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DIPLOMARBEIT

Titel der Diplomarbeit

„Die Güte von Mikrowellenfiltern aus Hochtemperatur-Supraleitern, hergestellt durch naßchemisches Ätzen oder maskierte Ionenbestrahlung“

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Abstract

Two and a half decades after the discovery of high temperature superconductors by Bednorz and Müller there are several applications like superconducting cables and superconducting coils for research magnets. The first widespread application of these materials in superconducting receiver front ends for wireless communication base station systems renews the interest in development and design of HTS superconducting film technology.

The presented work qualitatively compares superconducting microstrip resonators produced by conventional etching processes and masked ion beam direct structuring (MIBS). This novel method uses He^+ ions to create defects in high temperature superconducting films instead of the common etching procedure for HTS material. MIBS converts the irradiated parts of the film to non-superconducting areas whereas the protected ones stay intact concerning their superconducting properties. The resolution of the structuring process is only limited by the masking technique and nanostructuring has been successfully demonstrated with this method. While wet etching or ion milling are standard methods to achieve high temperature superconducting microstrip circuits, MIBS is a novel technique in macroscopic structuring of films.

The essential parameter for comparison of the etched and MIBS structured microstrip resonators is the quality factor of the resonance peaks. To obtain the quality factor of a particular filter structure in the superconducting state, the sample was immersed in liquid nitrogen while its response curve was measured using a vector network analyzer. The main result of this work is the finding that superconducting filters fabricated by MIBS had a slightly higher quality factor as compared to filters prepared by the conventional etching procedure.

Zusammenfassung

Zweieinhalb Jahrzehnte nach der Entdeckung der Hochtemperatursupraleiter durch Bednorz und Müller gibt es einige Anwendungen dieser Materialien wie supraleitende Kabel oder supraleitende Spulen für Forschungsmagnete mit hohem Magnetfeld. Die erste weit verbreitete Anwendung dieser Materialien, in supraleitenden Empfängern in Front-Ends für Basisstationen der Mobilfunknetzwerke, erneuert das Interesse an Entwicklung und Design von supraleitender Filmtechnologie.

Diese Arbeit vergleicht supraleitende Microstrip-Resonatoren welche durch konventionelles Ätzen oder durch „Masked Ion Beam direct Structuring“ (MIBS) hergestellt wurden. Dieses neuartige Verfahren verwendet Helium Ionen um Defekte in hochtemperatursupraleitenden Filmen hervorzurufen und kommt ohne das Ätzen des HTS Materials aus. MIBS zerstört die supraleitenden Eigenschaften der bestrahlten Teile des Films und belässt die Eigenschaften der vor Strahlung geschützten Teile intakt. Die Auflösung dieses Verfahrens ist im Wesentlichen nur von der verwendeten Maske abhängig und es konnte damit bereits erfolgreich Nanostrukturierung demonstriert werden. Während Ätzen oder „ion milling“ Standardverfahren beim Strukturieren von HTS Filmen sind, ist MIBS relativ neu um makroskopische Strukturen auf HTS Filmen zu realisieren.

Der Gütefaktor der geätzten und bestrahlten Resonatoren wird als hauptsächlicher Parameter zum Vergleich herangezogen. Um den Gütefaktor der Filter im supraleitenden Zustand zu erhalten, werden diese in ein Bad aus flüssigem Stickstoff getaucht und dort auf der Siedetemperatur desselben gehalten. Währenddessen wird die Antwortkurve mit einem Vektor Netzwerk Analysator aufgenommen. Das wichtigste Resultat dieser Arbeit ist die Erkenntnis, dass supraleitende Filter, die mit MIBS hergestellt wurden, einen etwas höheren Gütefaktor aufweisen als jene, die mit konventionellen

Ätzmethoden fabriziert wurden.

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1 Introduction

Superconductivity was discovered by the dutch physicist Heike Kamerlingh Onnes in 1911 [1]. Kamerlingh Onnes main field of research has been the liquefaction of gases like helium. During research on the properties of matter at very low temperatures using liquefied helium he discovered that the resistance of a mercury sample dropped sharply below the boiling point of helium at 4.2 K. The sample had no resistance at all below this temperature. In the subsequent years this behavior was observed in many metallic elements like niobium or lead. The critical temperature T_C of this metals is at 9.2 K for niobium or 7.2 K for lead which is still very low.

Perfect conductivity is not the only characteristic a superconductor exhibits. In 1933 Meissner and Ochsenfeld discovered that superconducting material also shows perfect diamagnetic behavior. Two years later F. and H. London developed a theory to describe superconductivity. They introduced the London penetration depth λ_L which describes the length of penetration of the static magnetic field in a superconductor. The London penetration depth and the critical temperature T_C characterized a superconductor in this theory. The simple theory of the London brothers was not enough to describe superconductivity in detail. Ginzburg and Landau developed a phenomenological theory using the wave function of the superconducting state. Bardeen, Cooper and Schrieffer (BCS) developed a microscopic theory. Later on Ginzburg-Landau-Theory was derived from BCS-Theory in a limit.

Applications of low temperature superconductors (LTS) such as superconducting magnets, used in magnetic resonance imaging, generators and motors were developed in the second half of the twentieth century.

In 1986 Bednorz and Müller discovered superconducting behavior of

$\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$, a ceramic compound [2]. Intensive research led to the discovery of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ by several groups. $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ has a critical temperature of 92 K and can be cooled using liquid nitrogen or mechanical cryocoolers instead of the much more expensive liquid helium. Materials with still higher critical temperature were found at the end of the 1980s by replacing the rare earth elements in the ceramic compound. Bismuth and thallium cuprates have a critical temperature of 110 K and 125 K, respectively. The highest critical temperatures of above 130 K were discovered in the Hg-Ba-Ca-Cu-O system [3]. Due to their high T_C the cuprates are called high temperature superconductors (HTS).

Exploring practicability of superconductors in microwave applications started in the 1950s. Resonant cavities with LTS inner surface coating were produced achieving quality factors between 10^{10} and 10^{11} [4]. Today, epitaxially grown low loss HTS films are available and in use in wireless and satellite communication. As the operation temperature of some satellites is below the critical temperature of $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ (TBCCO) this compound is commonly used. YBCO and TBCCO have similar characteristics at the typical operation temperature of HTS devices. As YBCO fabrication is more mature than TBCCO fabrication, YBCO technology is widely used in wireless communication industry. YBCO microstrip filters are commercially available for wireless service providers and there are thousands of superconducting receiver front end systems deployed all over the world. With their help wireless network operators are in the position to increase their coverage or capacity even in noisy RF areas like cities [5].

2 Theory

2.1 Microwave Filters

Microwaves cover a spectrum of 300 MHz to 300 GHz which corresponds to a vacuum wavelength of 1 m to 1 mm respectively [6]. Microwave filters are used for selection of small parts of the spectrum to prepare a signal for receiver electronics. For example mobile phones use frequencies around 1 GHz and 2 GHz. The corresponding half wavelength microwave filters realized in conventional microstrip technology have a typical size of around 10 cm.

Bandpass filters are required to let a specific set of frequencies pass and block all others. This set of frequencies is called bandwidth. The bandwidth is one of the most important characteristics of a filter along with the quality factor and the frequency response.

The passband bandwidth of a filter is $B = f_U - f_L$ where f_U is the upper cut off frequency and f_L is the lower cut-off frequency. Generally the frequency where the amplitude of the signal is reduced by 3 dB is defined as the cut off frequency.

There exist some very different possibilities to realize radio frequency filters. Microwave filters can be made of lumped elements, planar structures, cavities and other methods using dielectric resonators.

2.1.1 Quality Factor

In the ideal case of no loss at all a resonator does not lose energy due to damping at the resonance frequency and is able to sustain resonating end-

lessly. As there is unavoidable energy dissipation in every real resonating system there has to be a parameter to quantify this.

The quality factor is a very important characteristic of a filter. It describes the damping at the resonant frequency and is inverse proportional to the damping factor. A high quality factor indicates a sharp resonance peak in the transmission curve.

Figure 2.1 shows a resonance peak with the quantities needed to compute the Q factor in a measurement. The diagram shows the normalized impedance Z/Z_R over the frequency. In the case of impedance the quality factor is calculated from the full width at half maximum of the transmission curve at the resonance frequency. The quality factor is then calculated with the help of formula 2.1.

$$Q = \frac{f_R}{\Delta f} = \frac{f_R}{f_{HU} - f_{HL}} \quad (2.1)$$

If the response curve is measured in terms of power the full width half maximum matches the -3 dB bandwidth so formula 2.2 can be used.

$$Q = \frac{f_R}{\Delta f} = \frac{f_R}{f_{U(-3dB)} - f_{L(-3dB)}} \quad (2.2)$$

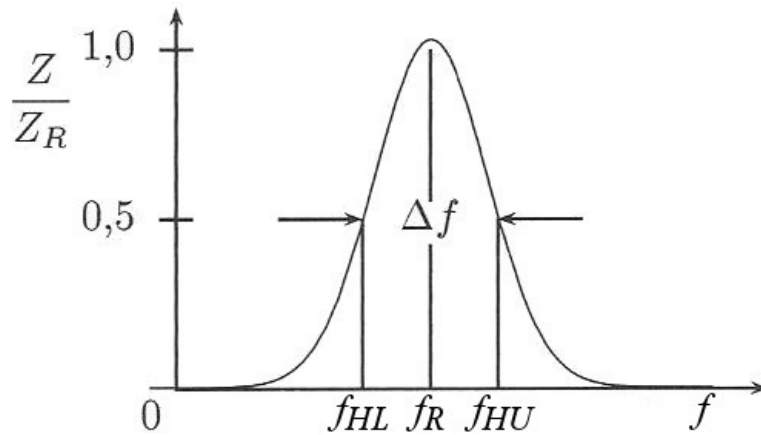


Figure 2.1: On the computation of the Q factor. After: [7]

2.1.2 Lumped Element LC filters

Lumped element filters consist of actual inductors and capacitors. These elements can be either surface mounted components that are built to form circuits on printed circuit boards or made of thin film printed on substrates forming spirals for inductors or gaps in the conducting material for capacitors. They are easy to build and often used for prototyping but they have their limits. The challenge lies in the manufacturing of these components. The higher the frequency is, the smaller the inductors become and at some point it is not possible to form proper coils. Lumped element surface mounted filters are usable up to around 12 GHz and thin film lumped element filters up to 100 GHz.

The simplest way to make a filter is with a so-called “LC element” consisting of an inductor and a capacitor. Picture 2.2 shows the equivalent circuit diagram of such a filter.

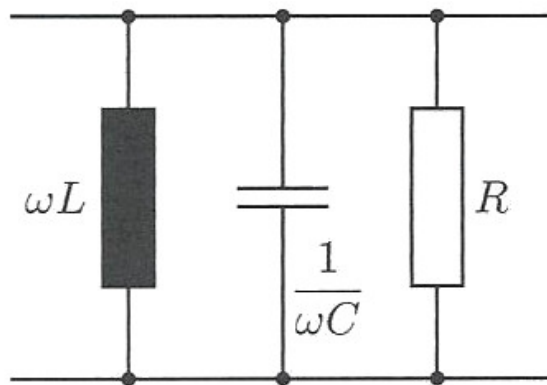


Figure 2.2: Lumped element filter equivalent circuit diagram. Source: [7]

2.1.3 Cavity filters

Cavity resonators basically are hollow spaces bounded by metallic walls. Every hollow conductor is a resonator for some mode of an electromagnetic wave. Due to the rather complex boundary conditions of an arbitrary space and the ease of production commonly used cavity filters are of circular or rectangular cross section. Aiming for highly symmetrical volumes is favorable for simulation calculations. Figure 2.3 shows the picture of a cavity filter with rectangular cross section. The function of the screws on top of

the cavity is to tune the resonance frequency to some extent.

Resonant modes of the electro magnetic field occurring in cavity filters are transverse. Transverse mode of propagation means that magnetic (TM), electric (TE) or both (TEM) field components are allowed perpendicular to the direction of propagation of the electro magnetic wave only. Due to this restriction and the boundary condition of the cavity walls, only transverse field distributions that fit inside the metal walls are admitted.



Figure 2.3: Rectangular waveguide bandpass filter. Source: [8]

2.1.4 Planar filters

Planar filters are made of striplines, coplanar waveguides or microstrips. They are geometrical structures made of the conducting material that acts as the waveguide. The simplest microstrip microwave filter is realized with dipole resonators. This filter consists of one or more half wavelength pieces of microstrip capacitively coupled at their ends to the rest of the circuit as shown in figure 2.4.



Figure 2.4: Microstrip end-coupled resonator filter. Source: [9]

Microstrip microwave filters with higher Q value, less damping and narrower bandwidth consist of several dipole resonators coupled in parallel

and with parallel feed lines. Figure 2.5 represents such a bandpass filter for telecommunications appliance. It has 2006 MHz center frequency and 1 % bandwidth. The cross area of the filter substrate is 38 mm $\times$ 30 mm. The transmission and reflection curve of this particular filter are shown in figure 2.6. The filter has been designed by [10].

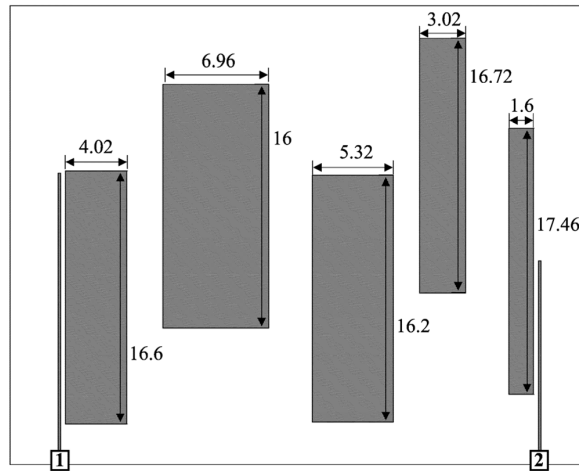


Figure 2.5: Microstrip parallel resonator filter. Dimensions are in mm.
Source: [10]

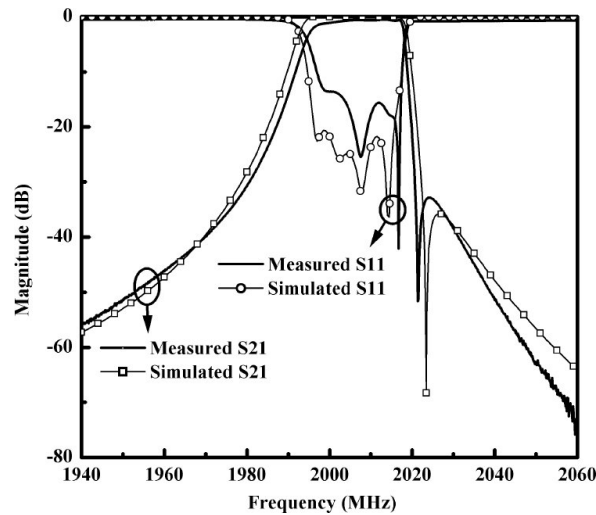


Figure 2.6: Simulated and measured frequency response. Source: [10]

To provide even higher performance, filters with more complex geometry were tested like hairpin or open-loop resonators.

2.2 Microstrip Line

A microstrip line is a transmission line where the ground plane is separated from the conducting structure by a dielectric substrate. Conventional microstrips use copper as metalization and an epoxy substrate such as FR-4, a standard material for printed circuit boards, as dielectric. For high frequency applications it is necessary to use low loss tangent materials like sapphire (Al_2O_3) or quartz.

The microstrip line is the most common transmission line used in microwave and RF engineering [11] due to its low production cost, low weight and simple manufacturing process. In principle the microstrip line is a printed conducting path on top of a substrate which has a metalization on the opposite side as shown in figure 2.7. The guided electromagnetic wave travels partly through the dielectric substrate and partly through the air above the microstrip line. Thus the medium in which the wave propagates is inhomogeneous. This inhomogeneity prevents a true transverse electromagnetic (TEM) wave to form. In TEM mode there is no electric or magnetic field component in the direction of propagation of the wave.

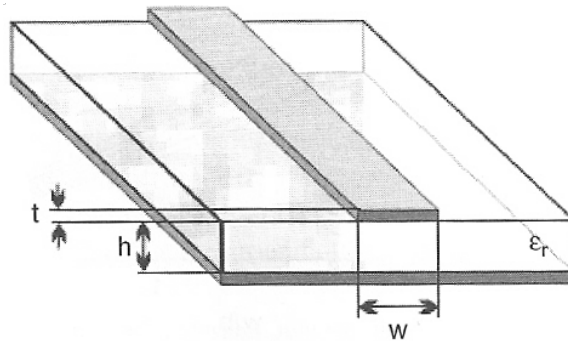


Figure 2.7: Microstrip line schematic. Source: [11]

Only in the limit of zero frequency there exists a true TEM mode for the microstrip line. As long as the wavelengths of the frequencies used, are much longer than the cross section of the conducting strip is wide, the propagation mode can be approximated by the static solution. Thus, the mode of propagation on a microstrip line is called *quasi*-TEM mode. The

electric field distribution for the static case is shown in figure 2.8.

