Recent developments in microwave filters based on GaN/Si SAW resonators, operating at frequencies above 5 GHz

Alina-Cristina BUNEA[1], Dan NECULOIU[1], Adrian DINESCU[1], Leo Arij FARHAT[2]
[1]National Institute for R&D in Microtechnologies – IMT Bucharest
[2]ESTEC, ESA
alina.bunea@imt.ro

Outline

- **Introduction**
- **Design of SAW-BPF**
- **Fabrication and characterization**
- **Thermal stability analysis**
- **Conclusions & Future developments**

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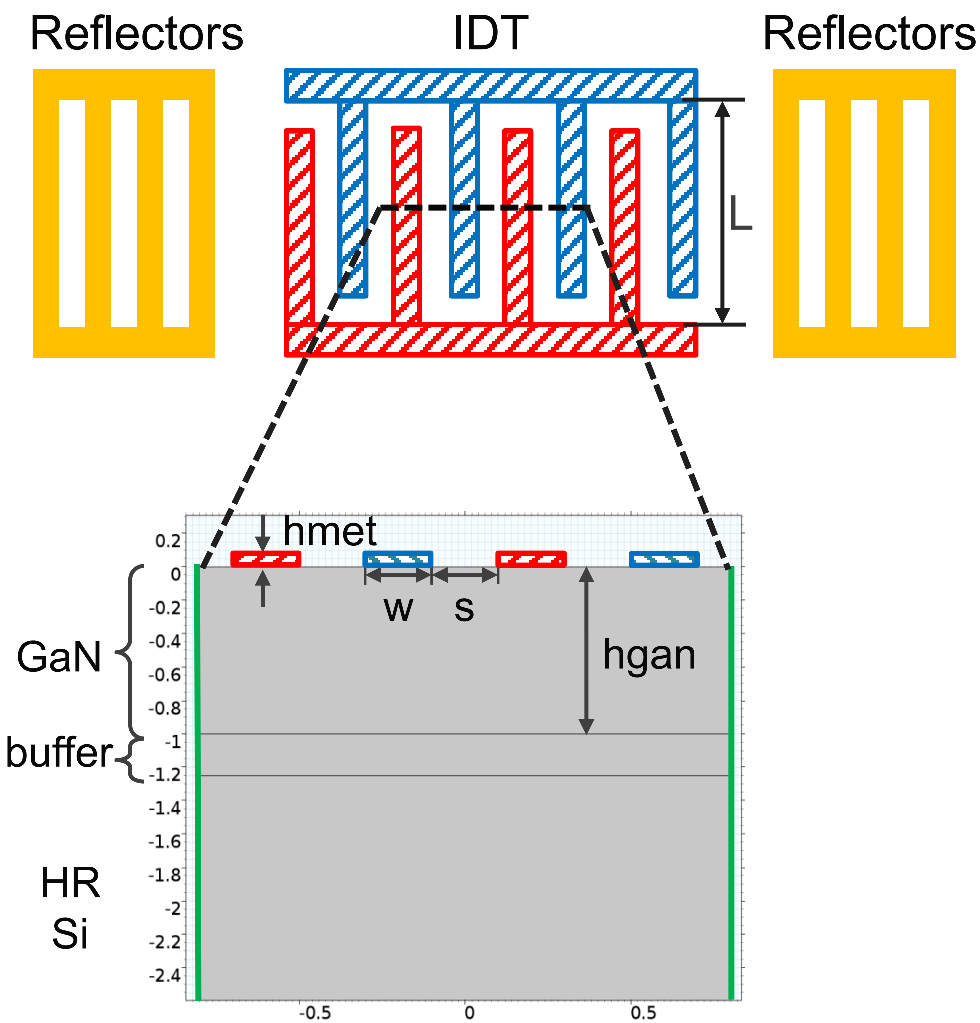
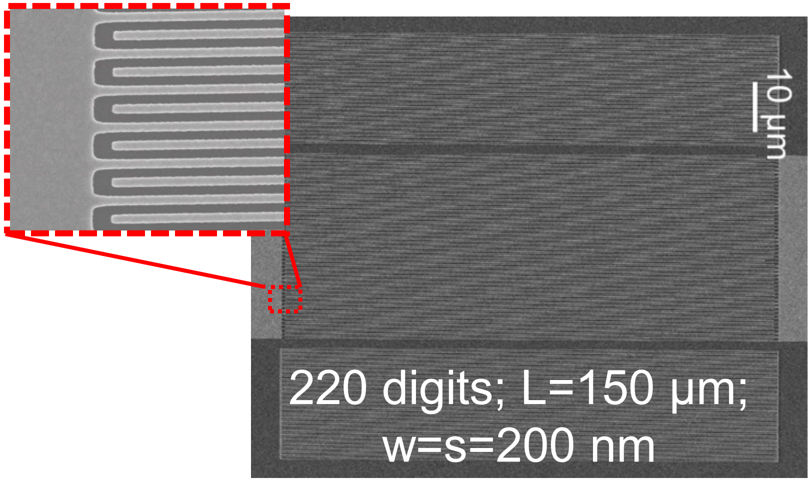
Introduction

- "*Microwave filters based on GaN/Si SAW resonators, operating at frequencies above 5 GHz*" (ESA project No. 40000115202/15/NL/CBi)

- **Main project objectives**: design, fabrication and characterization of monolithic integrated band pass filters processed on GaN/Si, operating at >5 GHz
  - IDTs with digit/interdigit widths below 200 nm
  - use of multiple SAW-Rs integrated monolithically with printed inductors (connected in series or in parallel)

Surface Acoustic Wave (SAW) resonator





Custom grown wafer specifications

	NTT-AT Japan
Si Wafer resistivity	>6000 Ohm·cm
Si Wafer thickness	500±25 µm
Si orientation	(111)±0.1°
Si wafer diameter	3" (76.2 mm)
Wafer bow	<30 µm
Buffer thickness	300 nm
Buffer content	AlN
GaN thickness	1 µm

