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Optimizing Electromagnetic Performances of L-PBF Aluminium Waveguides through Surface Roughness Control

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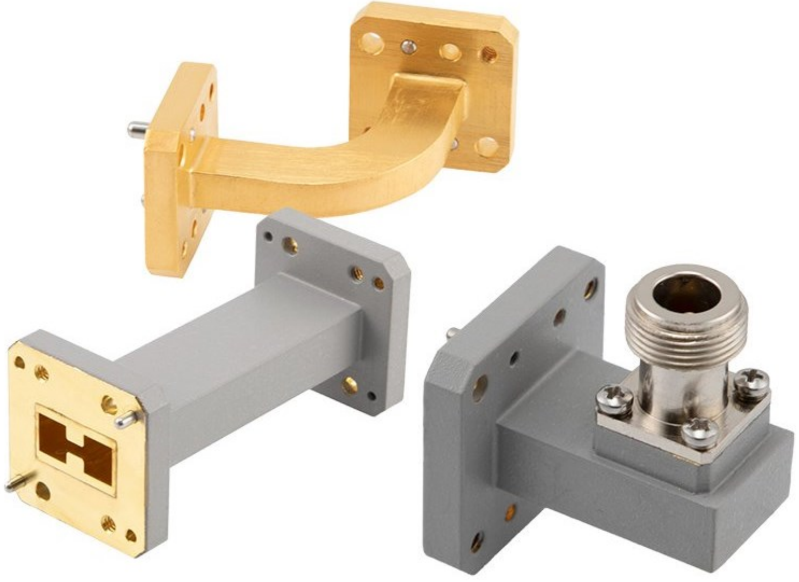
Introduction and context of the study

- **Waveguides are key components in high-frequency applications, used to guide electromagnetic (EM) signals with minimal losses**.
  - *Highly conductive materials (copper, brass, aluminum)*
  - *Primarily manufactured by CNC machining*

- **The Ka-band (26.5–40 GHz) is used in aerospace applications** such as satellite telecommunications and high-resolution radar. Waveguides in the Ka-band feature:
  - *Smaller internal dimensions (shorter wavelengths)*
  - *Tighter manufacturing tolerances*
  - *High-quality inner surface finish*

- **Conventional machining restricts waveguide design** whereas **L-PBF enables complex geometries** but introduces **higher surface roughness** and **non-equilibrium microstructures**.
  - → **EM performance of L-PBF waveguides in the Ka-band?**
  - → Investigation of the combined effects of surface roughness and electrical properties

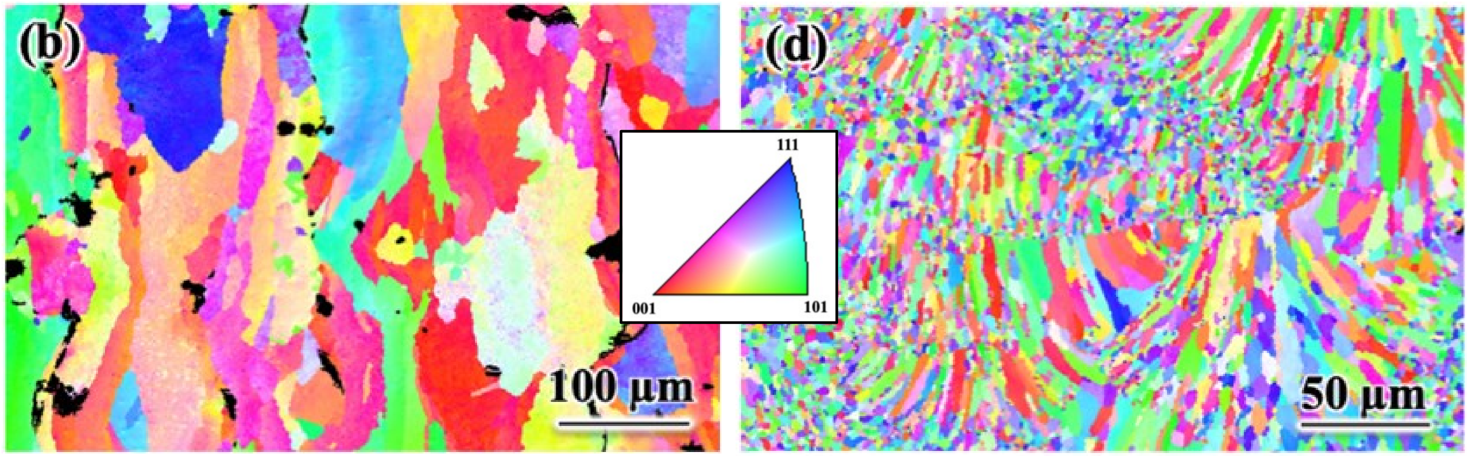


Materials used in this study

Alloys	Al	Si	Mg	Cu	Fe	Zn	Mn	Ti	Cr	Zr
AlSi10Mg	Bal.	10.09	0.51	0.02	0.12	0.03	0.07	0.03	-	-
6061-Zr	Bal.	1.04	0.68	0.35	0.30	0.01	0.11	0.06	0.12	2.33

Chemical compositions of the studied alloys (wt%)

Alloys	CuZn30 (brass)	AlSi10Mg	6061-Zr
Density (g/cm^3)	8.5	2.67	2.83
HV – lowest	60 – 80 (annealed)	60 – 90 (solutionized)	50 – 60 (solutionized)
HV – highest	120 - 180 (work-hardening)	100 – 130 (T6 HT)	110 – 120 (T6 HT)
Electrical conductivity (MS/m)	14 – 17	15 – 20 (T6 HT)	20 – 25 (T6 HT)
L-PBF printability	Low	High	Medium



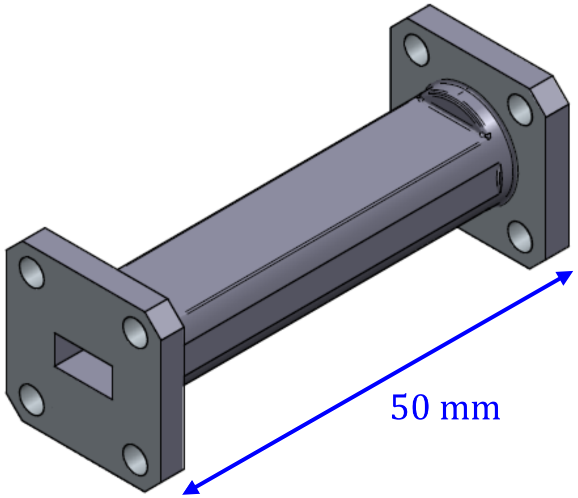
A. Mehta et al., Additive manufacturing and mechanical properties of the dense and crack free Zr-modified aluminum alloy 6061 fabricated by the laser-powder bed fusion ***Additive Manufacturing, 2021***