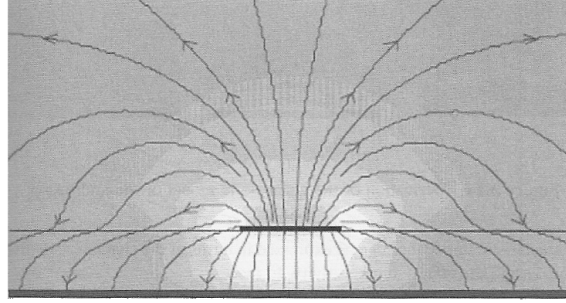


Figure 2.8: Microstrip electric field distribution. Source: [11]

Due to the frequency dispersion of real wave parameters the effective electric permittivity ε_{eff} has to be introduced. This term can be computed with the help of equations 2.4 or 2.6 and is kind of an average between the electric permittivity ε_r of the dielectric and of the air above the microstrip line which is set to the vacuum electric permittivity $\varepsilon = 1$. The effective electric permittivity varies between

$$\frac{\varepsilon_r + 1}{2} \leq \varepsilon_{eff} \leq \varepsilon_r \quad (2.3)$$

depending on the ratio $u = W/h$ of the width W of the conducting strip and the height h of the substrate. The characteristic impedance Z_0 of a microstrip line is given by its geometry and materials in use and depends on the ratio u as well. Optimal power transfer at the connection of the coax line to microstrip circuit occurs if the characteristic impedance matches the coax connector impedance. For calculations closed-form expressions for Z_0 and ε_{eff} are needed and have been reported by Harold Wheeler and summarized in [12]. If $u < 1$ the following equations are valid [13, 14].

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[\left(1 + 12 \frac{h}{W} \right)^{-1/2} + 0.04 \left(1 - \frac{W}{h} \right) \right] \quad (2.4)$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}} \log \left(8 \frac{h}{W} + 0.25 \frac{W}{h} \right) \Omega \quad (2.5)$$

If $u \geq 1$ equations 2.6 and 2.7 are valid [4].

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left(1 + 12 \frac{h}{W} \right)^{-1/2} \quad (2.6)$$

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}}} \times \left[\frac{W}{h} + 1.393 + \frac{2}{3} \log \left(\frac{h}{W} + 1.444 \right) \right] \Omega \quad (2.7)$$

The model of the microstrip line with a homogeneous dielectric surrounding the conductor as figure 2.9c shows, is capable of providing true TEM mode wave propagation. The configuration in figure 2.9b is also capable of providing true TEM and called suspended microstrip but it is technically difficult to realize this type of transmission lines.

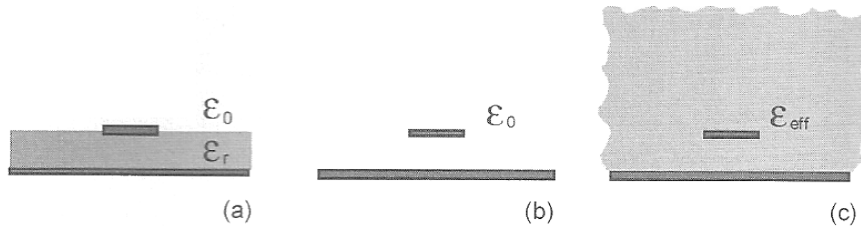


Figure 2.9: Graphical explanation of ε_{eff} . Source: [11]

Due to the effective permittivity the guided wavelength in the microstrip is shorter than the vacuum wavelength. Equation 2.8 shows the correlation between the guided and vacuum wavelength.

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \quad (2.8)$$

With λ_g corresponding to the guided wavelength and λ_0 corresponding to the vacuum wavelength respectively.

3 Simulation

This chapter is about the simulation of the response curve of the superconducting filter package.

3.1 Software

The applied simulation software is called *Sonnet Suites 13* by Sonnet Software Inc. ©. Sonnet Suite contains several pieces of software for designing and simulating 3-D planar structures (e.g. microstrip circuits). Sonnet was used to calculate the response curves and the current densities of the copper on FR-4 filter and the YBCO on alumina filter in the resonator box. The mathematical techniques Sonnet Suite uses were developed by Rautio and Harrington at Syracuse University [15, 16].

Sonnet Suite performs an electromagnetic analysis of a given geometry of planar conducting material in or on a dielectric using surface meshing and the method of moments. It takes several parameters into account like coupling, dielectric dispersion, loss and many more. Sonnet uses fast fourier transformations for the analysis of the planar circuits to be able to achieve results as fast as possible.

There are two approximations the software has to use. The first one involves the finite numerical precision every computer has to deal with and the second approximation arises from the subsectioning of the conducting material into finite elements.

Sonnet Suite uses a metal box as shielding of the circuit and solves the current distribution on the circuit material. The material is assumed to be of zero thickness. Figure 3.1 shows an example sketch of a simulation box.

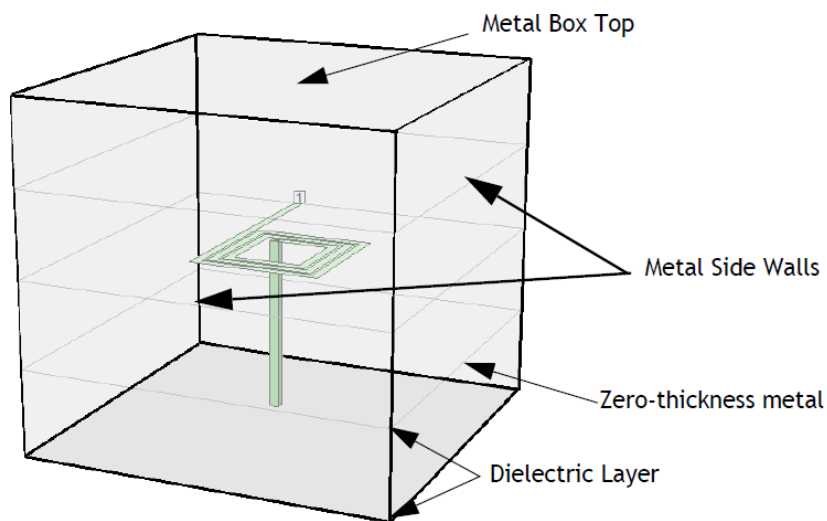


Figure 3.1: Example simulation box. Source: [17]

To be able to apply fast fourier transformations Sonnet Suite breaks the circuit into many small subsections. The biggest part of the occurring currents flows within the edges of the circuit material. This is the reason why Sonnet Suite creates more subsections at the circumference of the conductor geometry. After subsectioning the software firstly calculates the electric field and secondly the “coupling” between every pair of subsections [17].

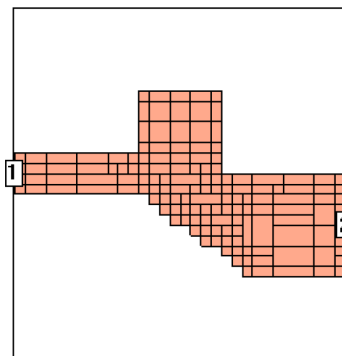


Figure 3.2: Example circuit for illustration how subsectioning works. Source: [17]

The tangential electric field on the surface of the circuit material generated by all subsections has to be zero if the material is lossless. Subsequently the boundary condition for method of moments is zero voltage across the conductor. To account for lossy material the boundary condition gets modified so that the tangential electric field becomes bigger than zero as there

are proportional currents in the circuit material. Ohm's Law connects voltage and current through resistivity. Thus the parameter we vary is the surface resistivity of the circuit material to introduce loss.

Once the currents in the circuit are calculated the scattering matrix components follow immediately.

3.2 YBCO on Alumina

The simulation of superconducting material is more challenging than simulating conventional metal. Superconductors interact in a slightly different way with electromagnetic fields than metals. Due to this reason the surface inductance L_s is introduced as a parameter of the simulation. The Alumina wafer had a thickness of 0.4 mm and the air volume above had the dimensions of $35\text{ mm} \times 10\text{ mm} \times 6\text{ mm}$. Figure 3.3 shows the simulation box of YBCO on alumina and figure 3.4 details the dimensions of the simulated YBCO microstrip resonator.

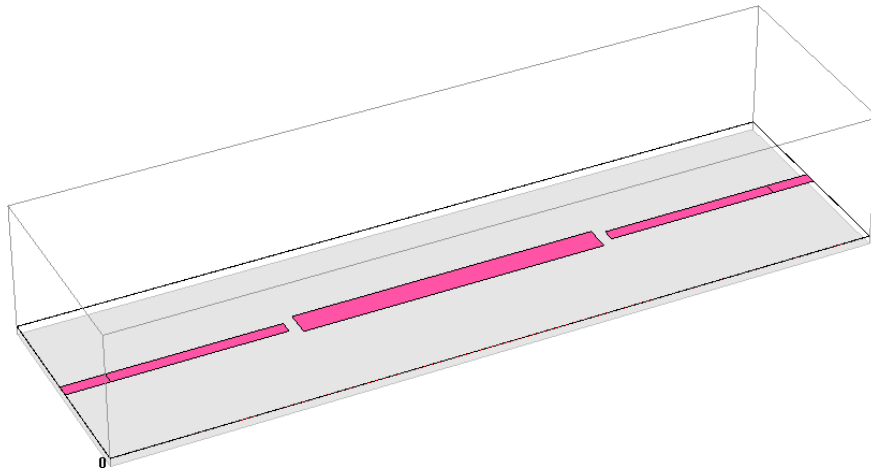


Figure 3.3: Sketch of the YBCO simulation box.

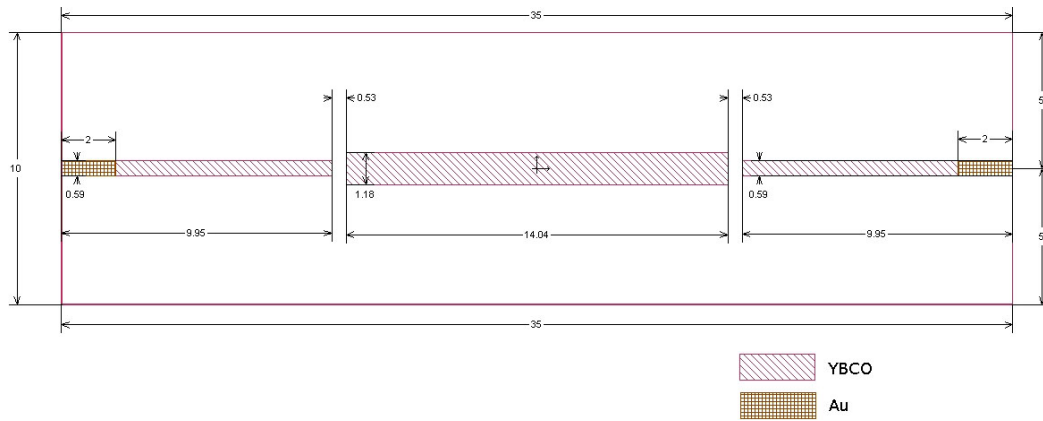


Figure 3.4: Dimensions in mm of the simulated YBCO filter.

3.2.1 Transmission Curve

Figure 3.5 shows the calculated transmission curve of the YBCO filter. The fundamental resonance of the YBCO filter is at 3.821 GHz, the second harmonic at 7.57 GHz. The quality factor is $Q = 2881$.

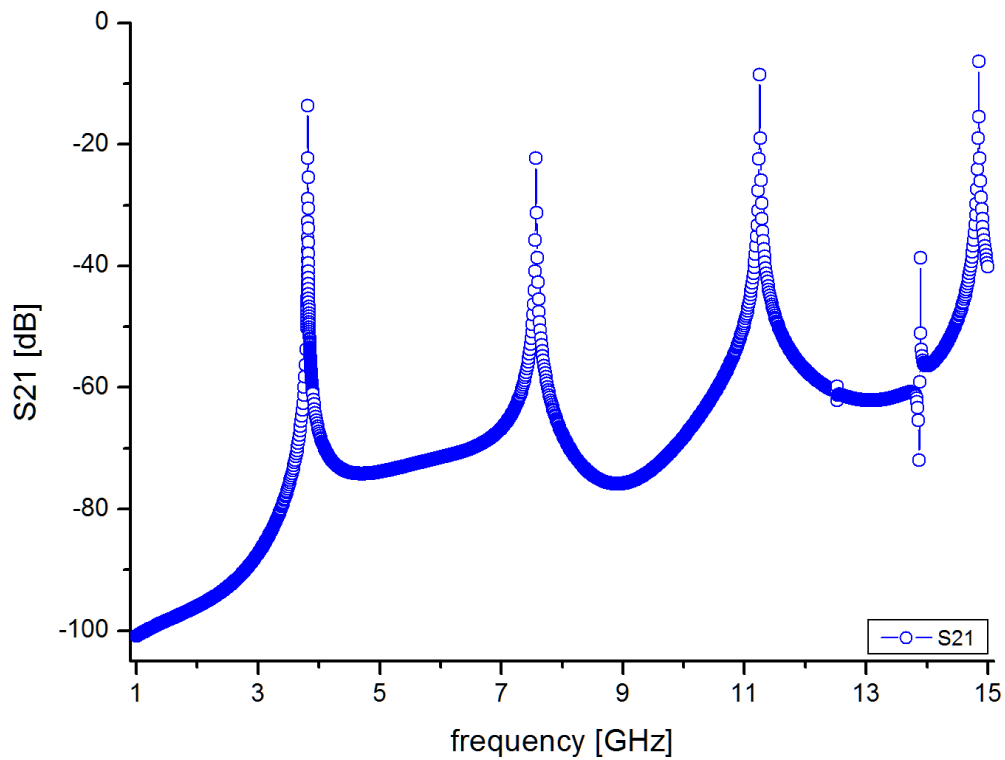


Figure 3.5: Simulated transmission curve for YBCO.

The parameters for YBCO filter simulation are:

Table 3.1: Simulation parameters of the YBCO filter

Parameter	Value
Thickness	340 nm
Conductivity	$\infty \Omega^{-1} \text{ m}^{-1}$
Surface Inductance L_s	1.4755 pH/sq
$\epsilon_{\text{Alumina}}$	9.9

3.2.2 Current Density

Figure 3.6 depicts the current density at 3.81 GHz. The current runs along a very narrow part of the long side of the dipole resonator at the resonance frequency. The oscillating electromagnetic field forms a standing half wave on the resonator. It is easily seen that the current density is highest in the middle of the long side of the resonator and does not spread over the entire surface.

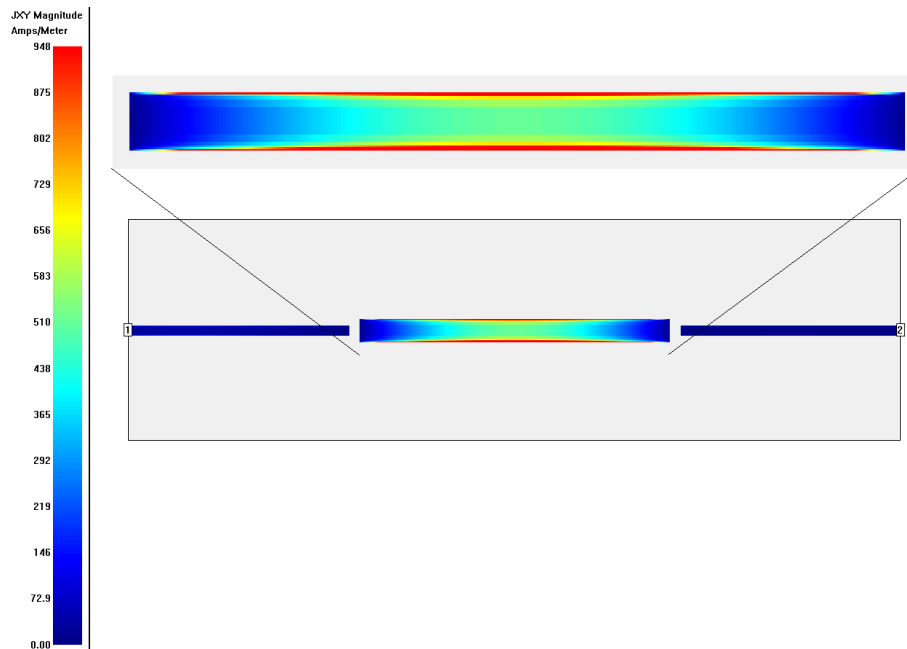


Figure 3.6: Simulated surface current density for a 14mm long YBCO dipole filter at 3.81 GHz.

