ESA Contract Number: 4000130082/20/NL/HK

High Frequency Millimetre-Wave Voltage Controlled Oscillator

Final Presentation

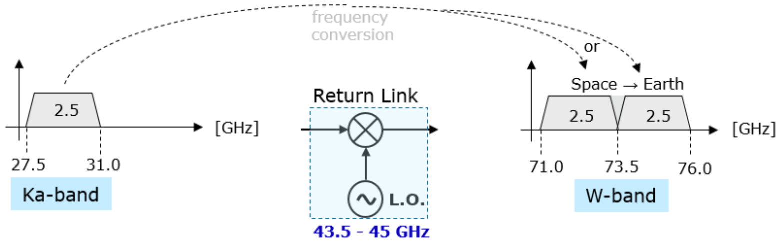
29 March 2023

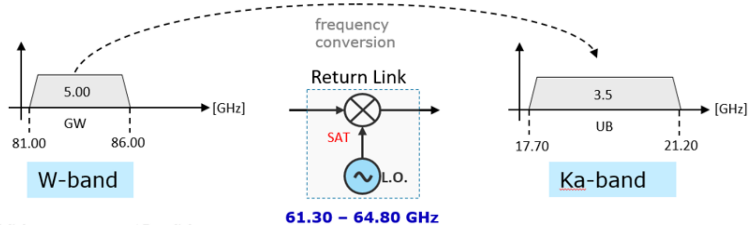
Contents

- **Introduction**
- Concept (resonator, phase shifter, active element, topology)
- Design and Verification
- Compliance matrix and comparison with state-of-the-art
- Conclusions

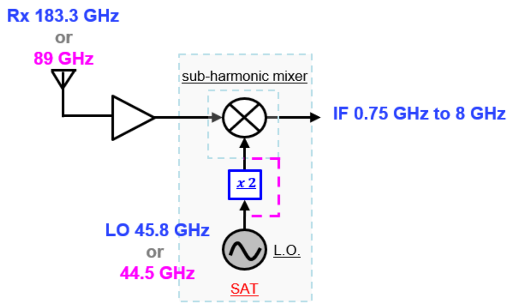
Introduction: Scenarios

HTS (High Throughput Satellites)
Broadcast DVB-S2X standard





EO (Earth Observation)
Remote Sensing Front-End Rx Radiometer



DVB-S2X Standard Phase Noise Requirements

Offset (Hz)	PROFILE "2012-Ka-Non DTH" SSB (dBc/Hz)			
	uplink	satellite	downlink	tot-equiv
10	-42	-33	-42	-32.93
100	-72	-62	-72	-61.96
1K	-82	-80	-82	-78.73
10K	-92	-90	-92	-88.73
100K	-102	-95	-102	-94.83
1M	-112	-106	-112	-105.74
10M	-122	-116	-122	-115.74
50M	-124	-118	-124	-117.74

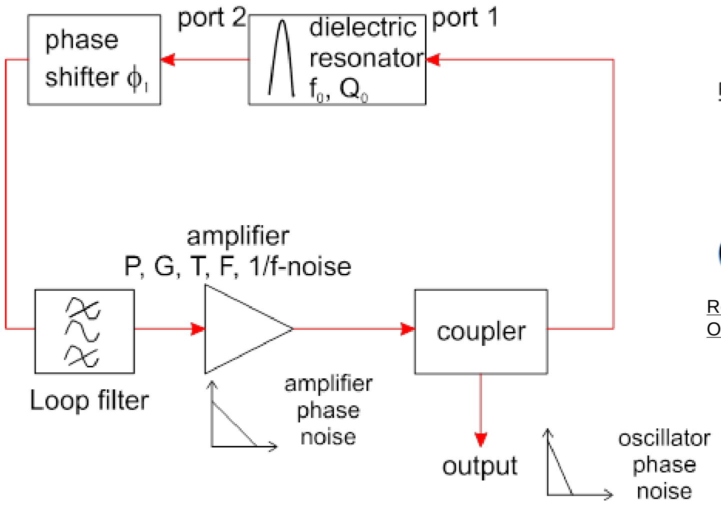
Possible LO frequencies for EO applications

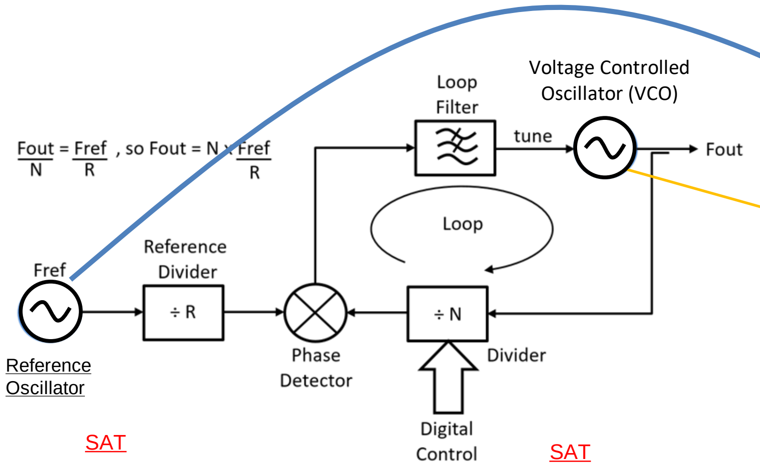
Rx freq	LO freq	VCO freq							
		1/2	1/3	1/4	1/6	1/8	1/9	1/12	Instrument
54	46	23.0	15.3	11.5	7.7	5.8	5.1	3.8	MWI, MWS
89	44.5	22.3	14.8	11.1	7.4	5.6	4.9	3.7	MWI, MWS
118	59	29.5	19.7	14.8	9.8	7.4	6.6	4.9	MWI
166	83	41.5	27.7	20.8	13.8	10.4	9.2	6.9	MWI, MWS
183	91.5	45.8	30.5	22.9	15.3	11.4	10.2	7.6	MWI, MWS, ICI
229	114.5	57.3	38.2	28.6	19.1	14.3	12.7	9.5	MWS
243	121.5	60.8	40.5	30.4	20.3	15.2	13.5	10.1	ICI
325	162.5	81.3	54.2	40.6	27.1	20.3	18.1	13.5	ICI
448	224	112.0	74.7	56.0	37.3	28.0	24.9	18.7	ICI
664	332	166.0	110.7	83.0	55.3	41.5	36.9	27.7	ICI
1080	540	270.0	180.0	135.0	90.0	67.5	60.0	45.0	Juice lower edge
1280	640	320.0	213.3	160.0	106.7	80.0	71.1	53.3	Juice upper edge

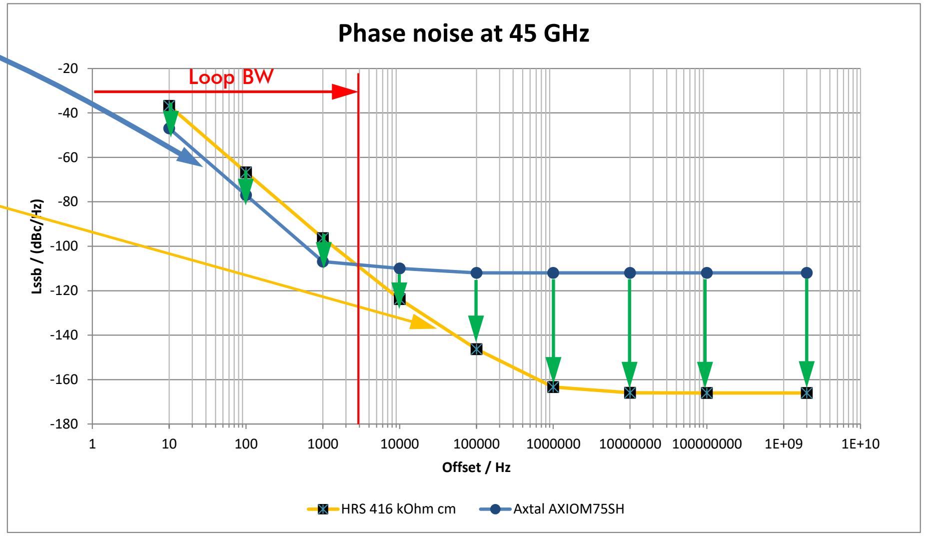
baseline
alternative

- Communication links with enhanced phase noise requirements.
- Local Oscillator: Dielectric Resonator Oscillators (DRO's) available up to 30 GHz only.
- LO frequency must then be obtained by means of additional multiplier circuits and band-pass filters.

Introduction







$$L_{ssb}(f) = 10 \cdot log\left[\frac{1}{2}\cdot\left(1+\frac{f_0^2}{4Q_l^2 f^2}\right)\cdot\left(1+\frac{\alpha}{f}\right)\cdot\frac{GFkT}{P}\right]$$

f0	4.50E+10	Hz
fc	300	Hz
Ql	24696	
k	1.38E-23	J/K
T	290	K
F_eff	6.31	corr. to 8dB
Ps (at amplifier input)	5.00E-04	W

- Target: mm-wave oscillator with very low phase noise, lightweight, low power consumption.
- Usable in PLL-configuration.

- Introduction
- **Concept (resonator, phase shifter, active element, topology)**
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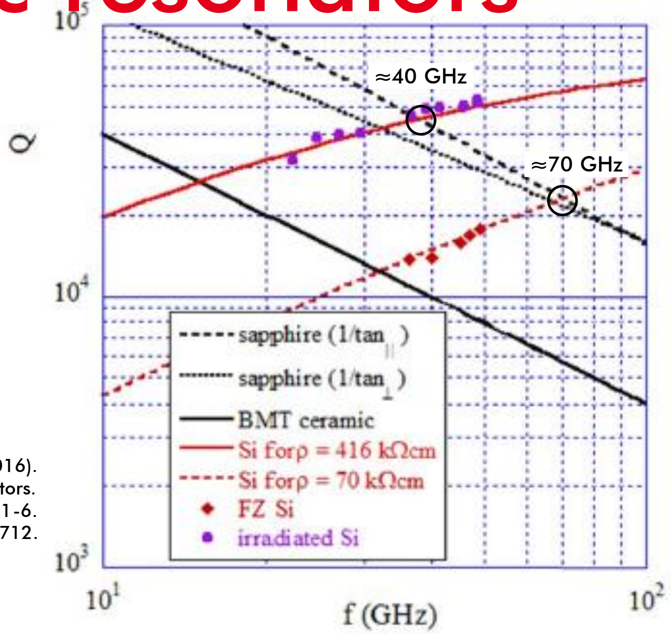
Resonators and phase shifter

Dielectric resonators



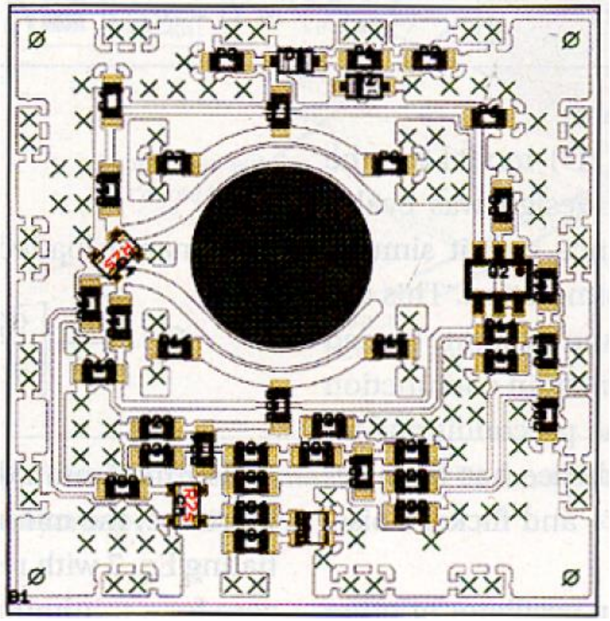
Krupka, Jerzy & Kaminski, Pawel & Jensen, Leif. (2016). High Q-Factor Millimeter-Wave Silicon Resonators. IEEE Transactions on Microwave Theory and Techniques. PP. 1-6. 10.1109/TMTT.2016.2607712.

HRS:

$$tan\delta = \frac{\varepsilon''}{\varepsilon'} + \frac{1}{\rho\omega\varepsilon_0\varepsilon'},\ tan\delta_{diel} = \frac{\varepsilon''}{\varepsilon'}$$

- Q is limited by tanδ of the underlying dielectric.
- Sapphire best below 40 GHz.
- Temperature-compensated dielectrics: BMT, BZN
  - Qxf(GHz)= 40,000 to 250,000 corresponding to max. Qmax of 5,500 at 45 GHz.
- HRS:
  - Losses are both electric and dielectric leading to an inverted frequency dependence of the losses.
  - Standard material with resistivity up to 70 kOhm cm, proton / neutron irradiated material up to 416 kOhm cm. Available from Topsil GlobalWafers Semiconductor Materials A/S, DK-3600 Frederikssund.

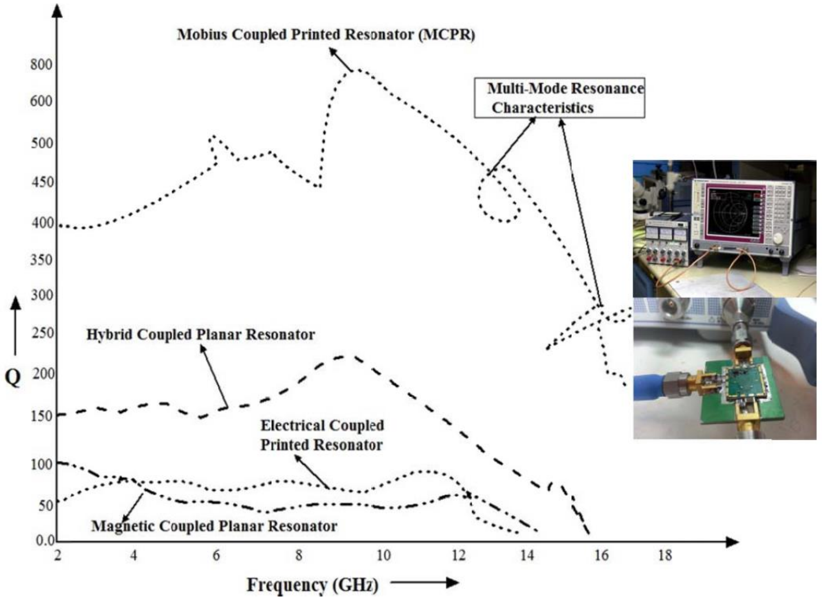
TE011-type resonator

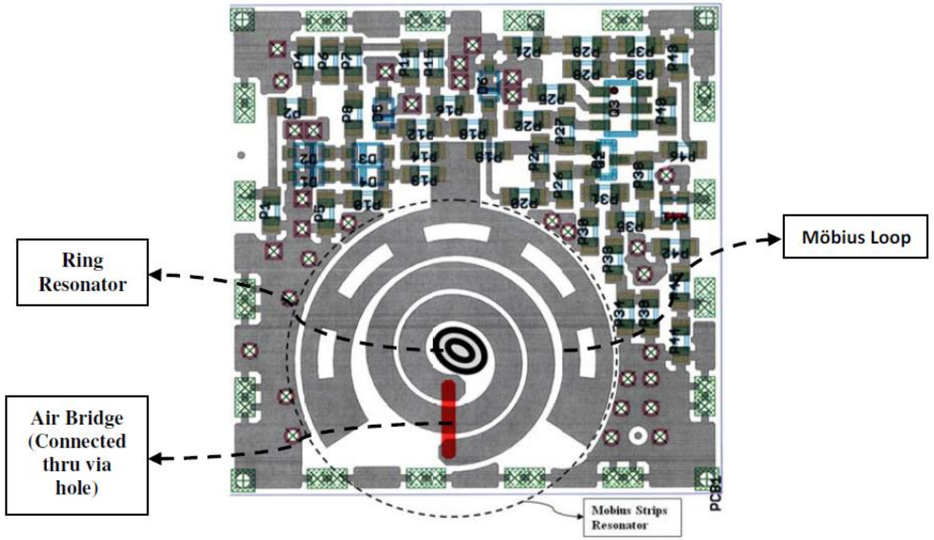


Synergy, 10 GHz

- Conductor losses at enclosure (top and bottom surface) deteriorate Q.
- **Not suited for high-Q applications with Q ≈ 50,000.**

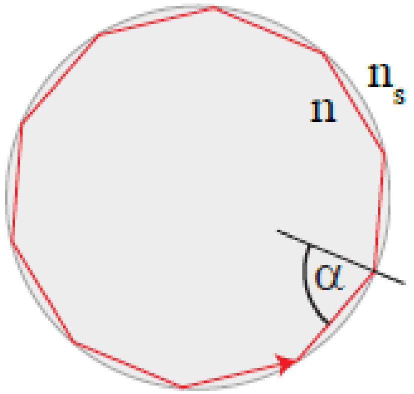
Möbius resonator and other approaches

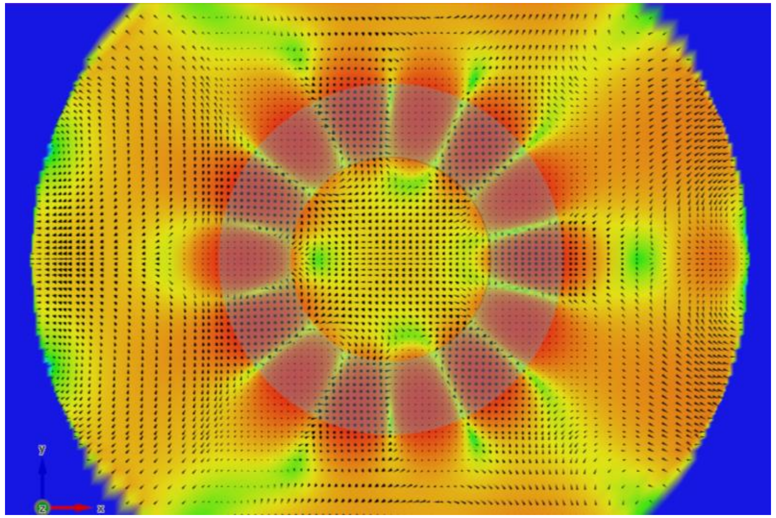




- Möbius structure is a surface with only one side and only one boundary component.
- Q-values relatively low.
- Metamaterials: Are engineered periodic composites that have negative refractive-index characteristic not available in natural materials. In this case the achievable quality factors are of the order of 500 at 100 GHz. Also too low.

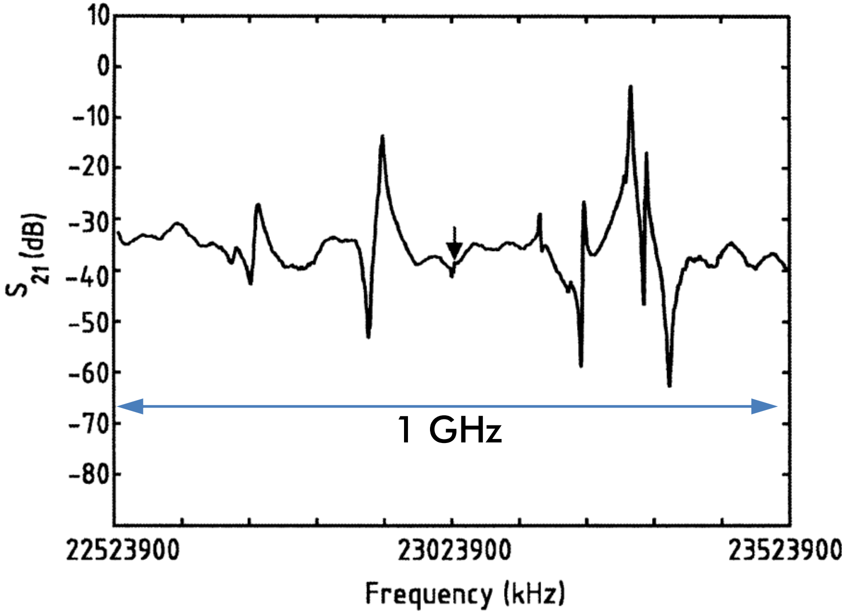
Whispering Gallery (WG) mode resonator

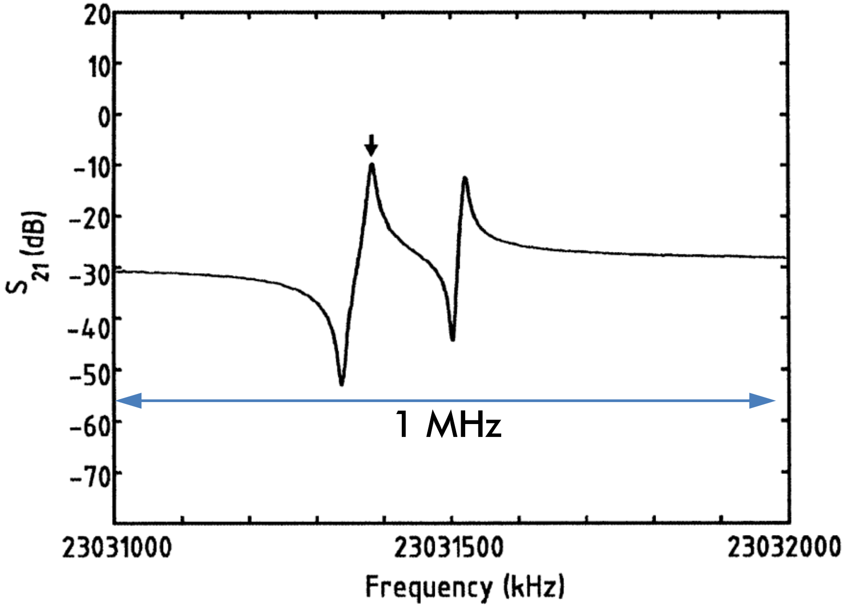




- Azimuthal high-order modes are subject to total reflection at the interface between the dielectric resonator and the surrounding air.
- Electromagnetic energy is strongly concentrated within the dielectric resonator and the conductor losses at the walls of the enclosure can be suppressed to a negligible level.
- **Q is limited by tanδ of the underlying dielectric only.**

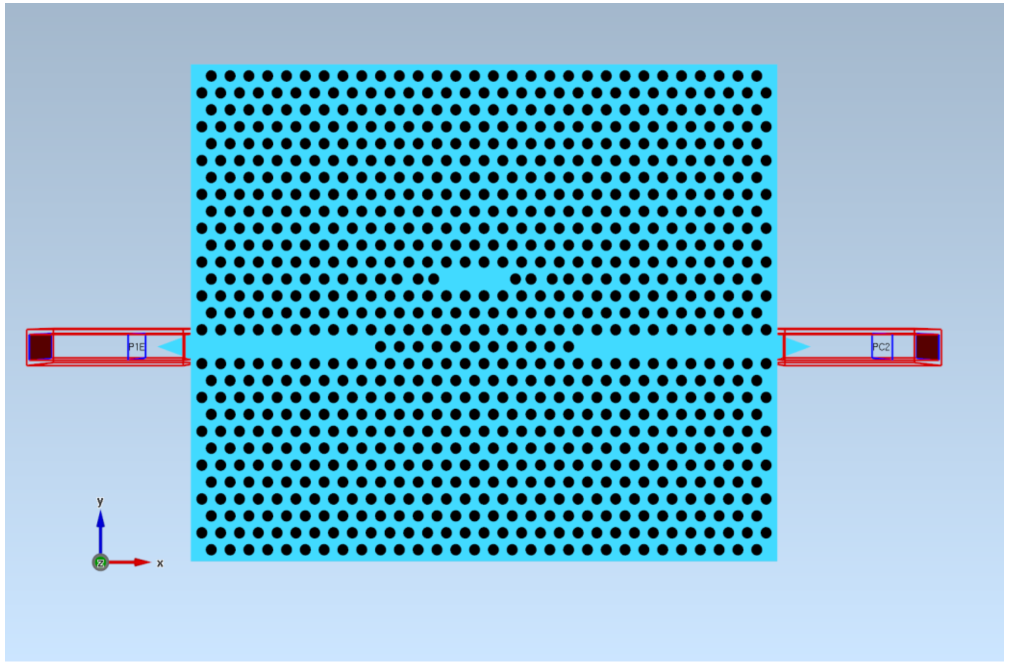
Whispering Gallery (WG) mode resonator





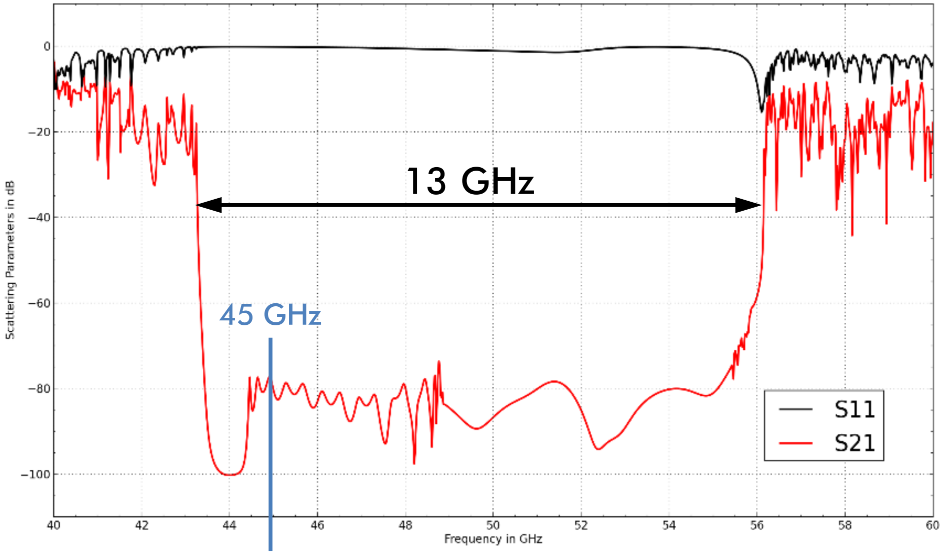
- Disadvantages of using Whispering Gallery Mode Resonators:
  - Higher order mode has to be chosen in order to achieve sufficient confinement of the electromagnetic wave inside the dielectric cylinder $\Rightarrow$ many other TE / TM and hybrid dielectric resonator modes in the vicinity of the high-Q WG-mode (left plot).
  - WG resonator modes are dual modes. Frequency difference between these two modes is governed by small imperfections of the shape of the dielectric cylinder. A narrowband filter is required to single out the wanted resonance (right plot).
- Filter needs to be very selective $\Rightarrow$ high-order needed $\Rightarrow$ considerable insertion loss $\Rightarrow$ enhanced feedback path noise figure and increased phase noise.

Photonic crystal (PC) resonator



- Defect resonators embedded within a periodic bandgap structure.
- Periodic bandgap structure is created by e.g. etching a periodic hole structure into HRS wafer.
- **Q is limited by tanδ of the underlying dielectric only.**

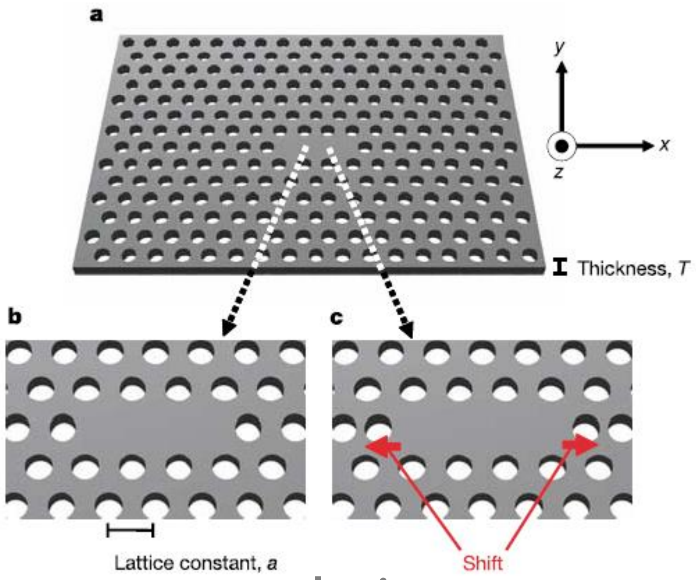
Photonic crystal (PC) resonator

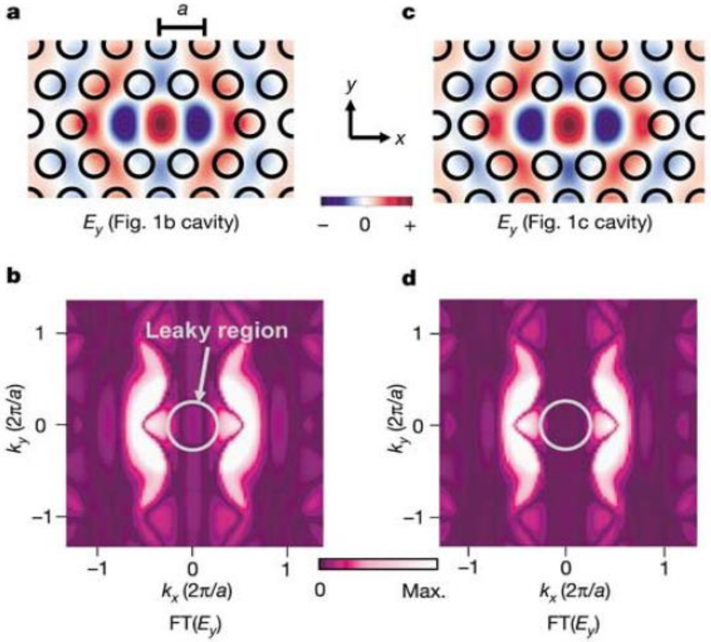


Parameter	Value
Length	56573 µm
Width	40109 µm
Periodicity a	1831 µm
Hole Radius r	549.3 µm
Thickness h	1000 µm
Taper Width	2370 µm
Taper Length	2700 µm
Permittivity ε_r	11.66
Loss Tangent tanδ	2.3×10^{-5}
Conductivity σ	1.43×10^{-3} $(\Omega\cdot m)^{-1}$

- 1st step: design of bandgap.
- Resonator resides within bandgap.