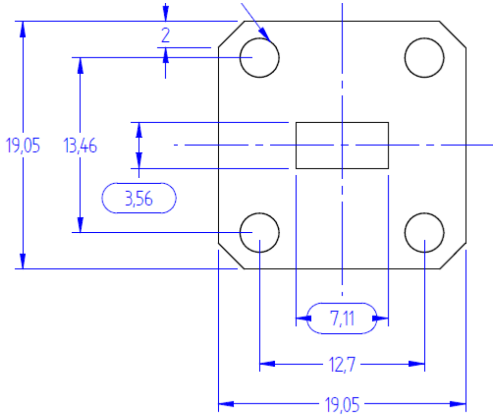
Addition of Si to 6061 Al alloy:

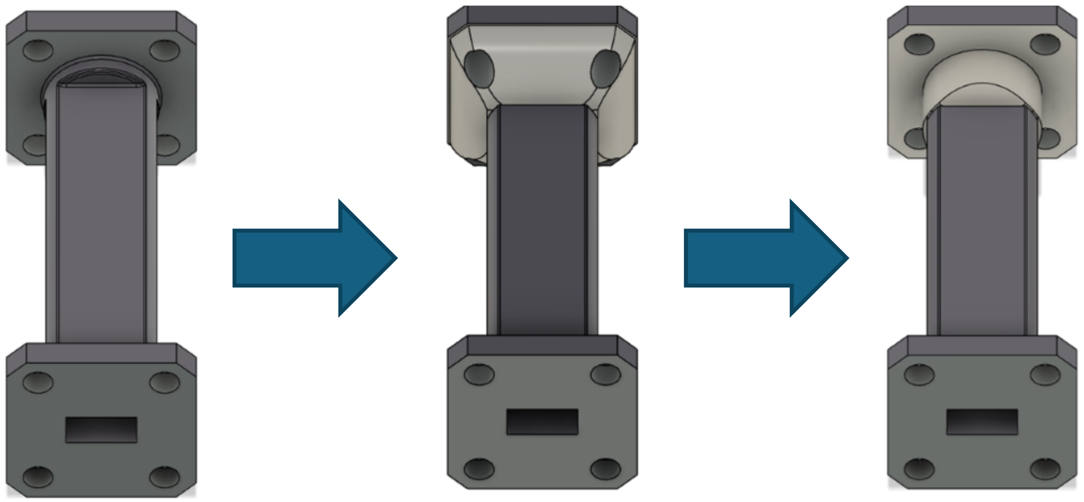
→ Grain refinement to mitigate columnar grain formation

→ Prevention of hot cracking during L-PBF solidification

Part geometry and L-PBF parameters







Original geometry | **Adapted geometry** (addition of supports) | **Tested geometry** (machined supports)

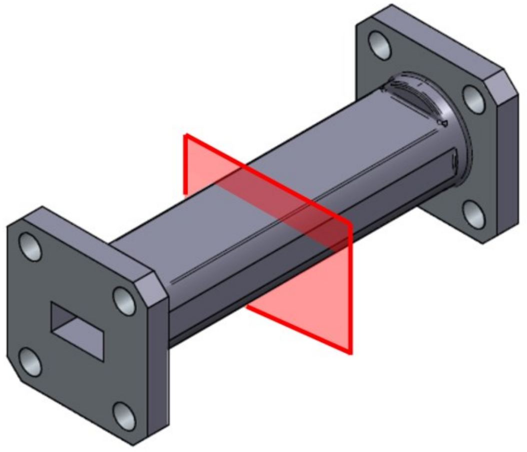
WR-28 straight waveguides:

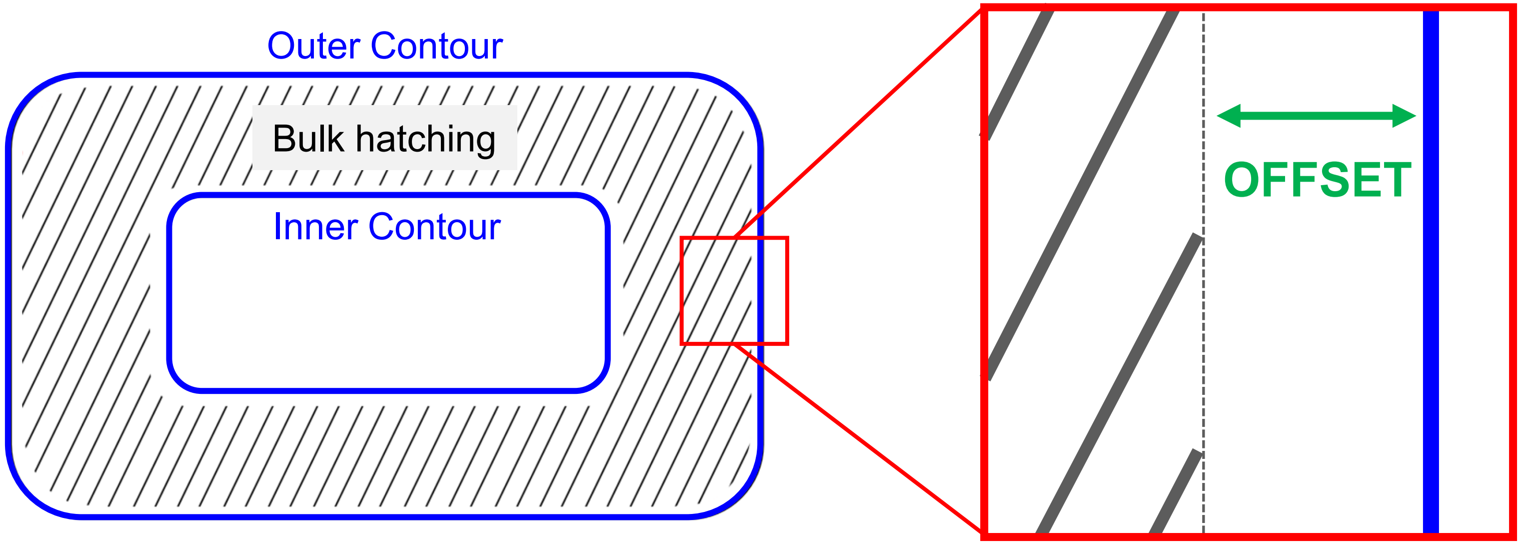
- Internal channel = 7.11×3.56 mm²
  → **Ka-band: [26.5 – 40 GHz]**
- Height = **50 mm**
- UG-599/U-M flanges
- **Vertically built** by LPBF
- Two Al alloys : **AlSi10Mg** & **6061-Zr**

