

Improving the coherence time of superconduct- ing qubits by de- sign

A procedure to cal-
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Improving the coherence time of superconducting qubits by design

A procedure to calculate participation ratios

by

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Preface

Preface...

R.A. Koster
Delft, January 2016

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Introduction

Since the introduction of the transmon quantum bit (transmon qubit) by Koch et al. in 2007 [2] as a promising candidate of qubits there have been investigations into sources of decoherence of these qubits. C. Wang et al. found that surface dielectric dissipation is probably still the major limiting factor for the coherence time of transmon qubits [3]. The different surface dielectrics introduced to the system during production have distinct material compositions [1] and as a result will have a different impact on the coherence time [3]. Qubit structure design itself will dictate how the Electric field is distributed through the dielectrics.

The goal of this research is to determine this distribution and to use this information to design a transmon qubit in such a way as to be able to avoid concentrating the Electric field in regions containing more lossy dielectric material. Being able to do so may better the ability to design transmon qubits with longer coherence times.

The following section will provide necessary background information to substantiate the above. Information particularly relevant to this research will be provided in the next chapter.

Quantum computing and quantum bits

-General information about quantum computing. Benefits, application etc. -quantum bits; importance of longer coherence time

Restatement of the problem -Role of dielectric lossy materials -why is this research important?!

-Knowing how design choices influence the participation ratio of lossy layers.

Restatement of the response - "In order to address this problem, I will ...".

Roadmap -How will the thesis proceed

2

Theory

The transmon qubit

The qubit under investigation during this project is the so called transmon qubit. A traditional transmon qubit consists of a pair of Josephson junctions connected to two superconducting pads. The structure is surrounded by a grounded metal plane. Other parts of the structure are the transmission line resonator, the quantum bus resonator and the

LC-circuits

The transmon qubit can be treated as a simple LC-circuit. The Josephson junction is replaced by an inductor and the different capacitors are replaced by an single equivalent capacitor. The resulting simplified system can be seen in figure 2.1.

Energy in an LC-circuit

In order to determine the participation ratio of the lossy layers in storing energy in the system, the total energy must be know. The total energy stored in an LC-circuit at any time can be calculated as follows:

$$W = \frac{1}{2}CV^2 \quad (2.1)$$

Where C is the total capacitance of the system and V the voltage over the systems.

Electric fields

Perfect Electric Conductor

As the qubit is supercooled to temperatures of only a few mK, the metal in the qubit is treated as a Perfect Electric Conductor (PEC).

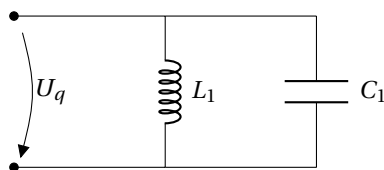


Figure 2.1: A simple parallel LC-circuit

Continuity rules

Stored energy

The energy stored in the Electric field in a material can be calculated using equation (2.2)

$$W = \frac{\epsilon}{2} \int |E|^2 dV \quad (2.2)$$

Where ϵ is the permittivity of the material and V is the volume occupied by the material.

Sources of decoherence

In order for the qubit to be coherent . . . The source in question during this project is the layers of lossy material in the system.

Lossy materials

During production of qubits, different procedures introduce lossy materials to the structure. An important property of each of these materials is their permittivity. It will determine the strength of the field and the energy stored inside the layers.

Two-Level Systems

The participation ratio

To determine what kind of structure design may improve coherence time the participation ratio of lossy layers can be calculated. If the assumption is made that the Electric field remains constant inside the lossy layer equation (2.2) can be rewritten as follows:

$$W = \frac{\epsilon}{2} t \int |E|^2 dA \quad (2.3)$$

Where ϵ is the permittivity of the material and t is the thickness of the lossy layer. Furthermore, A is the surface area of the lossy layer.

3

Model of the system

In order to calculate the participation ratio of the different lossy layers in an arbitrary structure it is simulated using 3D EM simulation software called CST.

Josephson junction

During simulation in CST, the Josephson junction is replaced by an inductor. By tuning the inductance together with the capacitance of the structure a specific resonance frequency can be reached.

Lossy layers

The relatively small thickness of the layers suggests that the impact they have on the Electric field is small. During simulation their impact is neglected and the layers are therefore omitted. The exclusion of thin lossy layers prevents the necessity for mesh elements with sub-nano meter size. This significantly reduces the number of mesh elements and in turn the computation time of the simulation. A simple representation of the structure can be seen in figure 3.1.

Ground

To further reduce the number of mesh elements, the ground pad is replaced by a thin sheet of PEC. Considering the field in the ground region is small compared to the field at the edges of the pads its contribution to the participation ratio is also small. Investing more computation time on the ground region by increasing the density of mesh elements there would therefore also have limited impact on the participation ratio.

title

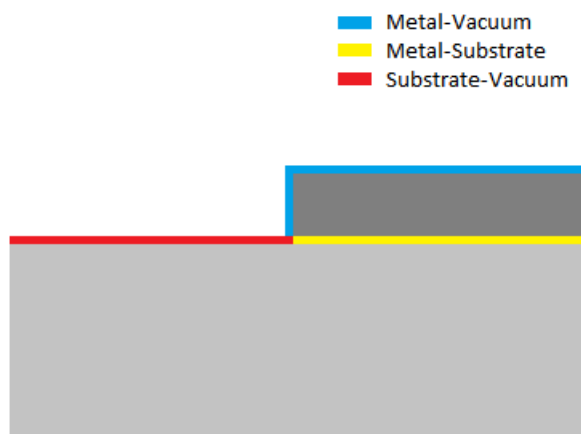


Figure 3.1: Simplification of the system including three lossy layers. The substrate and metal are depicted in light and dark grey respectively

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CST procedure

This chapter will detail the steps that should be taken to easily set up a qubit simulation in CST. The determination of the capacitance of the qubit and the electric fields in the structure will be treated separately as the second process is more complex. Both simulations make use of the Frequency Domain Solver. Settings applicable to both processes are the frequency range and the boundaries.

- Under 'Simulation' click 'Frequency' and set the desired values.
- Again under 'Simulation' click 'Boundaries' and set the fields as in figure 4.1
- Click 'Open Boundary...' and under 'Automatic minimum distance to structure' select 'Fraction of wavelength' and set to 8. Click 'OK'.

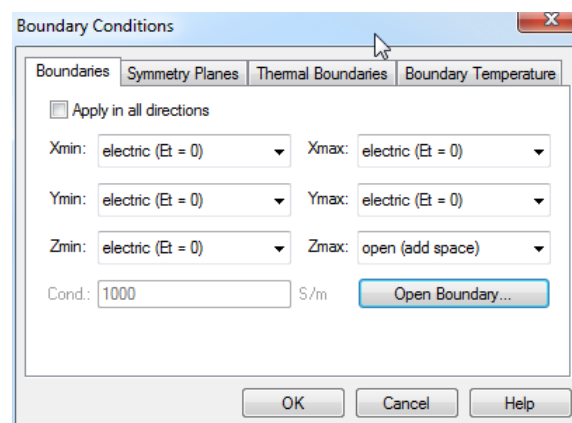


Figure 4.1: Settings for the boundary conditions of the simulations. All except 'Zmax' are set to 'electric ($E_t = 0$)'. 'Zmax' is set to 'open(add space)'.

The capacitance

As show in equation (2.1) the capacitance of the structure must be known to calculate the total energy in the qubit. The value of the capacitance converges very quickly as the mesh is refined. This simulation should always include a Discrete Port connected to the capacitor pads.

Modeling

The qubit design can be imported to CST or created in CST itself. Figure 4.2 shows a qubit designed in CST. It includes two metal pads connected by a discrete port and is surrounded by a metal ground sheet. For the determination of the capacitance, the inductor representing the Josephson junction should be omitted from the simulation.

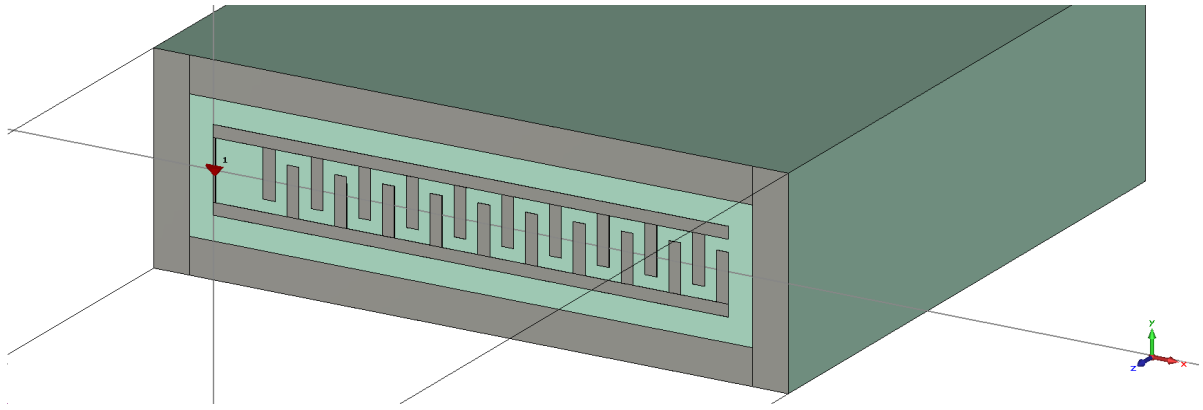


Figure 4.2: An example of a qubit design with the substrate in green, the metal parts in grey and the port indicated by the red cone. No lumped element representing the Josephson junction is present in the model.

Meshing

The default settings for the tetrahedral meshing can be used during calculation of the capacitance. This will yield a very rough initial mesh with few mesh elements and will ensure short simulation times.

Post processing

In the post processing templates window, the capacitance of the simulated structure can be retrieved;

- Under '*Post Processing*' select '*Template Based Post Processing*'.
- In the pop-up window, in the first selection box choose '*S-Parameters*'.
- In the second selection box choose '*Z-parameter*'.
- In the pop-up window check the '*C*' option and click '*OK*'.

This will yield a 2D graph showing the capacitance of the structure as a function of frequency.

Now include a second template;

- In the first selection box choose '*General 1D*'.
- In the second selection box choose '*0D or 1D Results from 1D Result (Rescale, Derivation, etc)*'.
- In the pop-up window select '*y at given x*' and set '*Evaluate at x =*' to the desired frequency. Click '*OK*'.

After simulation, the result should be a single value of the capacitance at the required frequency.

Simulation setup

To ensure convergence of the capacitance, results from the post processing templates can be used as targets for the simulation;

- Under '*Simulation*' choose '*Setup Solver*'.
- Under '*Adaptive mesh refinement*' make sure the '*Adaptive tetrahedral mesh refinement*' is checked and click '*Properties*'.
- In the pop-up window under '*Number of passes*' set the maximum to at least 8.
- Under '*Check after broadband calculation:*' mark the '*0D result Template...*' as active and select the 0D result of the capacitance from the post processing template above.
- Set the required Threshold and Checks as desired and click '*OK*'.

This will ensure the simulation keeps refining the simulation until your demands on accuracy are met or until maximum amount of mesh refinement passes is reached. After every mesh refinement pass the results are updated and can be checked. In the Navigation Tree click '*Tables*' → '*0D Results*' → '*C1,1_0D_yAtX*'. The first result will be viewable once the first pass of the simulation is completed. When the simulation is finished the capacitance of the structure can be extracted from the plot. An example is given in figure 4.3.

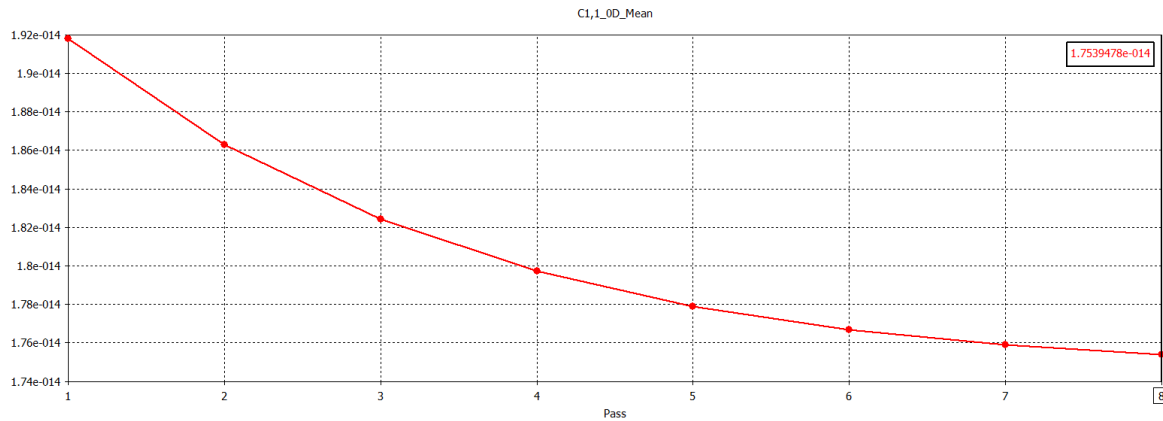


Figure 4.3: An example of the data retrieved on the capacitance of a qubit design. On the y-axis is the capacitance in Farad. On the x-axis is the number of mesh refinement passes. Highlighted is the value of the capacitance after 8 passes.

The electric field

Now that the capacitance of the structure is known the more extensive simulation of the electric field can be set up.

Modeling

Using equation (4.1) the inductance needed to reach a certain resonance frequency can be calculated.

$$L = \frac{1}{(2\pi)^2 f_0^2 C} \quad (4.1)$$

Where f_0 is the required frequency and C is the capacitance.

Now to include such an inductor;

- In the simulation menu add a '*Lumped element*'.
- Set the element '*Type*' to be '*RLC parallel*'
- Set the value of the inductance as calculated and leave the other values at zero.
- Make sure the '*Monitor voltage and current*' is checked.
- Set the location as desired or use picked points.

Next, to ensure a fine initial mesh, the edges on the side of the pads are rounded. In order to make this possible each pad must be a single object. To achieve this the '*Boolean*' operation can be used to combine multiple object into one;

- In the Navigation Tree, under '*Components*' select all objects pertaining to one pad.
- Under '*Modeling*' click the '*Boolean operator*'.

Now that the pad consists of a single object, its side edges can be rounded.

- Under '*Modeling*' click '*Picks*' and choose '*Pick Edge Chain*' (or use Shift+E)
- Select all the edges laying in the xy -plane.

Figure 4.4 show what the selection should look like. Once the right edges are selected they can be rounded;

- Under '*Modeling*' click '*Blend*'.
- Set the '*radius*' to be half the height of the pad.

The result should be as in figure ??.

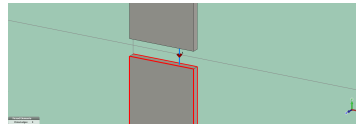


Figure 4.4: A selection of two Edge Chains in red. One at the level of the substrate and another at the level of the top of the pad.

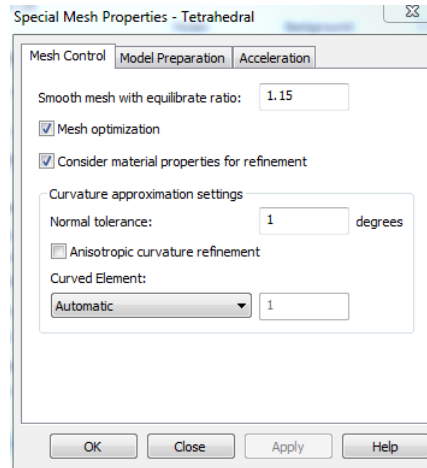


Figure 4.5: The required settings for the Mesh Properties. The Anisotropic curvature refinement must be unchecked!

Meshing

In order to obtain a fine initial mesh the *Global mesh properties* can be changed;

- Under '*Simulation*' click '*Global mesh properties*'.
- In the pop-up window click '*Specials*'.
- Under the '*Mesh Control*'-tab set '*Smooth mesh with equilibrate ratio*' to 1.15.
- Set '*Normal tolerance*' to 1 degree.
- **Uncheck** the '*Anisotropic curvature refinement*'.

See figure 4.5 for the settings.

Simulation setup

To be able to view and save field data, include a field monitor;

- Under '*Simulation*' click '*Field Monitor*'.
- In the pop-up window select the e-field monitor and choose a frequency.
- Click '*OK*', the monitor should be visible in the Navigation Tree.

Exporting data

To calculate the participation ratio the simulated electric field is exported as an ASCII file. In order to separate data pertaining to different lossy layers the data for the field on the Pads, Substrate and Ground can be exported separately.

- In the Navigation Tree under '*Components*' hide all objects until only the Pads are visible.
- Again in the Navigation Tree open the '*2D Results*' folder.
- Select the '*Abs*' component of the '*E-Field*'.

- Under '*Post Processing*' click '*Import/Export*' and click '*Export as ASCII file*'.

Repeat these steps for the Substrate and Ground.

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Matlab procedure

Importing data

Separating data for different layers

Calculating energies and participation ratio

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