3.3 Copper on FR-4

The simulated structure was originally designed by *Tesat-Spacecom* [18] and also realized for comparison in copper on FR-4 instead of YBCO on Al_2O_3 . The FR-4 substrate had a thickness of 1 mm and the volume of air above the substrate had dimensions of $35\text{ mm} \times 10\text{ mm} \times 5.4\text{ mm}$. After creating the structure in *Sonnet Suites 13* its transmission curve (see figure 3.11) and the current distribution were calculated.

A sketch of the simulated volume with the copper filter structure inside is shown in figure 3.7. The blue rectangles represent the metalization. Below this plane the substrate resides and the volume above is filled with air. The box walls are assumed to be grounded when simulating the response curve. The air volume above the metalization was of 5.4 mm height.

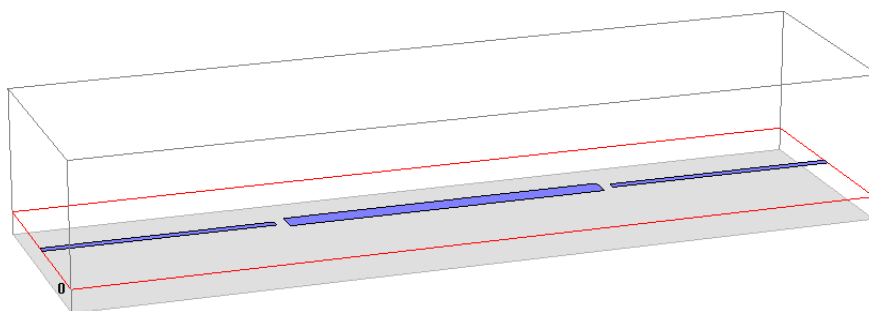


Figure 3.7: Sketch of the copper simulation box.

3.3.1 Finding a copper filter with 4.3 GHz resonance frequency

As can be seen from chapter 2 filter of same geometry but with different substrate materials resonate at different wavelengths. In reverse, changing the geometry on a given substrate, in the case of a single resonator this means varying the length of the dipole, should result in a different resonance frequency. Trying to find a copper filter with 4.3 GHz fundamental resonance frequency we used the formula $\lambda_g = \lambda_0 / \epsilon_{eff}$ to calculate dipole lengths that have 4.3 GHz resonance on FR-4 substrate.

With the aid of the formulas in chapter 2 and the measurement results of the 14 mm copper filter in chapter 6 the length of a dipole resonator

with 4.3 GHz resonance frequency has been derived. Since the exact ε_{eff} of the FR-4 substrate is not known, two features in the experimental curve of figure 6.1 could possibly attributed to the resonance frequency of the 14 mm resonator. Either a big notch at 6.84 GHz or the peak at 5.79 GHz in figure 6.1. Thus, two different resonator lengths were computed according to these two features:

Frequency [GHz]	Guided half wave length $\lambda_g/2$ [mm]
6.84 $\hat{=}$	22.36
5.79 $\hat{=}$	18.91

3.3.2 Transmission Curves

3.3.2.1 14 mm filter

The dimensions of the filter are displayed in figure 3.8.

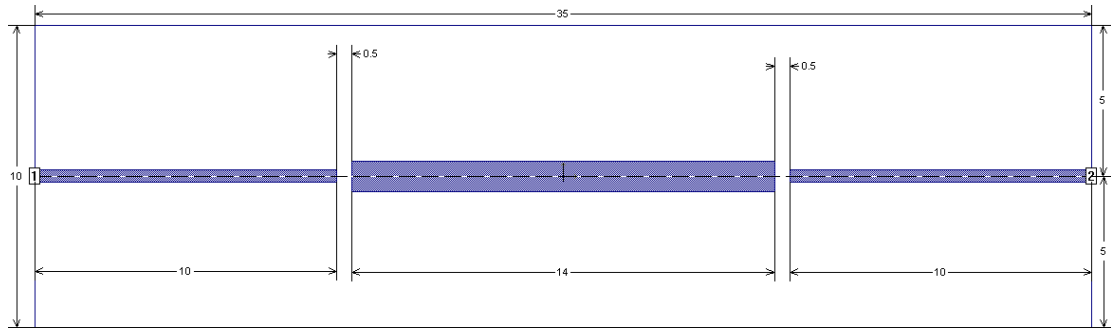


Figure 3.8: Dimensions of the 14 mm copper filter structure. All lengths in mm.

The red curve in figure 3.11 shows the simulated transmission parameter S_{21} of the copper filter with 14 mm dipole resonator. The fundamental resonance is located at 5.71 GHz and the second harmonic at 11.19 GHz. The simulation software warns about estimated cavity resonances of the box at 14.39 GHz. This possibly influences the frequency of the second harmonic and results in the lower dipole resonance frequency of 11.19 GHz instead of 11.42 GHz.

Relevant simulation parameters for all three of the copper filters are outlined in table 3.2.

3.3.2.2 18 mm filter

The dimensions of the 18 mm copper filter are slightly different to the dimensions of the 14 mm filter. The gap between the dipole resonator and the feed lines is 1 mm instead of 0.5 mm as shown in figure 3.9. The bigger gap causes weaker coupling of the dipole resonator to the feedlines. This in turn results in a lower transmission parameter S_{21} at the resonance frequency.

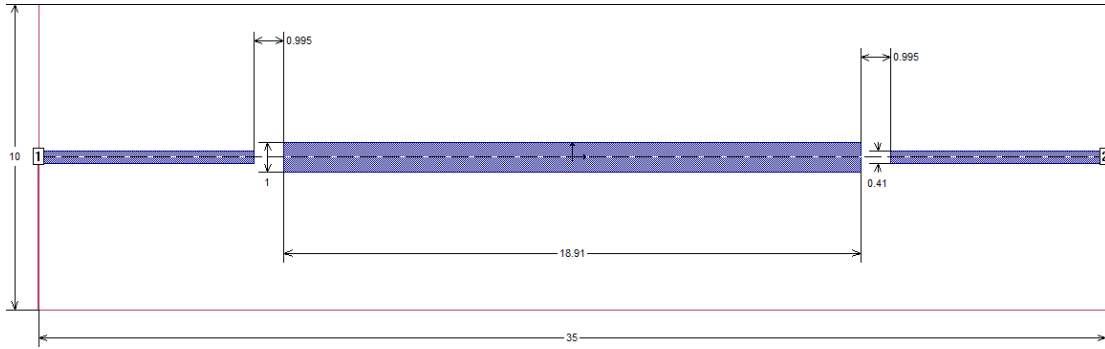


Figure 3.9: Dimensions of the 18 mm copper filter structure. All lengths in mm.

The corresponding transmission curve in figure 3.11 has a resonance peak at 4.3 GHz. This result will be used later to interpret the 5.79 GHz peak in the experimental transmission curve 6.1 of the 14 mm copper resonator and to distinguish between dipole-filter resonances and resonances of the metallic box.

3.3.2.3 22 mm filter

The dimensions of this copper filter are displayed in figure 3.10.

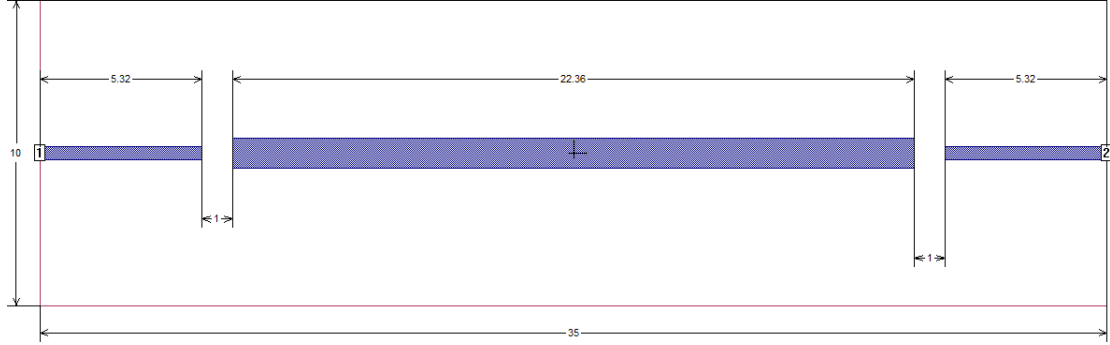


Figure 3.10: Dimensions of the 22 mm copper filter structure. All lengths in mm.

The frequency of the fundamental resonance of the 22 mm copper filter is about 3.67 GHz and confirms that a good estimate of the resonance frequency can be obtained by using the length of the dipole resonator as single parameter according to equation 2.8.

Table 3.2: Simulation parameter of the copper filters.

Parameter	Value
Metallization thickness	35 μm
Metallization conductivity	$5.8 \times 10^7 \Omega^{-1} \text{m}^{-1}$
ϵ_{FR-4}	4.4

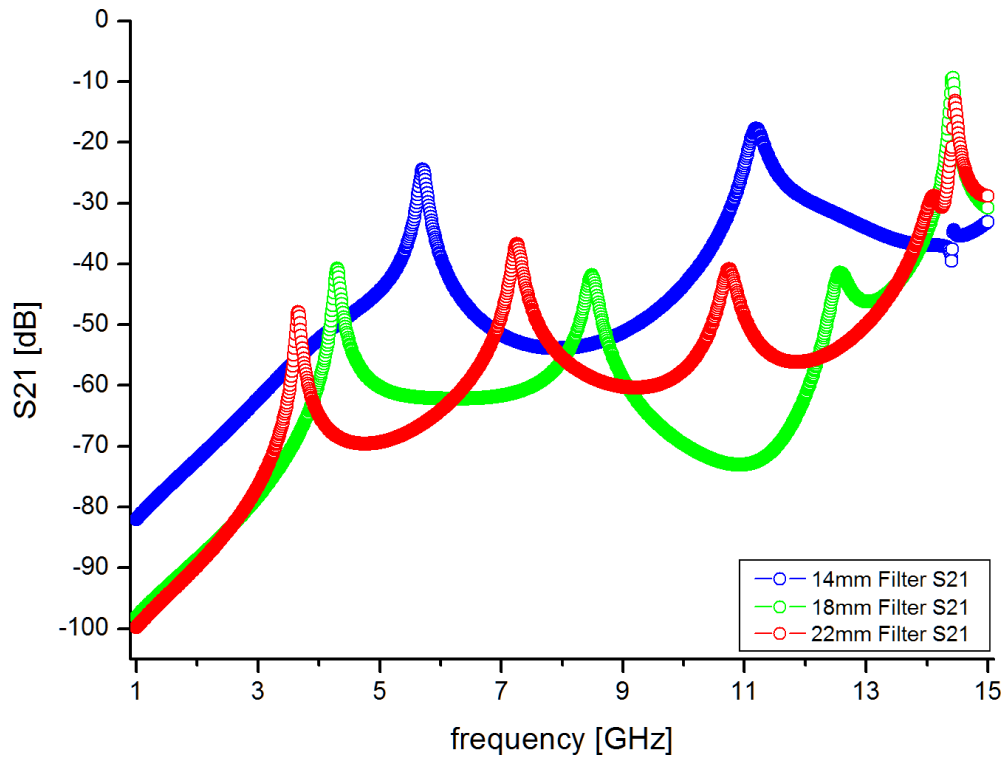


Figure 3.11: Simulated transmission curves for copper dipole-filter structures.

3.3.3 Current Density

The simulation software computes the surface current density in the metallization layer as well as the S-Matrix at every frequency displayed in the transmission curve. As figure 3.12 shows, at the resonance frequency the major amount of the current runs along the long edges of the resonator strip. Figure 3.12 represents the surface current density at the resonance frequency of 5.71 GHz in contrast to figure 3.13 where the surface current density at 2.2 GHz, for off the resonance, is displayed. At 2.2 GHz almost no power is coupled into the dipole resonator.

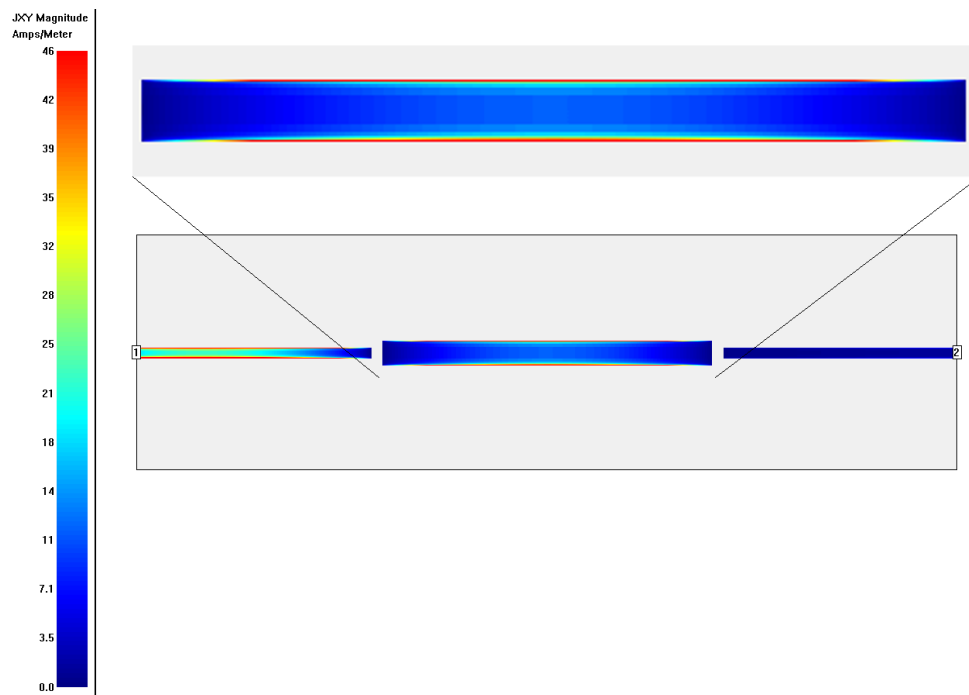


Figure 3.12: Simulated surface current density for the 14 mm copper structure at the resonance frequency of 5.71 GHz.

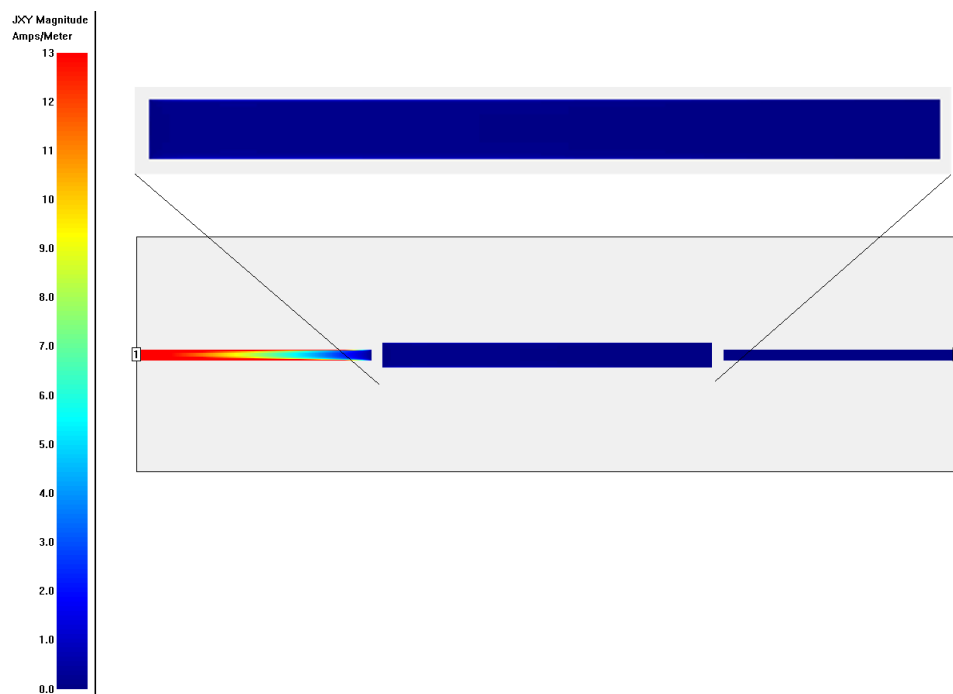


Figure 3.13: Simulated surface current density for 14 mm copper structure at 2.2 GHz, off the resonance frequency.

3.4 Calculated quality factors of the dipole filters

The quality factors Q of the different copper dipole structures and the YBCO resonator are shown in table 3.3. However, the values presented here have to be treated with caution. The simulation calculated the amplitude of the transmission parameter S_{21} with a step width of 1 MHz. This means that especially in the case of the YBCO filter the next data point in the response curve is well below -3 dB compared to the peak at the resonance frequency. The values of the upper f_U and lower frequency f_L used to compute the quality factor where, thus, obtained by screen reading of an interpolated line between data points acquired by the simulation.