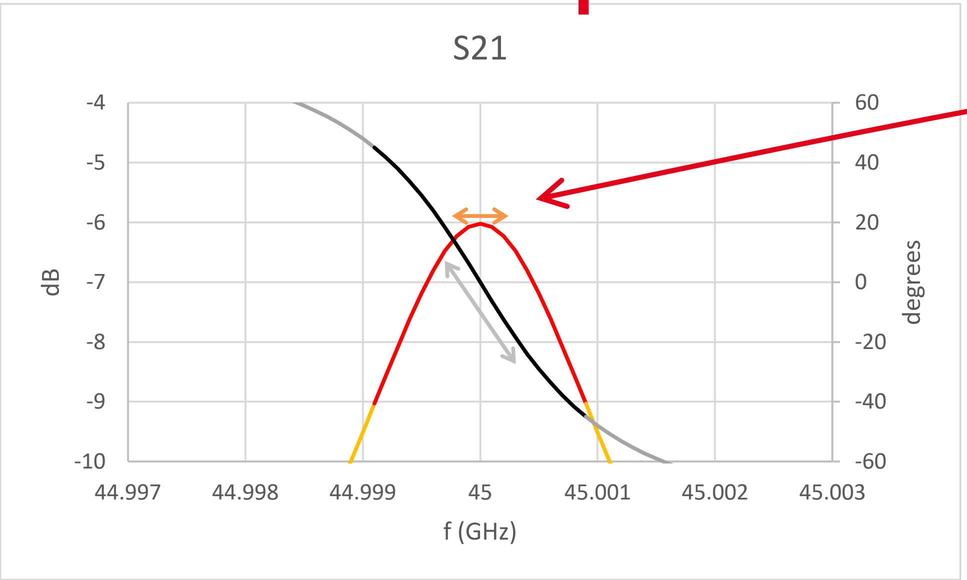
Photonic crystal (PC) resonator

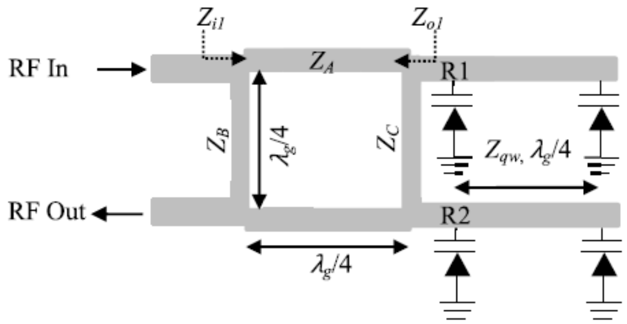


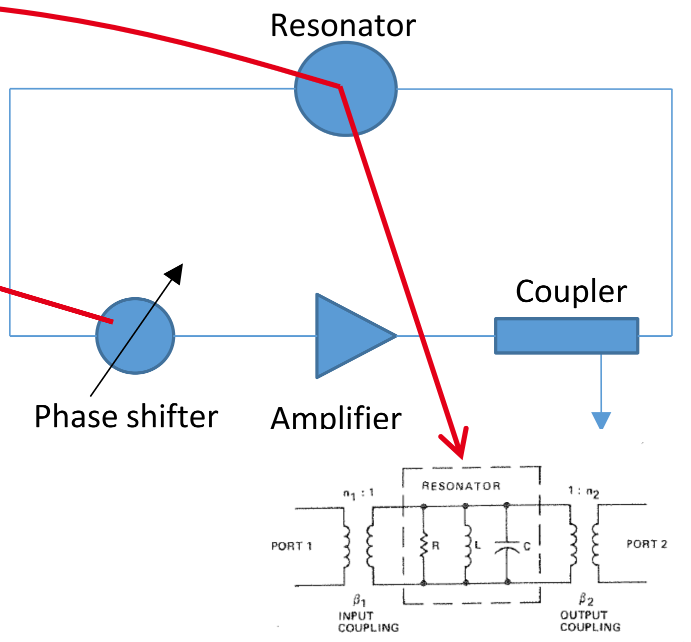


- 2nd step: resonator design:
  - Shifting one air rod on either side of the resonator creates windowing effect on the electromagnetic field amplitudes.
  - This eliminates wave-vectors at low magnitudes $< 2\pi/\lambda_0$ and minimises leakage of the electromagnetic energy from the dielectric in to the surrounding air.
  - Reason: Within air the maximum possible magnitude of the wave-vector is $2\pi/\lambda_0$. Within the cavity larger values than that are possible.
  - Quality factor comparable to those obtained by WG-resonators are within reach at mm-wave frequencies. No spurious mode due to presence of energy gap, no dual modes.
- **PC resonator approach adopted for this project.**

Electronic phase shifter approach

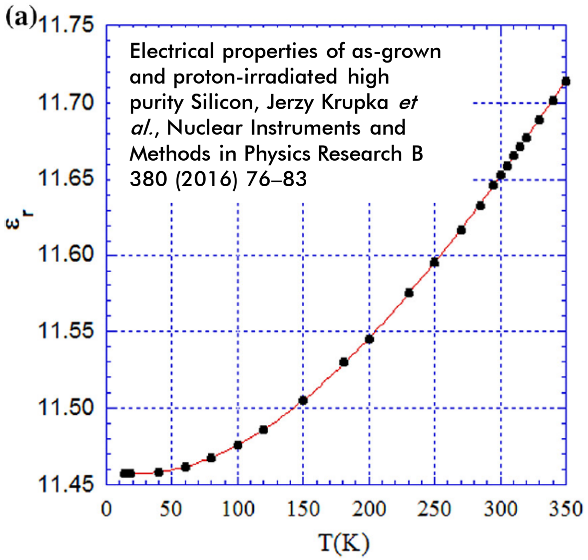






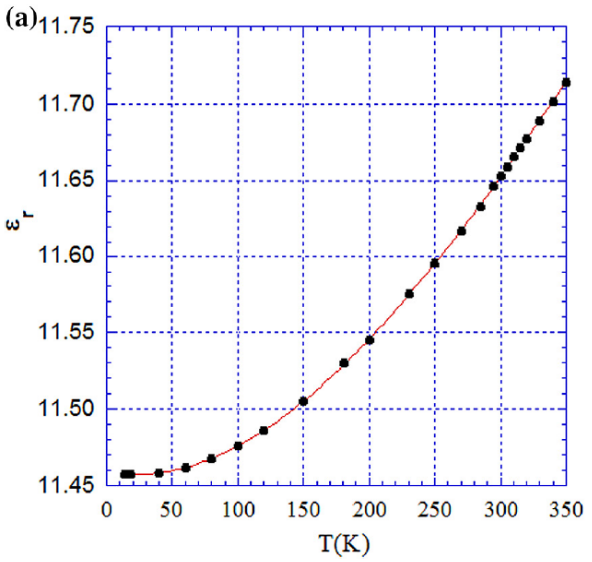
- Electronic Phase shifter needed for:
  1. Secure start-up of the oscillator (phase condition): 360 ° needed.
  2. Adjustment of the oscillator frequency: compensate **manufacturing tolerances** and **temperature drift (dominated by permittivity of resonator)**.
  3. Tuning input in PLL configuration:
- Phase vs. frequency is governed by phase(S21) of resonator.
- E.g. +/-45 ° degree phase shift corresponding to +/-900 kHz electric tuning range for Q0 = 50,000. Other tuning mechanisms required for 1. and 2.
- **Electronic tuning range decreases with increasing resonator Q.**

Impact of ambient temperature variation on f

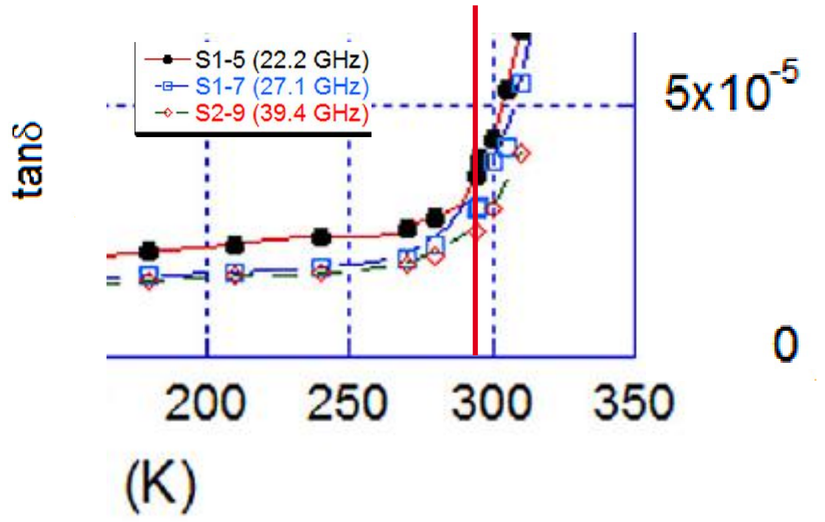


- HRS: Slope of permittivity $d\varepsilon/dT = 1.2\cdot 10^{-3}$/K (250-290 K).
- Corresponding slope of **resonance frequency f**: $df/f = -0.5\cdot d\varepsilon/\varepsilon$ = -51.8 ppm/K.
- f = 45 GHz
  - df/dT = -2.33 MHz/K (diel. filling factor κ = 100 %)
  - df/dT = -1.17 MHz/K (diel. filling factor κ = 50 %)
- Ambient temperature change from -20 to +40 °C results in variation of resonance frequency of -139.8 MHz (κ = 100 %) or -70.2 MHz (κ = 50 %).
- Electronic varactor phase shifter tuning range (< 1 MHz) not sufficient.

Impact of ambient temperature variation on f

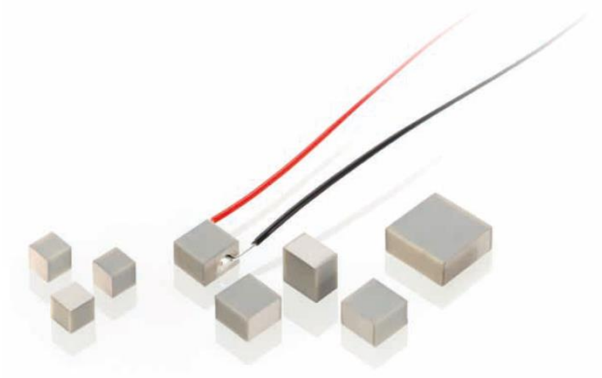


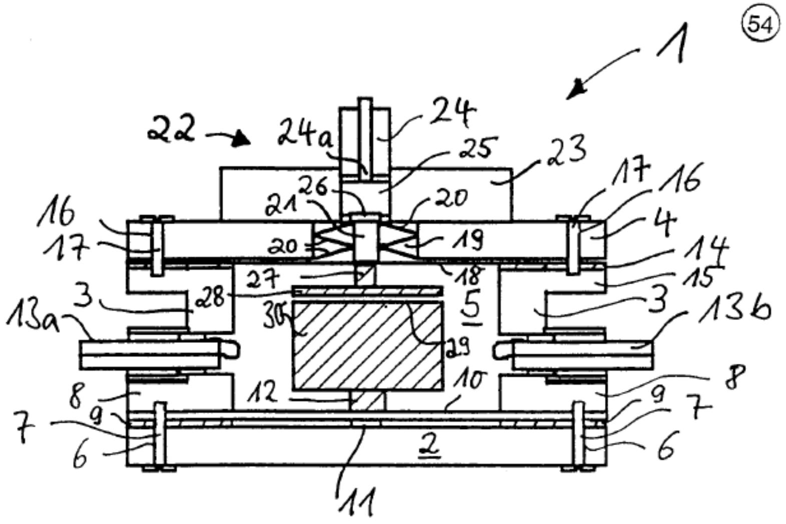
Electrical properties of as-grown and proton-irradiated high purity Silicon, Jerzy Krupka *et al.*, Nuclear Instruments and Methods in Physics Research B 380 (2016) 76–83

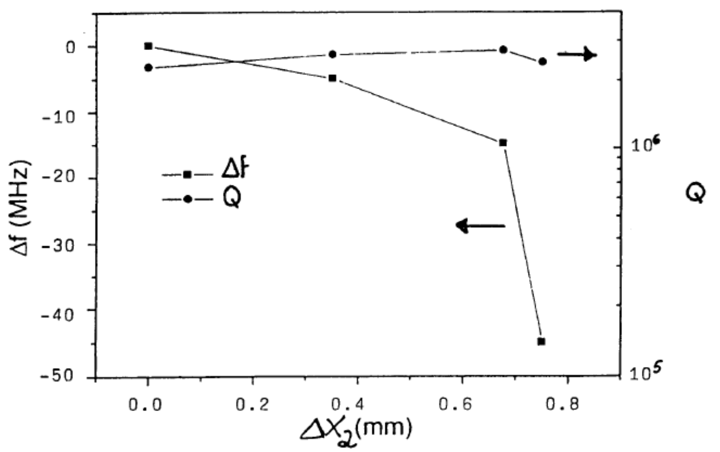


- Two possible routes (or combination of the two):
  1. **Active temperature control.**
     - Required precision:
       – κ = 100 %: +/-300kHz/(2.33MHz/K) = +/-0.13 K
       – κ = 50 %: +/-150kHz/(1.17MHz/K) = +/-0.13 K
     - **Temperatures > 290 K must be avoided in order to stay with high-Q (reason: thermal activation of electrons into conduction band within HRS. Intrinsic and cannot be avoided).**
  2. **Tuning of resonator frequency (see next page).**

Example: WGM-DRO electromechanical tuning



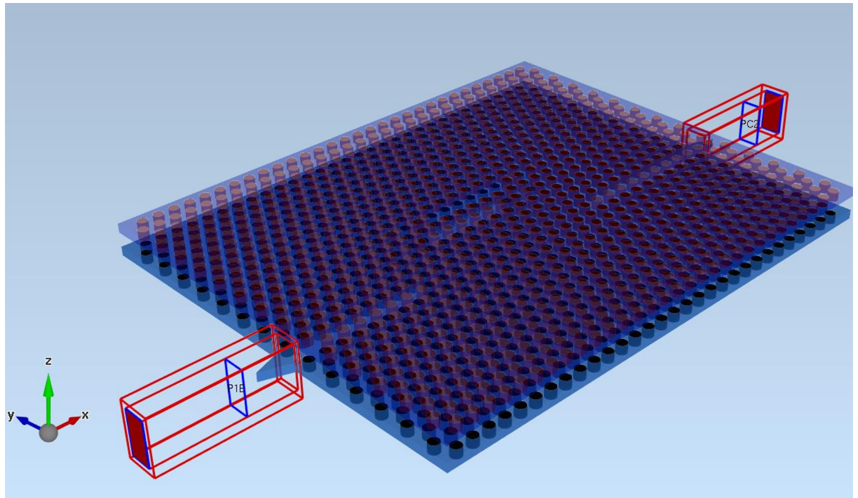


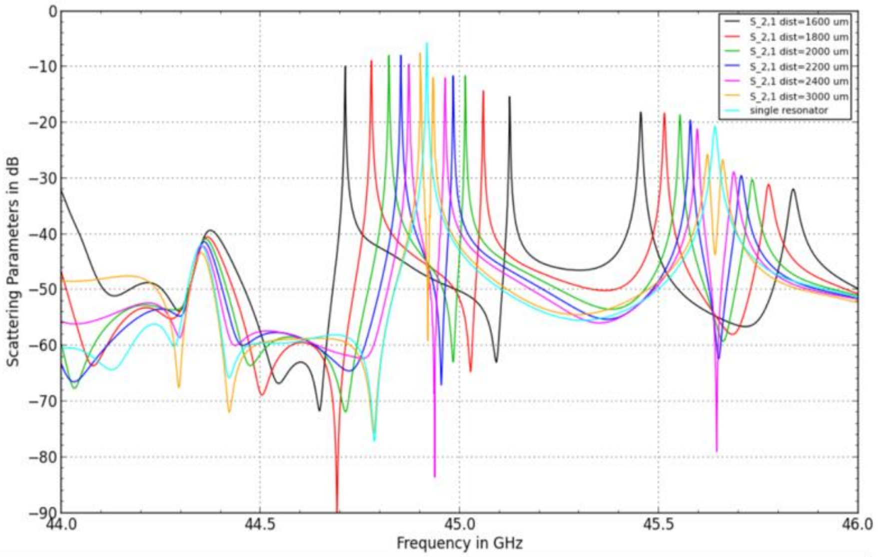


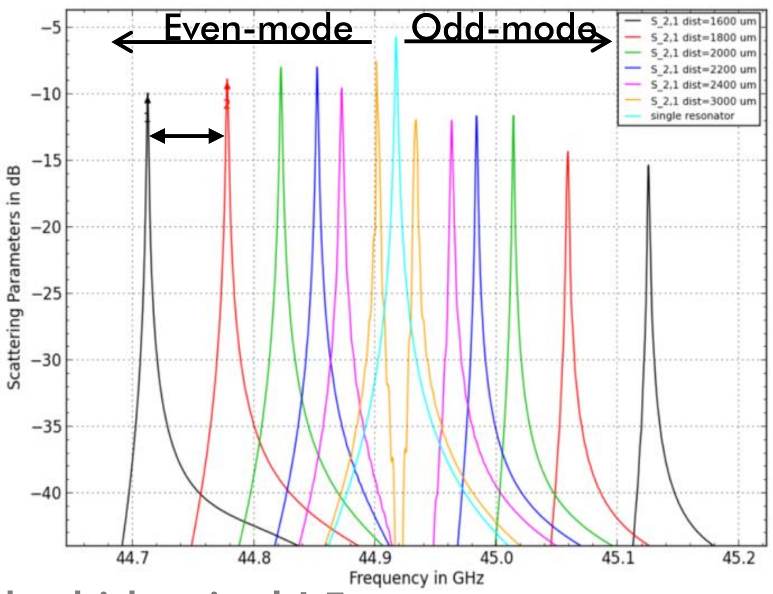
DE000019841078C1, 2000: Ghosh et al.

- Variation of distance between resonator and dielectric disc.
- Combined mechanical (differential threads) / piezoelectric drive necessary. Piezoelectric travel range typically 2 to 15 μm.

Wideband Frequency Tuning Approach: PCR



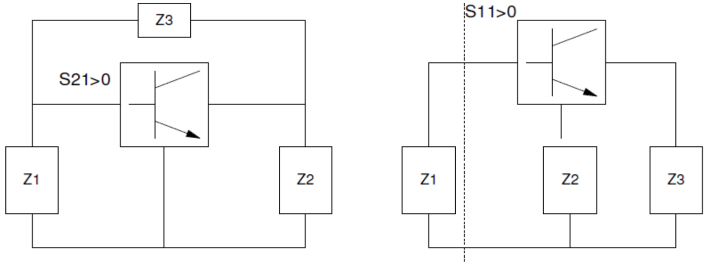


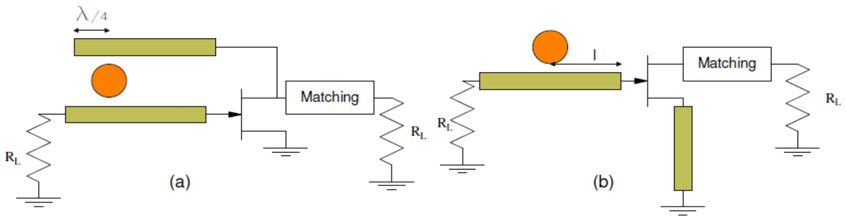


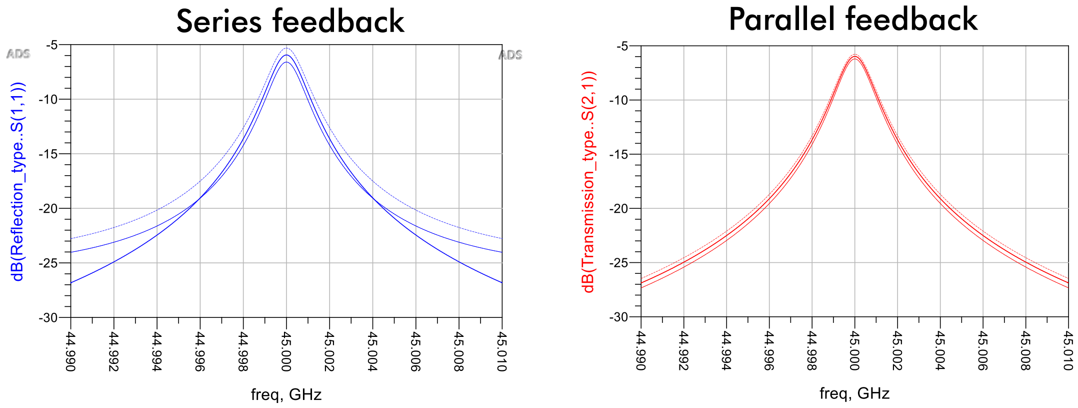
- The tuning mechanism is the variable distance dz between the two stacked identical L5 resonators.
- The resonance splits into an even- and an odd-mode resonance with decreasing distance dz.
  - The unwanted mode has to be suppressible by a waveguide bandpass filter
- A good range for tuning is between 1600 μm and 1800 μm distance
  - **The corresponding tuning range is 60 MHz**
  - The tuning sensitivity can be approximated with 300 kHz/um.
- Difficult mechanical construction. Not realised in this project.

Oscillator topology

Oscillator topology



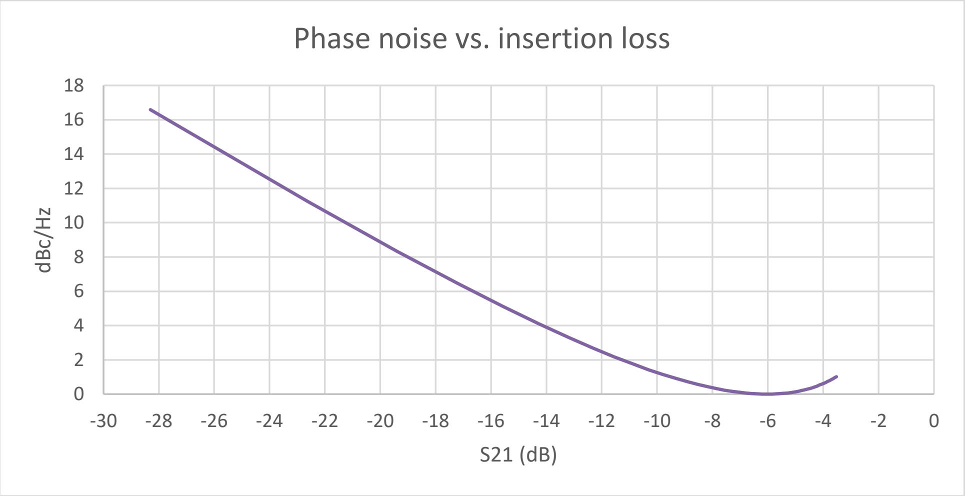




Impact of port mismatch (+/- 5 Ohm)

- Photonic Crystal Resonator cannot be integrated on the die of the active element ⇒ two principle oscillator topologies (with similar phase noise) are possible:
  - Series feedback (right):
    - Transistor needs to be instable at the desired oscillation frequency. Is achieved e.g. by tuning microstrip line length attached to the transistor source. Resonator operates as reflection type and stabilises oscillation frequency.
  - Parallel feedback (left)
    - Parallel feedback uses a resonator in transmission and an amplifier, which is required to be stable.
    - Easier to design and test, because amplifier is stable and can be tested on its own.
- Parallel feedback is adopted in this project.

Oscillator topology: resonator coupling strength

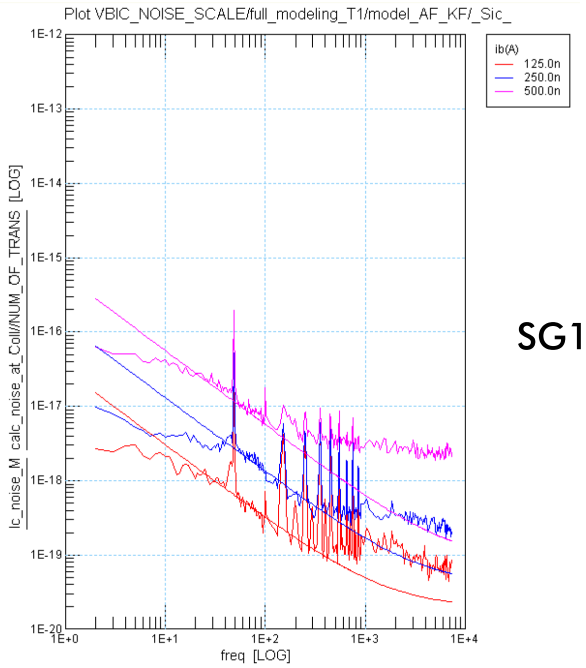


- Investigation of Leeson equation with symmetrical coupling to resonator and assuming that amplifier noise, gain, and output power are constant upon variation of the coupling (and resonator IL).
- Result: Best phase noise for IL = 6 dB.
- However, minimum is shallow and variation of the amplifier noise, gain and saturated output power has been neglected ⇒ **Rule of thumb only.**

Active part: 1/f noise

Active part & 1/f-noise

Device	Size (µm)	L_g/W_e (nm)	γ	Id (mA)	Vd (V)	LFN@1kHz (A^2/Hz)	LFN@1kHz / $V_d \cdot I_d$ (A/Hz.V)	LFN@10kHz (A^2/Hz)	LFN@10kHz / $V_d \cdot I_d$ (A/Hz.V)	LFN@100kHz (A^2/Hz)	LFN@100kHz / $V_d \cdot I_d$ (A/Hz.V)
GaN HEMT 1	2x75	250	1.5	19.252	10	4.26E-16	2.2143E-15	2.41E-17	1.253E-16	1.76E-18	9.1315E-18
GaN HEMT 2	4x75	250	1.3	27.376	10	2.27E-16	8.3065E-16	3.26E-17	1.19E-16	2.67E-18	9.7604E-18
GaN HEMT 3	2x50	250	1.3	20.037	10	6.75E-16	3.3678E-15	2.56E-17	1.275E-16	8.63E-19	4.305E-18
GaN HEMT 4	4x50	250	1.3	38.964	10	1.53E-15	3.9216E-15	6.66E-17	1.71E-16	1.75E-18	4.4965E-18
GaN HEMT 5	8x50	250	1.3	81.034	10	3.10E-15	3.828E-15	1.45E-16	1.784E-16	3.48E-18	4.2957E-18
GaN HEMT 6	4x50	250	1.5	4.732	10	4.50E-16	9.5139E-15	1.71E-17	3.618E-16	1.43E-19	3.0283E-18
GaN HEMT 7	8x50	250	1.5	52.604	10	2.79E-15	5.3114E-15	6.66E-17	1.265E-16	6.55E-19	1.2446E-18
InGaP HBT 1	4x20	1000	1.2	9	3	7.00E-18	3.8889E-16	5.30E-19	1.963E-17	1.10E-19	4.074E-18
InGaP HBT 2	2x20	1000	1.2	9	3	4.095E-18	1.5167E-16	4.538E-19	1.681E-17	1.324E-19	4.904E-18
GaAs pHEMT 1	2x20	150	1	12.611	3	1.42E-16	3.7507E-15	3.00E-17	7.924E-16	2.59E-18	6.8512E-17
GaAs pHEMT 2	4x20	150	1	24.833	3	1.87E-16	2.5101E-15	4.40E-17	5.911E-16	4.98E-18	6.682E-17
GaAs pHEMT 3	2x20	100	1	5.547	3	1.43E-16	8.6113E-15	2.00E-17	1.199E-15	2.64E-18	1.5852E-16
GaAs pHEMT 4	4x20	100	1	11.251	3	1.81E-16	5.3536E-15	3.35E-17	9.919E-16	3.85E-18	1.1412E-16
GaAs pHEMT 5	2x40	100	1	11.491	3	1.83E-16	5.3201E-15	2.76E-17	8.015E-16	4.06E-18	1.1786E-16
GaAs pHEMT 6	4x40	100	1	24.883	3	2.65E-16	3.5499E-15	3.88E-17	5.191E-16	4.71E-18	6.3055E-17



SG13

- Hardly any design PDKs come with an 1/f noise model for the active devices.
- In fact, the only PDK’s we have found are IHP’s SGB25 and SG13 design kits.
- SGB25 (fT/fosc: 80/95 GHz) vs. SG13 (fT/fosc: 230/340 GHz) ⇒ SGB25 not further considered.
- **Literature study: 1/f noise of HBT devices significantly lower than GaN / GaAs devices.**

Phase noise estimation

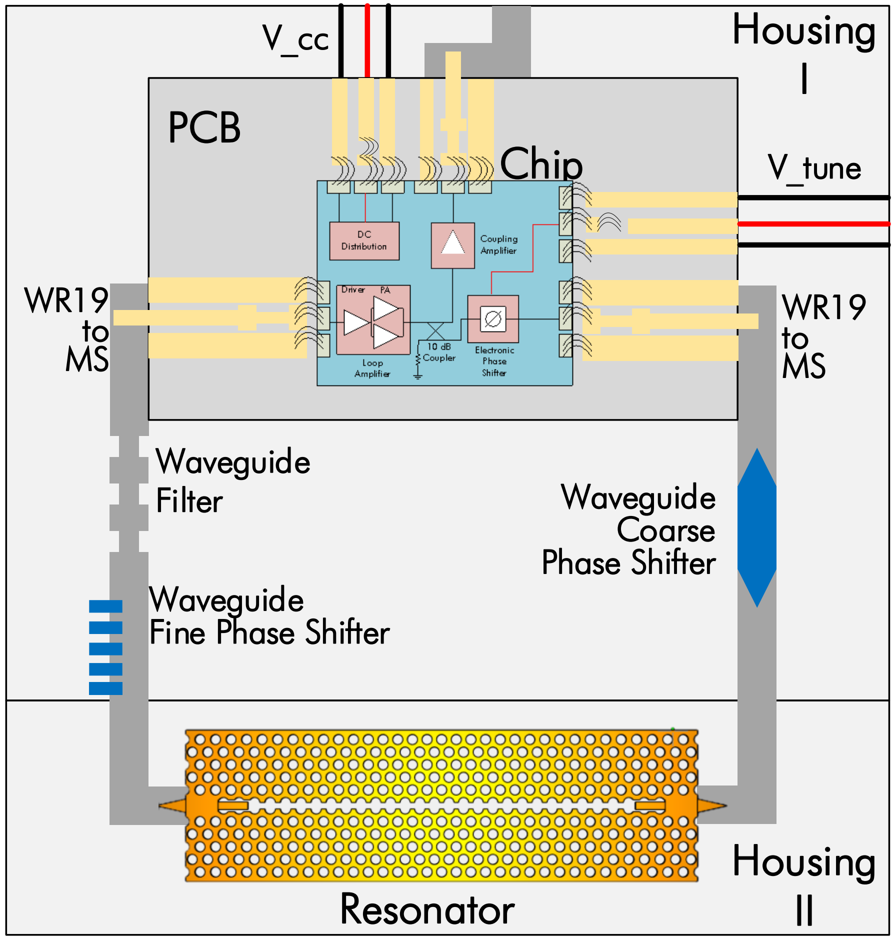
Projected phase noise at 45 GHz

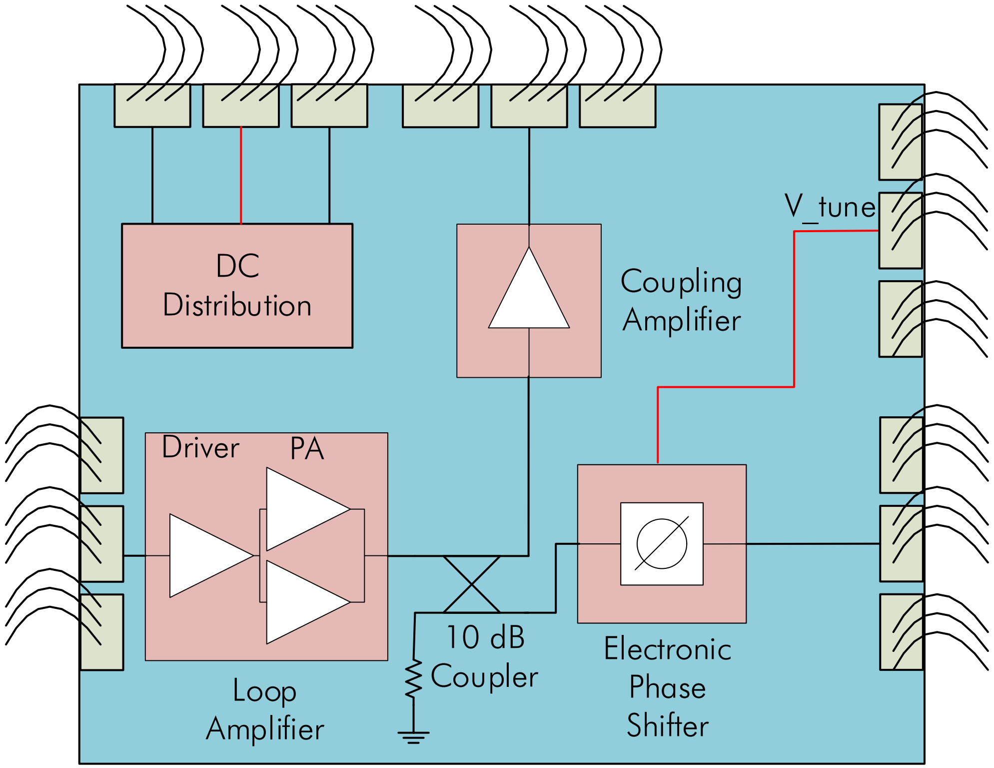
Offset freq. (Hz)	Lssb(45 GHz) (dBc/Hz)
10	-36.8
100	-66.7
1000	-96.4
10000	-123.8
100000	-146.3
1000000	-163.3
10000000	-165.9
100000000	-166.0
2000000000	-166.0

- Leeson equation:
  - 1/f corner frequency = 10 kHz, effective noise figure = 8 dB
  - Amplifier input power = -3 dBm
  - Resonator loaded Q = 25,000 at 45 GHz and 28.000 at 65 GHz corresponding to the electron / dielectric loss of proton irradiated HRS with resistivity of 416 kOhm cm.