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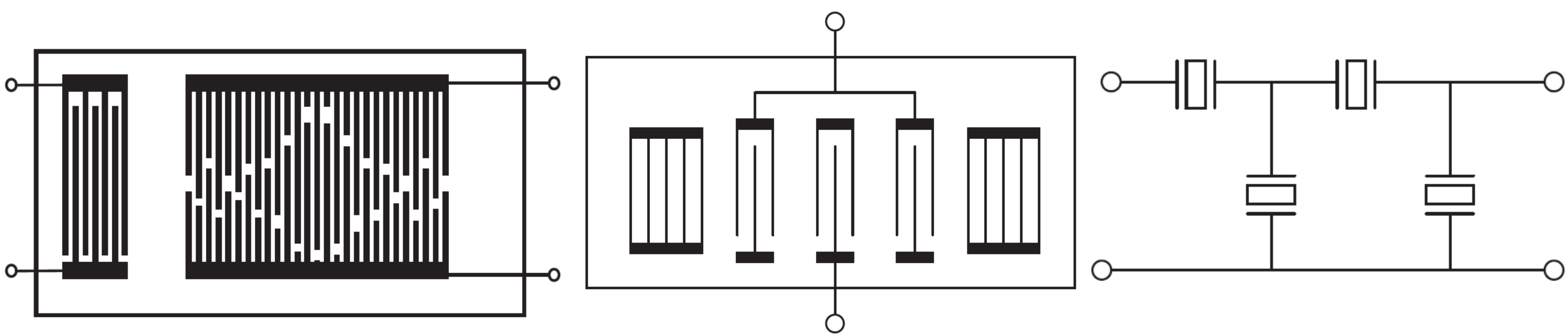
SAW Bandpass Filters:

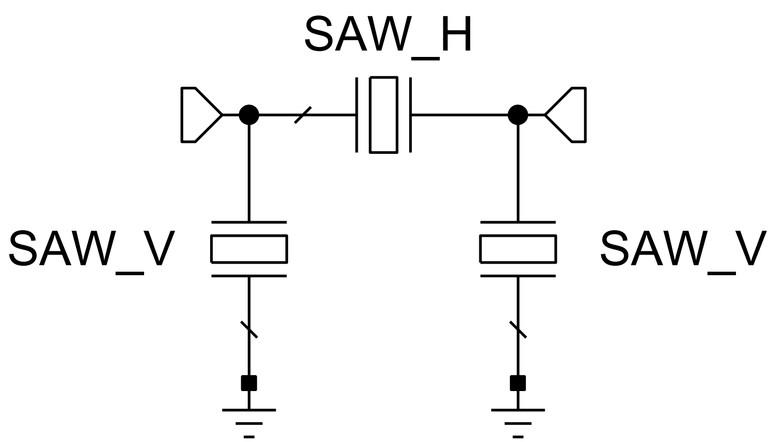
a) Delay line type filters: high propagation losses
b) Longitudinally-Coupled Resonator filter: difficult to implement in CoPlanar Waveguide topology
c) Impedance Element Filters (ladder filters): performances limited by the SAW resonators parameters



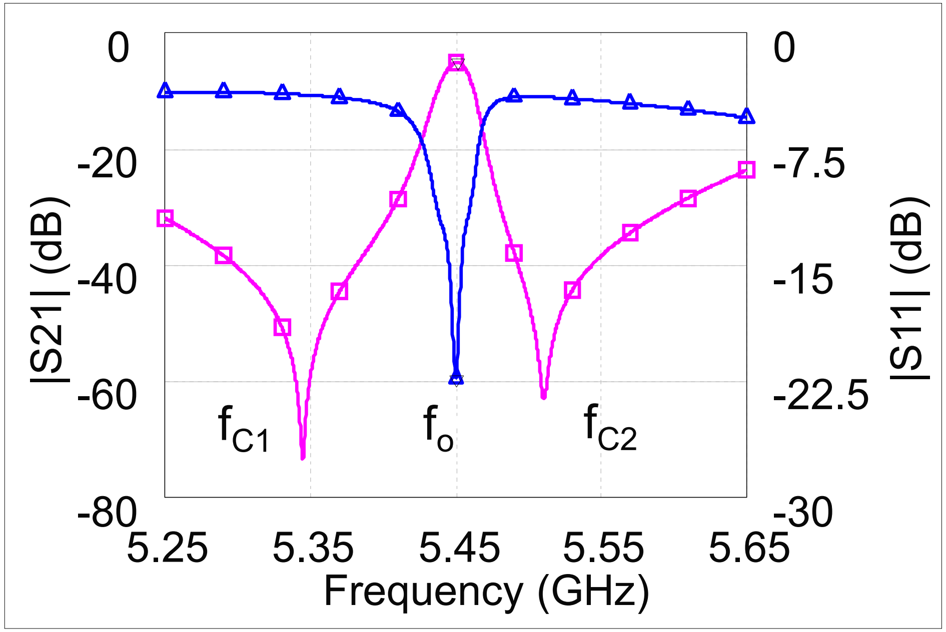
(a) (b) (c)

Impedance Element Filter in PI topology

Selected filter configuration using Impedance Element Filter approach:



PI type configuration



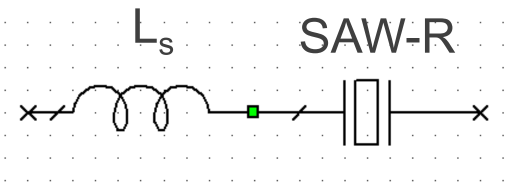
The SAW-R components were selected for a resonance frequency around 5.5 GHz, corresponding to digit/interdigit widths of 200 nm.

