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# Novel mm-Wave Oscillator Based on an Electromagnetic Bandgap Resonator

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- Introduction / Motivation
- Resonator Properties
- Electromagnetic Bandgap Diagram
- L5 and Low Filling Factor Resonators
- Oscillator Block Diagram, Layout and Aspect
- Measurement Results
- Benchmark
- Conclusion and Next Steps

- Phase noise on a local oscillator signal is detrimental to any radio system
- Reference piezoelectric oscillators are limited in frequency to a maximum of 100 MHz and high frequency LO's based on DRO's are usually available up to 30 GHz.
- Deriving GHz range signals from this reference requires frequency multiplication or synthesis. However, the multiplication process increases the phase noise of the output signal according to  $20 \log$  of the multiplication factor and complexity of the circuits
- The ultimate goal is to demonstrate electromagnetic bandgap resonators can be utilized for application in high frequency oscillators with great benefits in obtaining high Q-factor and therefore low phase noise

# Resonator Properties

## Floating Zone - High Resistivity Silicon from TopSil Global Wafers S/A

- Losses are both ohmic and dielectric leading to an reciprocal frequency dependence of the losses
- Standard material with resistivity up to 70 kΩ.cm, neutron irradiated material up to 416 kΩ.cm
- Above 35 GHz, the irradiated Silicon has the lowest loss than other dielectric materials (at room temperature)
- Strong/Steep increase in loss tangent above room temperature, moderate increase for the dielectric constant

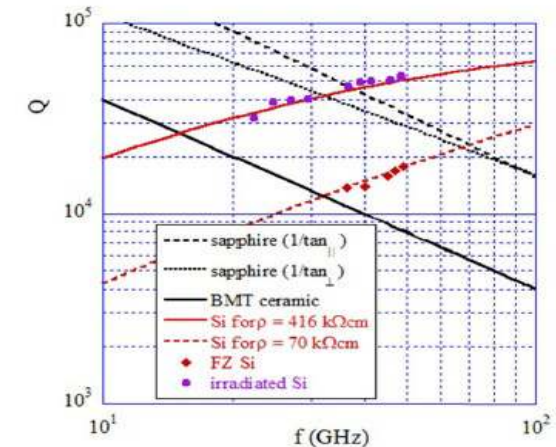
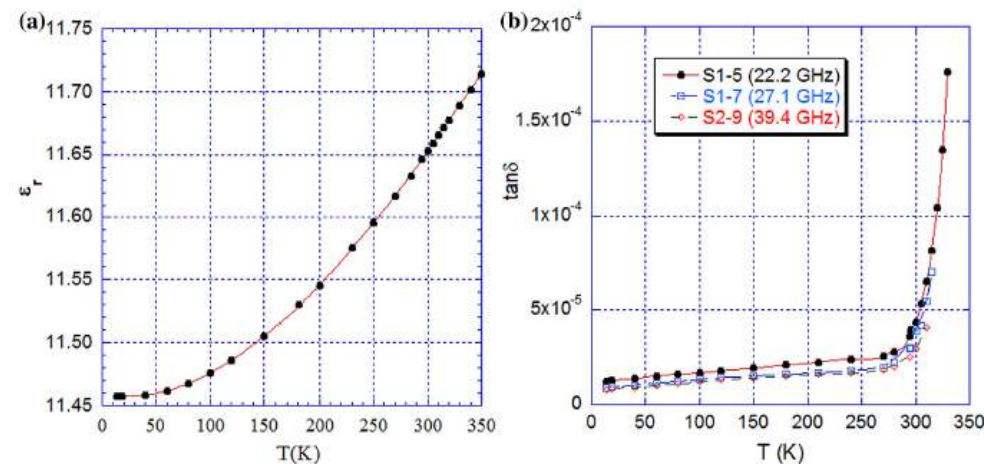
$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} + \frac{1}{\rho\omega\varepsilon_0\varepsilon'}, \quad \tan\delta_{diel} = \frac{\varepsilon''}{\varepsilon'}$$

### FZ-HIRES™



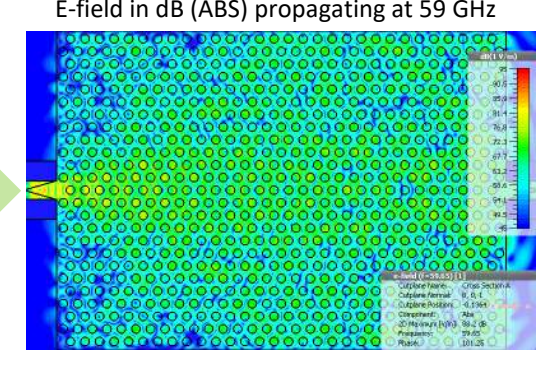
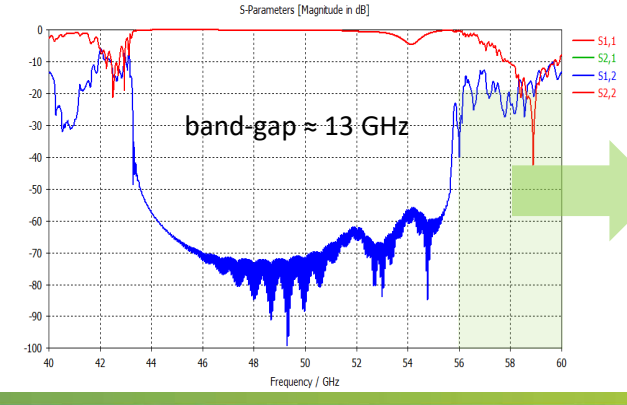
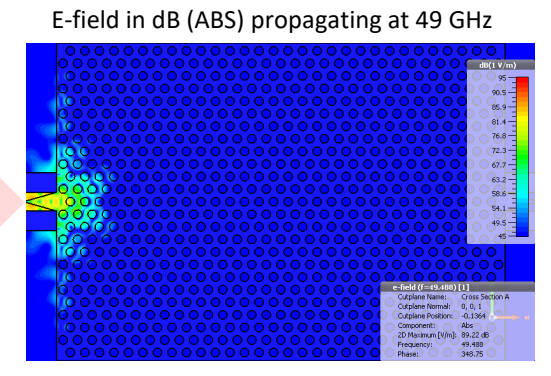
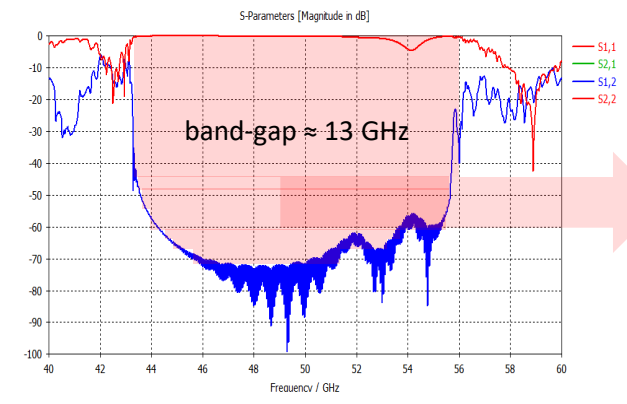
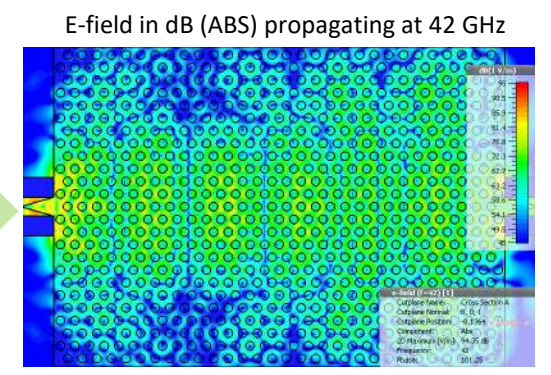
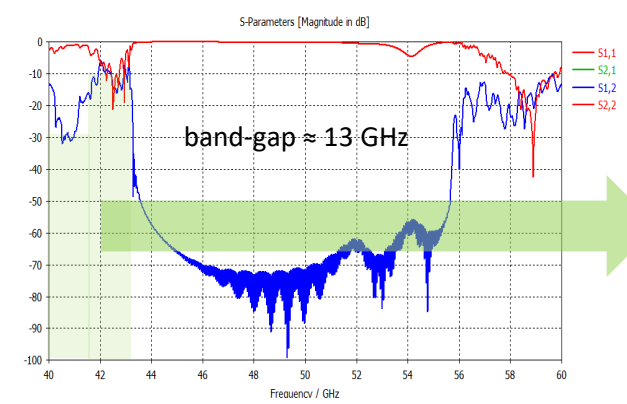
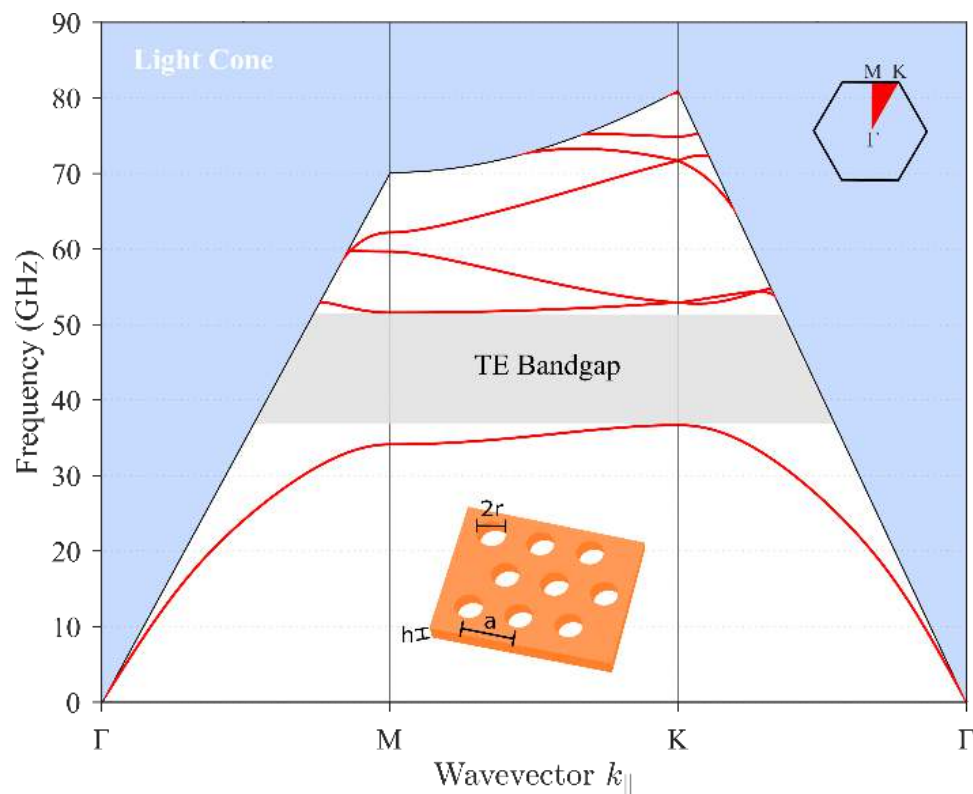
Topsil high resistivity float zone silicon (HiRes™) is well suited for microwave and millimeter wave circuits and devices. It is a good candidate for a GHz IC substrate; that is a substrate for monolithic integration of digital, analog and interface functions on a single chip. It has low oxygen levels and bulk resistivities approaching 70kΩcm.

Typical devices that will benefit from using HiRes™ silicon are GHz & THz applications, RF MEMS switches, High-Q inductors and capacitors, GHz transmitter and receiver circuits, GHz mixers, GHz power amplifiers, low loss microstrip transmission lines and coplanar waveguides, micromachined thin film bulk acoustic resonators (FBAR), RF LDMOS and BiCMOS devices, and millimeter-wave attenuators.



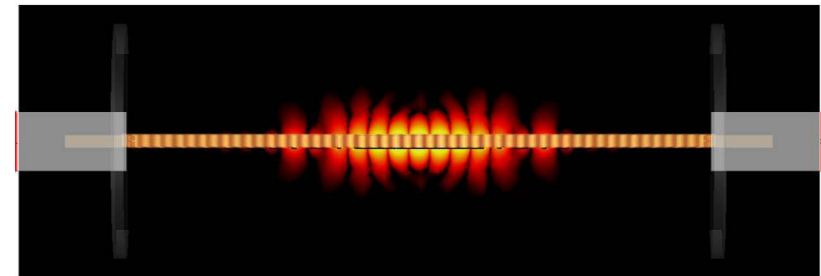
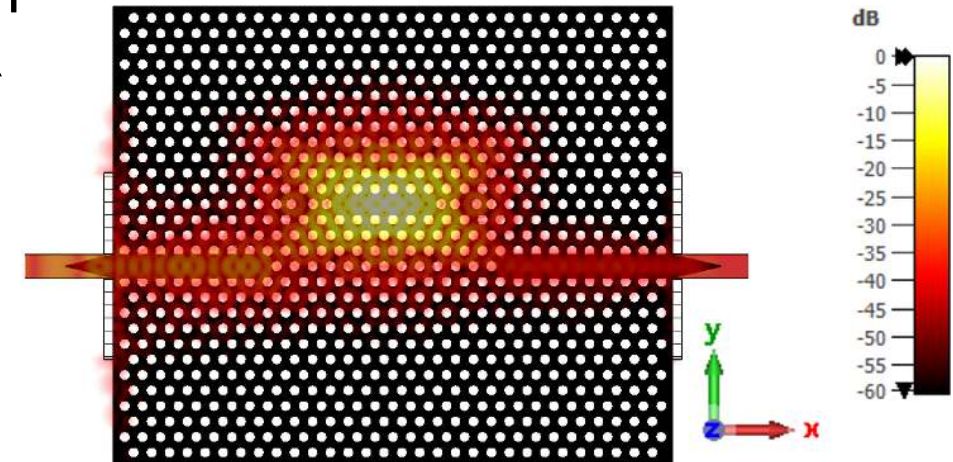
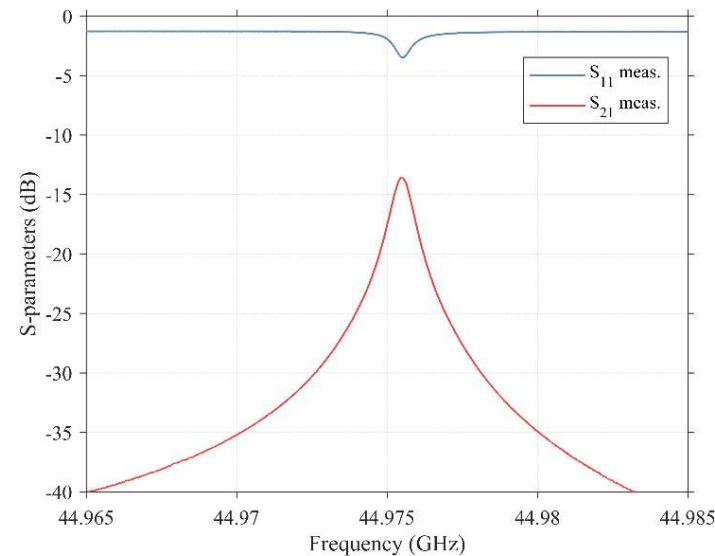
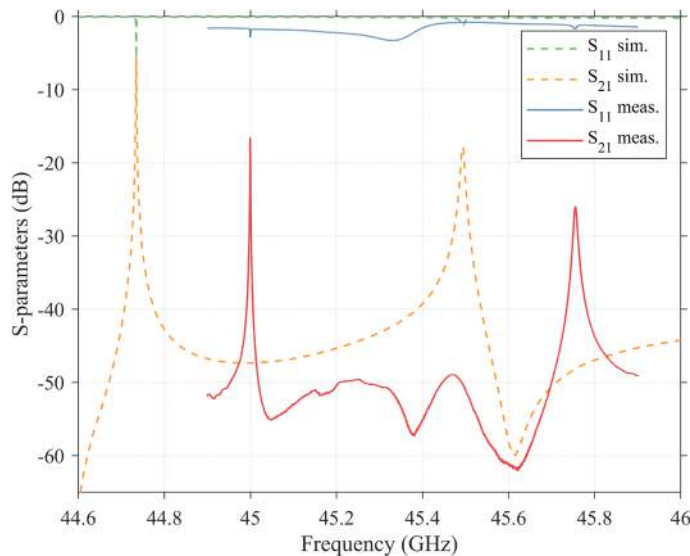
J. Krupka, W. Karcz, P. Kaminski, L. Jensen; "Electrical properties of as-grown and proton-irradiated high purity Silicon", Nuclear Instruments and Methods in Physics Research B, May 2016



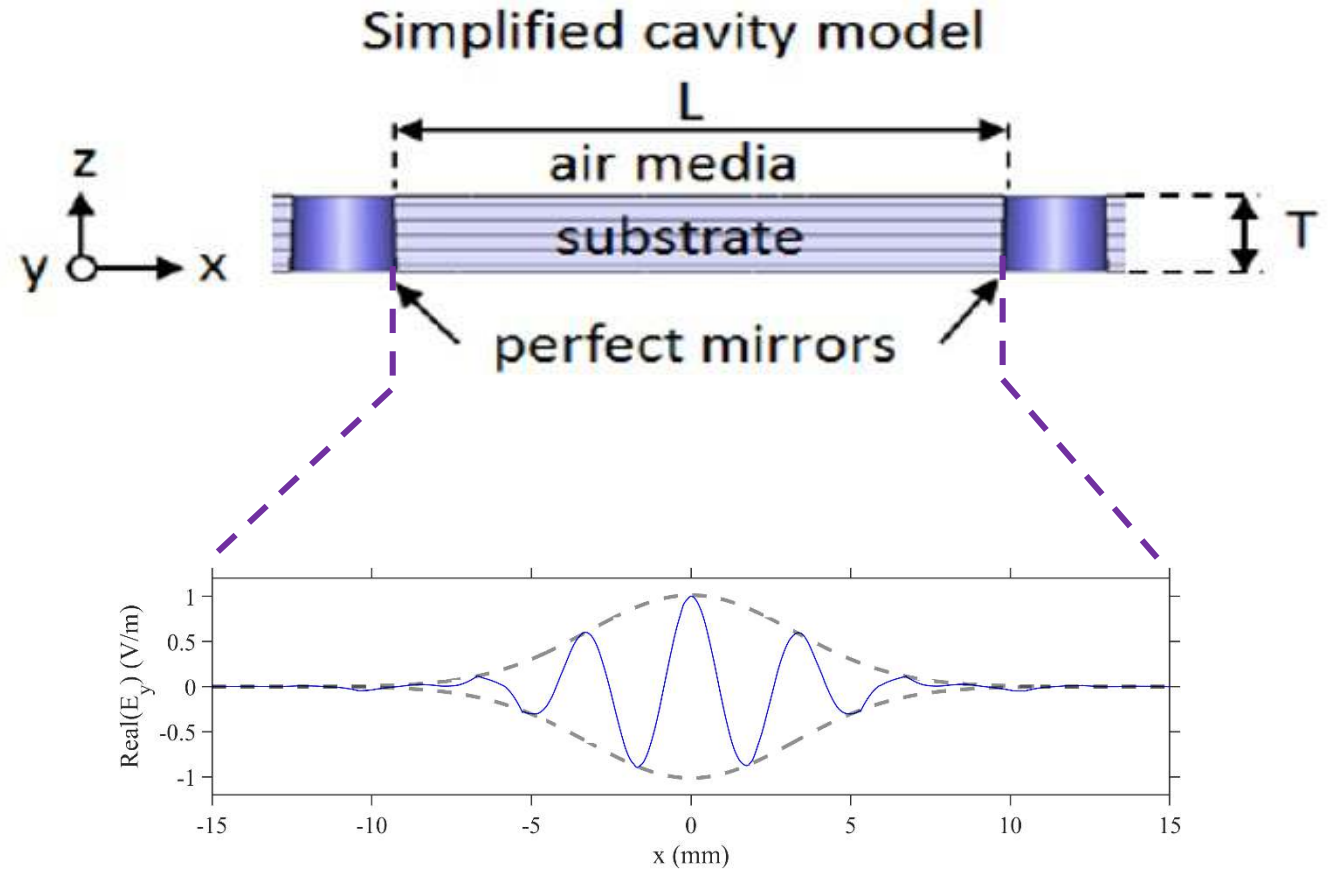
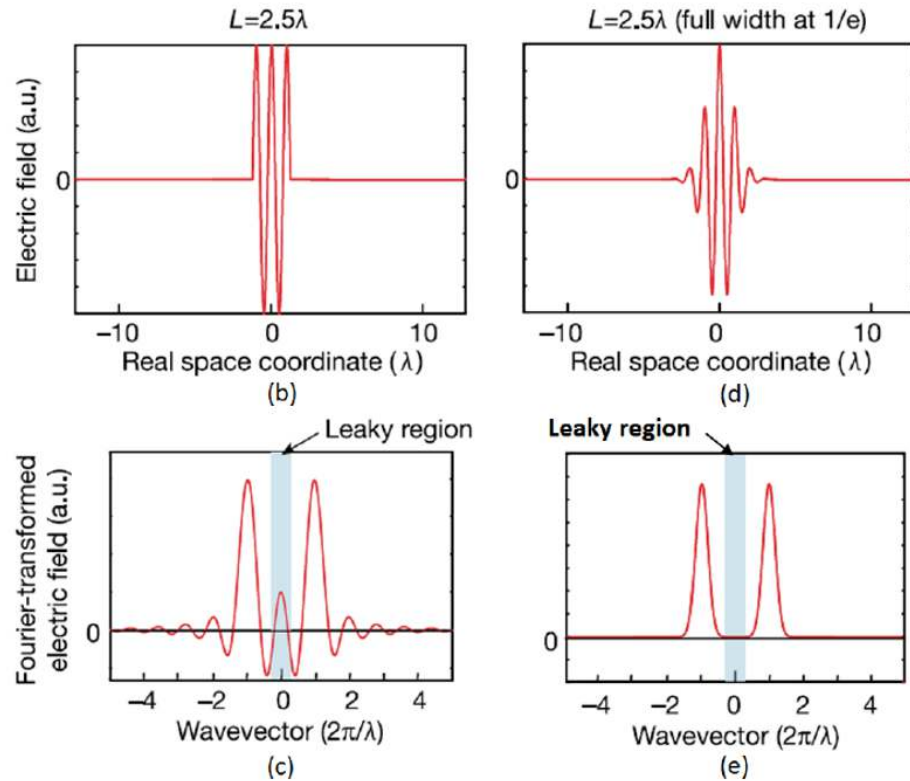


# L5 Resonator

- Simulated / Measured  $Q_u = 54,000 / 74,000$
- Simulated / Measured  $I_{loss} = -6 \text{ dB} / -14 \text{ dB}$
- Shift in frequency of 0.15 % (**300 MHz @ 45 GHz**)
- Note the large 60 dB plot range  $\rightarrow$  shows confinement to silicon
- Dielectric filling factor 95%, temperature stability = 2.33MHz/K



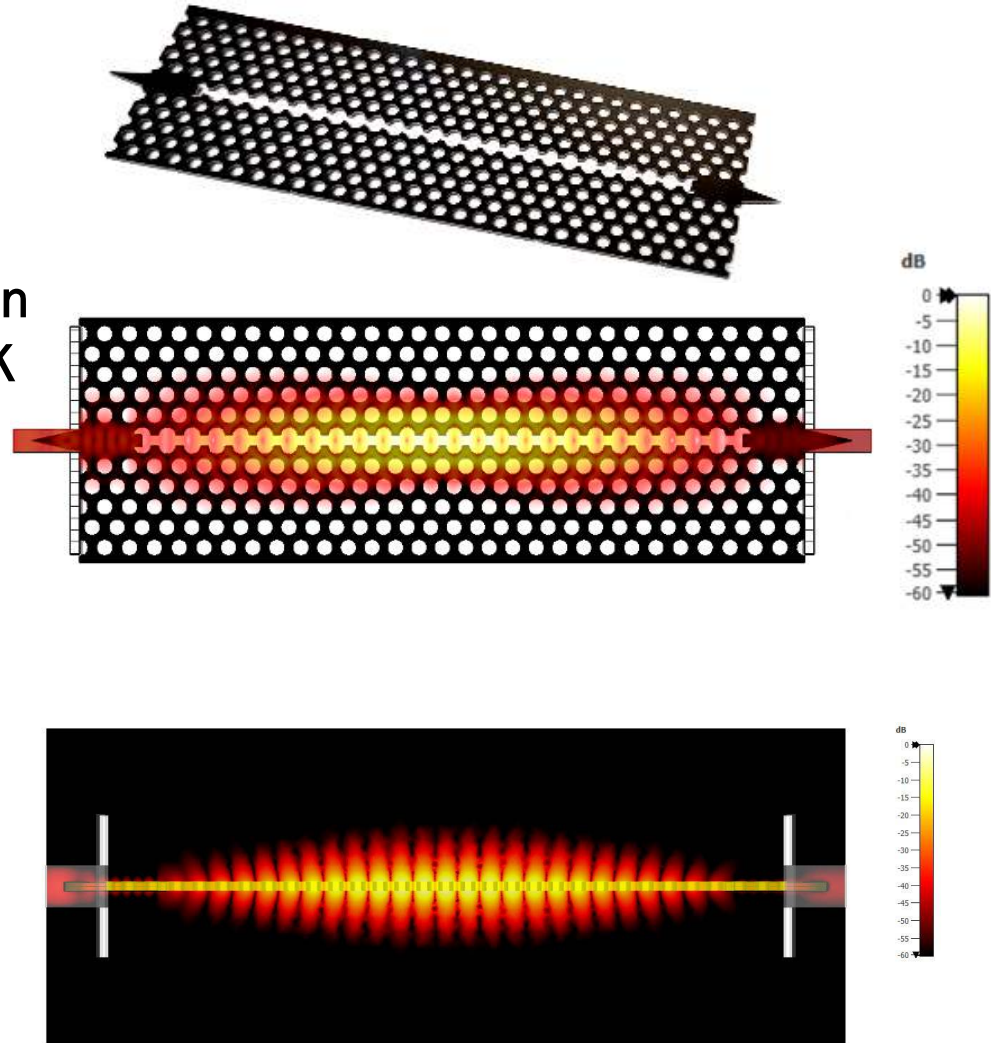
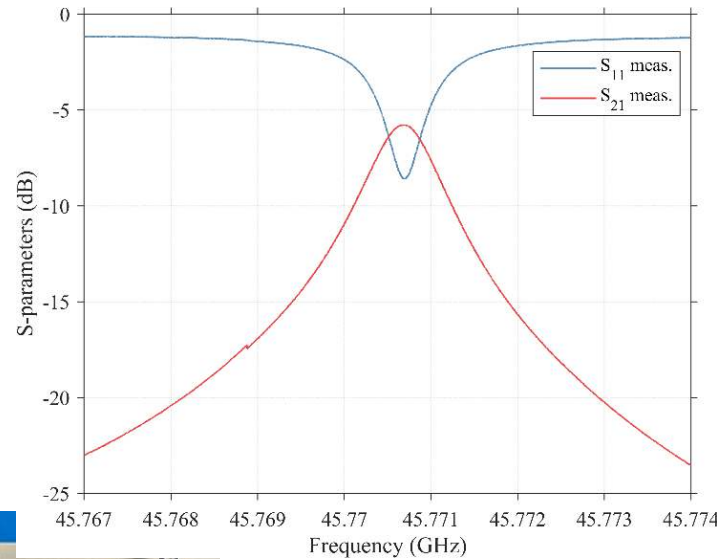
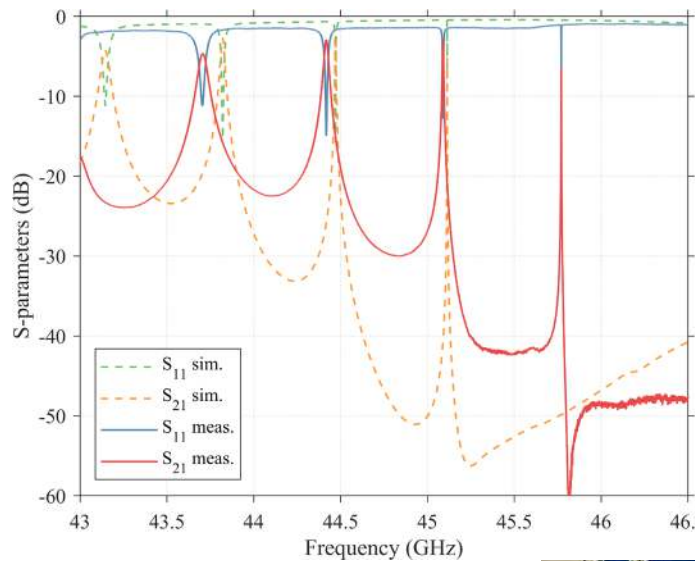
# L5 Resonator Diagrams





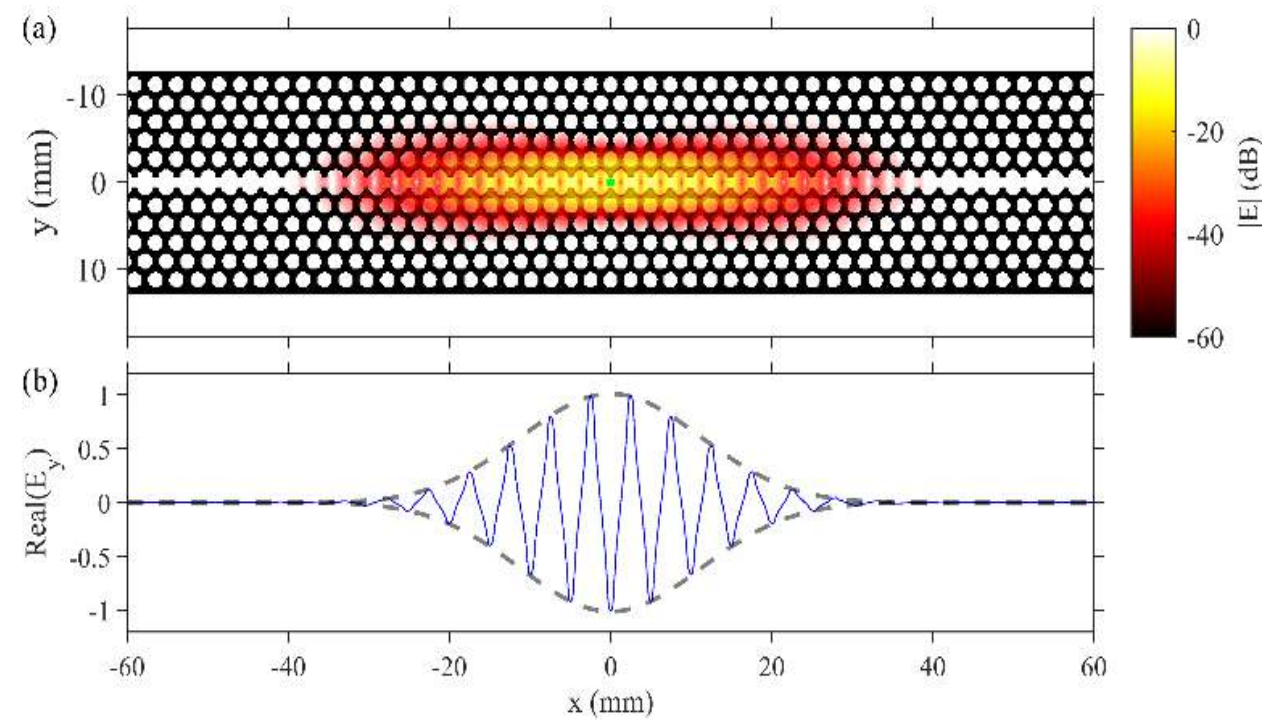
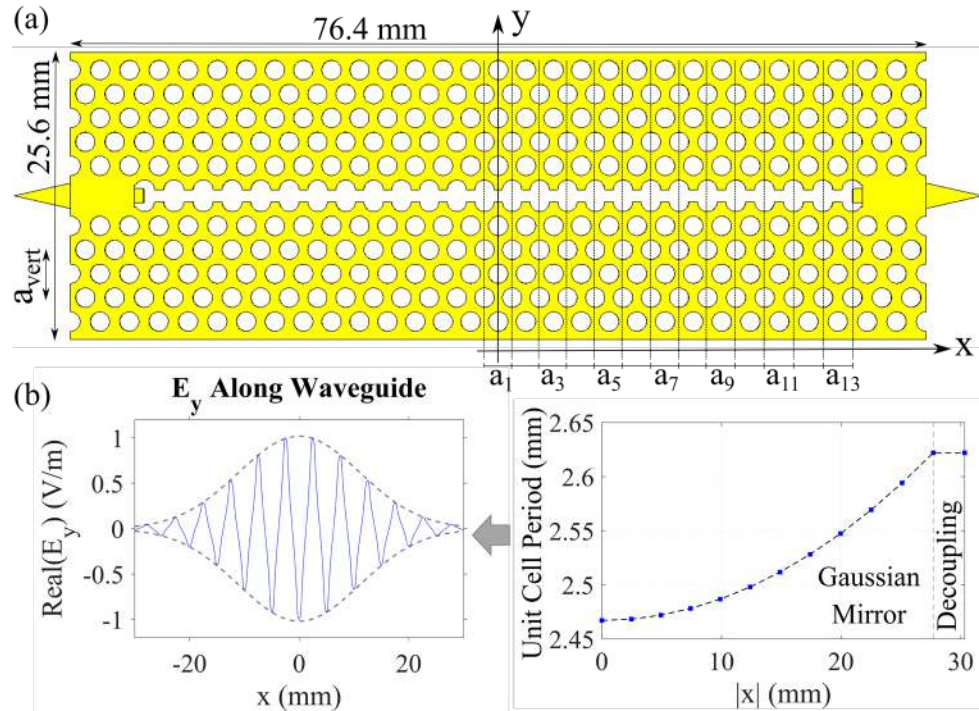
# Low Filling Factor Resonator

- Simulated / Measured  $Q_u = 89,400 / 108,300$
- Simulated / Measured  $I_{loss} = -7.2 \text{ dB} / -5.8 \text{ dB}$
- Shift in frequency of 1.3 % (**620 MHz** @ 45 GHz)
- E-field strongly confined in the slot region
- Note the large 60 dB plot range  $\rightarrow$  shows confinement to silicon
- Dielectric filling factor 47%, temperature stability = 1.17 MHz/K

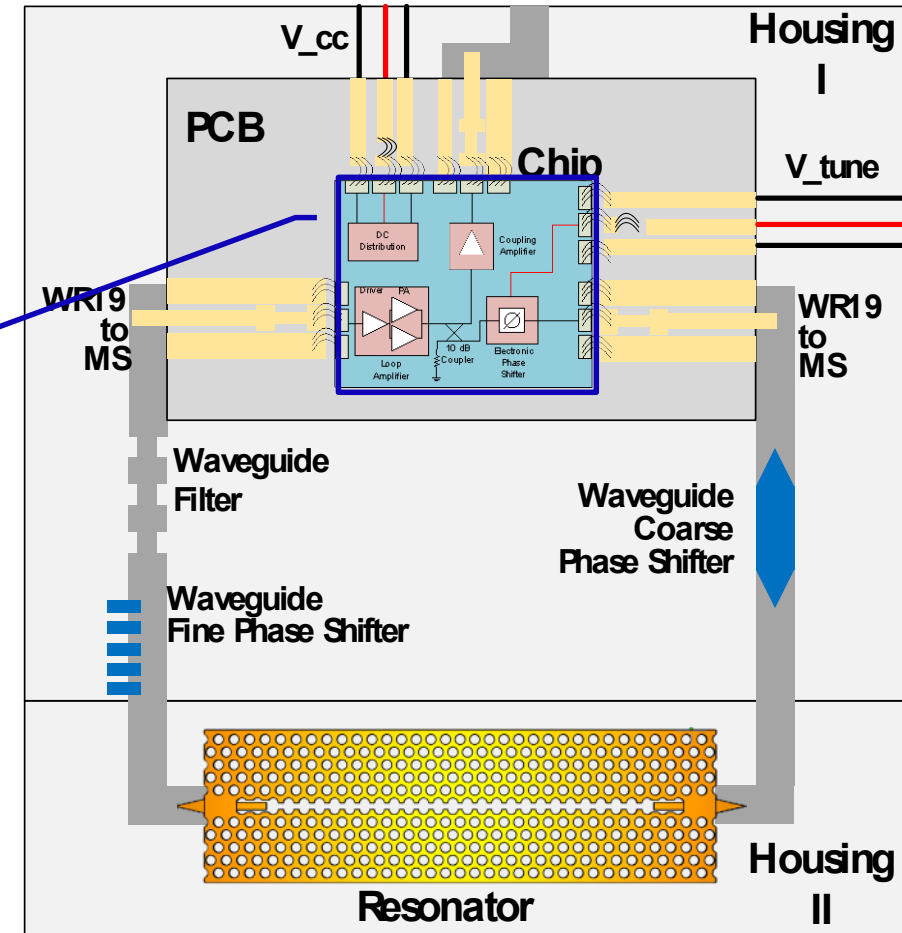
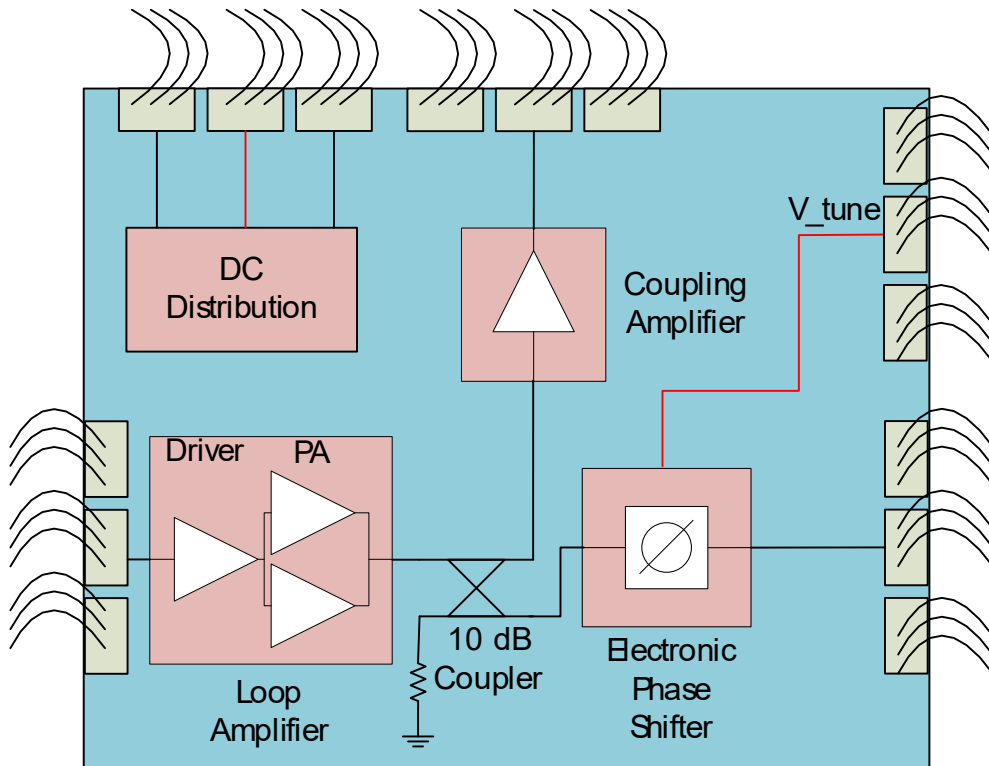




- Engineered low dielectric filling factor mode
- Photonic crystal confines energy to air slot
- Dielectric filling factor  $\sim 47\%$

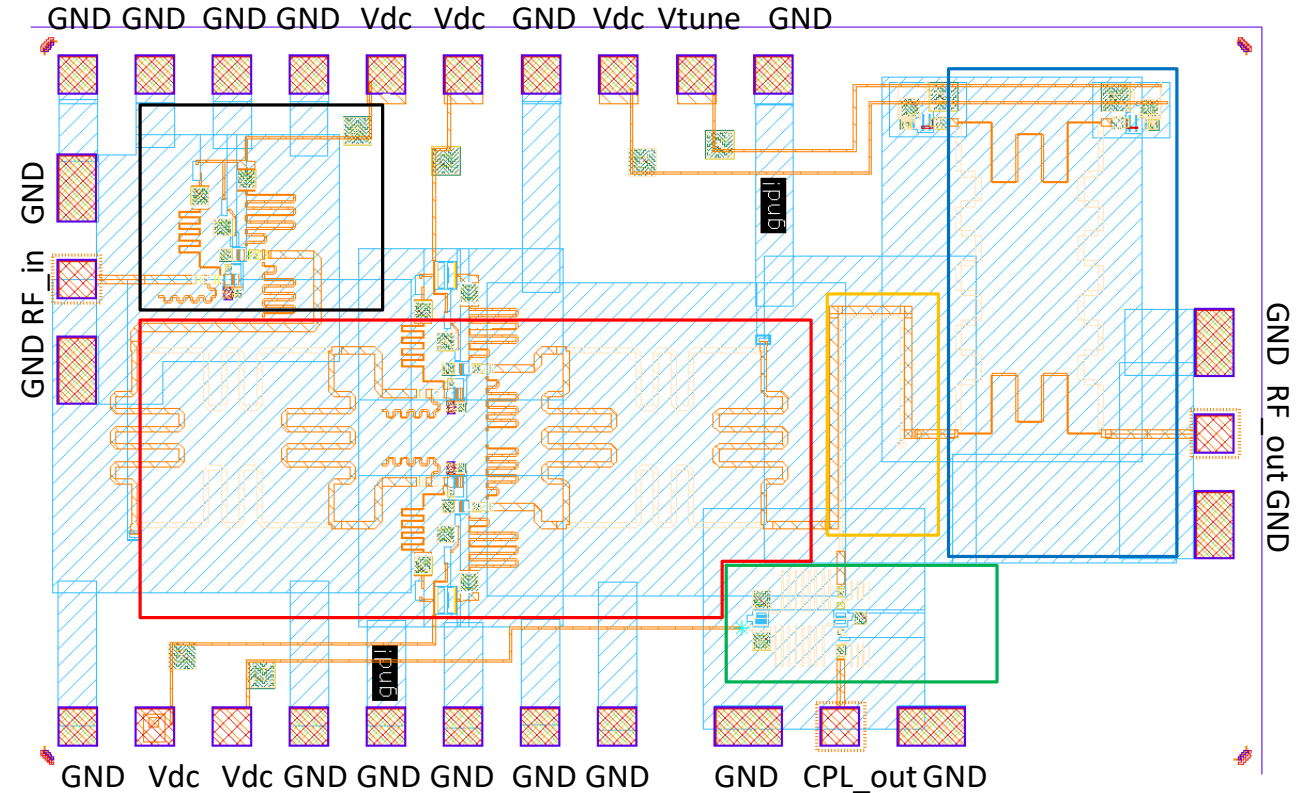


# Oscillator Block Diagram



# Oscillator Layout

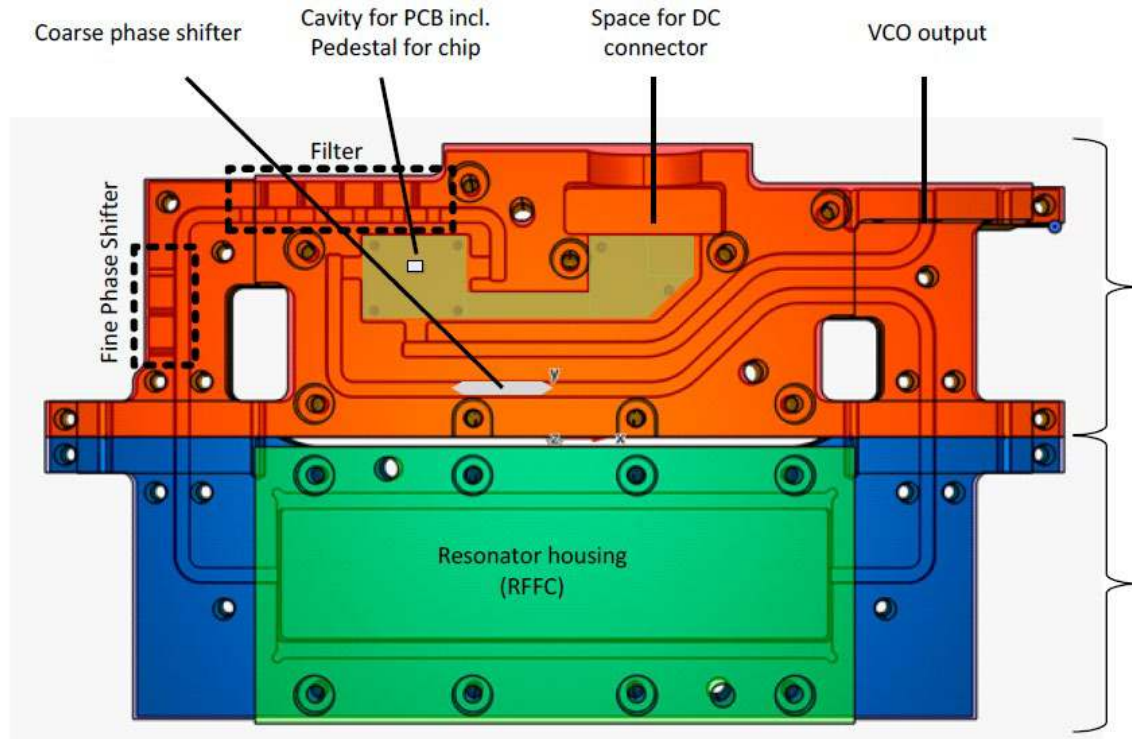
- First Stage Amplifier
- **Balanced Power Amplifier**
- **Coupling Amplifier**
- **10 dB Coupler**
- **Electrical Phase Shifter**



total chip area is 2.5 x 1.5 mm<sup>2</sup>



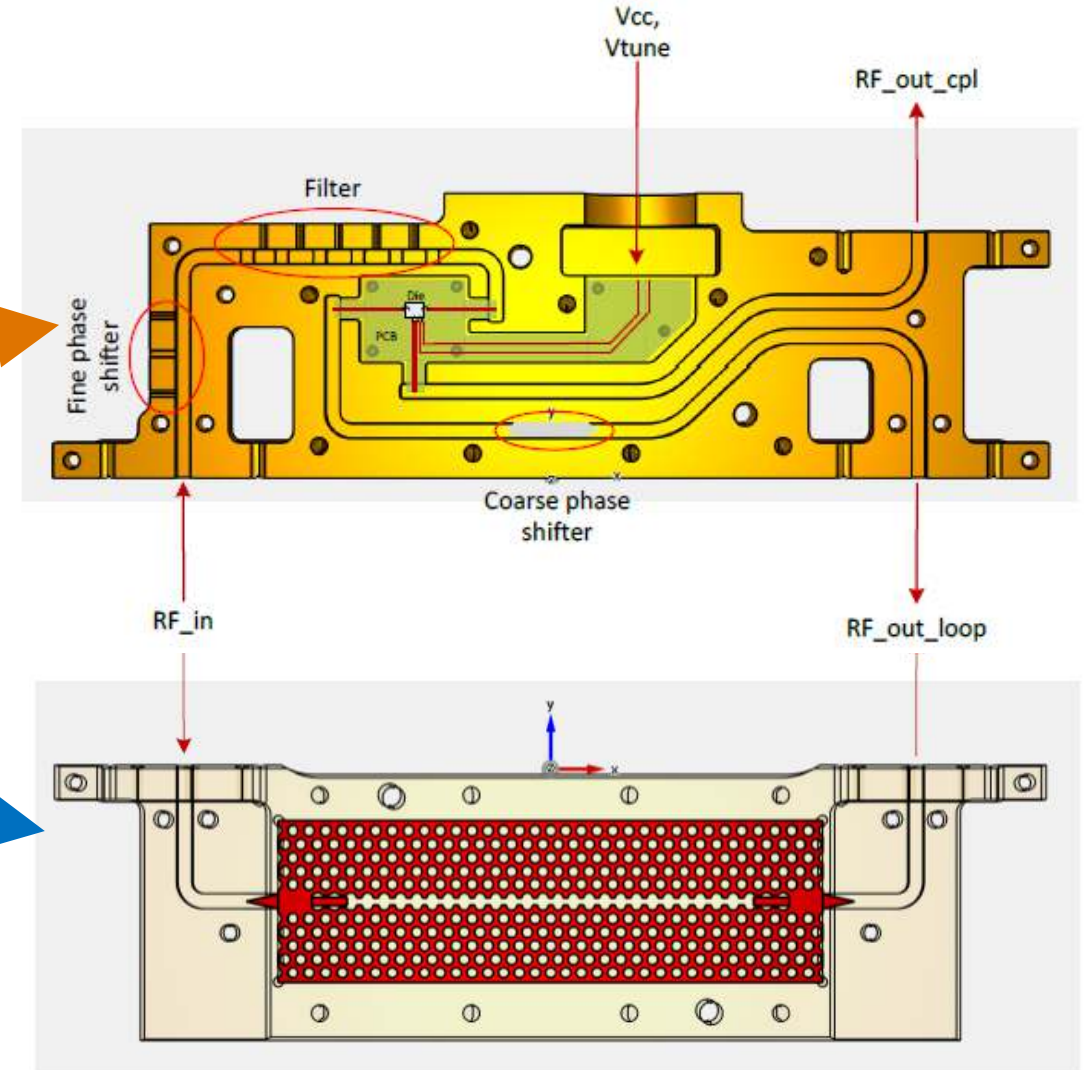
# Oscillator Aspect



Size 157 x 88 x 29 mm  
Weight 442 g

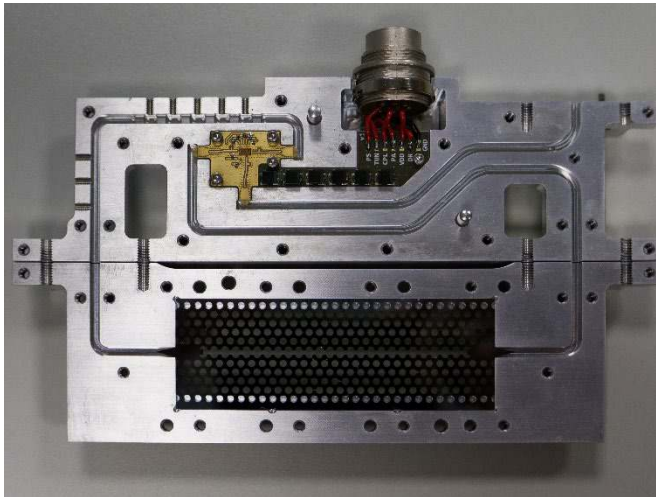
Active part

Resonator



Oscillator performance using the **low filling factor** resonator

- -10°C used as operating temperature (no significant phase noise improvement below that)
- Output Frequency = 45.77 GHz
- Output Power = -1.2 dBm
- Electronic (varactor) tuning range = -239 KHz (4.9 ppm @ 45 GHz)
- Power consumption = 215 mW
- Size & Weight = 157 x 88 x 29 mm / 442 grams



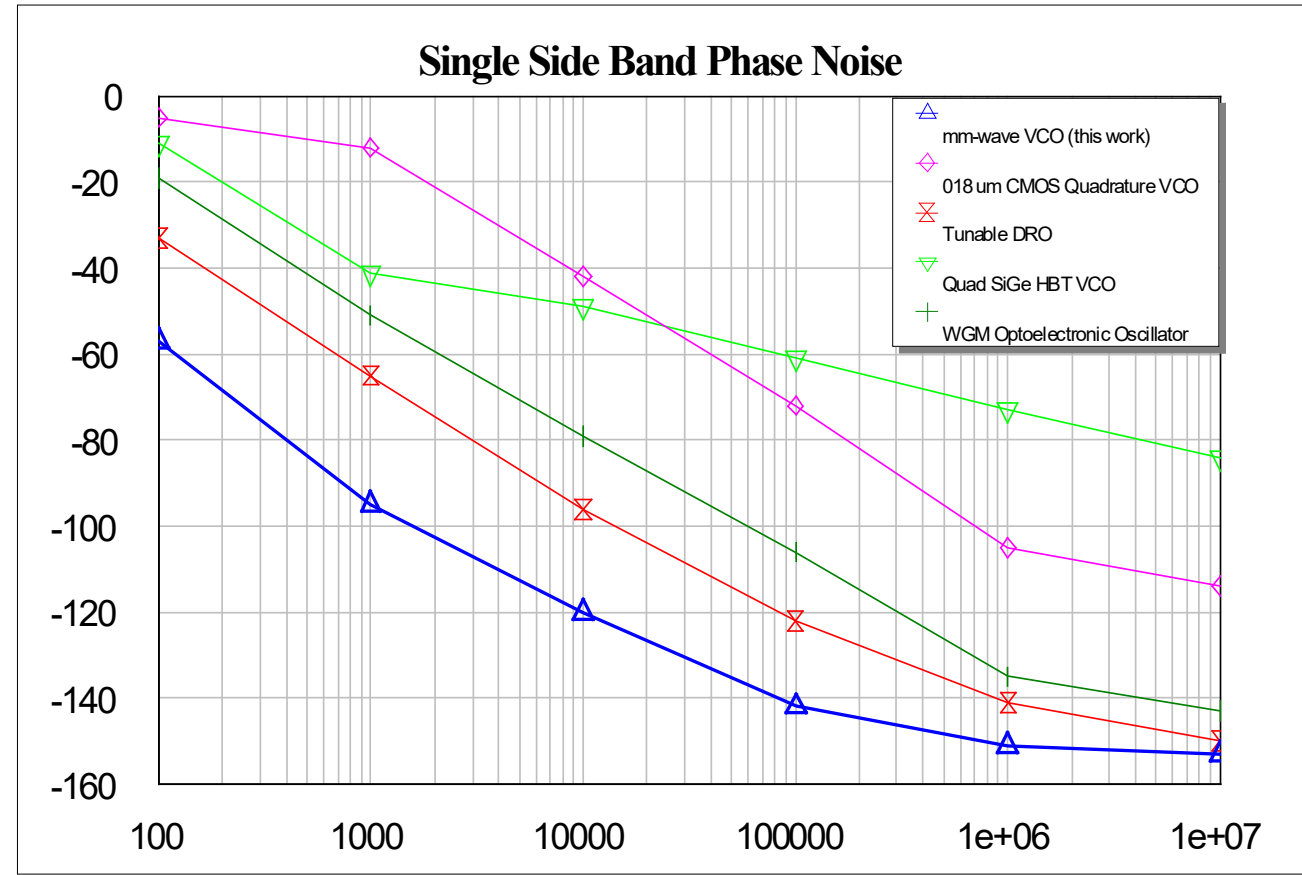
SSB Phase Noise @ -10 °C



SSB Phase Noise -40°C - to +22°C

	-40°C	-20°C	-10°C	0°C	+22°C
100 Hz	- 51.4	- 58.2	- 56.9	- 54.4	- 53.2
1 KHz	- 93.5	- 94.3	- 94.5	- 94.0	- 89.5
10 KHz	- 120.3	-120.3	- 120.3	- 119.1	- 114.7
100 KHz	- 145.6	- 142.3	- 142.6	- 143.7	- 136.4
1 MHz	- 151.2	- 150.1	- 151.0	- 150.7	- 148.7
10 MHz	- 155.8	- 153.2	- 152.4	- 152.0	- 145.2

Different state-of-the-art technology oscillators  
All SSB phase noise figures normalized to 45 GHz





# Conclusion

- Successfully demonstrated high performance millimetre-wave oscillator based on EBG resonator operating directly in fundamental mode at 45 GHz
- A break-through in terms of performance achieving best-in-class phase noise values at 45 GHz; achieved resonator Q-factor of 108,300 never reported before (for room temperature and planar geometry)

## Future Steps

- Increase the technology readiness level (TRL) to demonstrate critical functions in relevant environment
- Technology scalable to operate at higher frequencies (up to about 90 GHz)
- Address the frequency drift by employing alternative materials for the resonator which are less temperature dependent, and/or thermally regulate the oscillator