- Introduction
- Concept (resonator, phase shifter, active element, topology)
- **Design and Verification**
- Compliance matrix and comparison with state-of-the-art
- Conclusions

Overview of the full system

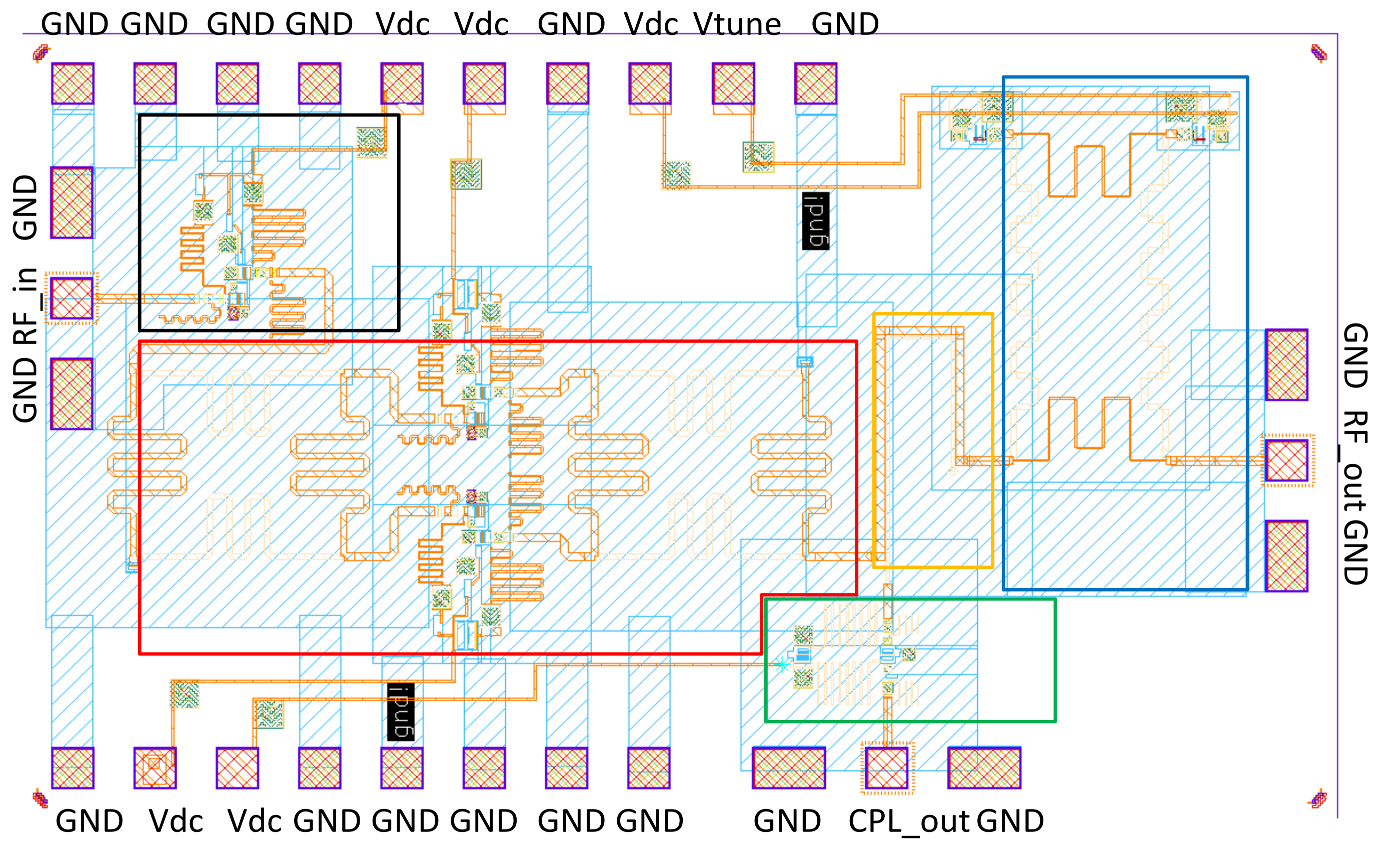




Main chip layout

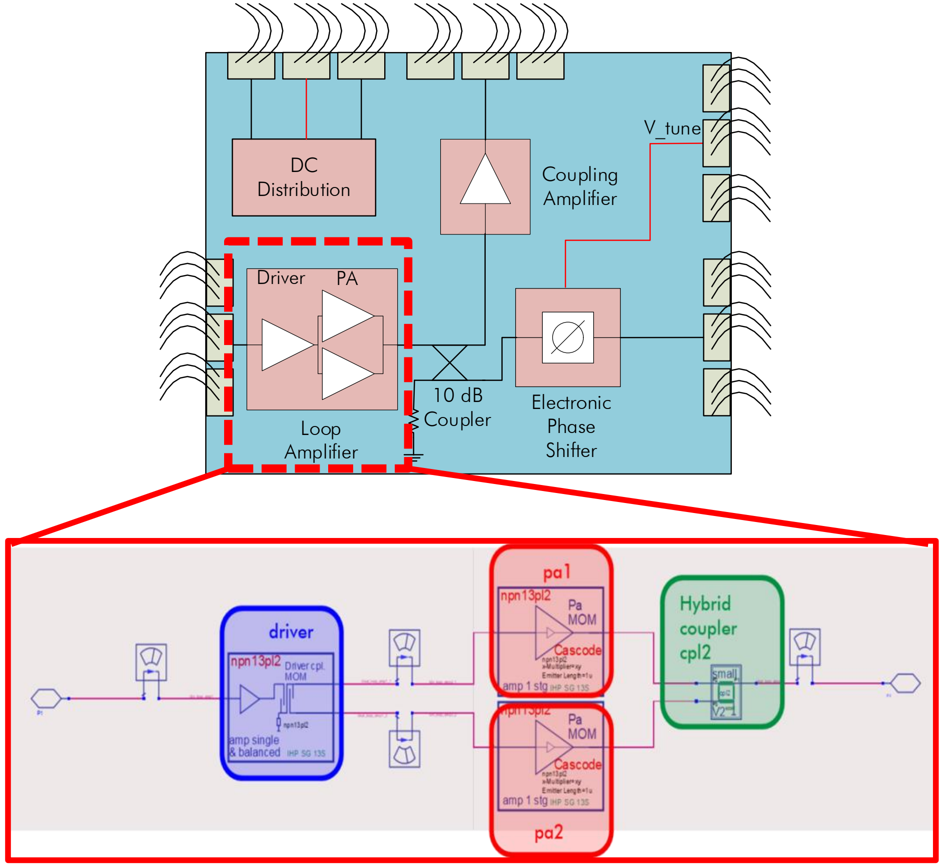
- First stage amplifier
- Balanced power amplifier
- Coupling amplifier
- 10 dB coupler
- Electrical phase shifter

➢ The total chip area is 2.5 x 1.5 mm².



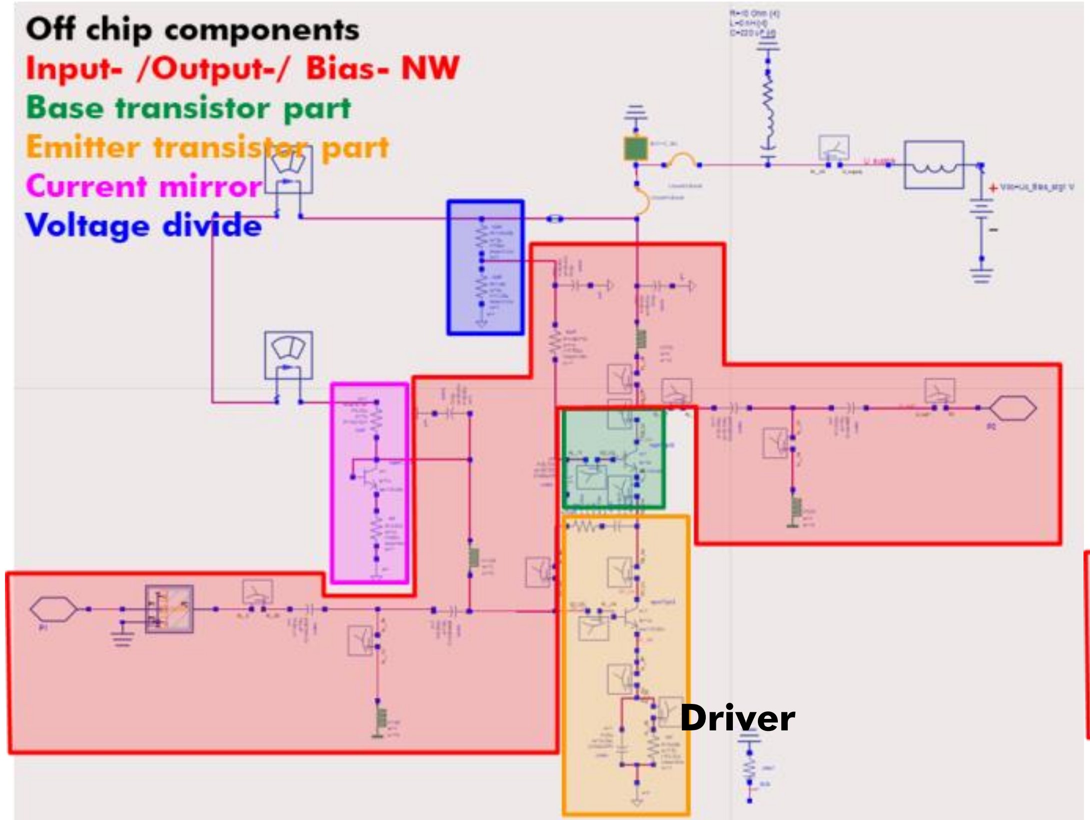
Loop amplifier

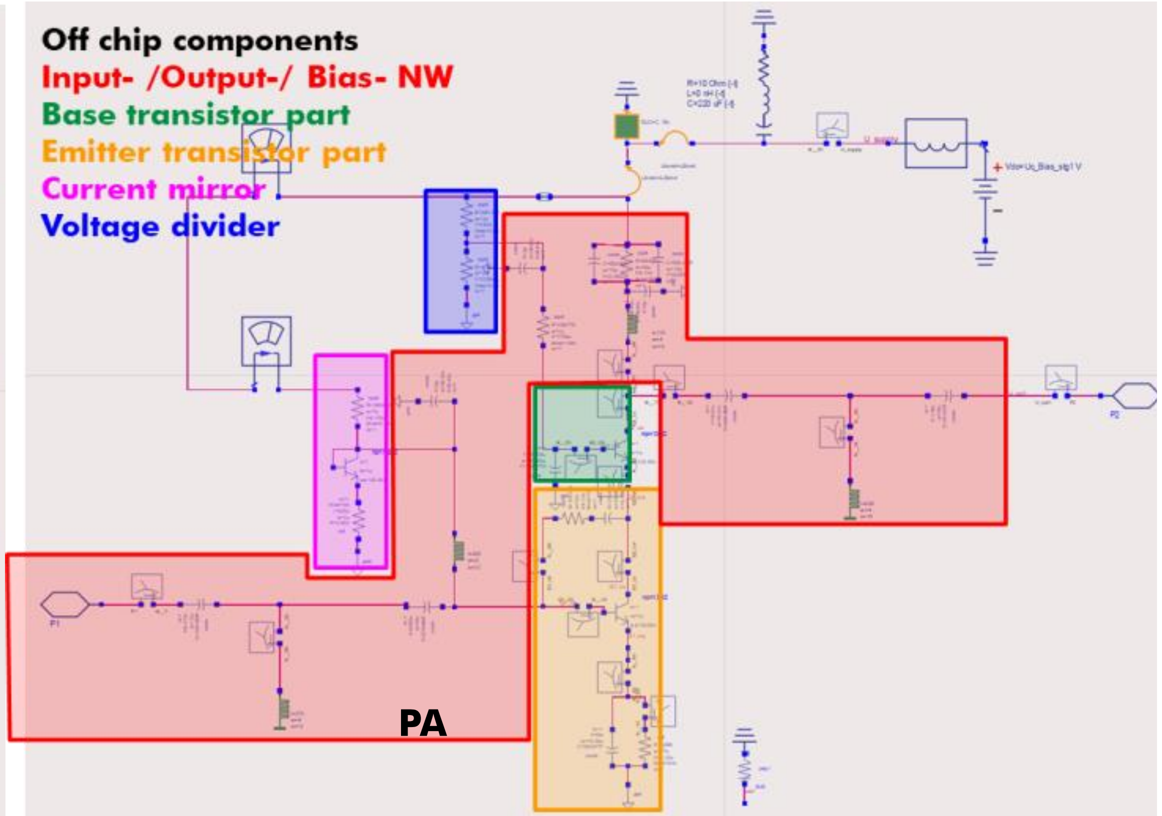
- The loop Amplifier is realized in a two stage design with a driver stage and a balanced PA stage
- The signal is split and combined by a 90° Branchline coupler.
- The design was mainly driven by an **optimised phase noise** performance while simultaneously satisfying the gain and power requirements.



Loop amplifier

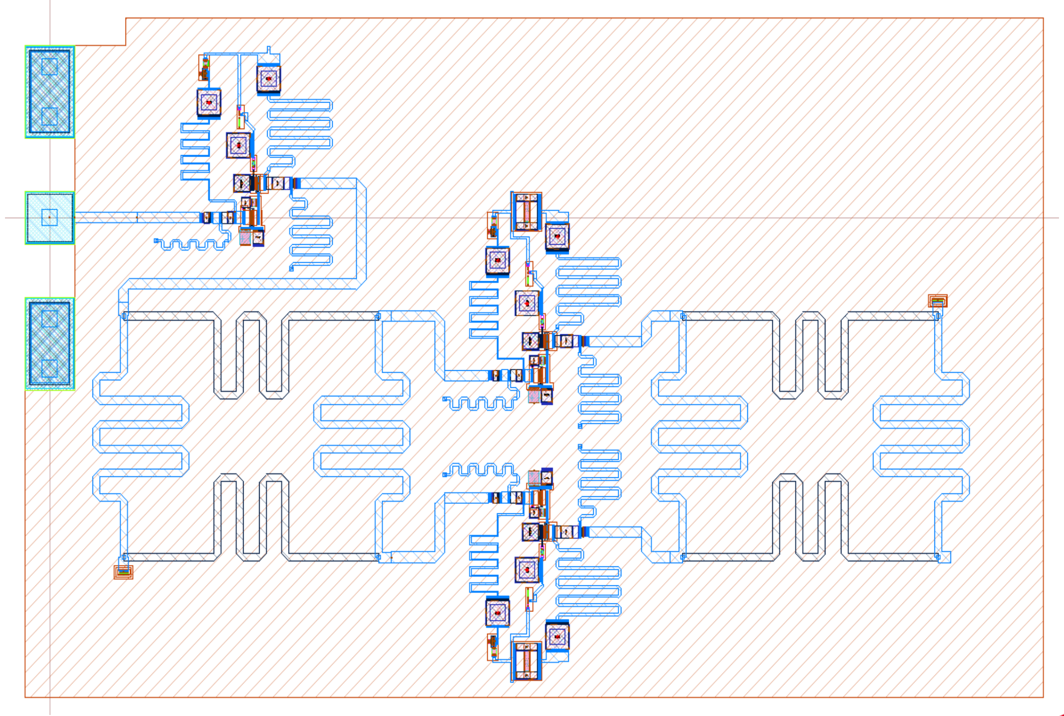
- For the Driver as well as the PAs a single stage cascode amplifier was used.





Loop amplifier

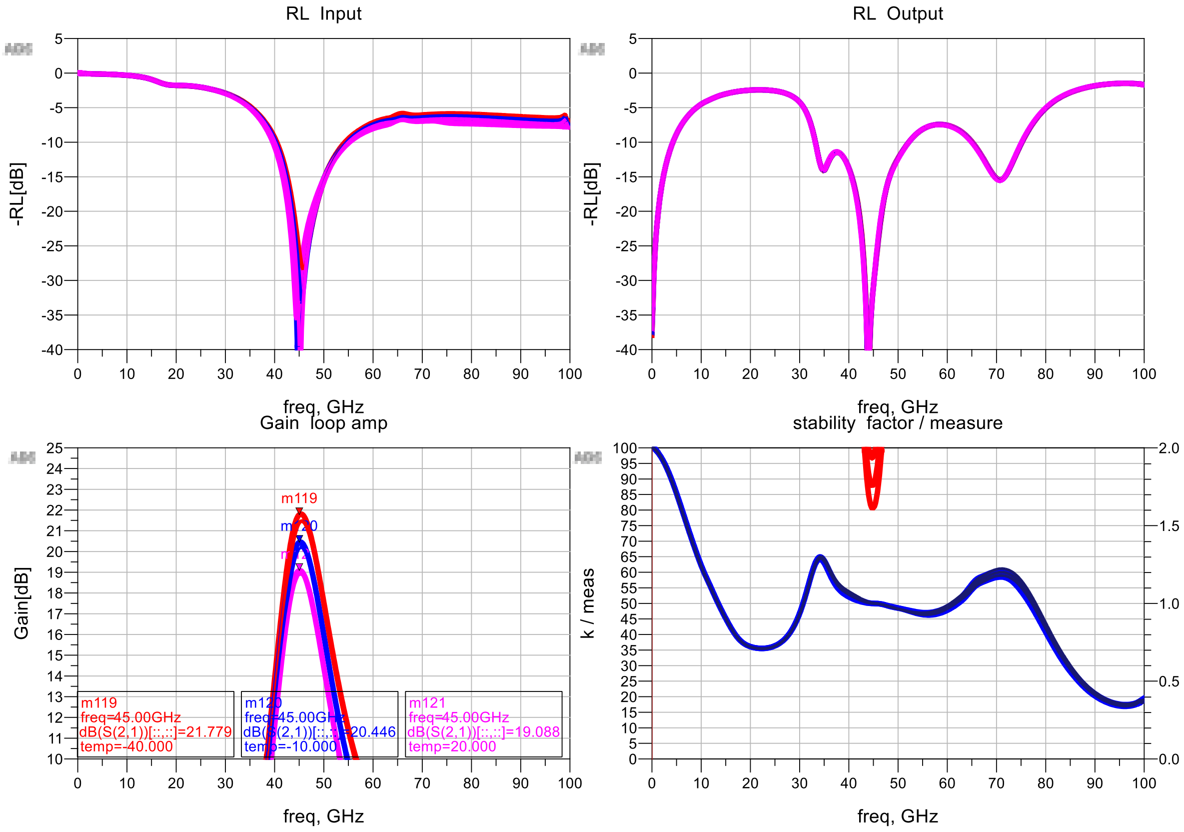
- Based on this layout, 2.5D EM simulations in Momentum were carried out including
  - routing of the interconnections,
  - in- and output pads of the chip,
  - Inductors,
  - Capacitors,
  - meander lines.



- The output of these simulations was then included into the ADS circuit simulation.

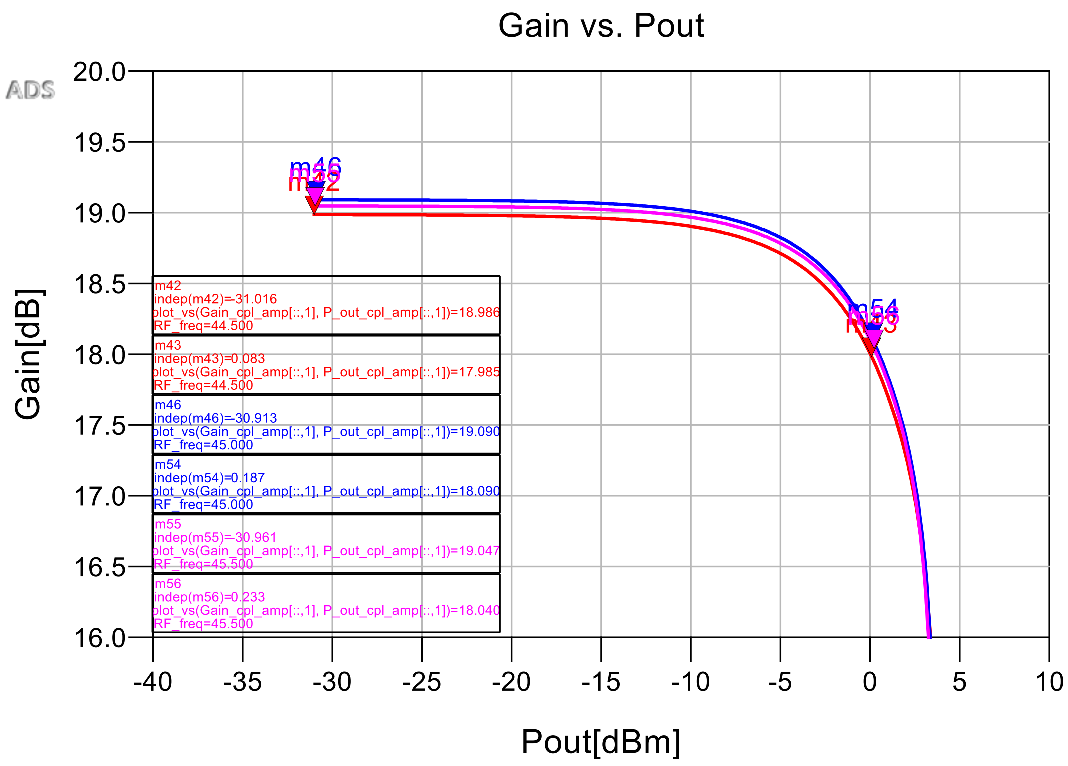
Loop amplifier: Design

- Good in- and output matching
- Unconditionally stable over the complete frequency and temperature range
- The small signal gain ranges from 19.1 dB (T = +20°C) to 21.8 dB (T = -40°C)
- Unconditionally stable over the complete frequency and temperature range

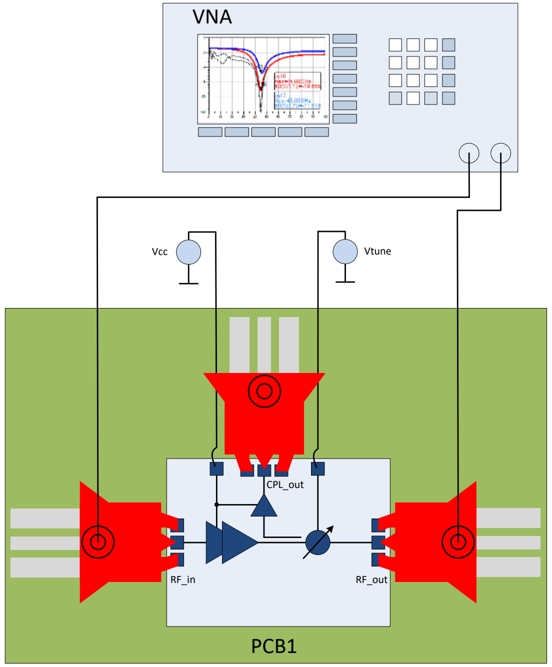


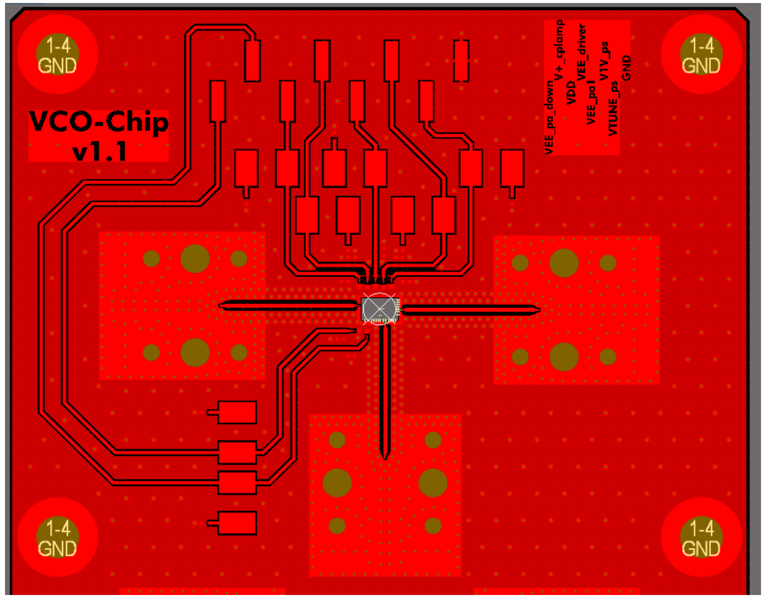
Loop amplifier: Design

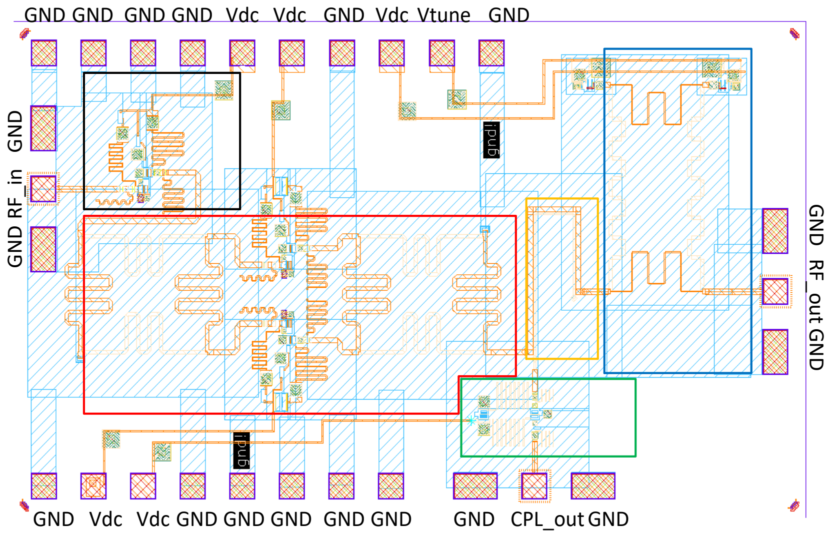
- Power sweep was performed at +20 °C,
  - ➢leads to the smallest gain
- P_{1dB} = 0.19 dBm at the nominal frequency
- Variation of 0.15 dB over 1 GHz bandwidth around the nominal frequency



Amplifier and phase shifter S-parameters and gain compression (on-wafer): Setup

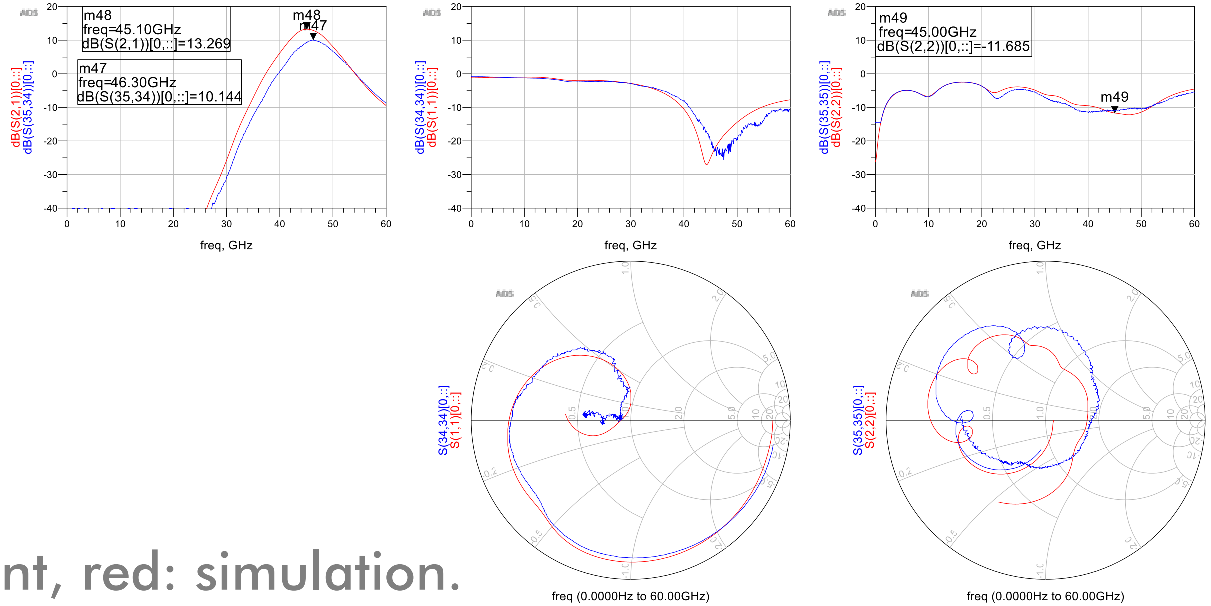






- 150 μm GSG-probes used during measurement.
- Measurement at room temperature.

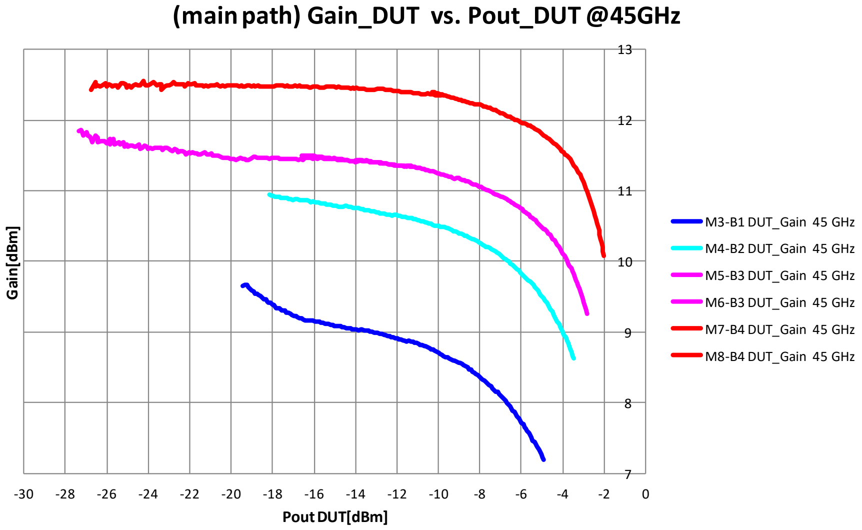
Measurement: Amplifier and phase shifter S-parameters and gain compression (on-wafer)



- Blue: measurement, red: simulation.
- Bias conditions Driver, PA, Coupling Amp. / Vcc_ps / Vtune:
  - Simulation: 2.11 V & 11.2 mA, 2.44 V & 22.6 mA, 1.50 V & 33.5 mA, 1 V, 0 V.
  - Measurement: 2.10 V & 11.3 mA, 2.42 V & 22.6 mA, 1.50 V & 30.15 mA, 1 V, 0 V.
- Overall match is good. However, approx. 3 dB less peak gain. At 45 GHz the difference is 4 dB. Simulated oscillation margin is only 2 dB (L5 resonator).
- Root cause: Simulation accuracy of the SG13S design kit.
- Bias optimization needed in order to realise enough gain needed for oscillation.

