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THz Micromachining

enabling the large-scale exploitation of the THz frequency spectrum?

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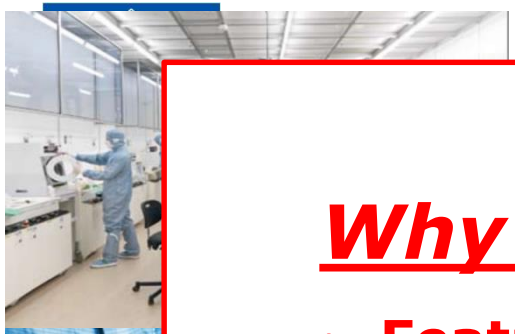
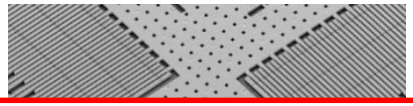




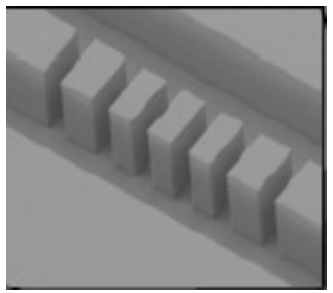
Micro-mechanics

s

Why Micromachining for THz systems?

- **Feature size/tolerance: down to µm**
- **Surface roughness: down to nm**
- **Ultra-high aspect ratio geometries:**
  - **Vertical features: up to 110:1**
  - **Horizontal features: 1000:1**
- **Alignment accury:**
  - **Within chip: < 1 µm**
  - **Between chips: <2 µm**
- **High product uniformity**
- **Low cost in high volumes**

- **Integrated MEMS microactuators**
  => reconfigurable systems
  with near-ideal performance



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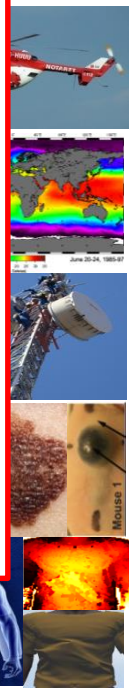
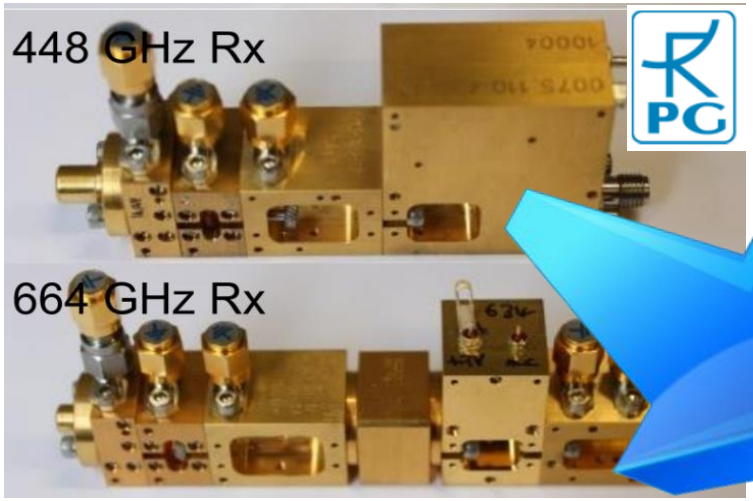
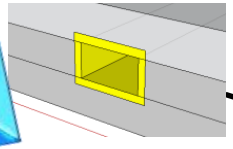


? THz micromachining revolutionizing exploitation of THz spectrum ?

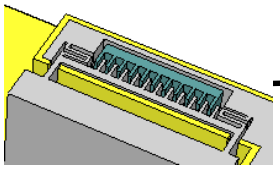
Micromachining & MEMS enabling new ways of building THz components and systems



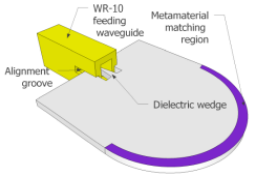
1000x smaller
1000x lighter
100x lower cost
10x less power consumption
reconfigurable
volume-manufacturable

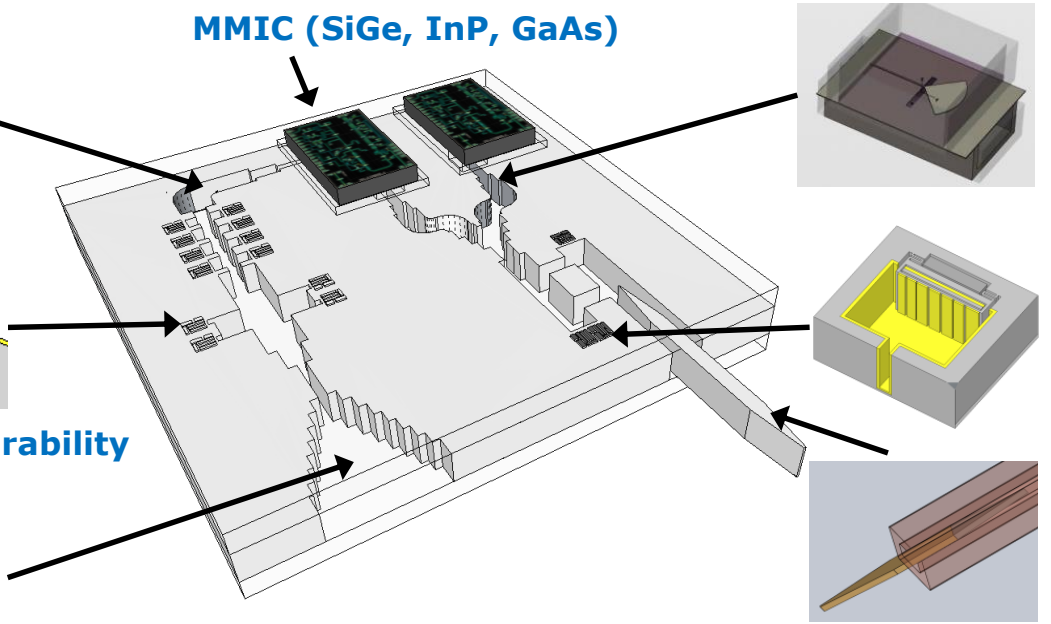


up to 2.5 THz



MEMS reconfigurability





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

Key players in micromachining for THz

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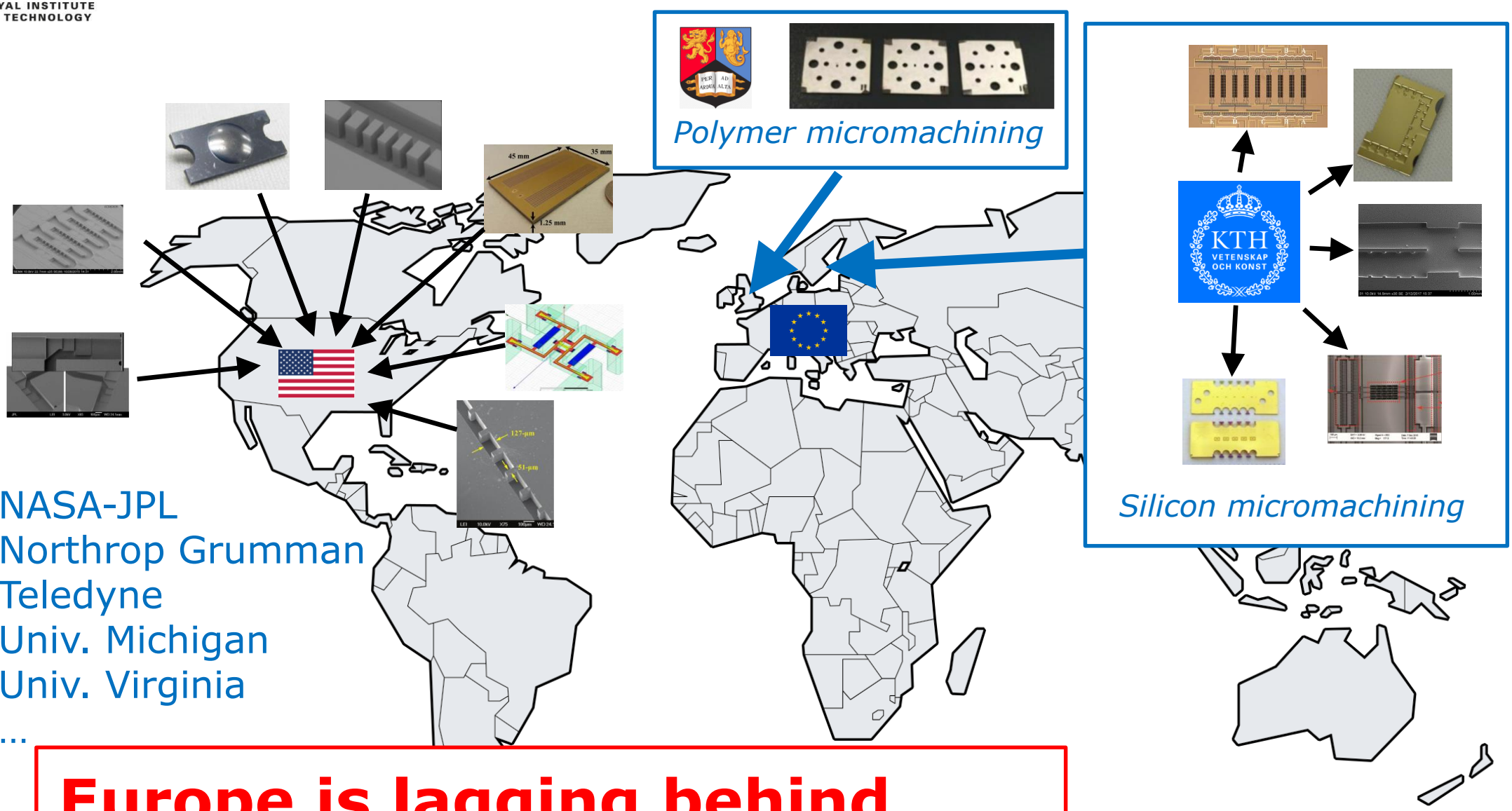

