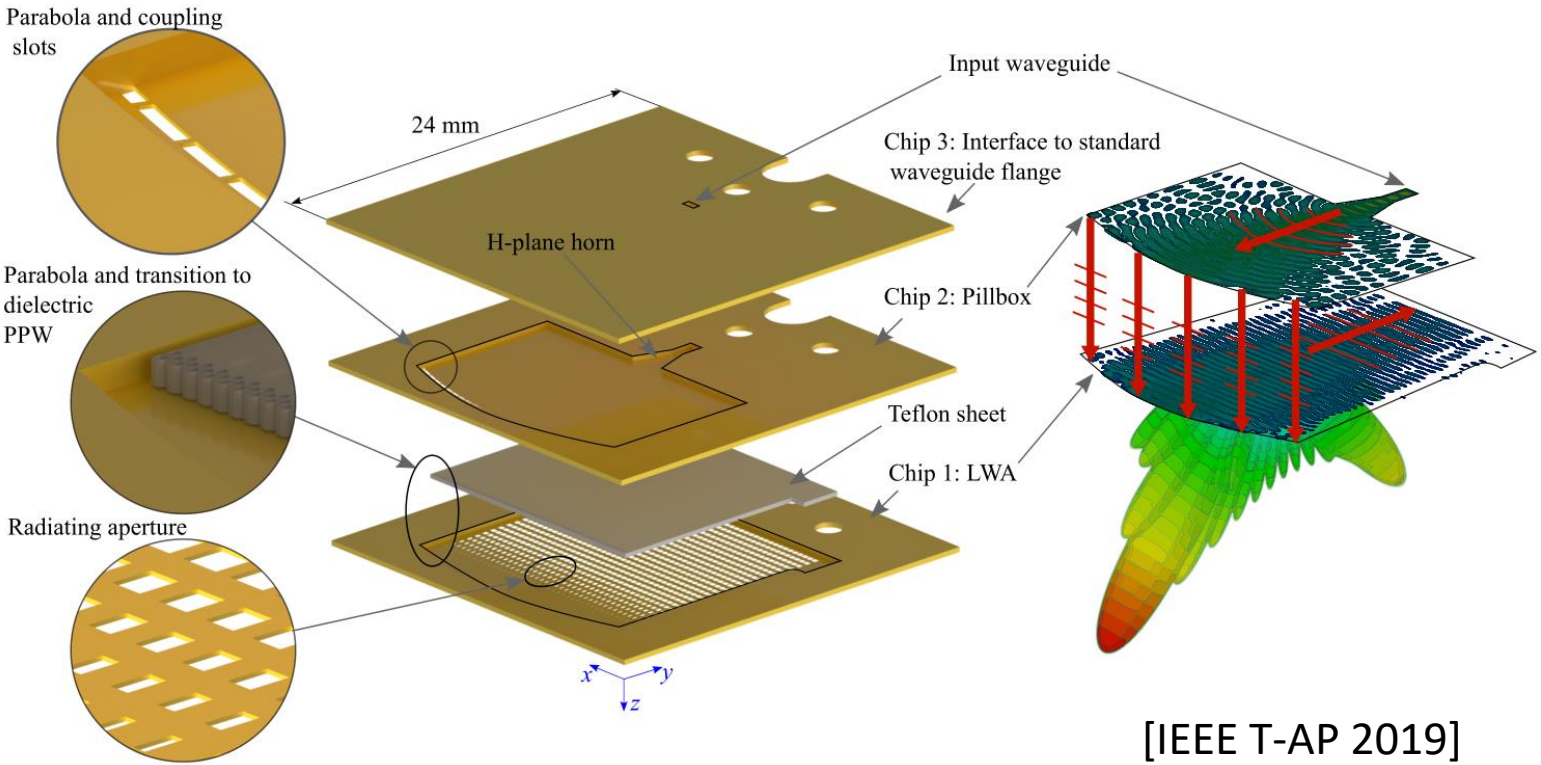
32x32 antenna array: 1024 elements
320-400 GHz, 80 GHz BW

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

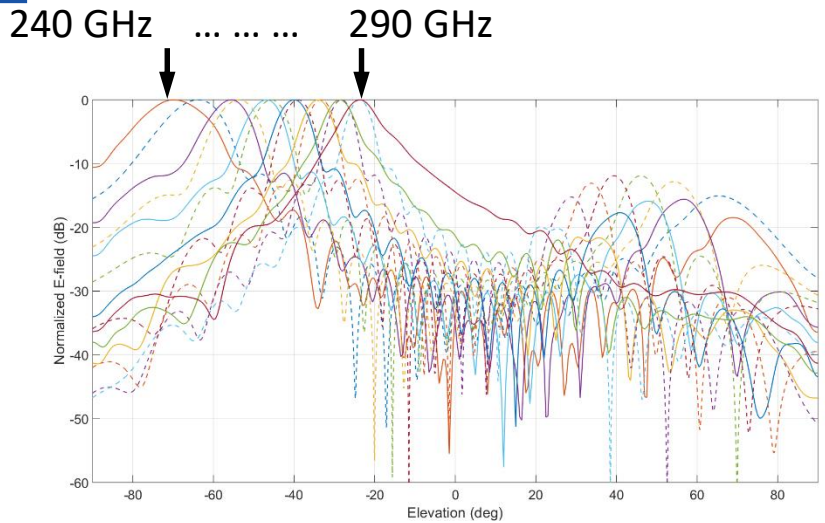


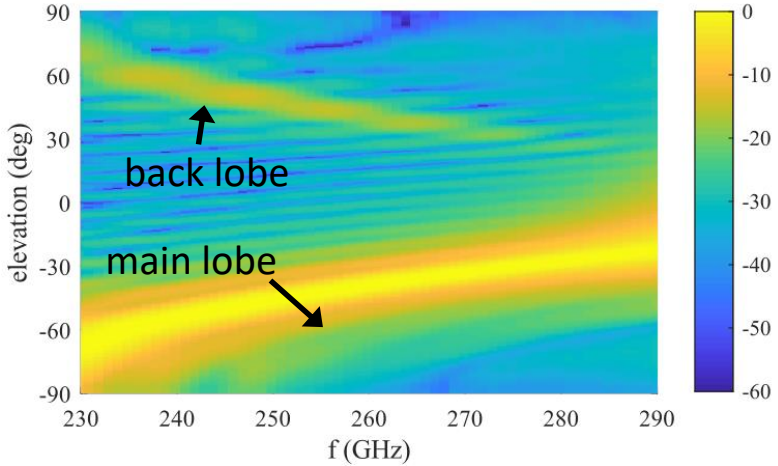
Micromachined Pill-Box Beam Steering Antenna



