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”Laser-machined substrate technology (LMST) for Q-band applications”

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Millimeter-wave technologies

New incoming communication technologies such as the fifth generation (5G) require more capacity and data performance[(1)].

Millimeter-wave broadcasting emerges as a promising solution to provide higher bandwidth, data rate and spectrum efficiency for point-to-point[(2)] communications, inter-satellite links[(3)], semi-autonomous 5G networks[(4)], vehicular communication[(5)], health care applications[(6)], etc.

New bands (24.25 – 27.5, 31.8 – 33.4, 37 – 40.5, 40.5 – 42.5, 42.5 - 43.5, 45.5 - 47, 47 - 47.2 and 47.2 - 50.2 GHz) for 5G worldwide deployments have been treated recently by WRC-19[(7)].

Millimeter-wave technologies

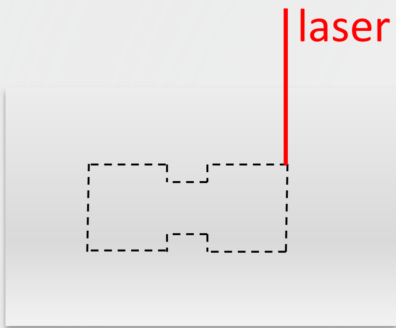
Several technological approaches[8] have been proposed so far for mm-Wave Q-band applications with different balance in performance, cost and size.

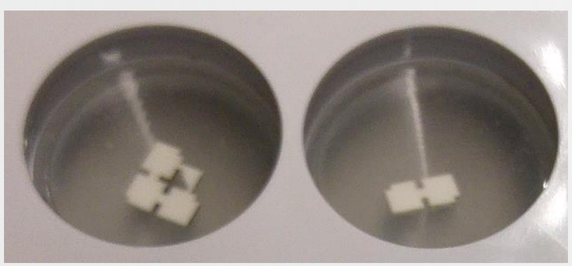
	Q	Size	Process complexity	Cost
SIW (organic substrate)[8]	↓	↑	↓	↓
LTCC[9]	↓	↘	↑	↗
Micro-machined silicon wafers[10]	→	↗	↗	→
u-Coax[11]	→	↘	↗	→
Air-filled SIW[12]	↗	↑	→	↘
Crystalline Quartz[13]	↑	→	→	→
LMST (this work)	→	↓	↘	→

LMST process

Laser Machined Substrate Techology (LMST): fabrication flow

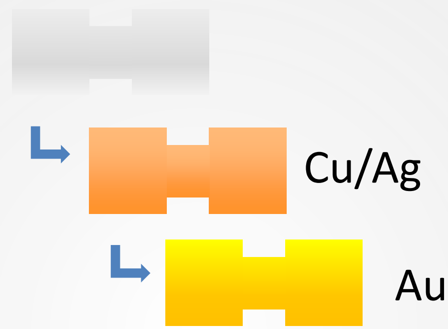
LASER MICRO-MACHINING

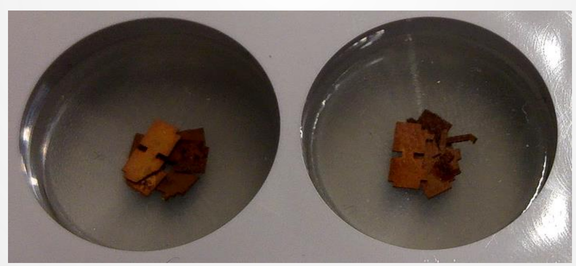




Separation of the devices from the substrate by means of a (25±10) µm spot YAG laser.

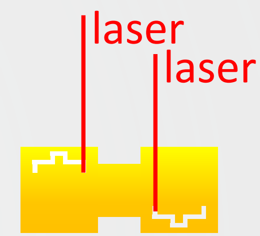
3D PLATING

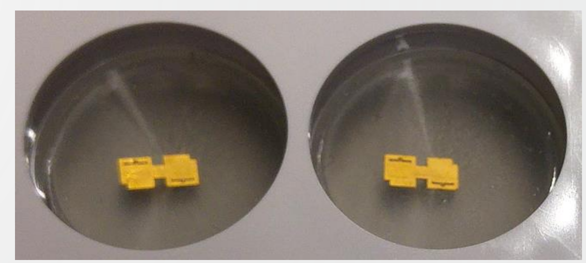




Metal layer deposition by electroless copper/Jet Metal© (2-3 µm thickness) and gold electrolysis (0.2µm) for protection.

LASER ETCHING





Laser etching is used on the metal layer to create coplanar lines and input/output accesses.

Laser Machined Substrate Techology (LMST): features

Advantages

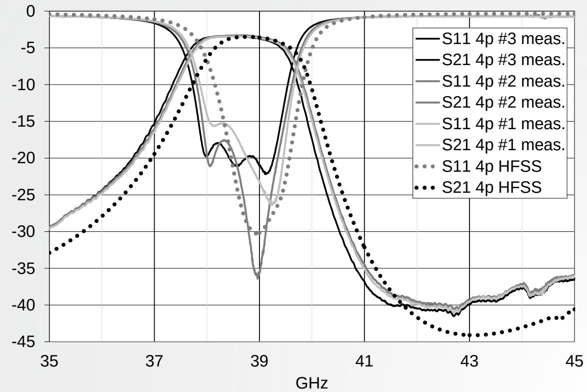
- ✓ Generic fabrication flow for 2D/2.5D passive devices.
- ✓ Machining of different kinds of substrate materials.
- ✓ Simple 3-steps manufacturing process.
- ✓ Good accurracy and repeatability for (up-to) Q-band applications.
- ✓ Compact devices with good performances when applied to low-loss Alumina substrates.
- ✓ Possibility to design SIW or SMD devices.