- NASA-JPL
- Northrop Grumman
- Teledyne
- Univ. Michigan
- Univ. Virginia
- …

Europe is lagging behind …

Where is Europe?

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Recent examples of
micromachined sub-THz
devices&systems
at KTH Royal Institute of Technology

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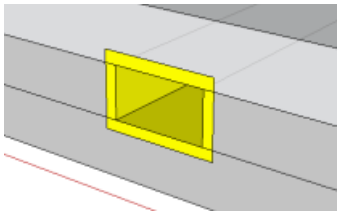
Lowest-loss sub-THz waveguide technology

enabled by micromachining

KTH's ultra-low loss 110-330 GHz micromachined waveguides at



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

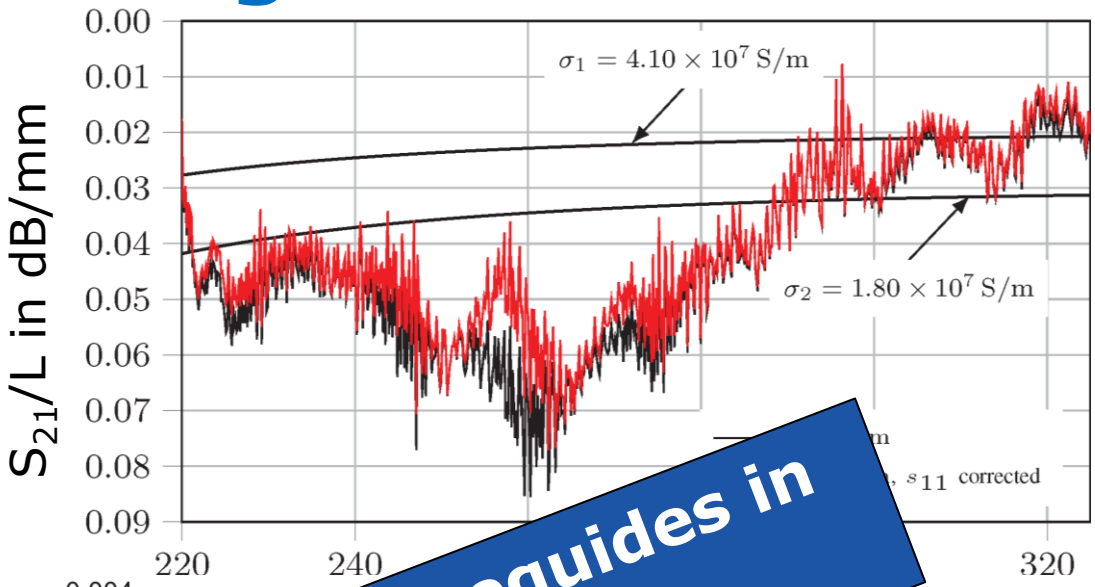
[IEEE THzSciTec 2018]

Best performance of any waveguide in these bands!

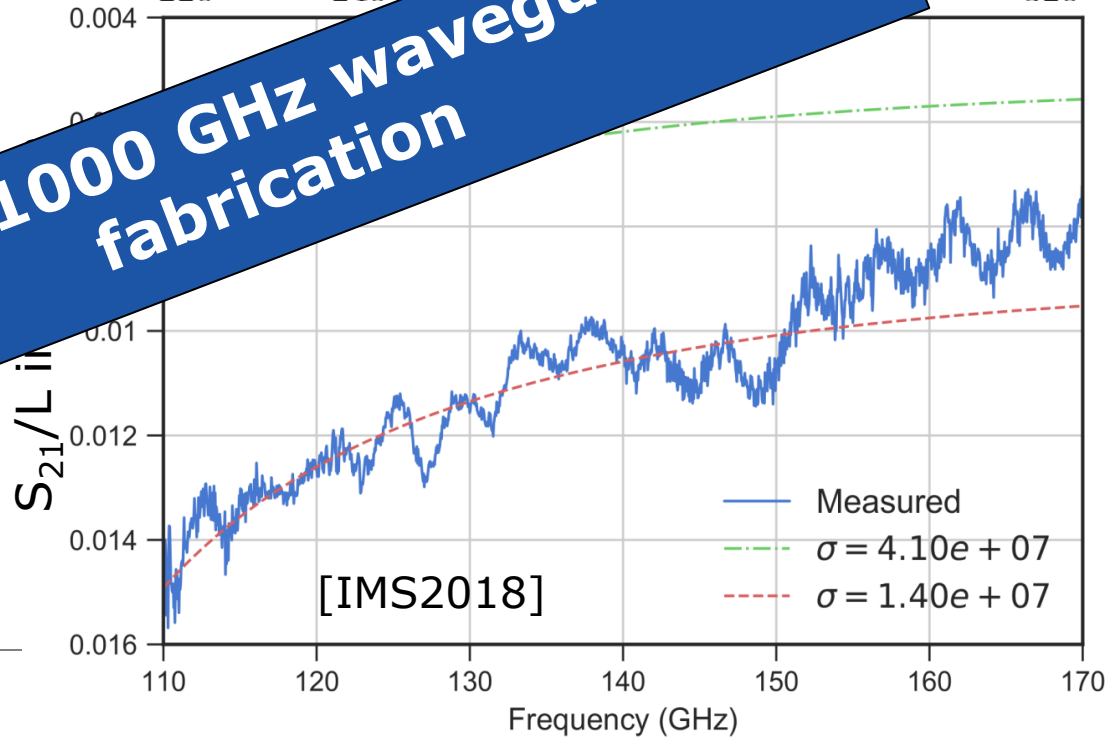
World-record high-Q_{UL} in these bands!