Table 3.3: Quality factors of simulated filters (Dominant Mode)

Filter	Frequency [GHz]	Q
Simulation YBCO	3.821	6421
Simulation Cu 14 mm	5.710	48
Simulation Cu 18 mm	4.300	49
Simulation Cu 22 mm	3.660	49

4 Materials and Preparation

High temperature superconductors are a complex class of materials. The following chapter describes the material itself and the processes used to create our specimen.

4.1 $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$

Cuprates are oxides with copper planes. Many of them are superconducting with the highest transition temperatures known today. Most of the cuprates are relatively easy to fabricate starting from basic oxides. Cuprates like $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ can be produced as films, poly crystals or single crystals.

The crystal structure of copper oxides is called perovskite structure named after CaTiO_3 [19]. The general formula of perovskites is ABX_3 meaning that every B atom is surrounded by X atoms in form of an octahedron. This structure is shown in figure 4.1.

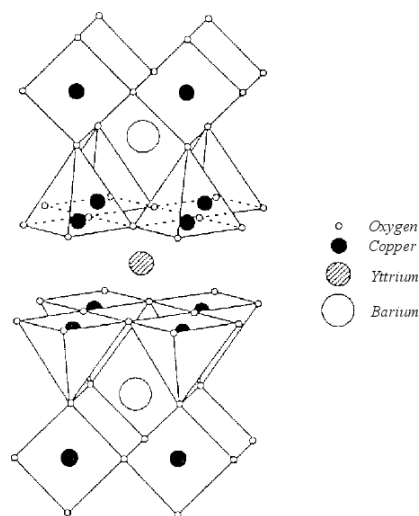


Figure 4.1: Perovskite structure. After: [20]

In $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ δ represents the reduction from the stoichiometric oxygen saturation value. $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ is often called by the first letters of the elements in the compound: YBCO. All cuprates have a layered structure where copper oxide planes and interlayers alternate. The interlayers in the case of YBCO are BaO and Y planes. To take a closer look at the crystal structure of YBCO, it is shown in figure 4.2.

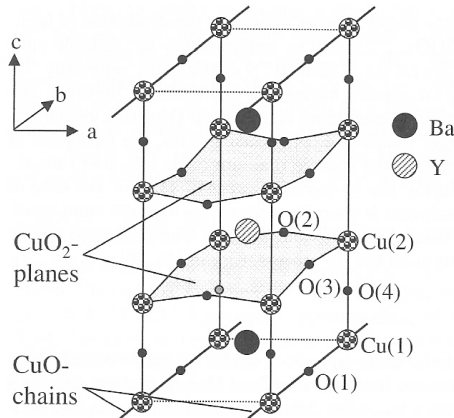


Figure 4.2: YBCO lattice. Source: [21, 22]

Two copper oxide planes are separated by yttrium planes and these CuO_2 planes are located close to each other, forming a CuO_2 bi-layer. Next to each copper ion four oxygen ions form a square and with the oxygen from the neighboring BaO planes the oxygen ions form a tetrahedron around the copper ion. Between the BaO planes there are planes of copper and oxygen forming chains oriented in the crystallographic b direction. Most HTS have a similar crystal structure.

The copper oxide chains are essential for the superconductivity of YBCO. They provide the charge carriers to the CuO_2 planes. These carriers form the superconducting pairs. For this process the oxygen content of the material is very important. YBCO has different properties in respect to its oxygen content. The parameter δ can be varied between 0 and 1. If δ is between 0.6 and 1 YBCO behaves as an antiferromagnetic insulator. For values of δ below 0.6 YBCO becomes superconducting below its transition temperature T_C . The lower δ , the higher is the amount of oxygen in the compound. The inserted oxygen fills the vacancies in the CuO chains in the interlayer between the BaO planes. A phase diagram is shown in figure 4.3

where the oxygen content is called x and corresponds to $x = 1 - \delta$.

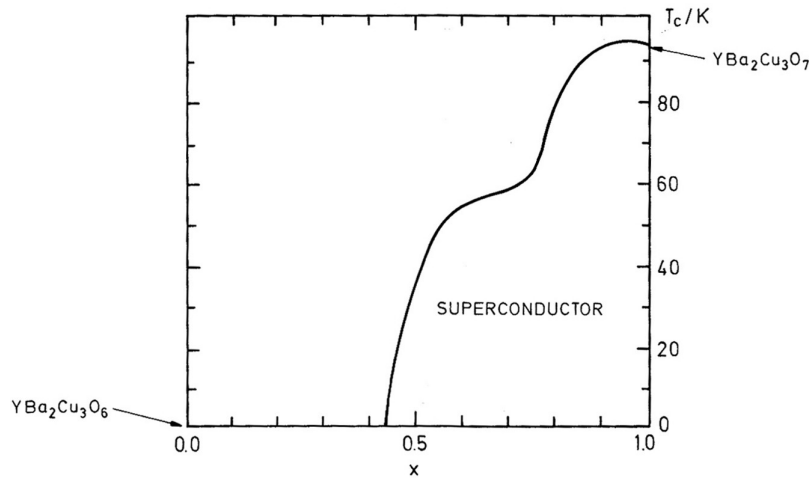


Figure 4.3: Electronic phase diagram of YBCO. Source: [23]

The variation of the oxygen concentration is called doping and can be achieved via heating of the sample in pure oxygen environment to increase the oxygen content or heating in argon environment to reduce the oxygen content. The introduced oxygen forms the CuO chains in the interlayer between the BaO planes and produces electron holes in the CuO₂ planes as it binds two electrons. With increasing oxygen concentration the characteristics of YBCO change from antiferromagnetic to conductor. It is seen in figure 4.3 that optimally doped YBCO has a transition temperature T_C of around 90 K and there exists a plateau between $\delta \approx 0.4$ and $\delta \approx 0.25$ where the critical temperature is about 60 K. The oxygen chains in this doping regime are partially ordered [24].

4.2 Substrates

Microstrip circuits can be produced on a large variety of substrates. Depending on the type of conductor material different substrates have to be chosen.

4.2.1 Substrates for copper

If copper is applied as the metalization, epoxy materials as FR-4 are commonly used. Circuits with these materials can be manufactured like any

other printed circuit board (PCB). Microstrip PCBs are cheap and easy in production, they are reliable and they benefit of their small size compared to coaxial waveguides. A disadvantage of these circuits is their relatively high loss compared to superconducting circuits [25, p7]. Table 4.1 summarizes a few characteristics of common substrates.

Table 4.1: Some characteristics of RT/Duroid 5880, Fused Quartz and FR-4. Source: [26, 27]

	RT/Duroid 5880	Fused Quartz	FR-4
ε	2.2	3.78	~ 4.4
Loss Tangent	0.001	0.0001	0.02
Dielectric strength [kV/mm]	11.8 (short term)	100	20
Mechanical strength	Moderate	Low	Moderate
Cost	Low	Moderate	Low

The differences between the so called soft substrates like Duroid and FR-4 and the hard substrates like fused quartz are not only their physical properties. It is possible to solder on packaged parts directly to the soft substrate whereas hard substrates are used in radio frequency integrated circuits (RFIC) where all the components are realized in microstrip. Furthermore hard substrate devices have to be wirebonded to the rest of the circuitry.

4.2.2 Substrates for YBCO

Suitable substrates for YBCO films are Magnesium Oxide (MgO), Lanthanum Aluminate (LaAlO_3) and Sapphire (Al_2O_3). These compounds have a similar atomic lattice to YBCO. Depending on the mechanical and electrical requirements one of them is chosen. Table 4.2 displays some of the characteristics of this three substrates.

Table 4.2: Some characteristics of MgO, SrTiO₃ and Al₂O₃. Source: [4]

	MgO	LaAlO ₃	Al ₂ O ₃
ε	9.6-10	23-25	9.4-11.6
Loss Tangent @ 77 K	10^{-5} - 10^{-6}	10^{-4} - 10^{-5}	10^{-5} - 10^{-8}
Mechanical strength	Low	Moderate	High
Anisotropy	Isotropic	Slightly Anisotropic	Anisotropic
Fragility	Low	High	Moderate
Surface Roughness	Low	High	Low

In our case sapphire (Al₂O₃) is used. Sapphire has a low loss tangent of $\tan \delta \leq 10^{-5}$ [21, p266] and if it is cut out in the correct orientation which is the so called “r-cut” [1-102] for YBCO the surface of the sapphire substrate shows minimal lattice mismatch to epitaxially grown YBCO films. In order to achieve high Q values the substrate material has to have a low loss tangent and the conductor material has to have low resistivity which is in the case of a superconductor approaching zero for not too high frequencies.

4.3 Etching

This method of preparing a superconducting microwave filter is similar to the method of producing conventional copper microstrip line filters and waveguides. Base material is an Al₂O₃ wafer covered with YBCO and gold coating on both sides instead of the epoxy coated with copper. The YBCO wafer was commercially fabricated by THEVA Dünnschichttechnik GmbH [28]. The preparation of the filter structure was performed at the Johannes Kepler University Linz by the group of J.D. Pedarnig.

Production of the specimen using this method involves the following steps:

- Cutting a piece of 35 mm × 10 mm off the 3” wafer
- Applying photoresist onto both sides

- Exposure through photomask on the top side
- Etching gold on top side to form contact pads for the feed lines
- Applying photoresist onto the YBCO
- Exposure through photomask on the top side
- Etching YBCO to pattern the dipole resonator and the feed lines

An adhesion-promoting agent manufactured by *Merck* is used to ease the application of the photoresist. On both sides of the wafer a photoresist S1818 (produced by *Shipley*) layer is applied, exposed on the top side, and then the whole specimen is immersed in diluted potassium iodide solution to remove the unwanted gold layer on the top side. The composition of the solution is shown in table 4.3. After this procedure another layer of photoresist is applied to the now accessible YBCO layer and developed through a photolithographic mask which has been printed on polymer foil. The subsequent standard wet etching of the YBCO layer has been carried out with standard parameters.

The etching process takes about 10 seconds for a 300 nm thick film at a temperature slightly higher than room temperature in diluted HCl (0.1 vol.%) [29]. After the etching treatment the specimen is rinsed with water and the remaining photoresist is dissolved using acetone. Finally the specimen is washed with isopropanol and dried using compressed air.

Table 4.3: Composition of the KI Solution for gold etching.

Component	
150 mL	water
16 g	potassium iodide
4 g	iodine

4.4 MIBS - Masked Ion Beam direct Structuring

As an alternative production method, Masked Ion Beam direct Structuring was used. Preparation and irradiation were performed by J.D. Pedarnig and his group at the Johannes Kepler University Linz [30].

- Cutting a piece of 35 mm × 10 mm off the 3" wafer
- Applying photoresist on both sides
- Exposure through photomask
- Etching gold to form a mask to protect the dipole resonator and feed lines from irradiation
- Irradiation with helium ions
- Removing the gold mask from the resonator and feed lines (after measurements of the sample resulting from the previous processing step)

With this method patterning of the YBCO film by etching off material is replaced by ion irradiation. Instead of structuring the gold and the YBCO film, only the gold layer has to be etched away. The applied photoresist S1813 (produced by Shipley) has a film thickness of 1.3 μm and the photolithographic mask has been printed on a polymer foil. After exposure of the photoresist the gold layer is etched with diluted potassium iodide solution. On top of the resonator and the feed lines the gold film and the photoresist stay intact. These two layers are then used as the mask for the ion irradiation as shown in figure 4.4.

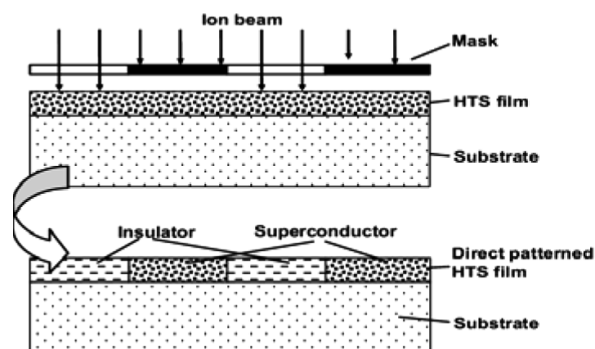
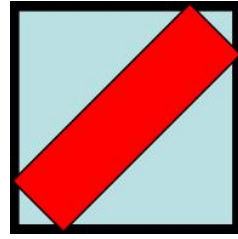


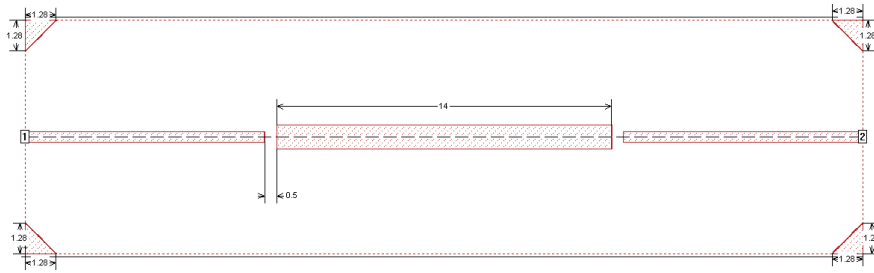
Figure 4.4: Principle of masked ion beam direct structuring. Source: [31]

4 Materials and Preparation

Due to the limited available area of exposure of $30\text{ mm} \times 30\text{ mm}$ in the ion implanter the specimen has to be mounted diagonally as shown in figure 4.5(a). The resulting geometry due to the available area and the irradiation mask of intact YBCO is displayed in figure 4.5(b). The YBCO at the corners of the wafer has to be manually scraped off in a separate processing step. To be able to irradiate the wafers with ions the feed lines have to be grounded via the gold layer on top of them.



(a)



(b) All dimensions in mm

Figure 4.5: Available irradiation area vs. size of specimen. After: [30]

SRIM/TRIM (Stopping and Range of Ions in Matter / Transport of Ions in Matter) [32] simulations have been done to evaluate the penetration depth of the helium ions used to destroy the superconducting properties of the YBCO layer. SRIM/TRIM is a Monte-Carlo method to calculate the collisions and the energy transfer of the irradiation ions to the target atoms on their path through the sample. SRIM/TRIM is a statistical method and requires only the composition, the density and thickness of the target materials, the kinetic energy of the incident ions and the total number of ions to perform the calculations.

One simulation has been carried out for the case of photoresist on gold on YBCO and another one has been done for the case of YBCO on sapphire. Figure 4.6 shows the simulation to determine if helium ions at 100 keV are

stopped by a 1.3 μm photoresist and 1 μm gold layer before they reach the YBCO layer. Table 4.4 summarizes the input parameter of the simulation.

Table 4.4: SRIM Parameter.

Helium Ion Energy = 100 keV, Number of ions = 1000

		PMMA-Au-YBCO	YBCO- Al_2O_3
	Density [g cm^{-2}]	Thickness [$\text{\AA}$]	Thickness [$\text{\AA}$]
PMMA	0.95 [32]	1300	
Au	19.311 [32]	1000	
YBCO	6.35 [33]	3400	3400
Al_2O_3	3.98 [32]		5000

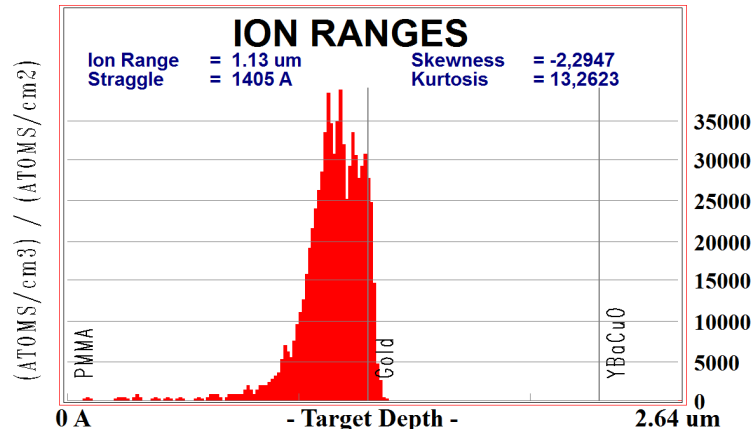


Figure 4.6: Ion range of He+ ions at 100 keV.

The simulation indicates that most of the helium ions are stopped in the photoresist and a few at the interface to the gold layer. Therefore the superconducting properties of the YBCO layer are not perturbed in areas where the gold layer has not been removed.

