Report: Horse shoe Capacitor

Written by Samuel

Cool down: August 29, 2018.

Purpose: Measuring effect of horse shoe capacitor on the total self-capacitance (and thus resonance frequency) of **λ/4 resonators** as applied in the xmon design (see fig. 1). Design is found in Clewin Layout named FourXmons27.cif).

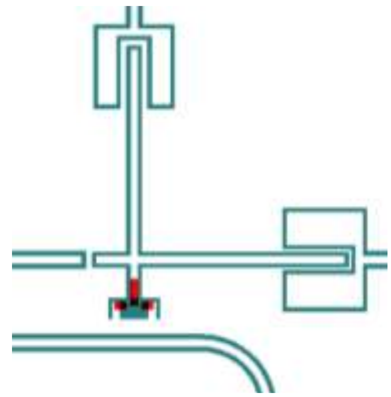


Fig. 1: Xmon coupled to resonators by means of horseshoe capacitors.

Design: Eight λ/4 CPWRs coupled by **200/25 µm** (length/gap) as depicted in fig. 2, where frequencies of "ordinary" resonators are designed to be above those with horse shoe capacitors (see table, next page).

According to Martinis write-up (https://web.physics.ucsb.edu/~martinisgroup/papers/Martinis2014b.pdf) these coupling parameters give **C_C ~ 0.7 fF**, which in return produce **Q_C ~3e5** (Goppl). However, our (Elisha's and my) experience shows this is rather an order of magnitude lower, in particular this is critical coupling for λ/4 and our aluminum.

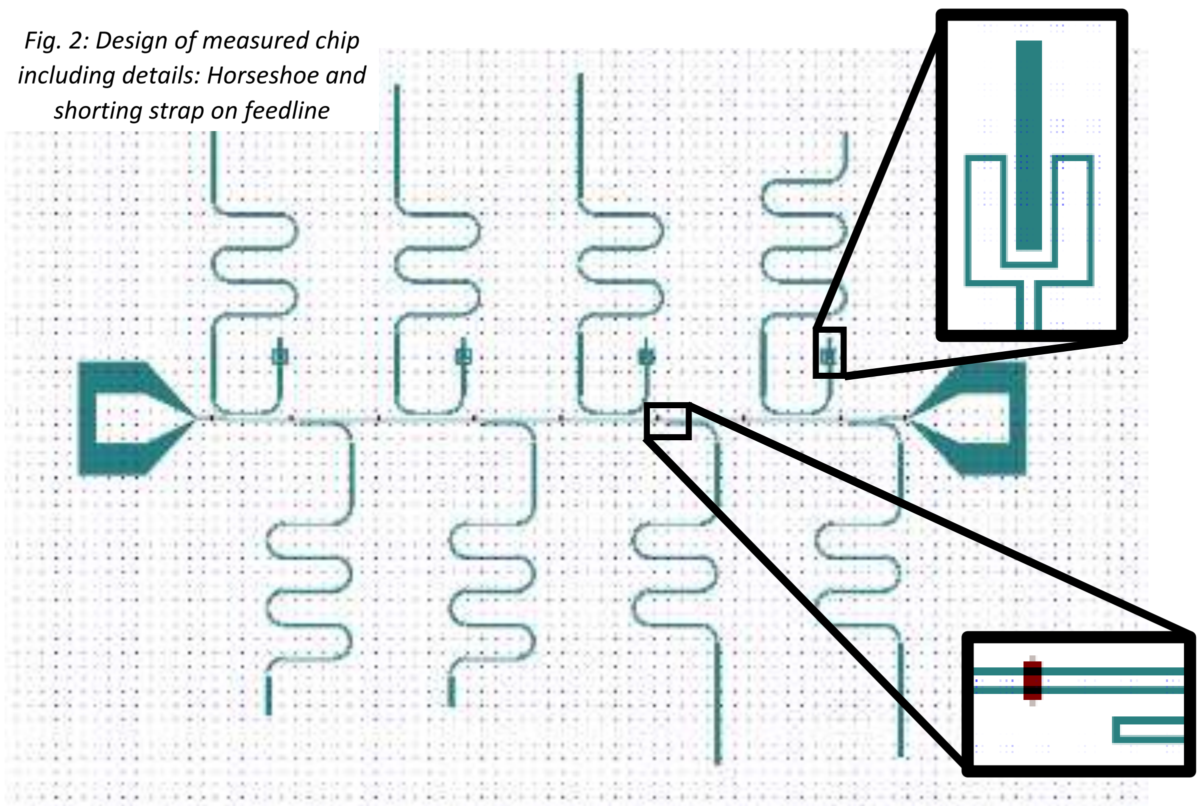


Fig. 2: Design of measured chip including details: Horseshoe and shorting strap on feedline