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

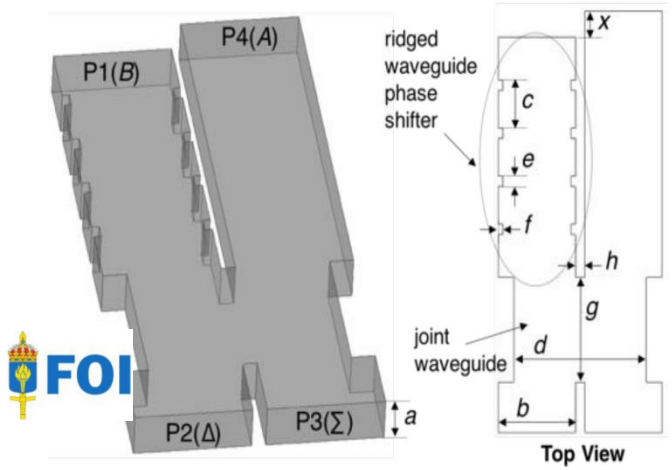
[IEEE IMS 2018]

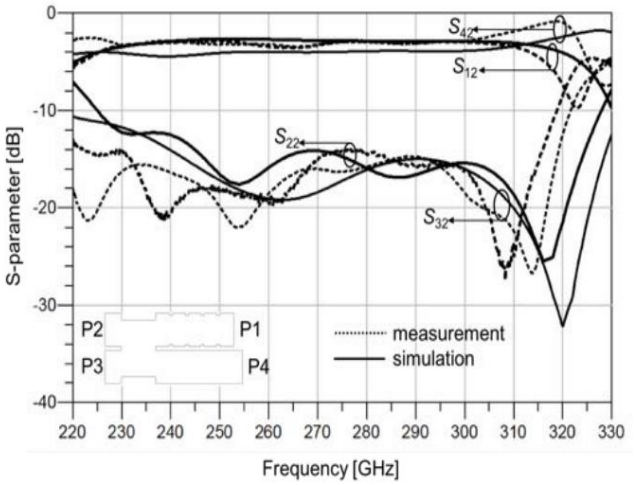


500 and 1000 GHz waveguides in fabrication



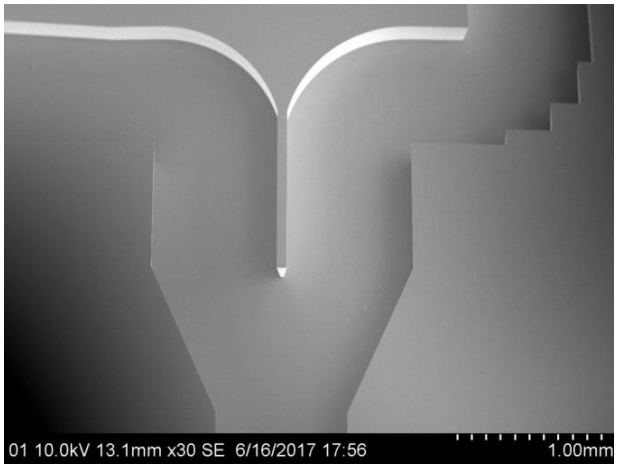
Waveguide components 220-330 GHz => building blocks for sub-THz systems

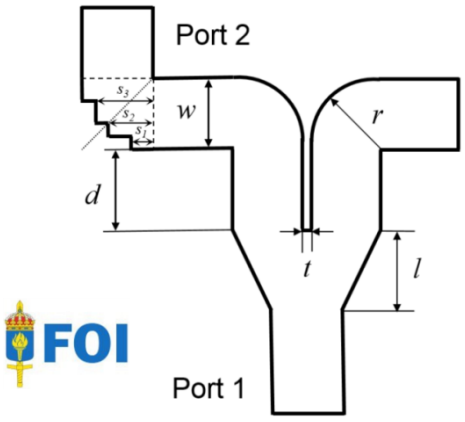




Very low loss, full-band 3-dB coupler

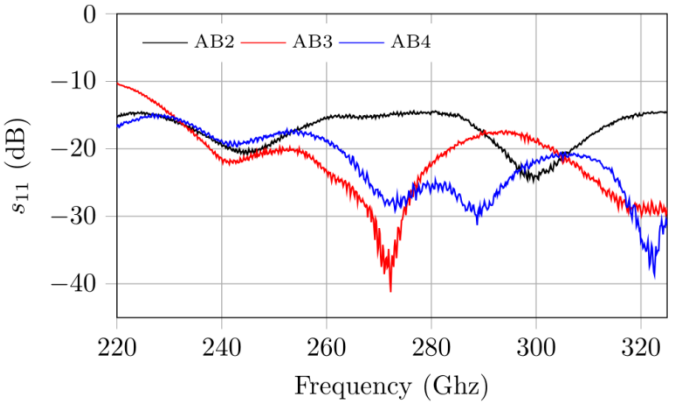
[EuMC 2017]





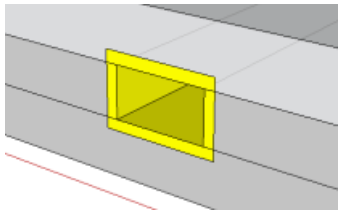
Very low loss power combiner/splitter

[APMC 2017]



Integrated matched loads, absorbers, attenuators

[EuMC 2017, IMS 2018]



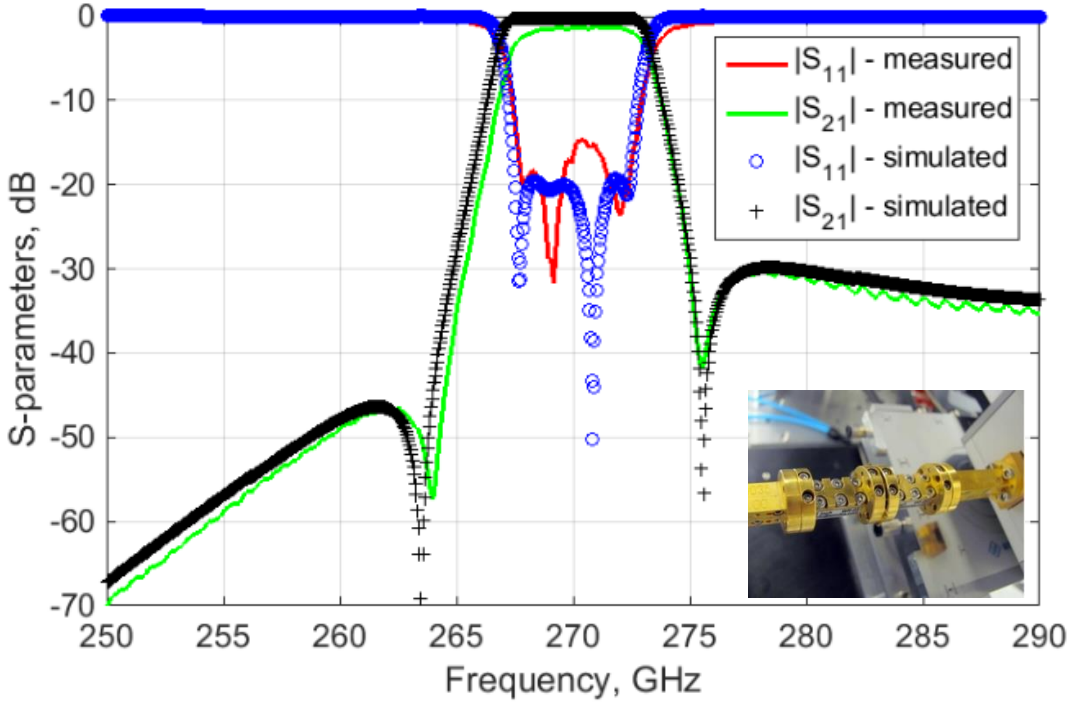
"Super low-loss" waveguides

Sub-THz filters with unparalleled Q-factors

enabled by micromachining

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

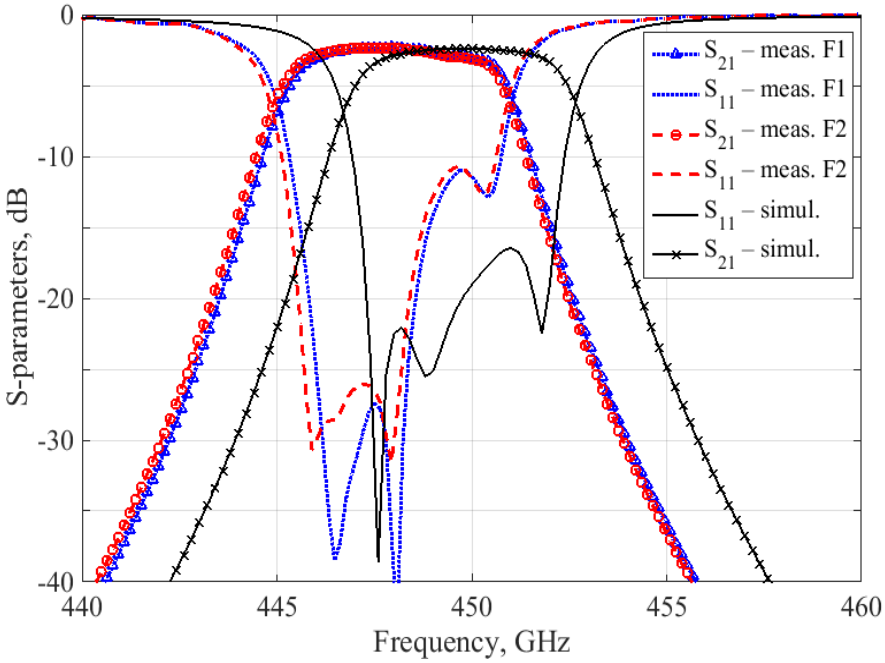
270 GHz, narrow-band:



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

[IEEE IMS 2017, IEEE TMTT 2019]

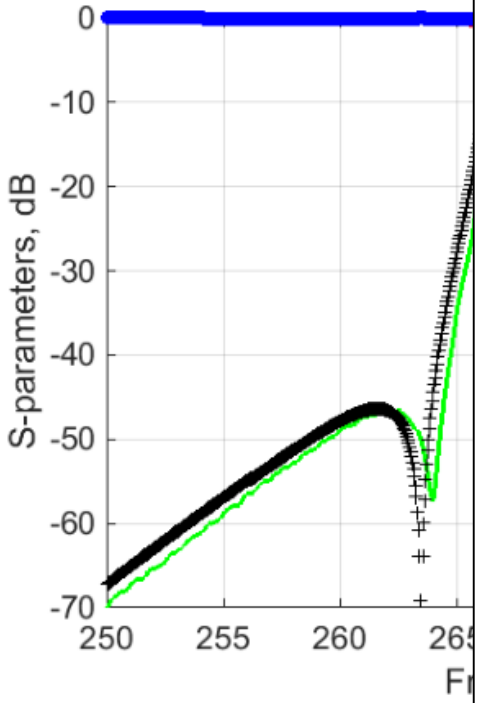
450 GHz, ultra narrow-band:



- 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

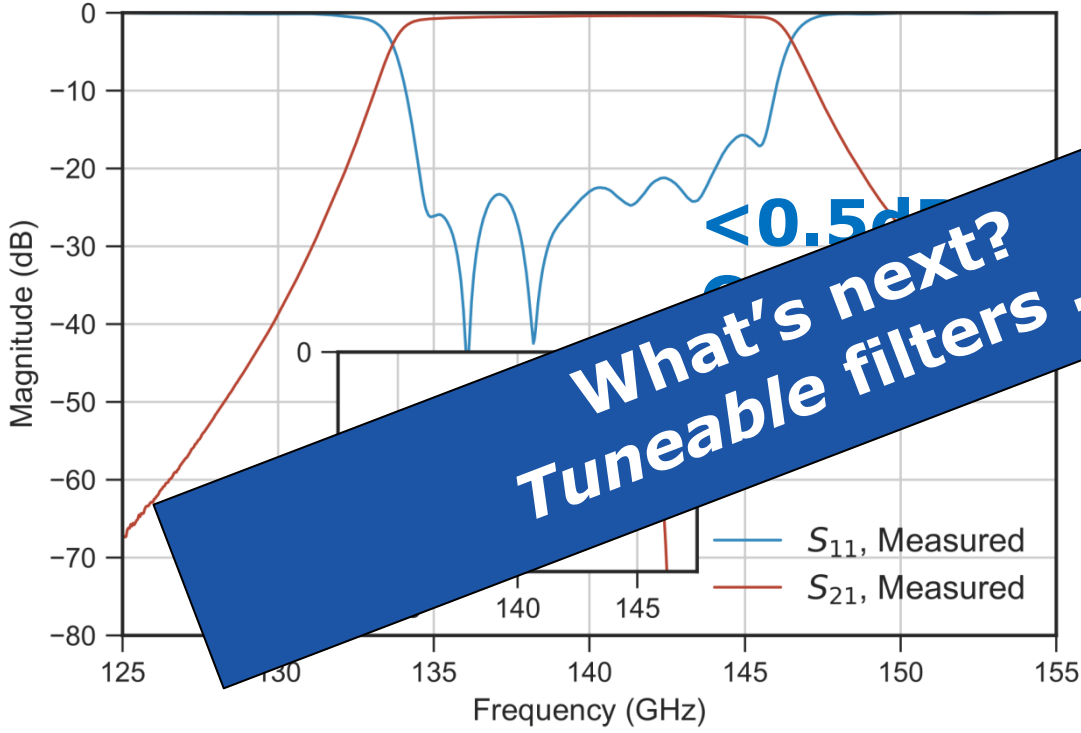
270 GHz, narrow-band:



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

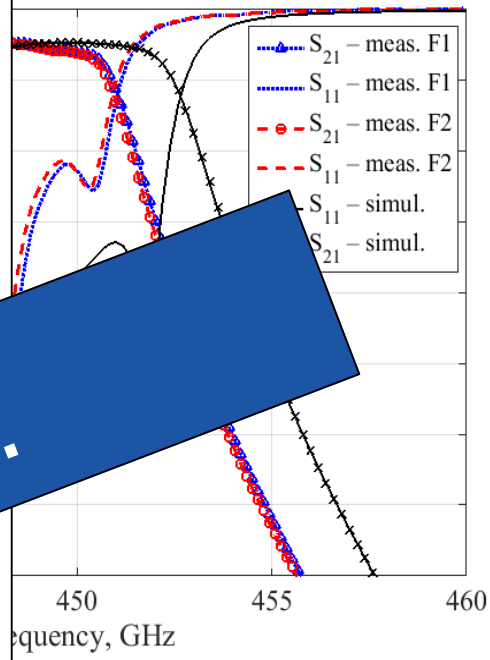
[IEEE IMS 2017,
IEEE TMTT 2019]

Wide-band example: 5.2% FBW
141-148.5 GHz telecom filter



What's next?
Tuneable filters ...

450 GHz, ultra narrow-band:



4p
IL=2.5dB
0
filter at sub-mm wave frequencies! [IEEE TSTT,2019]

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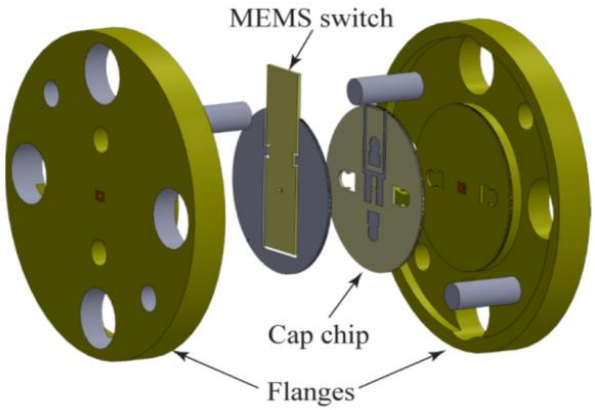
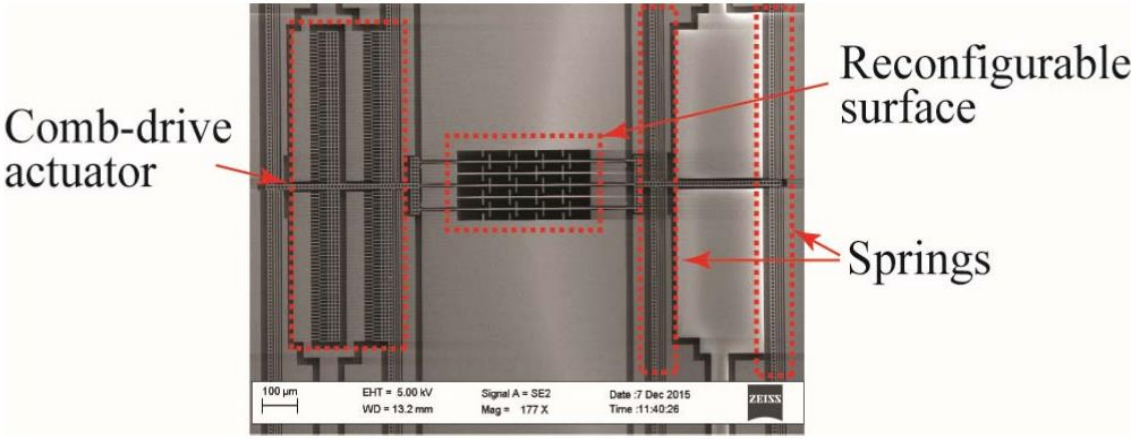
MEMS-reconfigurable sub-THz devices

enabled by micromachining

MEMS waveguide switches by KTH
(micro electro mechanical systems)

