Analysis of 1803.3 Dev 1 and Dev 2

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The devices are shunt cavities on an SRON chip; Dev 1 is open and Dev 2 shorted to ground. NbTiN, Al_2O_3 and NbTiN thicknesses are 100 nm, 50 nm and 150 nm, respectively. Chip was fabricated by Felix, measurements were performed in the He7/Entropy by Mark and Felix. The python file for analysing the data is in `CloudStation/projects/Felix/programming/Loptimize` and is called `F1_parameters.py`.

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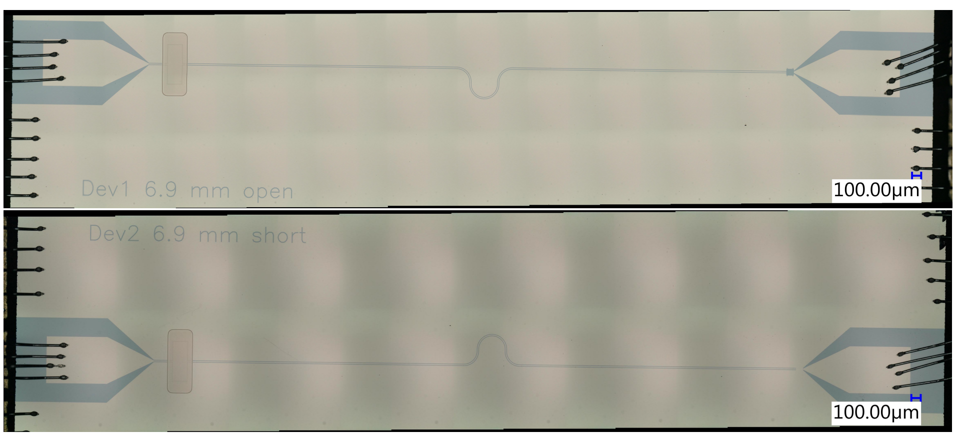

Figure 1. Optical micrograph of the analysed devices.

I. DEVICE PARAMETERS

A. Geometric parameters

Chip dimensions	10 mm × 10 mm
Substrate	Silicon (TOPSIL, high-res), $\epsilon_r = 11.7$, $h = 550\,\mu m$
Base layer	$t = 100$ nm NbTiN (SRON Evatec)
Dielectric layer	50 nm Al2O3 thermal ALD
Top shunt layer	150 nm SuperAJA NbTiN

B. Calculation of transmission line parameters

S (Width of center conductor)	TL: 12 µm, Launcher: 500 µm
W (Width of gaps)	TL: 5 µm, Launcher: 200 µm
Z_0 (Characteristic impedance)[1]	TL: 45.4 Ω, Launcher: 44.8 Ω
l (TL length)	6900 µm

All formulas used below are taken from[2] and[3].

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} \tag{1}$$

$$k_0 = \frac{S}{S + 2W} \tag{2}$$

$$k_0' = \sqrt{1 - k_0^2} \tag{3}$$

$$Z_0 = \frac{30\pi}{\sqrt{\epsilon_{\text{eff}}}} \frac{K(k_0)}{K(k_0')} \tag{4}$$

$$C' = 4\epsilon_0 \epsilon_{\text{eff}} \frac{K(k_0)}{K(k_0')} \tag{5}$$

$$L' = \frac{\mu_0}{4} \frac{K(k_0')}{K(k_0)} \tag{6}$$

$$\omega_{0,\text{geo}} = \frac{1}{l\sqrt{L'C'}} \tag{7}$$

$$\lambda_{\text{London}} = \sqrt{\frac{L_k t S}{\mu_0 g(S, W, t)}} \tag{8}$$

$$\lambda_m = \sqrt{\frac{\hbar \rho}{\pi \mu_0 \Delta_0}} \tag{9}$$

$$L_s = \mu_0 \lambda_m \coth\left(\frac{t}{\lambda_m}\right) \approx \frac{\mu_0 \lambda_m^2}{t} \tag{10}$$

$$\tag{11}$$

For the SRON devices, we expect a typical magnetic penetration depth of $\lambda_m = 275\,\text{nm}$. For the 511 nm films from their paper[4], this results in a sheet inductance of $0.363\,\text{pH}/\square$. Note that $\widetilde{g} \neq g(S, W, t)$! While the latter is typically on the order of unity, the former is on the order of 10^5.

