Designing and Manufacturing a High-Frequency Low-Pass Infrared Filter for Quantum Information Processing Applications

by

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A research project submitted in partial

fulfillment of the requirements for the degree of

Masters of Sciences in Quantum Science and Technology

School of Physics

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I have read and I understand the plagiarism provisions in the General Regulations of the University Calendar for the current year, found at: http://www.tcd.ie/calendar

I declare that the assignment being submitted represents my own work and has not been taken from the work of others save where appropriately referenced in the body of the assignment.

Signed: Patrick Sinnott
Date: 14/07/2022

Abstract

In this report, I discuss my efforts to design and manufacture a High-Frequency Low-Pass Infrared Filter for use in CQT's superconducting circuit quantum information processor. The purpose of the filter is to block noise-generating radiation in the high frequency (>70GHz) range but allow low frequency, in-band signals (4-8GHz) to pass through unimpeded.

My design was inspired by the recently proposed HERD filter [1] but I have made a number of alterations and improvements to this filter and propose a model which shows an improved performance in simulations. This improved filter is currently being manufactured and its simulated performance is presented alongside the steps required to complete the manufacturing process.

Contents

Chapter 1

Introduction

1.1 Microwave Filtering

Superconducting quantum circuits represent a promising architecture for quantum information processing, in recent years quantum simulation using superconducting qubits has become a reality. [4] The field of experimental quantum computing is making steady progress towards the realization of a machine that can solve a certain class of problems exponentially faster than classical computers.

However in an experimental setting, superconducting qubits are not perfect or well isolated and the fidelity of quantum states degrades over time. [5] One limitation on this particular architecture is that it is extremely sensitive to environmental perturbations. One of these environmental perturbations is due to quasiparticles—broken Cooper pairs—in the superconductor.

Cooper pairs are the charge carriers in our Superconducting circuits and they consist of paired state of electrons which have a lower energy than the Fermi energy, which implies the pair is bound. If a photon above the energy of the energy gap of the superconductor enters the circuit it can excite and break these cooper pairs, giving us quasiparticles which are essentially free electrons. These loose charged particles can cause huge disruption to our qubit states.

The exact effect of quasiparticles on a superconducting circuit is still very much an open question and an active area of research. However there is certainly enough evidence to assume that this effect is far from negligible and should be mitigated as much as possible. [6] [7] This is where our Infrared-Photon Blocking Filters come in to play. We are interested in filters which allow low-frequency radiation used for driving our qubit transitions to pass through, yet offer high-impedence for the high frequencies which lead to quasiparticle generation.

We are interested in blocking signals in the high-frequency range (>70Ghz)

1.1.1 Scattering Parameters

Our primary method for quantifying the performance of infrared filters will be the analysis of scattering parameters.

The scattering matrix or S matrix of a system of N ports is defined as:

$$\begin{bmatrix} V_1^- \\ V_2^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1N} \\ S_{21} & S_{22} & \cdots & S_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ S_{N1} & S_{N2} & \cdots & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \\ V_N^+ \end{bmatrix} \tag{1.1}$$

where V_i^- is the amplitude of reflected voltage at port i and V_j^+ is the amplitude of the incident voltage at port j. Each S_{ii} is the reflection coefficient for the port i.
Our terms S_{ij} are the important ones as they correspond to transmission coefficients from port i to port j:

$$S_{ij} = \frac{V_i^-}{V_j^+} \tag{1.2}$$

These transmission coefficients may also be reformulated as attenuations for signals travelling from port i to port j through:

$$\text{Attenuation [dB]} = -20\log_{10}\left(|S_{ij}|\right) \tag{1.3}$$

This will be our main quantity of interest.