500-750 GHz switch:

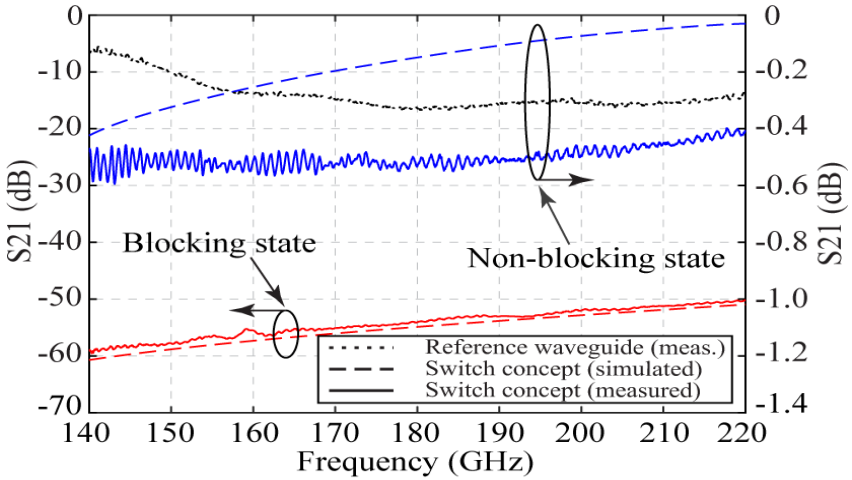




- Insertion loss: 2.5 dB
- Isolation: 18-25 dB

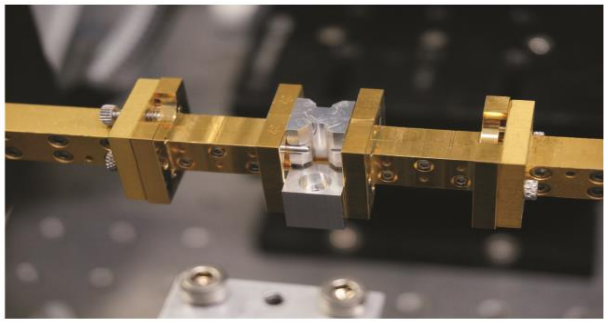
[IEEE THzSciTec 2017]

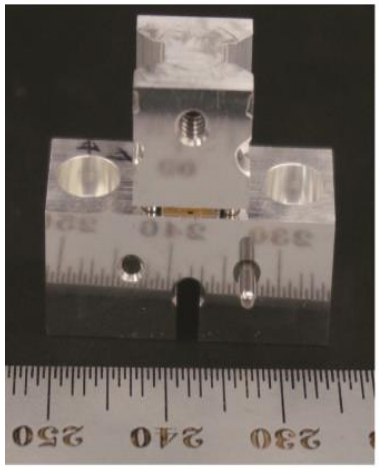
140-220 GHz switch:

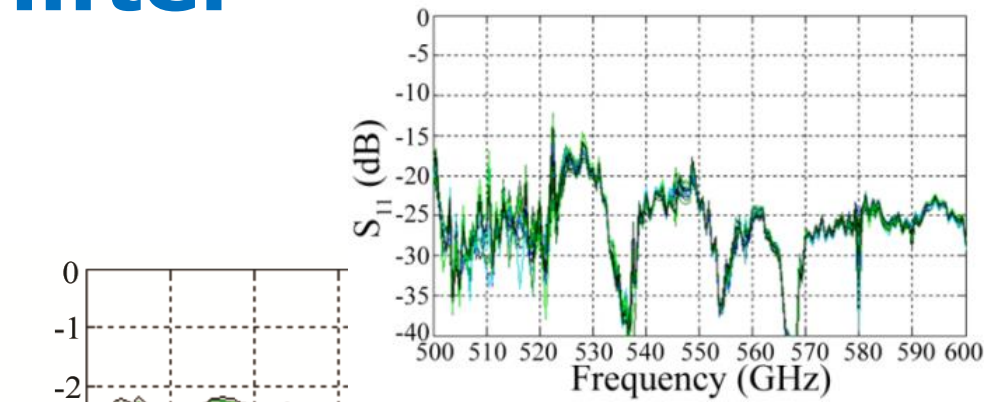


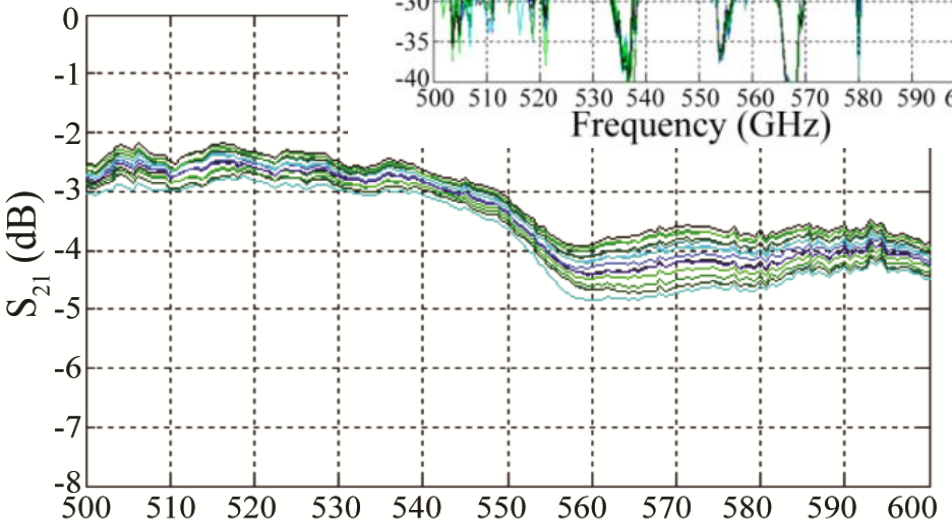
- Insertion loss: <0.6 dB
- Isolation: >50 dB
- For whole 140-220 GHz band

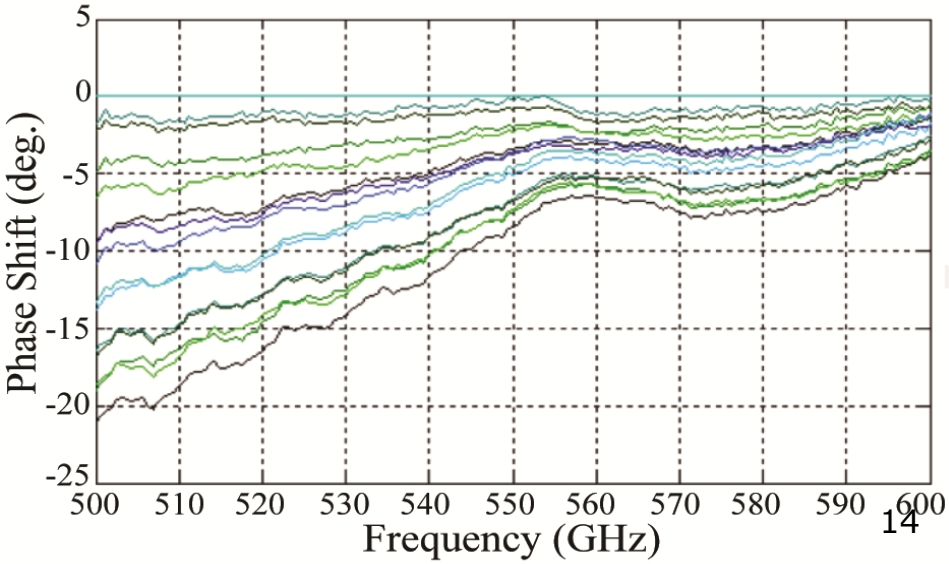
500-600 GHz 3.3 bit MEMS phase shifter











- 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]