For analyzing the 100 nm NbTiN films they sent us, we refer to[5]. A typical 100 nm film on Si has $R_s = 11\,\Omega$, and using the simple expression $L_s = \frac{\hbar R_s}{\pi \Delta}$ this results in $L_s = 1\,\text{pH}/\square$. Our transmission line has a length of 6.9 mm and a width of 12 µm, which means in $l/S = 575\,\square$, which means an overall $L_k = 575\,\text{pH}$, or $L_k' = L_k/l = 83.3\,\text{nH/m}$. Since we did not measure the film resistance, we cannot accurately calculate the surface inductance. However, we are able to extract the London penetration depth, which is all we need since we can get L_k of each device just by plugging in the geometry. Our $\lambda_{\text{London}} \approx 300\,\text{nm}$. For the device geometry of 1803.3 Dev 1, this results in an $L_k = 91.9\,\text{nH/m}$, compared to $L_g = 381\,\text{nH/m}$.

For the fabricated device, the resulting **transmisson line** parameters are as follows:

Purely geometric	Including L_k ($\lambda_L = 300\,\text{nm}$)
$\epsilon_{\text{eff}} = 6.35$	$\epsilon_{\text{eff}} = 7.88$
$Z_0 = 45.38$	$Z_0 = 50.55$
$L' = L_g' = 381\,\text{nH/m}$	$L' = L_g' + L_k' = (381 + 91.9)\text{nH/m}$ $L_k'/L' = 0.194$
$C' = 0.185\,\text{nF/m}$	$C' = 0.185\,\text{nF/m}$
$v_{\text{ph}} = 0.397c$	$v_{\text{ph}} = 0.356c$

The resulting **launcher** parameters are barely affected by the kinetic inductance contribution, due to the large gaps. We also include a calculation for an optimized geometry (i.e. better matched to 50 Ω environment):

Purely geometric	Including L_k ($\lambda_L = 300\,\mathrm{nm}$)	Optimized geometry ($S = 400\,\mu\mathrm{m}$, $W = 235\,\mu\mathrm{m}$)
$\epsilon_{\mathrm{eff}} = 6.35$	$\epsilon_{\mathrm{eff}} = 6.37$	$\epsilon_{\mathrm{eff}} = 6.35$ (6.37)
$Z_0 = 44.85$	$Z_0 = 44.93$	$Z_0 = 50.09$ (50.18)
$L' = L'_g = 381\,\mathrm{nH/m}$	$L' = L'_g + L'_k = (381 + 1.34)\mathrm{nH/m}$ $L'_k/L' = 0.004$	$L' = L'_g = 421\,\mathrm{nH/m}$ (421+0.001) (0.004)
$C' = 0.185\,\mathrm{nF/m}$	$C' = 0.185\,\mathrm{nF/m}$	$C' = 0.168\,\mathrm{nF/m}$ (0.168)
$v_{\mathrm{ph}} = 0.397c$	$v_{\mathrm{ph}} = 0.396c$	$v_{\mathrm{ph}} = 0.397c$ (0.396)

For the **shunt capacitor**, the parameters are the following:

Shunt capacitor	$t = 50\,\mathrm{nm}$ of Al_2O_3 ($\epsilon_r \approx 9$)
Interior surface	$A_1 = 65\,778\,\mu\mathrm{m}^2$
Exterior surface	$A_2 = 66\,880\,\mu\mathrm{m}^2$
Total capacitance	$C_s = \frac{\epsilon_0\epsilon_r}{t}\frac{A_1 A_1}{A_1+A_2} \approx 53\,\mathrm{pF}$
Stray capacitance	$\sim 3 - 6\,\mathrm{pF}$?[6]

II. FINAL CALCULATIONS USING FORMULAS FROM DANIEL'S DOCUMENT

A. Short $\lambda/2$ resonator

Assuming the device is short, **Device 2**, the lumped equivalents of the shorted $\lambda/2$ resonator are as follows:

$$C_l = \frac{2C'l}{\pi^2} = 0.259\,009\,771\,109\,\mathrm{pF} \tag{12}$$

$$L_l = \frac{L'l}{2} = 1.632\,914\,927\,01\,\mathrm{nH} \tag{13}$$

$$f_{0,\mathrm{unloaded}} = \frac{1}{2\pi}\sqrt{\frac{1}{L_l C_l}} = 7.738\,918\,589\,23\,\mathrm{GHz} \tag{14}$$

$$f_{0,\mathrm{loaded}} = \frac{1}{2\pi}\sqrt{\frac{2C_l+C_s}{L_l C_l C_s}} = 7.757\,805\,500\,24\,\mathrm{GHz} \tag{15}$$

$$Q_{\mathrm{ext}} = \frac{\omega_0 Z_0 C_s (C_l + C_s)}{C_l} = 26851.9229784 \tag{16}$$