Drawbacks

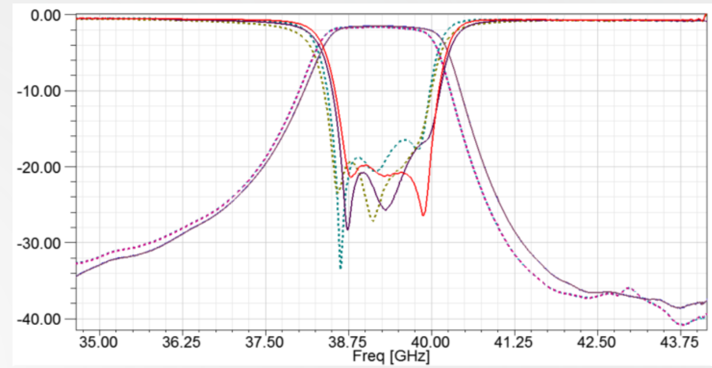
- ✓ Thickness limitations due to laser machine focal distance.

Previous work

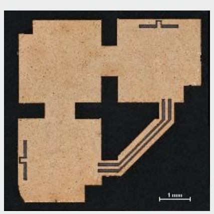
4-pole Chebyshev filter (copper plating)

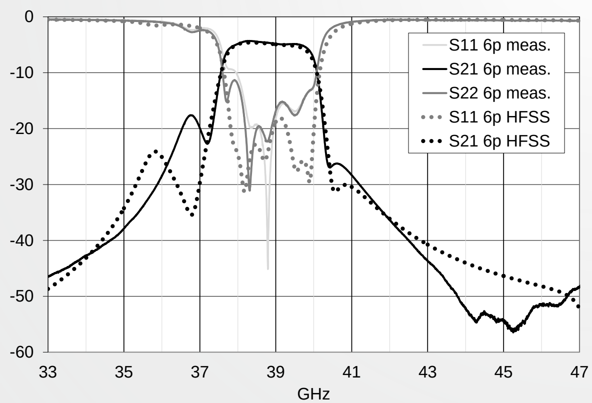


4-pole Chebyshev filter (silver plating)



6-pole quasi-elliptic filter (copper plating)



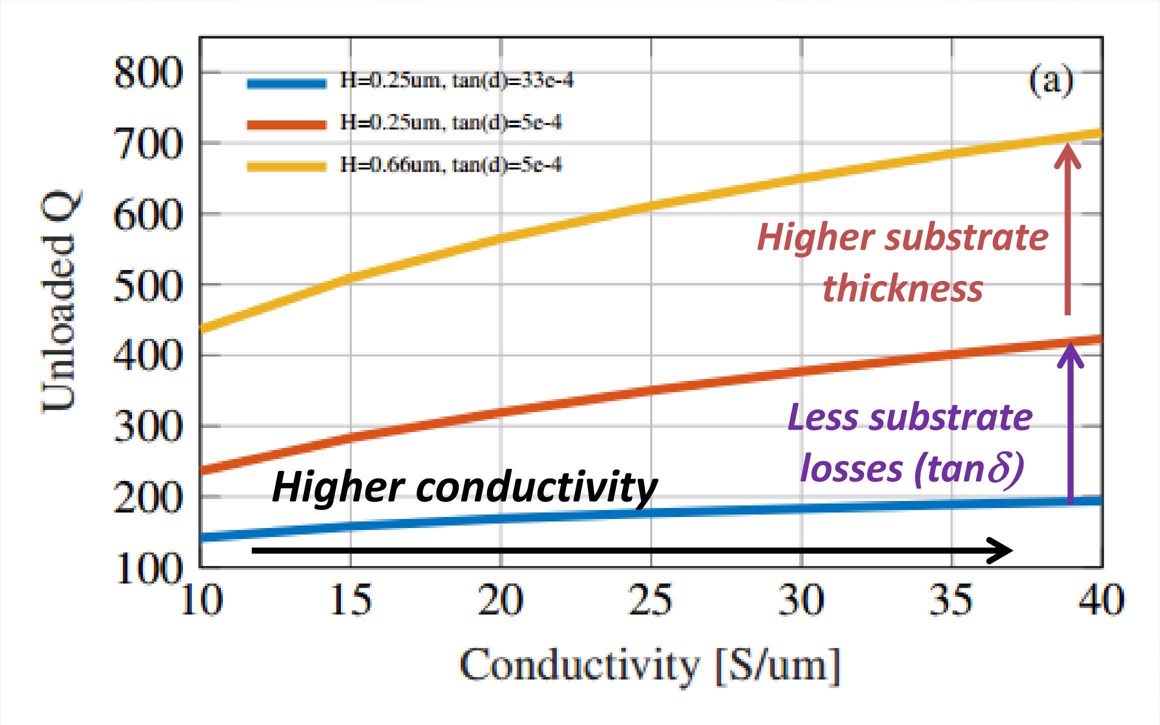


Filter	Alumina charact. @ f = 40 Ghz	fo [GHz]	FBW [%]	IL [dB]	RL [dB]	Q	Size [mm]
4-pole Chebyshev [14]	$\varepsilon_r = 9.75$ $\tan\delta = 33.10^{-4}$ **Thickness** 0.25 mm	39.0	3.8	> 3.5	15-20	~ 150	2.77 x 6.08
6-pole quasi-elliptic [14]		39.0	6.41				5.86 x 5.86
4-pole Chebyshev [15]	$\varepsilon_r = 9.94$ $\tan\delta = 2.5.10^{-4}$ **Thickness** 0.6 mm	39.3	3.2	1.51	16-20	400	5.98 x 2.76