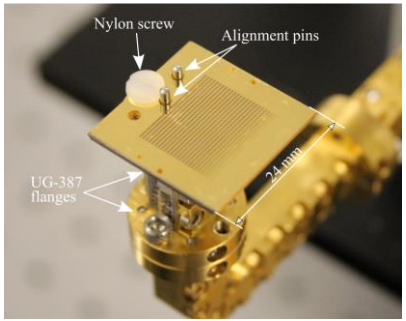
[IEEE T-AP 2019]

Micromachined Pill-Box Beam Steering Antenna



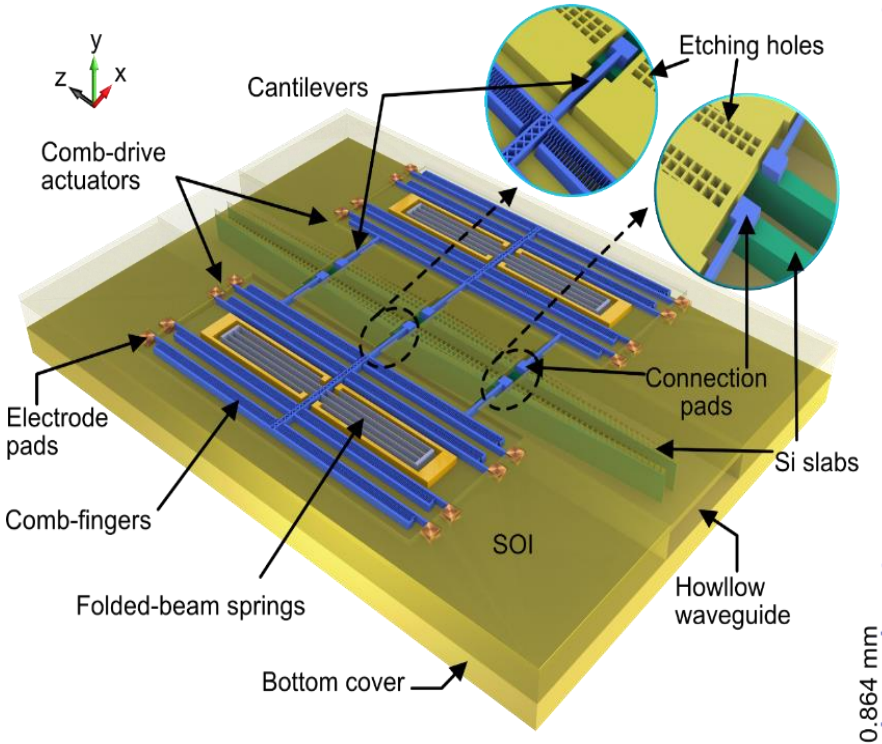


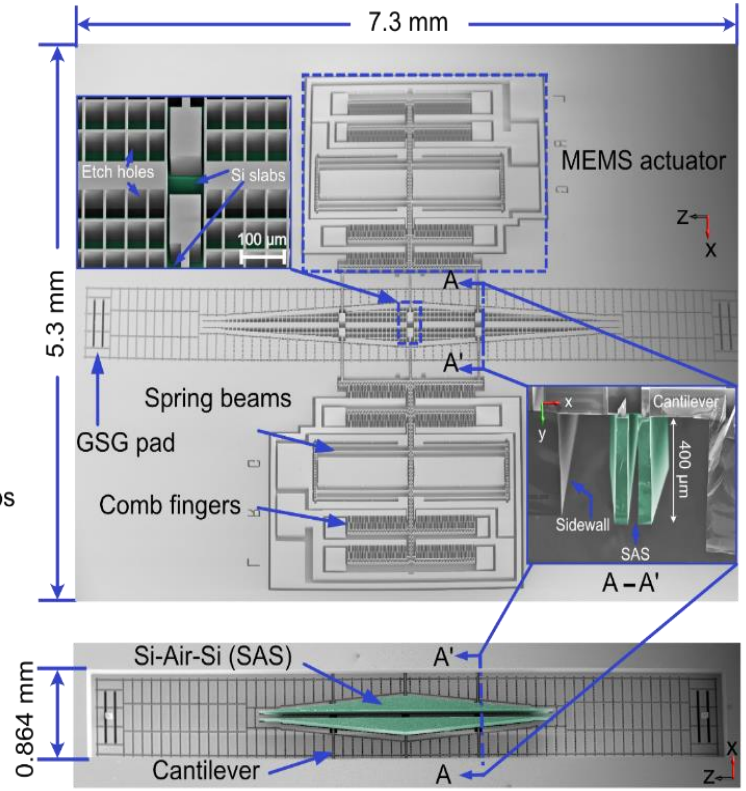
- size: 24x24x0.9 mm^3
- 220-300 GHz frequency sweeping
  => 20˚-75˚ scanning (55˚ field of view)
- measured gain: 28.5 dBi
- measured average HPBW: 7˚



[IEEE T-AP 2019]

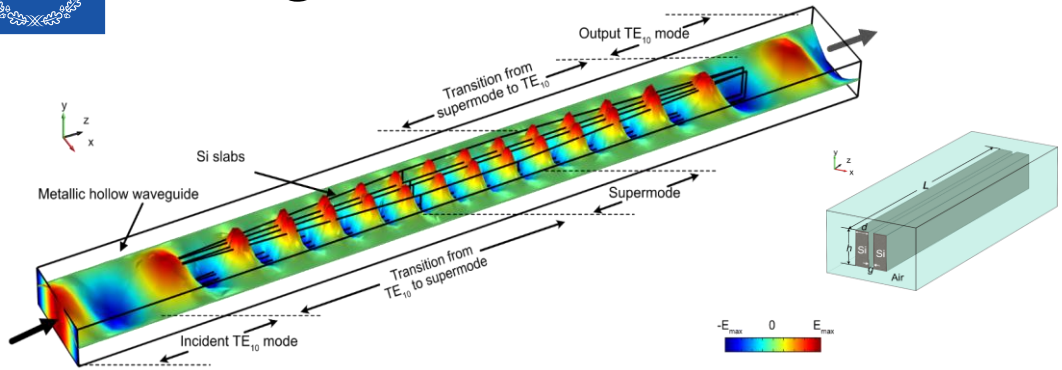
Integrated MEMS Phase Shifter

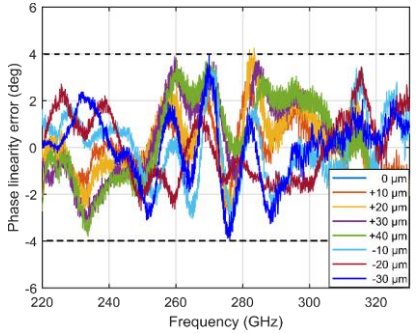




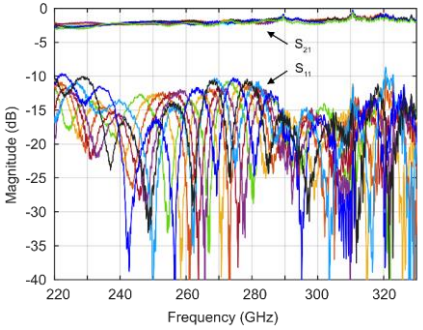
[IEEE T-MTT 2021]