B. Open $\lambda/4$ resonator

Assuming the device is open, **Device 1**, the lumped equivalents of the open-ended $\lambda/4$ resonator are as follows:

$$C_l = \frac{8C'l}{\pi^2} = 1.036\,039\,084\,44\,\mathrm{pF} \tag{17}$$

$$L_l = \frac{L'l}{2} = 1.632\,914\,927\,01\,\mathrm{nH} \tag{18}$$

$$f_{0,\mathrm{unloaded}} = \frac{1}{2\pi}\sqrt{\frac{1}{L_l C_l}} = 3.869\,459\,294\,62\,\mathrm{GHz} \tag{19}$$

$$f_{0,\mathrm{loaded}} = \frac{1}{2\pi}\sqrt{\frac{2C_l+C_s}{L_l C_l C_s}} = 3.907\,096\,169\,97\,\mathrm{GHz} \tag{20}$$

$$Q_{\mathrm{ext}} = \frac{\omega_0 Z_0 C_s (C_l + C_s)}{C_l} = 3430.21257971 \tag{21}$$

III. MEASUREMENTS

The device was measured in the He7/Entropy fridge by Mark, see Fig.2. `quickQ.py` with fitmodel `ftype="+A"` reveals $Q_{\mathrm{int}} = 4.0908909 * 10^4 \pm 3.0548369 * 10^1$, $Q_{\mathrm{ext}} = 3.8590416 * 10^4 \pm 1.3629282 * 10^1$, $f_0 = 7.515\,996\,4\,\mathrm{GHz} \pm 86.469\,542\,\mathrm{Hz}$ and $\theta = -3.4245547 * 10^{-2} \pm 3.3963561 * 10^{-4}$. The internal quality factor is surprisingly low, considering the SRON hanger cavities that reach a few hundreds of thousands. An explanation of this could be high dielectric losses from the $Al2O_3$ flakes all around the resonator.

So the external Q is a factor 1.437 times higher than expected. Assuming all the other values are correct, the higher Q_{ext} could be explained by a shunt capacitance of $C_s = 63\,\mathrm{pF}$, yielding $Q_{\mathrm{ext}} = 37896$. This increase in C_s might be due to either stray capacitance, or the over-exposure of the top plate of the shunt, which resulted in a significantly larger area and a probably increased capacitance (see Fig.4). Also, not to neglect is the possibility of the fitting not returning the true value of quality factors.

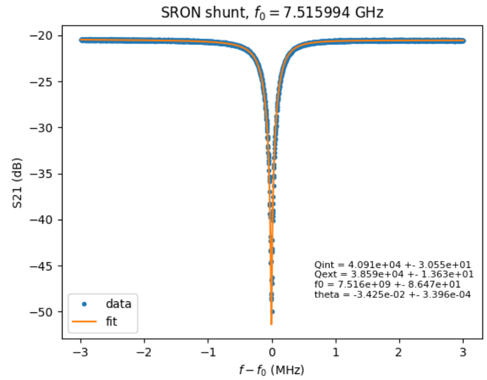

Figure 2. Microwave response $|S_{11}|^2$ of the shorted device (blue points) and fit (orange line).