Parameters	AlSi10Mg	6061-Zr
Pre-alloyed powders	**[15 – 53 µm]**	**[15 – 45 µm]**
L-PBF machine	**ProX DMP 200** (UC Louvain)	**ProX DMP 200** (LGF - LTDS)
Laser power	232 W	270 W
Laser scanspeed	1400 mm/s	1450 mm/s
Hatch spacing	70 µm	70 µm
Layer thickness	30 µm	30 µm

Various L-PBF contour strategies to control surface roughness

Modification of surface finish inside and outside the internal channel using different Bulk–Contour strategies



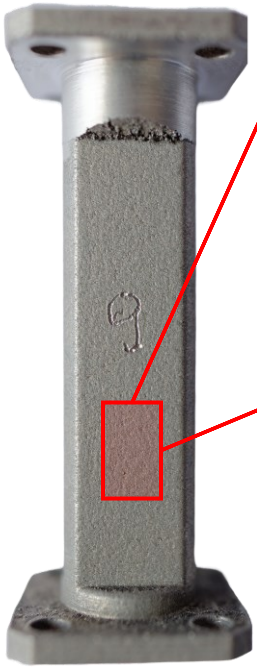


1. **Bulk / contour order:**
   - Bulk first / Contour second
   - Contour first / Bulk second

2. **Various offsets with fixed contour laser scanspeed (= 1450 mm/s)**
   - 0 µm
   - 30 µm
   - 60 µm
   - 90 µm
   - 120 µm

3. **Various contour laser scanspeed with fixed offset (= 80 µm)**
   - 500 mm/s
   - 700 mm/s
   - 1450 mm/s

Inner / Outer waveguide surface roughness



Photographs of the outer surface of *6061-Zr* waveguides

- **Contour first**
- Offset 80 µm
- 300 W
- **500 mm/s**

- **Contour first**
- Offset 80 µm
- 300 W
- **700 mm/s**

- **Contour first**
- Offset 80 µm
- 270 W
- **1450 mm/s**

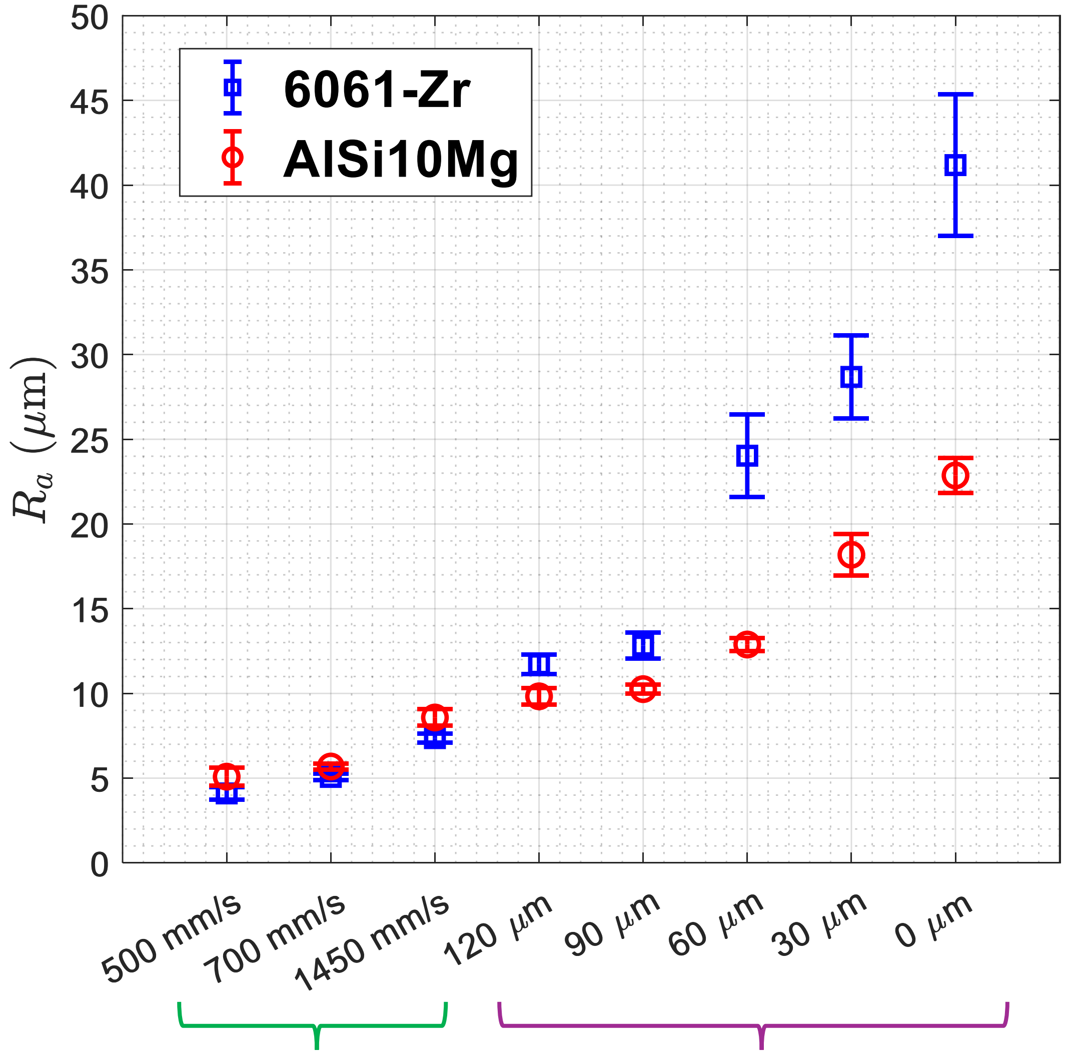
- **Bulk first**
- **Offset 120 µm**
- 270 W
- 1450 mm/s