Measurement: Large signal compression main path at 45 GHz / Bias optimisation

IMST

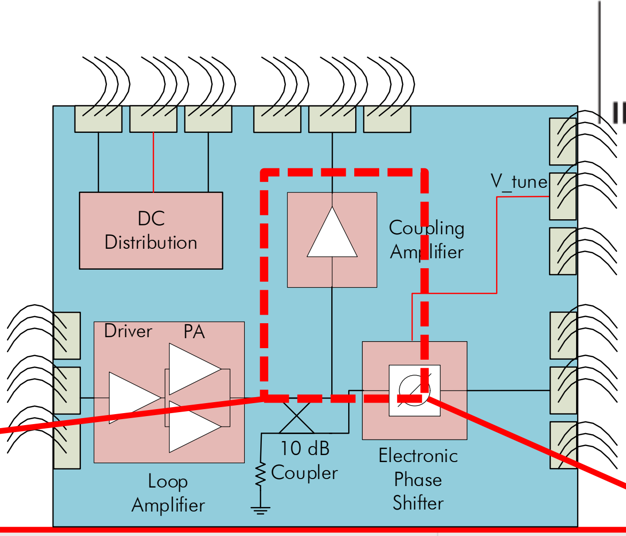


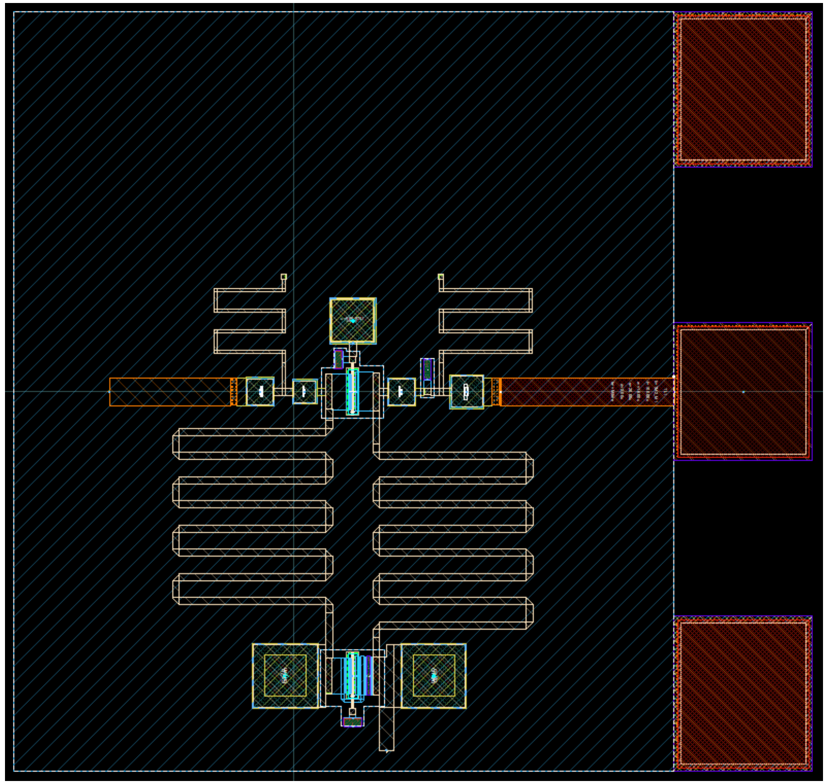
	V_clamp U[V]	Driver U[V]	Driver A[mA]	Pa1_Pa2 U[V]	Pa1_Pa1 A[mA]	Cpl_Amp U[V]	Cpl_Amp A[mA]	Ps_Vcc U[V]	Ps_tune U[V]	Max DUT_Gain [dB]	DUT_P1dB [dBm]
Bias1	3	2,1	11,3	2,42	22,6	1,5	30,15	1	0	9,30	-7,79
Bias2	3	2,6	15,11	2,66	25,38	30	15,1	1	0	11,03	-6,77
Bias3	3,1	2,6	15,11	3,03	30	1,5	30,19	1	0	11,45	-4,85
Bias4	3,47	2,9	17,46	3,43	35,03	1,5	29,8	1	0	12,50	-3,80

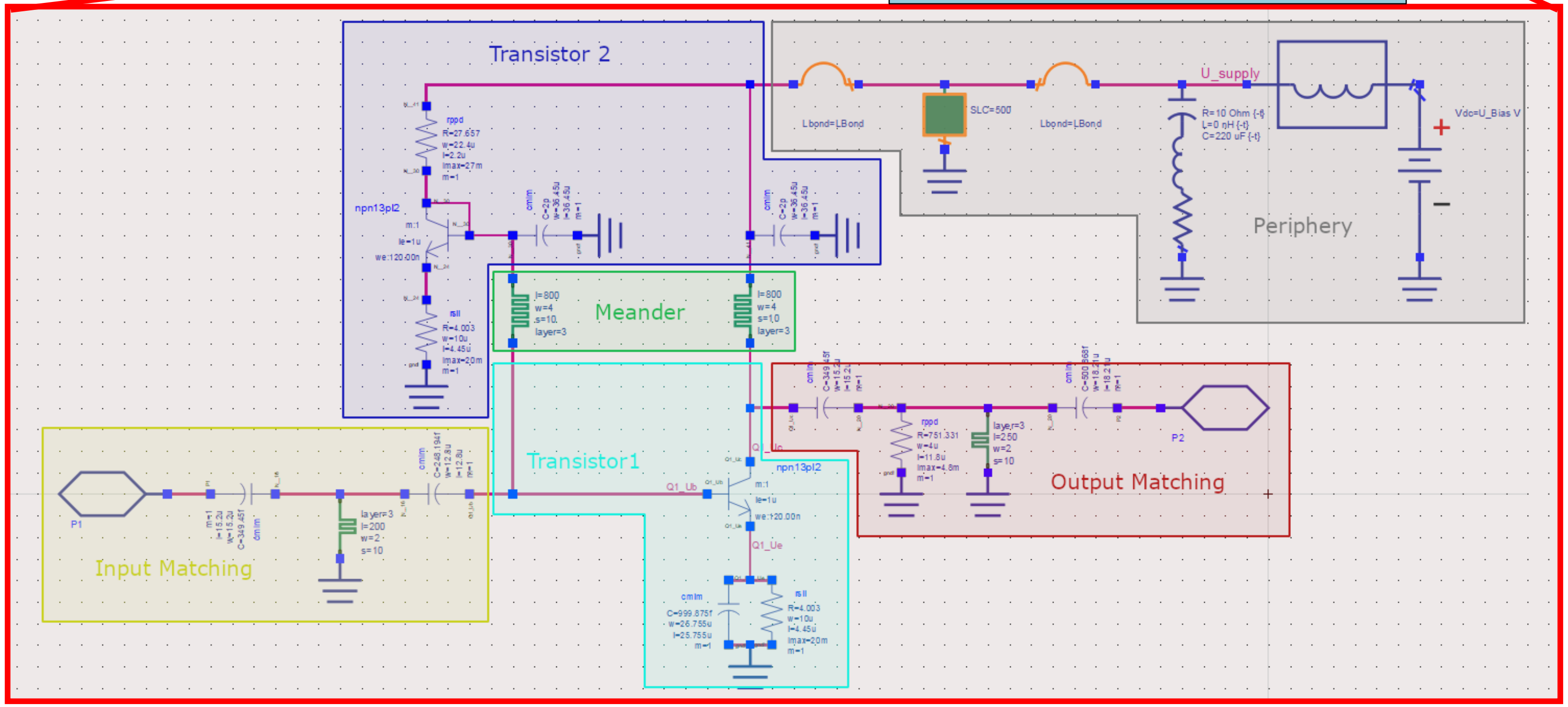
- Using default bias (Bias 1), measured output P1dB is only -7.8 dBm. (simulation: -5.2 dBm).
- With the elevated Bias 4, both small signal gain (12.5 dB) and P1dB (-3.8 dBm) reach acceptable levels.

Coupling amplifier

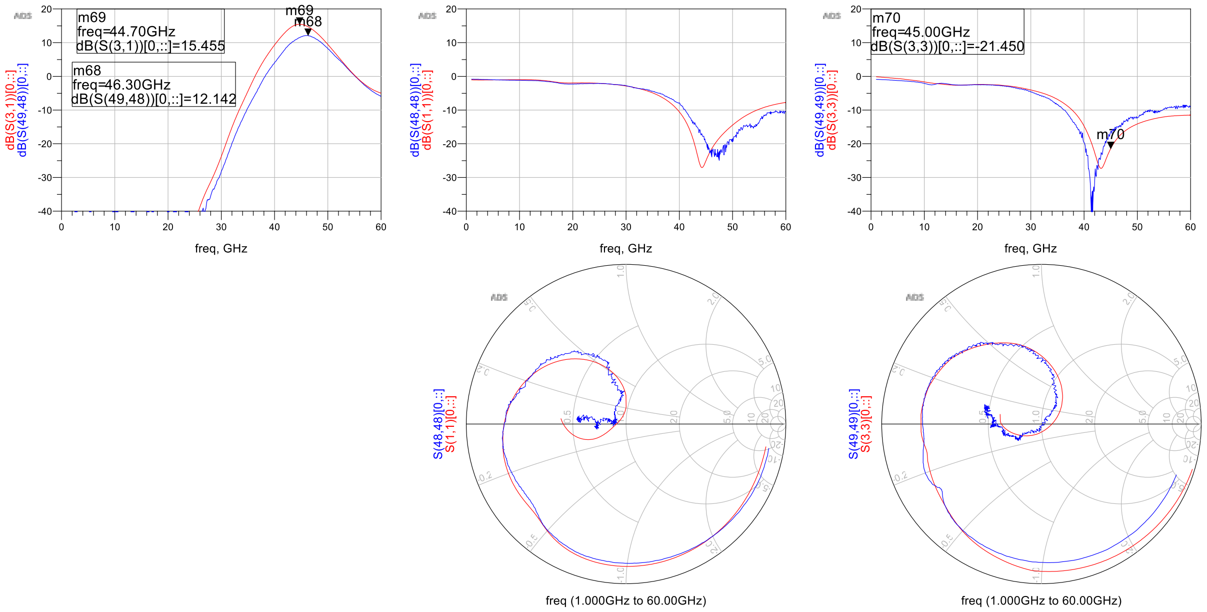
- Standard common-emitter single-stage amplifier





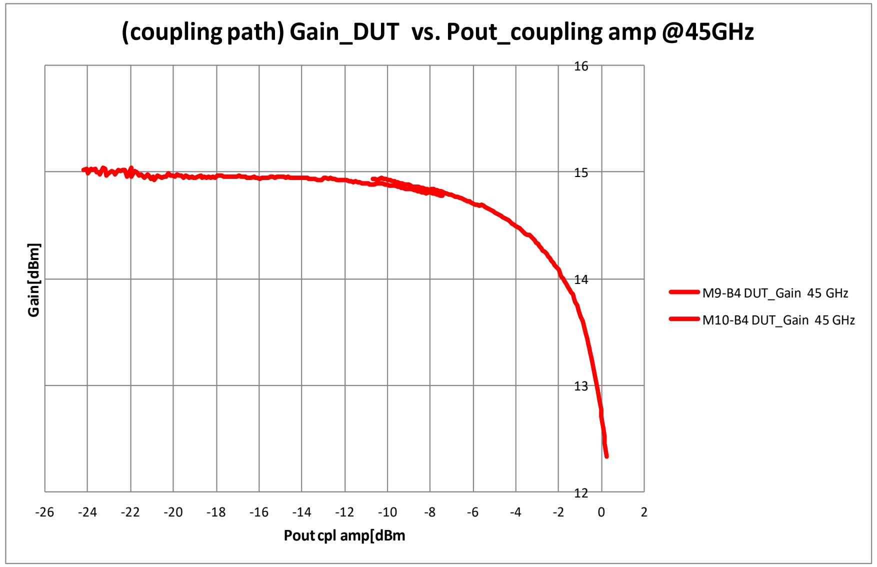


Results coupling amplifier path



- Blue: measurement, red: simulation.
- Bias conditions Driver, PA, Coupling Amp. / Vcc_ps / Vtune:
  - Simulation: 2.11 V & 11.2 mA, 2.44 V & 22.6 mA, 1.50 V & 33.5 mA, 1 V, 0 V.
  - Measurement: 2.10 V & 11.3 mA, 2.42 V & 22.6 mA, 1.50 V & 30.15 mA, 1 V, 0 V.
- As for main path, general agreement of simulated and measured S-parameters is quite good. Again, as for the main path, 3.4 dB gain are missing in the measurement and a 1.5 GHz frequency shift is observed.

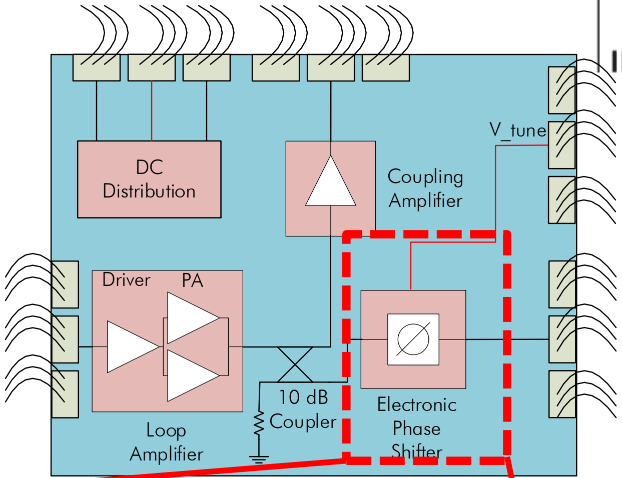
Measurement: Large signal compression Coupling Path at 45 GHz

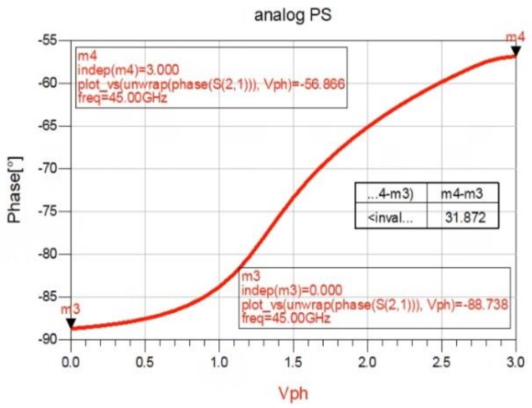


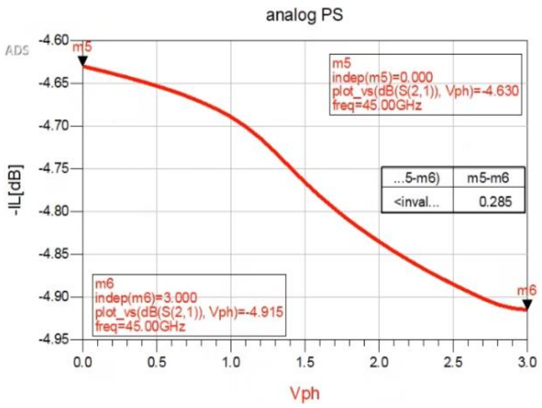
- Using Bias 4, coupling path gain is 15 dB at 45 GHz and output P1dB is -1.8 dBm.
- The small signal gain with Bias 4 is close to the simulated value for Bias 1. P1dB is even higher (measured: -1.8 dBm vs. -3.5 dBm simulated).

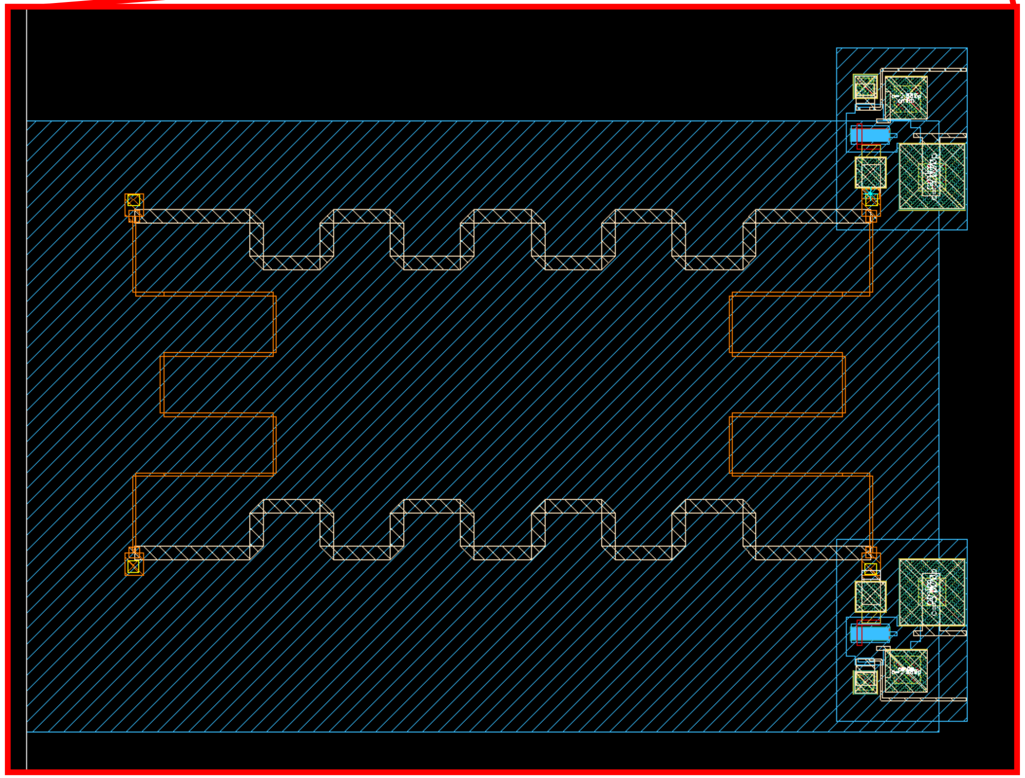
Electronical phase shifter

- Design of branchline coupler with varactor diodes.
- Total variation of the transmission phase = 32 °.

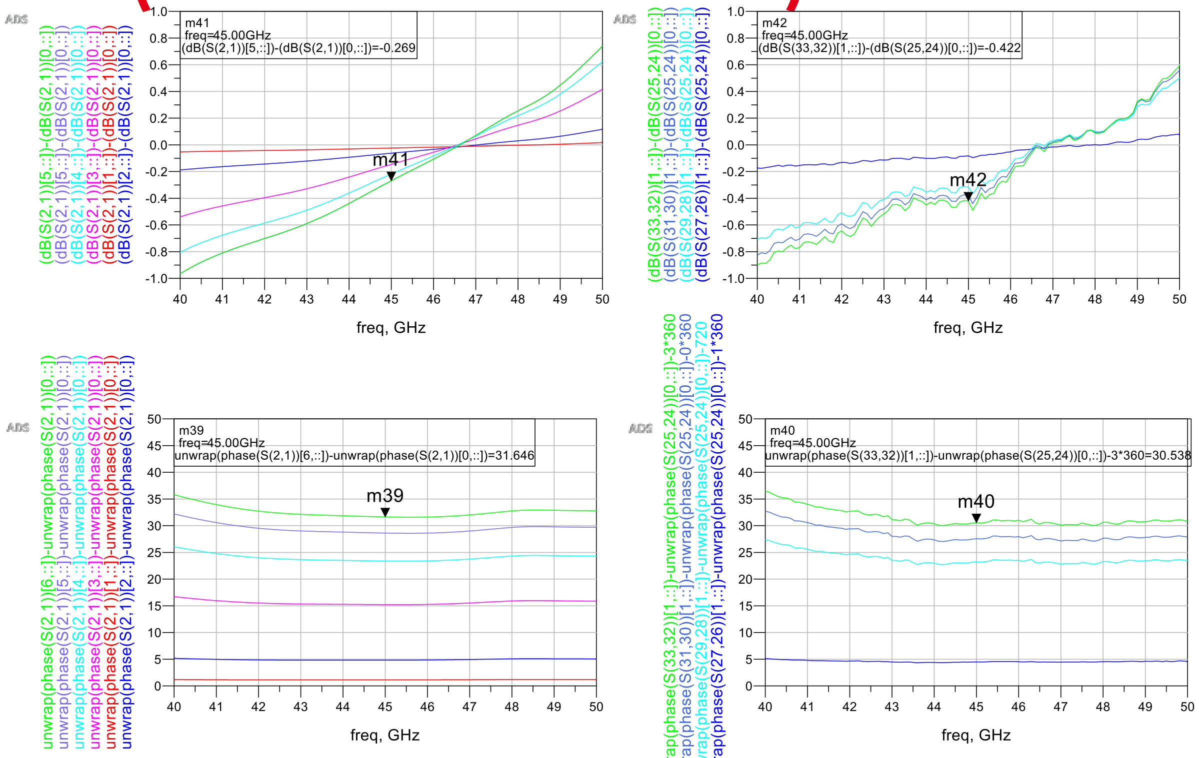








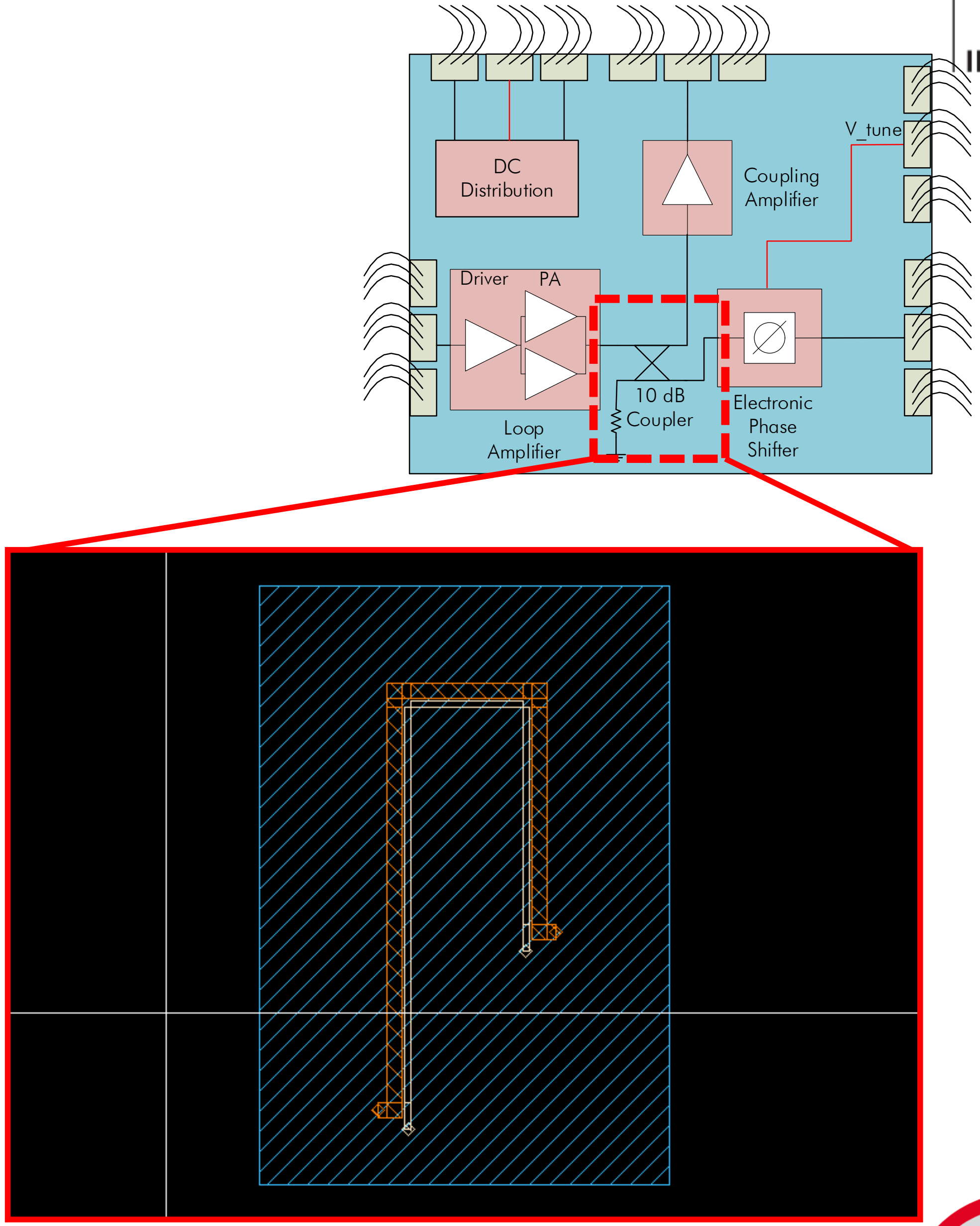
Measurement: Phase shifter phase shift and insertion loss (Vtune 0 to 3 V)



- Top graphs: IL change when varying tuning voltage from 0 to 3 V in steps of 0.5 V. Bottom graphs: phase shift when varying tuning voltage from 0 to 3 V in steps of 0.5 V. Left: simulation, right: measurement (same colour code as for simulation).
- Agreement between simulation and measurement is excellent. The total realised phase shift it 30.5 ° at 45 GHz.

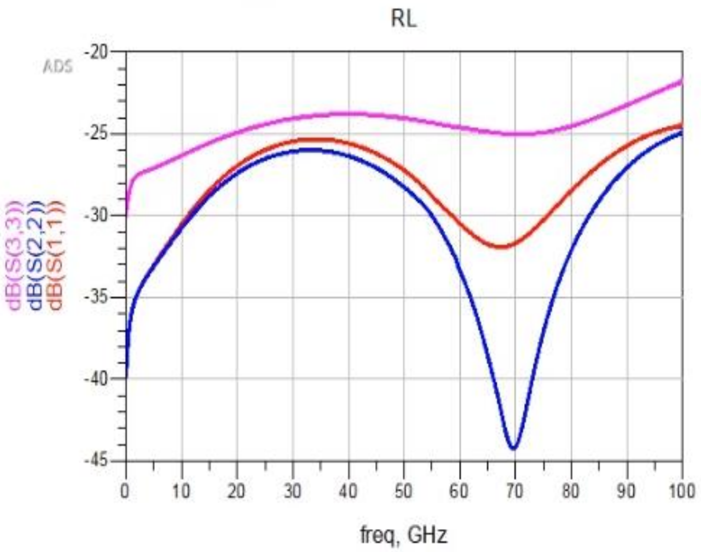
10 dB coupler

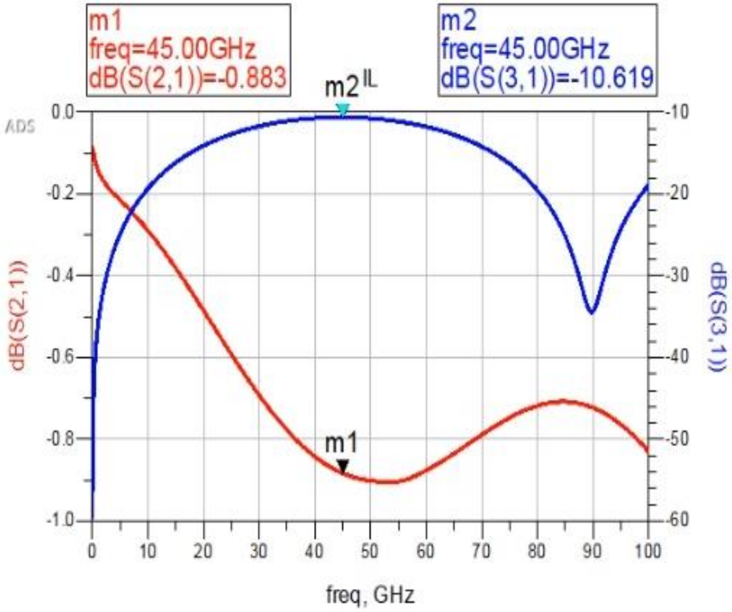
- For the 10 dB coupler a broadside microstrip coupler topology is chosen
  - Very low tolerances regarding the line width and layer height



10 dB coupler

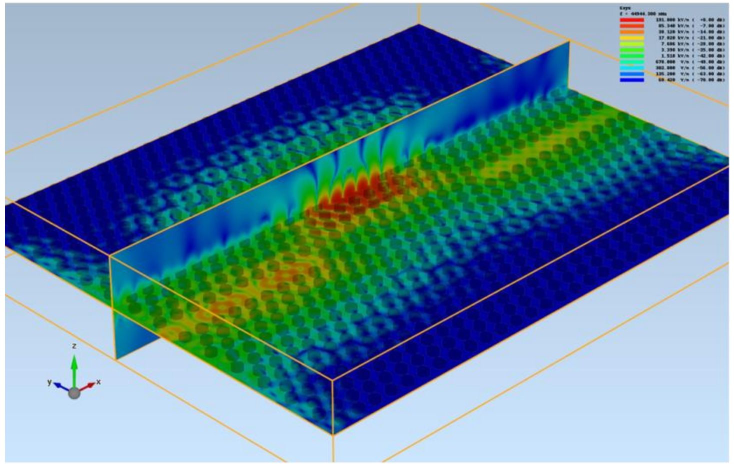
- 0.9 dB insertion loss in through part.
- 10.6 dB coupling loss.
- Good matching and isolation.

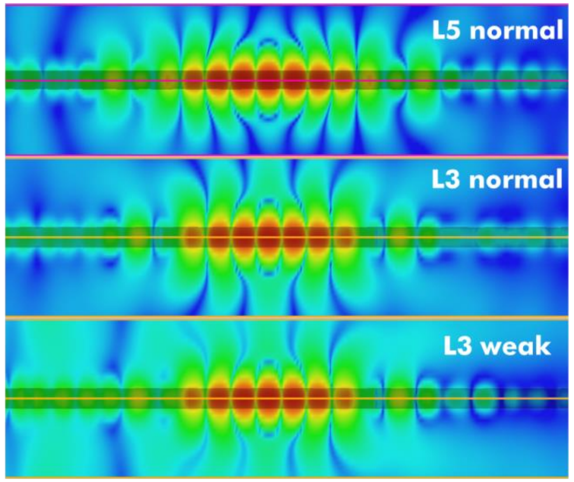




Resonator: L5 Cavity

Motivation: L3 vs. L5



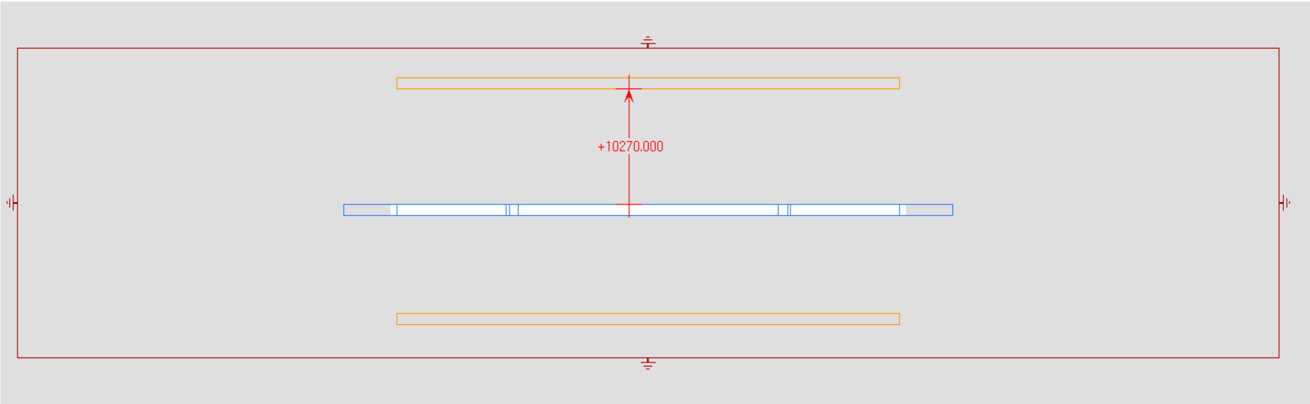


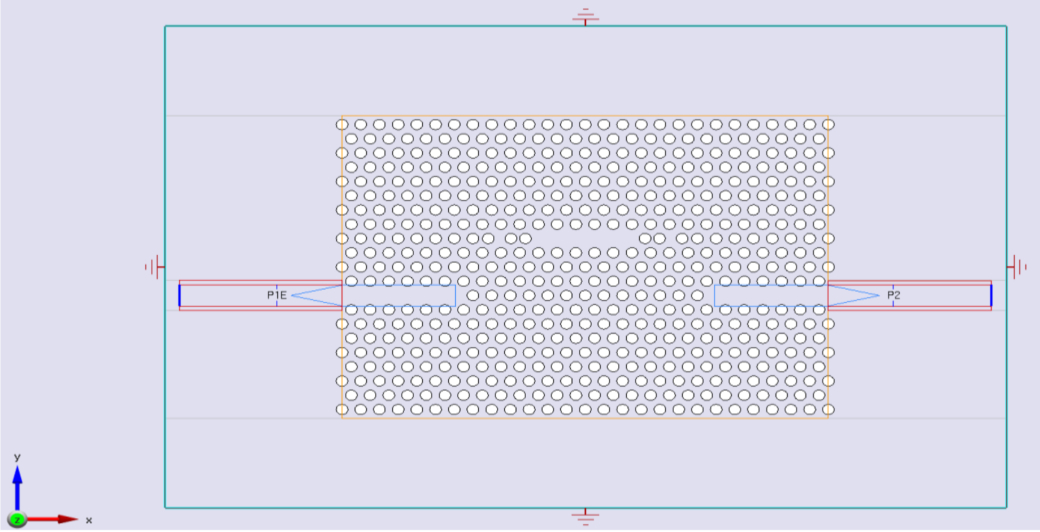
$$tan\delta = tan\delta_{diel} + \frac{1}{\rho\omega\varepsilon_0\varepsilon'} \; ; \; tan\delta_{diel} = \frac{\varepsilon''}{\varepsilon'}$$

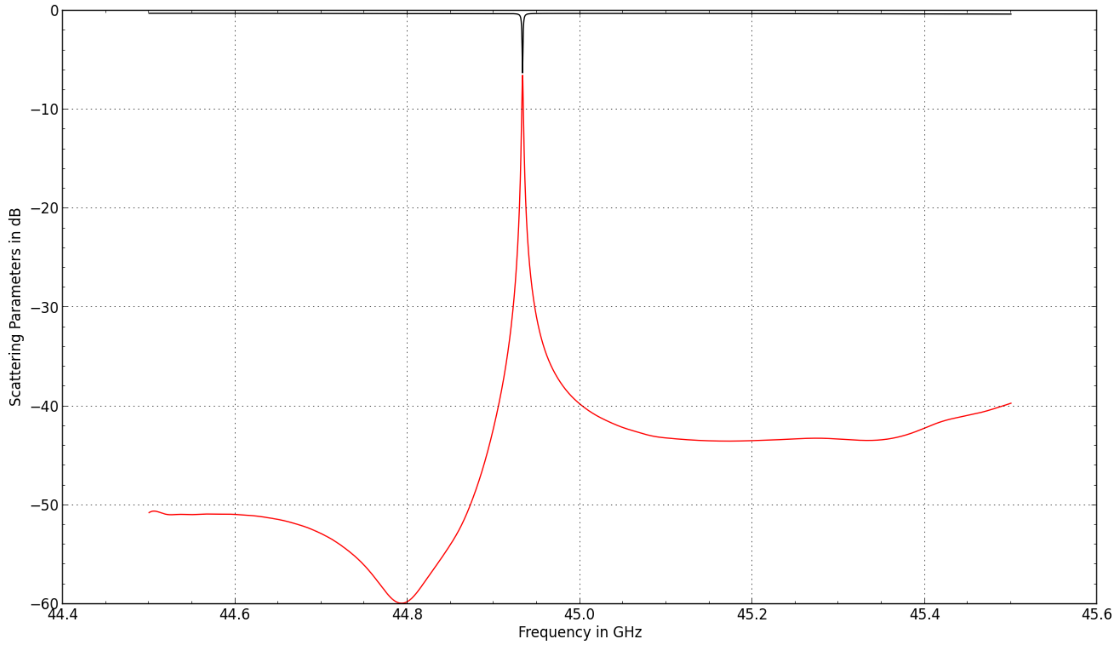
$$Q = \frac{1}{\left(tan\delta + \frac{1}{Q_{rad}}\right)}$$

- Q_0 limited due to radiation
  - Q_{rad} corresponds to the simulated Q_0 without dielectric losses.
  - For the simulated L3 Q_0 = 163,000 (without dielectric losses) leads to a calculated limit of Q_0 < 40,000.
  - With a loss tangent of $2{\cdot}10^{-5}$ ($tan\delta_{diel}$=$1.2{\cdot}10^{-5}$) for irradiated HRS material, Q_{rad} has to be very high (approaching 10^6).
- L3 resonance has higher field densities in z-direction compared to a L5 topology.
- Due to this reduced field leakage L5 is expected to come up with higher Q_{rad} and thereby higher Q0 values.