Having said this, it is important to take a look at the helium ion implantation in the YBCO layer when the gold layer on top has been removed. The helium ions have to penetrate the full thickness of the YBCO layer to provide full suppression of the superconducting properties. Figure 4.7 shows

that most of the ions reach a penetration depth of a few hundred nm inside the sapphire substrate and, thus, a majority penetrate through the YBCO layer

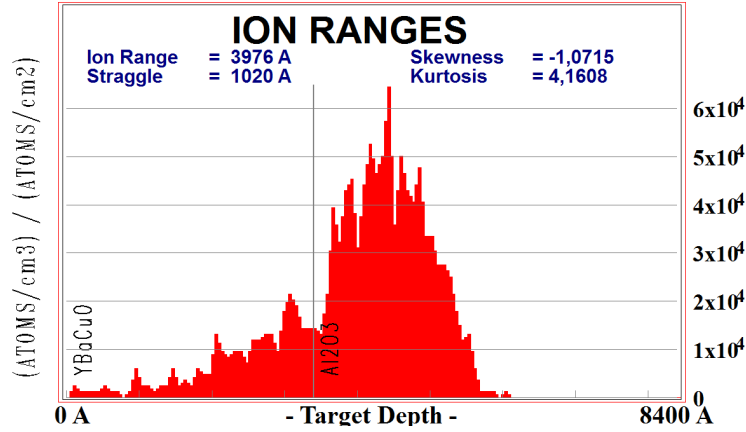


Figure 4.7: Ion range of He⁺ ions at 100 keV.

This leads to the expectation that superconductivity should be fully suppressed in the irradiated areas.

4.5 Samples

The filters were made of YBCO films on alumina substrate and copper on FR-4 glass epoxy laminate.

4.5.1 Copper on FR-4

All copper filters have been manufactured by Beta LAYOUT GmbH PCB-POOL© with standard technology for PCB processing. The thickness of the FR-4 laminate is 1 mm and the copper metalization has a thickness of 35 μm. The dimensions of the microstrip structure on the substrate and a picture are shown in figure 4.8 and 4.9 respectively.

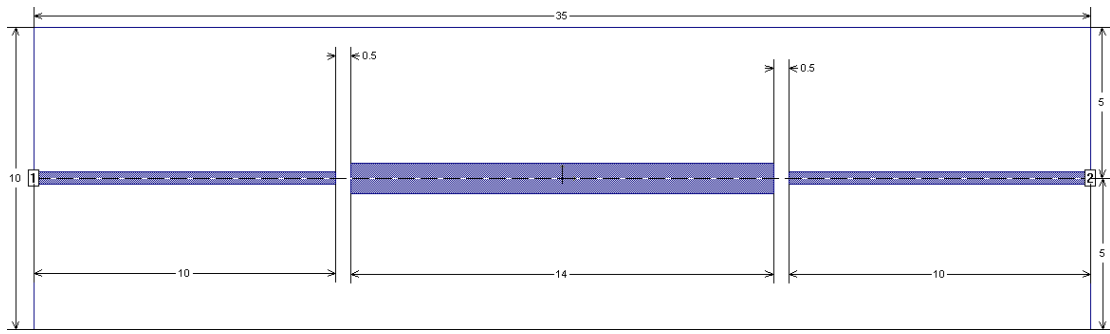


Figure 4.8: Dimensions in mm of the copper filter.

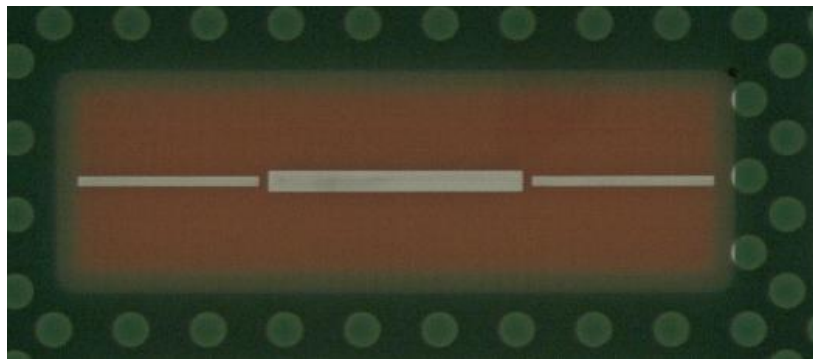


Figure 4.9: Picture of the copper filter.

4.5.2 YBCO on Alumina

All YBCO wafers were commercially produced by THEVA [28] and processed by the group of J.D. Pedarnig at the Institute of Applied Physics (Johannes Kepler University Linz). The wafers were “r-cut” [1-102] Al_2O_3 with a thickness of $d = 0.4 \text{ mm}$ and coated with a 340 nm YBCO film and 1 μm thick gold layer on both sides. The “bottom” side of the wafer did not experience any structuring whereas the “top” side was either etched or irradiated to achieve the intended microstrip dipole resonator. The design of the of the resonating structure and its feedlines has been supplied by Tesat-Spacecom GmbH & Co. KG [18].

4.5.2.1 Etched YBCO

The dimensions 4.10 and a picture 4.11 of the etched filter are shown below. To achieve a reasonable impedance match to the 50Ω SMA connectors

of the coax cables the feedlines have to be of the same width as the substrate thickness, if Al_2O_3 is used as a substrate. The following wet etching of the YBCO layer has been carried out to standard specifications [34].

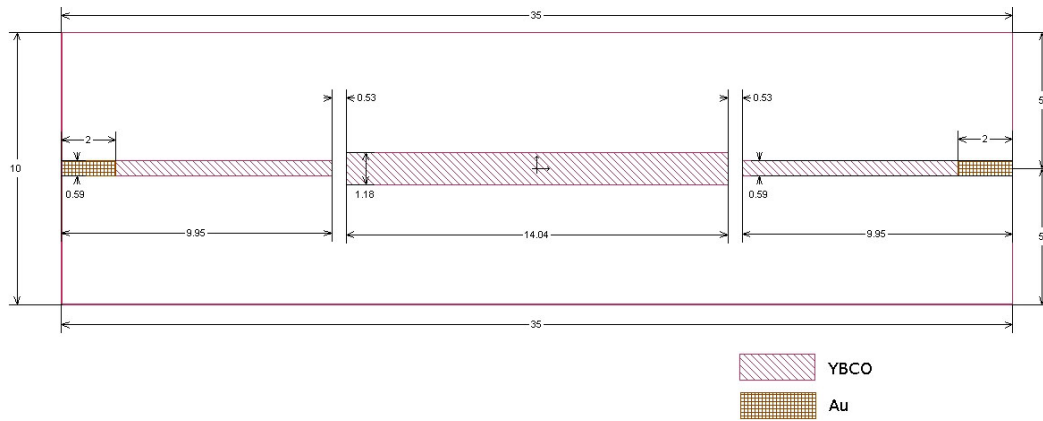


Figure 4.10: Dimensions in mm of the etched YBCO filter.

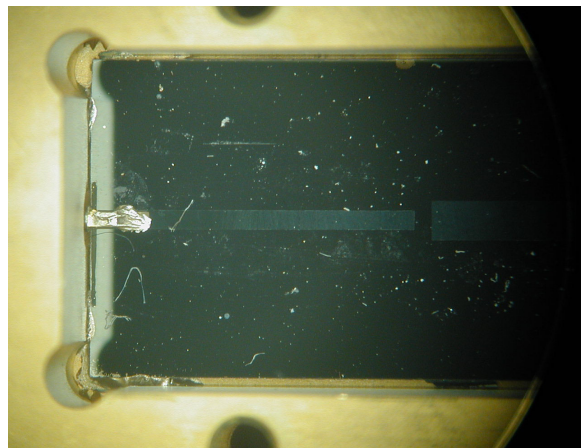


Figure 4.11: Picture of contact and feedline of the etched YBCO filter.

4.5.2.2 Irradiated YBCO

The irradiated specimen were exposed to helium ions with an energy of 100 keV. The photolithographic mask had a resonator stripline of 1.18 mm width and a gap between resonator and feedline of 0.52 mm. Due to some difficulties in the gold etching process and the limited irradiation area of the ion implanter some patches of the gold layer at the edges of the specimen had to be removed using abrasive paper.

Table 4.5 shows the parameters of the ion irradiation.

Table 4.5: Ion irradiation parameters.

Area of irradiation without mask	30 mm × 30 mm
Temperature	Room temperature
Incident Angle	0°
He ion energy	100 keV
Ion current	$\approx 0.7 - 1 \mu\text{A}$
Ion current density	$\approx 0.2 \mu\text{A cm}^{-2}$
Fluence	$1.5 \times 10^{16} \text{ cm}^{-2}$
Irradiation Time	400 min

The dimensions and a picture of the filter structure before irradiation are shown below in figure 4.12 and 4.13.

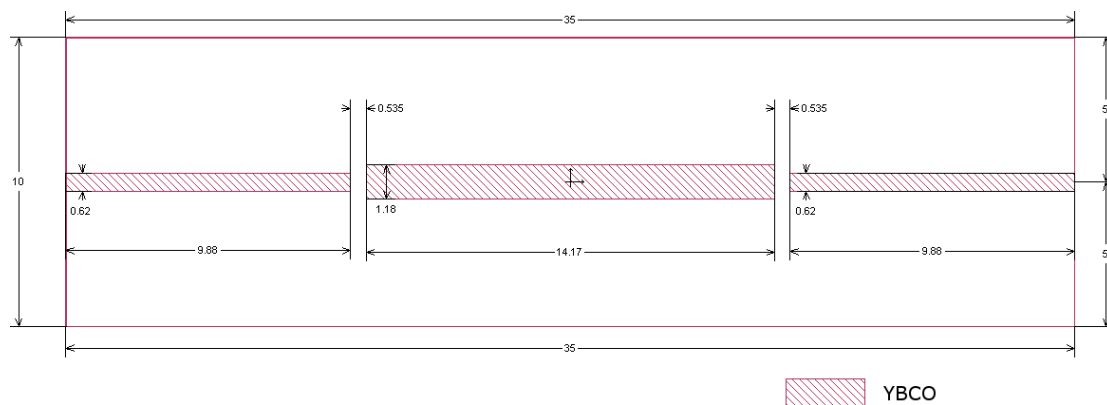


Figure 4.12: Dimensions in mm of the YBCO filter M1.



Figure 4.13: Picture of the YBCO filter M1 before irradiation.

After irradiation a black shiny coating of the gold parts has been observed. Picture 4.14 shows this coating. Most likely the coating was the remainder of the photoresist which got destroyed during the irradiation.

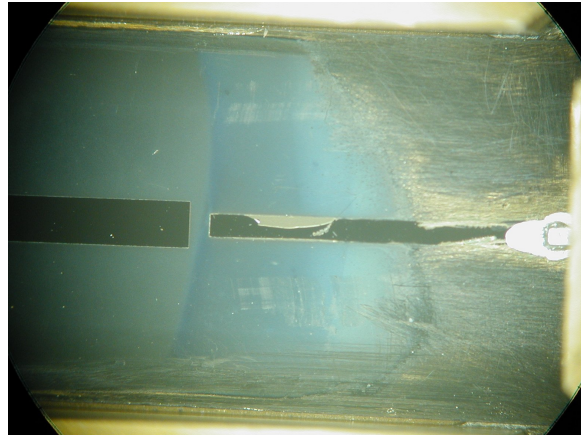


Figure 4.14: Picture of contact and feedline of the YBCO filter M1 after irradiation.

5 Experimental Setup

The experimental setup for the measurement of the transmission curves of the various dipole filters is described in this chapter.

5.1 Vector Network Analyzer

Network analyzers are commonly used in radio frequency measuring tasks. These instruments are designed to analyze networks efficiently and accurately. Network analyzers are the most complex and versatile measurement device in the radio frequency technology.

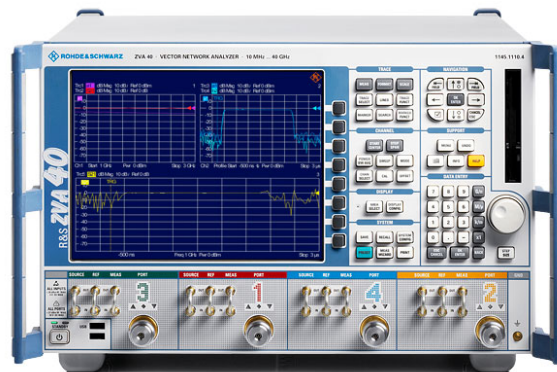


Figure 5.1: Vector Network Analyzer ZVA40. Source: Rhode & Schwarz ®

A network analyzer basically sends an electromagnetic wave to a device under test (DUT) and records the transmitted and reflected waves. Typical measurements are performed on so called two port networks. This means there is one input connector and one output connector. In a two port network there is possible reflection at each port and transmission from port 1 to port 2 and vice versa. The network analyzer measures the incident wave quantity a_n and the reflected wave quantity b_n as shown in figure 5.2, where a_n and b_n are represented by their amplitude and phase. The network ana-

lyzer then calculates the scattering matrix elements from these values.

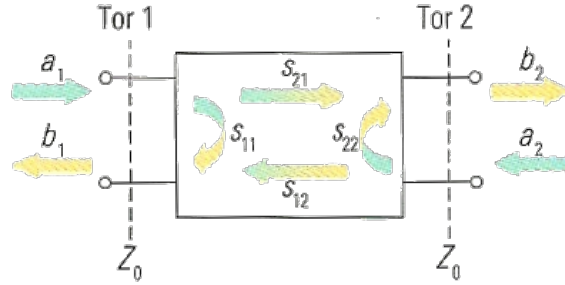


Figure 5.2: 2-port S-matrix wave scheme. Source: [35]

The scattering matrix **S** consists of the S-Parameters. These are the various ratios between the incident and reflected waves. In a forward measurement the wave quantities a_2 is forced to be equal to zero in order to get a reflection free port 2 as shown in figure 5.3 and to be able to measure the input reflection factor S_{11} and the forward transmission factor S_{21} .

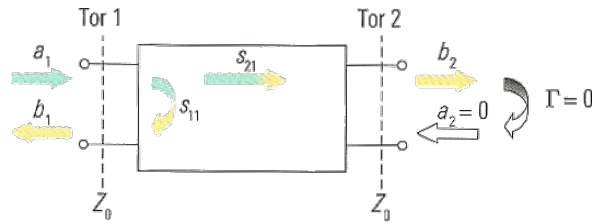


Figure 5.3: Forward measurement of the S-Parameters s_{11} and s_{21} . Source: [35]

S_{11} and S_{21} are calculated from the measured wave quantities as in equations 5.1.

$$S_{11} = \frac{b_1}{a_1} \bigg|_{a_2=0} ; S_{21} = \frac{b_2}{a_1} \bigg|_{a_2=0} \quad (5.1)$$

$$\mathbf{b} = \mathbf{S}\mathbf{a} \quad (5.2)$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad (5.3)$$

5.1.1 Measurement Bandwidth

The measurement bandwidth determines the signal to noise ratio. This means the lower the measurement bandwidth, the lower the broad band noise part of the signal. Typical values of the measurement bandwidth are 10 Hz, 100 Hz and 1 kHz. The trade off is the increase in measurement time needed. Reducing the measurement bandwidth by a factor of two results in doubled sweep time, but also better signal to noise ratio (see figure 5.4).

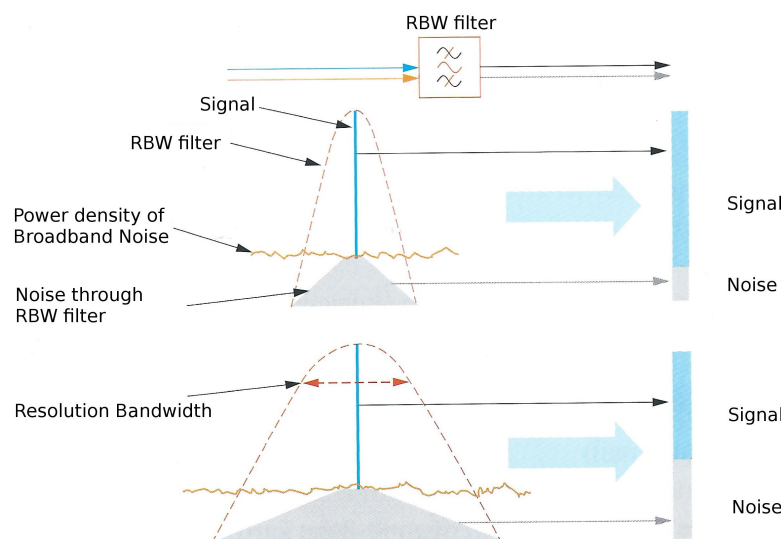


Figure 5.4: Measurement bandwidth. After: [35]

On the other hand, risk is always there to loose information because of an excessive bandwidth. The chosen bandwidth should be some magnitudes smaller than the typical operating frequency of the DUT.

