3D screen printing for high frequency devices implemented in Groove Gap Waveguide technology

Assessments to Prepare and De-Risk Technology Developments Framework (G617-241TA)

ESA A0/1-10537/20/NL/BJ

- Project Partners:
  - Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Dresden Germany
  - Chair of Microwave Engineering, Kiel University, Germany
- Project duration: 9 months
- Budget: 186.000€

Outline

AM @ Fraunhofer IFAM Dresden

MoldJet

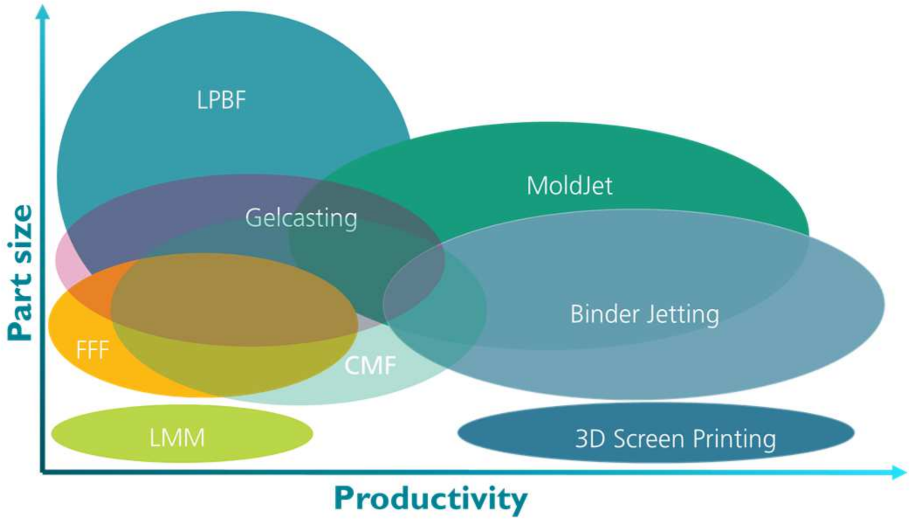
3D Screen Printing

FFF

LMM

PBF-EB

Gelcasting

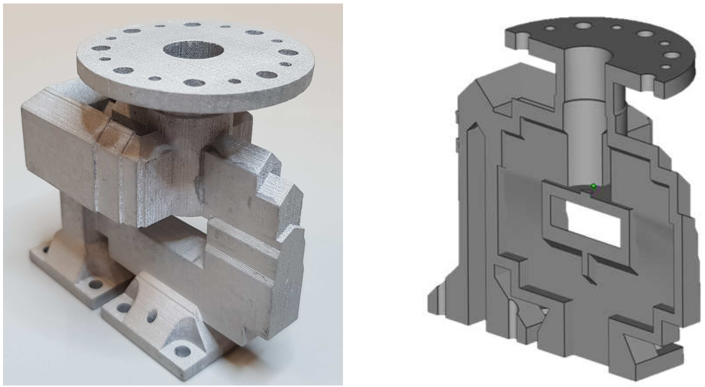


Our background / offer:

- **Material choice / Process development**
- **Material characterization**
- **Component Design / Simulation**
- **TCO analysis**
- **Transfer to industrial partners**

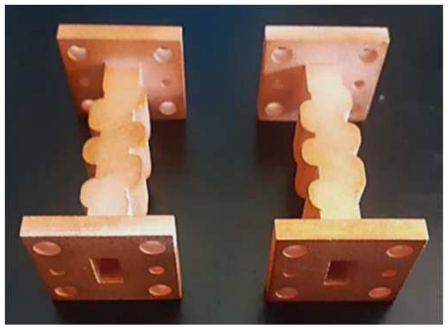
AM @ Fraunhofer IFAM Dresden, RF Applications

Orthomodal Transducer



Slotted Antenna

KA-Stop Band Filter



Horn Antenna

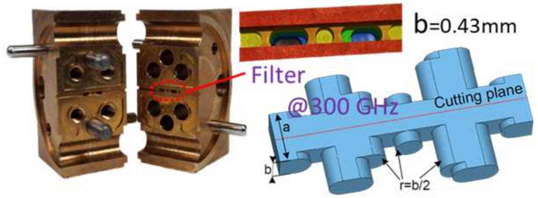
Kiel University – Chair of Microwave Engineering

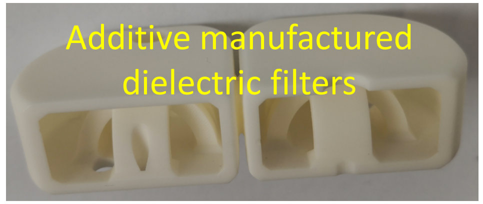
Head of Microwave Group:

Prof. Dr.-Ing. Michael Höft

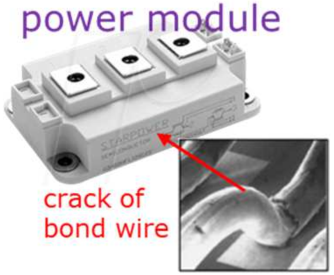
Fields of Research

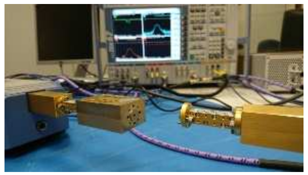
- Radar Applications
- Microwave Filters and Sensors
- Magneto-electric Sensors
- Components at Sub-mm and Terahertz Frequencies