1.1.2 Impedance of Filter

The characteristic impedance of a transmission line is given by the following equation[9, p. 50]:

$$Z \equiv \sqrt{\frac{R + i\omega L}{G + i\omega C}} \tag{1.4}$$

where R is the resistance of the line per unit length, L is the series inductance of the line per unit length, G is the conductance of the line per unit length, C is the series capacitance of the line per unit length and ω is the angular frequency $\omega = 2\pi\nu$. For a coaxial line with complex permittivity $\epsilon = \epsilon' - i\epsilon''$, permeability µ, surface resistance R_s and an outer conductor of inner radius b and an inner conductor with an outer radius of a, these parameters are:

$$\begin{aligned} R &= \frac{R_s}{2\pi}\left(\frac{1}{a} + \frac{1}{b}\right) \\ L &= \frac{\mu}{2\pi}\log\left(\frac{b}{a}\right) \\ G &= \frac{2\pi\omega\epsilon''}{\log\left(\frac{b}{a}\right)} \\ C &= \frac{2\pi\epsilon'}{\log\left(\frac{b}{a}\right)} \end{aligned} \tag{1.5}$$

Following this we may write:

$$Z = \frac{1}{2\pi}\sqrt{\frac{\mu}{\epsilon}}\log\left(\frac{b}{a}\right) \quad (1.6)$$

1.2 Existing Eccosorb Filters

There is a huge variety of Infrared filters being developed and used, the most relevant for our uses are the Eccosorb range.[2] These filters consist of a cylindrical central conductor surrounded by a coaxial epoxy resin. Depending on the choice of epoxy resin these filters can have varying attenuation at different frequencies.

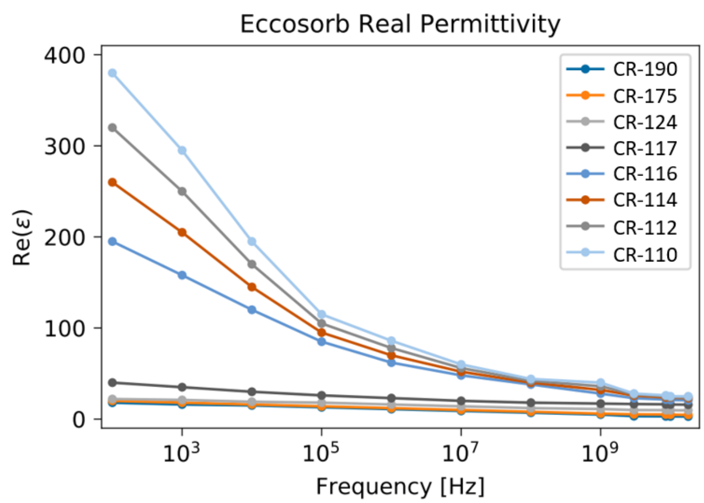


Figure 1.1: Permittivity of ECCOSORB resin

We are looking for a resin with a high permittivity in the GHz range, for reasons that we will discuss in section (2.2). We can see from Figure 1.1 (data from ECCOSORB official datasheet [11]) ECCOSORB CR110 has the highest permittivity in our range of interest.

One constraint we have on any filter type we are considering is that its impedance must match with the resistance of 50Ω, we can calculate this with Eqn 1.6

Results of a simulation of the performance of this type of filter filled with CR-110 resin can be seen in figure 1.1(b). Note: All simulations were performed through models created and simulated through ANSYS.

We can see reasonable attenuation at the frequency range of interest (> 80GHz) but there is certainly room for improvement. We also see attenuation which is higher than we would like for our in-band frequencies.

(a) Basic Eccosorb Filter.

(b) Filter attenuation.

Figure 1.2

1.3 HERD Filter

The HERD (High-Frequency Radiation Drain) filter is a new type of low-pass filter proposed by Rehammar, Robert, and Simone Gasparinetti. [1] based on a leaky coaxial waveguide. The filter has minimal insertion loss in the pass band, while at the same time high attenuation in the stop band is achieved.

The proposed design for HERD can be seen in Figure (2). The filter takes the form of a central copper conductor with a coaxial air dielectric, this is then surrounded by an outer conductor punctuated with a regular lattice of Hollow-Waveguide apertures. These apertures allow radiation of a high enough frequency to leak out.

The specifications and simulated attenuation of this proposed filter can be seen in Figure (3).

We will discuss what effect changing the properties of the filter has on the attenuation in a later section.