L5-design

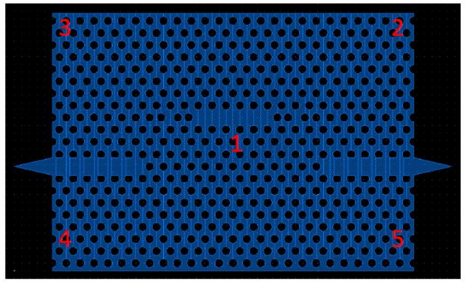




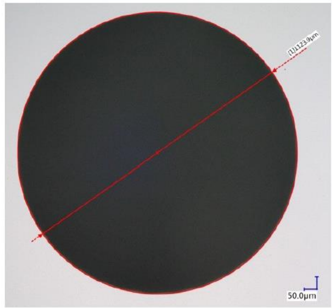


- With absorbers at bottom and top of housing no spurious observed in 1 GHz span.
- 6 dB insertion loss: Ql = 26,849, Q0 = 53,698.

L5 resonator production quality

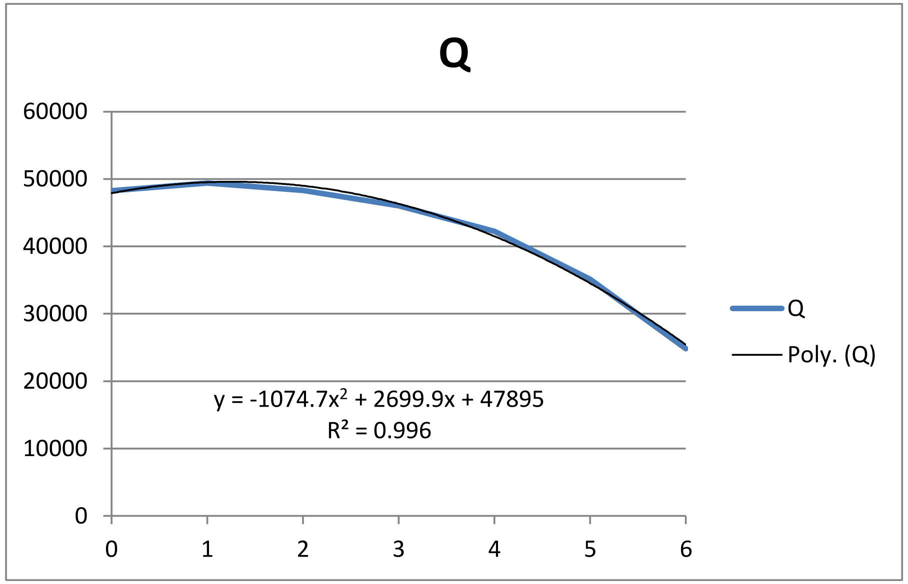


Measurement map



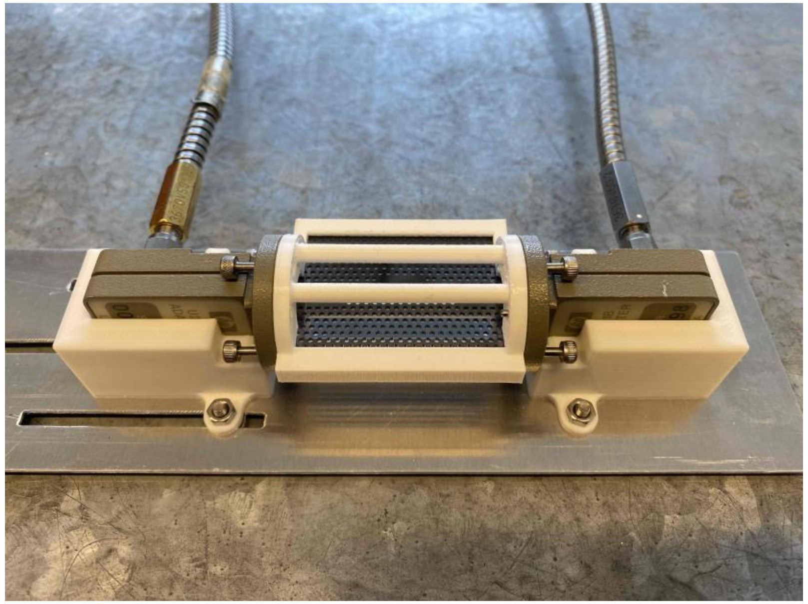
Measurement example (from bottom side)

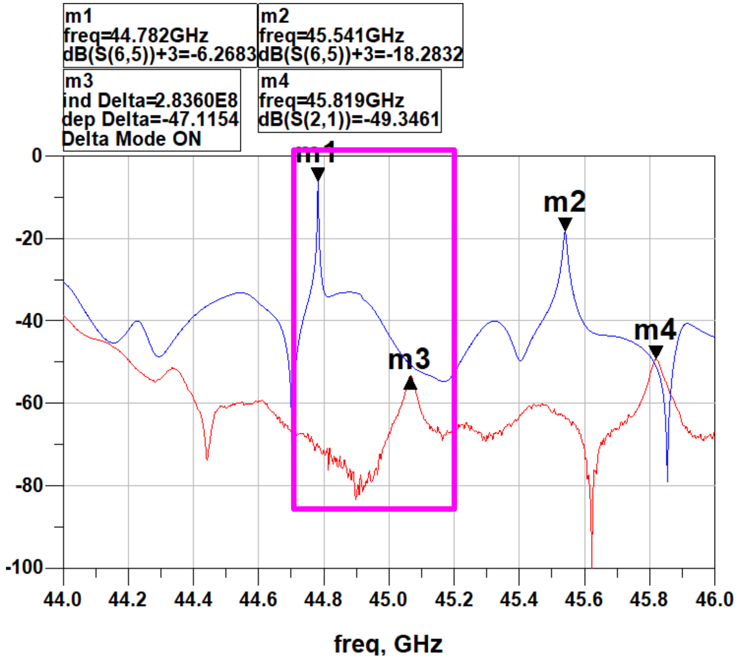
pos.	1	2	3	4	5	mean (µm)	Standard deviation (µm)	Standard deviation (%)
top diameter (µm)	1123,9	1122,0	1119,4	1119,8	1121,0	1121,22	1,81	0,16%
bottom diameter (µm)	1152,6	1151,1	1147,3	1160,6	1162,9	1154,90	6,60	0,57%
						mean (°)	Standard deviation (°)	
slope	90,82	90,83	90,80	91,17	91,20	90,96	0,20	



- DRIE etching of the resonator design carried out by Vmicro S.A.S, 27 rue Charles saint Venant, 59260 Hellemmes, France.
- Excellent etching quality was excellent: Hole diameters and the sidewall angles were compared to the design values at five positions of the resonator (1140 μm and 90 The agreement is very good.
- Deviation from 90 ° is sufficiently small to permit high Q-values.

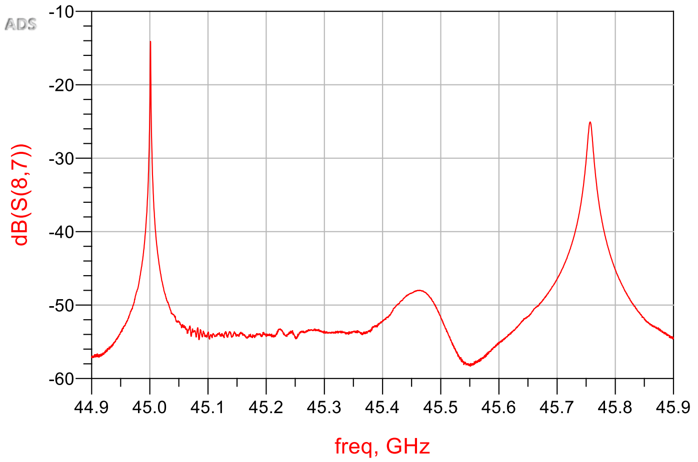
Resonator S-parameters and temperature sweep: L5

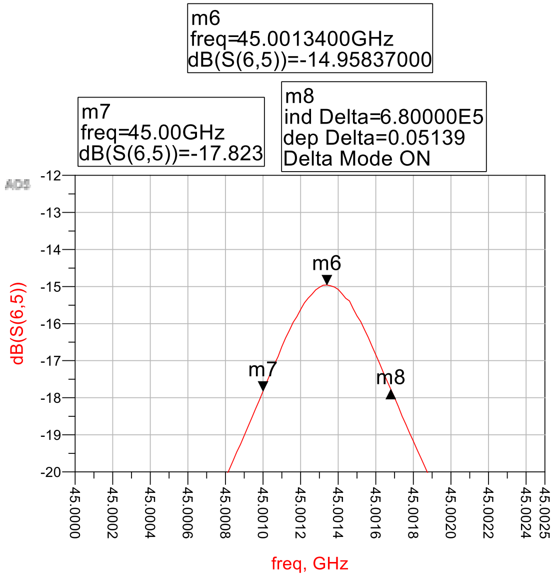


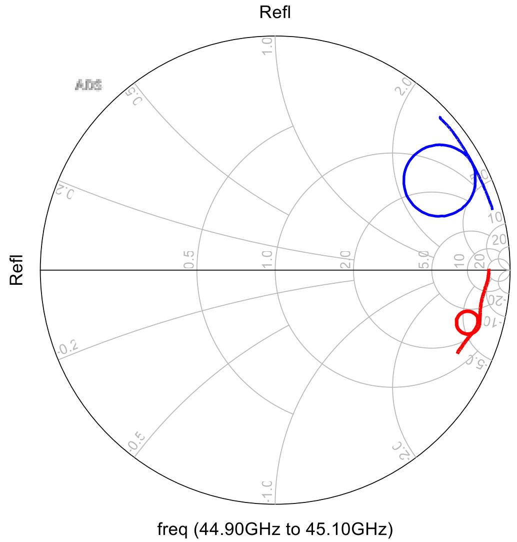


- Despite supreme etching quality the measurement results of the first samples were disappointing: Q of the resonators was very low in the measurements: For the sharpest resonance (L5, marker 1) the unloaded Q in simulation is 50,000. The measured Q for wanted resonance associated with marker 3 was only 1,800.
- Problem process temperature? O_2 plasma based cleaning post etching process (150 °C) was avoided and replaced by a solvent based cleaning used at a controlled temperature of less than 70 °C.

Resonator S-parameters and temperature sweep: L5





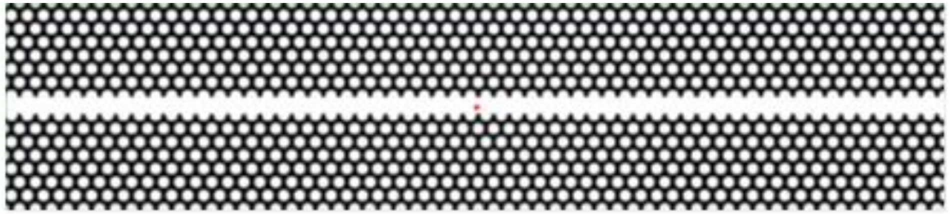


- Regarding the resonance frequency deviation is only 70 MHz (simulated: 44.93 GHz, measured: 45.00 GHz).
- Unloaded quality factor is even higher than simulated (simulated: 53,700, measured: 80,500) $\Rightarrow$ loss tangent of the neutron-irradiated HRS base material is lower than 2.1·10-5 (derived from a resistivity of 400 kOhm cm and a bulk loss tangent of $1.2 \cdot 10^{-5}$).
- Problem: coupling strength is very low: At resonance, S21 is only -15 dB as opposed to 6 dB per design.
- Cannot be explained real hole size.
- Coupling strength is strongly affected by small inaccuracies of the field solution as part of the 3D-FDTD simulation method. Also, the high-Q of the resonator presents a problem to the simulator as resonance estimation algorithms need to be used in order to come up with manageable simulation time.

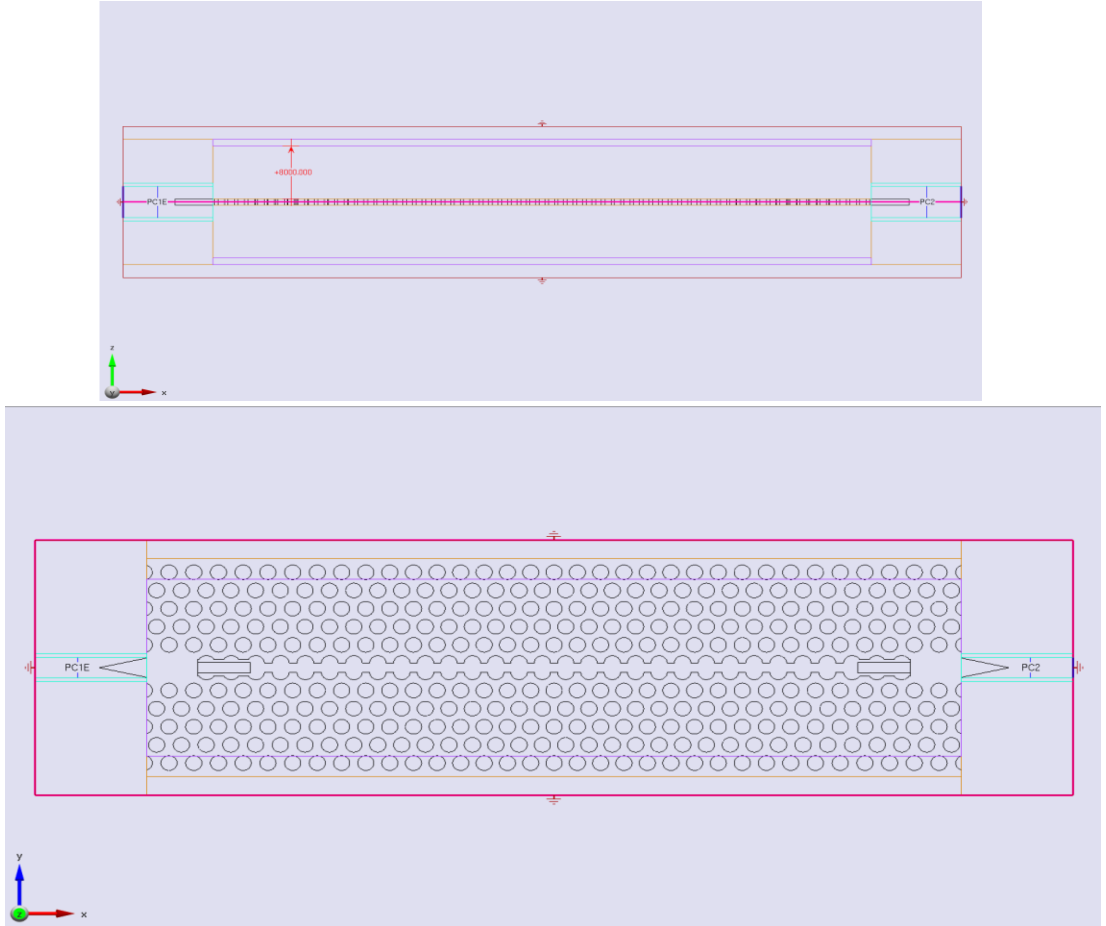
Resonator: Reduced Dielectric Filling Factor Cavity (RFFC)

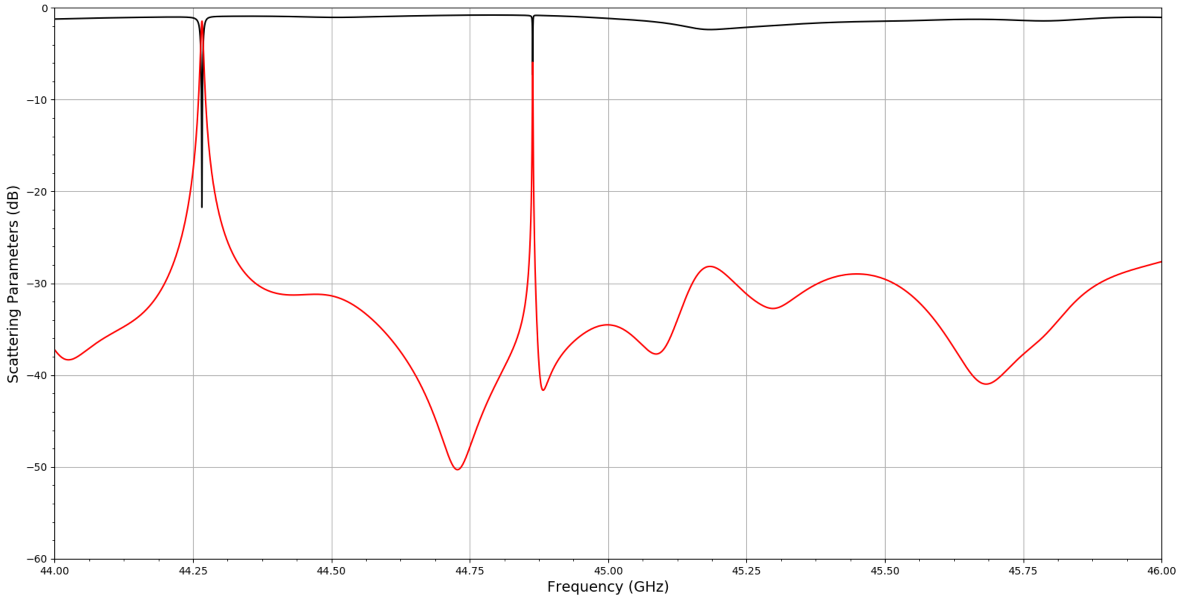
Q-optimisation

- Basic Idea: Reduction of dielectric filling factor of the resonator leads to reduction of dielectric losses.
- To minimise out-of-plane radiation loss (Q_{rad}), a Gaussian shape for the envelope of the resonant mode's electric field is needed.
  - Quadratically tapering the horizontal period of the first $N_{Gauss} = 8$ unit cells.
- The PCR was excited by an electric dipole source located at the centre of the structure and the Q-factor calculated by analysing the time-decay of the fields.
- Radiative Q-factor exceeded 800,000.
  - The unloaded Q-factor will be dominated by the material loss Q_{mat}.
- With a realistic loss tangent ($\tan\delta = 2.1 \times 10^{-5}$), the simulated Q-factor is 108,000
  - The low dielectric filling factor of the air slot mode has effectively doubled the unloaded Q-factor for a material loss limited design.



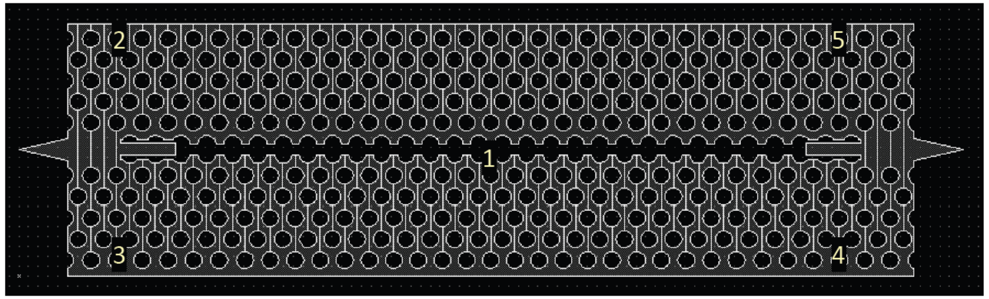
RFFC-design





- With absorbers at bottom and top of housing one spurious mode at ≈ 44.25 GHz.
- IL = 6 dB: Ql = 54,053, Q0 = 108,105.

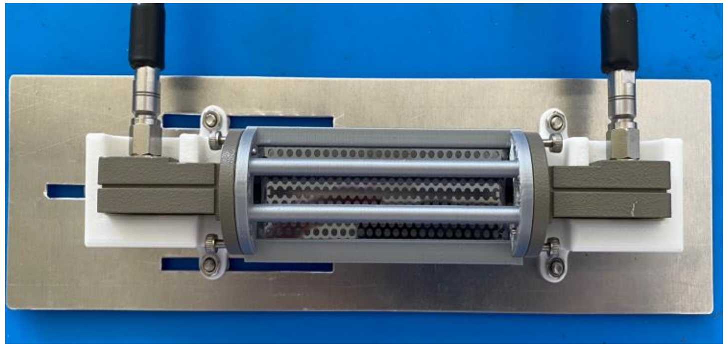
Resonator S-parameters and temperature sweep: RFFC

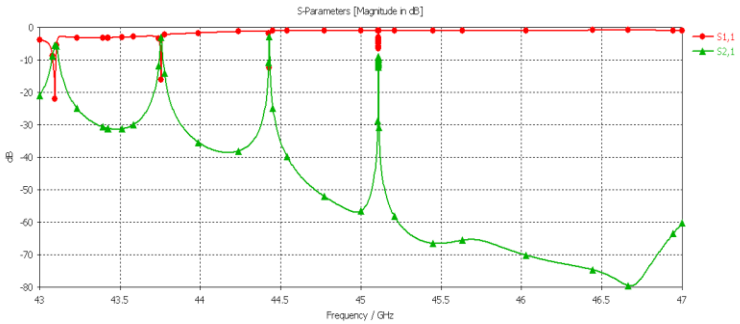


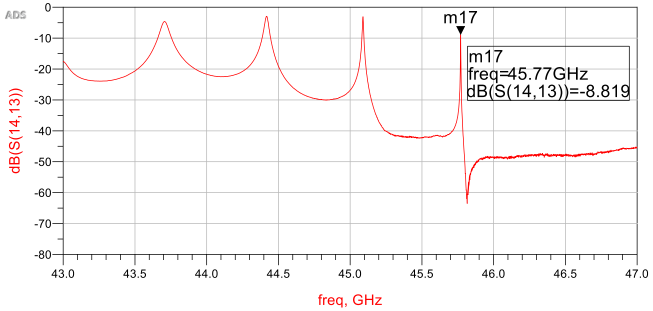
DEVICE 2 - 01	1	2	3	4	5	mean (µm)	Standard deviation (µm)	Standard deviation (%)
top diameter (µm)	1693	1689	1688	1692	1694	1691	2,59	0,15%
bottom diameter (µm)	1 736	1 729	1 737	1 738	1 732	1734	3,78	0,22%
						mean (°)	Standard deviation (°)	Standard deviation (%)
slope	91,23	91,15	91,40	91,32	91,09	91,24	0,13	0,14%

- As for L5 resonator, the agreement of the fabricated sample with the design is excellent (hole diameter design value: 1727 μm..

Resonator S-parameters and temperature sweep: RFFC

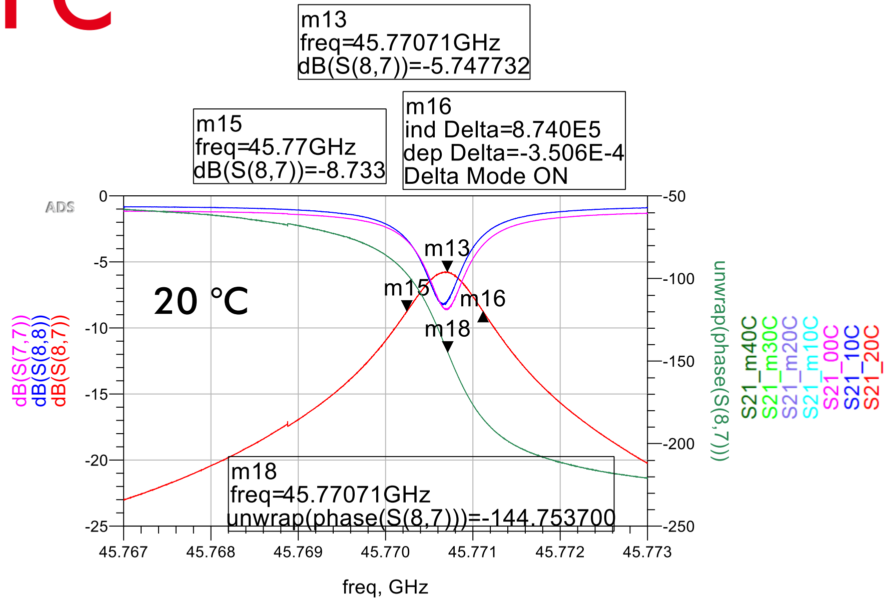


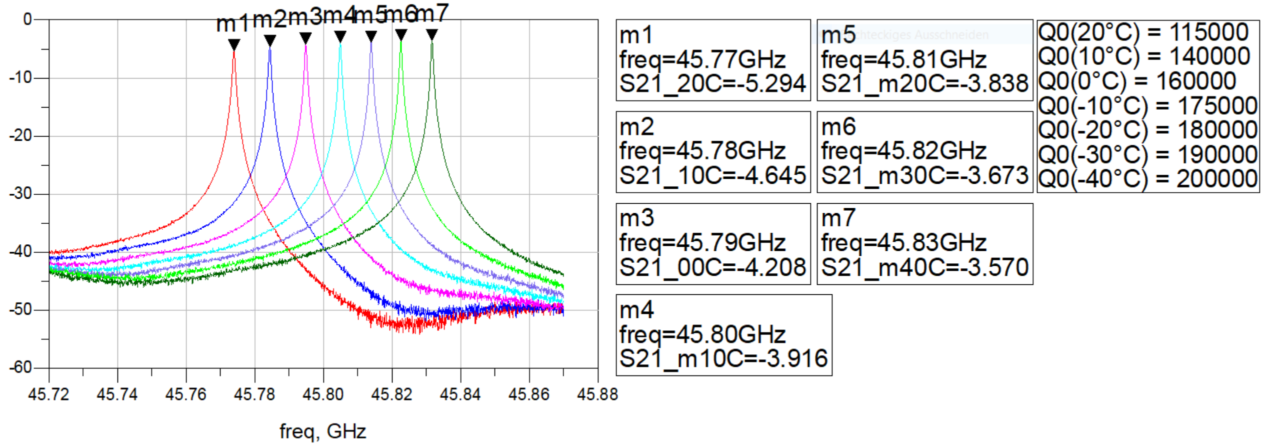




- Simulated and the measured wide band response of the RFFC resonator: Frequency response is shifted by 620 MHz corresponding to a fractional deviation of 1.3 %.
- Simulations have confirmed that this shift cannot be explained by the small deviations of the slot and hole diameters from the design values. Generally, the photonic crystal acts as a distributed reflectance. Therefore, probably a combination of several effects contributes to the frequency shift.

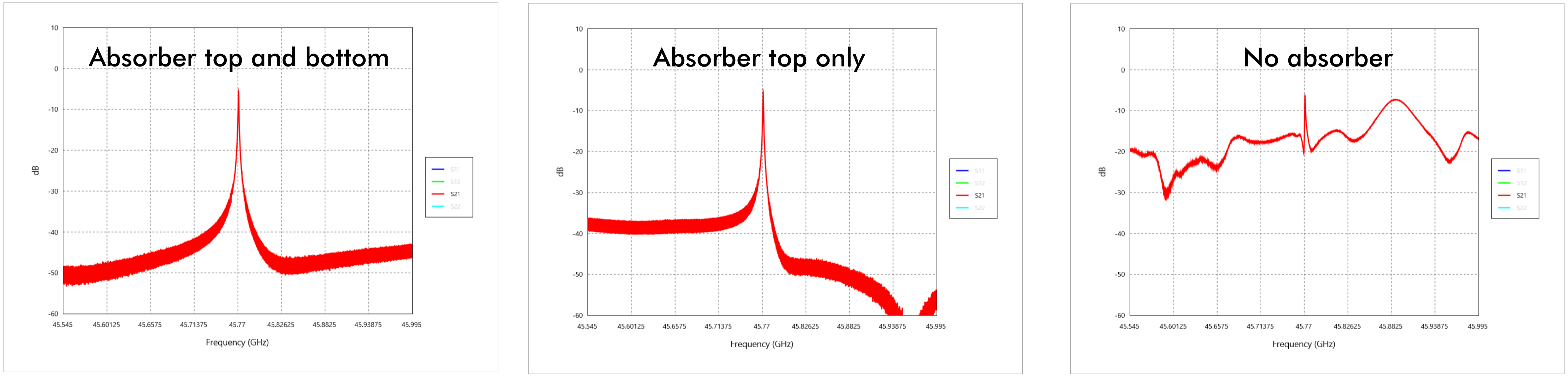
Resonator S-parameters and temperature sweep: RFFC





- S21 = -5.7 dB, loaded Q = 52,400, and unloaded Q = 108,300. Measured unloaded Q again higher than the expectation from the simulations: S21 = 7.2 dB, loaded Q = 50,400, unloaded Q = 89,400. Good match of S21.
- Q increases with decreasing temperature due to improving loss tangent.
- Confirms excellent material loss tangent of the irradiated HRS from Topsil.

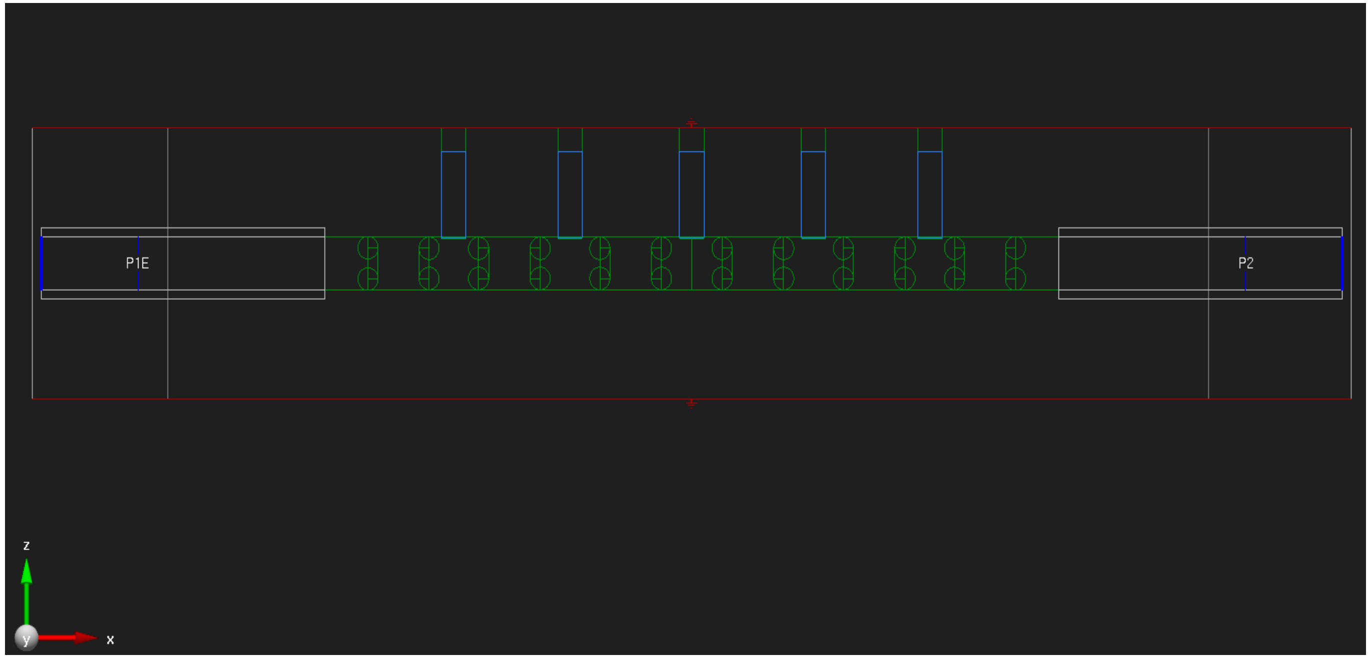
Resonator S-parameters and temperature sweep: RFFC in housing



- 1 mm thick Eccosorb BSR-1 sheets used.
- Unloaded Q with absorber sheets at the top and at the bottom:113,200, in case the absorber is situated at the top only it is 125,100. Compare this with the results using the plastic holder 108,300.
- Without absorber background S21 is too high.