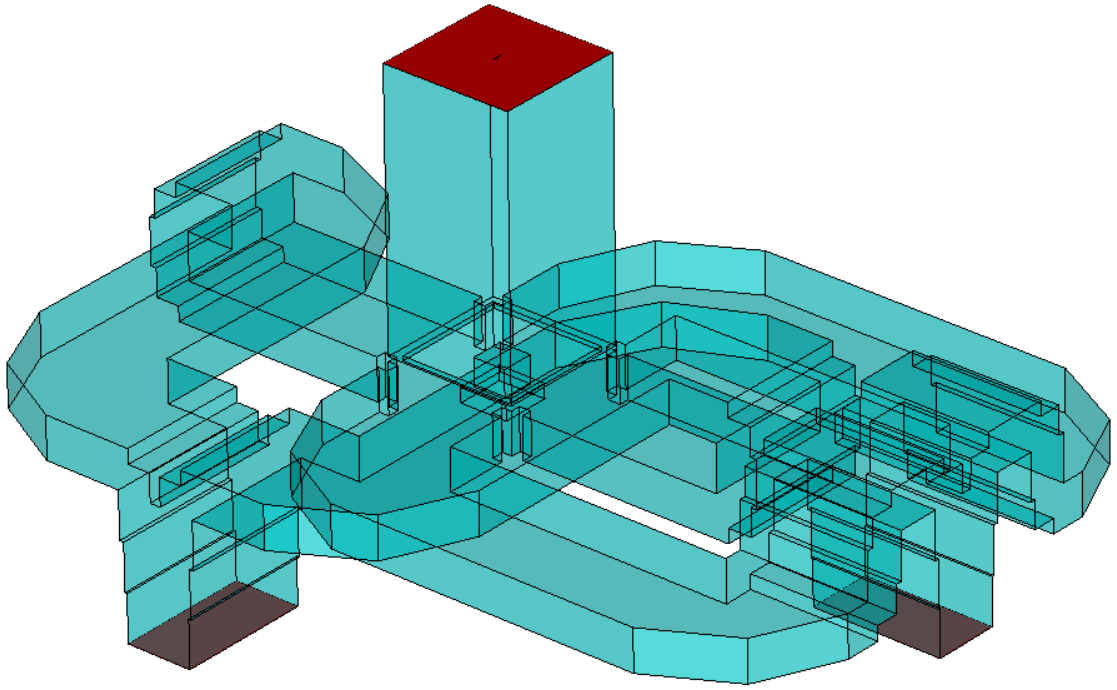
components  systems

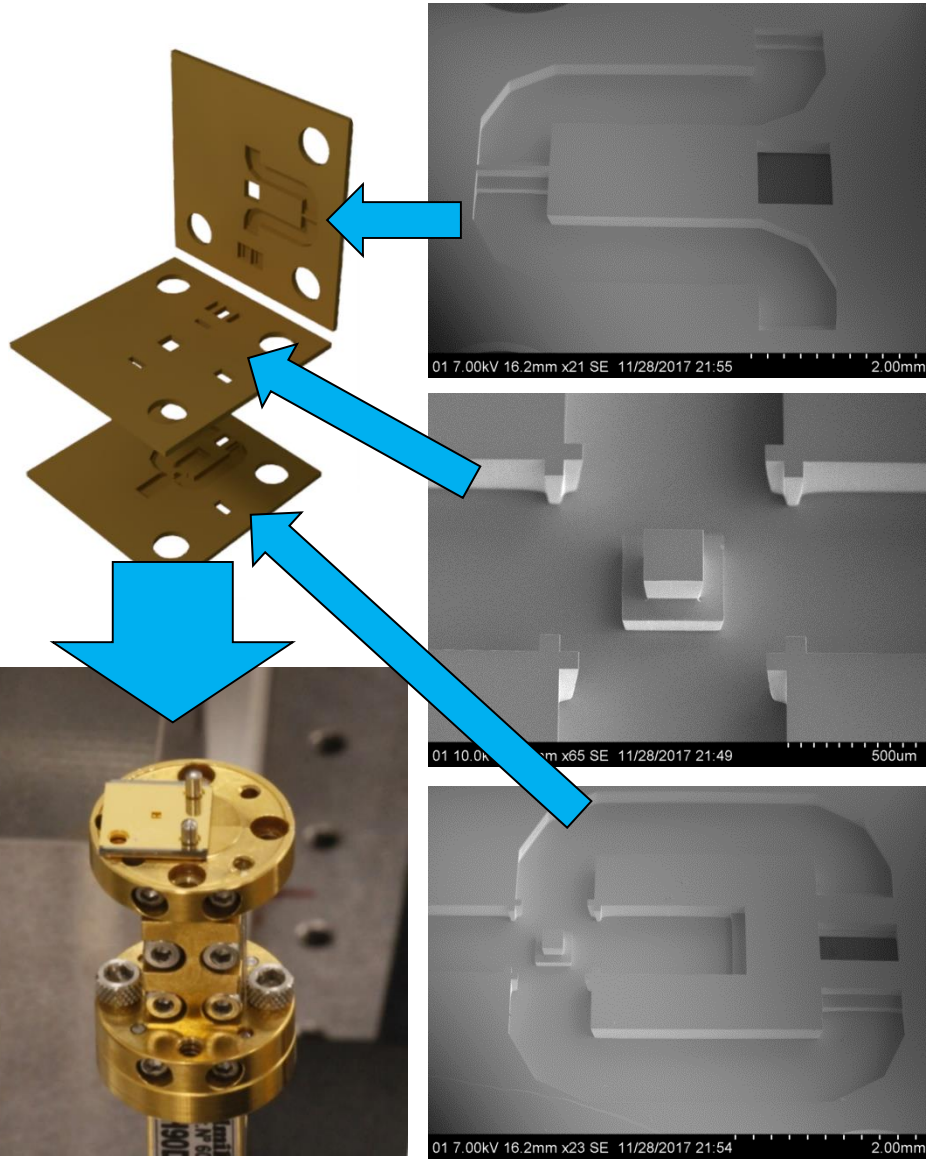
High-complexity devices and highly integrated sub-THz systems

enabled by micromachining

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

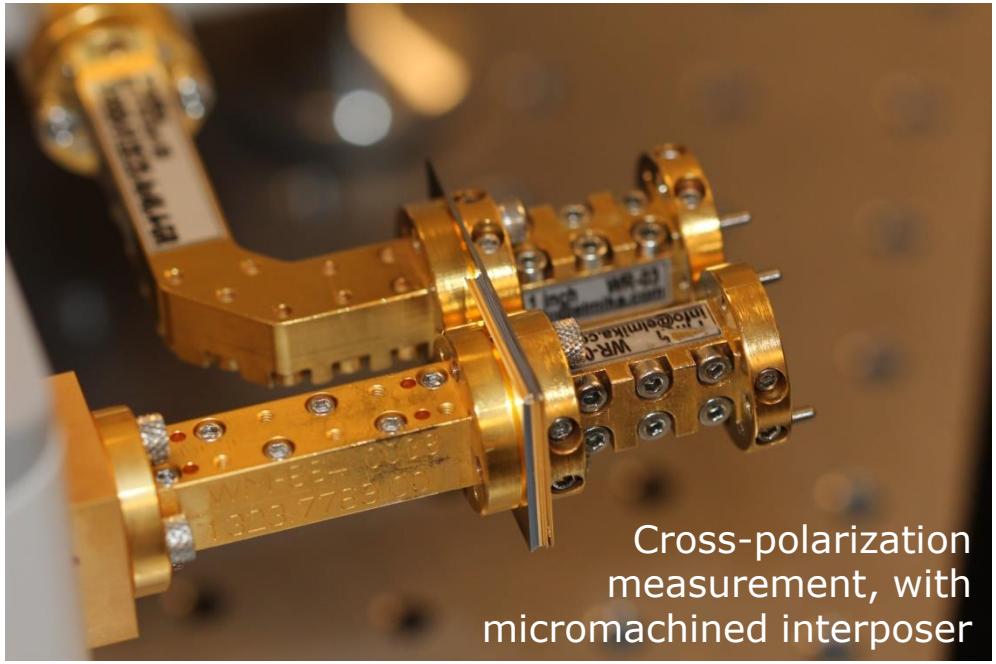
- First turnstile OMT above 110 GHz
- Micromachining enables devices at so far unreachable frequencies!
- Size only 5x5x0.9 mm^3