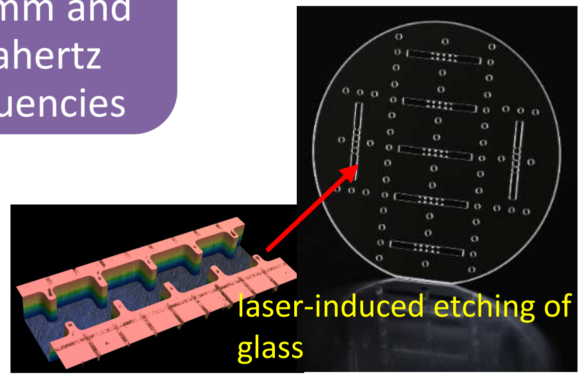




TDR meas. of power module



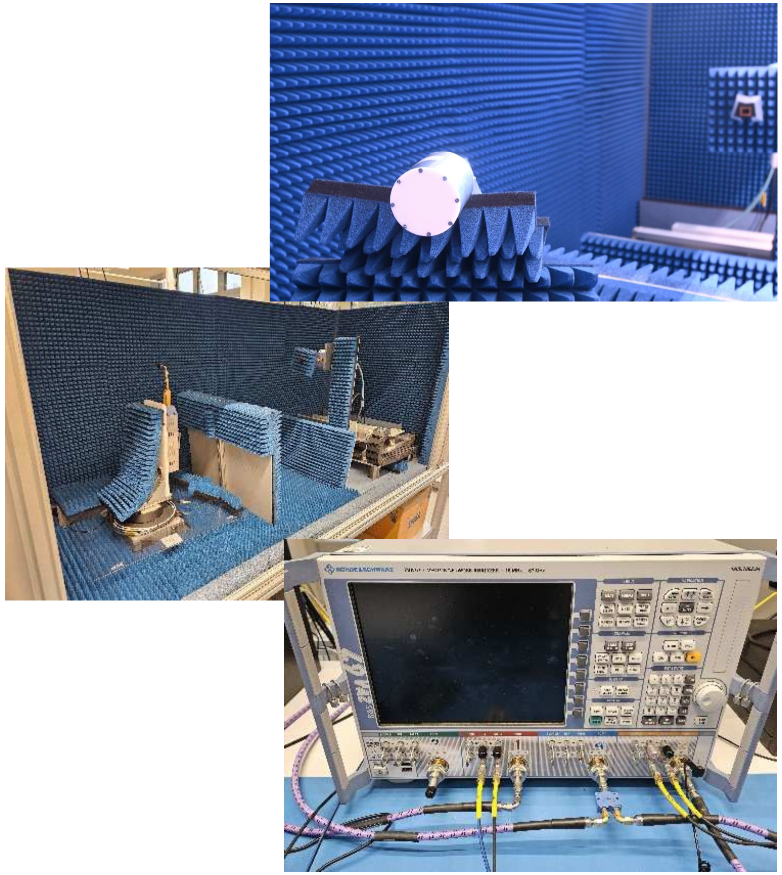




Kiel University – Chair of Microwave Engineering

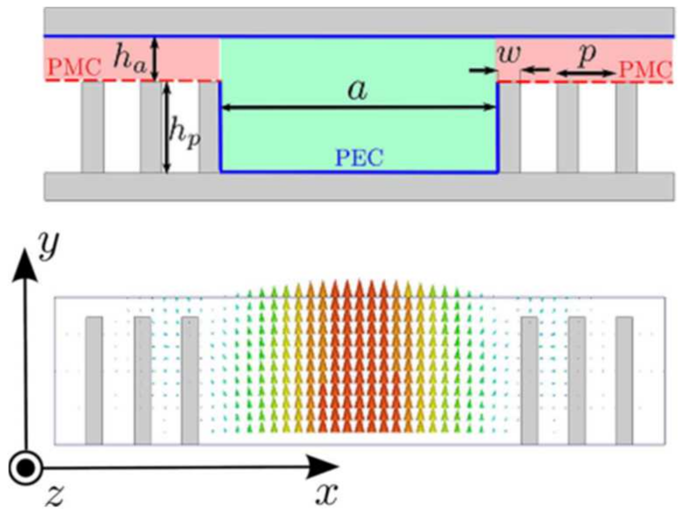
Facilities

- Measurement setup including network analyzers and frequency converters (10 MHz to 500 GHz)
- Spectrum and signal analyzers up to 50 GHz, Power Meter (up to 500 GHz)
- Workshop of technical faculty with high-precision CNC machine for manufacturing of sample holders
- Clean room
- Antenna anechoic chamber (3x5 m, absorbers specified from 300 MHz up to 110 GHz)
- Photo lithography laboratory
- Simulation tools: CST microwave studio, Agilent ADS/Momentum, Ansys HFSS (all as rented software with research licenses)



Motivation

- Groove Gap Waveguide (GGW) structures consist of two parts:
  - Periodic pin structure providing EM functionality
  - Flat cover
- Cover has no contact to pin structure
- PMC between pin and cover (for $h_a < \lambda/4$)
- PEC at inner pin row / cover

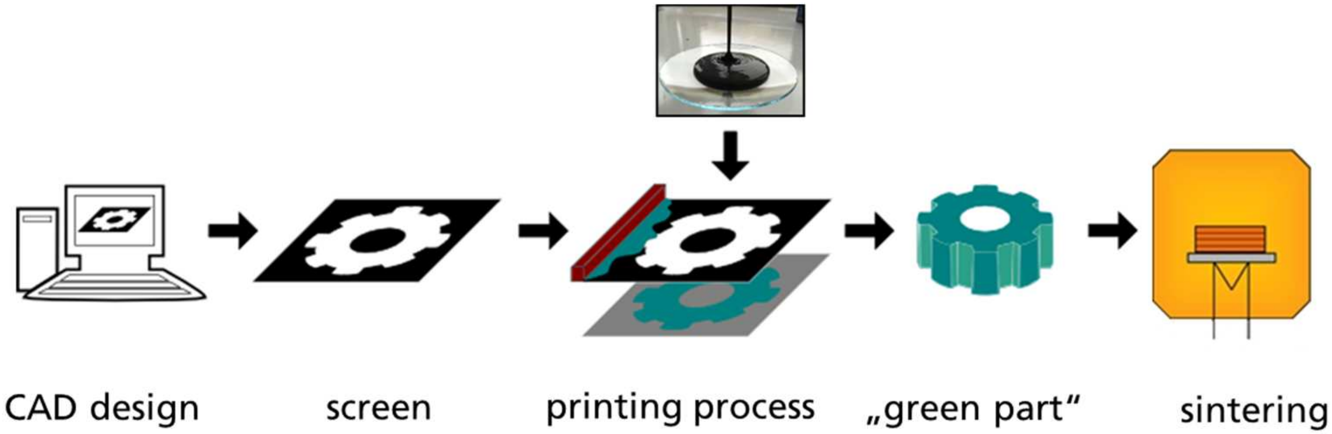


A. Berenguer et al., "Propagation Characteristics of Groove Gap Waveguide Below and Above Cutoff," in *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 1, pp. 27-36, Jan. 2016

- Advantages:
  - Imperfect material transition does not influence Q-factor
  - Reduced risk for PIM
- Disadvantages:
  - High manufacturing effort, especially at high frequencies

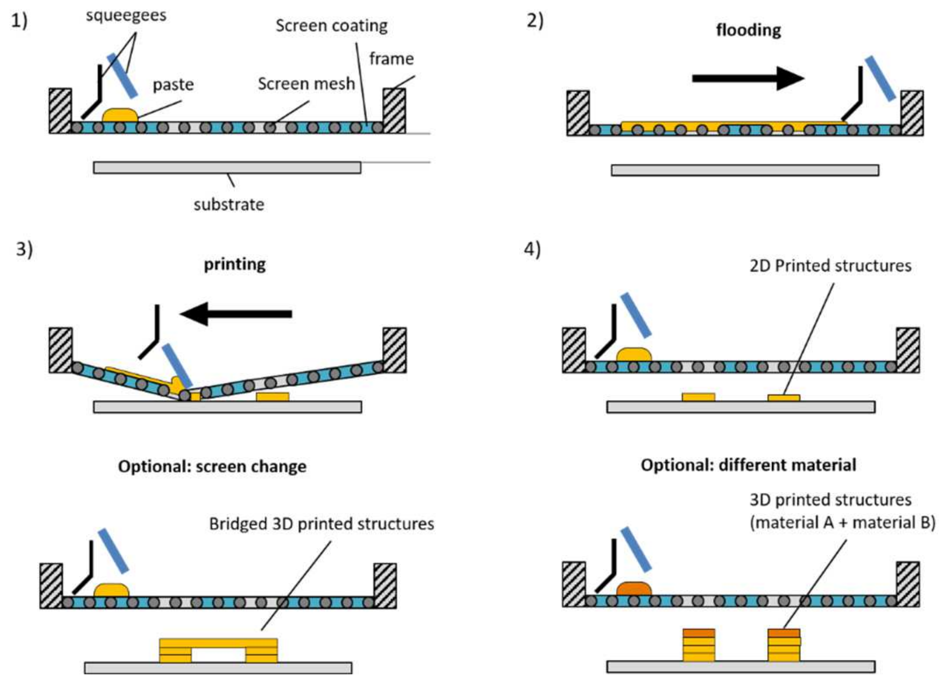
Additive screen printing to overcome this

Additive screen printing



- Additive screen printing is based on conventional 2D screen printing proces (widely used in e.g. solar industry)
- Geometry to be printed is transferred into a screen (mask)
- For each change in z-direction a new screen is necessary
- Structuring priniciple: material extrusion of a particle loaded suspension through a screen (mask)

Additive screen printing



Printing process– step by step

1. Screen is placed above a printing substrate
2. Screen is filled with printing suspension by flooding squeegee
3. Screen is pressed on to the substrate by moving squeegee
4. Printing suspension is transferred onto the substrate and dried

Process (step 1 to 4) is repeated until:

a) final height of the part is reached

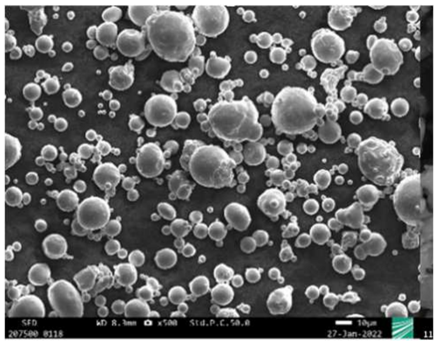
b) screen is changed (optional)

c) printing suspension is changed (optional)