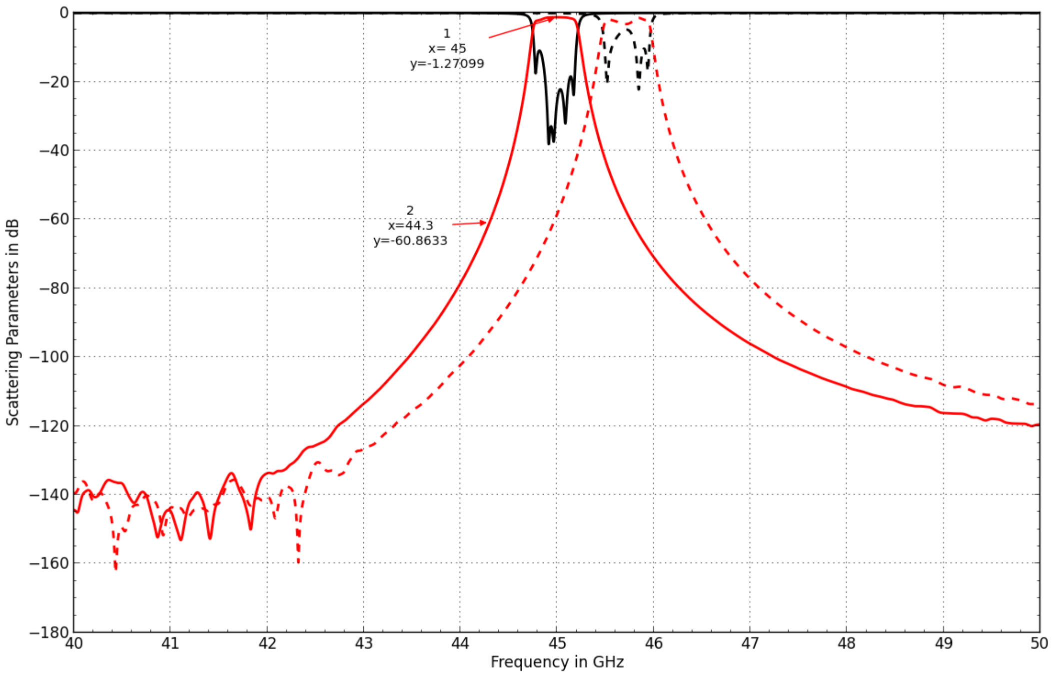
Filter and phase shifters

Filter Design (5th order)



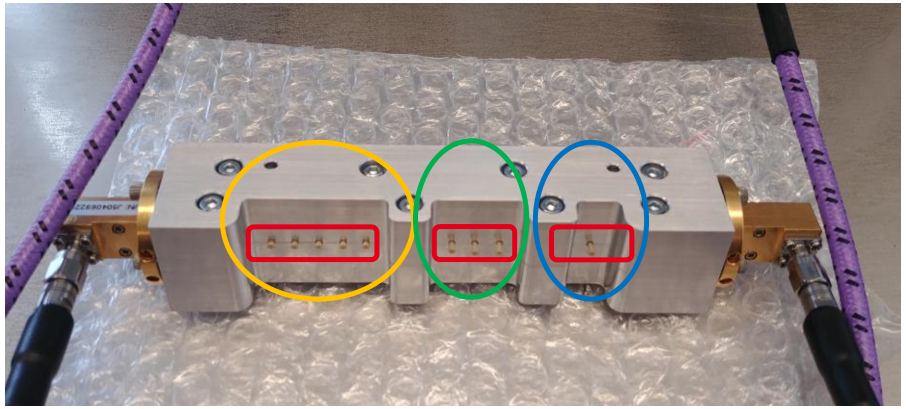
- Prevents oscillator from locking on unwanted modes.
- Manufacturing tolerances (+/-50 μm) can be compensated by means of M1.4 PEEK screws (blue).
- Centre frequency of the filter can only be lowered $\Rightarrow$ nominal design has been undersized on purpose by 50 μm. Then filter was re-tuned to 45 GHz by means of the PEEK screws.

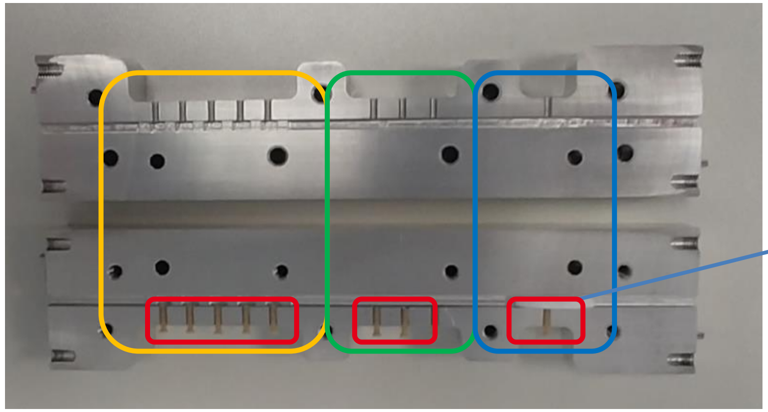
Filter Design



- Total tuning range: 700 MHz.
- Larger than manufacturing tolerances.

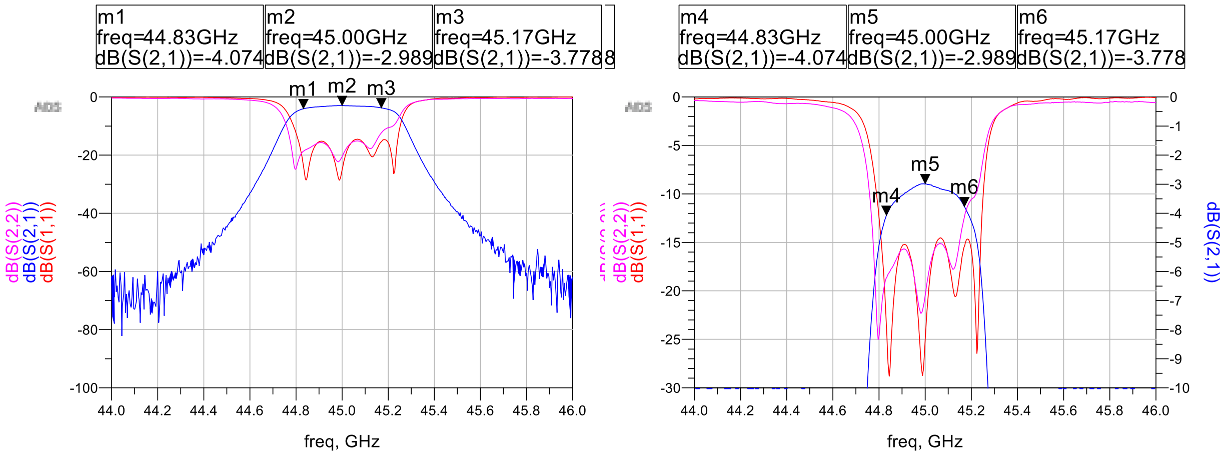
Measurement: Combined filter and mechanical phase shifter test structure measurement



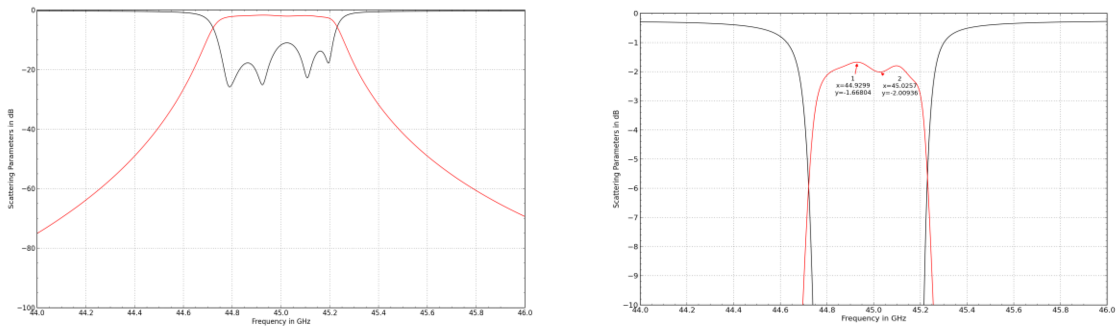


- Side view of test structure filter (yellow), fine phase shifter (green) and coarse phase shifter (blue).

Combined filter and mechanical phase shifter test structure measurement – waveguide filter



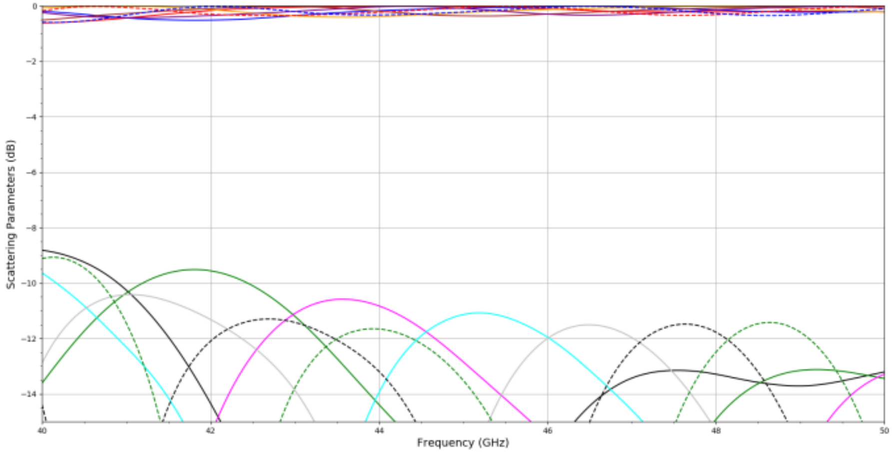
Measurement

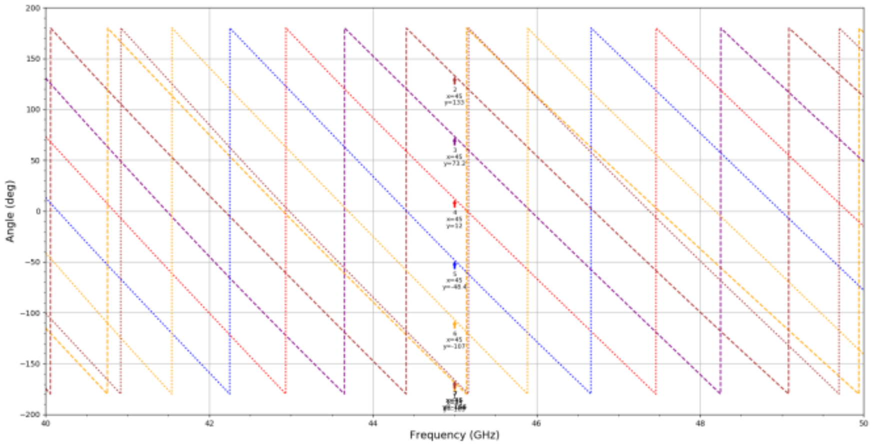


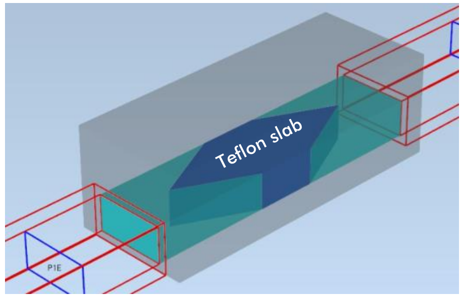
Simulation

- For the measurement, the fine phase shifter screws were retracted and no coarse phase shifter present.
- Compared with the simulated behaviour inband attenuation is 1.3 dB higher than simulated. The outband attenuation is similar.

Coarse phase shifter

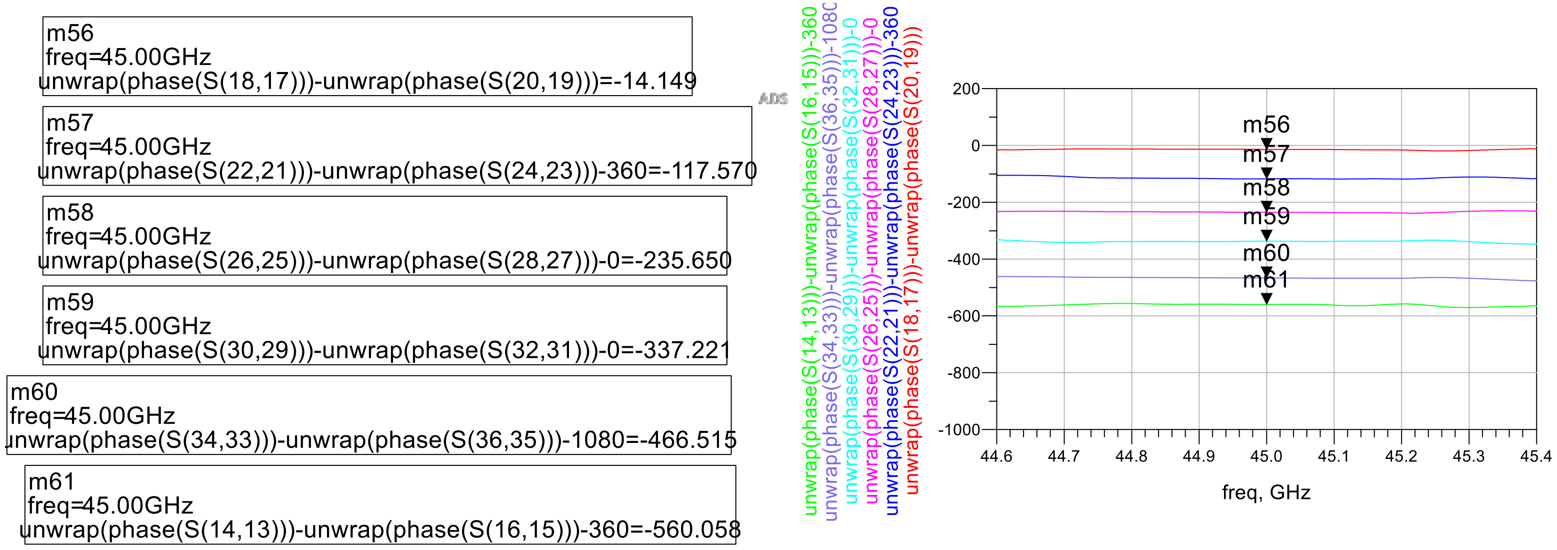






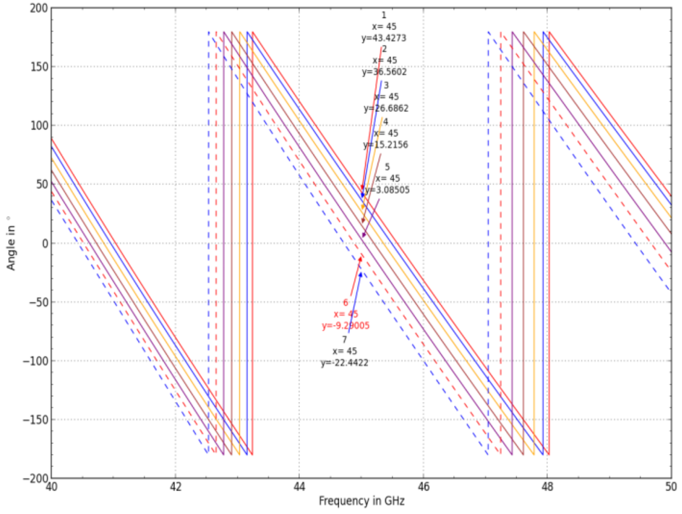
- By varying the length from 0 to 12 mm a phase shift of 360 ° can be realised.
- The phase step between two adjacent length settings is approximately 60 °.

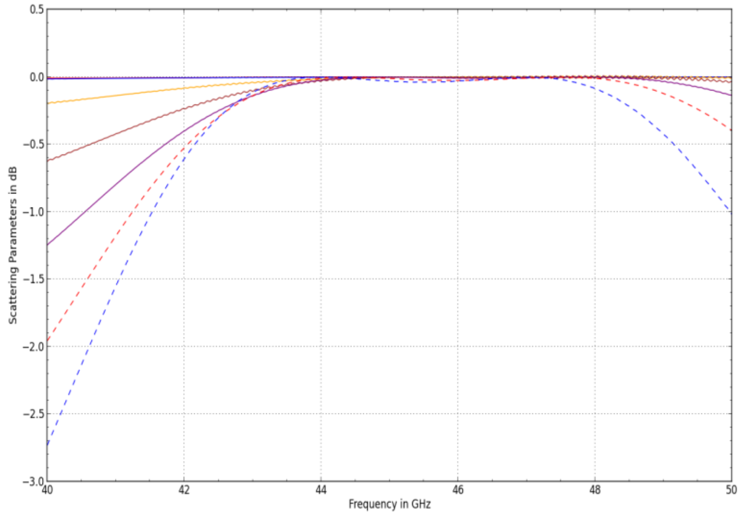
Measurement: Coarse phase shifter

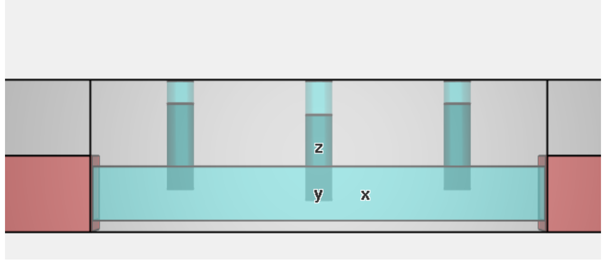


- Phase shift vs. coarse phase shifter length: 16, 20, 24, 28, 32, 36 mm (from red to green).
- Phase shift between two adjacent lengths of the phase shifters ≈ 120 °. Different than expected in simulation: phase shift for a length change of 4 mm is only 60 °.
- Origin might be a higher permittivity of the phase shifters than assumed in the simulation.
- Additional phase shifter lengths (18, 22, 26, 30, 34 mm) were manufactured to bring the tuning step down to smaller than 60 ° so that the step is within the tuning range of the fine phase shifter.

Fine phase shifter

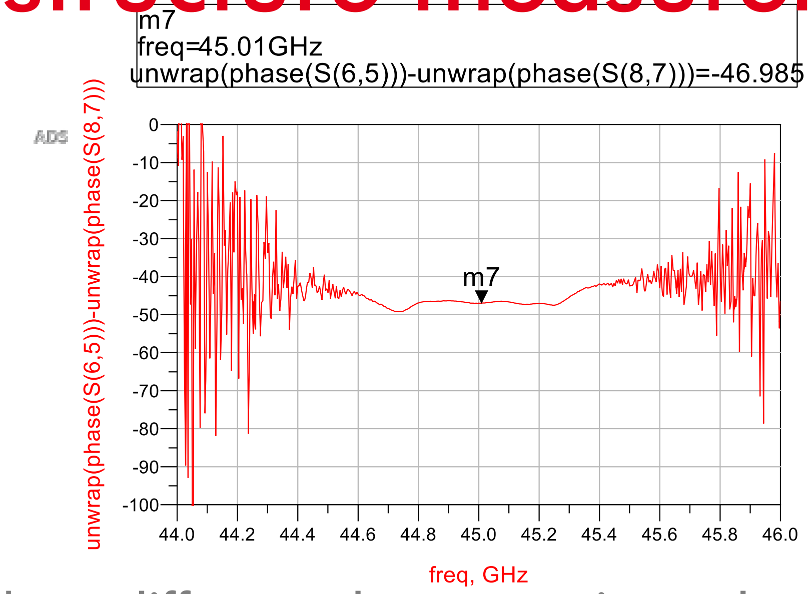


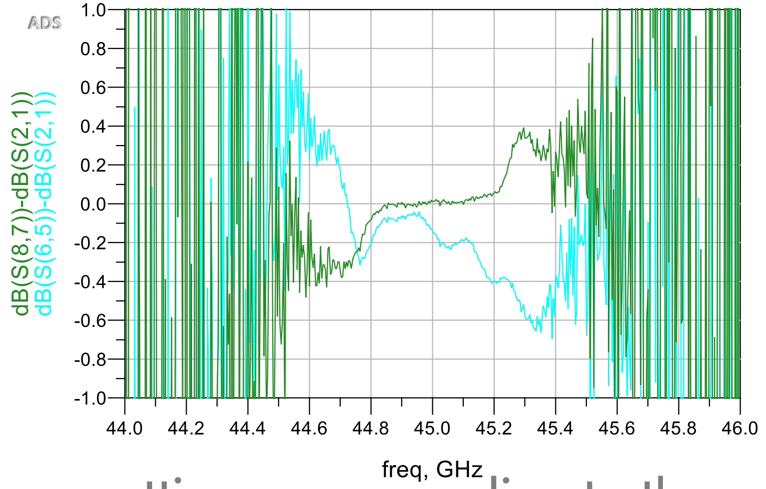




- For optimum insertion loss and match the insertion depth of the central screw is greater by a factor 1.5 than the insertion depth of both outer screws.
- Total phase variation at 45 GHz = 65 °.
- By means of the combination of the coarse and the fine phase shifter phase shifts up to 360 ° can be realised with resolution < 7°. Inside el. tuning range, therefore oscillator phase can be controlled with very fine resolution over wide total range.

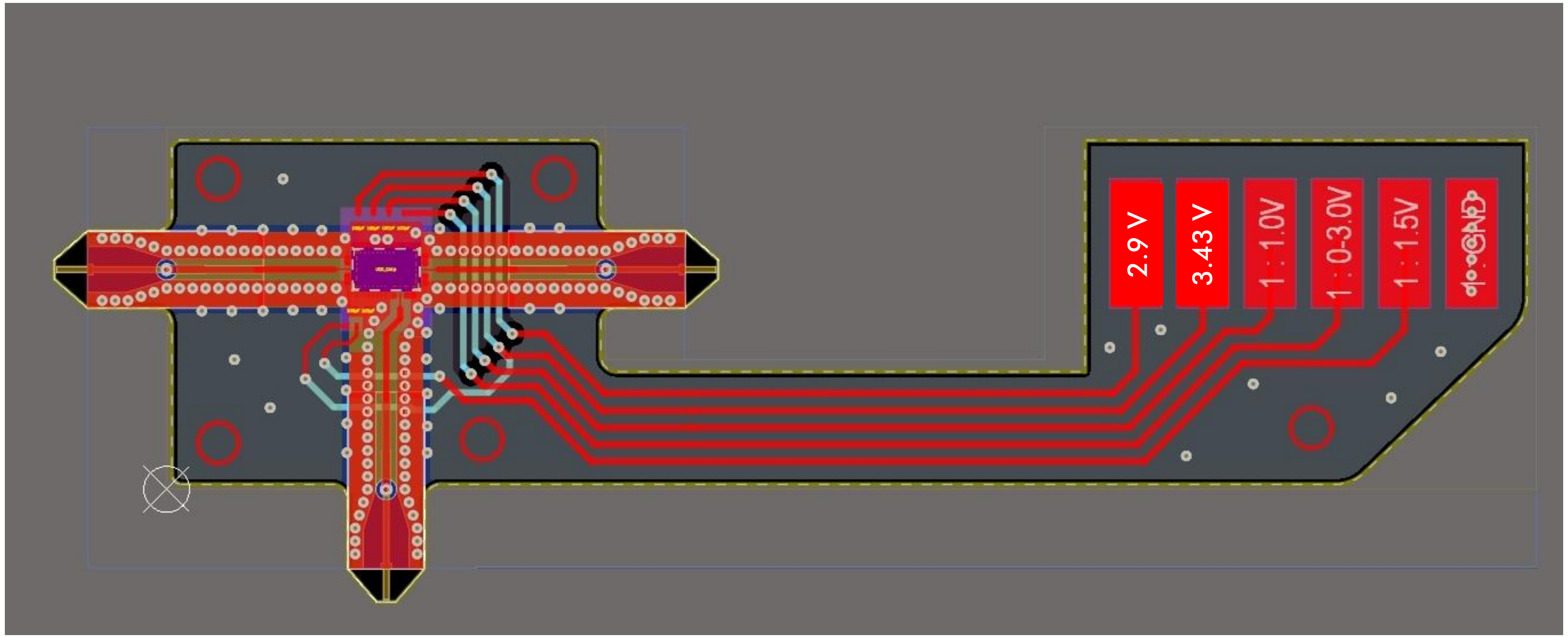
Combined filter and mechanical phase shifter test structure measurement – fine phase shifter





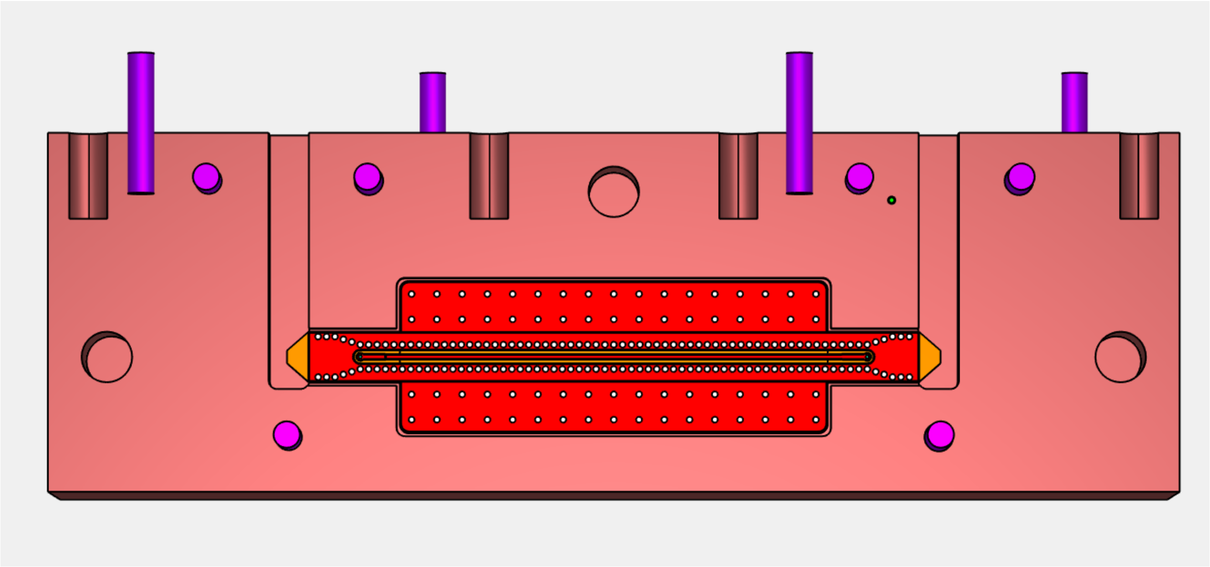
- Fine phase difference between min. and max. screw setting corresponding to the max. achievable phase variation is 47 ° (expectation from simulation: 65 °). Measured tuning accuracy better than 0.5 °!
- The change of the insertion loss of the filter curve with min. phase variation (green) and filter curve with max. phase variation (light blue) less than 0.2 dB (simulation: at least 0.9 dB).
- **Combination of coarse and fine phase shifter can control the phase up to 360 ° with a precision of better than 0.5 °. Combined with the electronic phase shifter an electro-mechanical adjustment of the phase can be carried out which allows for a safe startup of the oscillator.**

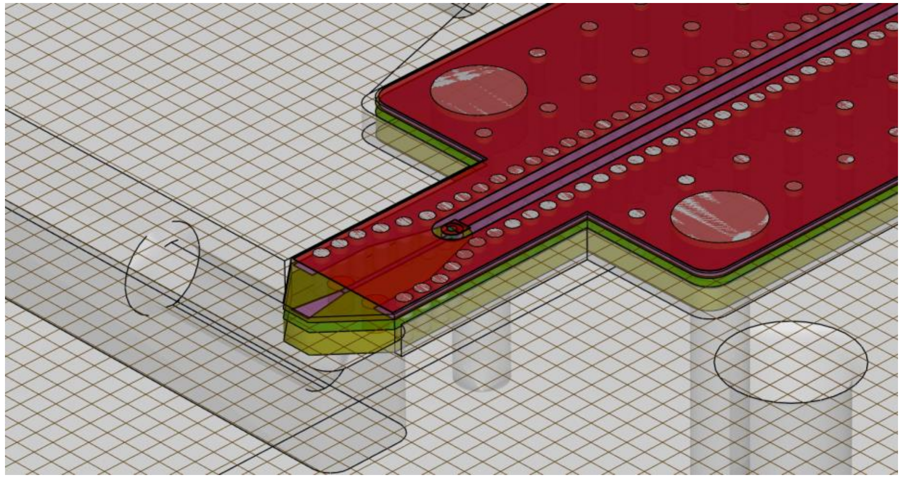
Test board design



- Test board contains the RF input and output lines to and from the active chip and the Vcc and Vtune lines.
- A four layer-PCB is used.
- RF-lines are routed on the top metal layer with the exception of the area of the transition to the waveguide where metal layer two is used. Apart from these small areas metal layer two is ground. Metal layers three and four are also ground. Metal layer three is also partly used for the routing of the Vcc / Vtune lines in the area where they cross the RF-line.
- Bond compensation networks were added before tapeout.

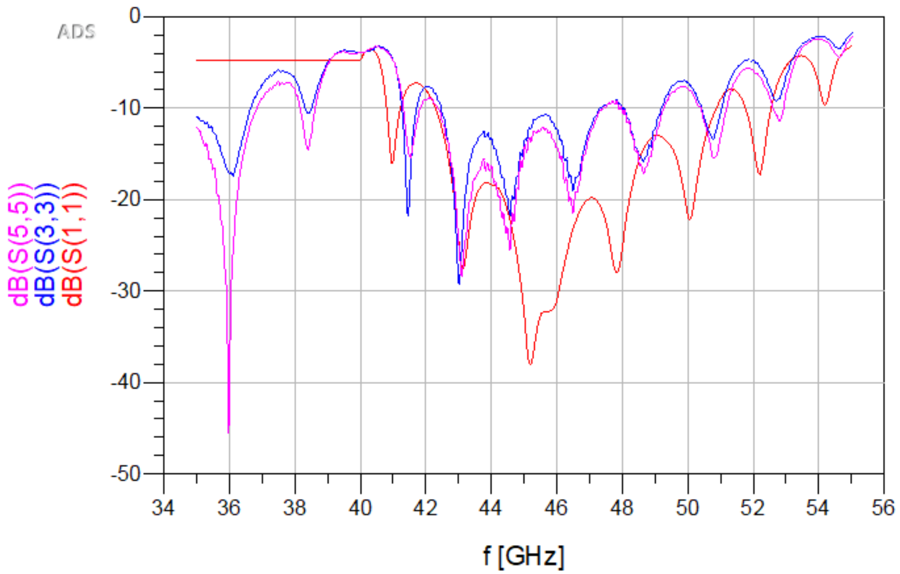
Test structure waveguide to microstrip transition

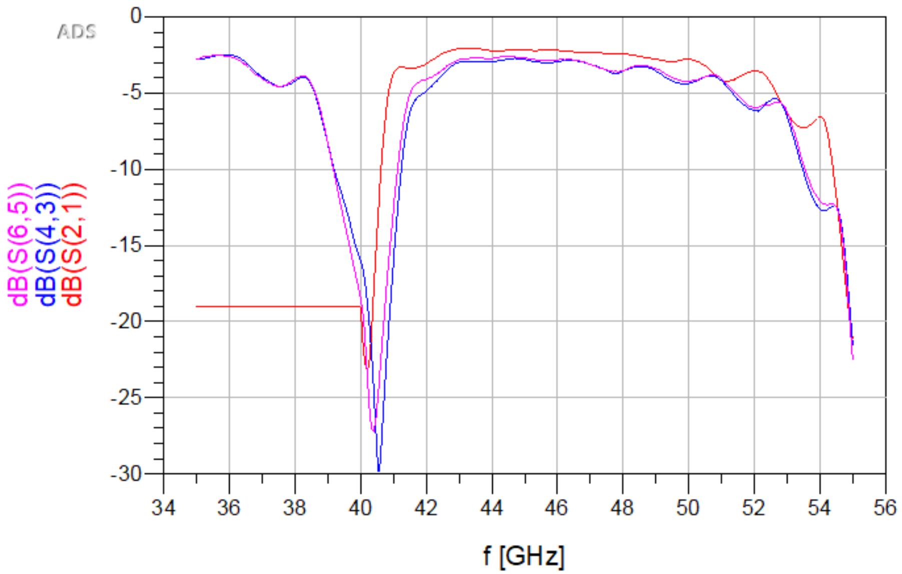




- PCB with two transitions is connected to two waveguides.
- 50 Ohm line on top layer, matching network on layer 2 in order to minimise sensitivity to small variations of vertical position in waveguide.
- Standard WR19 waveguide to coax adaptors are used to couple in and out of this structure. This way two transitions are measured in series.