5.2 Setup

The substrates with the filters were mounted in the box, shown in figure 5.8. As the FR-4 substrate of copper filters was 1 mm thick some of it had to be cut away to fit the inner conductor of the coax connector to

the microstrip feeding line because the box was designed for 0.4 mm substrates.

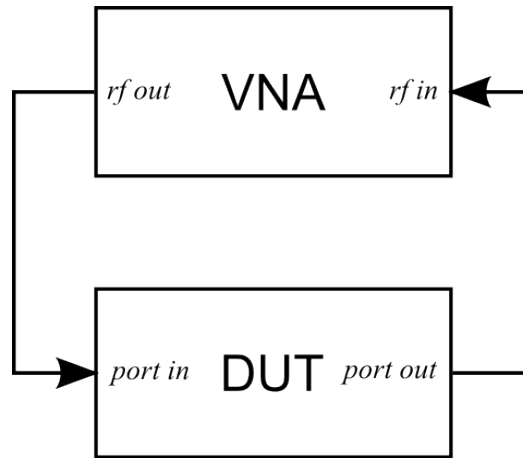


Figure 5.5: Setup.

5.3 Measurement Equipment

The response curves were measured with a *ZVA40 Rhode & Schwarz*® vector network analyzer in a two port setup. The resonator box was connected to the ZVA40 on ports 1 (rf out) and 2 (rf in) using two 50 Ω SMA coaxial cables suitable for radio frequency measurements up to 18 GHz. Figure 5.5 shows a schematic and a picture (figure 5.6) of the equipment.

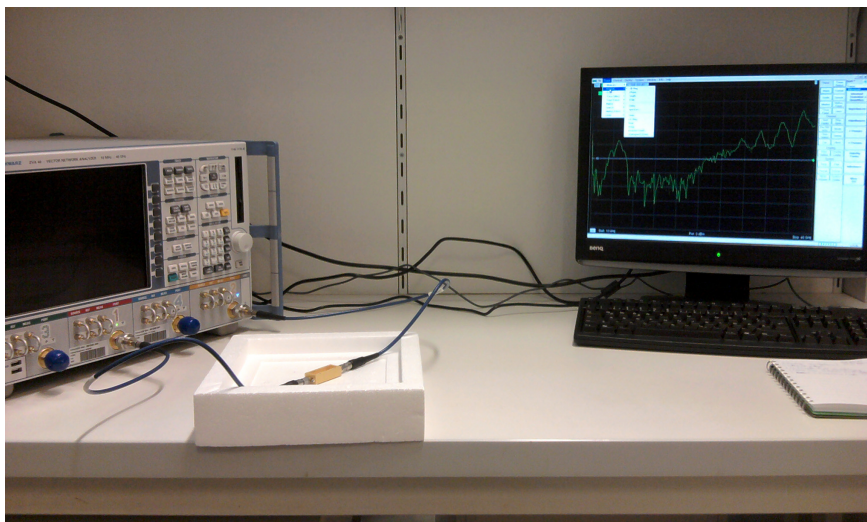


Figure 5.6: Picture of the measurement equipment.

Depending on the dielectric used in a coaxial cable it has different damping characteristics at different frequencies of electromagnetic waves. To study this property of the cables the transmission parameter S_{21} of the used cables connected via a coupler was measured. It is shown in figure 5.7. The measurement indicates that the cables introduce a damping of less than 1.5 dB in the range of interest. As most parts of the cables in the measurement setup were outside the liquid nitrogen the measurement was only done at room temperature.

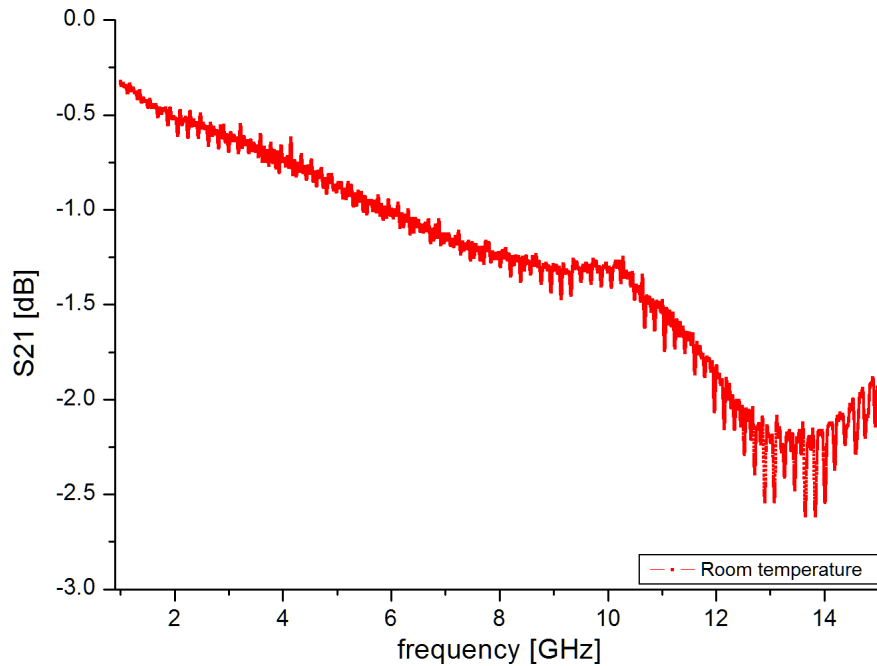


Figure 5.7: Damping of to coax cables.

Table 5.1: ZVA measurement parameters: cable damping.

Parameter	Value
Range	1 GHz-15 GHz
Number of Points	10 000
Measurement Bandwidth	1 kHz

Calibration of the vector network analyzer was impossible due to temperature restraints, while changing the standards. The standards would have

The resonator box was made of oxygen free high conductivity (OFHC) copper coated with gold. Figure 5.8 displays the inner dimensions of the resonator box. The samples were mounted on the little protrusion and fixated with silver paste. The coax connectors of the box were then connected to the top of the feedlines with silver paste as well.



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6 Results

The following chapter presents the transmission curves of the various specimen measured with the vector network analyzer. For the broad spectrum the network analyzer range was set from 1 GHz to 15 GHz.

The calculation of the quality factor has been done with data of narrower ranges to achieve a higher resolution around the superconducting resonance peaks. The range was then set from 3.75 GHz to 3.95 GHz for the dominant mode resonance and 7.55 GHz to 7.75 GHz for the second harmonic resonance.

6.1 Copper Filters

6.1.1 14 mm copper filter

Figure 6.1 shows the measured response curve of the 14 mm copper on FR-4 filter and table 6.1 represents the parameters for this measurement. There are two main peaks at 4.269 GHz and 5.956 GHz that could not be harmonics because of their frequencies. The third peak at 8.578 GHz and the forth peak at 11.589 GHz are the second harmonics of the 4.269 GHz resonance and the 5.956 GHz resonance respectively. The transmission parameter S_{21} is -26 dB at 4.269 GHz and -33 dB at 5.956 GHz in the cooled state.

The simulated and measured response of the 14 mm copper filter shown in figure 6.1 do not resemble each other very much. On the one hand the simulation only shows one resonance and its second harmonic whereas the measurement reveals another resonance at 4.269 GHz. Together with its second harmonic this second resonance is present in all measurements of all filters whether superconducting or normal conducting. At first sight

this resonance seems to be attributed to the filter box itself. This notion is supported by the fact that the inner length of the box, 35 mm, corresponds to $\lambda/2$ at 4.288 GHz with $\varepsilon = 1$. The question will be discussed in more detail in chapter 6.2.4 and 6.3. On the other hand the resonance frequency associated to the dipole resonator is slightly offset of about 0.25 GHz in the measurement to the simulation. This can be explained by the uncertainty of the dielectric constant of the substrate material FR-4.

Table 6.1: ZVA measurement parameters 14 mm copper filter

Parameter	Value
Range	1 GHz-15 GHz
Number of Points	10 000
Measurement Bandwidth	1 kHz

6.1.2 18 mm copper filter

Figure 6.2 shows the measured response curve of the 18 mm copper on FR-4 filter and table 6.2 represents the parameters for the measurement. At room temperature, the resonances of the dipole filter and the box almost coincide, only a slight shoulder at the resonance at the resonance frequency $f_R = 4.212$ GHz can be seen. On the other hand, cooling the filter box to 77 K and filling it with liquid nitrogen, results in a shift of the resonance frequencies, so that they can be clearly separated.

Table 6.2: ZVA measurement parameters 18 mm copper filter

Parameter	Value
Range	1 GHz-15 GHz
Number of Points	10 000
Measurement Bandwidth	1 kHz

6.1.3 22 mm copper filter

Figure 6.3 shows the measured response curve of the 22 mm copper on FR-4 filter and table 6.3 represents the parameters for the measurement. The dominant mode resonance frequency of the dipole filter is now at 3.859 GHz. Cooling the filter box moves the two resonances closer together.

Table 6.3: ZVA measurement parameters 22 mm copper filter

Parameter	Value
Range	1 GHz-15 GHz
Number of Points	10 000
Measurement Bandwidth	1 kHz

6.2 YBCO Filters

The transmission curves of the YBCO filters differ in a very important feature: They exhibit a resonance at the temperature of boiling nitrogen that does not exist at room temperature. This resonance peak corresponds to the superconducting state of YBCO at low temperature.

6.2.1 Etched Filter

The response curve of the etched sample is shown in figure 6.4. At room temperature, a resonance peak at 4.433 GHz together with its second and third harmonics dominate the transmission curve. As pointed out previously, it results from the resonance of the mounting box. The minimum attenuation at the peaks is about -60 dB.

In liquid nitrogen, however, the fundamental resonance of the box is shifted slightly to lower frequencies and the damping strongly reduced to about -20 dB due to the higher conductivity of the copper box.

The resonance of the YBCO dipole in the superconducting state shows up as a peak at 3.854 675 GHz with a quality factor of $Q = 5071$. The higher harmonics of this resonance are well visible and also have impressive quality factors. Table 6.4 displays the measurement parameters for the vector analyzer. The two point resistance of the etched filter was $> 20 \text{ M}\Omega$, thus, the feedlines were not electrically connected. All two point resistance measurements have been done with a METEX M-4650 multimeter and are accurate to at least $\pm 1\%$.

Table 6.4: ZVA measurement parameters YBCO filters

Parameter	Value
Range	1 GHz-15 GHz
Number of Points	10 000
Measurement Bandwidth	1 kHz

6.2.2 Irradiated Filter with Au

The production process of the irradiated YBCO filter allowed to measure the transmission curve of the not yet finished specimen with the additional gold layer on top. Across the ends of the feedlines the sample had a two point resistance of $3.3 \text{ M}\Omega$. The transmission curve is qualitatively similar to that of the etched filter in figure 6.4, but the maximum values of S_{21} at the resonance peaks are substantially lower.

6.2.3 Irradiated Filter without Au

Data of the YBCO filter M1 after removing the gold mask and its simulation are plotted in figure 6.6. The fully processed irradiated YBCO filter had a two point resistance of $10.2 \text{ M}\Omega$. It can be noted that the damping at the S_{21} peaks is very similar to the etched sample for fundamental and second harmonics, and even smaller for the third and forth harmonics. They are in good accordance with the calculations.

6.2.4 YBCO filter with indium

Most interestingly, all of the measurements have a resonance at about 4.269 GHz. This resonance is independent of the resonances of the dipole resonator. The resonance frequencies of the dipole resonators were calculated with the help of the formula $\lambda_g = \lambda_0 / \sqrt{\epsilon_{eff}}$ and found to be in good agreement with the measurements. As all of the filter regardless of which substrate was used had the same resonance in their transmission it seemed likely that the resonance is connected to some common feature of the experimental setup.

Essentially, the experiment contains two elements of the proper length scale: (1) the inner space of the filter box and (2) the (super)conducting backplane of the substrate.

Three different situations were tested. First, as in the other experiments, indium was only applied onto the protrusions of the filter box, where the wafer was fixated. Secondly a square was formed at the inside of the box bottom to electrically connect the backplane to the bottom of the filter box. Finally a spiral of indium conductor was placed between the backplane and the box bottom to maximize electrical contact. Figure 6.2.4 shows the measured transmissions of these three cases.

Results of these measurements, especially figure 6.7(c) where the 4.269 GHz resonance is totally gone, suggest that this resonance is connected to the backplane and is independent of the peaks due to the dipole resonance of the filter structures.

6.3 Copper filters without backplane

To proof the proposed connection between the resonance at around 4.3 GHz and the backplane of the filter structures the backplanes of the copper filters were removed and the transmission parameter then measured again. Figure 6.8 shows the transmission curves of the three resonators. The shift in the resonance frequency can be explained with bigger volume of dielectric between the guiding microstripline and the “new” backplane which is

the bottom of the resonator box in the absence of a metalization layer on the backside of the substrate. The added volume of air reduces the effective dielectric permittivity ε_{eff} in the transmission line equations as air and FR-4 have to be seen as a compound substrate. When ε_{eff} is reduced the vacuum wavelength is decreased and thus the resonance frequency is increased corresponding to:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \quad (6.1)$$

Evidently, the measurements do not find a resonance near 4.3 GHz in this configuration, confirming the above proposition.

6.4 Quality Factor

To calculate the quality factor Q the region around the superconducting peaks was measured with high resolution using the sweep parameters shown in tables 6.5 and 6.6. The measured transmission curves of the first and second harmonic of YBCO filters are displayed in figure 6.9 and 6.10, respectively. The quality factors of the copper filters have been calculated with data of the measurements in chapter 6.1.

As the transmission S_{21} is given in dB the quality factor was calculated with

$$Q = \frac{f_R}{f_{U(-3dB)} - f_{L(-3dB)}} \quad (6.2)$$

The values of the quality factor Q , the resonance frequency f_R , the upper frequency at f_U and the lower frequency f_L for the tested filters are summarized in tables 6.7 to 6.12. All data are collected at the temperature of the boiling point of liquid nitrogen.

Table 6.5: ZVA measurement parameters YBCO first harmonic

Parameter	Value
Range	3.75 GHz-3.95 GHz
Number of Points	10 000
Measurement Bandwidth	1 kHz

Table 6.6: ZVA measurement parameters YBCO second harmonic

Parameter	Value
Range	7.55 GHz-7.75 GHz
Number of Points	10 000
Measurement Bandwidth	1 kHz

Table 6.7: Quality factor of 14 mm copper filter

	Measurement	Simulation
f_R	5.956 GHz	5.71 GHz
S_{21} @ f_R	-33.2 dB	-24.4 dB
f_U	5.972 GHz	5.767 510 GHz
f_L	5.941 GHz	5.647 347 GHz
Q	193	48

Table 6.8: Quality factor of 18 mm copper filter

	Measurement	Simulation
f_R	4.510 GHz	4.30 GHz
S_{21} @ f_R	-32.2 dB	-40.8 dB
f_U	4.521 GHz	4.346 495 GHz
f_L	4.498 GHz	4.259 074 GHz
Q	189	49

Table 6.9: Quality factor of 22 mm copper filter

	Measurement	Simulation
f_R	3.859 GHz	3.66 GHz
S_{21} @ f_R	-40 dB	-47.9 dB
f_U	3.870 GHz	3.700 865 GHz
f_L	3.851 GHz	3.625 680 GHz
Q	197	49

Table 6.10: Quality factor of etched YBCO filter

Etched YBCO	
f_R	3.854 675 GHz
S_{21} @ f_R	−15 dB
f_U	3.855 066 GHz
f_L	3.854 305 GHz
Q	5071
f_R	7.628 753 GHz
S_{21} @ f_R	−18.2 dB
f_U	7.630 013 GHz
f_L	7.627 513 GHz
Q	3051

Table 6.11: Quality factor of YBCO filter M1 with gold.

M1 YBCO with gold	
f_R	3.804 905 GHz
S_{21} @ f_R	−23.6 dB
f_U	3.805 866 GHz
f_L	3.804 025 GHz
Q	2068
f_R	7.531 623 GHz
S_{21} @ f_R	−31.5 dB
f_U	7.534 584 GHz
f_L	7.528 903 GHz
Q	1326

Table 6.12: Quality factor of YBCO filter M1 without gold.

M1 YBCO without gold	
f_R	3.803 945 GHz
S_{21} @ f_R	−16.6 dB
f_U	3.804 305 GHz
f_L	3.803 625 GHz
Q	5595
f_R	7.529 703 GHz
S_{21} @ f_R	−23.6 dB
f_U	7.530 803 GHz
f_L	7.528 543 GHz
Q	3331

Table 6.13: Quality factor of simulated YBCO filter.