Designed freq [GHz]	Design freq [GHz] Considering altered C_l	Length [µm]	Q factor Considering only geometry (alteration due to displacement is small)	Measured freq [GHz]
6.6	**6.5076**	4.3816	3.3E+05	**6.147**
6.7	**6.6062**	4.3162	3.2E+05	**6.241**
6.8	**6.7048**	4.2528	3.1E+05	**6.328**
6.9	**6.8034**	4.1911	3.0E+05	**6.408**
7.1	**7.1**	4.0731	2.9E+05	**7.003**
7.2	**7.2**	4.0165	2.8E+05	**7.103**
7.3	**7.3**	3.9615	2.7E+05	**7.200**
7.4	**7.4**	3.9079	2.6E+05	**7.308**

Theoretical estimate of the resonance shift

Capacitance to ground change due to horse shoe, and is expected to be observed as a change in the self-capacitance per unit length, i.e. $C_l^{HS} = \frac{C_l L + \Delta C_{HS}}{L}$, where C_l is the original capacitance per unit length, and L the resonator length. ΔC_{HS} is the addition of capacitance to ground due to the horseshoe. The design includes a stripped "finger" (removal of Al) inside the horse shoe, imitating the qubit in fig. 1, but the wider traces (aiming for larger coupling to qubit) also enlarges the coupling to the ground. An estimate of this is shown in fig. 3, and with the given geometry, we expect ΔC_{HS}~20 fF. The self-capacitance of the λ/4 CPWR is otherwise $\boldsymbol{C_l L}$ **~700 fF** and it follows that $\boldsymbol{C_l^{HS} \sim 720}$**.** This alters frequencies by $\sqrt{\frac{700}{720}} \sim 0.986$.

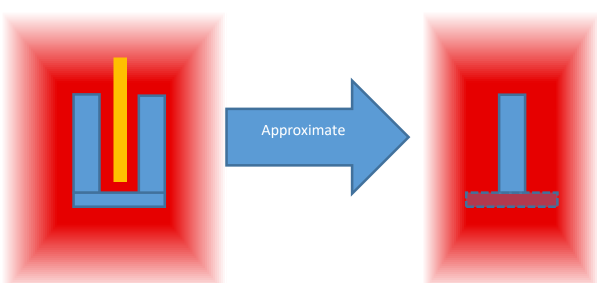


Fig. 3: Though the horse shoe has to branches (blue), the ground between them is occupied by the Xmon finger (or, in this measurement, its imitator; yellow) and we may therefore consider an ordinary rectangular CPW, with grounds on both sides. Since the base/bottom of the horse shoe is narrower and shorter than the branches, its capacitance to ground is ignored. Red: Electrical field

The table above does NOT consider the altered position of the coupling segment (between resonators and feed line). The cause of this alteration is the required distance between readout line and xmon, and the resonator is therefore coupled to the feed line at a distance ~500 µm from its end (where the wave function reaches maximum). Given the length of the λ/4 resonator ($L \sim 4$ mm), the wave function becomes ~$A\cos\left(\frac{\pi}{2} \cdot \frac{5}{40}\right) \cong 0.98\,A$, where A is its maximal value – a change relatively small, which will therefore be ignored for now.