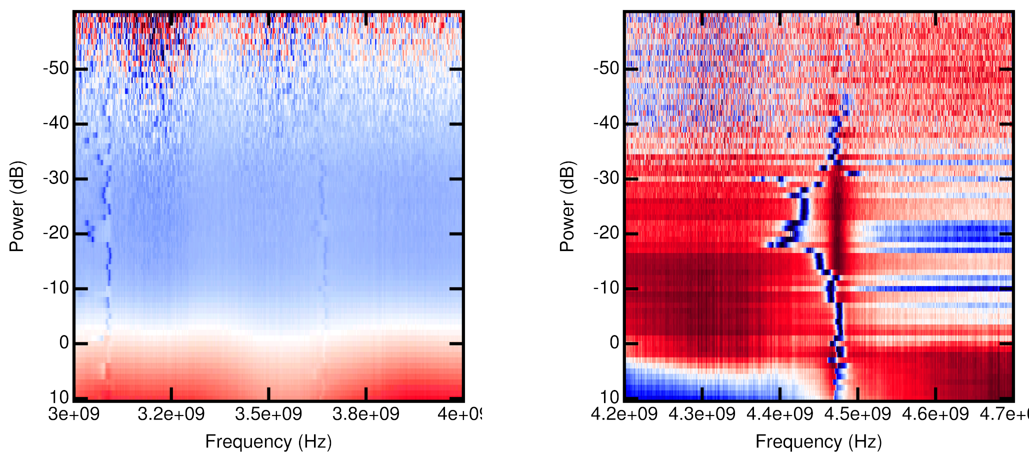

Figure 3. Microwave response $|S_{11}|^2$ of the open device as a function of power for different frequency ranges. It is unclear which of these three resonances is the one corresponding to the cavity. There might have also been a defect in the line (see Fig.4).

Also the frequency is 200 MHz higher than expected. This is most likely due to the assumption I made on the London penetration depth of 300 nm. For a slightly larger 340 nm, we get a 200 MHz shift down to 7.525 GHz, without any effect on Q_{ext}.

Measurements of the open reference cavity (Dev 2 on the same chip, see Fig.3) do not show a pronounced frequency at the expected f_0, but instead three jittering features appear around 3.1 GHz, 3.55 GHz and 4.5 GHz, all with horrendously low quality factors. This might be due to a defect in the transmission line resonator, see Fig.4.

IV. CONCLUSION

We will abort the fabrication of shunt cavities based on Al_2O_3 because of all the dielectric flakes remaining when buffer-etching. Instead, we will continue using SiN_x deposited via PECVD. I will simulate the required shunt sizes for a 50 nm dielectric slab and based on these results will fabricate a chip with four cavities, two shorted, two open, with different shunt sizes.

REFERENCES

[1] http://janielectronics.com/szamitasok/Transmission%20Line/Coplanar%20Waveguide%20Calculator/janilab.php.
[2] http://qucs.sourceforge.net/tech/node86.html.
[3] http://www.diva-portal.org/smash/get/diva2:216977/FULLTEXT02.pdf.
[4] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7752837.

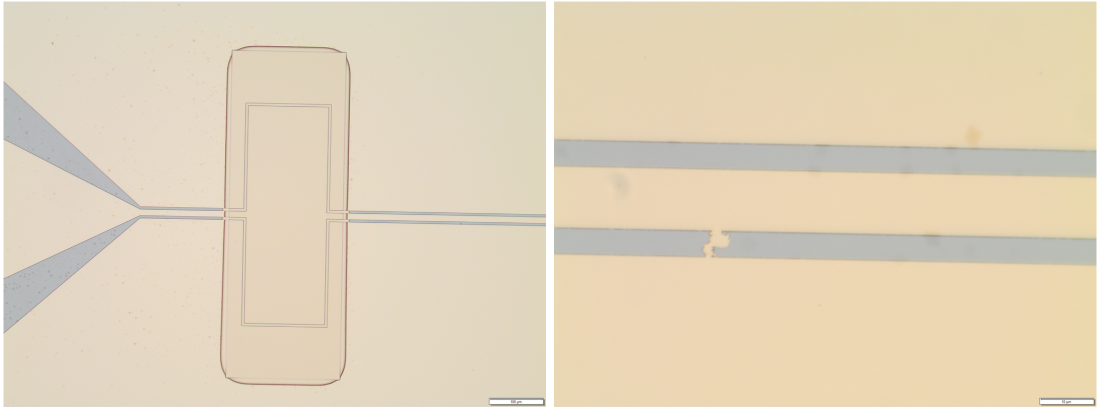

Figure 4. Fabrication defects of 1803.3. Left, the top plate for the shunts got exposed twice (due to the pattern being there twice in the `.gds`-file, and missing `Heal` in *LayoutBeamer*), resulting in a bigger area and an increased C_s. Right, A defect in the transmission line resonator of the open device might explain the jitter and three weird resonances. The dark spots around are Al_2O_3 flake residues that did not get properly etched in BHF, possibly explaining the low Q_{int}.

[5] 100 nm NbTiN from the LLS.docx.
[6] `https://arxiv.org/pdf/1508.05770.pdf`.