Integrated MEMS Phase Shifter



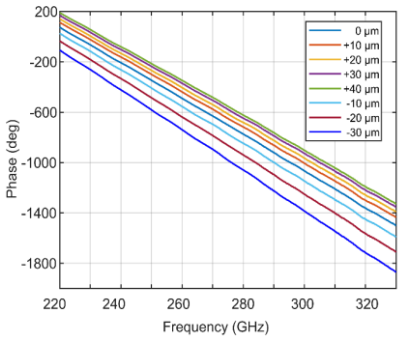


Phase Error

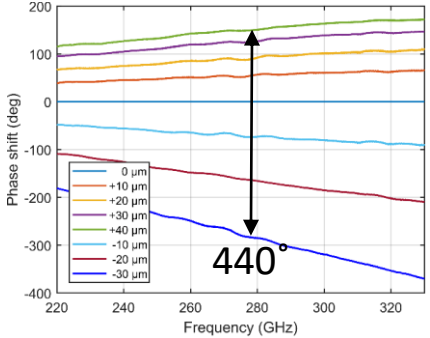


Insertion loss, return loss

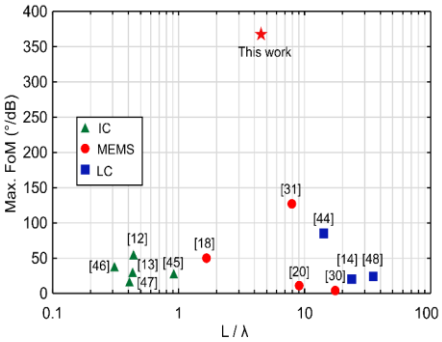
[IEEE T-MTT 2021]



Phase shift

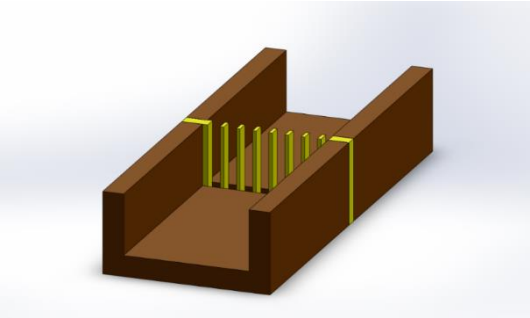


Phase shift

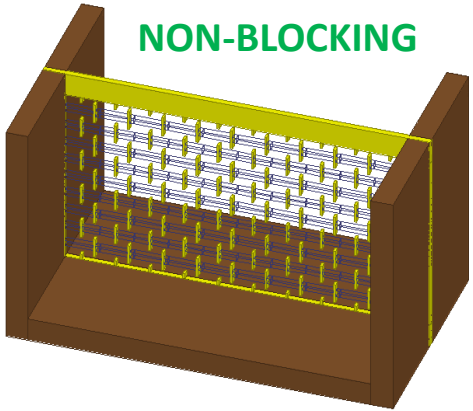


FoM

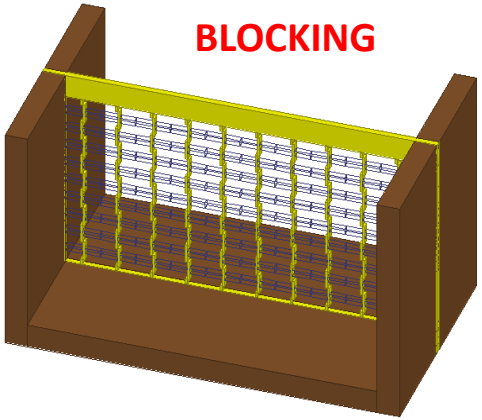
MEMS Waveguide Switches



NON-BLOCKING

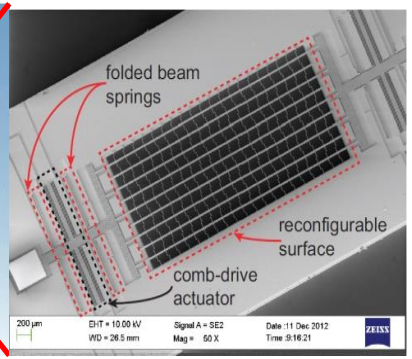


BLOCKING



MEMS:

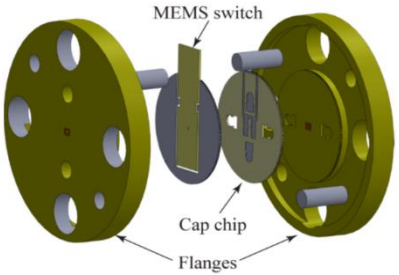
- 100 000 x smaller
- 100 000 x lighter
- 10 000 x faster
- equal performance

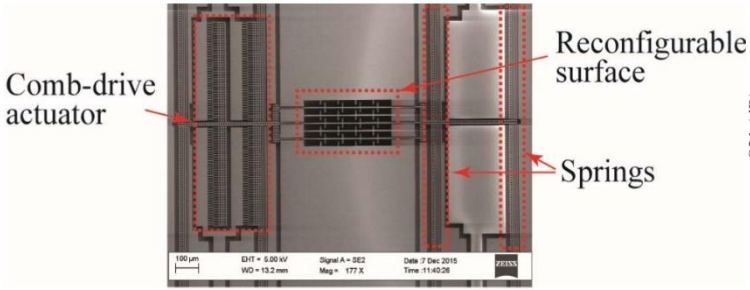


30 µm thick!
thinner than a hair

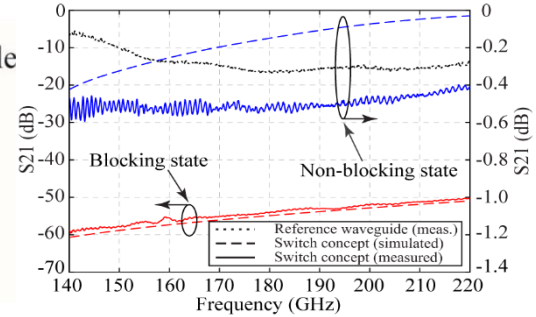
MEMS Waveguide Switches

	Generation 1 60-70 GHz	Generation 2 500-750 GHz	Generation 3 140-220 GHz	Generation 4 320-360 GHz	Generation 5 163-182 GHz
Type	SPST	SPST	SPST	SP4T	SPDT, X-switch
Insertion loss	0.3-0.4 dB	2.5 dB	<0.6 dB	<0.68 dB	<0.2 dB, <0.6 dB
Isolation	30-40 dB	18-25 dB	>50 dB	>30 dB	>40 dB, >35 dB