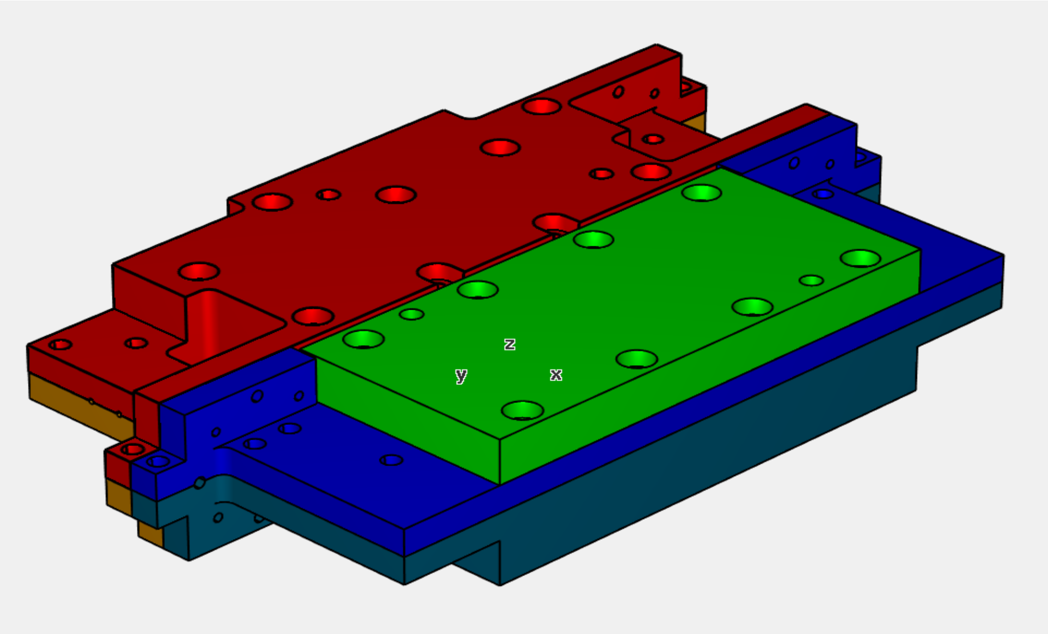
Verification of the waveguide to microstrip line transitions

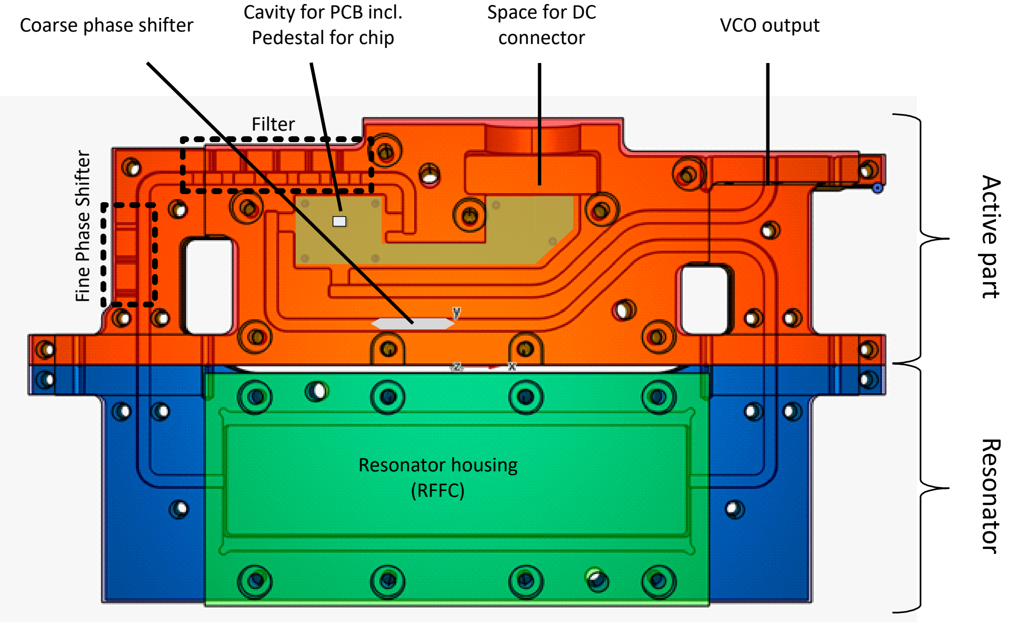




- Simulated (blue and pink) and measured (red) waveguide-to-microstrip transition performance.
- Insertion loss slightly worse than simulated (3 dB measured vs. 1.7 dB simulated).

Housing design

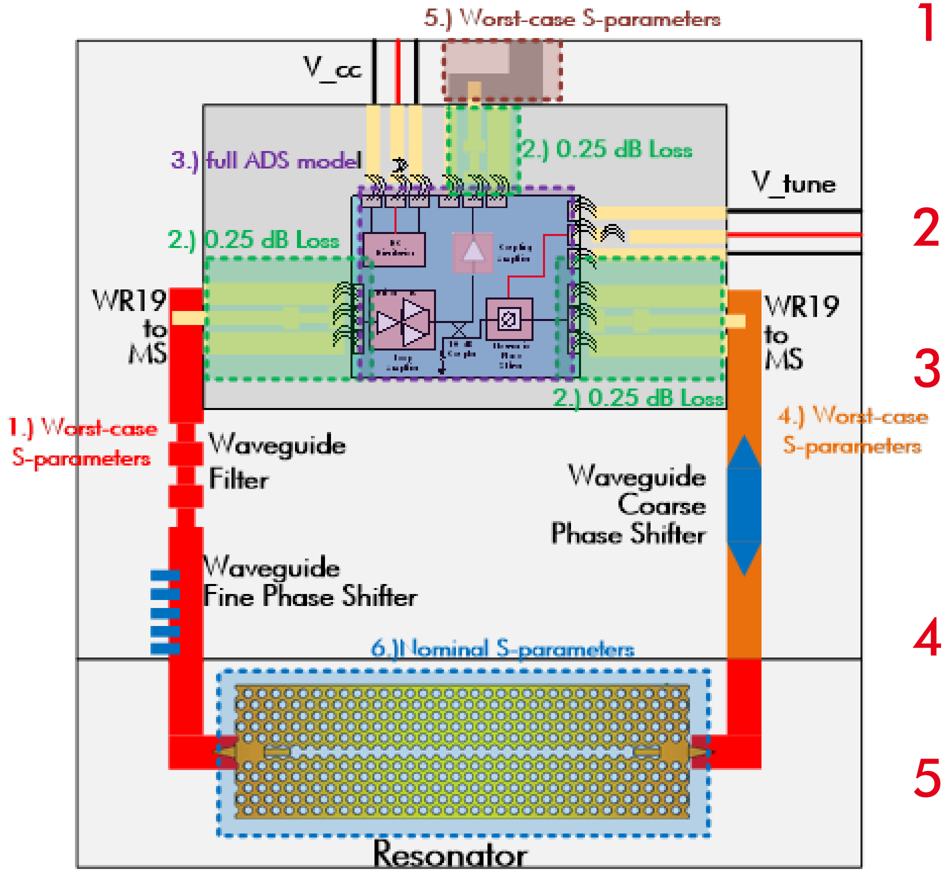




- The overall dimensions of the oscillator housing are 157 x 92 x 29 mm³ in case the RFFC resonator is used and 157 x 96 x 29 mm³ for the L5 resonator.
- Active part and resonator can be measured individually. Connection: standard WR19 flanges.

Total Oscillator Performance

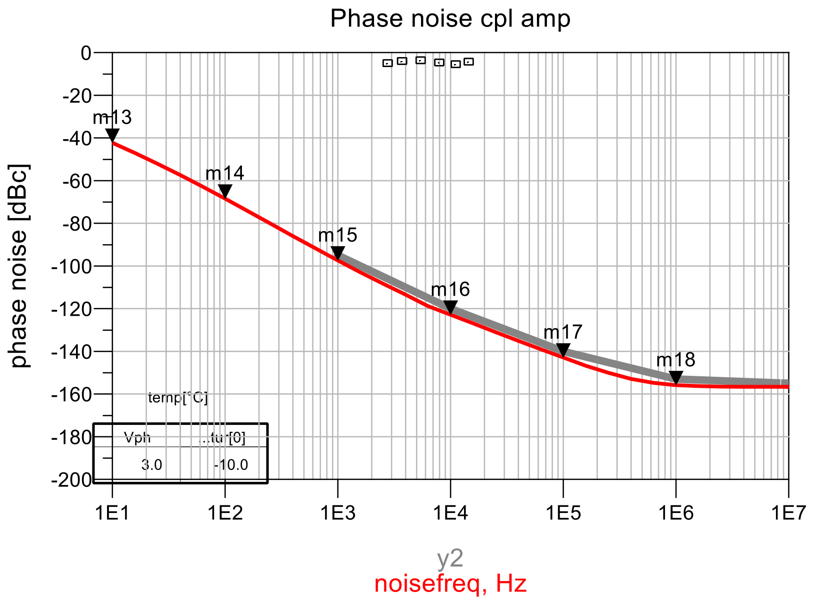
Simulation setup



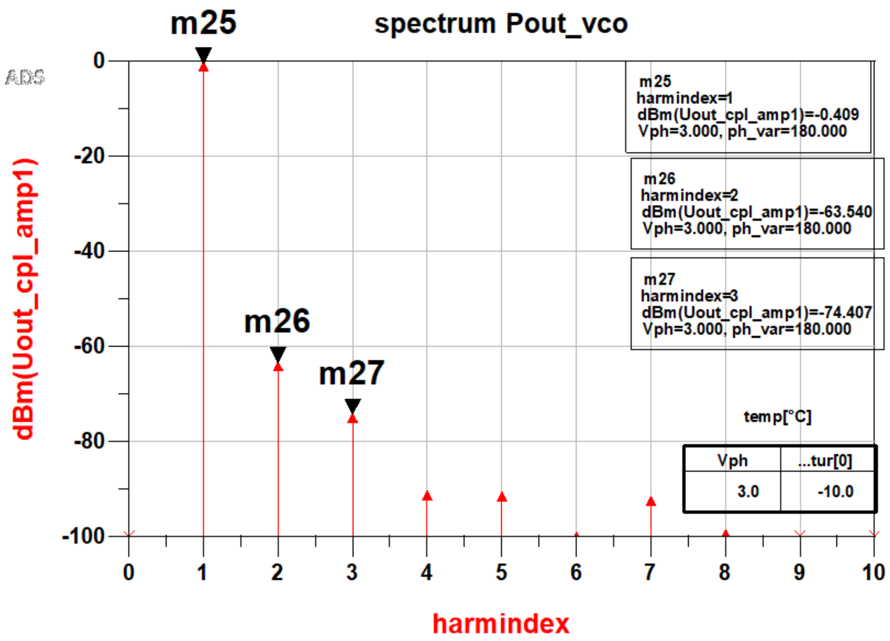
1. Worst-case S-parameters of the block fine phase shifter, the waveguide filter and the waveguide to μ-strip transition
2. 0.25 dB loss for losses of the bond compensation network and the bond wire to the die
3. Full ADS model of the loop amplifier, 10 dB coupler, electrical phase shifter and coupling amplifier, (electrical phase shifter fixed at Vtune = 3 V for maximum insertion loss)
4. Worst-case S-parameters of the block μ-strip to waveguide transition, coarse phase shifter / waveguide
5. Worst-case S-parameters μ-strip to waveguide transition / waveguide to the output of the oscillator
6. Nominal S-parameters of the resonators

Phase noise / output power (RFFC, IL = 6 dB), -10 °C

IMST



noisefreq	m13	noisefreq	m14	noisefreq	m15	noisefreq	m16	noisefreq	m17	noisefreq	m18
10.00 Hz	-42.233	100.0 Hz	-68.474	1.000 kHz	-97.446	10.00 kHz	-122.851	100.0 kHz	-142.941	1.000 MHz	-155.839



- Phase noise was simulated for typical semiconductor process parameters only.
- Phase noise in spec.
- Output power = -0.4 dBm.
- Power consumption: 151 mW.

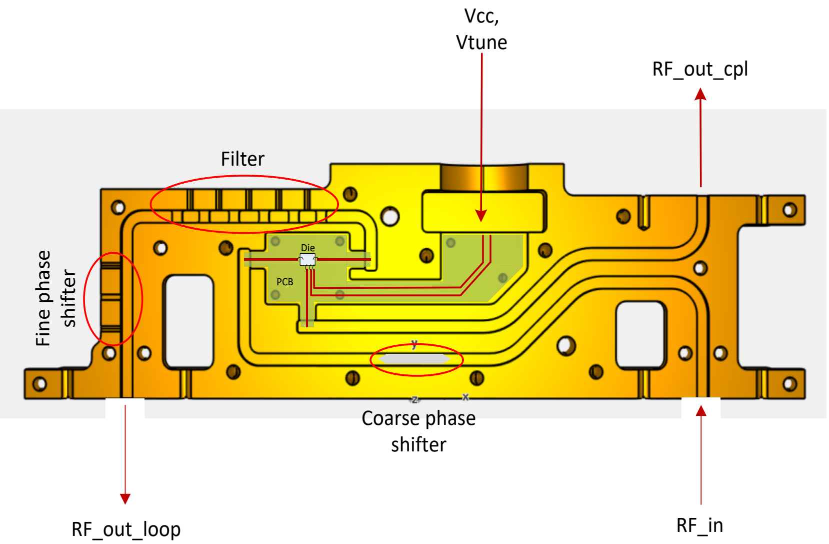
Phase noise summary

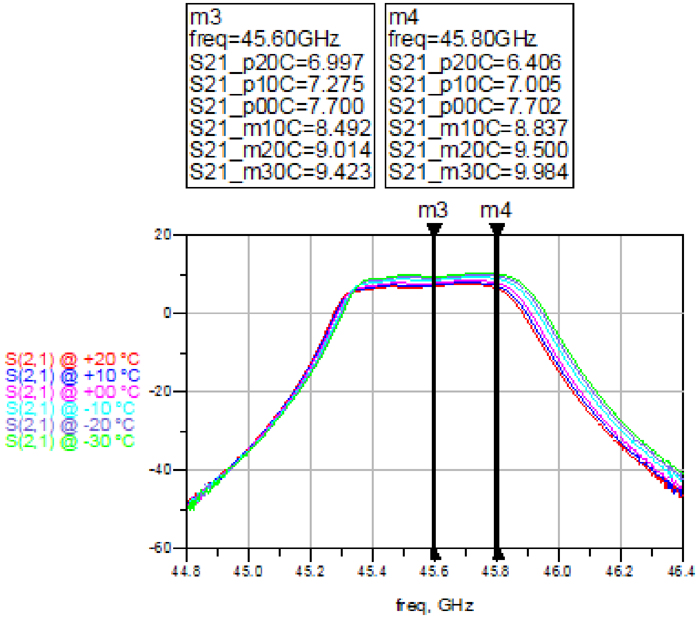
	RFFC, IL= 6 dB			
	20 °C	-10 °C	-40 °C	*Spec.*
10	-37	-42	-45	
100	-65	-68	-71	
1000	-94	-97	-100	*-95*
10000	-121	-123	-124	*-120*
100000	-142	-143	-144	*-140*
1000000	-155	-156	-157	*-153*

- Nominal temperature = -10 °C.

Measurement results

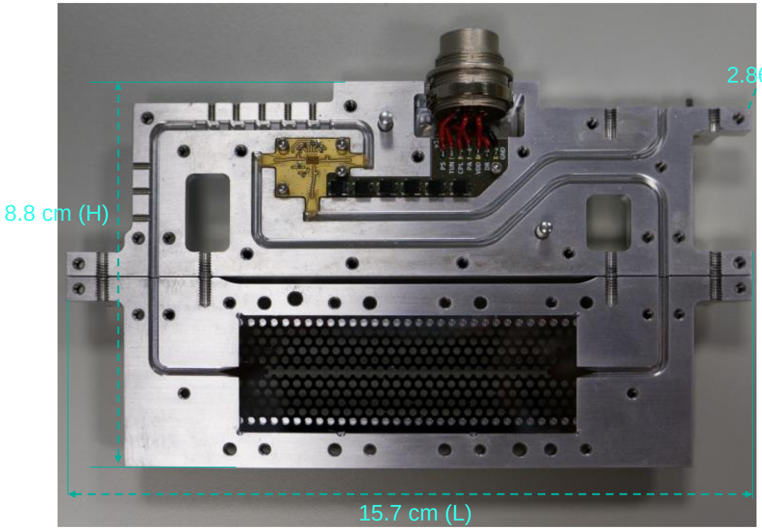
Combined amplifier, phase shifter and filter S-parameters and large signal behaviour

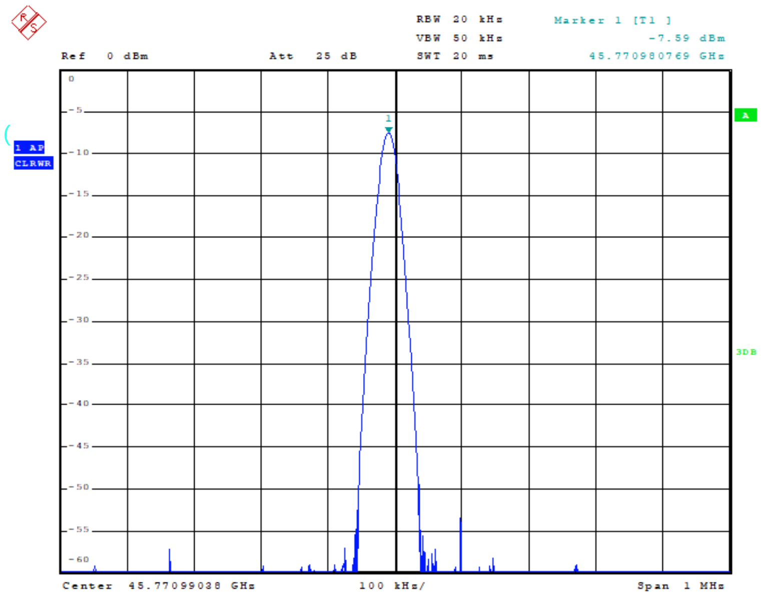


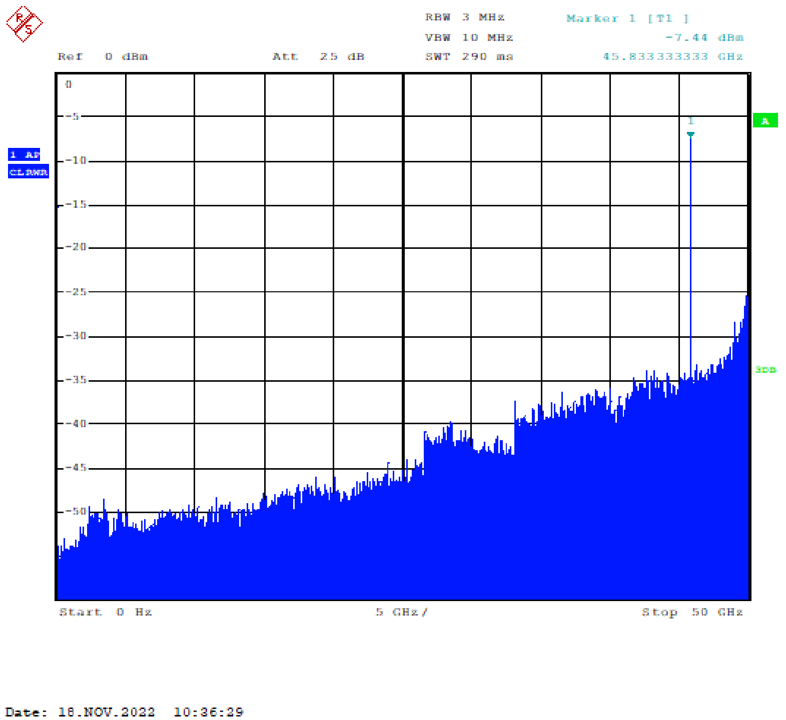


- S-parameters of the main path as a function of temperature (-30 to +20 °C).
- The waveguide filter tuned to the highest possible passband frequency range in order to allow for a good insertion loss when using the RFFC at 45.771 GHz.
- Between 45.6 and 45.8 GHz the minimum S21 is 6.4 dB (20 °C). RFFC has an insertion loss of 5.7 dB.
- S11 and S22 are smaller than 10 dB (not shown).

Oscillator measurements

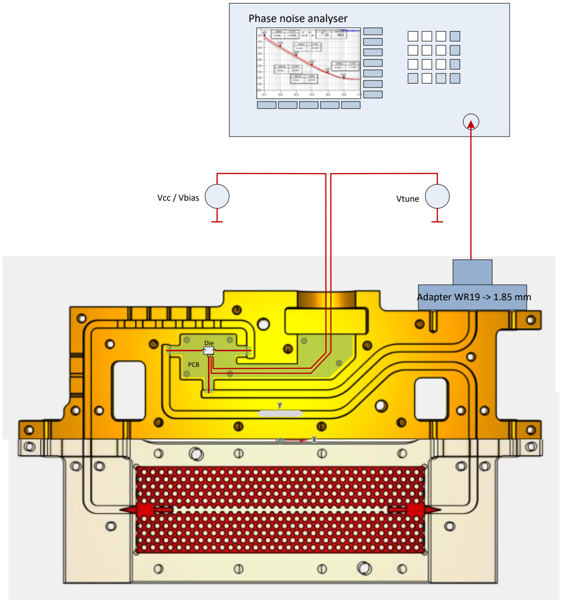






- After assembly of the oscillator Bias 4 was applied. A coarse phase shifter of 20 mm was used.
- Output frequency of the oscillator is very close to the resonance frequency of the RFFC.
- The measurement includes a cable with an insertion loss of 5.2 dB ⇒ output power = -2.4 dBm.
- No wideband spurious observed.

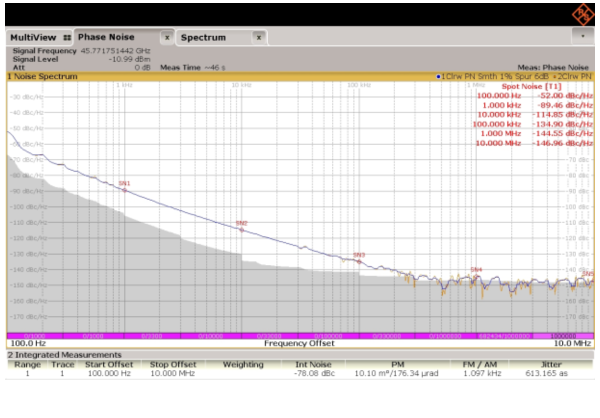
Oscillator measurements: phase noise and el. tuning range (room temperature)



Offset / Hz	Vtun = 0 V	Vtun = 1 V	Vtun = 2 V	Vtun = 3 V
1.00E+02	-52	-42	-41	-47
1.00E+03	-89	-84	-82	-85
1.00E+04	-115	-113	-109	-110
1.00E+05	-135	-135	-133	-133
1.00E+06	-145	-147	-148	-149
1.00E+07	-147	-148	-149	-151
Freq. Shift / kHz	0	-39	-181	-239
Freq. Shift / %	0.00E+00	-8.52E-05	-3.95E-04	-5.22E-04
Freq. Shift / ppm	0.00	-0.85	-3.95	-5.22
Output power / dBm	-5.8	-5.9	-3.7	-4

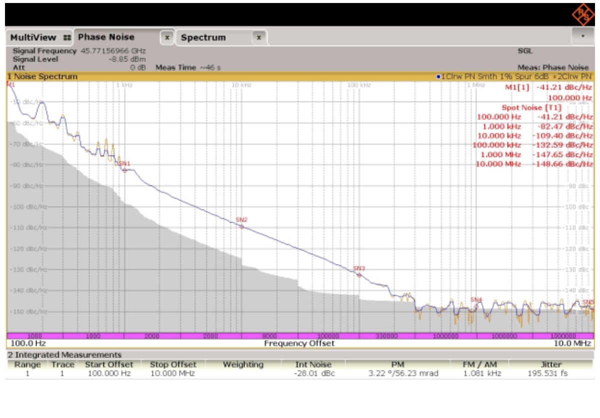
- Room temperature.
- SSB phase noise performance at room temperature upon variation of the varactor tuning voltage from 0 to 3 V.
- Phase noise at 10 kHz offset is higher by about 5 dB for tuning voltages larger than 1 V.
- The maximum tuning range is -239 kHz (5.22 ppm).

Oscillator measurements: phase noise and el. tuning range (room temperature)

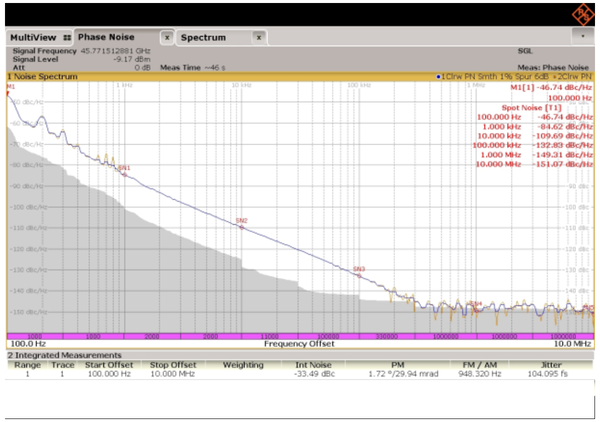


0 V

1 V



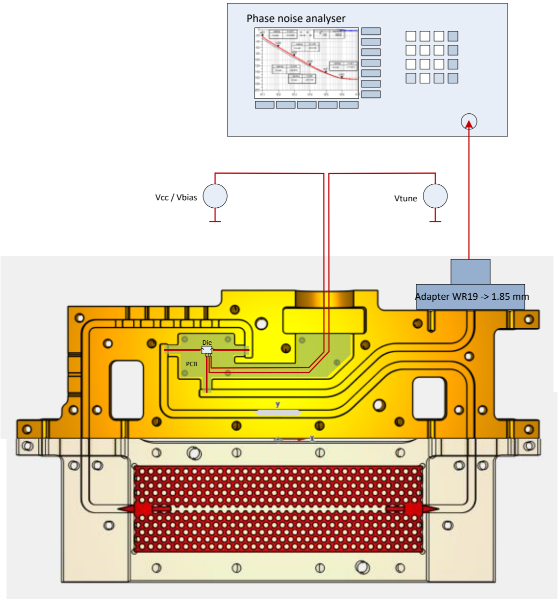
2 V



3 V

- Room temperature.
- SSB phase noise performance at room temperature upon variation of the varactor tuning voltage from 0 to 3 V.
- **Above 300 kHz offset phase noise is limited by RSWP50 phase noise resolution limit.**
- Phase noise at 10 kHz offset is higher by about 5 dB for tuning voltages larger than 1 V.
- The maximum tuning range is -239 kHz (5.22 ppm).

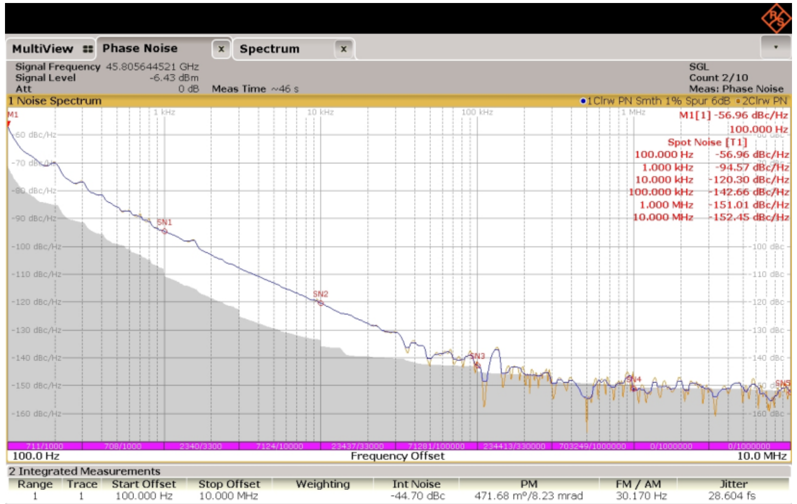
Oscillator measurements: phase noise and el. tuning range (temperature dependence)



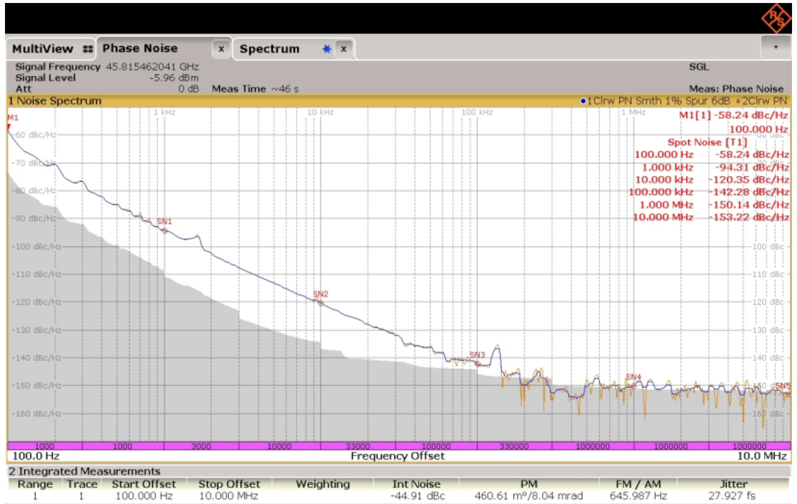
Offset / Hz	20 °C	-10 °C	-20 °C	-40 °C
1.00E+02	-52	-57	-58	-51
1.00E+03	-89	-95	-94	-94
1.00E+04	-115	-120	-120	-120
1.00E+05	-135	-143	-142	-146
1.00E+06	-145	-151	-150	-151
1.00E+07	-147	-152	-153	-156
Freq. Shift / MHz	0	34	44	62
Output power / dBm	-5.8	-1.2	-0.8	-0.6

- It is seen that from room temperature to -10 °C the phase noise decreases by up to 8 dB.
- This is due to the increase of the resonator quality factor when decreasing the temperature. Below 10 °C, only minor improvements in terms of phase noise are observed.
- Therefore, it was decided that the nominal operating temperature of the oscillator is -10 °C

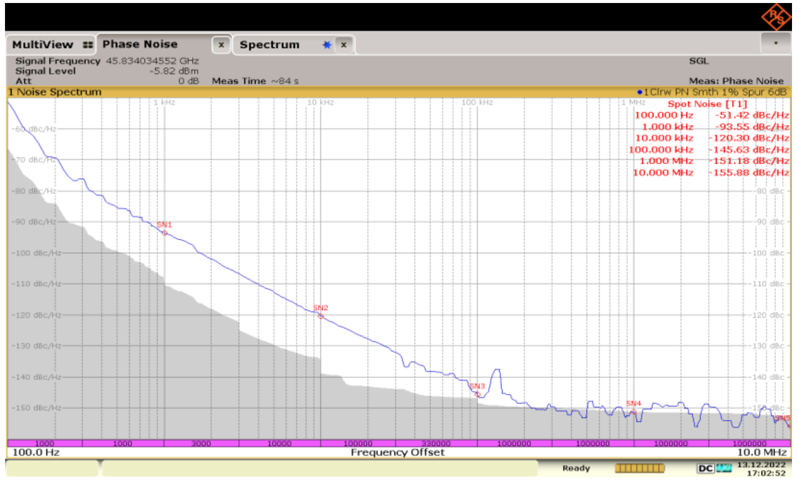
Oscillator measurements: phase noise and el. tuning range (temperature dependence)



-10 °C



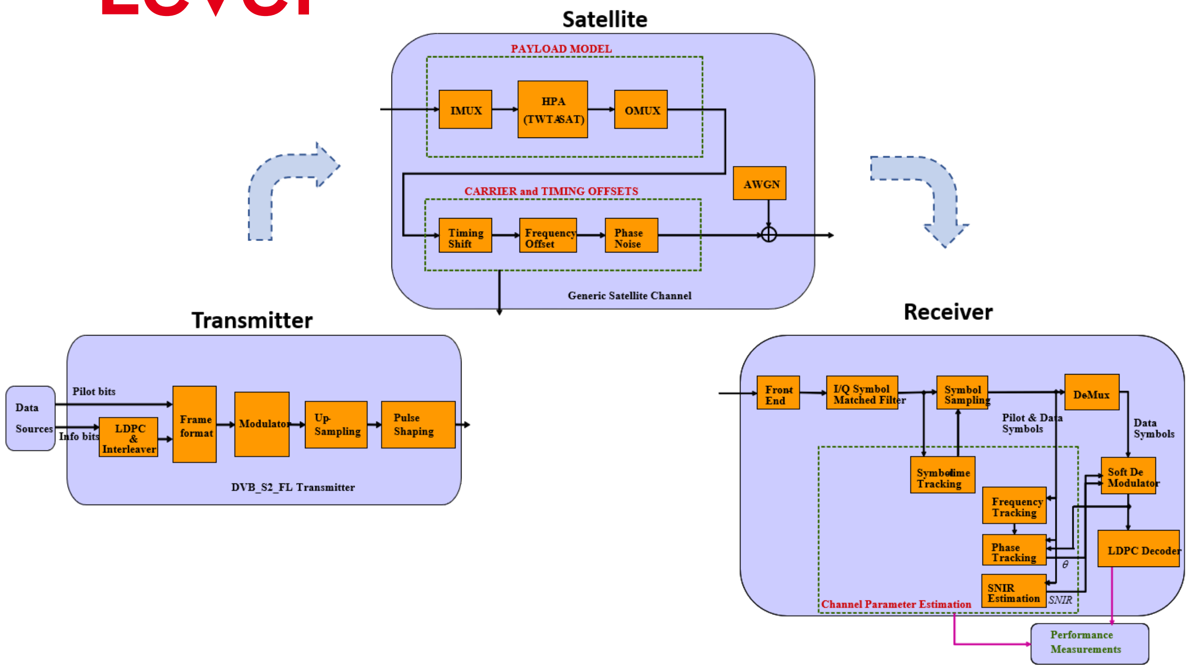
-20 °C

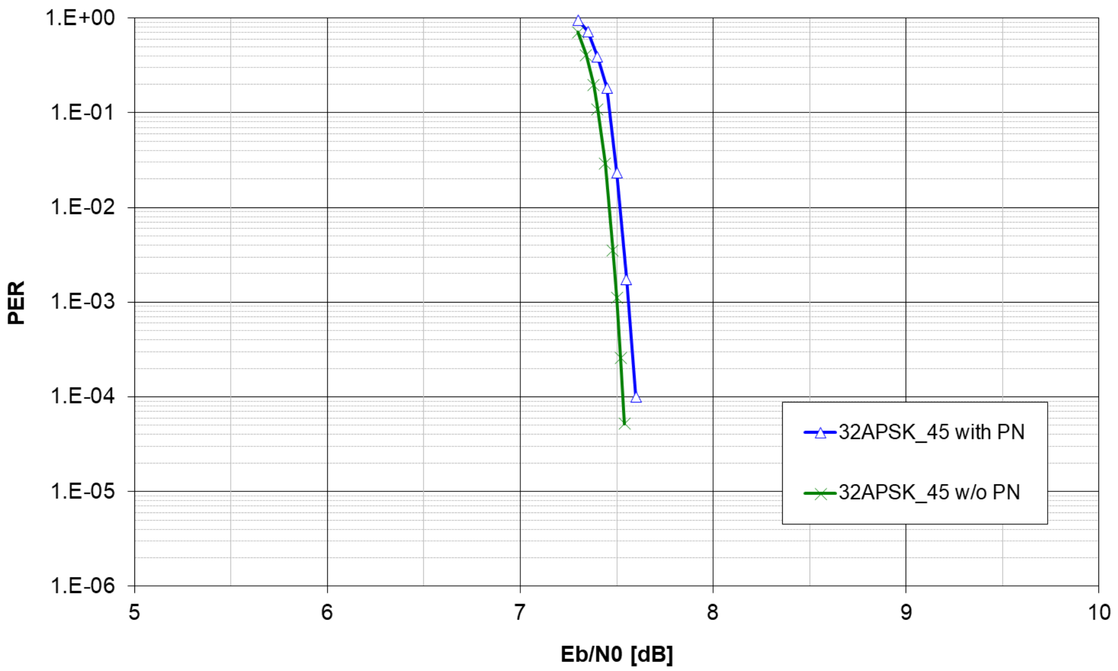


-40 °C

- It is seen that from room temperature to -10 °C the phase noise decreases by up to 8 dB.
- This is due to the increase of the resonator quality factor when decreasing the temperature. Below 10 °C, only minor improvements in terms of phase noise are observed.
- Therefore, it was decided that the nominal operating temperature of the oscillator is -10 °C.
- **Above 300 kHz offset phase noise is limited by RSWP50 phase noise resolution limit.**

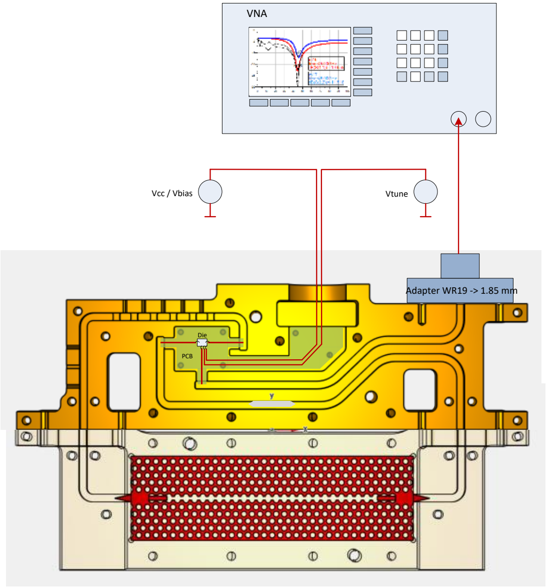
Phase Noise Impact on System (end-to-end) Level

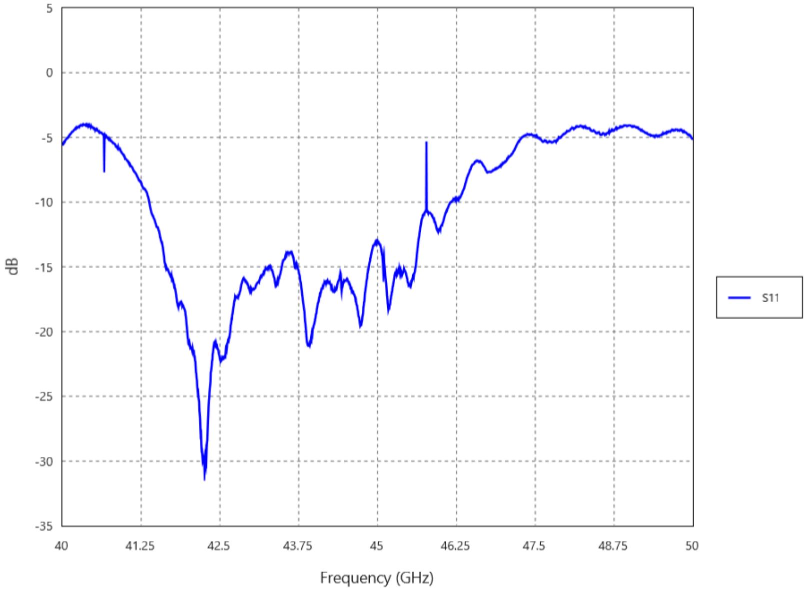




- System simulator in a DVB-SX2 broadcast scenario application.
- Transmitter and receivers on ground and a satellite channel model.
- DVB-S2X waveform generator, frame format, 32-APSK modulation scheme, RF impairments, additive white Gaussian noise as well frequency and phase tracking used.
- The total phase noise from phase noise transmitter, satellite and receiver.
- Eb/N0 (energy per bit to noise power spectral density ratio) with phase noise achieved in this project shifted up by 0.05 dB only!

Oscillator measurements: phase noise and el. tuning range (output return loss)





- Return loss larger than 10 dB. Peak at 45.77 GHz is caused by the oscillation itself.

- Introduction
- Concept (resonator, phase shifter, active element, topology)
- Design and Verification
- **Compliance matrix and comparison with state-of-the-art**
- Conclusions

Compliance matrix

Parameter	Specification RFFC	Results / Compliance	Comment
Output frequency	45 GHz	45.771 GHz	
Tuning Range	**Electronic tuning range**: 4.9 ppm corr. to 220 kHz at 45 GHz	239 kHz, C	Accurate setting of frequency correcting for fabrication tolerances
	Thermal tuning range: +/-30 MHz corresponding to temperature variation +/- 26 °C	62 MHz from +20 to -40 °C, C	
Output power	0 dBm typ.	-1.2 dBm, NC	At nominal temperature = -10 °C
Output power variation vs. tuning voltage	Max. 1 dB	2 dB, NC	At nominal temperature = -10 °C
PN@1 kHz	-95 dBc/Hz typ.	-95 dBc/Hz, C	At nominal temperature = -10 °C
PN@10 kHz	-120 dBc/Hz typ.	-120 dBc/Hz, C	At nominal temperature = -10 °C
PN@100 kHz	-140 dBc/Hz typ.	-143 dBc/Hz, C	At nominal temperature = -10 °C
PN@1 MHz	-153 dBc/Hz typ.	-151 dBc/Hz, NC	At nominal temperature = -10 °C
PN@10 MHz	-155 dBc/Hz typ.	-152 dBc/Hz, NC	At nominal temperature = -10 °C
Tuning Voltage (V)	0-3	0-3, C	
Supply Voltage (V)	2.11 / 2.44 / 1.5	2.9 / 3.4 / 1.5	
Supply Current (mA)	12 / 14 / 34	17.5 / 35 / 30, NC	At nominal temperature = -10 °C
Output Return Loss	10 dB	C	At nominal temperature = -10 °C
Sub-harmonics	none	C	At nominal temperature = -10 °C
Harmonics (2nd)	-10 dB	C	As per simulation (D4)
Harmonics (3rd)	-25 dB	C	As per simulation (D4)
Spurious	-70 dB	< -25 dB	Result limited by dynamic range of signal analyser
Mass	600 g	442 g, C	Including coaxial to waveguide connector
Power Consumption (oscillator only without temperature control)	150 mW	215 mW, NC	At nominal temperature = -10 °C
Nominal operating temperature	-10 °C	C	
Operating Temperature Range	-35 °C to +17 °C	C	

Comparison with other oscillators

Comparison Chart of State-of-Art Local Oscillators									
		LMX2615-SP Texas Inst. Inc. COTS product	**OE3710** OEWaves Inc. COTS product	**K-Band MMO** Synergy Microwave IEEE, 2016	**NOVELO** IMST under ARTES (now in EPPL)	**Push-Push VCO from PL-DRO** SpaceForest under PIIS	**High Purity LO** Kongsberg under ARTES	**OEO** ESTEC-Lab. experiment	**mm-wave VCO** under TDE (this work)
45 GHz carrier SSB Phase Noise in dBc/Hz	10 Hz	-	-25	-	-55	-7	-	-29	-
	100 Hz	-75	-55	-	-67	-44	-59	-52	-57
	1 KHz	-81	-85	-94	-76	-77	-93	-86	-94
	10 KHz	-90	-110	-118	-82	-106	-120	-117	-120
	100 KHz	-97	-130	-147	-87	-122	-136	-129	-143
	1 MHz	-108	-135	-165	-104	-127	-144	-120	-151
	10 MHz	-132	-135	-169	-126	-131	-144	-119	-152
	100 MHz	-142	-135	-	-138	-131	-144	-119	-153
Output Power	dBm	+5.0	+5.0	+11.68	+3.27	+0.79	?	+2.14	-1.2
Short-term drift	MHz	< 2	0.003	?	< 2	< 1.087	< 2	< 5	< 73
Power Consumption	W	< 1.280	< 2.500	< 0.547	< 1.600	< 0.425	< 3.600	< 3.300	< 0.215
Volume	cm3	< 50	0.88 + ctl. board	?	< 50	1557	2100	45143	395
Weight	Kg	< 0.10	0.0057 + ctl. board	< 0.20	< 0.10	1.147	< 1.5	< 15	0.442

All single-side band phase noise (dBc/Hz) offset values from the different type of oscillators are normalised to 45 GHz carrier frequency in order to be equally comparable
The values highlighted in green colours represents the 1st and 2nd best single-side-band phase noise (in dBc/Hz) offset value amongst the different state-of-art oscillators

Conclusions I: Achievements

- The outcome of this project can be judged as a considerable success:
  - Both the active die and RFFC resonator performed very close to the expectations from the simulations.
  - Technological challenges in terms of the precision of the resonator fabrication process have been overcome.
  - Therefore, the ambitious targets in terms of the projected VCO phase noise were met: **The values are best-in-class at millimetre frequencies.**
  - **TRL 4 has been reached.**
  - The thermal gradient of the oscillator frequency which is caused by the thermal variation of the permittivity of the HRS material call for a wider frequency control range or a change of the RFFC resonator material system.

Alternative base materials for RFFC

ELECTRICAL PROPERTIES[1]	TYPICAL VALUES[2]						DIRECTION	UNITS	CONDITIONS	TEST METHOD
	TMM3	TMM4	TMM6	TMM10	TMM10i	TMM13i				
[1] Dielectric Constant (process)	3.27 ± 0.032	4.50 ± 0.045	6.00 ± 0.080	9.20 ± 0.230	9.80 ± 0.245	[3]12.85 ± 0.35	Z	-	10 GHz	IPC-TM-650 method 2.5.5.5
[2] Dielectric Constant (design)	3.45	4.70	6.3	9.8	9.9	12.2	-	-	8 GHz - 40 GHz	Differential Phase Length Method
[1] Dissipation Factor (process)	0.0020	0.0020	0.0023	0.0022	0.0020	0.0019	Z	-	10 GHz	IPC-TM-650 method 2.5.5.5
Thermal Coefficient of Dielectric Constant	+37	+15	-11	-38	-43*	-70	-	ppm/°K	-55 to +125°C	IPC-TM-650 method 2.5.5.5

Standard Thicknesses		Standard Panel Sizes
0.015" (0.381mm) +/- 0.0015" 0.025" (0.635mm) +/- 0.0015" 0.030" (0.762mm) +/- 0.0015" 0.050" (1.270mm) +/- 0.0015" 0.060" (1.524mm) +/- 0.0015" 0.075" (1.900mm) +/- 0.0015"	0.100" (2.500mm) +/- 0.0015" 0.125" (3.175mm) +/- 0.0015" 0.150" (3.810mm) +/- 0.0015" 0.200" (5.080mm) +/- 0.0015" 0.250" (6.350mm) +/- 0.0015" 0.500" (12.70mm) +/- 0.0015"	18" X 12" (457mm X 305mm) 18" X 24" (457mm X 610mm) *Additional panel sizes available

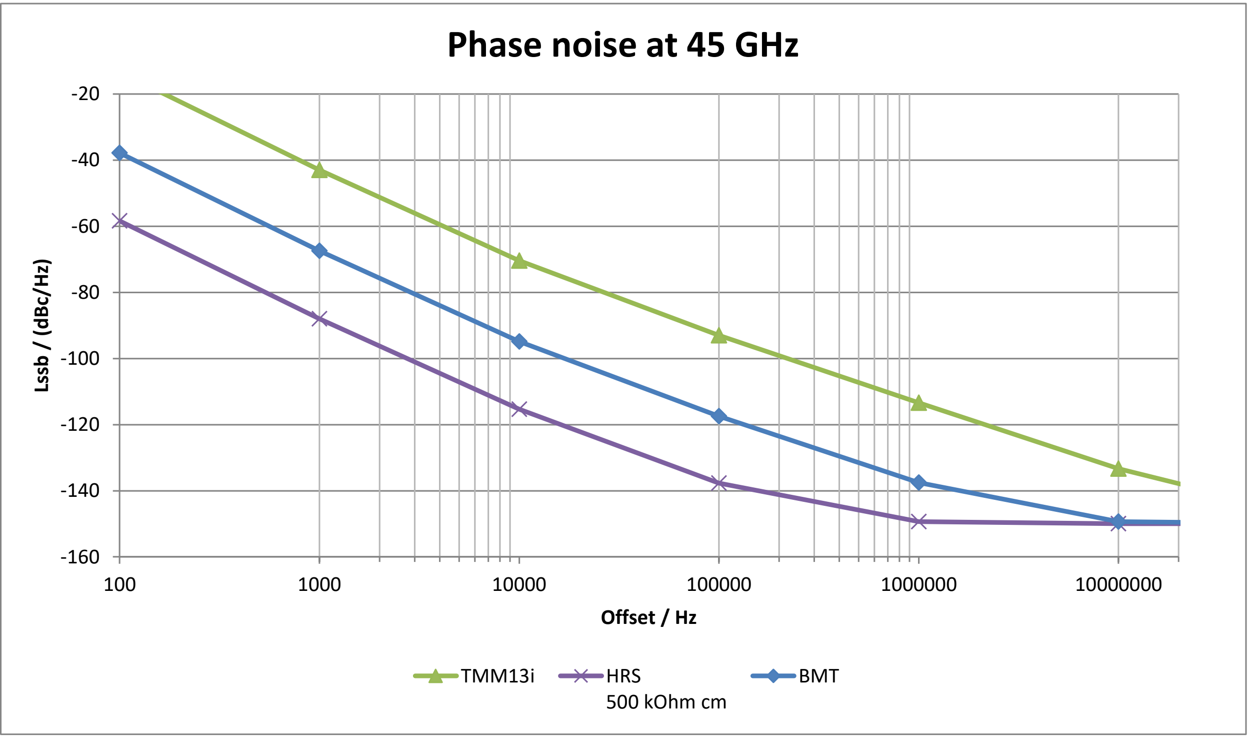
- Rogers temperature compensated substrate material series TMM:
  - „TMM® thermoset microwave materials are ceramic, hydrocarbon, thermoset polymer composites designed for high plated-thru-hole reliability stripline and microstrip applications. TMM laminates are available in a wide range of dielectric constants and claddings."
  - Thermal coefficient of dielectric constant: -70 ppm/K (HRS: 1200 ppm/K).
  - Loss tangent approx. 0.002 at 10 GHz (irradiated HRS: 0.00002 at 45 GHz).
- Microwave ceramics, BMT:
  - Thermal coefficient of dielectric constant: -5 ppm/K (HRS: 1200 ppm/K).
  - Loss tangent approx. 0.0004 at 10 GHz (irradiated HRS: 0.00002 at 45 GHz).

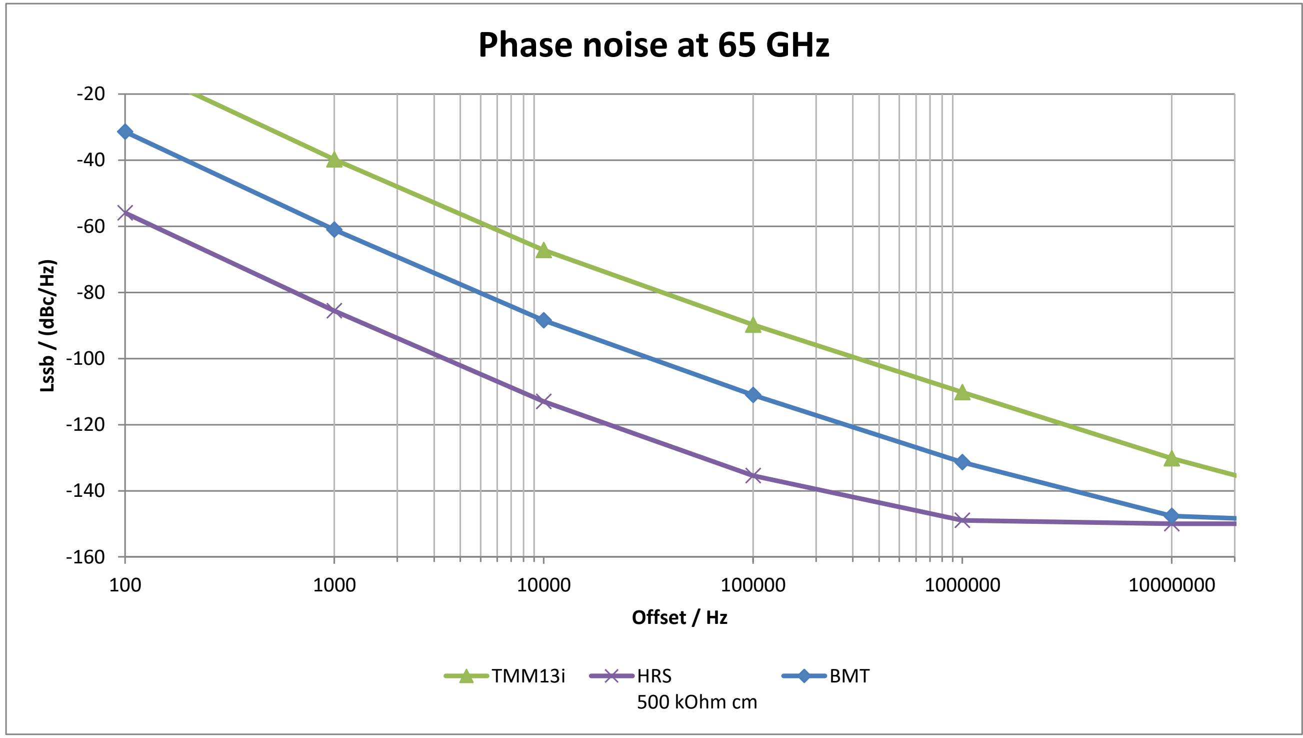
Alternative base materials for RFFC

	Frequency shift at 45 GHz (-40 to +20 °C) / MHz	deps/dT*1000 (+20 °C) / °C	df/f (+20 °C) ppm/K RFFC, filling factor = 0.5	tan_delta @ 45 GHz	tan_delta @ 65 GHz	Ql(45 GHz) (S21 = -6 dB)	QL(65 GHz) (S21 = -6 dB)	Resonance 3 dB bandwidth @ 45 GHz (MHz)
RFFC TMM13i substrate	3.63	-0.0700	**1.35**	3.00E-03	3.00E-03	333	333	135.00
BMT	-0.14	0.0050	**-0.05**	1.80E-04	2.60E-04	5556	3846	11.70
RFFC HRS (500 kOhmcm)	-69.50	1.2000	**-25.74**	1.69E-05	1.54E-05	59170	64966	0.69

- RFFC with diel. filling factor of approx. 0.5.
- For BMT / Rogers material, temperature variation < resonance 3 dB bandwidth ⇒ **varactor phase shifter can compensate total temperature variation of oscillator frequency.**
- **Achievable phase noise?**

Alternative base materials for RFFC: phase noise





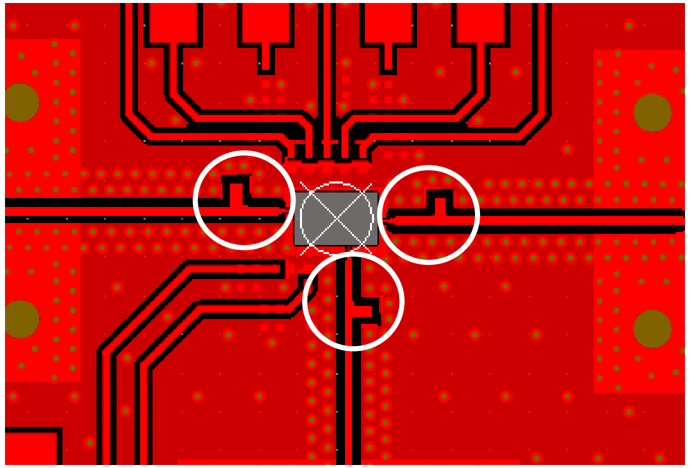
- Phase noise comparison at 45 and 65 GHz.

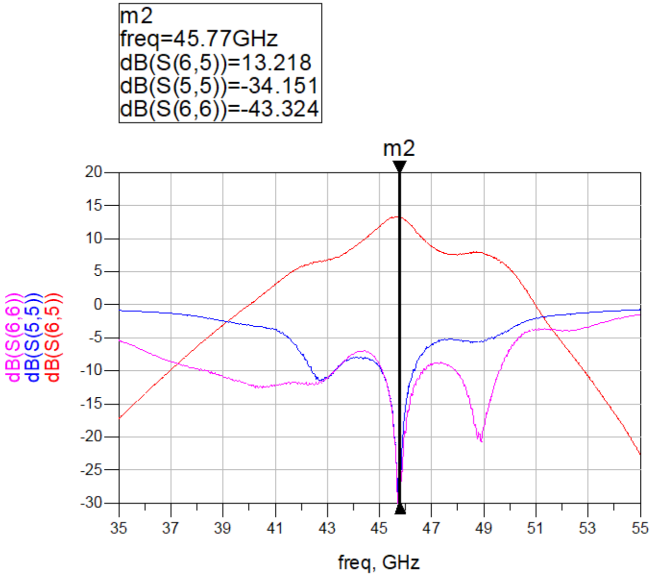
Conclusions II: Next steps

- Temperature stabilised microwave ceramics offer reasonable loss tangent and do not require mechanical frequency tuning to compensate thermally induced oscillator frequency variation.
- Phase noise sufficiently low for Earth Observation and DVB-S2X communication purposes.
- Currently needed DRO frequency multipliers / filters will not be needed any more.
- Follow-on project to increase TRL.

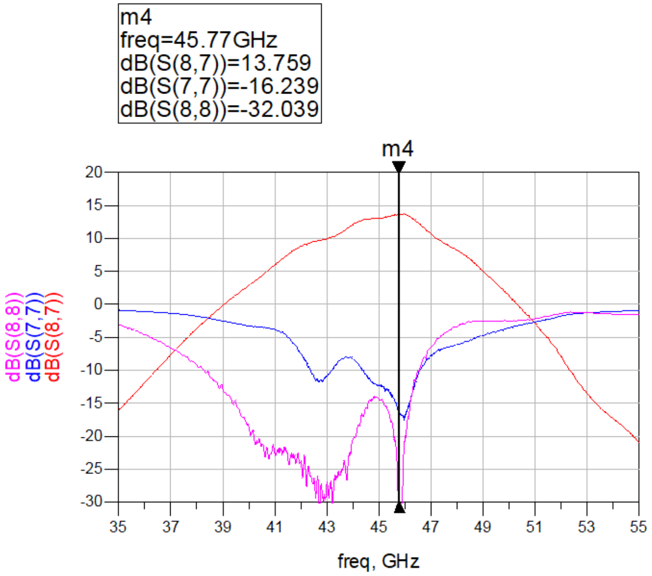
Appendix

S-parameters with matching network: Simulation





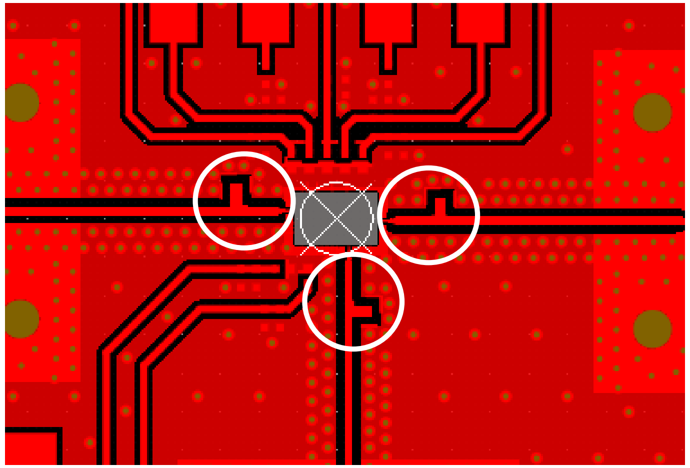
Main path

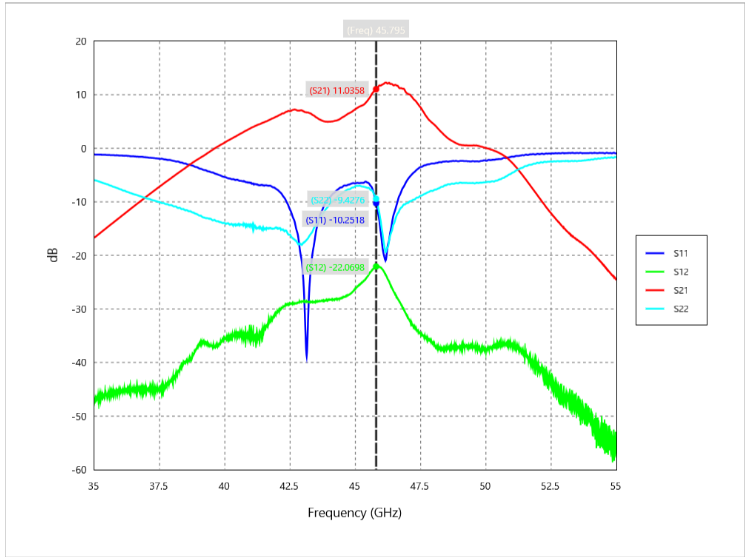


Coupled path

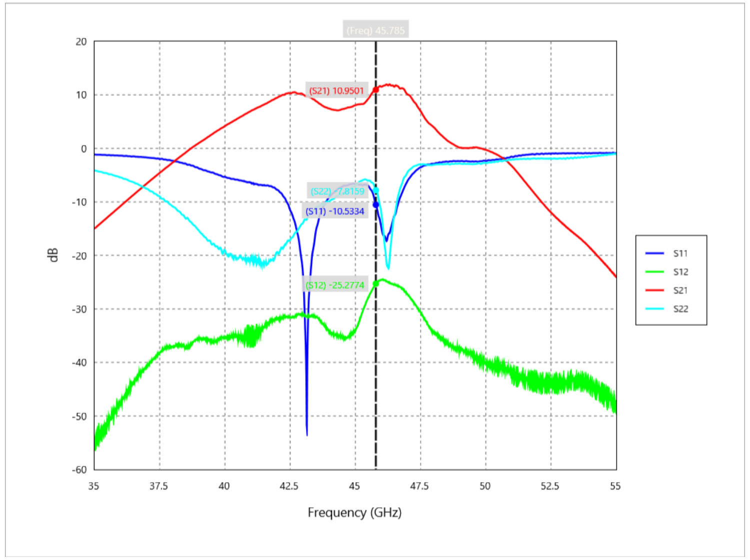
- Bias 4 used in simulation.
- Optimisation carried out for frequency of 45.77 GHz due to RFFC resonance frequency shift.

S-parameters with matching network: Measurement





Main path



Coupled path

- Point of optimum performance has shifted to higher frequencies (46.2 GHz): Match is better than -15 dB, main path gain is 12.3 dB, coupled path gain is 11.8 dB. Both values are lower than the expected values (0.9 dB for the main path and 2 dB for the coupled path).
- Most likely, these differences originate from slight deviations of the realised bond wire shape from the shape used in simulation.
- At 45.77 GHz, input and output match are around -8 to -9 dB. The measured gain of both the main and coupled path is 11.0 dB.
- Realised phase shift when varying the tune voltage from 0 to 3 V is 34.4 °.