$$f_{s,SAW\_H} = f_0 = f_{p,SAW\_V}$$

$$f_{p,SAW\_H} = f_{c2} > f_0 \qquad f_{s,SAW\_V} = f_{c1} < f_0$$

Design procedure – Analytic design

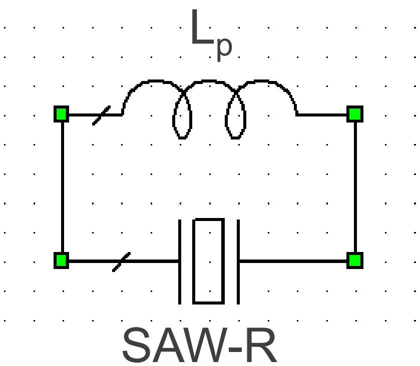
Effect of a series inductor L_S << L_m: same f_p, but:



$$\omega^4 + \left(\frac{1}{L_s C_0} - \omega_p^2\right)\omega^2 - \frac{\omega_p^2}{L_{ser} C_0} = 0$$

$$(\omega_s')^2 \simeq \frac{\left(\omega_p^2 - \frac{1}{L_s C_0}\right) \pm \sqrt{\left(\frac{1}{L_s C_0} - \omega_p^2\right)^2 + 4\frac{\omega_p^2}{L_s C_0}}}{2}$$

Effect of a parallel inductor L_P << L_m: same f_s but:

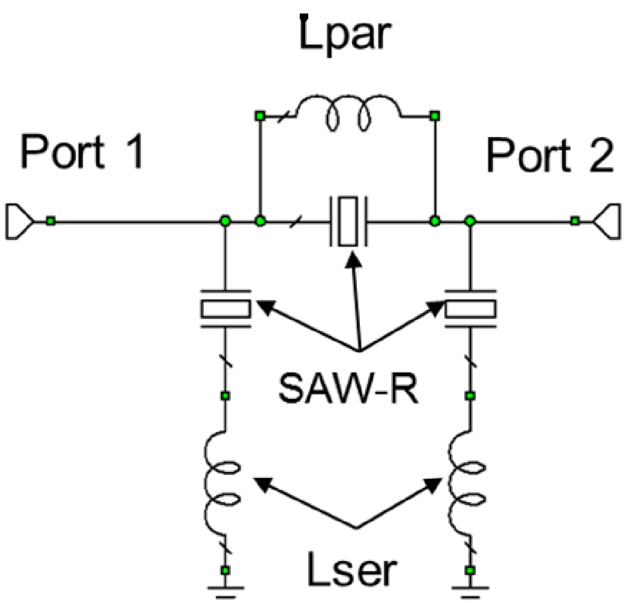


$$\omega^4 - \omega_p^2\omega^2(1-\eta) + \eta\omega_s^2\omega_p^2 = 0$$

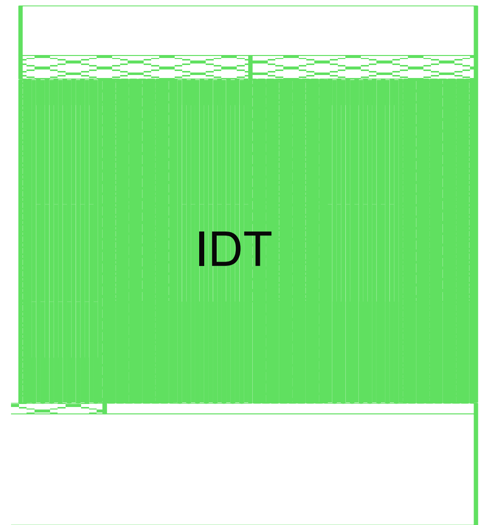
$$\eta = \frac{L_m}{L_p(1 + L_m C_0 \omega_s^2)}$$

$$\left(\omega_p'\right)^2 \simeq \frac{1}{2}\omega_p^2\left[(1-\eta) \pm \sqrt{(1-\eta)^2 - 4\eta\frac{\omega_s^2}{\omega_p^2}}\right]$$

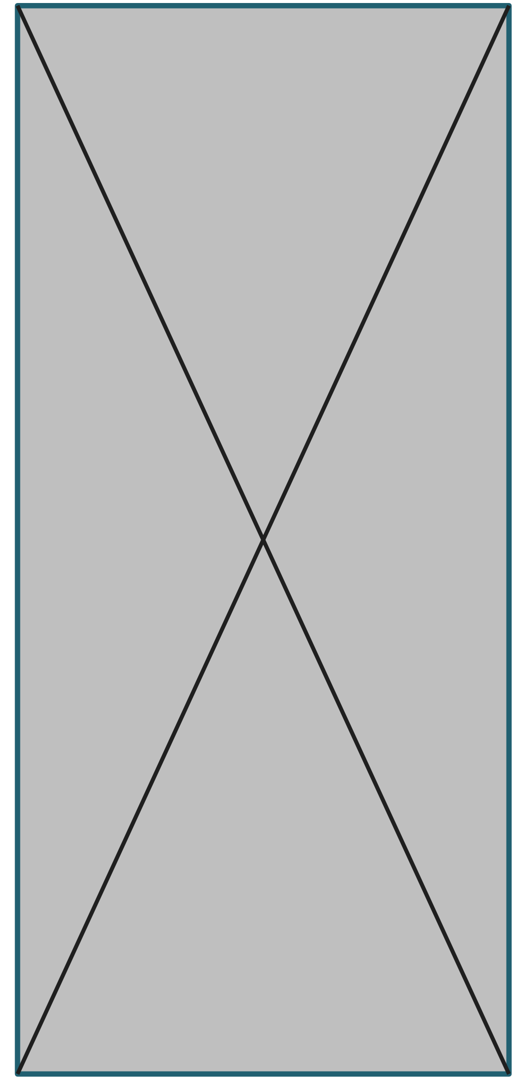
Band Pass Filter in PI configuration



Digit/interdigit widths=200 nm

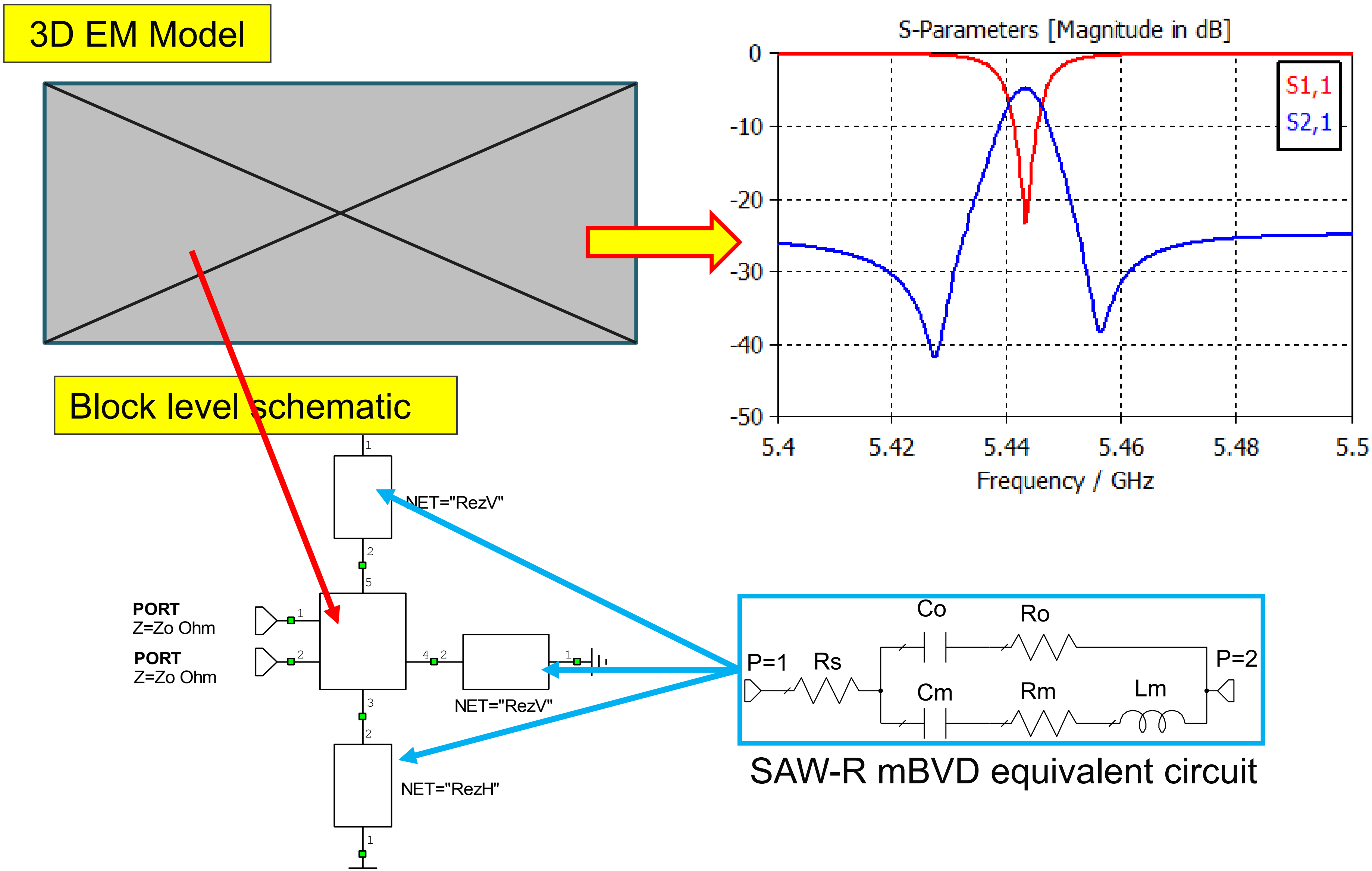


- very compact of only **3x0.8 mm²**
- the series printed inductors have a width of 20 µm
- input/output CPW lines have the gap-signal-gap widths of 50-100-50 µm, for a characteristic impedance of ~50Ω



The circuit layout of the BPF in PI configuration

Co-simulation approach for filter design



Schematic used for filter design

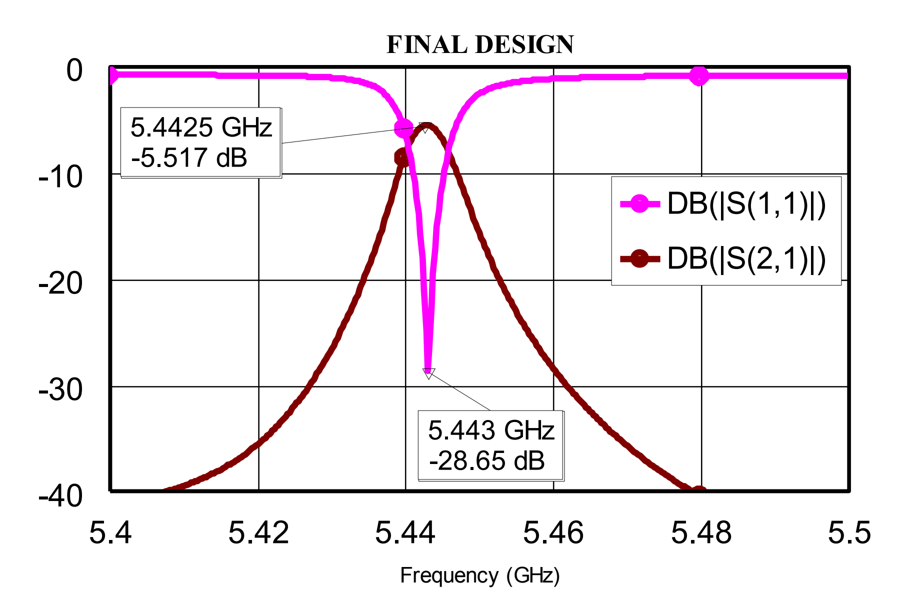
Band Pass Filter in PI configuration

Equivalent circuit parameters for the vertical (V) and the horizontal (H) SAW-R

	Co [pF]	Cm [fF]	Lm [nH]	Rm [Ω]	Ro [Ω]	Rs [Ω]
SAW-R-V						
SAW-R-H						

Layout parameters for the vertical (V) and the horizontal (H) SAW-R

	No. of digits	Digit length [μm]
SAW-R-V		
SAW-R-H		



Simulation results for the PI configuration BPF

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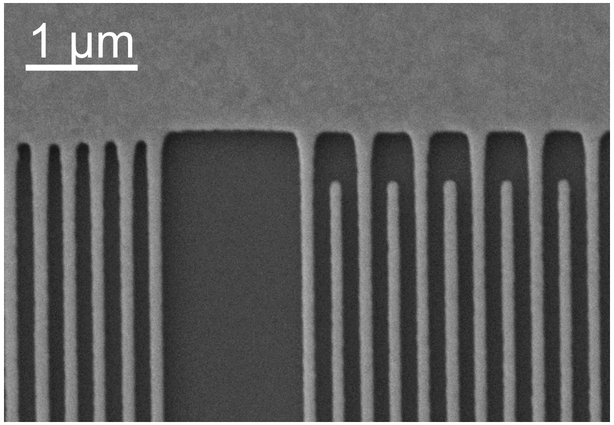
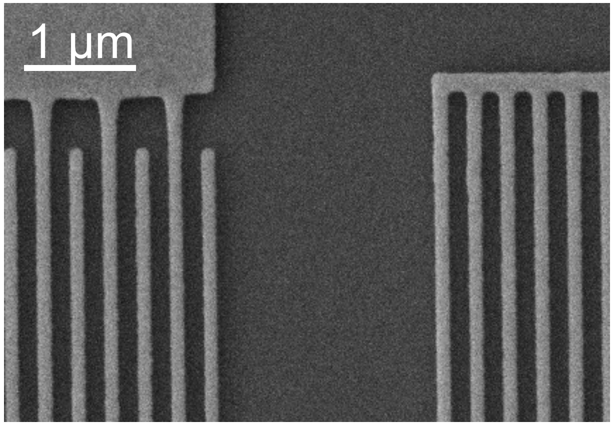
Fabrication of SAW-Rs operating > 5 GHz

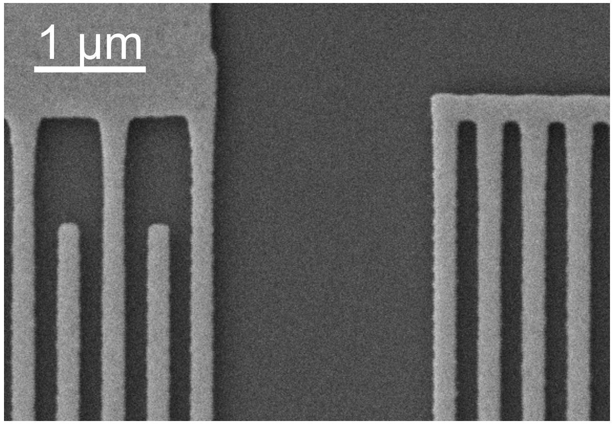
- SAW-R on GaN/Si for frequencies beyond 5 GHz
  - IDTs with digit/interdigit widths below 300 nm
  - nanolithographic patterning of the IDTs
  - writing field limited to a maximum of 100x100 µm^2 to avoid the negative charging and stitching effects
- e-beam lithography
  - maskless lithography technique; dedicated EBL machine - Raith e-Line; electron resist PMMA 950k A4
- metal layers deposited using a highly directional e-beam evaporation equipment (Temescal FC 2000)
  - favors the lift-off process -> neat lines without side walls



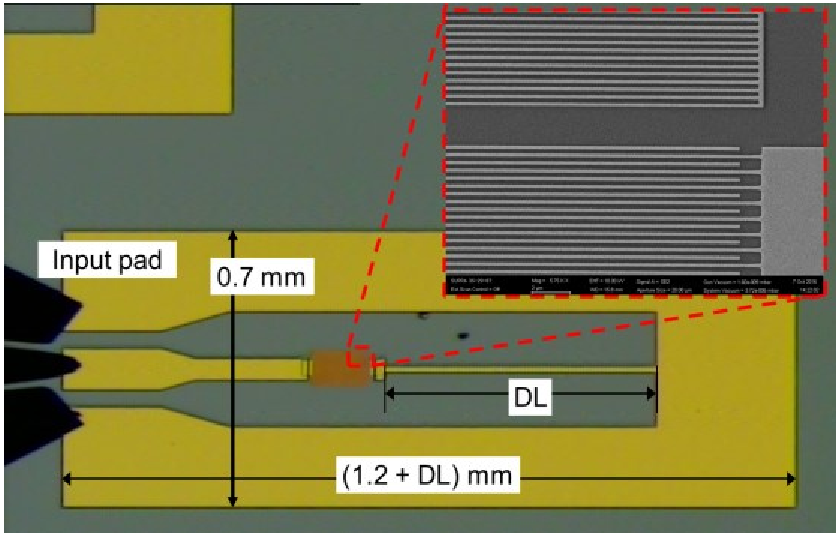
Digit width = 130 nm

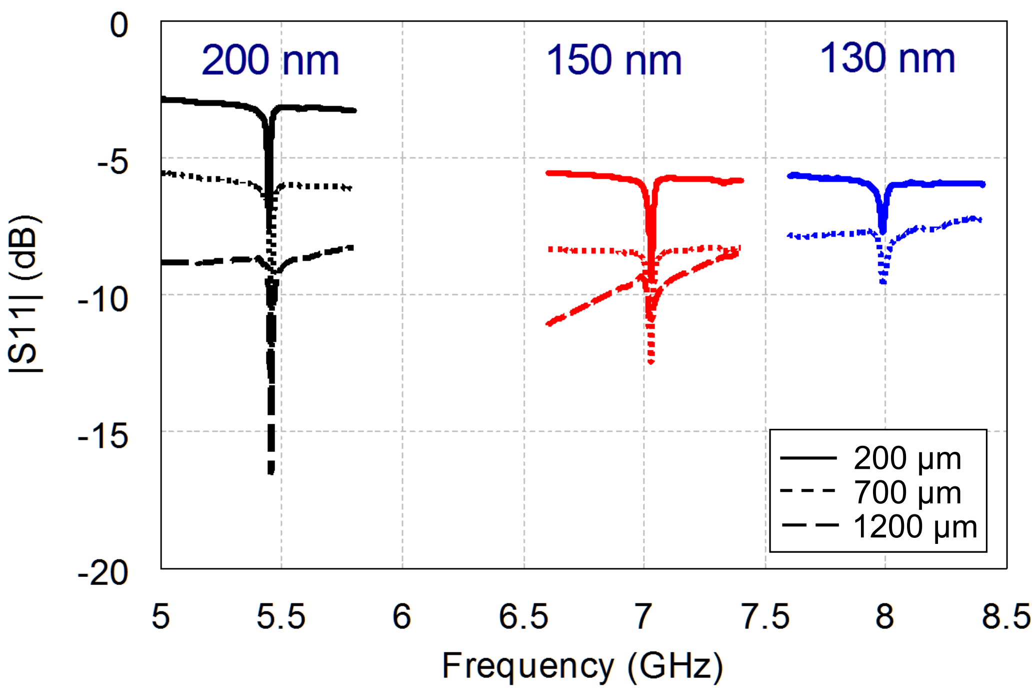


Digit width = 150 nm



Digit width = 200 nm

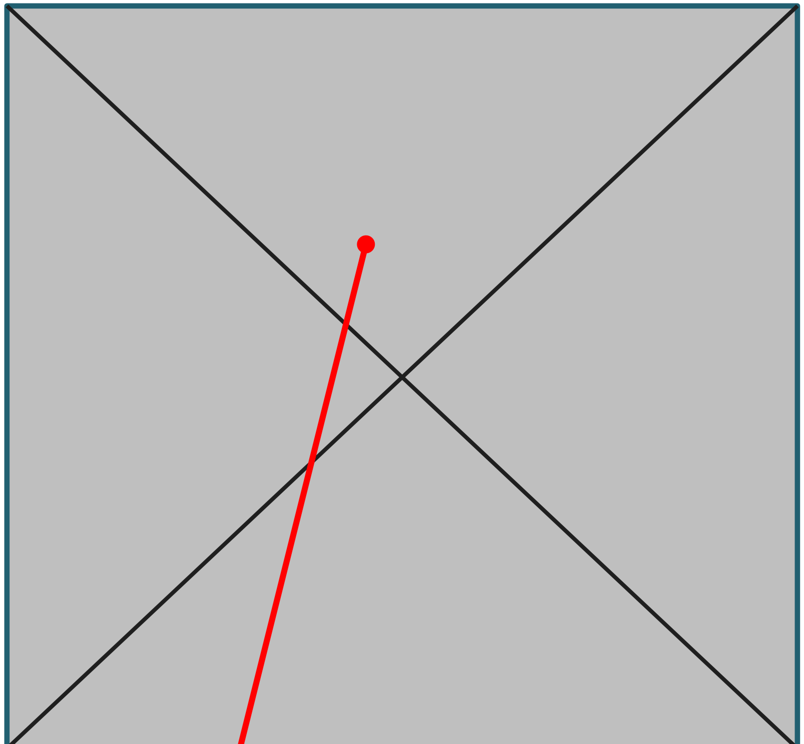




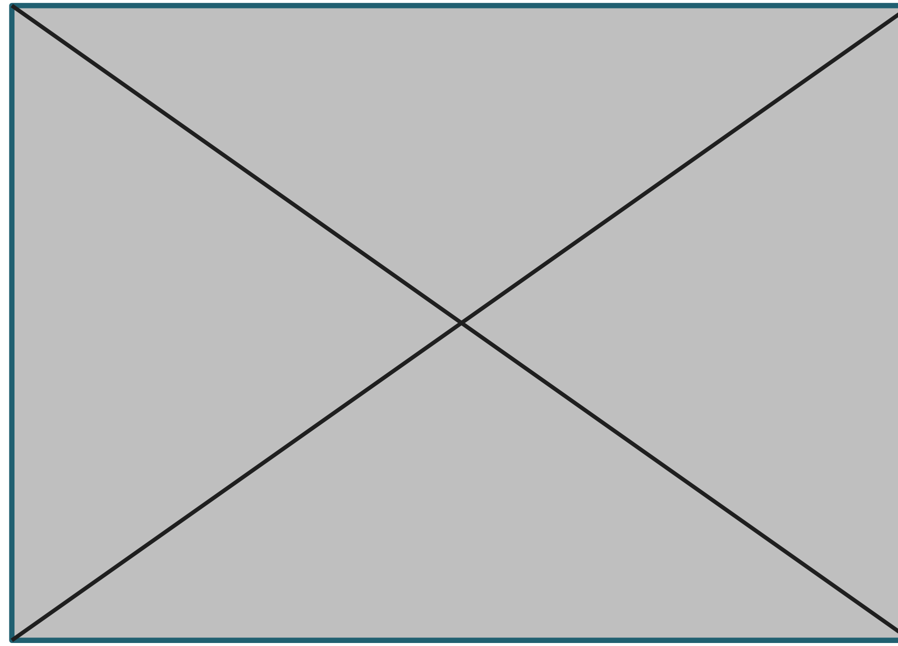
Thermal stability analysis between 20°C – 150°C

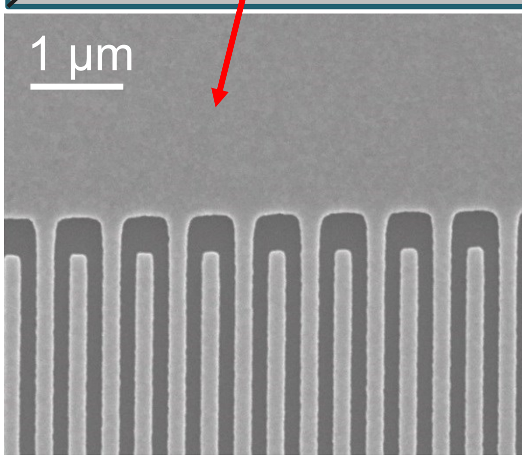
Pitch	DL = 0.2 mm		DL = 0.7 mm		DL = 1.2 mm	
	fres @ 20°C [GHz]	TCF [ppm/°C]	fres @ 20°C [GHz]	TCF [ppm/°C]	fres @ 20°C [GHz]	TCF [ppm/°C]
0.4 µm	5.4485	NA	5.4585	-43.72	5.4565	-43.25
0.3 µm	7.0285	-41.66	7.0265	-40.47	7.0255	-39.88
0.26 µm	7.9865	-43.23	7.9895	-42.7	NA	NA

Measurement results for the PI-type filter



Measurement vs. simulation





Parameter	Re-simulated	Measured
Insertion losses	10.5 dB	10.3 dB
Return loss	8.6 dB	9.2 dB
Out of band rejection	~22 dB	~20 dB
-3dB bandwidth	8.3 MHz	10 MHz
Central frequency	5.506 GHz	5.5 GHz

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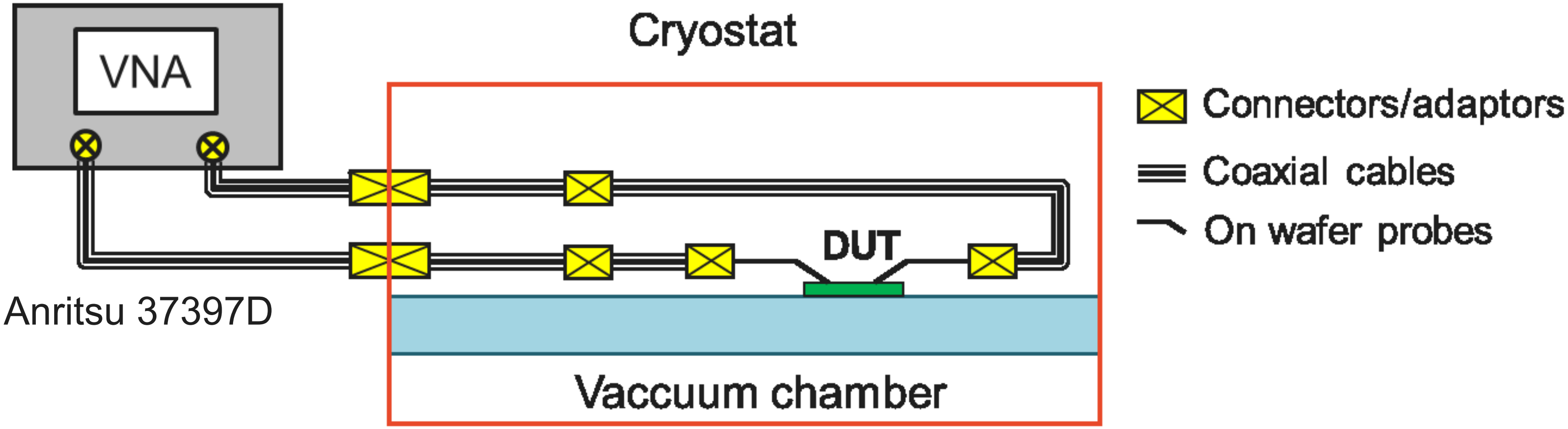
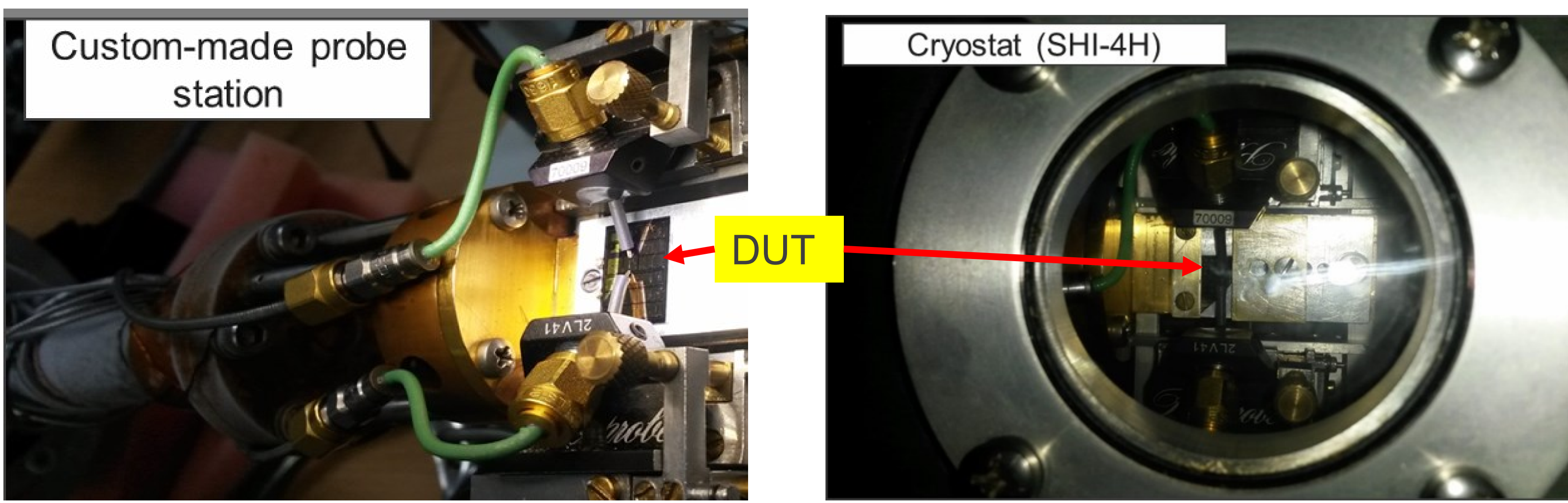
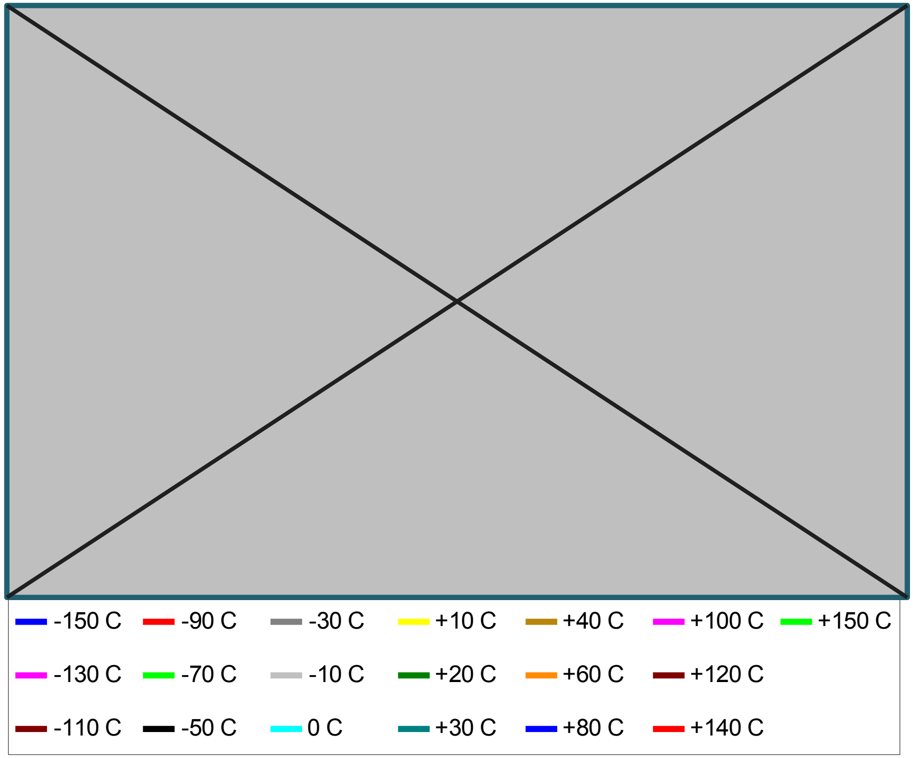
Measurement setup for thermal analysis

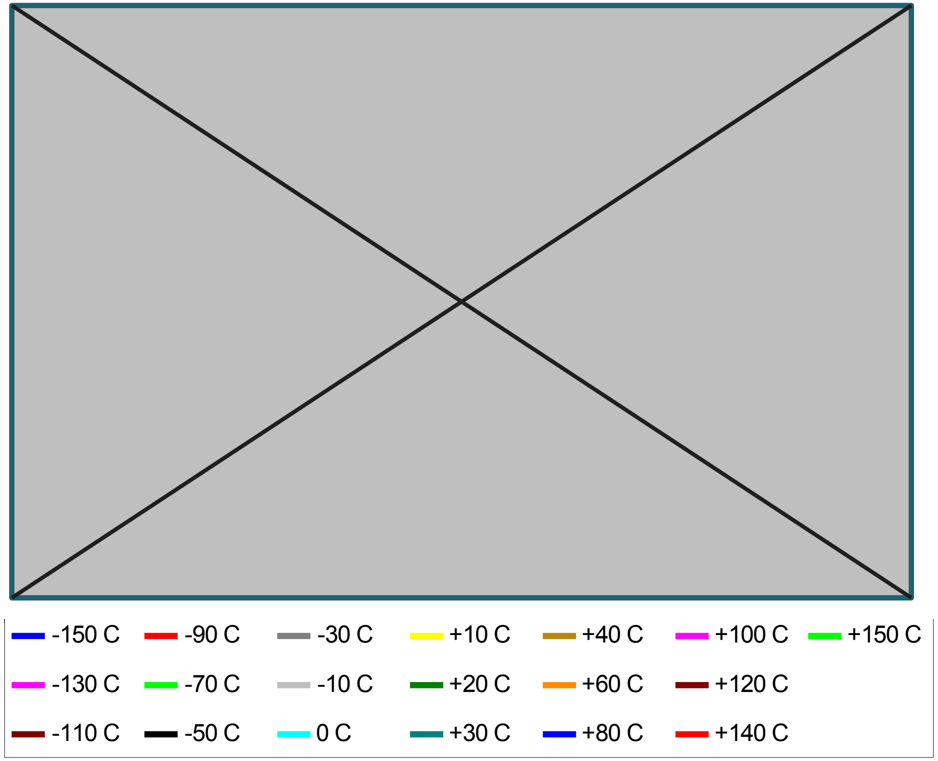


In-house developed on-wafer measurement setup used to record S parameter measurements at different temperatures



Thermal stability analysis -150…+150°C





- General shape of the frequency response is preserved
- Filter selectivity becomes worse with the temperature increase

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Results vs. SotA

BPF Parameter	Results	SAW-BPF SotA [1]	[2]	[3]	[4]
Insertion losses	10.3 dB	25.5 dB/ 24.4 dB	14 dB	27 dB/ 35 dB	33 dB
Return loss	9.2 dB	N.A.	N.A.	N.A.	0.4 dB
Out of band rejection	20 dB	~35 dB	15 dB	23 dB/ 15 dB	10 dB
-3dB bandwidth	10 MHz	N.A.	20.2 MHz	N.A.	N.A.
Central frequency	5.5 GHz	237.8 MHz/ 493.7 MHz	2.1 GHz	1.625 GHz/ 2.25 GHz	5.64 GHz
Operating temperature	-55°C… +125°C	N.A.	N.A.	N.A.	N.A.
Obs.		Delay lines /Fe-doped GaN on sapphire	Resonator on membrane	GaN/ sapphire	Delay line GaN/Si

Reported results are beyond the state of the art for SAW on GaN/Si based band pass filters

[1] Y. Fan et. al., *"Surface acoustic waves in semi-insulating Fe-doped GaN films grown by hydride vapor phase epitaxy"*, **Applied Physics Letters**, 105, 062108 (2014)

[2] A. Ansari et. al, "*Gallium nitride-on-silicon micromechanical overtone resonators and filters*", **Proc. IEEE Int. Electron Devices Meeting (IEDM)**, 20.3.1–20.3.4, (2011)

[3] T Palacios et. al, "*High frequency SAW devices on AlGaN: Fabrication, Characterization and integration with optoelectronics*", **IEEE Ultrasonics Symposium**, **2002**

[4] A Muller, et al. "*SAW devices manufactured on GaN/Si for frequencies beyond 5 GHz*" IEEE **Electron Devices Lett**. Vol. 31, pp 1398-1400, **Dec 2010**

Conclusions

- **Compact (3x0.8 mm^2) monolithic integrated SAW-BPF operating @ 5.5 GHz**
  - 10 dB IL; 20 dB rejection; 10 MHz -3dB BW
- **SAW-BPF on GaN/Si**
  - monolithic integration of active devices (HEMTs) possible
  - can be used in harsh environments and extreme temperature conditions

Thank you for your attention!