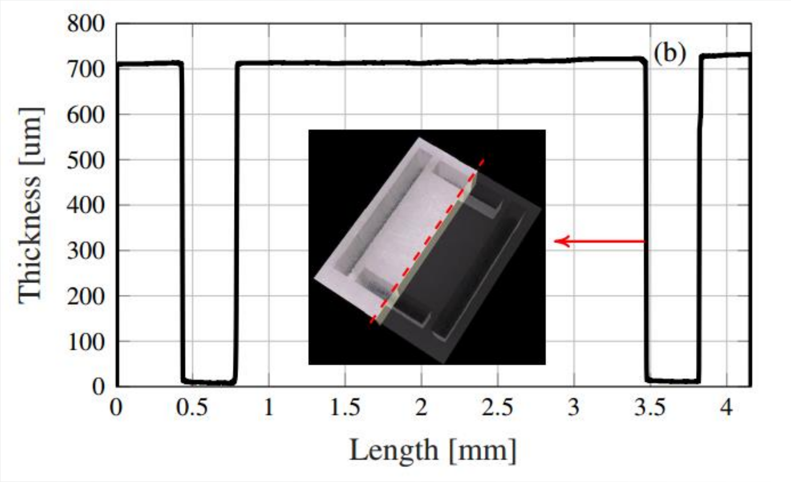
Ideal Qmax ~ 700

Improving the quality factor

Improvements on the quality factor can be achieved by increasing the conductivity of the metal layer, decreasing the losses of the substrate and selecting thicker substrates (better Q with TE_{10X} modes).

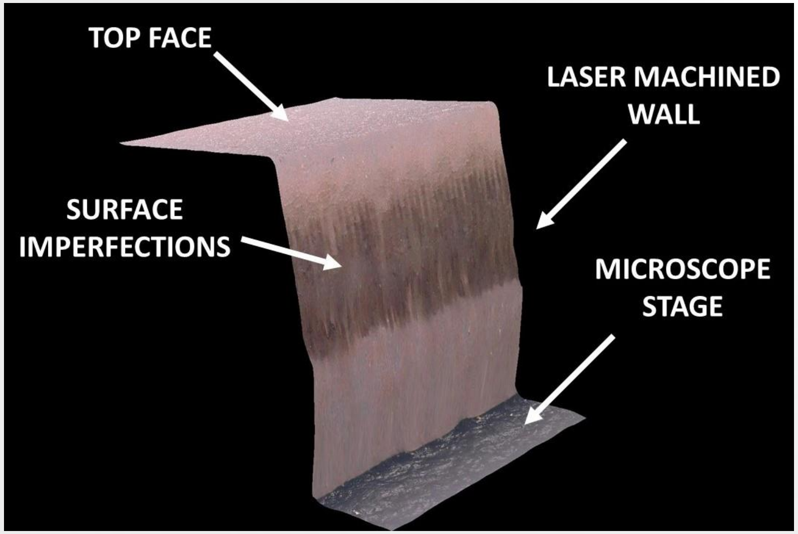


Laser engraving: Side walls



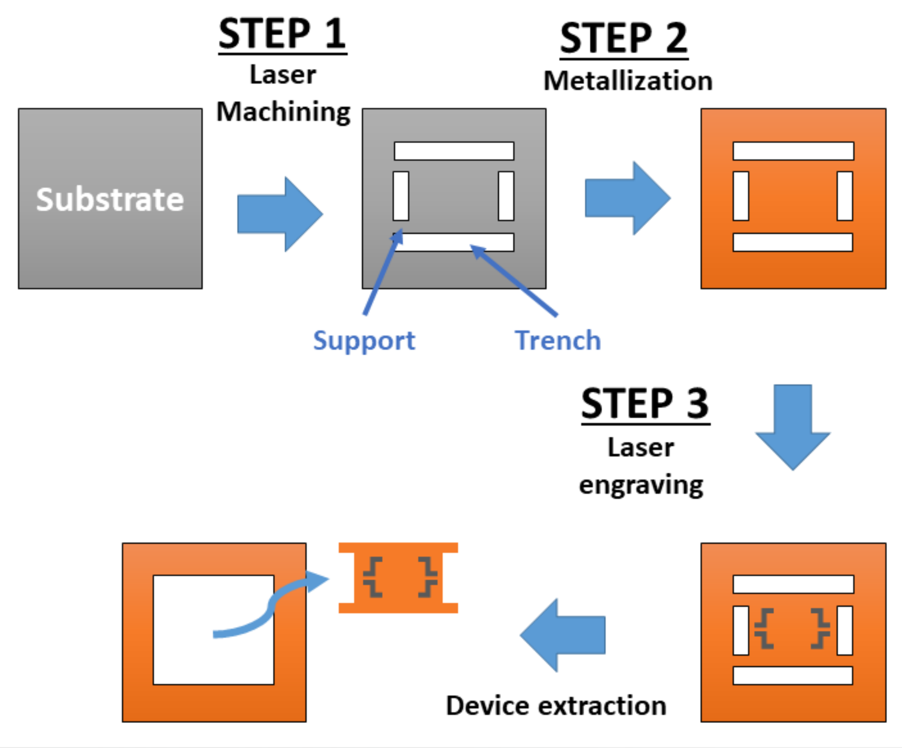
The machining quality of the device pattern on the substrate will determine the:

- final proccess dispersion.
- adherence of the metal layer on the side walls (critical impact in the quality factor).