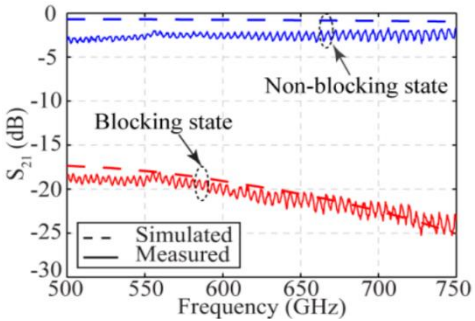




500-750 GHz switch

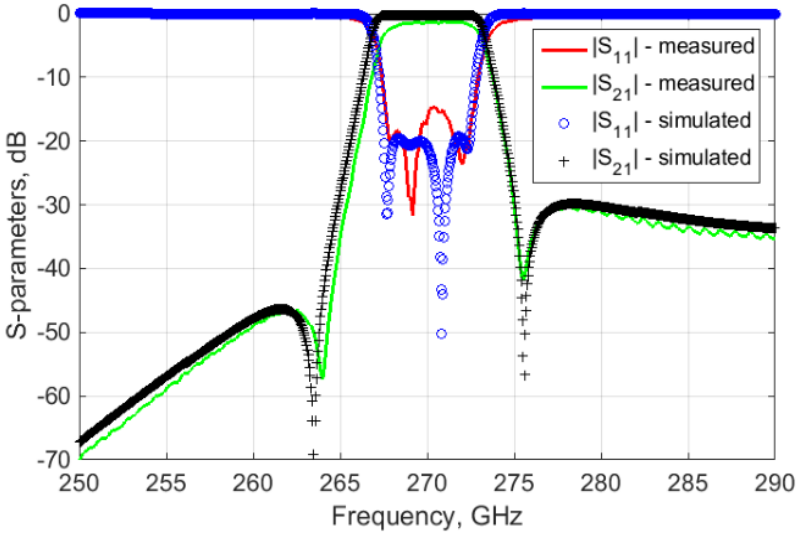


140-220 GHz switch

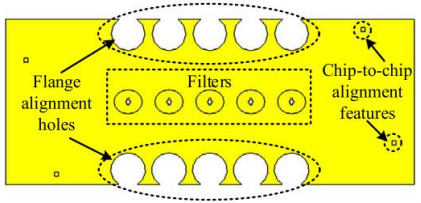


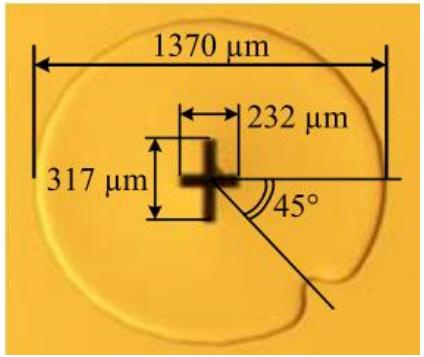
500-750 GHz switch

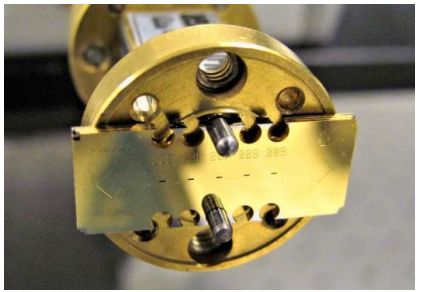
270 GHz Narrow-Band 4p2z Filter

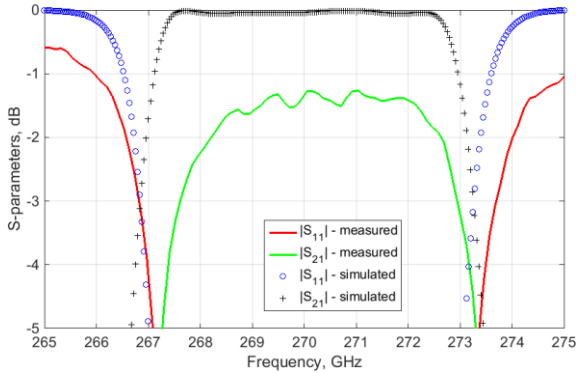


- f_0 = 270 GHz, 1.85% frac. BW (267.5…272.5 GHz)
- avg. IL=1.5dB (best IL=1.25dB)
- avg. RL=18dB (worst = 16dB)
- rejection: >30 dB (<264, >276 GHz)





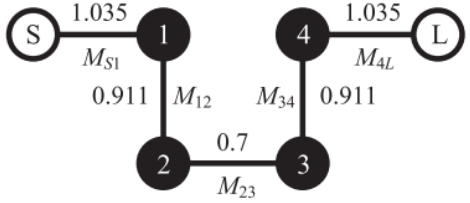




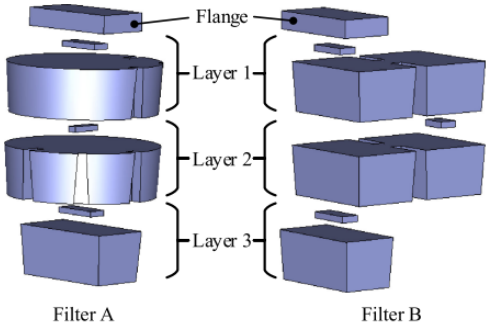
Best performance for any comparable filter design in any technology in this frequency band

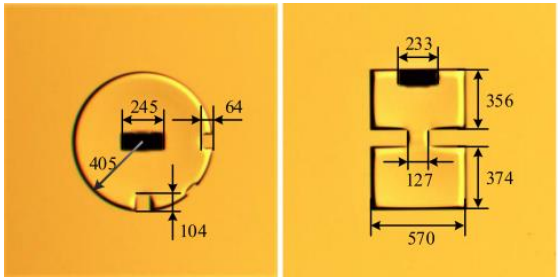
450 GHz Sub-mm Wave Filters

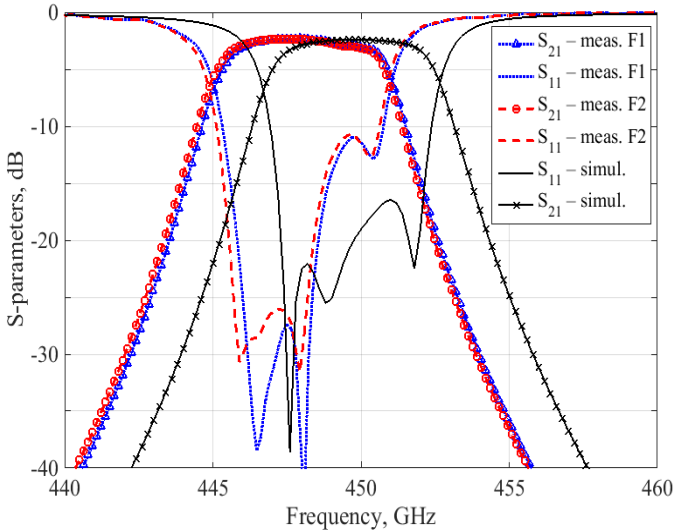
- f_0=450 GHz, 4p
- 1.00% FBW, IL=2.5dB
- $Q_{unloaded}$=790
- first 1%-FBW filter at sub-mm wave frequencies!