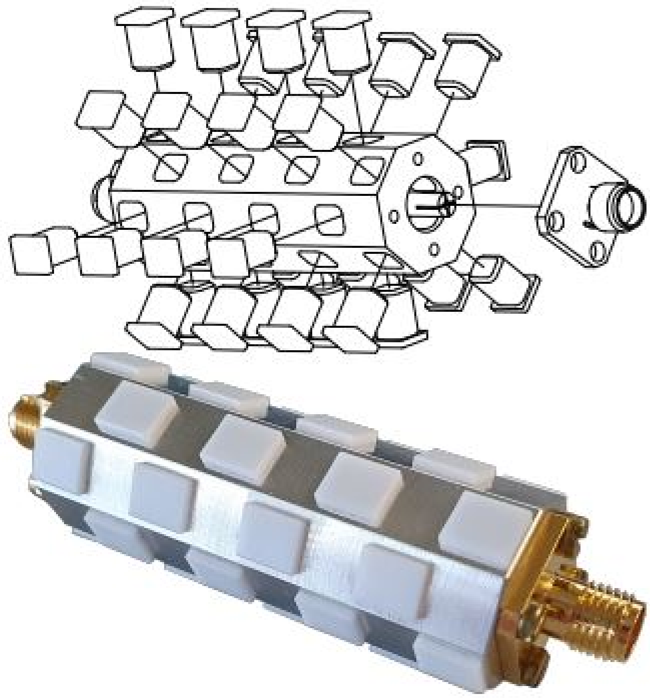
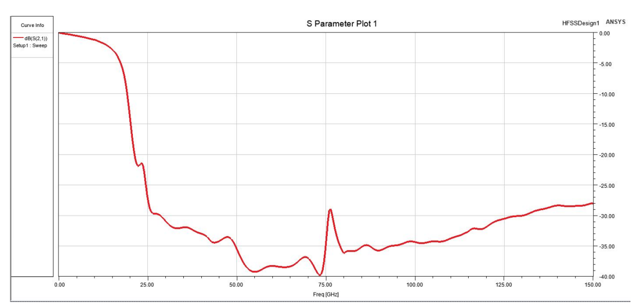


Figure 1.3: Herd Filter Design

Inner Radius – r_1	1.59mm
Outer Radius – r_0	3.65mm
Number of Sections - N	4
Aperture Depth - d	4.85mm
Aperture Shape	Rectangular
Aperture Dimensions - a , b	4mm x 5mm
Aperture Material	PTFE (Teflon)

(a) HERD Filter specifications



(b) Original HERD filter attenuation.

Figure 1.4

Chapter 2

Methods

2.1 Design of improved HERD Filter

There are a number of possible improvements to this proposed HERD filter that are worth considering. We will examine each property of the filter individually and then collaborate each of these properties in to a new filter design.

2.1.1 Coaxial Radii

For our design, the radii of the inner conductor and outer dielectric will be fixed by two constraints:

Firstly, we will match the inner conductor radius r_i to that of our transmission line $r_i = 0.66mm$ to avoid working with complex adaptors.

We then need to match the radius of the dielectric r_0 to that of the inner conductor to ensure the filter has an impedance of 50. Using eqn. (5.1) we find an outer radius of $r_0 = 1.519mm$

The size of these radii is important as it places restrictions on the possible sizes of our apertures, which determine the attenuation properties of our filter which we will see in a later section.

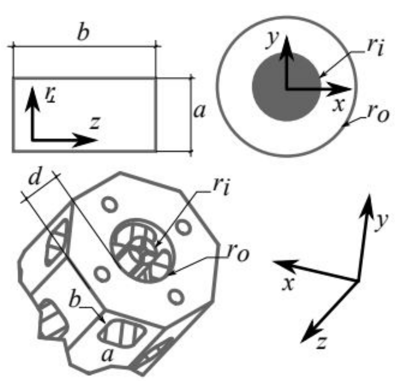


Figure 2.1: Herd Filter Dimensions

2.1.2 Number of Sections

A section is defined as a set of 2×4 hollow waveguide (HW) apertures placed tangentially on the faces of the filter. It is proposed in the source paper [1] that increasing the number sections will increase the performance of the filter at high frequencies. Fig 2.2 shows this analysis.