- **Bulk first**
- **Offset 90 µm**
- 270 W
- 1450 mm/s

- **Bulk first**
- **Offset 60 µm**
- 270 W
- 1450 mm/s

- **Bulk first**
- **Offset 30 µm**
- 270 W
- 1450 mm/s

- **Bulk first**
- **Offset 0 µm**
- 270 W
- 1450 mm/s



- **Contour first** / Bulk second
- Contour offset: 80 µm
- **Increasing contour scanspeed**

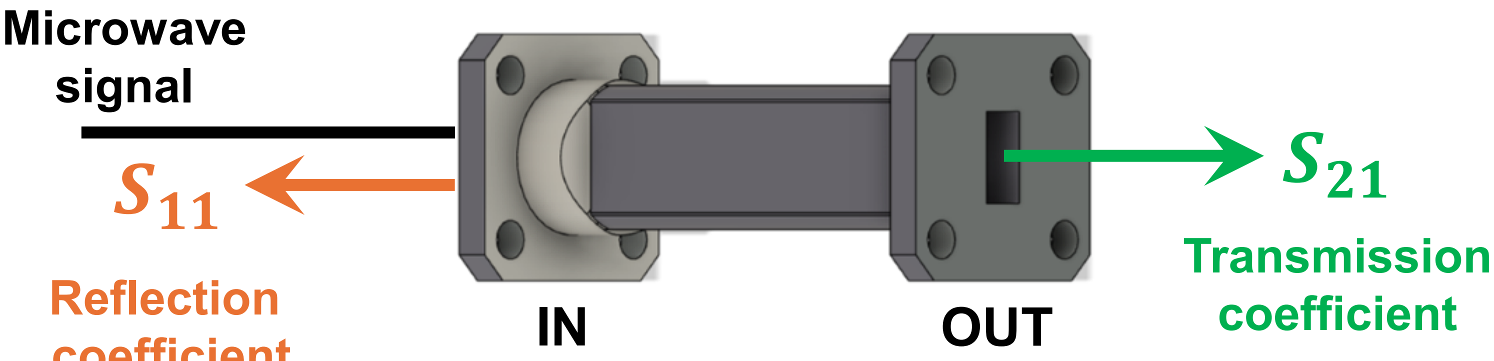
- **Bulk first** / Contour second
- Contour scanspeed: 1450 mm/s
- **Decreasing contour offset**

Effect of inner surface roughness on waveguide EM performance

Measurement of EM characteristics: S parameters

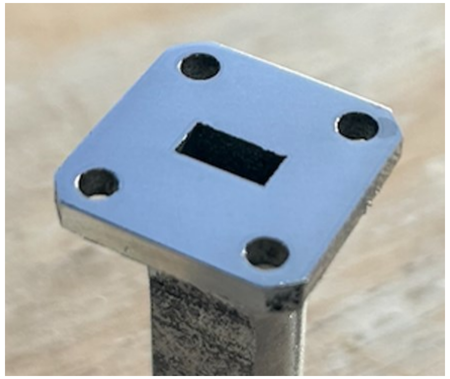
Mainly depends on **Flange connection:**

- Flange roughness
- Bolt tightness



Mainly depends on **part characteristics** and **material properties:**

- Channel roughness
- Electrical resistivity



→ **Flange polishing** (up to 3 µm diamond abrasive) **to reduce S_{11}**

S parameters measurement using a **Vector Nework Analyzer (VNA)**

→ *Keysight PNA-X N5247B 67 GHz 4-Ports*

→ *Coax-to-WR28 transitions to the VNA*

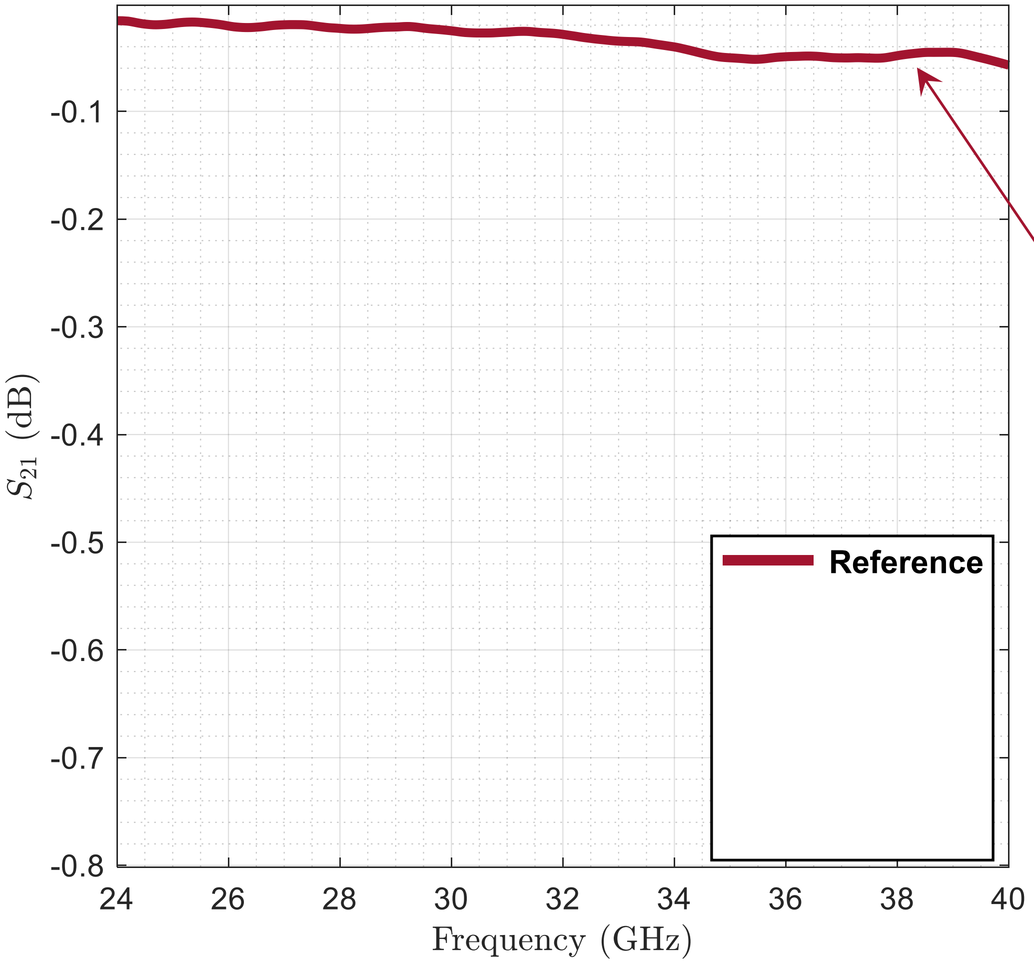
Assessment of EM losses:

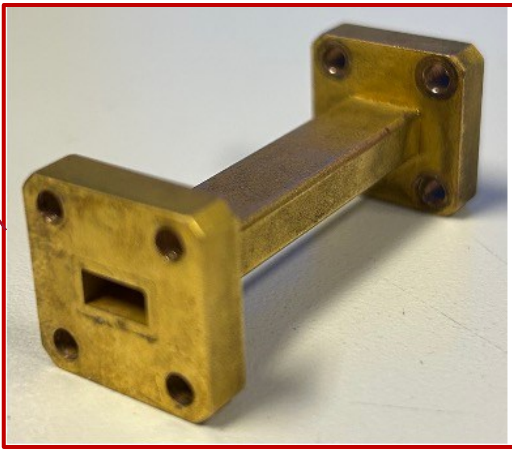
Absorption coefficient

$$1 - |S_{11}|^2 - |S_{21}|^2$$

Effect of inner surface roughness on waveguide EM performance

Variation of the transmission coefficient S_{21} across the Ka-band



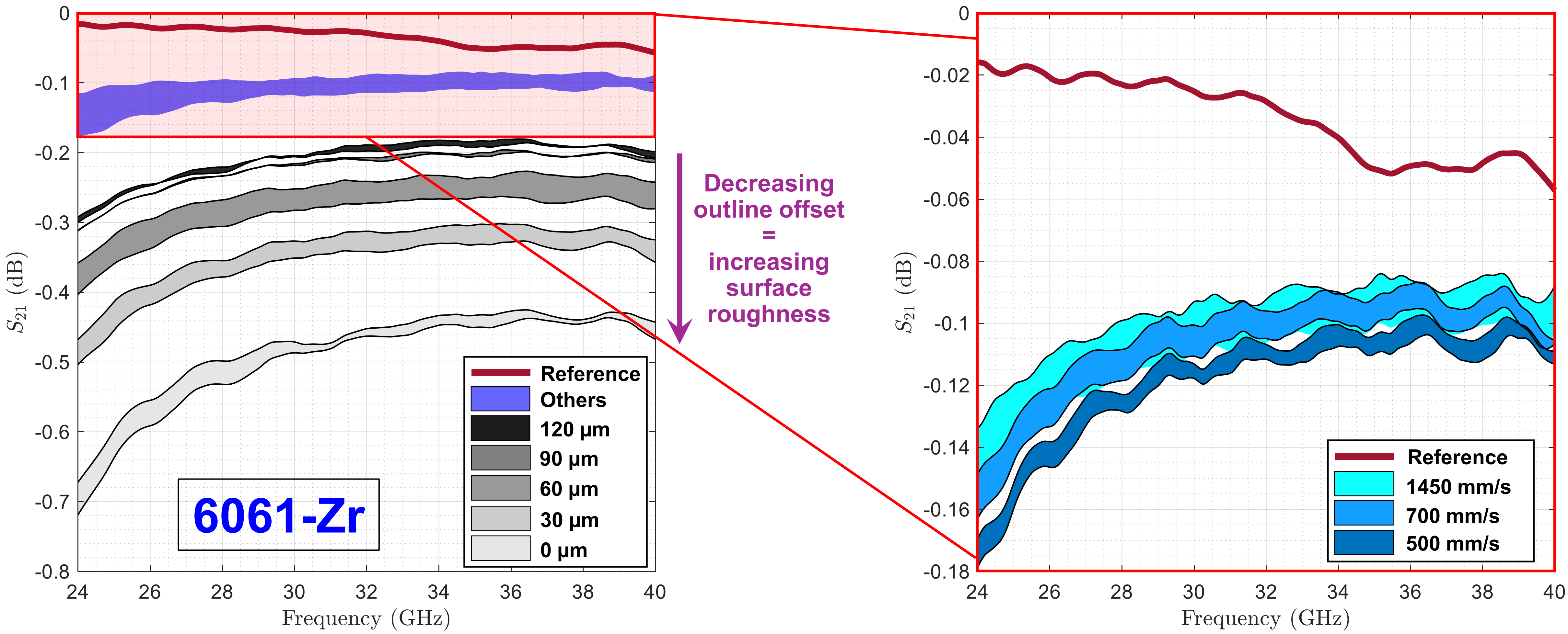


Reference waveguide :