Simulated YBCO	
f_R	3.821 GHz
S_{21} @ f_R	−13.6 dB
f_U	3.821 245 GHz
f_L	3.820 650 GHz
Q	6421
f_R	7.570 GHz
S_{21} @ f_R	−22.3 dB
f_U	7.573 342 GHz
f_L	7.567 758 GHz
Q	1356

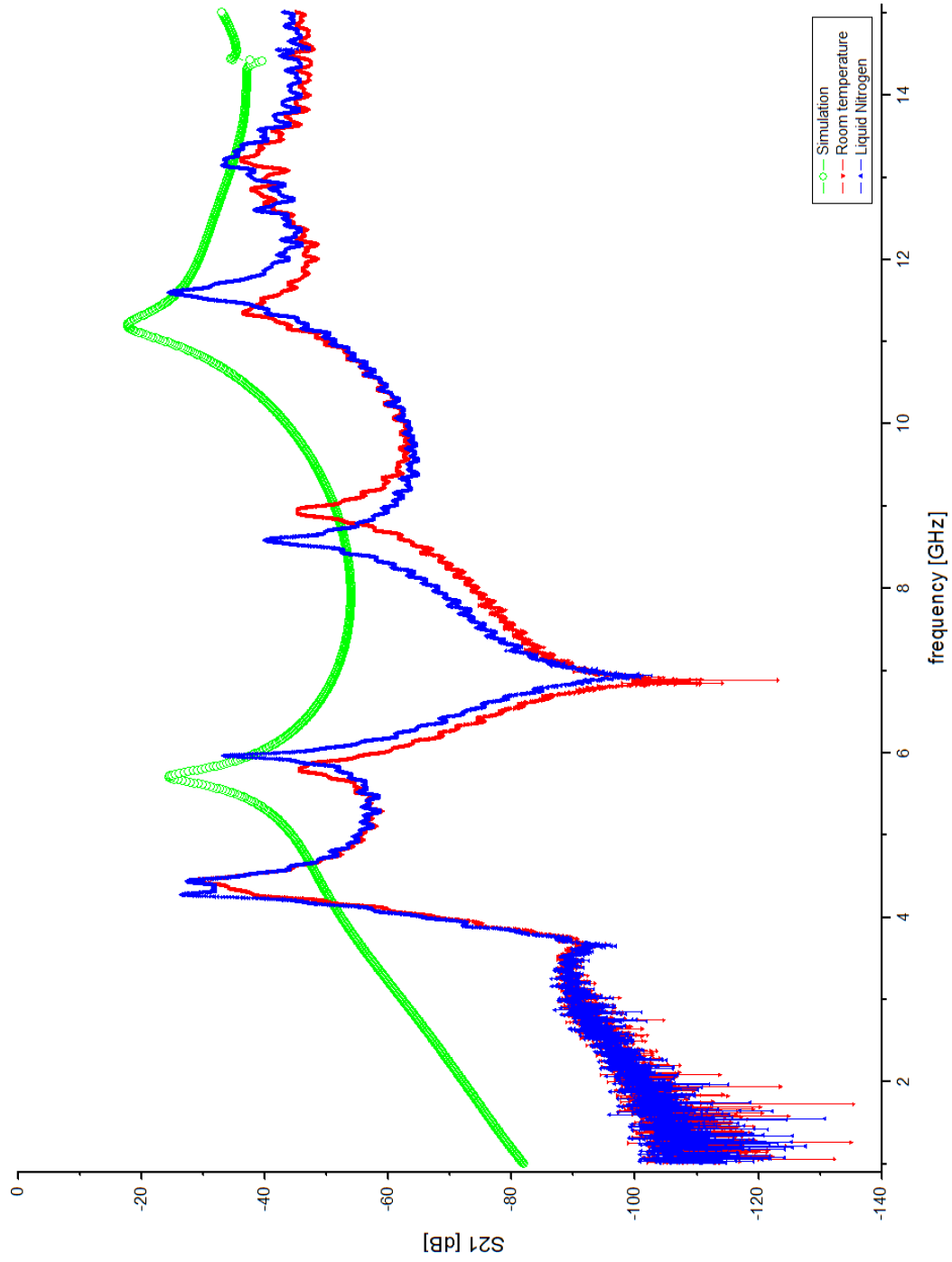


Figure 6.1: 14 mm simulated and measured transmission.

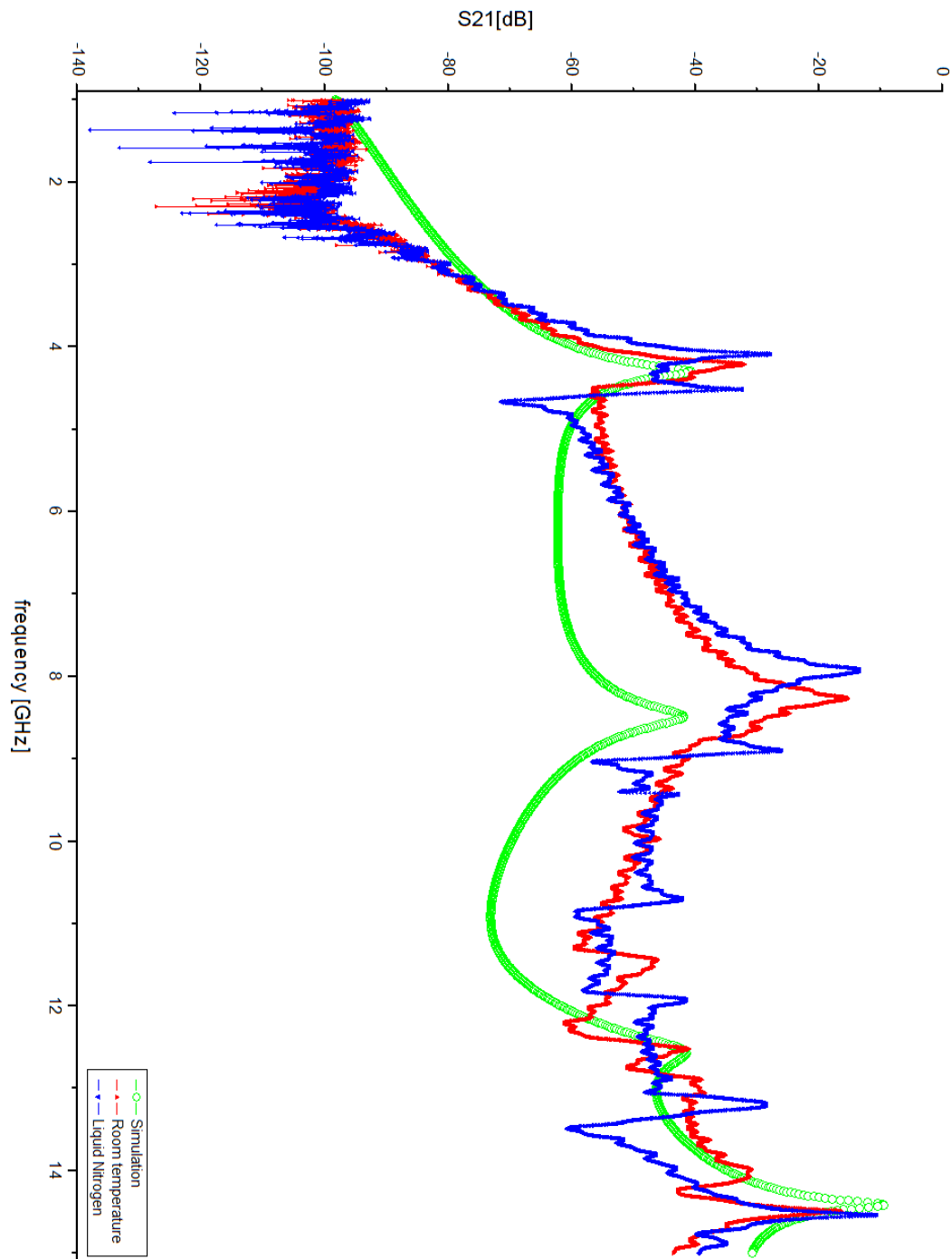


Figure 6.2: 18 mm simulated and measured transmission.

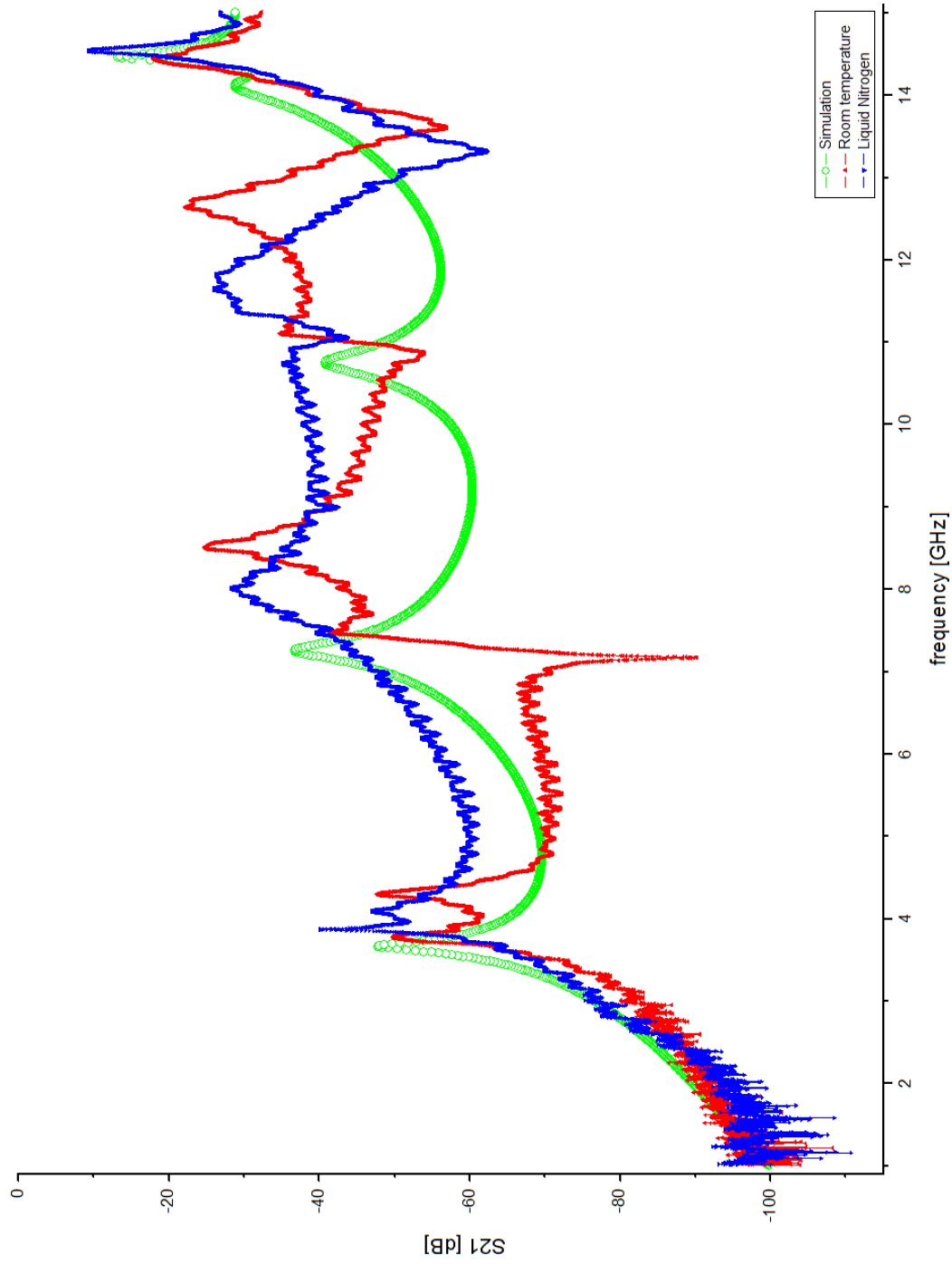


Figure 6.3: 22 mm simulated and measured transmission.

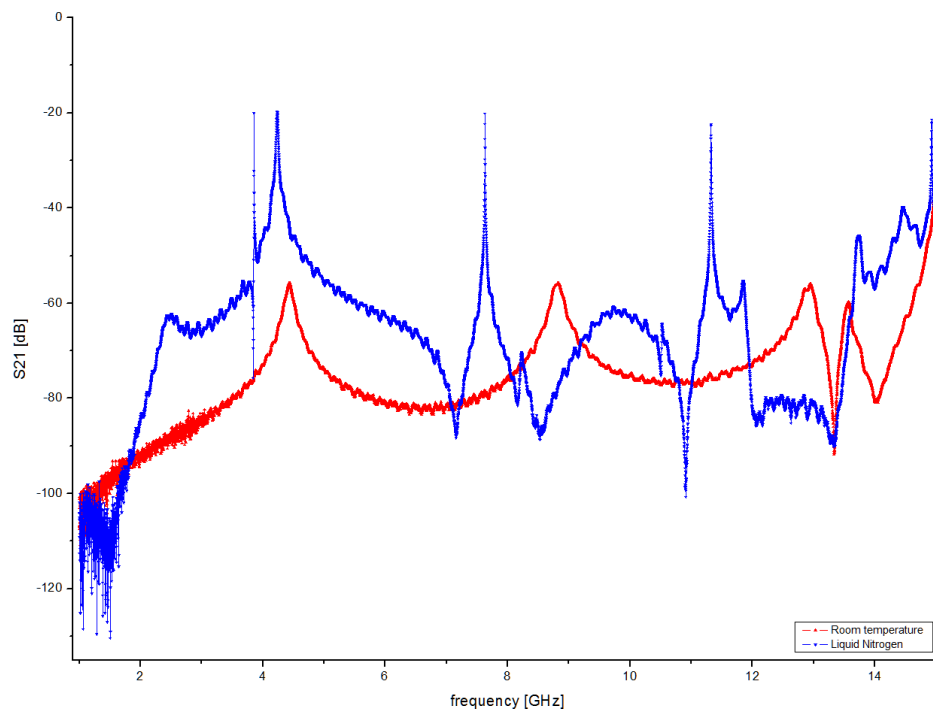


Figure 6.4: Transmission curve of the etched YBCO filter.

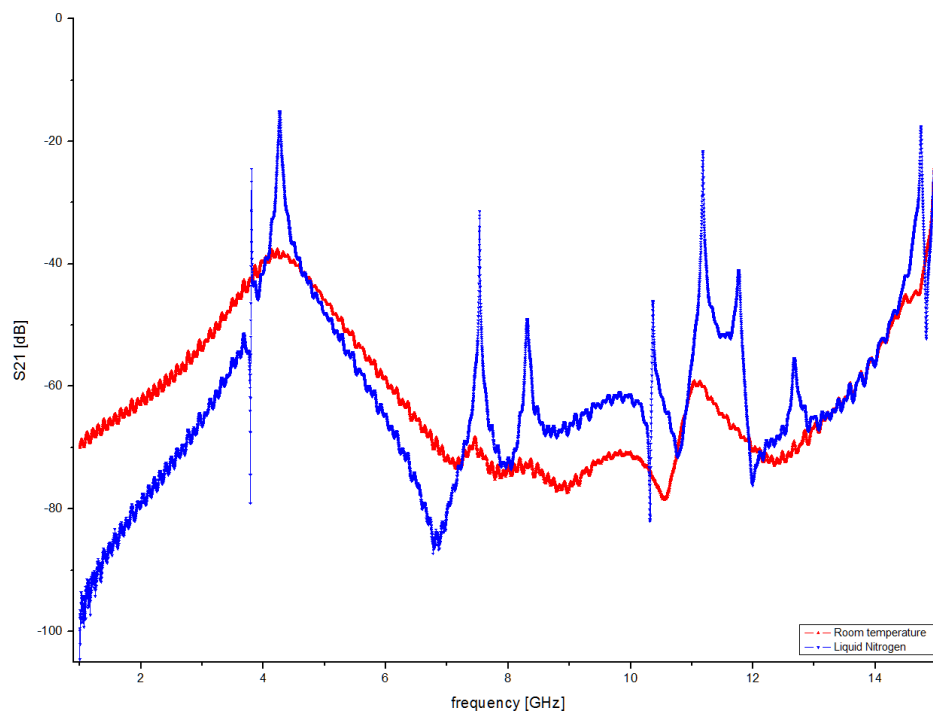


Figure 6.5: Transmission curve of the YBCO filter M1 with gold on top.