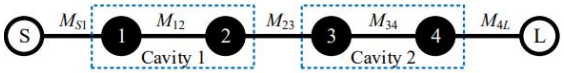
[IEEE TSTT,2019]

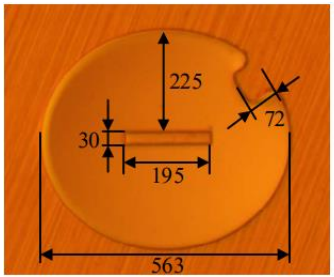


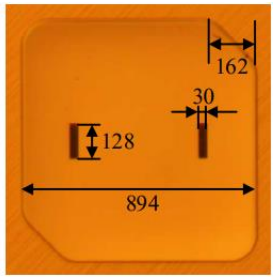


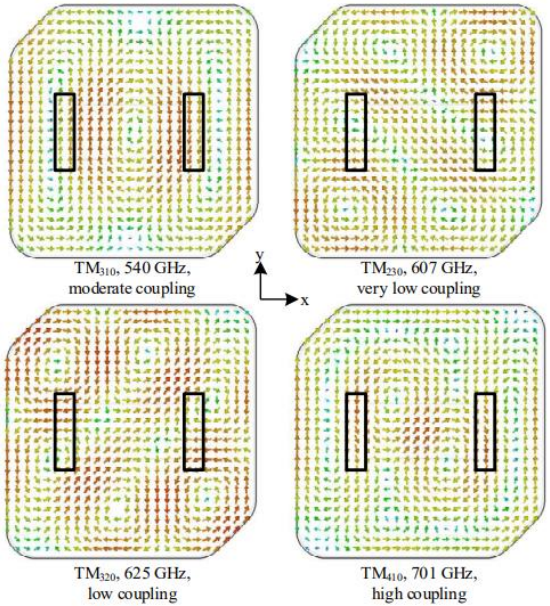


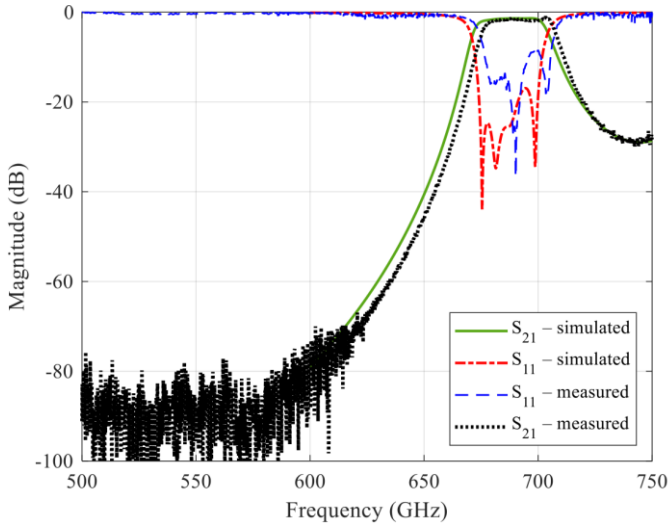
Q of 950 at 700 GHz



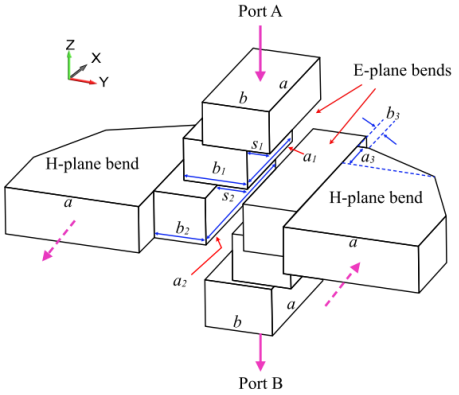


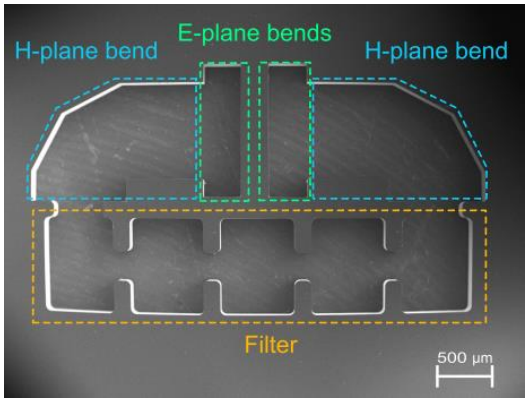


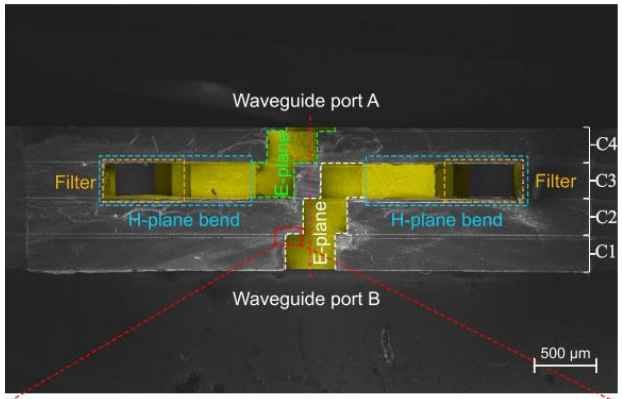


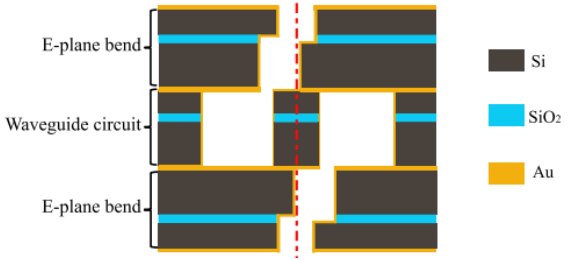


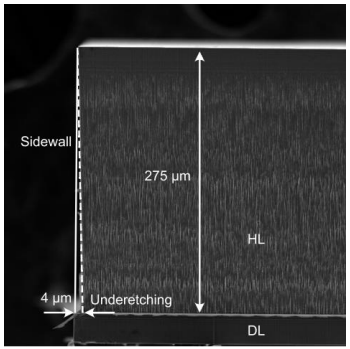
Axial Port Filters with Integrated E-plane Bends