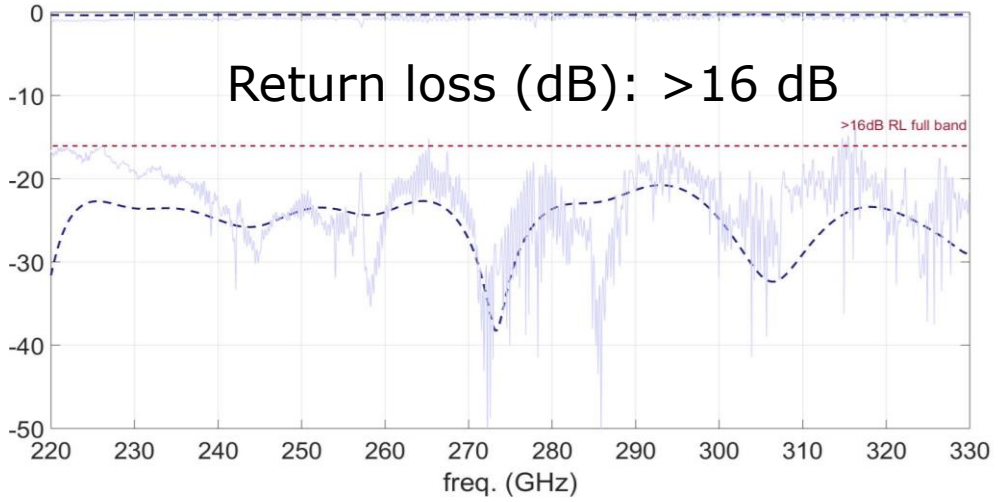


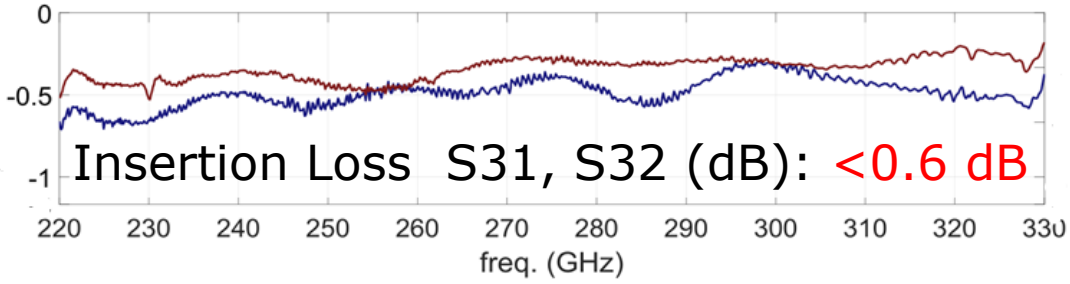


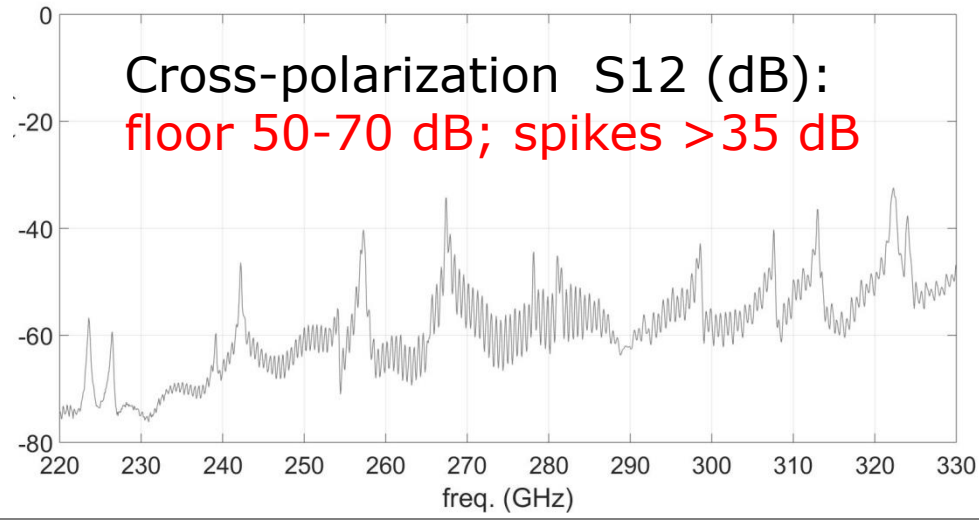
Combining very complex 3D geometries (9 etched Si layers)

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









Highly-integrated, micromachined D-band communication link

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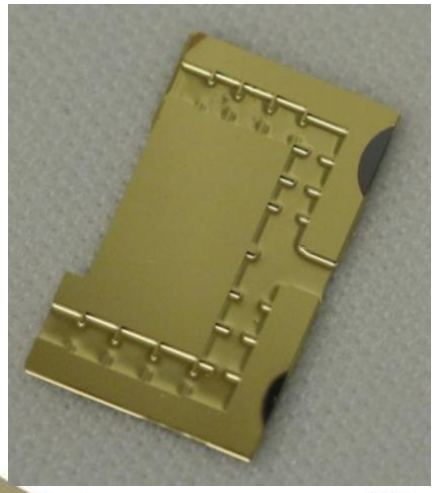

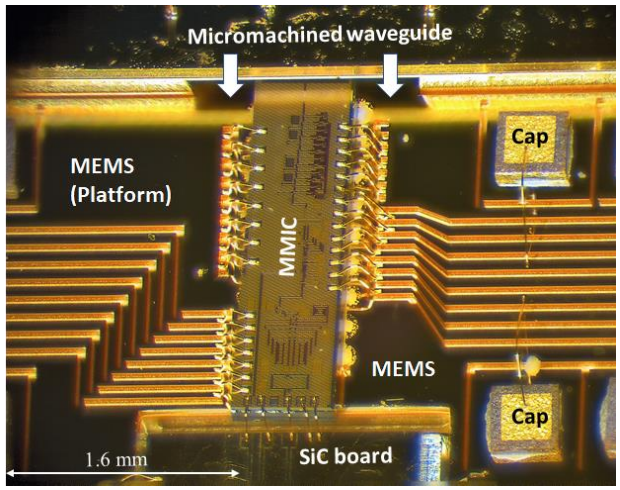

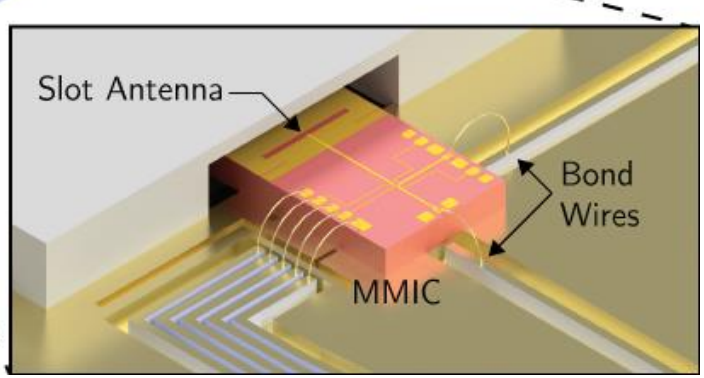

M3TERA

[unpublished]

"Moving-MEMS" for THz beam steering

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Phased (line) array based on MEMS waveguide phase shifters
- 500-600 GHz, 0-90°, 3.3bit, 2.5 dB IL
- 220-330 GHz, 0-360°

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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

238-248 GHz car radar
- Micromachined beam-steering front-end

Micromachined "pill-box" beam-steering antenna at 270 GHz

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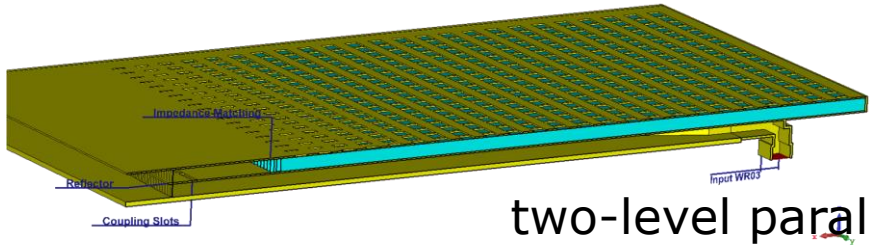
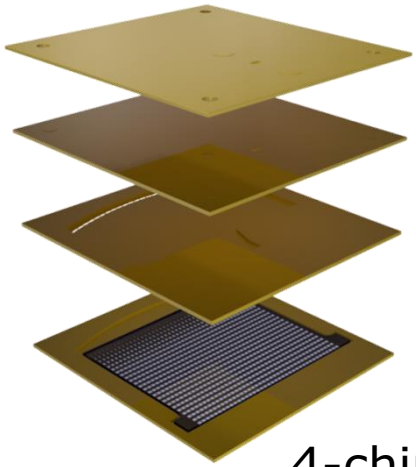
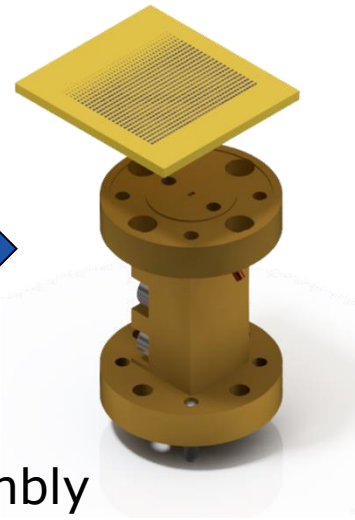
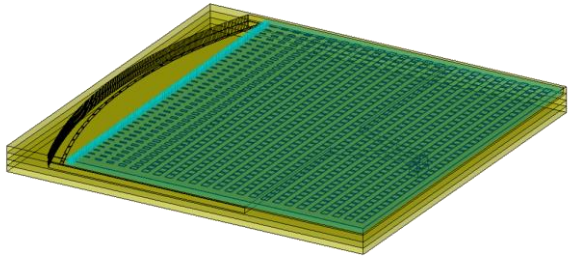


two-level parallel-plate waveguide system

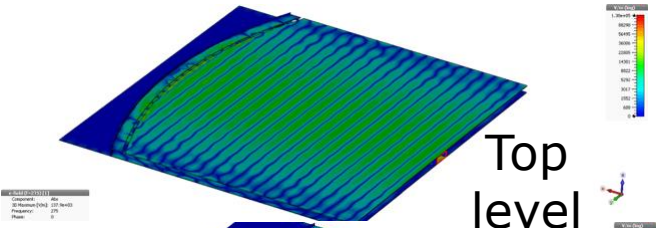




4-chip assembly



shallow, parabolic cylinder reflector



Top level

Bottom level

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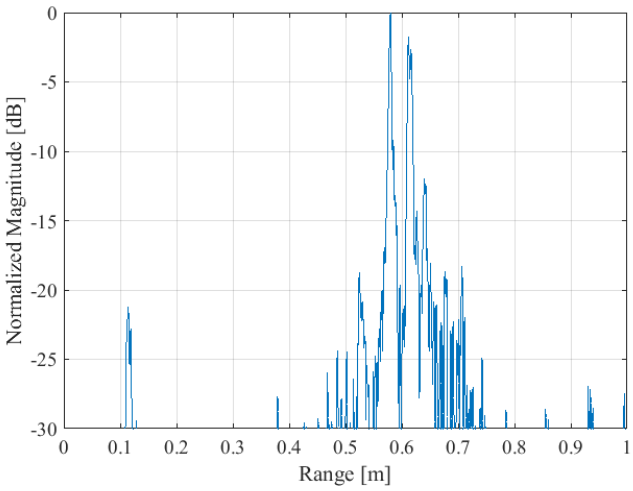
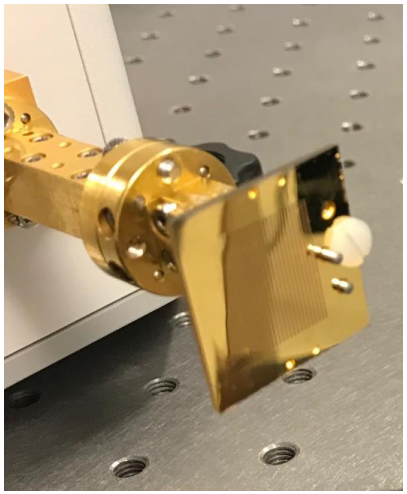
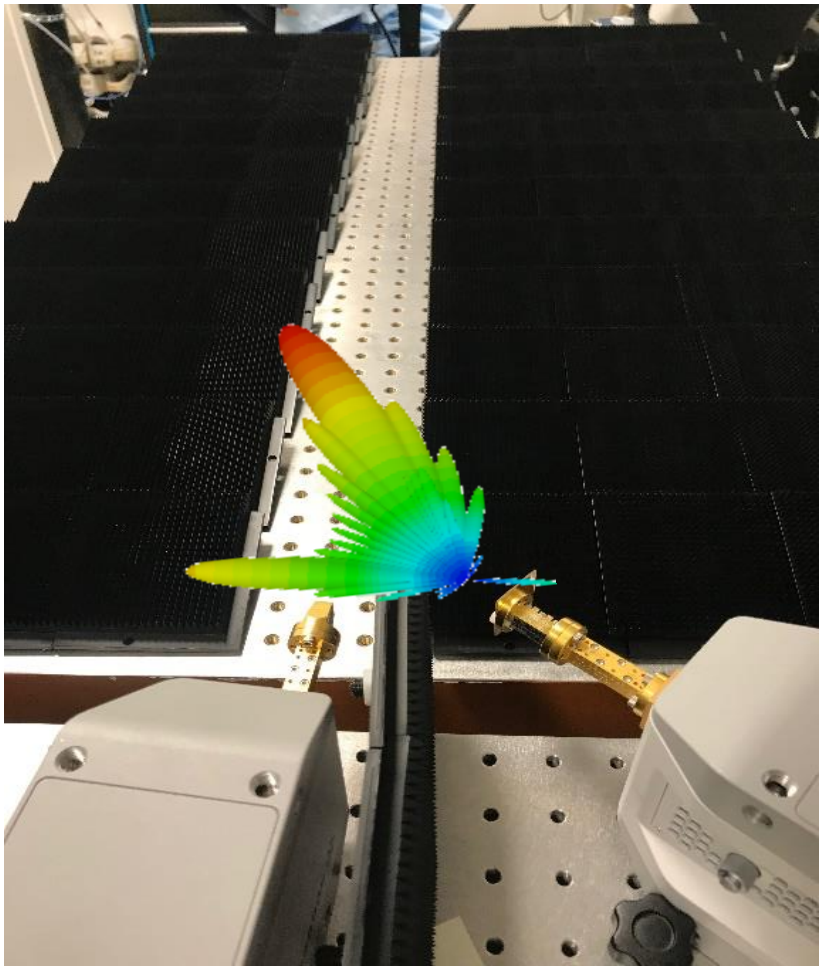
Micromachined "pill-box" beam-steering antenna at 270 GHz

Micromachined radar front-end:

- 20 x 20 x 0.9 mm^3
- 220..300 GHz freq. sweep, 20..75° scanning (55° FoV) 3.5-10° HPBW
- <1.5 cm range resolution *at* <10° angular resolution







Challenges & Conclusions

- THz system integration:
  - *bottleneck* for *large-scale exploitation* of THz frequencies!!!
  - a system needs many components around the active circuits
- micromachining: an enabling technology for high performance, miniaturized, volume-manufacturable sub-THz systems:
  - high miniaturization, very low loss, very small tolerances
  - high product uniformity, volume manufacturable, very low cost in high volume

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