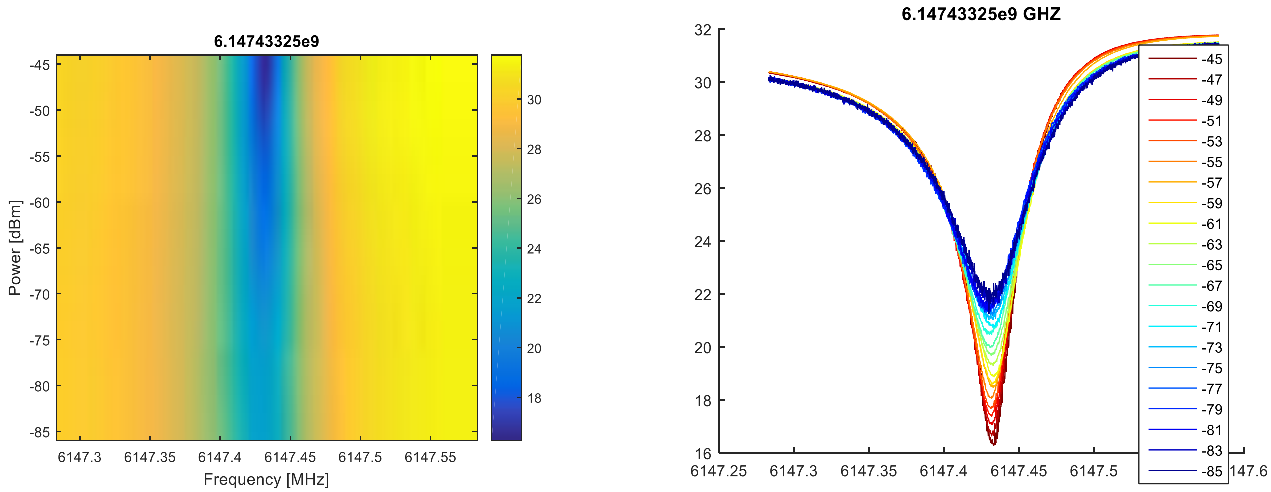


Fig. 4: Power dependence of the lowest resonance shows some an-harmonicity, but the frequency is not remarkably power dependent.

Results and discussion

The first four resonances moved by **~ ½ GHz**, not only **~100 MHz** as expected. Also the four "ordinary" resonators, which (by Elisha's help and Naftali's check) should be spot-on the resonances, I aimed for, missed by some **100 MHz**.

The main question is: Can we use the four "high frequency" (ordinary) resonances to calibrate the lower ones (with horse shoe capacitors) and then estimate the effect of the horse shoe capacitors?

As the power sweep to the right shows (on one of the "high" frequencies, i.e. normal ones), the exact resonance was not easy to determine, and it moved back-and-forth ~1 MHz (ignore, for now, the fact, that this was supposed to show power dependence).

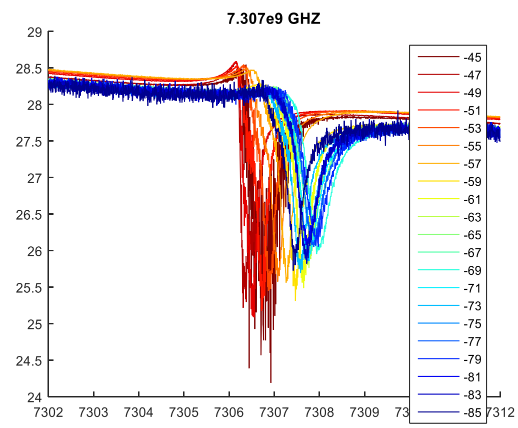
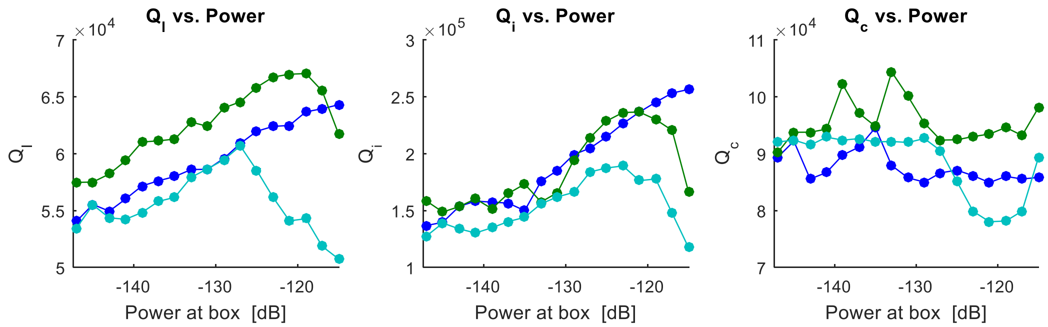


Fig. 5: "Unsteady" (dancing…) resonance. Though this is a power plot, it was clear that the resonance "moved around" as a function of time. Not fit was therefore intended.

Reasonable fits were only found for three of the four horse-shoe-bound resonators. The results (below on the graphs) show coupling Q's of ~ 1e5 (9e4 – right diagram), and internal Q's of just a bit more. This is more or less consistent with our assumption that 200/25 µm coupling length/gap produce the critical coupling.

Problems: Bad resonances, not steady, hard to fit. Maybe the lack of magnetic shielding (this device was in OB3, the cupper mounting box. In the next cool down, I will transfer the wafer to an aluminum box to test this assumption.



Q_l vs. Power
$\times 10^4$
7
6.5
6
5.5
5
Q_l
-140
-130
-120
Power at box [dB]
Q_i vs. Power
$\times 10^5$
3
2.5
2
1.5
1
Q_i
-140
-130
-120
Power at box [dB]
Q_c vs. Power
$\times 10^4$
11
10
9
8
7
Q_c
-140
-130
-120
Power at box [dB]