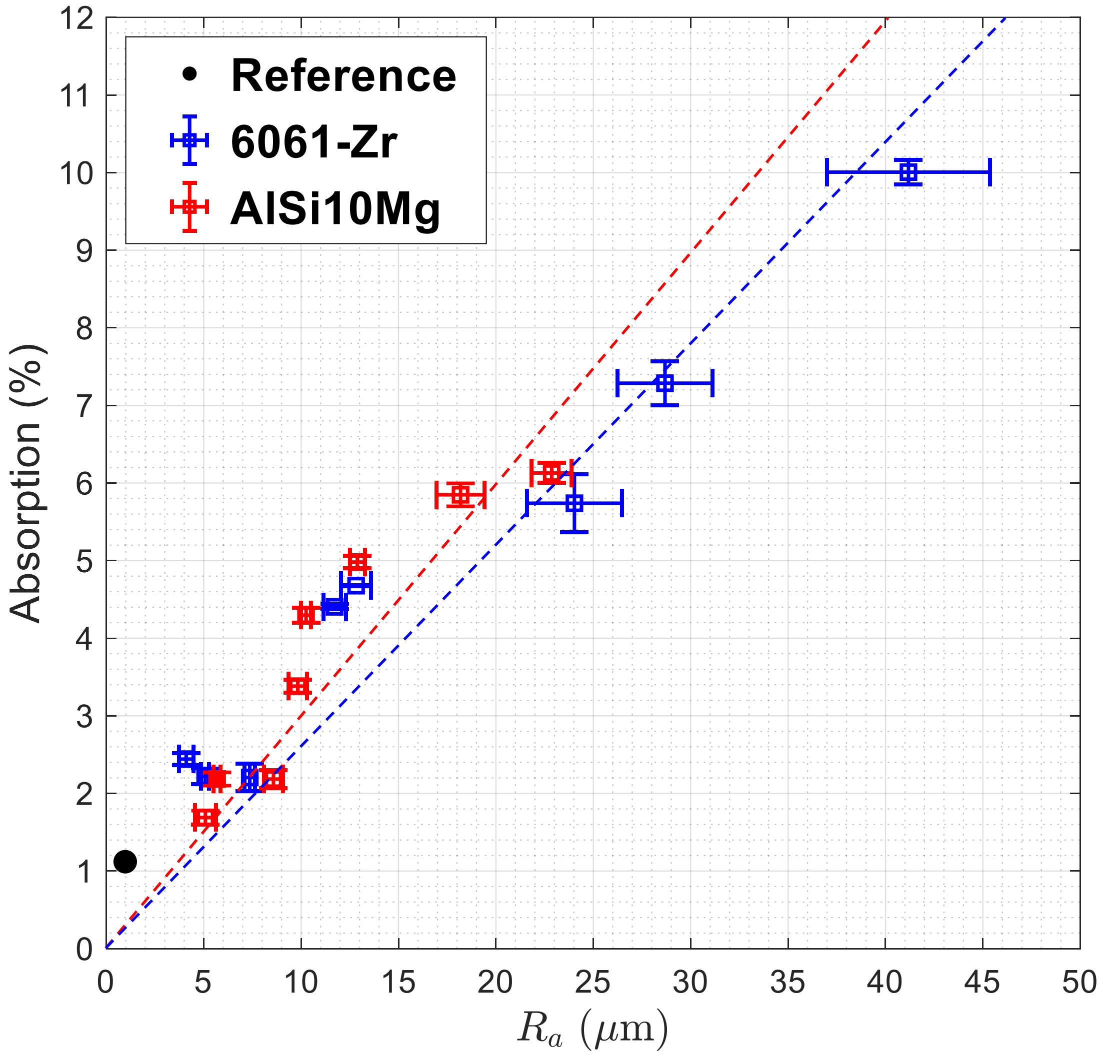
- **CNC machining**
- **Brass coating**
- **$R_a \approx 1$ µm (channel)**

Effect of inner surface roughness on waveguide EM performance

Variation of the transmission coefficient S_{21} across the Ka-band



Effect of inner surface roughness on waveguide EM performance



Absorption = $1 - |S_{11}|^2 - |S_{21}|^2$

→ For all measured samples, S_{11} **remained below** $-20\ dB$, indicating that reflection losses did not affect the measurements.

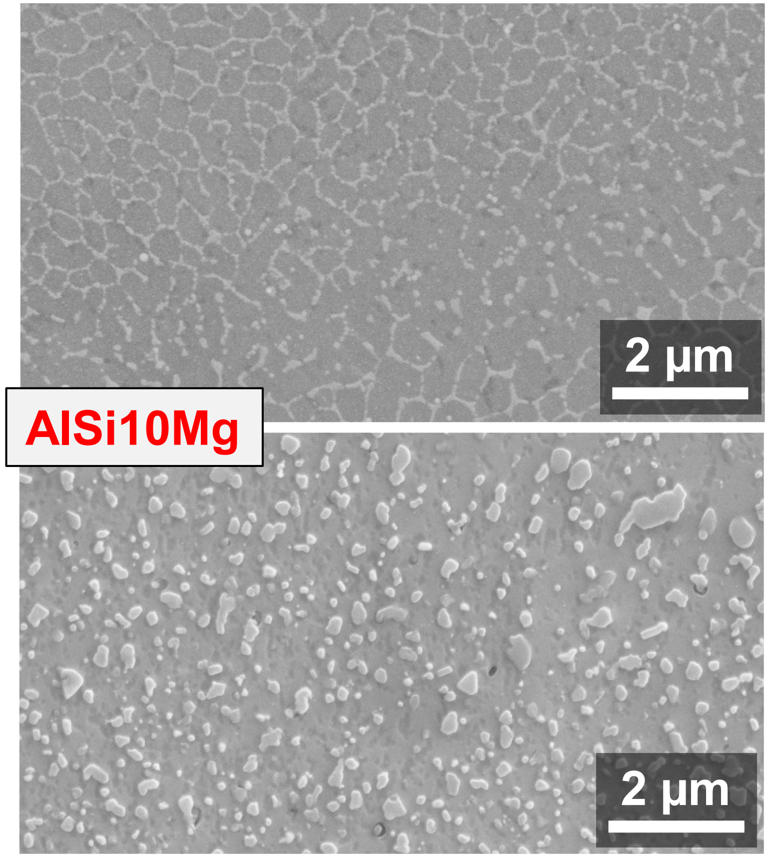
→ **Waveguide losses appear to exhibit a linear dependence on inner surface roughness.**