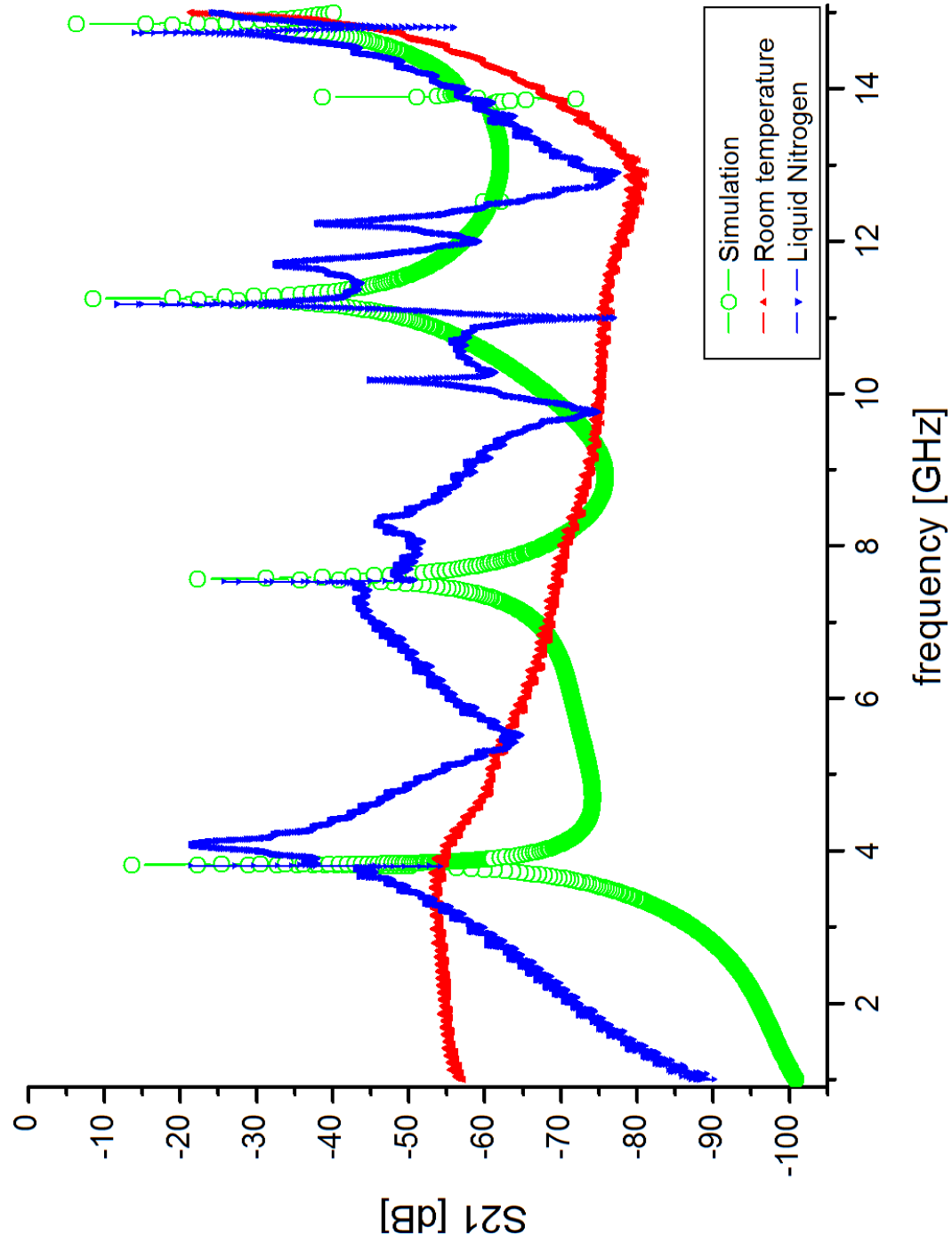
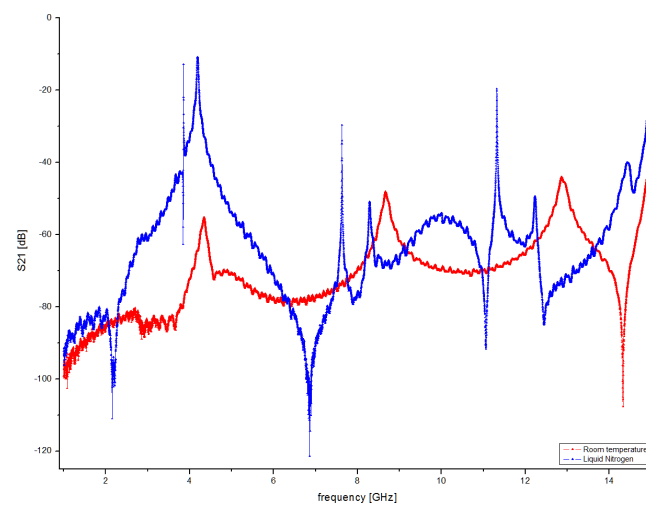
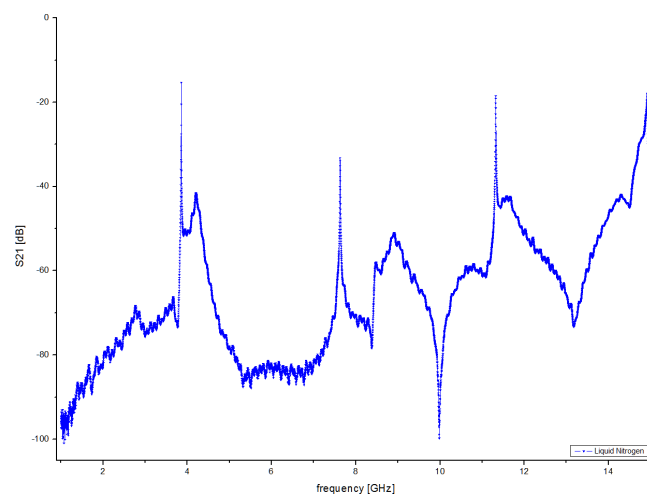


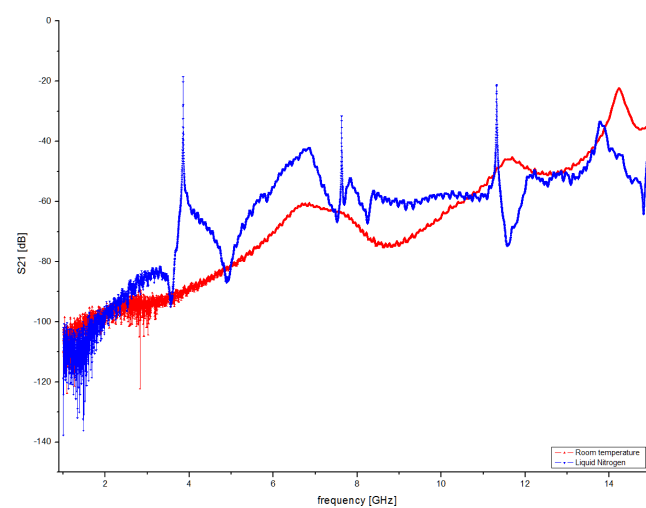
Figure 6.6: Simulation versus Measurement of the YBCO filter M1.



(a) Indium on protrusions

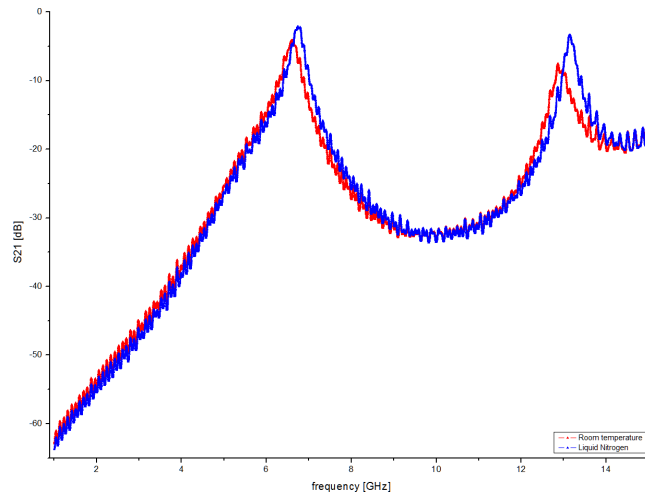


(b) Indium square

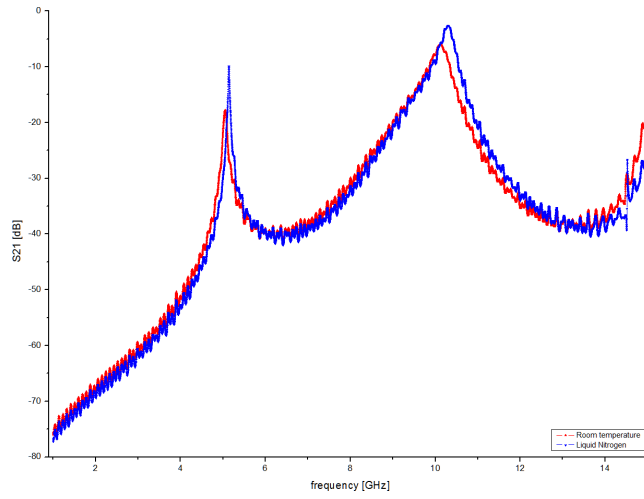


(c) Indium spiral

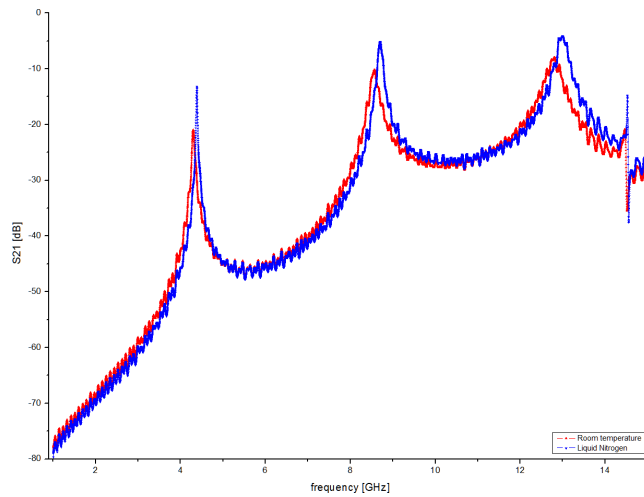
Figure 6.7: YBCO filter with indium backplane to box connections.



(a) 14 mm without backplane



(b) 18 mm without backplane



(c) 22 mm without backplane

Figure 6.8: Transmission curves of copper filters without backplane.

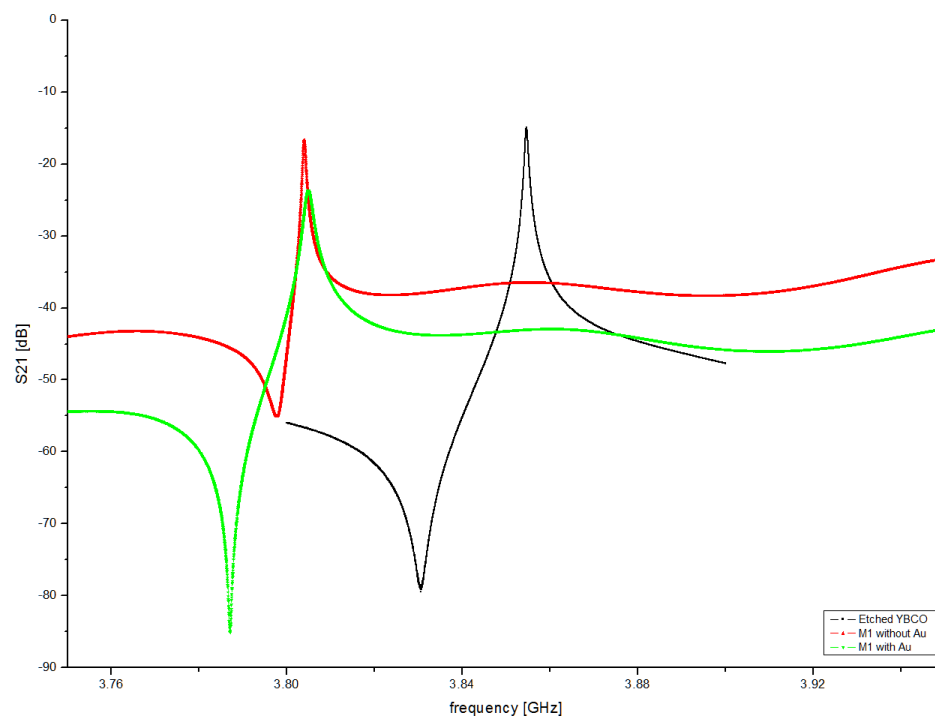


Figure 6.9: Measured response of superconducting filters around 3.8 GHz.

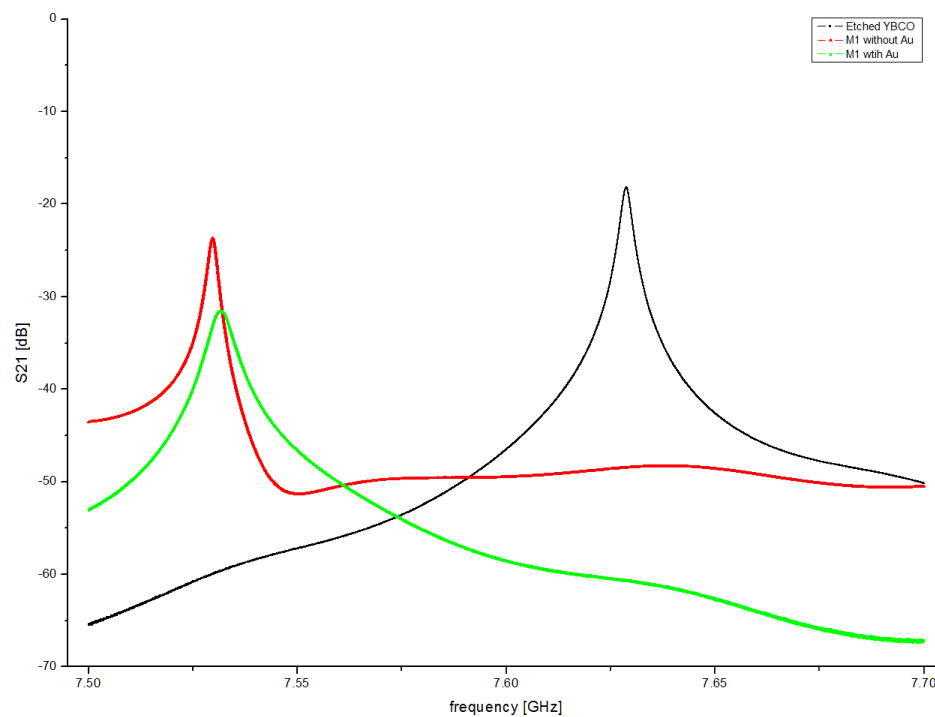


Figure 6.10: Measured response of superconducting filters around the second harmonic at 7.6 GHz.

7 Summary and Conclusion

In the presented work a 14 mm long microstrip dipole resonator has been realized in different materials as well as in different production techniques. Furthermore, a copper resonator on FR-4 corresponding to a resonance frequency of 4.3 GHz has been produced. The dipole resonator geometries have been also simulated using 3D planar electromagnetic analysis. The measurements of the transmission parameter S_{21} have been carried out at room temperature and at the boiling point of liquid nitrogen. To compare the filter performance the quality factors have been calculated from the measurements and simulations for all samples at 77 K.

Tables 7.1 to 7.3 summarize the measured and simulated resonance peaks and their corresponding quality factors.

Looking at the quality factors the difference between the superconducting microstrip filters and the conventional ones becomes apparent. The quality factors of the superconducting filters are about 25 times bigger than the ones of the conventional filters, which is predicted by the difference in conductivity.

The etched and the irradiated superconducting YBCO filters show similar quality in their response curves. Despite the fact that the two-point resistance across the irradiated sample is finite, there is little difference in the behavior between the etched and irradiated filter in the superconducting state concerning the quality factor of the resonators. Actually the quality factors of the MIBS sample without gold cover is slightly better than the etched one.

MIBS fabricated superconducting YBCO filters have an excellent performance in the microwave frequency range and can be manufactured by a

simple process. They offer the additional advantage that the surface of the YBCO filter stays intact and, thus, is more robust against environmental influences.

Table 7.1: Quality factor of copper filters (Dominant Mode)

Filter	Frequency [GHz]	Q
14 mm	5.956	193
18 mm	4.510	189
22 mm	3.859	197
Simulation 14 mm	5.710	48
Simulation 18 mm	4.300	49
Simulation 22 mm	3.660	49

Table 7.2: Quality factor of YBCO filter at 3.85 GHz peak

Filter	R_{12} [M Ω]	Frequency [GHz]	Q
Etched	∞	3.854675	5071
M1 with gold	3.3	3.804905	2068
M1 without gold	10.2	3.803945	5595
Simulation	—	3.821	6421

Table 7.3: Quality factor of YBCO filter at 7.65 GHz peak

Filter	Frequency [GHz]	Q
Etched	7.628753	3051
M1 with Gold	7.531623	1326
M1 without Gold	7.529703	3331
Simulation	7.570	1356

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