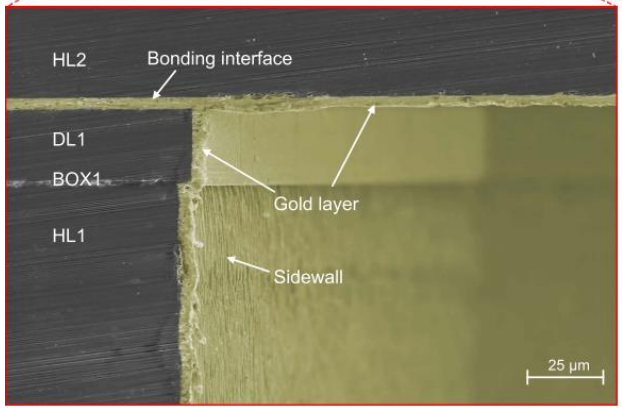






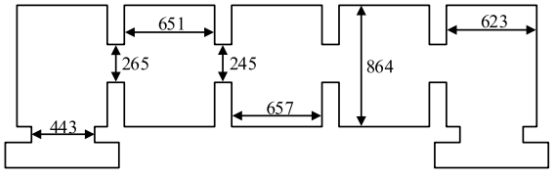






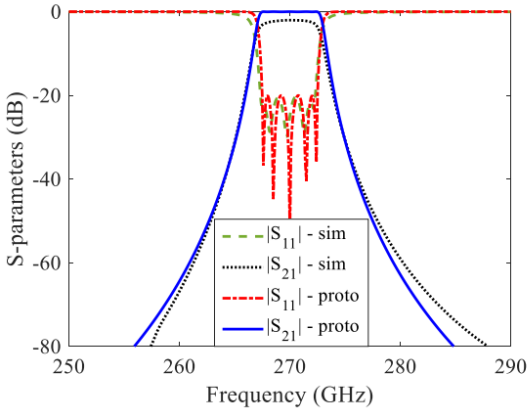
[IEEE TMTT, 2022]

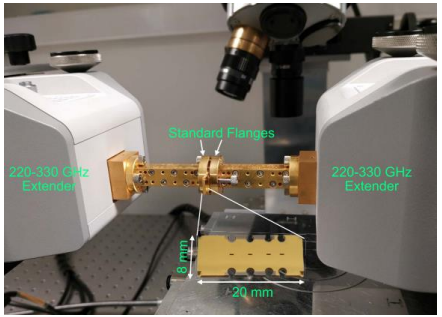
Axial Port Filters with Integrated E-plane Bends



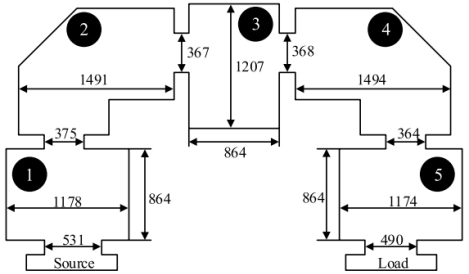
(a)

(b)

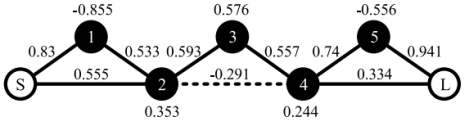


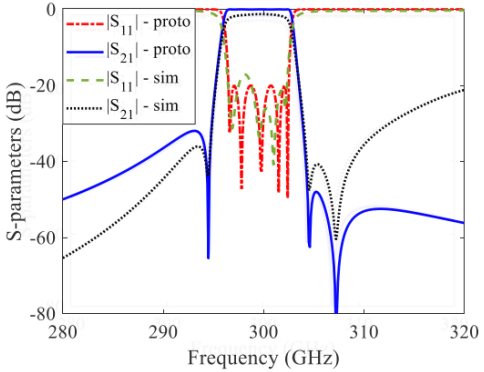


[IEEE TMTT, 2022]



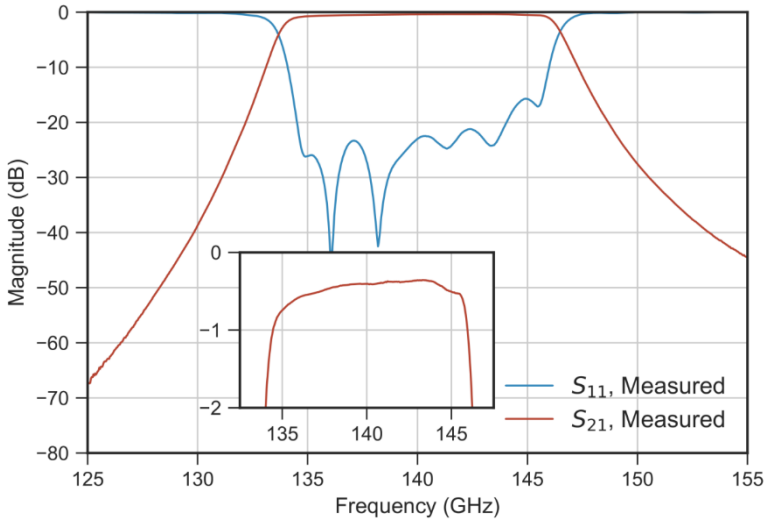
(a)





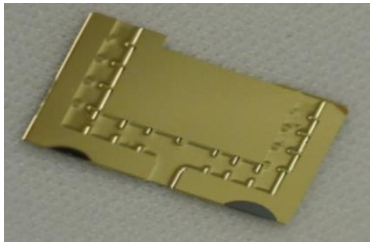
D-Band Diplexer

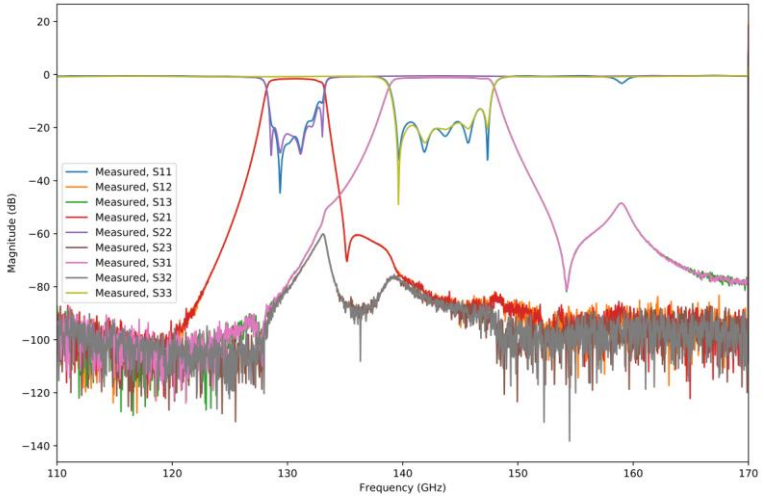
Wide-band example:
5.2% FBW, 141-148.5 GHz