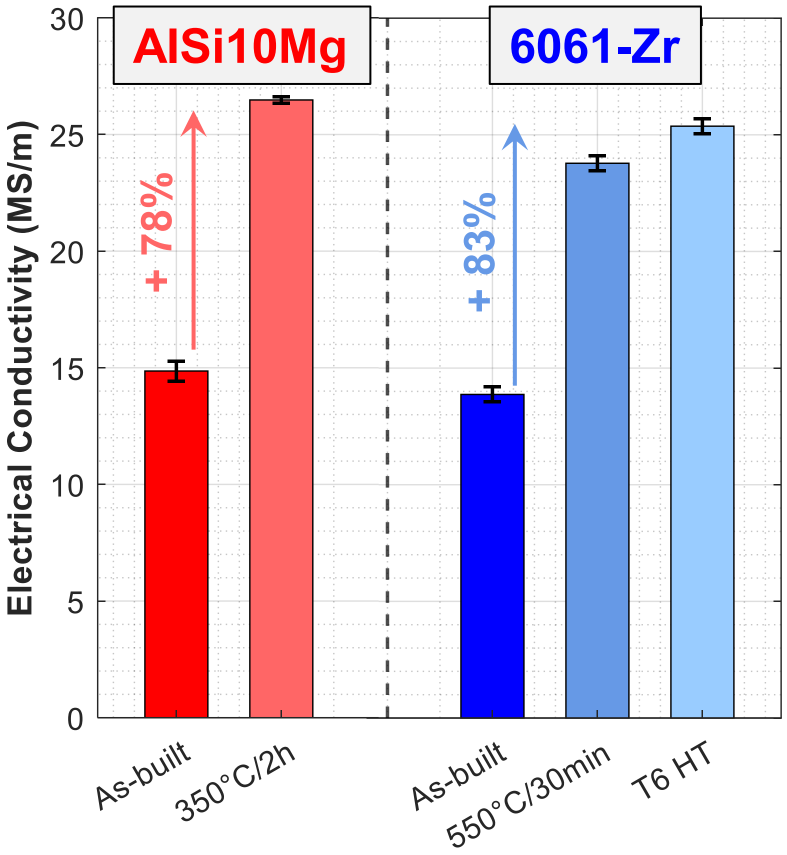
→ Samples with the **best surface roughness** exhibit **waveguide losses comparable to the CNC-machined brass reference**:

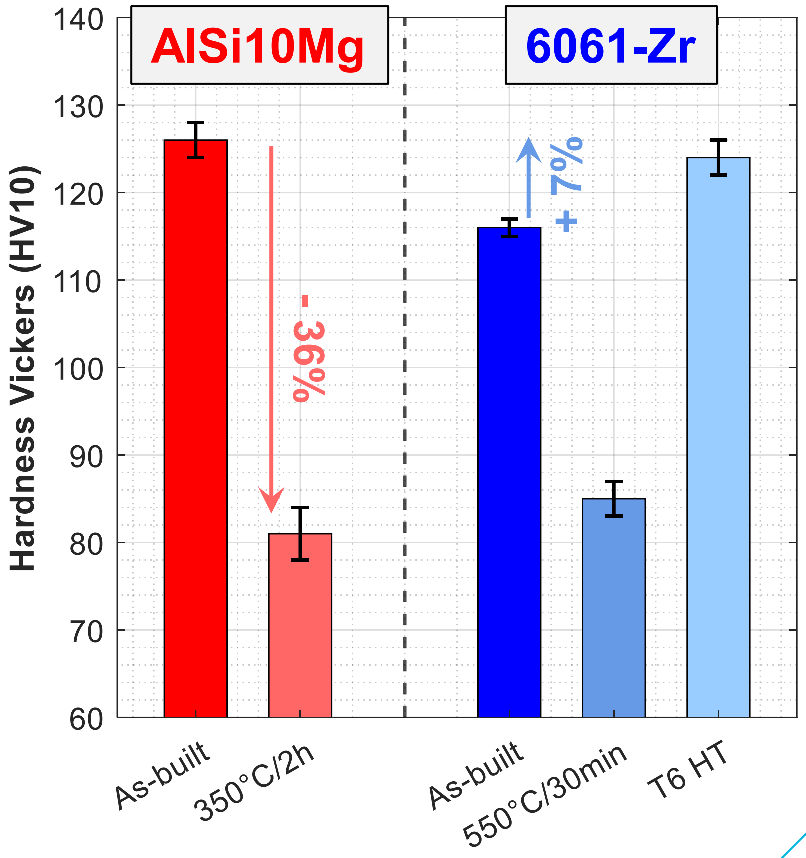
- Reference: $S_{21} \approx -0.05\ dB$ / Absorption ≈ 1.1%
- Best sample: $S_{21} \approx -0.07\ dB$ / Absorption ≈ 1.7%

Effect of post-processing heat treatments on waveguide EM performance

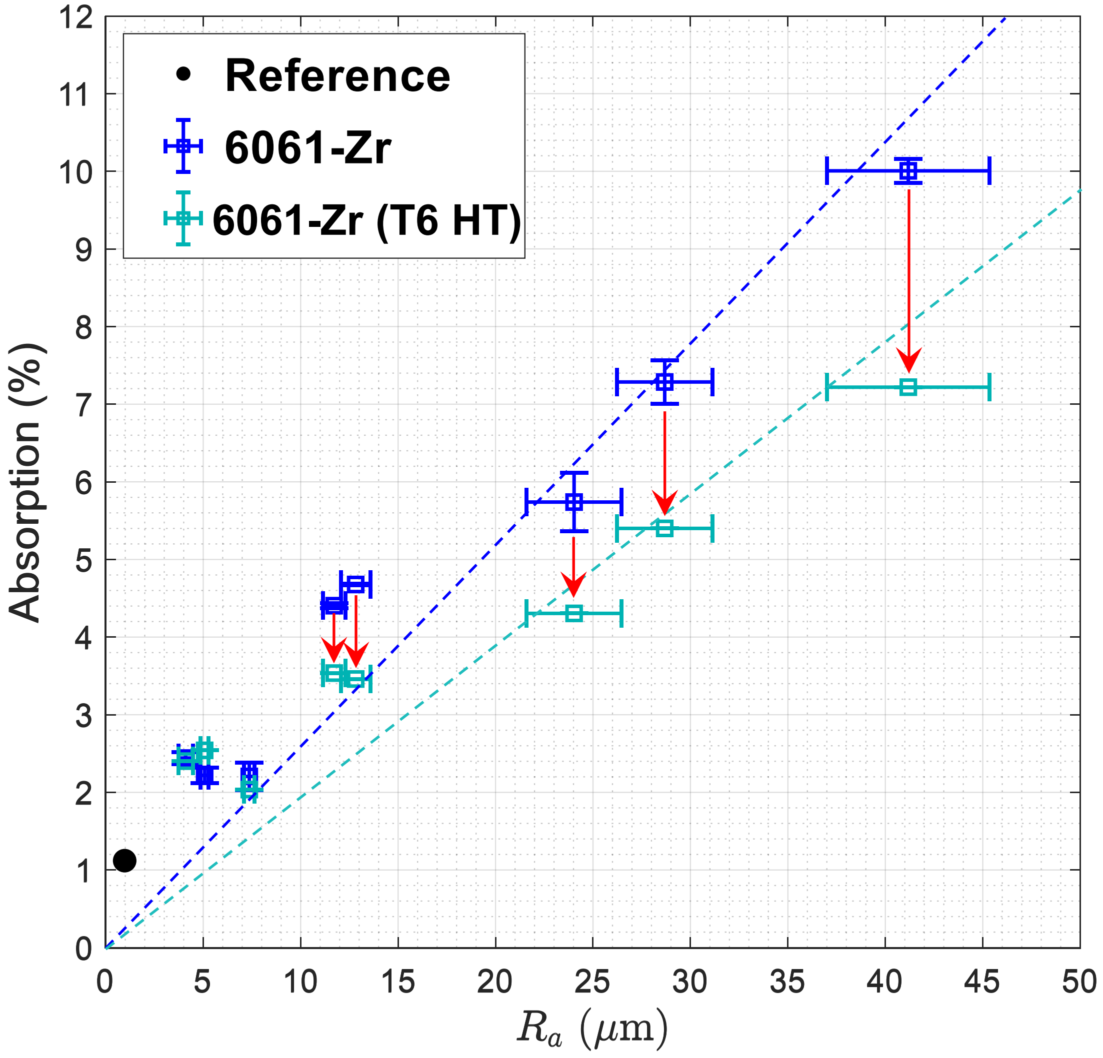
- **AlSi10Mg**: direct ageing at **350°C/2h** → Si-rich solidification cells are transformed into Si-rich agregates
- **6061-Zr**: **T6 HT** = homogenization at **550°C/30min** + ageing at **180°C/4h** → solid solution is depleted in Zr, Mg, Si