Additive screen printing

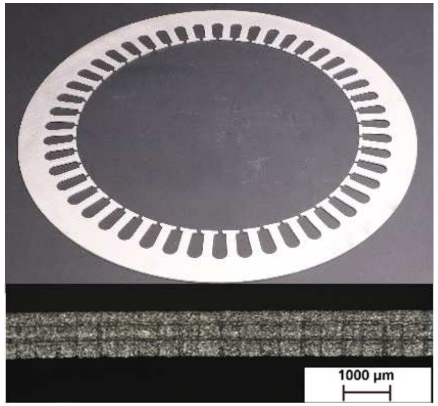
Materials

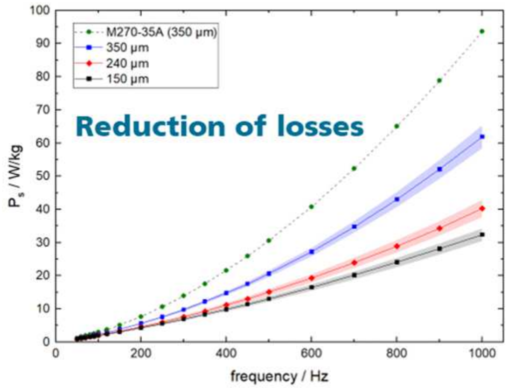
- **Spherical powders (d90 < 30 µm)**
    - Steels
    - **Soft-magnetic**
    - Copper
    - Refractories
    - Ceramics



Applications

- **Electric sheet stacks for high performance engines (Metallic-Ceramic)**





> 50%
Reduction Thickness

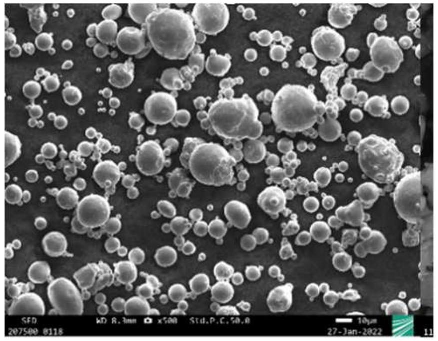
> 50%
Reduction loss of energy

~ 6%
Increase of cycle efficiency (WLTP)

Additive screen printing

Materials

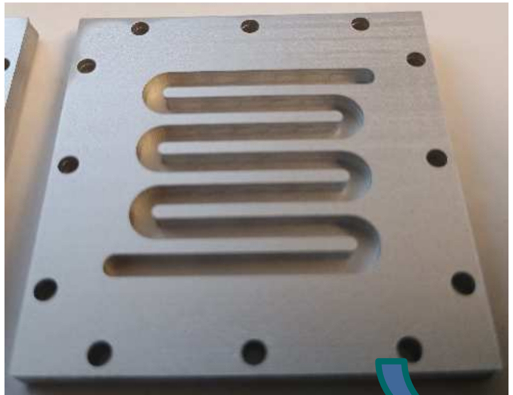
- **Spherical powders (d90 < 30 µm)**
  - **Steels**
  - Soft-magnetic
  - **Copper**
  - Refractories
  - Ceramics



Applications

- **High Performance Cold Plates for Cooling (GaN-Chips, Battery Packs)**

Conventional



Optimized

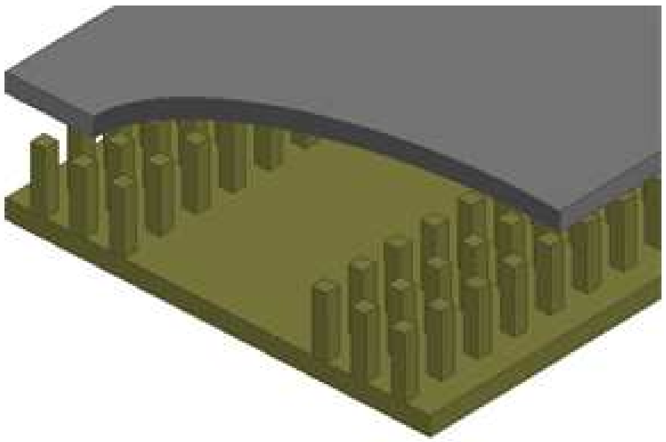
KI generated Flow fields

Optimization of pressure drop, heat exchange rate, weight

Goals of the Project

Technical goals and defined specifications:

- **Choice and development of a suitable material system with high lateral resolution**
- **Design and fabrication of a measurement setup for electrical characterization of the GGW components to be manufactured**
- **Design and fabrication of a through lines, a resonators and filters for W- (75 to 110 GHz) and D-Band (110 to 170 GHz)**

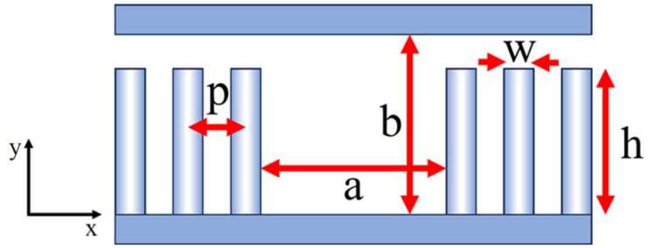


Component	Specific requirements
Resonator	Resonance frequency 90 GHz (W-Band), 140 GHz (D-Band)
Bandpass filter	3rd order, band edges: 90 and 92 GHz (W-Band), at 140 and 143 GHz (D-Band)
Through line	25 dB return loss

Realization of GGW Parts - Design

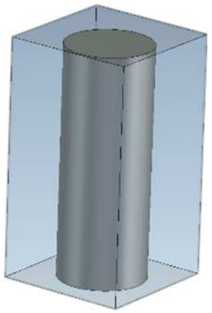
Groove Gap Waveguide Design

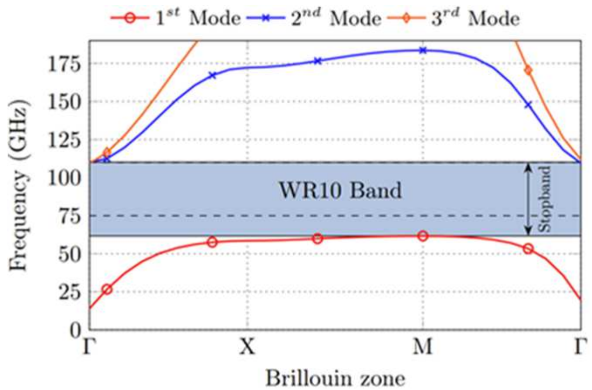
- Cylindrical pins to avoid sharp edges (critical for thermal post-processing)
- Three rows of pins with p < λ/2
- Gap between pins and cover < λ/4
- Identical design for W-Band (75 to 110 GHz) and D-Band (110 to 170 GHz) with different dimensions
- Dimensioning of the pins by investigation of the periodic unit cell to avoid propagating modes in the W- or D-Band

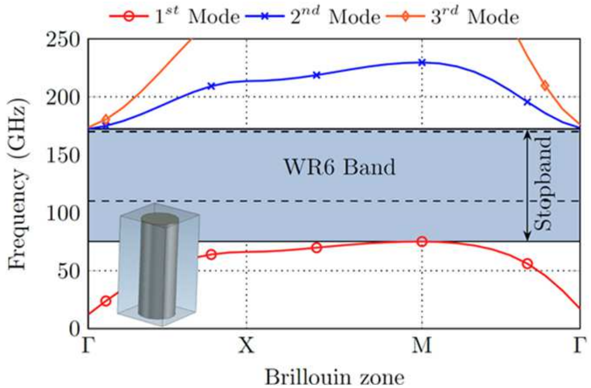


Frequency Band	a [mm]	b [mm]	h [mm]	p [mm]	w [mm]
W-Band	2.54	1.27	1.1	0.55	0.35
D-Band	1.651	0.8255	0.79	0.45	0.3

Unit cell

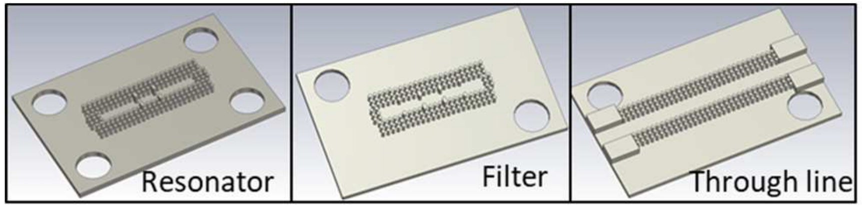


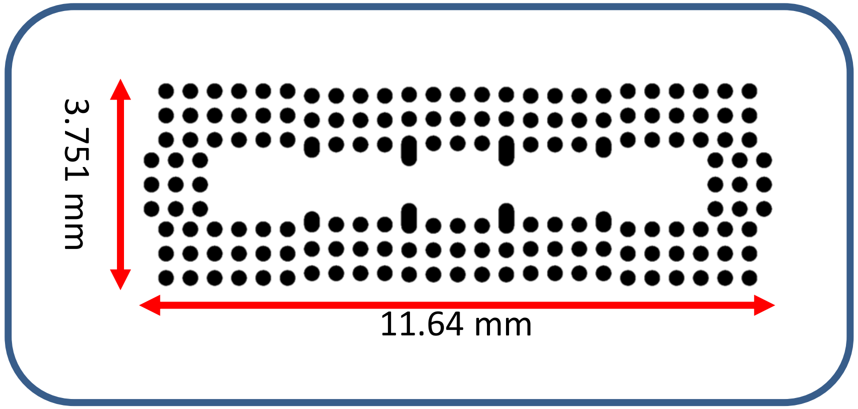




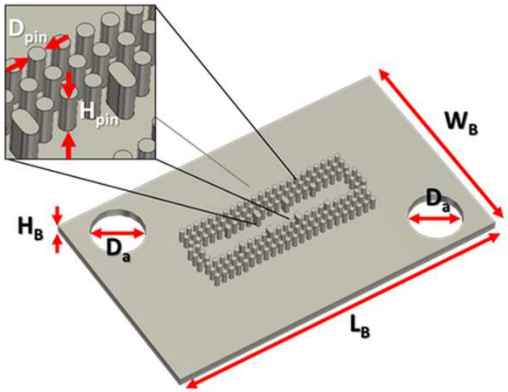
Realization of GGW Parts - Design

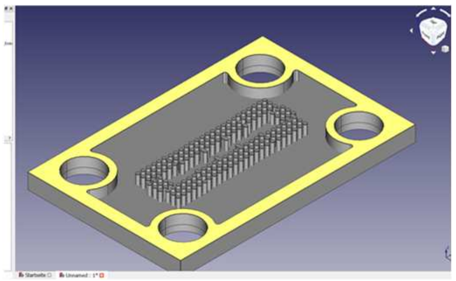
- Base plates with identical dimensions für W- and D-Band
- Three different components: 3rd order filter, resonator, through line
- I/O coupling from the top for filters and resonators (for through lines from the side)
- Coupling apertures realized by elongated pins
- Final iteration with stiffening frame



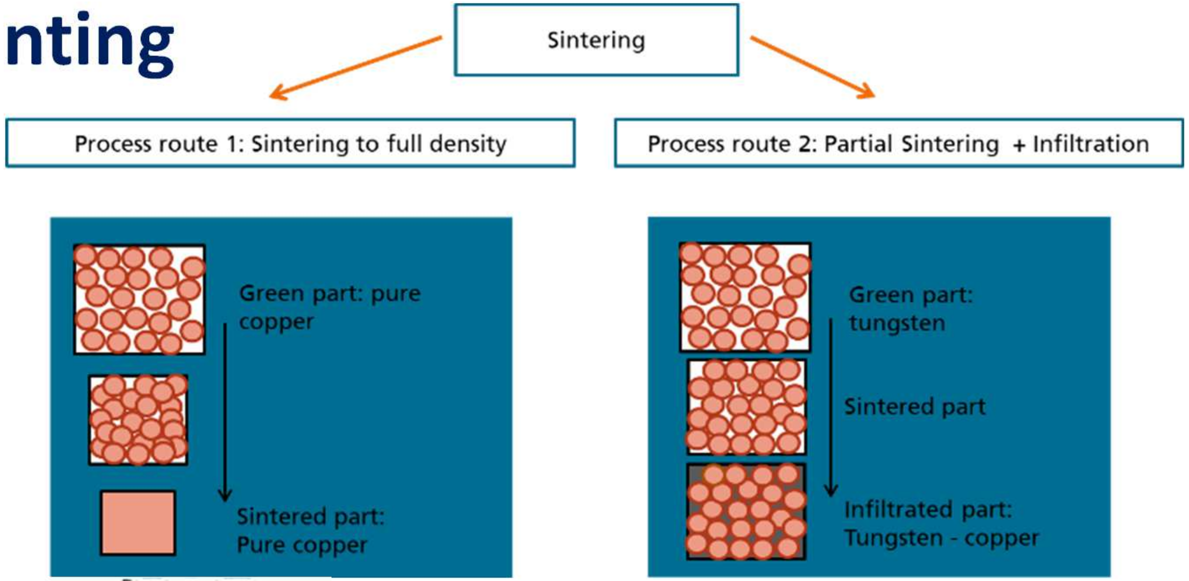


Top view 3rd order D-Band filter.

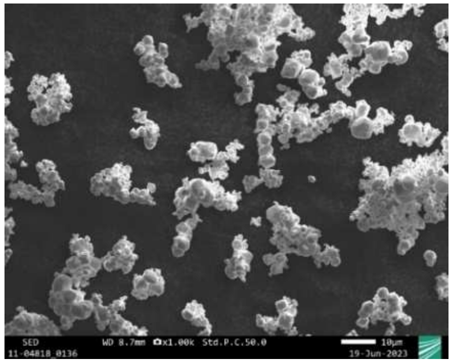




Realization of GGW Parts - Printing



- **Specification:**
  - Manufacturing accuracy (x-y-direction) : +/- 15 µm
  - Manufacturing accuracy (z-direction): +/- 10 µm
  - Surface Roughness: Ra < 3 µm
- **Materials-System: Tungsten Copper**

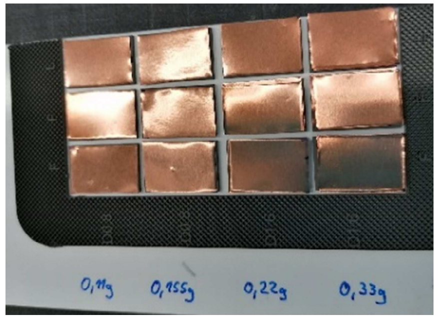


Tungsten powder

screen

Printer

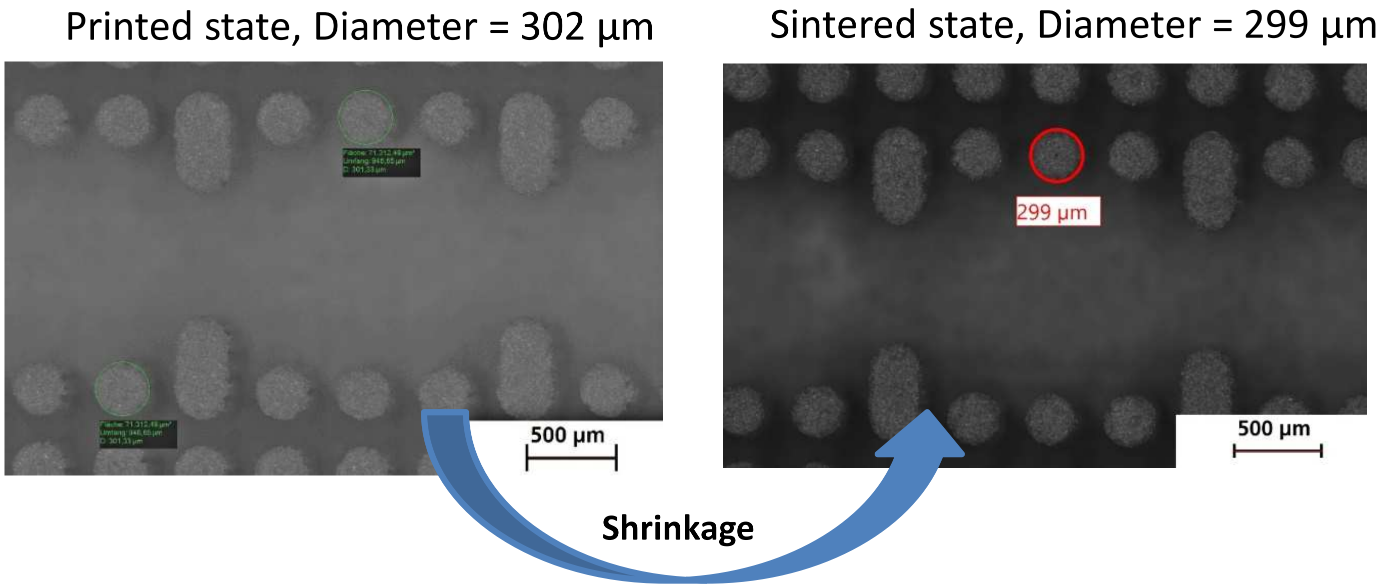
Printed parts



Printed parts

Realization of GGW parts: Example D-Band Components

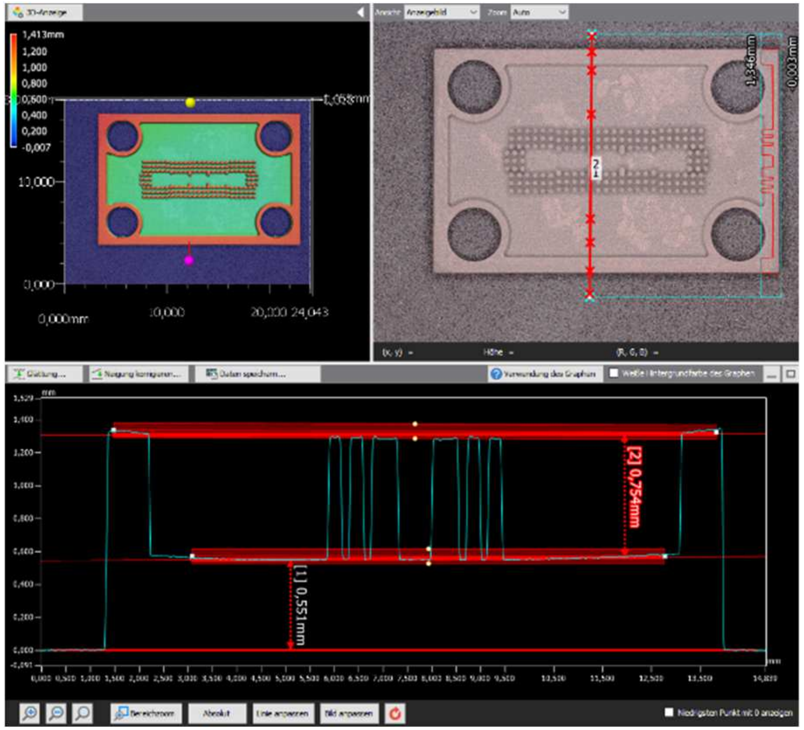
- **Heat treatment: 1200°C, pure hydrogen**



- **Uniform shrinkage (x,y,z)**
- **High precision requires exact enlargement of the screen layout which compensates the shrinkage**

Properties of GGW parts- Example D-Band components

- **Geometrical characterization, Filter**

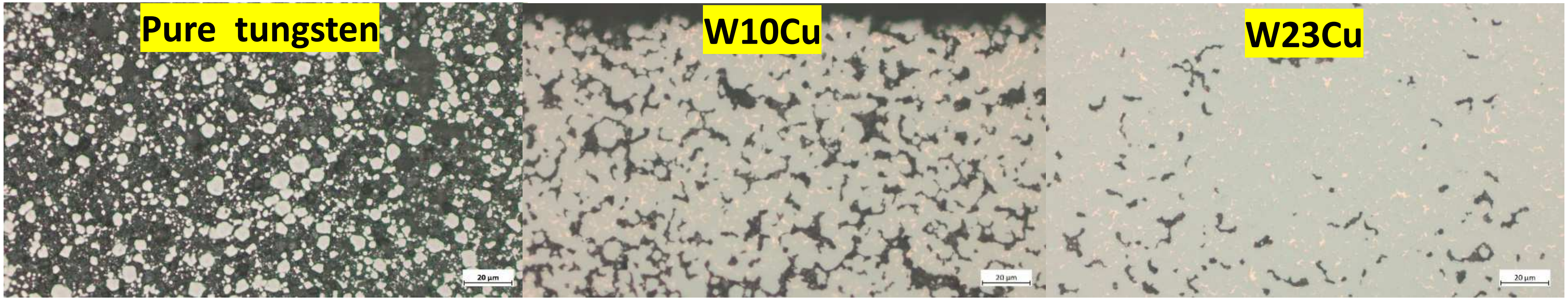


Iteration	Pin diameter Dpin [µm]	Surface roughness Ra [µm]	Pin height [mm]
Target values	300	<4	0.79
1st	291-292	2.4 to 4	0.744
2nd	301-302	2.8 to 3.9	0.754

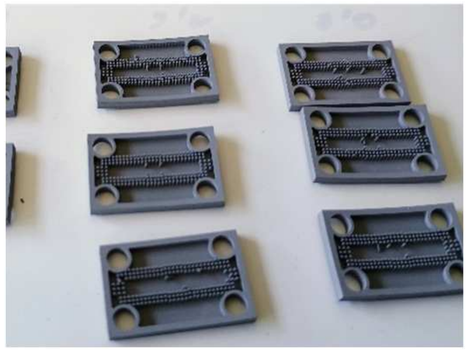
- **Adjustment of screen dimensions allows high precision parts**
- **Good surface quality**
- **Deviations of pin height observed (measurement issue of the printer)**

Properties of GGW parts- Example D-Band components

- Microstructure after sintering



Infiltration with 0.05 mm Foils

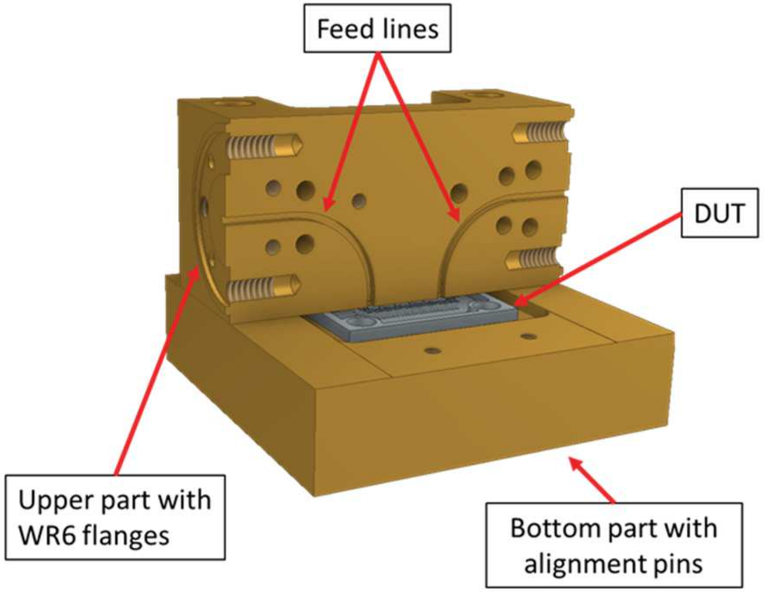


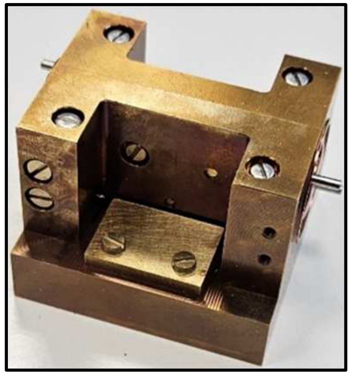
- Green density determines maximum amount of copper (powder, suspension)
- Shrinkage rate depends on amount of copper infiltrated (4% for nearly dense parts)
- Copper foil quality important (oxygen content) → deformations

Properties of GGW Parts

Measurement Setup for Electrical Characterization

- Setup for characterization of resonators and filters
- Made of brass
- Upper part with feed lines and waveguide flanges manufactured in E-plane cut for I/O coupling from the top
- Lower part contains the GGW structure
- Tapered alignment pins
- Integration of recesses and clamping plates
- Identical Design for W- and D-band (with different dimensioned feed lines)

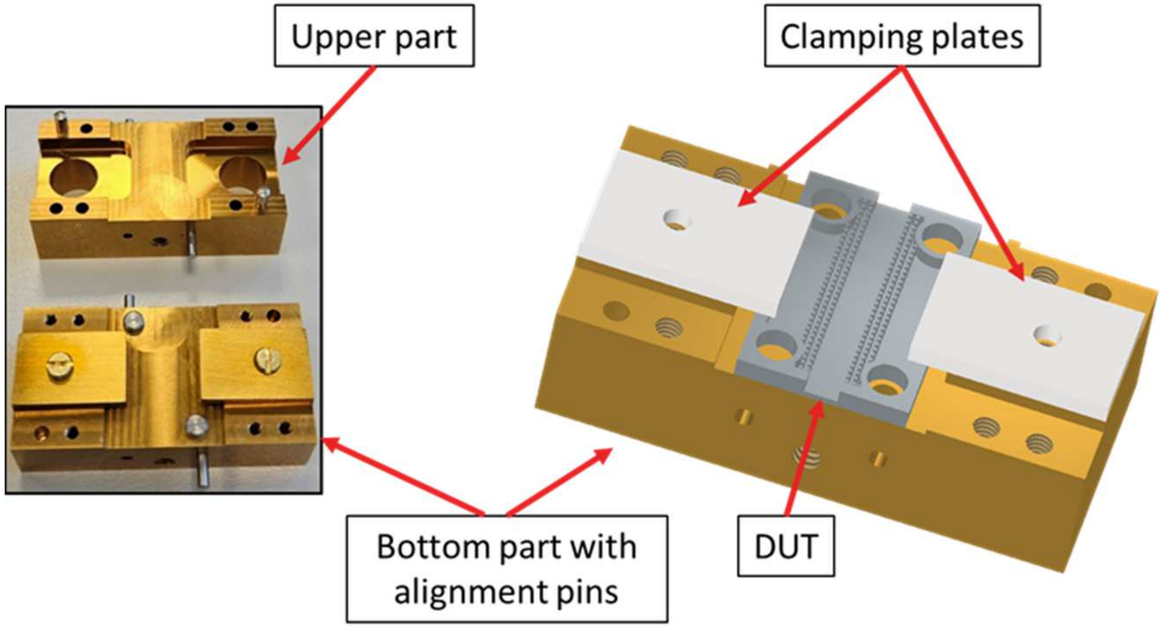




Properties of GGW Parts

Measurement Setup for Electrical Characterization

- Setup for characterization of through lines
- Made of brass
- Upper part as cover
- Lower part with tapered alignment pins and clamping plates
- Identical design for W- and D-band (with different height)



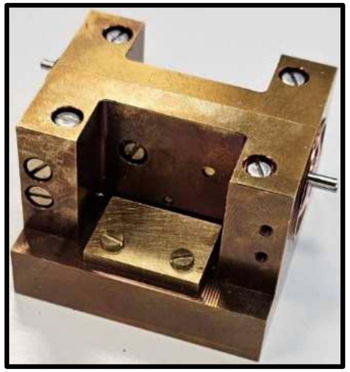
Properties of GGW Parts

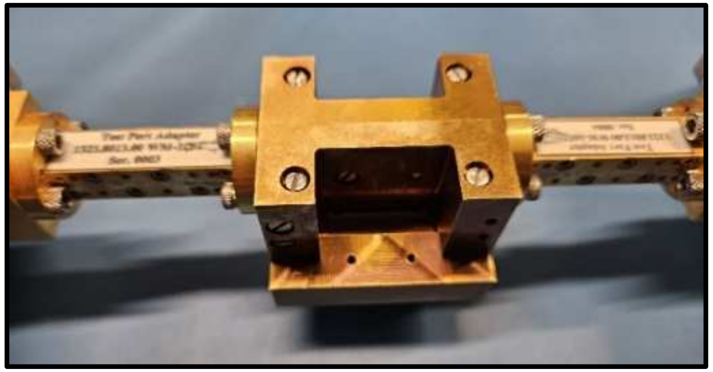
Electrical Characterization

- Results of final iteration
- D-Band: Two resonators, two filters and two through lines
- W-Band: One resonator and one filter (due to the limited time of the project it was not possible to drive more iterations for W-band)

Measured components of final iteration

Type	Printed Part
D-Band Resonator	04818_0256
D-Band Resonator	04818_0257
D-Band Filter	04818_0253
D-Band Filter	04818_0254
D-Band Through Line	04818_0254
D-Band Through Line	04818_0258
W-Band Resonator	04818_282
W-Band Filter	04818_299





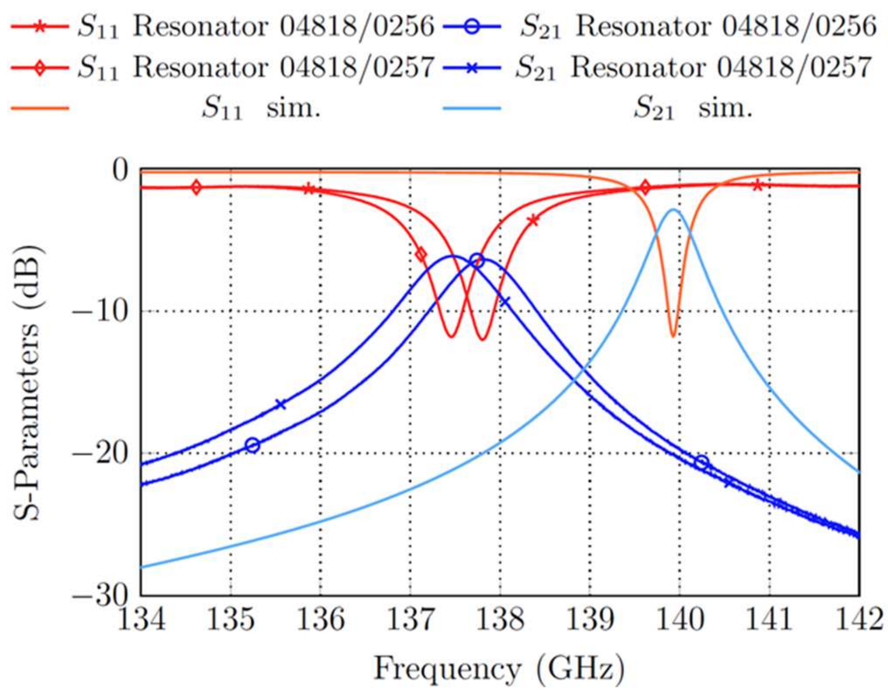
Properties of GGW Parts

Electrical Characterization

- **Two D-Band resonators were characterized**
- **Downward shift in frequency for both resonators**

	Simulation	Resonator 04818_0256	Resonator 04818_0257
fres [GHz]	140	137.8	137.48
Q0		408	385

➢ **Frequency shift caused by bending effects of the base plate caused by sintering**

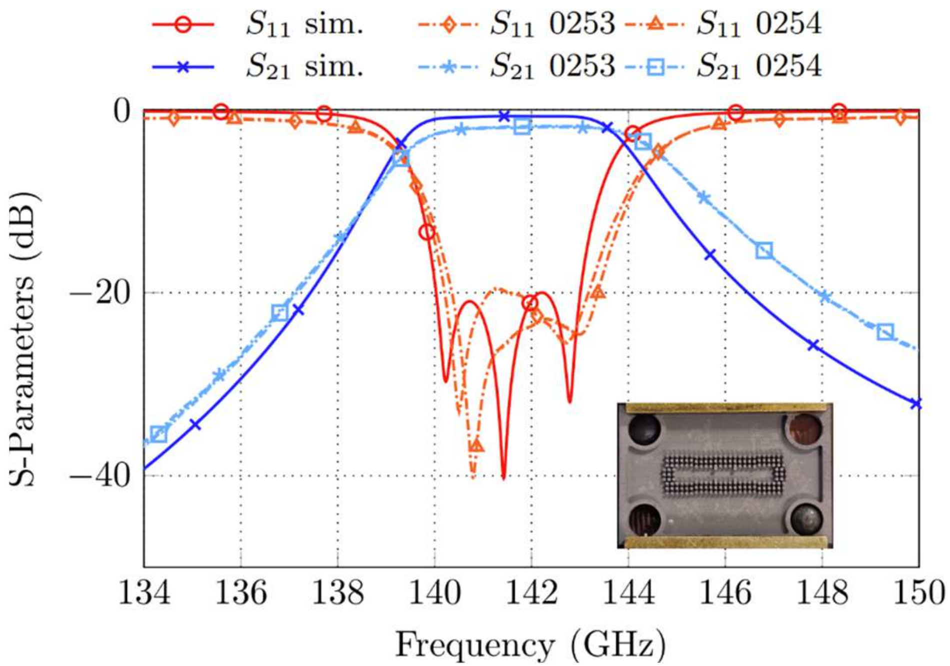


Properties of GGW Parts

Electrical Characterization

- Two D-Band filters were characterized
- Only small deviations between measurement and simulation
- Simulation with conductivity of tungsten due to an unknown conductivity of the tungsten-copper composition

	Simulation	Filter 04818_0253	Filter 04818_0254
fo [GHz]	141.5	141.69	141.86
RL [dB]	20	19.53	22.93
IL [dB]		1.92	2.22
BW [GHz]	3	2.97	3.01
Qo		280	280



Properties of GGW Parts

Electrical Characterization

- **Comparison with other technologies show comparable results to CNC milling**

COMPARISON WITH OTHER FILTERS ABOVE 100 GHZ AND WITH OTHER ADDITIVELY MANUFACTURED GGW FILTERS.

Ref.	Technology	Structure	f_0 (GHz)	FBW	IL (dB)	RL (dB)	f_0 offset
[14]	SLA	Waveguide	107.2	6.34%	0.95	>11	7.2%
[15]	SU-8 Process	Waveguide	102	5%	1.2	>10	2%
[16]	Micro Laser Sintering	Waveguide	180	11%	2.9	>17	1.4%
[2]	CNC Milling	Groove Gap Waveguide	145	4.14%	2.2	>20	≈ 0.65%
[3]	CNC Milling	Groove Gap Waveguide	65	1.4%	1.1	12.5	N/A
[4]	SLA	Groove Gap Waveguide	94	3.2%	0.61	>15	≈ 0.43%
This work	3D Screen Printing	Groove Gap Waveguide	140	2.56%	2.21	>19.53	0.25%

[2] J. L. Vazquez-Roy, E. Rajo-Iglesias, G. Ulisse, and V. Krozer, "Design and realization of a band pass filter at D-band using gap waveguide technology," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 41, pp. 1469–1477, 2020.

[3] M. Rezaee and A. U. Zaman, "Groove gap waveguide filter based on horizontally polarized resonators for V-band applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 7, pp. 2601–2609, 2020.

[4] D. Santiago, A. Tamayo-Domínguez, M. A. G. Lao, T. Lopetegi, J. Fernández-González, R. Martínez, and I. Arregui, "Robust design of 3D-printed W-band bandpass filters using gap waveguide technology," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 44, pp. 98–109, 2023.

[14] M. D'Auria, W. J. Otter, J. Hazell, B. T. W. Gillatt, C. Long-Collins, N. M. Ridler, and S. Lucyszyn, "3-D printed metal-pipe rectangular waveguides," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 5, no. 9, pp. 1339–1349, 2015.

[15] C. A. Leal-Sevillano, J. R. Montejo-Garai, M. Ke, M. J. Lancaster, J. A. Ruiz-Cruz, and J. M. Rebollar, "A pseudo-elliptical response filter at W-band fabricated with thick SU-8 photo-resist technology," *IEEE Microwave and Wireless Components Letters*, vol. 22, no. 3, pp. 105–107, 2012.

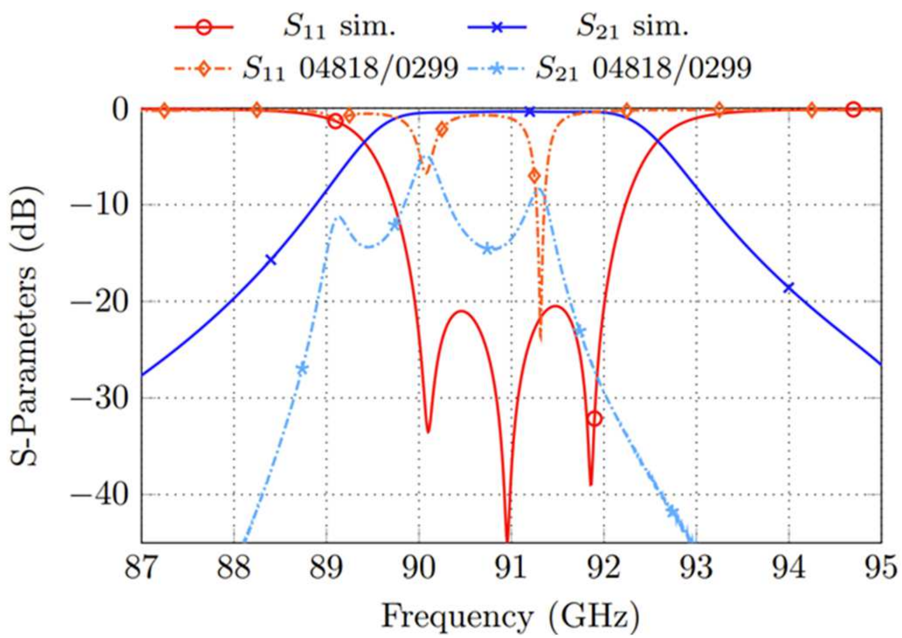
[16] T. Skaik, M. Salek, Y. Wang, M. Lancaster, T. Starke, and F. Boettcher, "180 GHz waveguide bandpass filter fabricated by 3D printing technology," in *2020 13th UK-Europe-China Workshop on Millimetre-Waves and Terahertz Technologies (UCMMT)*, 2020, pp. 1–3.

Properties of GGW Parts

Electrical Characterization W-Band Components

- Due to the limited time available for the de-risk project, the focus was set on the D-band components it was not possible to make all the necessary adjustments to the printing process for the production of the W-band components.

- One W-Band filter was characterized
- All three resonances are shifted to lower frequencies
- I/O coupling too weak
- Inter-resonator couplings also too weak (deviations between lateral shrinkage in x- and y-direction
- Geometrical analysis shows a reduced height of the DUT of 50 µm
- Extracted unloaded Q ≈ 520



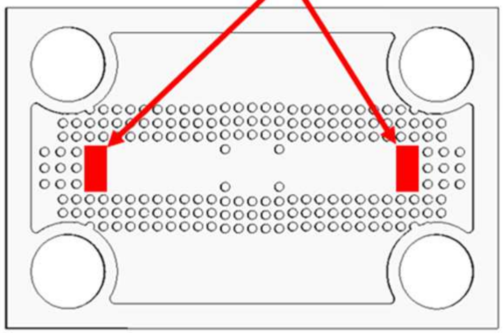
	S	1	2	3	L
S	0.0000	-0.7184	0.0000	0.0000	0.0000
1	-0.7184	1.1140	-0.2809	0.0000	0.0000
2	0.0000	-0.2809	0.7337	-0.2307	0.0000
3	0.0000	0.0000	-0.2307	0.6339	-0.8086
L	0.0000	0.0000	0.0000	-0.8086	0.0000

Properties of GGW Parts

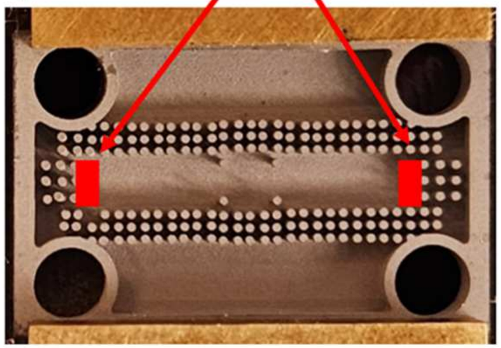
Electrical Characterization

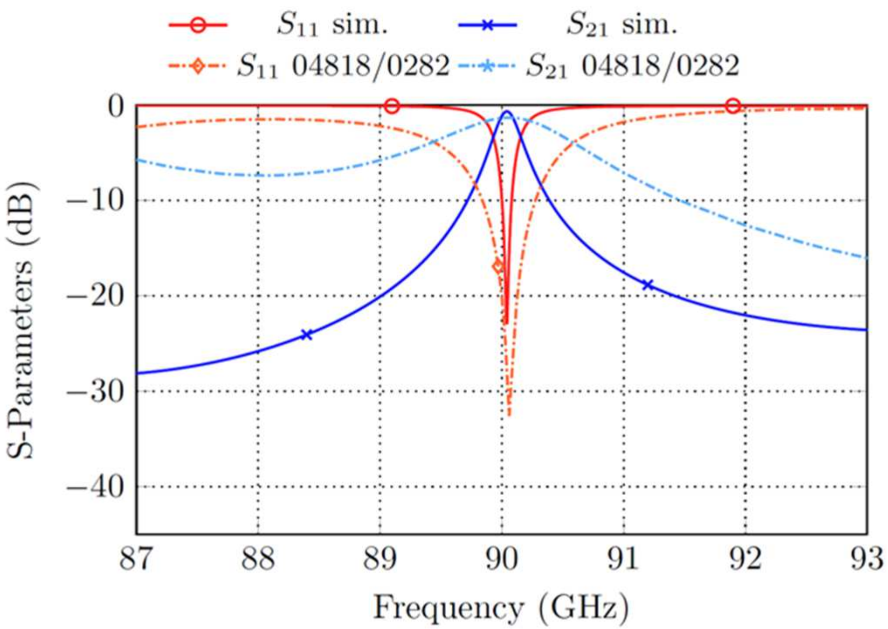
- **One W-Band resonator was characterized**
- **Resonance frequency only shifted by 8 MHz compared to simulation**
- **Higher lateral shrinkage due to higher copper content causes a misalignment of the DUT which leads to greater reflections**

Positions of WR-10 waveguide ports in simulation



Positions of WR-10 waveguide ports in measurement due to the too large lateral shrinkage of the base plate (schematic illustration)





Printed part	Resonance frequency (simulation)	Resonance frequency (measured)	Unloaded quality factor
W-Band Resonator 04818 -0282	**90.052 GHz**	**90.06 GHz**	**480**

Lessons Learned

- **Processing**
  - Tungsten Printing process reliable
  - Infiltration process to be optimized for full dense parts
  - Dimensional Deviations due to mismatch of screen enlargement and sintering shrinkage (iterative process)

- **Electric Contact and Alignment**
  - Challenges were encountered in achieving good electrical contact and precise alignment with measurement sample holders.
  - This was addressed by refining the measurement setup and improving alignment between components and sample holders.
  - For future projects, I/O coupling from the top is preferable. However, a more broadband realization must be found for this approach

Intended Future Work

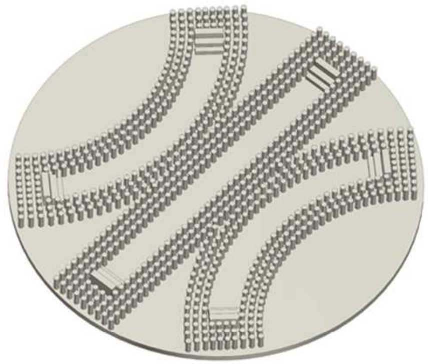
Intended GSTP Development Project

TESAT

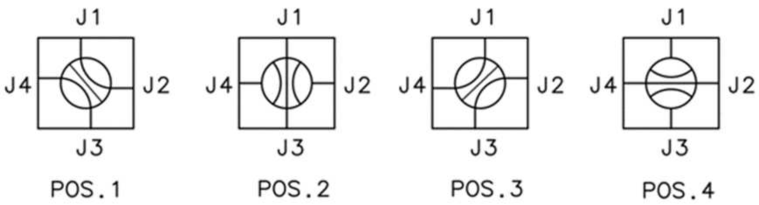
Fraunhofer IFAM

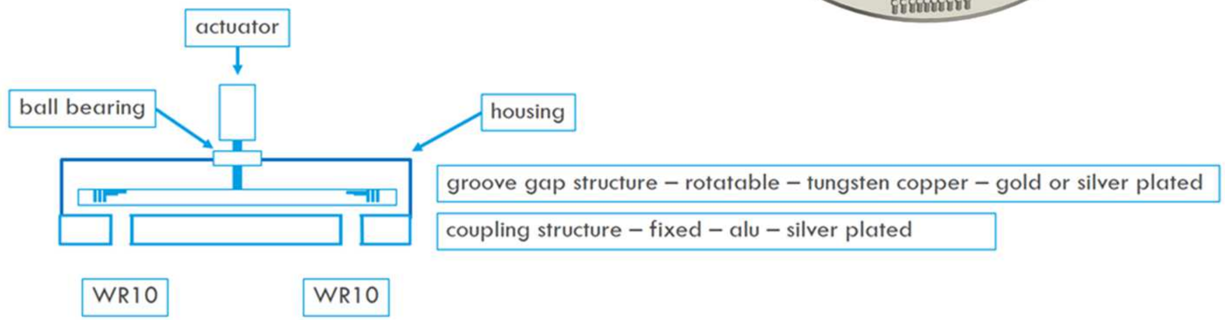
C | A | U
Kiel University
Christian-Albrechts-Universität zu Kiel

- **Partners:**
  - **TESAT Spacecom, Backnang, Germany**
  - **Fraunhofer IFAM, Dresden, Germany**
  - **Kiel University, Germany**



- **2 years project**
- **Topic: Development of a 3D screen printed high-power W-Band R-type switch in GGW technology**





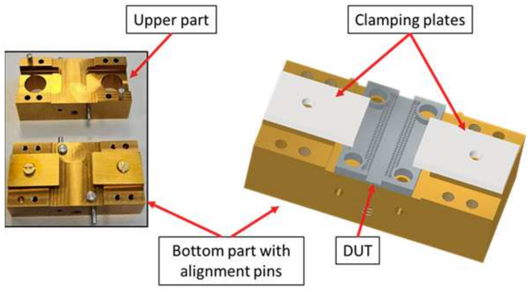
Thank you for your attention!

Properties of GGW Parts

Electrical Characterization

- **Two D-Band trough lines were characterized**
- **Lateral shrinkage is too large and bend base plate leads to contact problem between DUT and measurement setup**
- ➢ **Measurement was adapted for through line 04818_0258 (trimmed from both sides)**

Photo of the bent base plate



	Simulation	Through line 04818_0254	Through line 04818_0258
IL [dB]		3.22 to 11.09	2.39 to 6.07
RL [dB]	<25	13.71	9.13