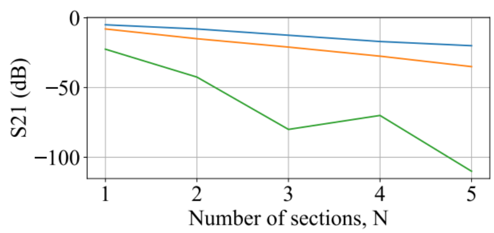


Figure 2.2: Simulated attenuation of HERD Filter at 60GHz for different number of sections.

Through a lot of experimentation I deduced that the sweet-spot was to have 5 sections as if you have 6 or more it means the size of the apertures has to be reduced which greatly deteriorates the performance of the filter, the relation between aperture size and attentuation is discussed in a later section.

2.1.3 Aperture Properties

The Hollow Waveguide apertures are the most important part of our filter design. They are the reason that high-frequency radiation is so heavily attenuated as they allow leakage of this radiation. Changing the properties of these apertures can change the attenuation properties of our filter in many, often-subtle ways.

It is important to keep the aperture depth sufficiently high, to ensure that our low-frequency (in-band) radiation does not tunnel through the apertures.For the frequencies below the cutoff point the field amplitude is attenuated as follows:

$$F(d) = e^{-\gamma d} \tag{2.1}$$

where λ is a frequency dependent decay function. Because of this relation I have kept close to the original aperture depth, even increasing it a bit to $d = 6.5mm$.

In this vein I have also tried to keep the aperture dimensions close to that of the original design, however due to the reduction in size of the filter and the increase in sections they needed to be slightly reduced. The cutoff frequency of the leaking apertures is set by the aperture cross-section and the dielectric constant of the material filling the cross-section. For a rectangular HW, the cutoff wavenumber is [10]:

$$k_{c,mn}^2 = \frac{1}{\varepsilon\mu}\left[\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2\right] \tag{2.2}$$

So as we can see the cutoff frequency has an inverse relationship with the size of the apertures. Due to our smaller apertures we will have a higher cutoff frequency than that of the original HERD filter. With dimensions $a \times b = 1.5mm \times 3.5mm$ (And filled with ECCOSORB CR-110) we find a cutoff frequency $\approx$ 12GHz. This should be suitable for our needs.

In the original design they used PTFE (Teflon) to fill the apertures. The attenuation properties of the filter are greatly affected by the dielectric constant ϵ of the substance which fills the apertures. Teflon has a value of $\epsilon = 2.2$. The propagation constant for the waveguides is:

$$\Gamma_{mn}^2 = k_{c,mn}^2 - k_0^2 \tag{2.3}$$

where we take $k_{c,mn}^2$ from Fig(2.2), and $k_0^2 = \omega^2 \varepsilon \mu$. From this we see that we would get higher attenuation using a substance with a higher dielectric constant, such as ECCOSORB CR-110 with $\epsilon = 4$

In the paper they propose that the use of Ridged Waveguides may improve the performance of the filter. I researched the optimum dimensions for double-ridged waveguides from Sun et. al [8] and incorporated them into my design, replacing the rectangular apertures.

It is also worth noting that in the paper they suggest that the even-spacing of the apertures may lead to worse performance of the filter due to possible resonance effects. I investigated this by irregularly spacing the apertures and I did not see any noticeable improvement in performance.

The final design can be seen modelled in ANSYS in Figure 2.2

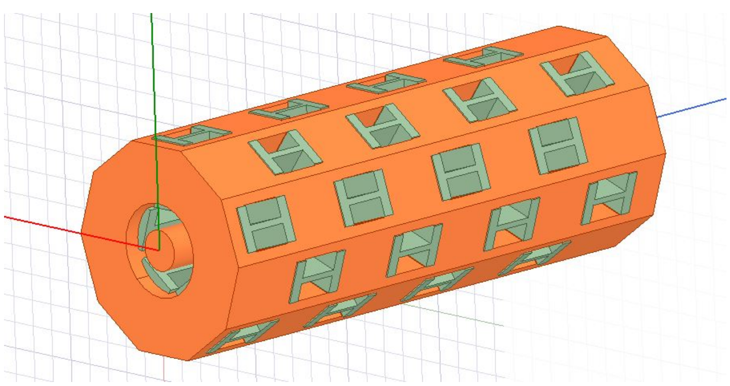


Figure 2.3: ANSYS Model of improved HERD Filter

2.2 Manufacture of HERD Filter

The first step for manufacture of our proposed filter was to develop the outer copper frame. This could be done relatively easily by making a model and dimensioned drawing on SOLIDWORKS and then sending it to a 3D printing specialist. These can be seen in Fig. 2.3
Note that two tapered holes were added to allow the filter to be mounted.