Characterization of laser etched side walls (0.66 mm thick Alumina substrates)	
Laser accurracy [µm]	10
Measured side wall slope [µm]	5
Total process dispersion [µm]	15

Trenches and supports



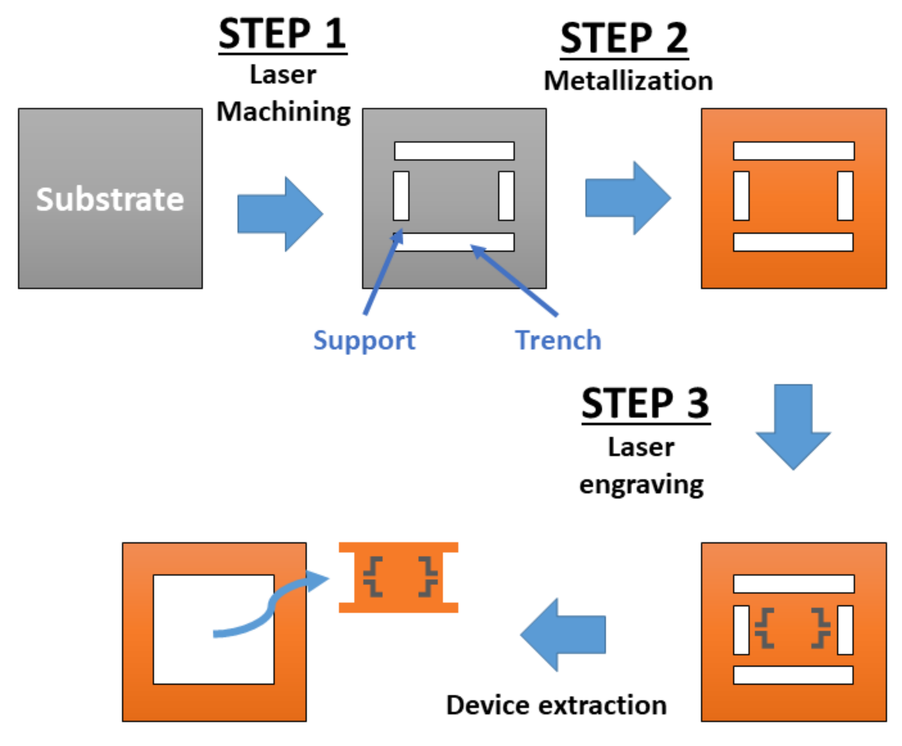
TRENCHES

- Avoid frictions that could hinder the extraction between the device and the substrate walls (STEP 3).
- Facilitates the metallization of the side walls.

SUPPORTS

- The devices remain attached to the substrate through supports after STEP 1 to facilitate the next steps.
- These supports are placed in order to produce minimum electromagnetic disturbance on the device.

Trenches and supports

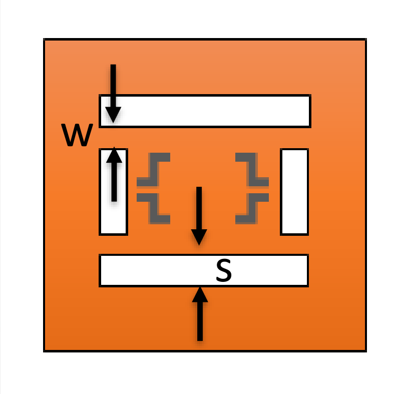


TRENCHES

- To ensure a good metallization and extraction the minimum recommended size (s) is **160 µm**.

SUPPORTS

- The minimum width (w) to avoid cracks on the supports is **200 µm**.

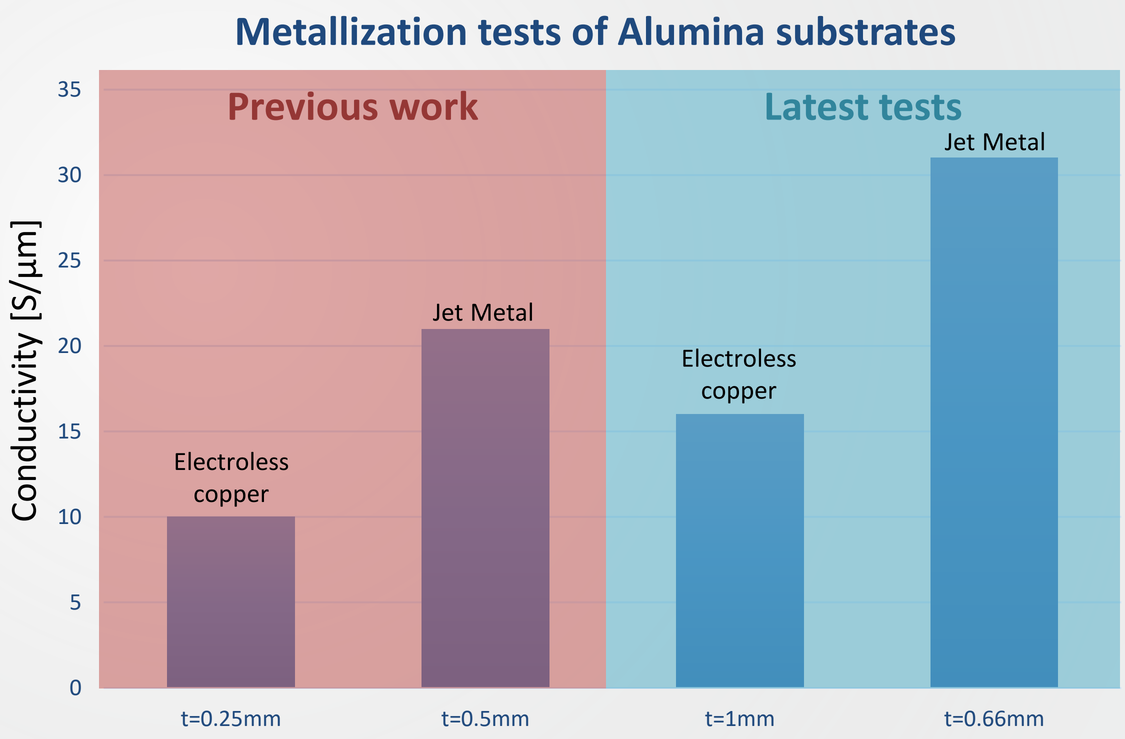


Improving previous work: Key considerations

CONDUCTIVITY IMPROVEMENT

Processes implemented in previous work show that Jet Metal plating has higher conductivity $\left(21\ \frac{S}{um}\right)$ than our lab scale electroless copper $\left(10\ \frac{S}{um}\right)$.

	Previous work
Electroless copper	10 S/µm
Jet Metal©	21 S/µm

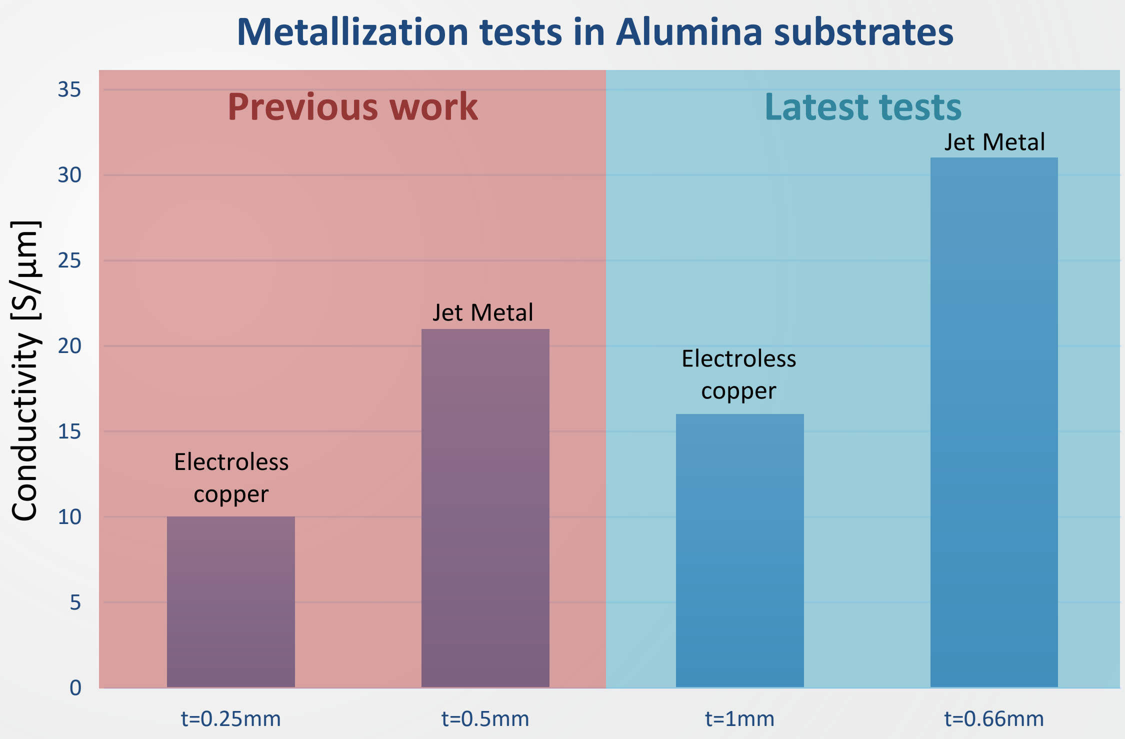


Improving previous work: Key considerations

CONDUCTIVITY IMPROVEMENT

Lastest tests performed to improve metal plating on Alumina substrates show an enhancement on the effective conductivity (side walls + top and bottom face).

	Previous work	Latest tests w/trenches
Electroless copper	10 S/um	16 S/µm
Jet Metal©	21 S/um	31 S/µm

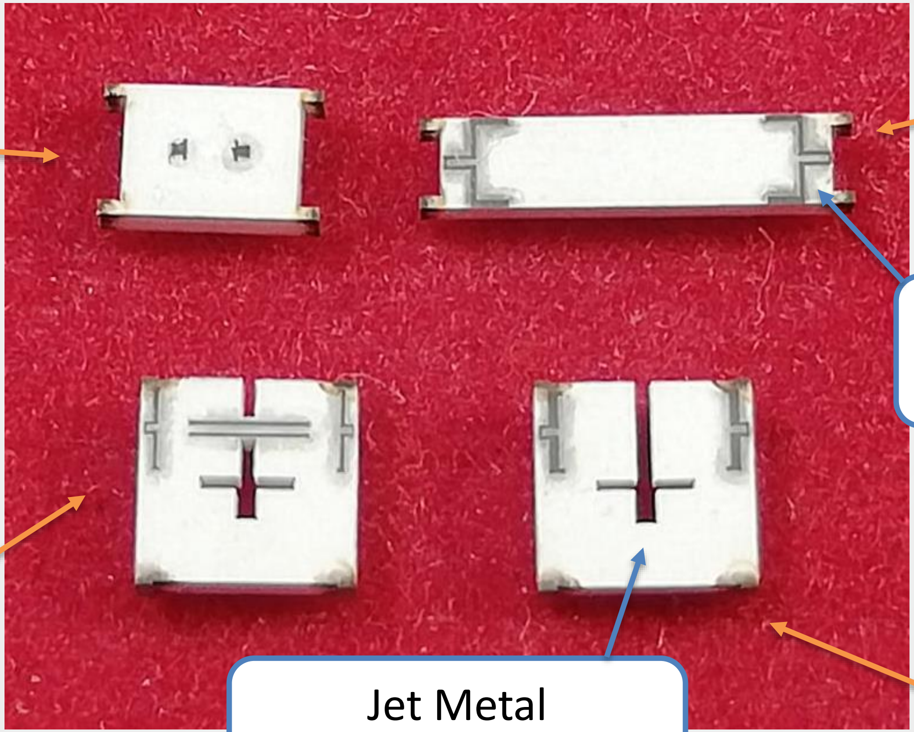


Q-Band ceramic devices

Manufactured devices (40.5 - 43.5 GHz)

Passive devices were designed and manufactured in a 0.66 um thick Alumina substrate (ε_r= 9.8 ± 0.4 and tan δ = 5.10^{-4}) to test the process enhancement.

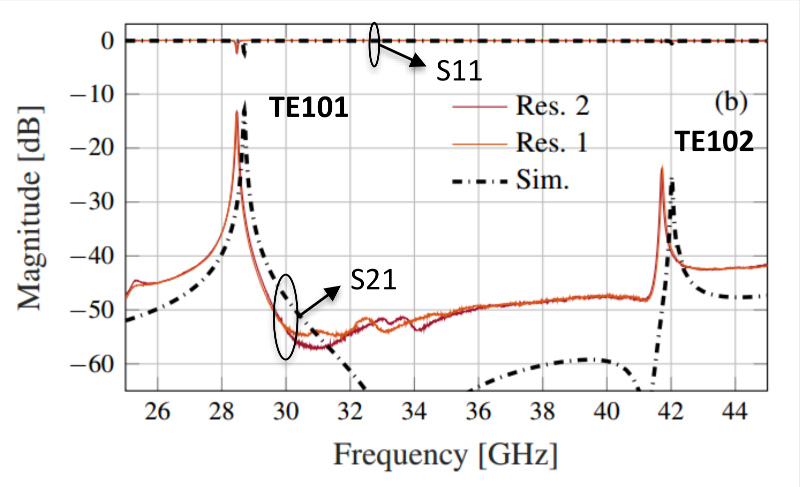
LASER ENGRAVING AND SEPARATION (STEP 3)

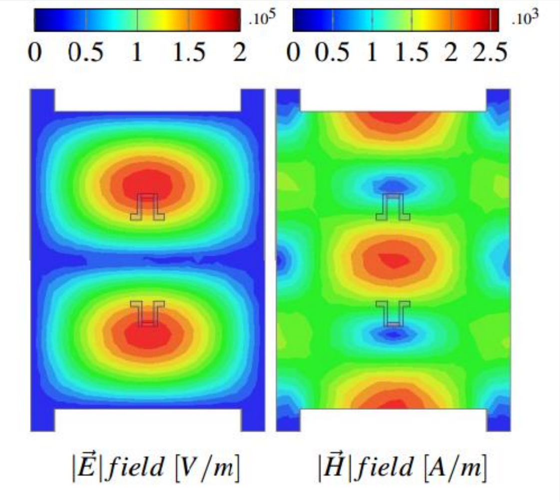


Basic blocks at 42 GHz

TE102 resonators

↑ Higher Q than TE101 (+19.5%).
↓ Lower sensitivity to manufacturing dispersions than TE101.
↓ Larger size (+46.8%).





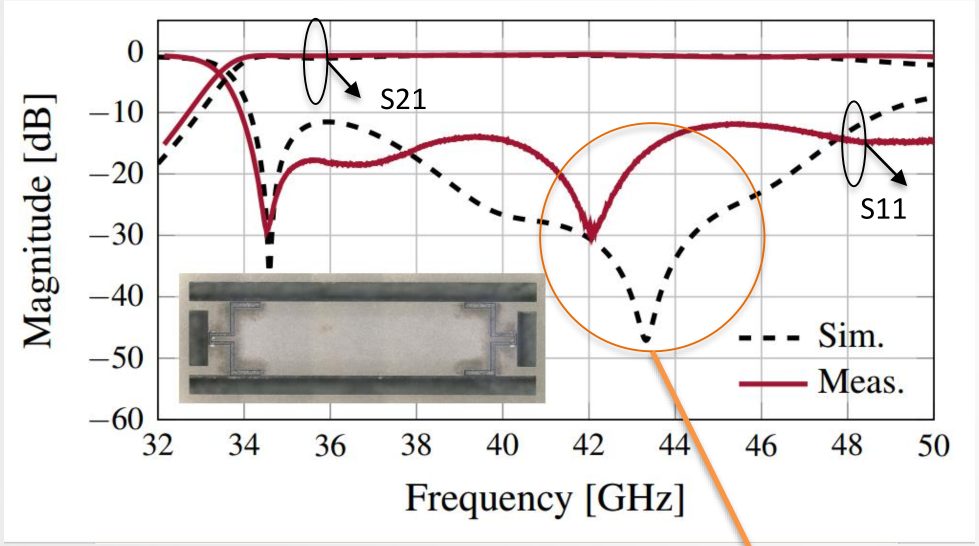
	Resonator 1	Resonator 2
Width (W) [mm]	2.102	2.090
Length (L) [mm]	2.687	2.676
|dW| [µm]	20	30
|dL| [µm]	13	24
|dfo|(TE102) [MHz]	296	331
|dfo|(TE101) [MHz]	223	249
Er	10.08	10.16
Q (TE101)	548	565
Q (TE102)	673	689

Measured quality factors drastically improved and close to the maximum value (Qmax=700).

Basic blocks at 42 GHz

Waveguides

Discrete ceramic waveguides could be useful components for power distribution in specific board regions.



Parameter	Value
Size [mm²]	1.45 x 6
Simulated bandwidth (|S11| < -20 dB) [GHz]	38.5 – 46.3
RL $_{BW=39.5\text{-}43.8\,GHz}$ [dB]	> 14
Attenuation $_{@BW=39.5\text{-}43.8\,GHz}$ [dB/mm]	< 0.13
f_{cutoff} (TE10) [GHz]	34.5
f_{cutoff} (TE20) [GHz]	66

Measurement mismatches

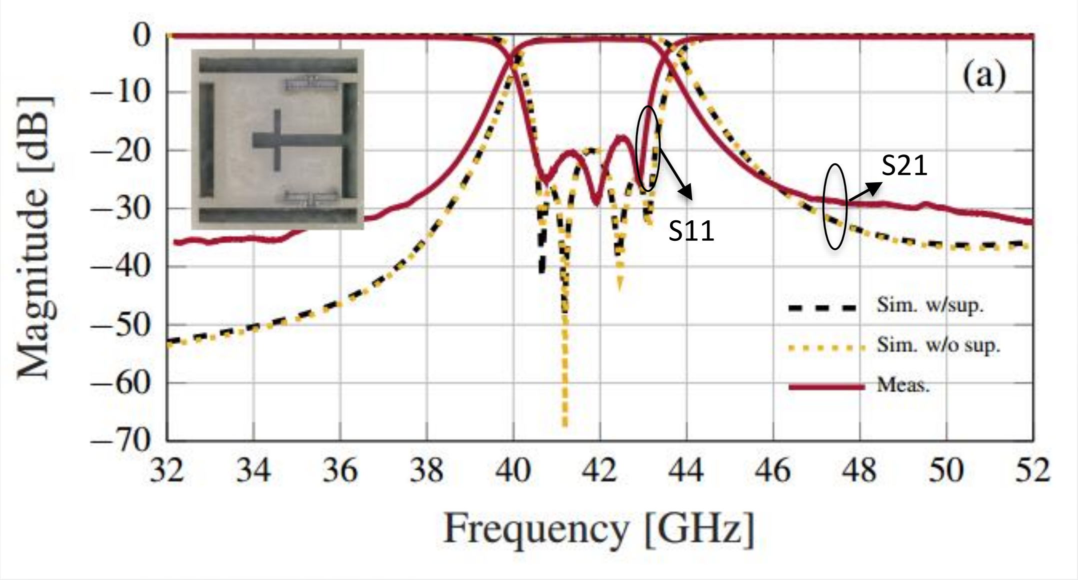
Discrepancies between measurements and simulations are due to:

- overetching on the coplanar accesses.
- difference of excitation position between lumped ports (on the edge of the access) and CPW probe tips (not exactly positioned on the edge).

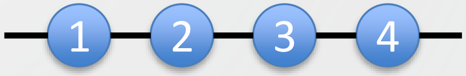
Basic blocks at 42 GHz

4-poles Chebyshev band-pass filter

- Size = 3.07 mm x 3.26 mm
- Bandwidth = 40.35 - 43.10 GHz
- Return loss ≥ 17.7 dB
- Insertion loss ≤ 1.1 dB



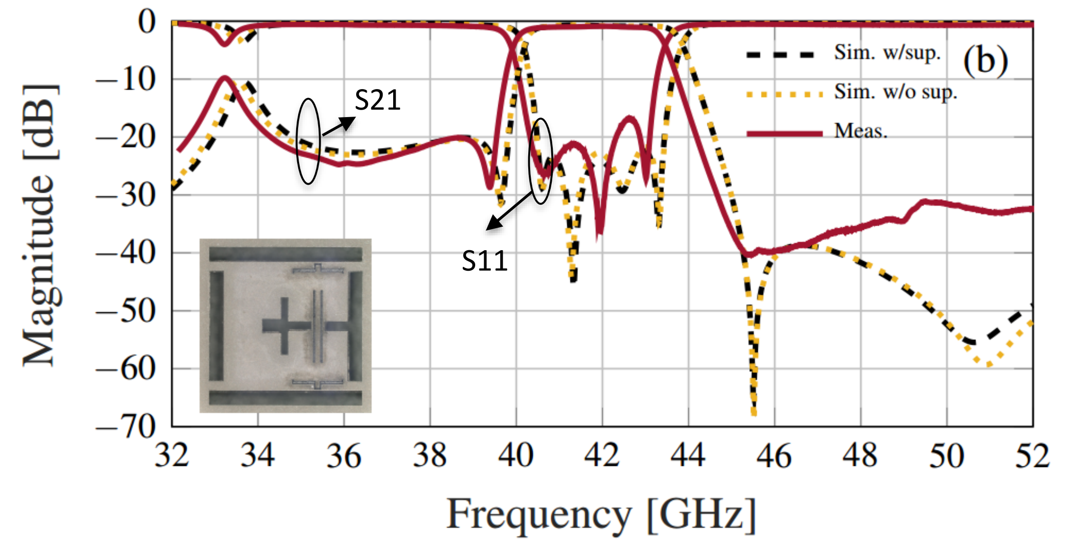
Coupling term	Value
m01, m45	1.04
m12, m34	0.91
m23	0.70
m11, m22, m33, m44	0



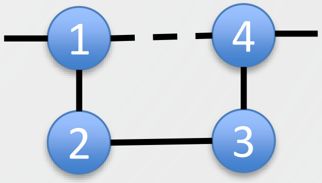
Basic blocks at 42 GHz

4-poles 2-zeros Chebyshev band-pass filter

- Size = 3.13 mm x 3.24 mm
- Bandwidth = 40.45 - 43.28 GHz
- Return loss ≥ 15.5 dB
- Insertion loss ≤ 1 dB



Coupling term	Value
m01, m45	1.02
m12, m34	0.87
m23	0.77
m14, m41	-0.17
m11, m22, m33, m44	0



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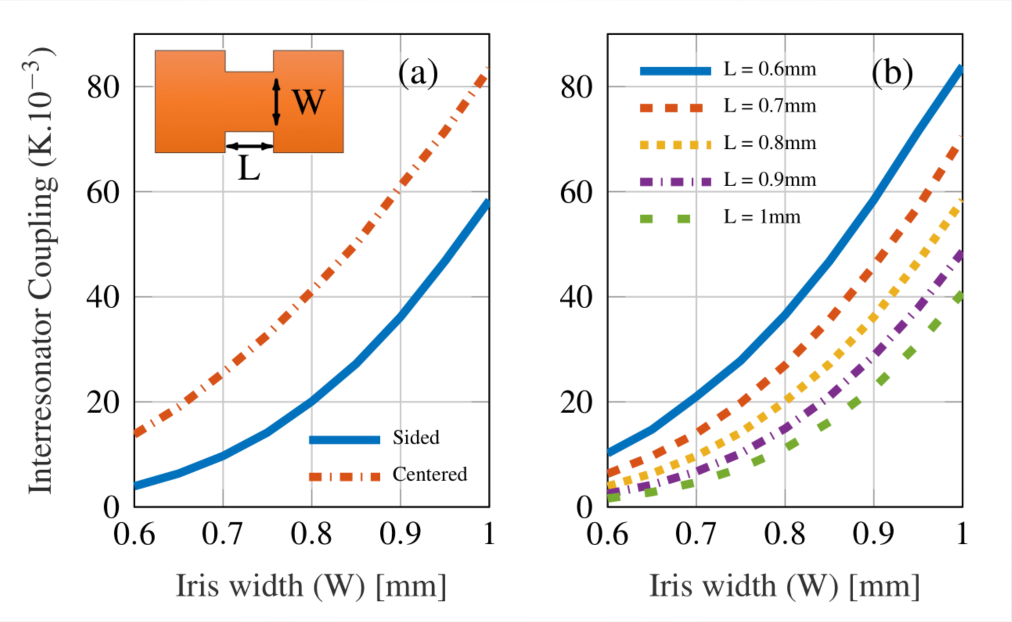
Sensitivity design considerations

Despite of having less coupling than a centered iris for the same size, irises placed on the side of the resonator:

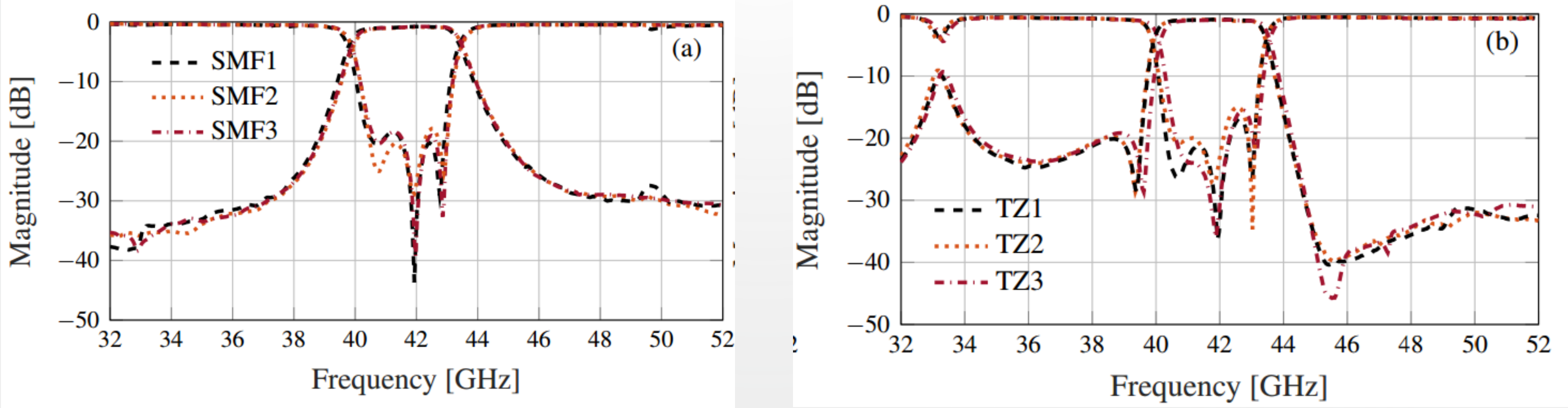
- ↓ simplify the pattern.
- ↓ reduce filter sensitivity to manufacturing dispersion.
- ↓ reduce the fabrication time.

- ✓ avoid violating size restrictions (structural damage) by increasing W and adjusting L to obtain the desired coupling value.
- ✓ Lead to a good balance between mechanical robustness, sensitivity and total size.



Basic blocks at 42 GHz: Repeatability

Sample		Size [mm²]	BW [GHz]	RL [dB]	IL [dB]	$Att._{@34GHz}$ [dB]	$Att._{@50GHz}$ [dB]	Ripple [dB]
SMF	1	3.38 x 3.11	40.2 - 42.9	18.4	0.78	34	29	0.25
	2	3.37 x 3.11	40.4 - 43.0	17.9	0.86	35	30	0.31
	3	3.37 x 3.11	40.4 – 43.0	18.1	0.77	34	30	0.41
TZ	1	3.34 x 3.12	40.2 – 43.1	16.5	0.87	18	31	0.31
	2	3.35 x 3.12	40.2 – 43.1	14.9	0.89	18	32	0.23
	3	3.32 x 3.10	40.4 – 43.3	15.5	0.94	17	32	0.21



Conclusions

- Technology characterization and constraints for 2D/2.5D passive devices in LMST technology has been presented.

- Fabrication dispersion related to laser uncertainty (10 um) and imperfections on the side walls (4 - 5 um) were identified, measured and tested in single-mode cavity resonators.

- Performances were enhanced from previous work up to the ideal quality factor by identifying the main sources of losses, improving the metallization process and applying design strategies that helps with metal layer deposition (trenches).

Conclusions

- The process addresses good accuracy for millimeter-wave devices manufactured in Alumina substrates up to 0.7 um thickness.
- Special attention must be paid during the laser etching step (STEP 3). Laser power must be controlled to avoid high overetching in the coplanar accesses.
- Design strategies were introduced and applied to reduce filters sensitivity for incoming Q-band 5G applications.
- Two different filter topologies (40.5 - 43.5 GHz) were designed and manufactured presenting good performances and fabrication repeatability.
- Compact area and competitive unloaded quality factor (689 at 42 GHz) for devices manufactured in low-loss Alumina substrates.

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