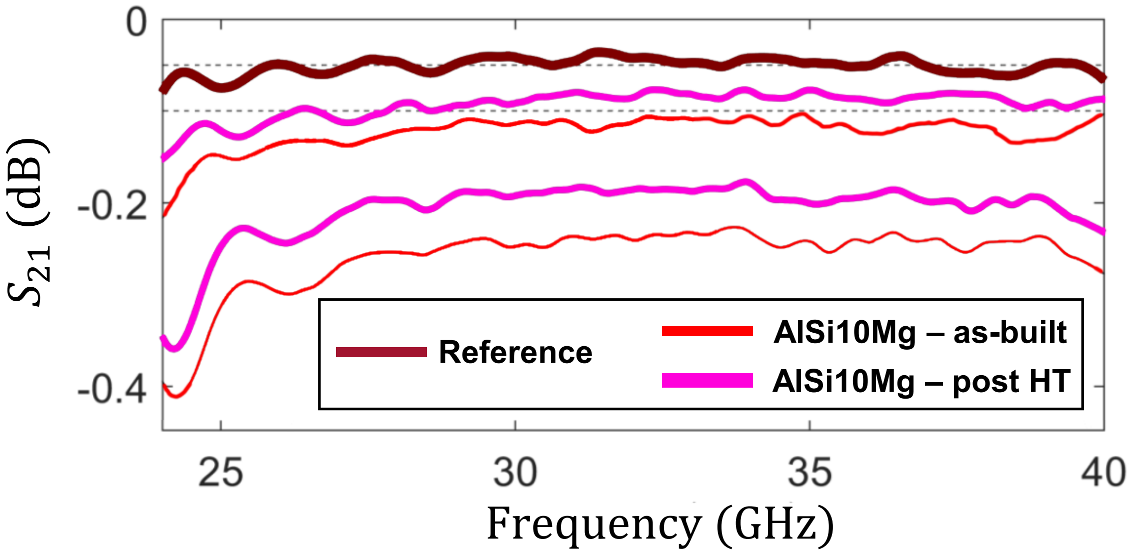
Effect of post-processing heat treatments on waveguide EM performance



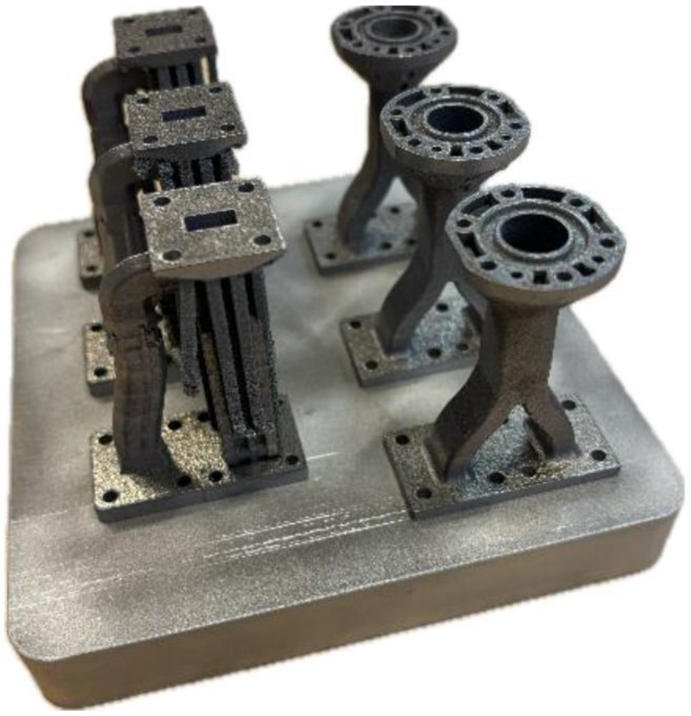
Absorption = $1 - |S_{11}|^2 - |S_{21}|^2$

→ **Increasing electrical conductivity reduces 6061-Zr waveguide losses**, particularly for samples with the highest surface roughness.

→ **Preliminary results** (obtained with different build parameters) **indicate that the same effect is observed in AlSi10Mg waveguides.**



Conclusions and perspectives



- ❑ **EM losses induced by surface roughness in L-PBF-built waveguides are not detrimental in the Ka-band** [26.5 – 40 GHz] **with optimized process parameters** ($R_a \approx 5\ \mu m$).

- ❑ **Heat treatments designed to increase electrical conductivity can further reduce EM losses**.

- ❑ **Both AlSi10Mg and 6061-Zr alloys are effective solutions for these applications:**
  - AlSi10Mg is more commercially available and easier to print
  - 6061-Zr offers a better strength–conductivity trade-off after HT

→ **L-PBF proved to be a suitable technique for fabricating waveguides and more complex communication devices.**

Future work:

→ *Further testing on more complex geometries*

→ *Investigation of upskin/downskin effects*

→ *Post-processing surface finishing*

Thank you for your attention

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