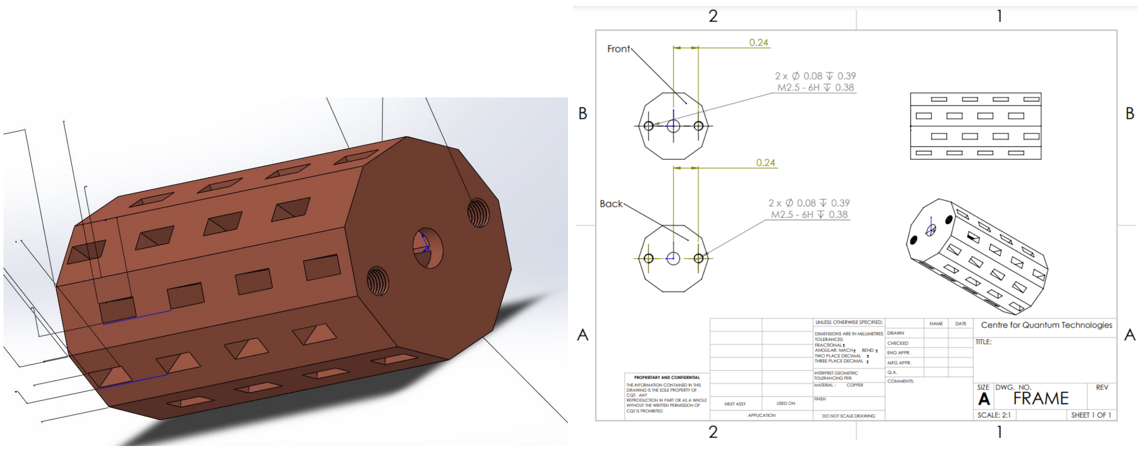


Figure 2.4: Solidworks design for 3D printing

Once we have the frame, the apertures needed to be filled with the Eccosorb CR-110 resin. The method for this will be inspired by Michael Fang (2015) [3].

I will follow these directions for the preparation of the ECCOSORB resin, however while in this paper the author injected the resin in to his filter, my idea is to prepare the ECCOSORB in a bath, cover the filter faces with airtight tape and submerge the filter in the resin. This will fill both the apertures and the central chamber with the resin.

This is the stage of the project I am working on currently. Over the next few days the ECCOSORB resin will be prepared and used to fill the apertures. The resin needs to be weighed out, mixed and heated to $> 70°C$ according to the chart in Figure 2.4.
The mixture needs to be put in to a vacuum chamber for a period of time for outgassing as any air in the mixture will lead to contamination.

After this is done, the central chamber will need to be re-drilled and the holes cut out to form the ridged-waveguides. A manufacturing specialist will be able to do this if a schematic is given to them.
The final step will be to mount the frame on to the brackets (Fig 2.5) with the conducting central

Recommended Frequency and Mixing Ratios by Weight

Series	Range (GHz)	Part X	Part Y
CR-110	26+	100	12.0
CR-112	12 - 18	100	8.2
CR-114	10 - 14	100	4.8
CR-116	6 - 12	100	3.0
CR-117	4 - 8	100	2.3
CR-124	5 and below	100	2.0

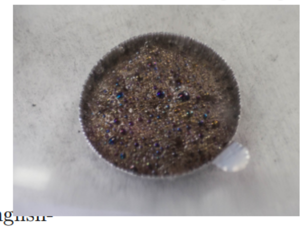
Use for high frequency filter   Use for low frequency filter

Recommended Cure Schedule

Temperature	Cure Time
165°F (74°C)	12 hours
200°F (93°C)	4 hours
250°F (121°C)	2 hours
300°F (149°C)	1 hour

(A) http://www.eccosorb.com/Collateral/Documents/English-US/CR.pdf

(B) Left: CR-110 Unmixed, Right: CR-110 Mixed, before out gassing



(C) CR-110 Out gassing in vacuum

Figure 2.5: ECCOSORB mixing and heating specifications

wire. I have ordered these brackets and they will need to be inserted in to either side of the frame and then soldered in the centre.The method for this will be tricky but I believe that heated solder can be placed on one bracket which is then mounted to the frame. The second bracket can then be carefully inserted until it joins with the first and this can be placed in an oven to allow the wires to fuse.