<0.5dB IL, Q_{UL}~1600

Telecom diplexer:
141-148.5, 129-134 GHz





<1.5dB IL, >60 dB isolation

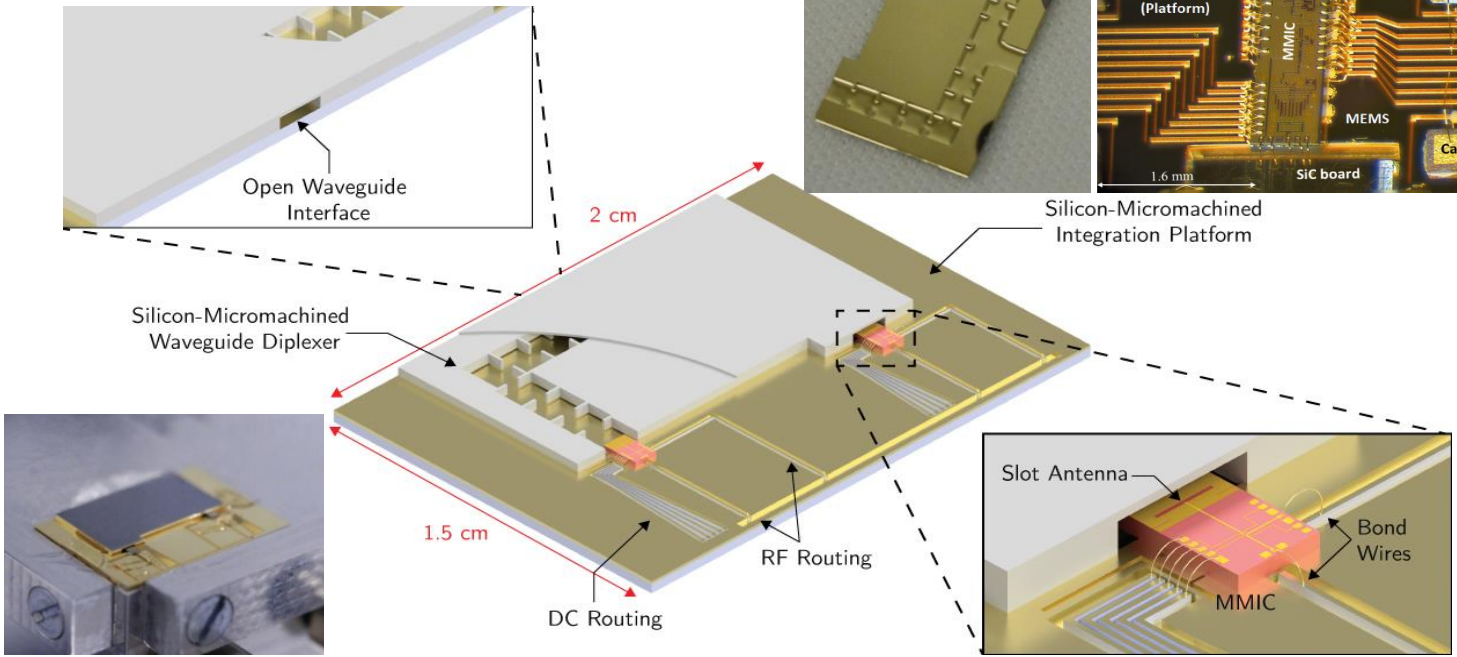
[IEEE IMS, 2018]

Contents

- Why silicon-micromachining?
- Low-loss micromachined waveguides and waveguide cavities
- Complex 3D Geometries and Components
- System Integration
- Conclusion

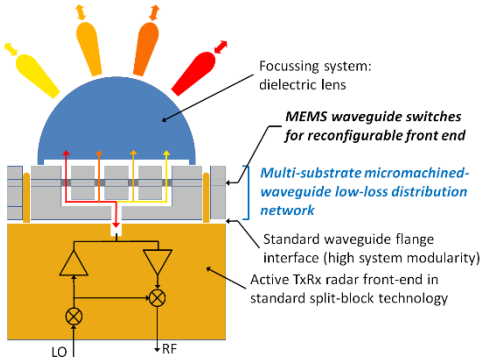
Highly- Integrated D-Band Communication Link

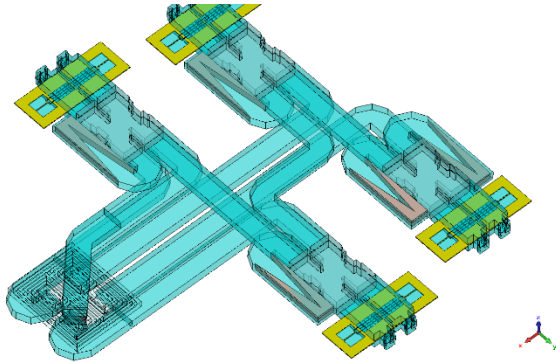
M3TERA

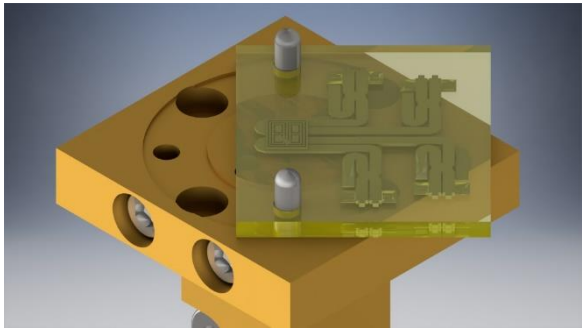


[IEEE THz Sci Tech 2019]

THz MEMS for Radar Beam Steering







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

Lens Antenna:

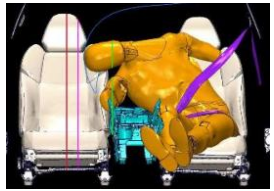
- Low e_r dielectric integrated lens antenna (ILA)
- CNC milled Rexolite 1422 lens
- 37 dB gain
- Side lobe level > 14 dB in the FoV