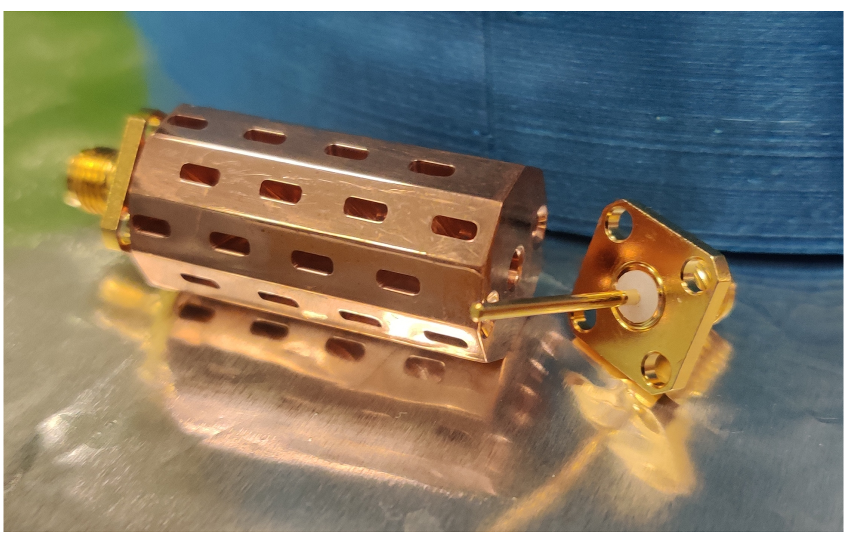


Figure 2.6: Manufactured filter with brackets

Chapter 3

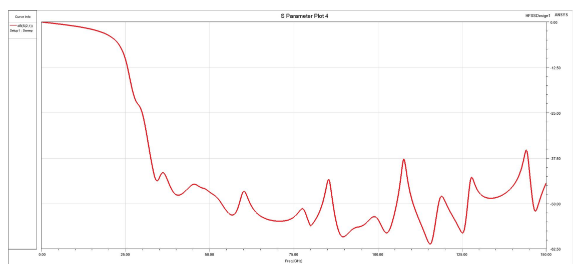
Results

3.1 Simulation of HERD Filter

Our improved HERD filter was simulated with ANSYS in the same manner as the previous filters and the attenuation observed can be seen in Figure 3.1

Inner Radius – r_1	0.66mm
Outer Radius – r_0	1.519mm
Number of Sections - N	5
Aperture Depth - d	6.55mm
Aperture Shape	Ridged Waveguides
Aperture Dimensions - a , b	1.5mm x 3.5mm
Aperture Material	ECCOSORB – CR110

(a) New HERD Filter specifications



(b) Filter Attenuation

Figure 3.1

We can see very low attenuation ($< 5dB$) at the low-frequency (in-band) range and very high attenuation ($> 40dB$) in the high-frequency range.
Previous ANSYS simulations have matched very closely with measured results so I am optimistic that this new filter design should perform similarly to the simulations.
The filter will be manufactured and tested within the next few weeks.

Chapter 4

Conclusions

In this paper, a new type of low-pass filter, named HERD, was presented in which coupling between a coaxial transmission line and apertures in the outer conductor is used to achieve attenuation above cutoff of the apertures. It was shown that a filter consisting of 5 sections and an outer radius $r_0 = 1.519$ mm of the coaxial transmission line can provide over 40 dB of attenuation above 70 GHz while at the same time providing very small insertion loss below 10 GHz.

This filter is currently being manufactured and it should be functional in the coming weeks. It is also worth noting that despite my extensive experimentation with the attenuation properties of the filter based on its specifications; it is entirely possible (even probable) that a better variant of this design exists.

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