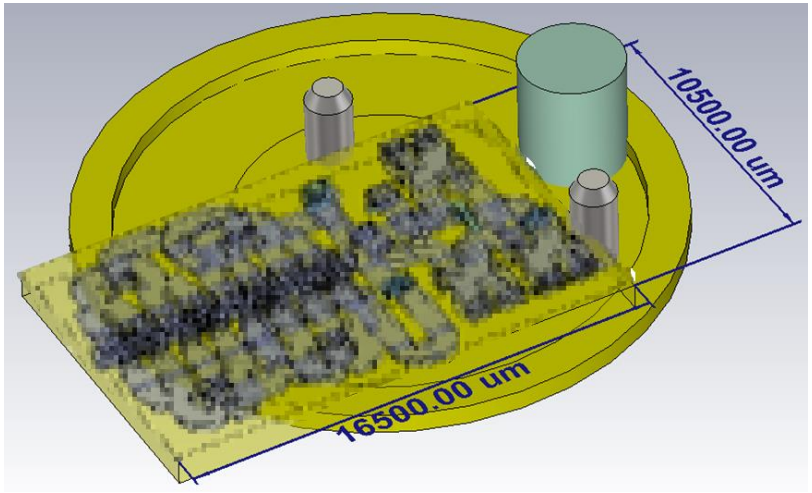
Next Gen. THz Car Radar Enabled by Microsystems

- In-cabin car radar for:
  - Passenger/driver monitoring
  - Left-child detection
- 240 GHz car radar, 10 GHz BW
- MEMS waveguide-switch circuit:
  - Beam-steering
  - Beam-shape switching
- Tapered 2x8 antenna array
- Signal processing:
  - AI networks
  - computational imaging

Car2TERA

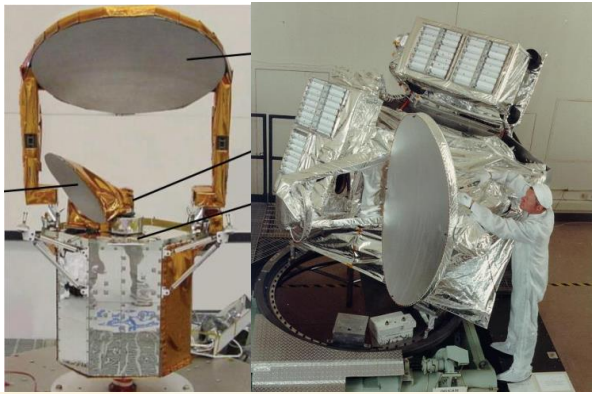
Terahertz sensors and networks for next generation smart automotive electronic systems

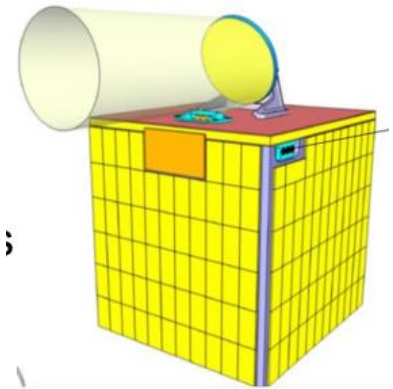


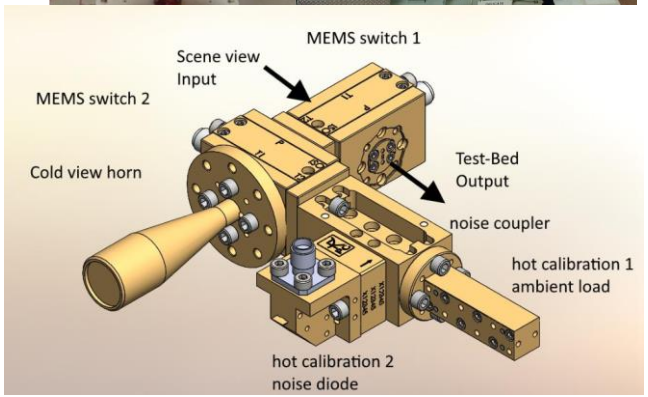


THz MEMS for Space

- New radiometers for next generation:
  - Weather satellites
  - Space-borne environmental sensing
  - Cube-sat & small-sat instrumentation







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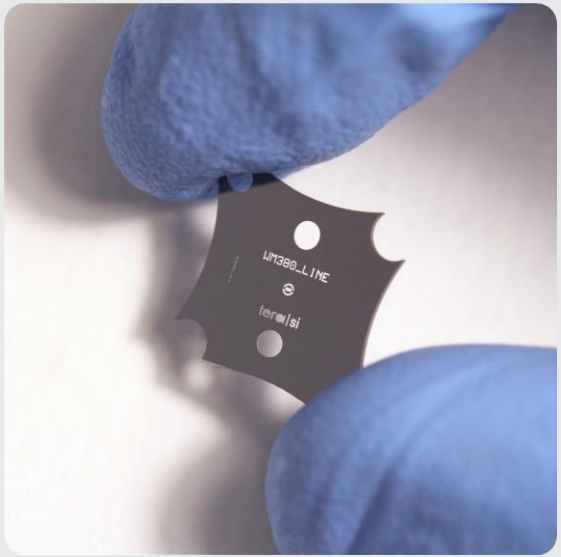
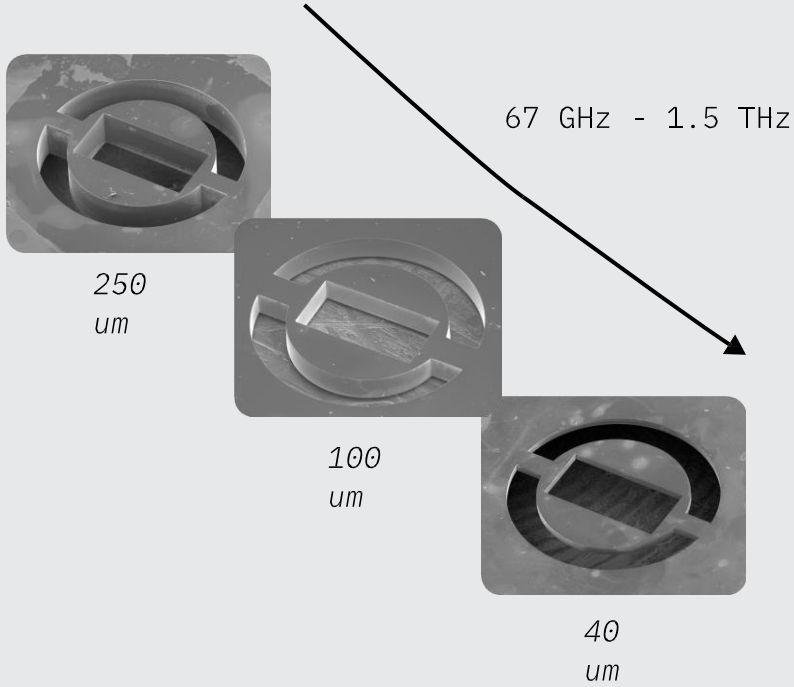
Precision components for 6G and beyond





terasi.io

THz TTASS

Conclusions

- micromachining: an enabling fabrication technology for high performance, miniaturized, volume-manufacturable sub-THz components & systems:
  - very small geometries, accurate feature sizes
  - very low surface roughness => low losses
  - high product uniformity, volume manufacturable
- A large number of micromachined-waveguide devices setting state-of-the-art performance were successfully implemented in this new technology: