Computations & Simulations for the Design of an Ultra-Sensitive Microwave Cavity

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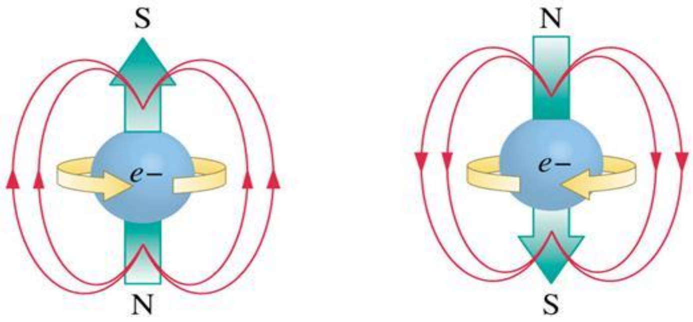
Project Overview

- ✓ Final aim
- ✓ Design requirements
- ✓ Goals and Deliverables
- ✓ Project Organisation

Spintronics

- Manipulation of electron spin for exploitation in applications relating to quantum information processing

- Creating a spintronic device requires the generation of spin-polarised electrons, typically via the application of an external field.



Ferromagnetism

Ferromagnetic materials:

- Exhibit a long-range ordering phenomenon due to the atomic level quantum mechanical interaction.
- Unpaired electron spins in the ferromagnetic material line up with each other in regions known as domains

Ferromagnetism:

- When ferromagnetic material is placed close to a small external magnetic field
- Domains align themselves with each other and the material is magnetised

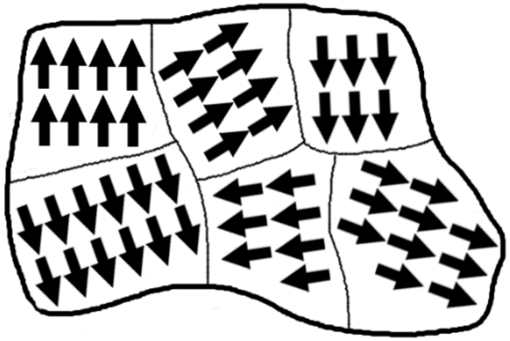


Figure 2: An unmagnetised ferromagnetic material

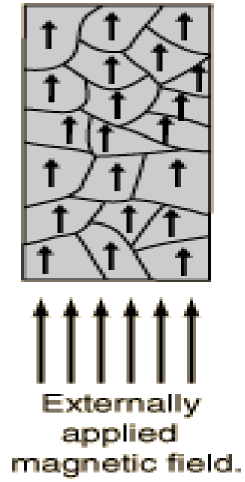
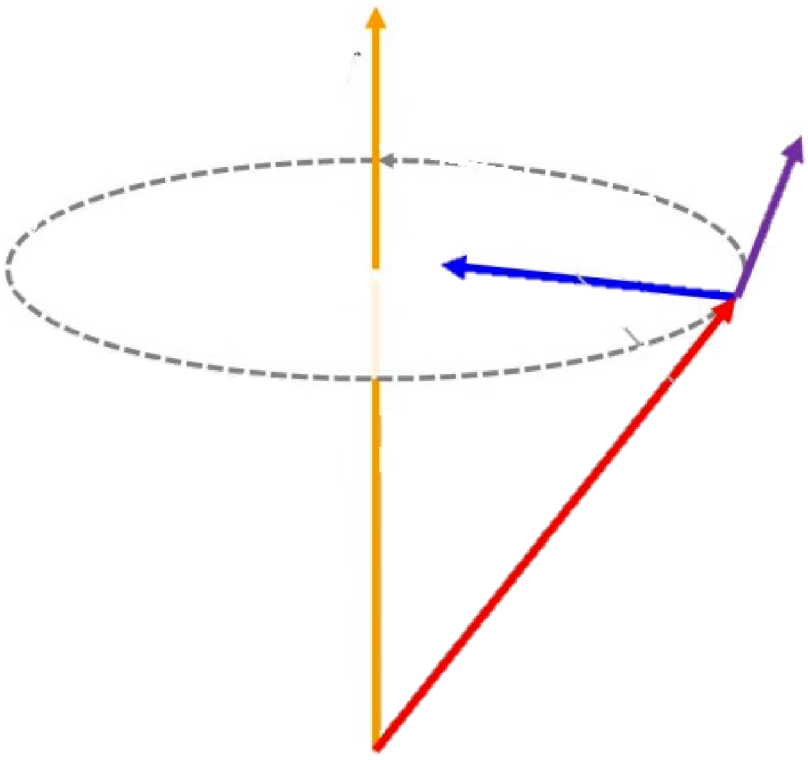


Figure 3: Domain aligning with the external magnetic field

Ferromagnetic Resonance (FMR)

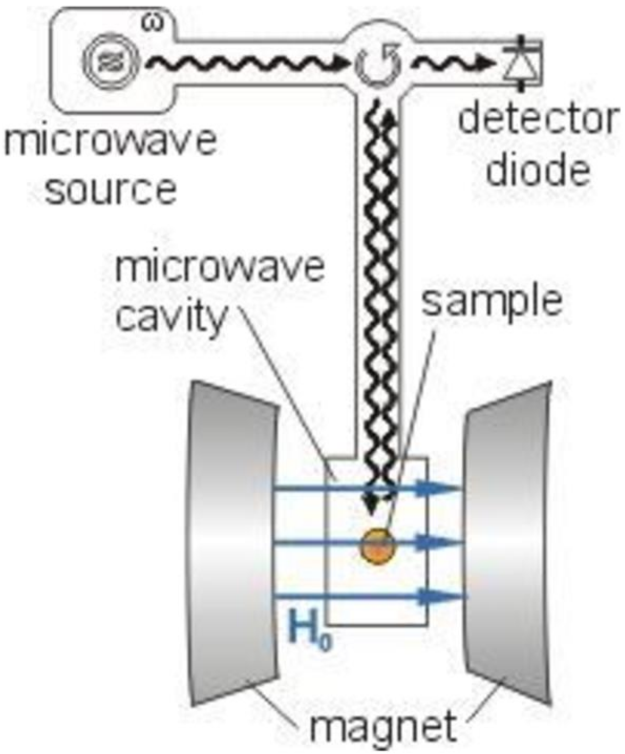
- A tool that can be used to probe the spins of ferromagnetic materials
- Measures magnetic properties by detecting the precessional magnetization motion in a ferromagnetic sample.
- Application of an external magnetic field causes the spins within a sample to align in the direction of the field



Ferromagnetic Resonance (FMR)

Experimental Setup:

- Sample placed in Ultra High Vacuum (UHV) inside a quartz glass tube, which would fit inside the cavity.
- Beyond this, there would be a magnet.
- During this experiment, what we are looking to observe and measure is the absorption derivative/ absorption intensity of the microwaves



Q-Factor

- Q indicates energy loss relative to the amount of energy stored within the system
- Higher the Q, lower the rate of energy loss
- Q-factor of a resonant cavity:

$$Q = 2\pi \frac{energy\ stored\ in\ cavity}{energy\ lost\ per\ cycle\ to\ walls}$$

- Q-factor tells you how long the photon can survive within the cavity (high = longer)
- More sensitive measurements of magnetism as a result due to greater interaction time

Designing the Cavity

Section Overview:

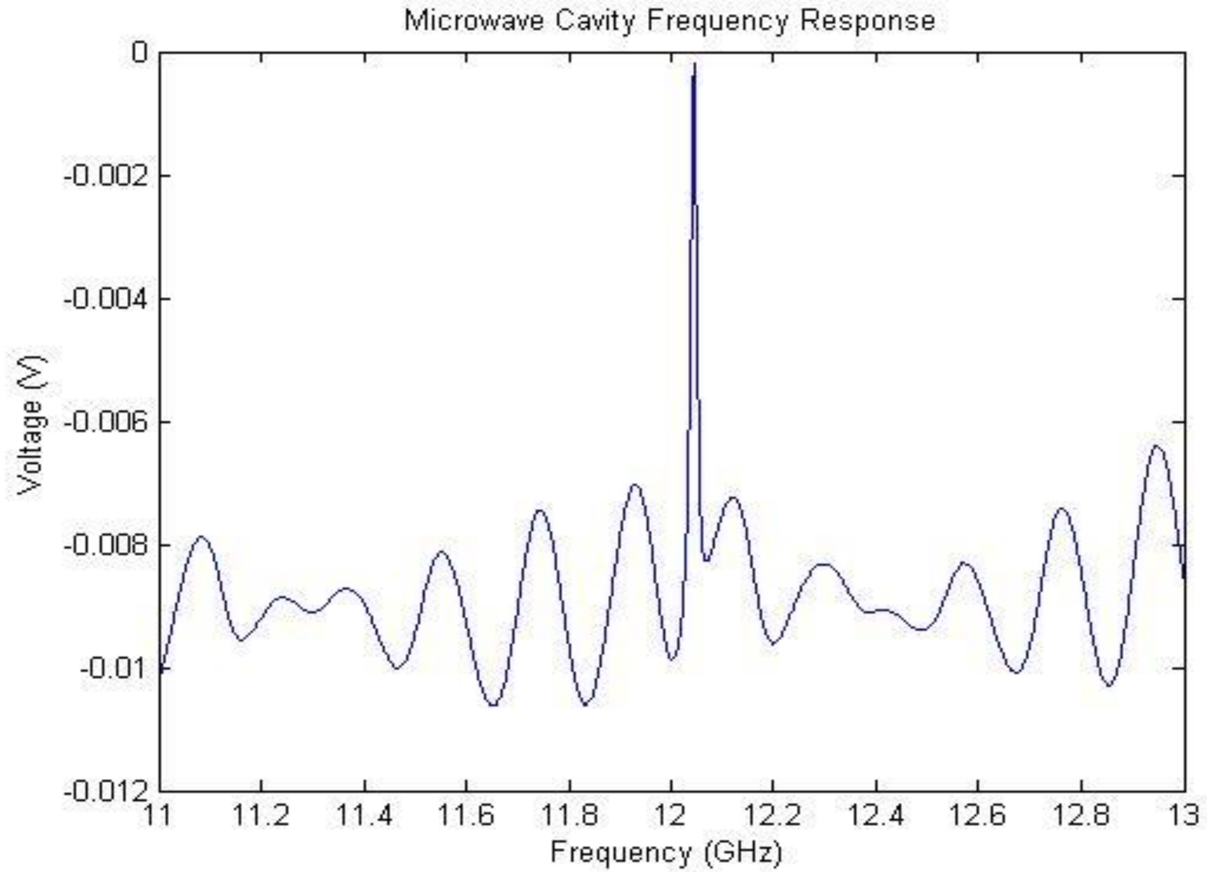
- Characterising the original cavity
- Goals for new cavity
- Design considerations
- Q-factor and resonant frequency predictions and patterns
- Analysis of copper and aluminium cavities

Original Cavity Analysis

Shape	Cylinder
Material	Copper (Cu)
Dielectric	PTFE
Resonant Frequency	12 GHz
Q-factor	2,000
Dimensions	a = 9.5 mm, d = 14 mm, t = 3 mm

Designing the Cavity

Original Cavity Frequency Response



Goals & Constraints

Design Goals:

- High Q-factor (in the thousands)
- Low resonant frequency (2 – 8 GHz)

Production Constraints:

- Thickness: $t > 2\ mm$
- Length: $10 < d < 80\ mm$
- Radius: $a > 6\ mm$

Important Factors:

- Cavity material
- Shape
- Resonant mode
- Dielectric

Material Selection

Aluminium

Advantages	Disadvantages
• Relatively inexpensive • Lightweight	• Oxidises in air, leading to degradation of Q-factor over time • Retains its sheen (could also be an advantage)

Copper

Advantages	Disadvantages
• Tried-and-tested material • Acquires a green hue upon oxidation • Although, this can be prevented by gold-plating the cavity	• Suffers similar degradation in Q-factor as aluminium

Shape of the Cavity

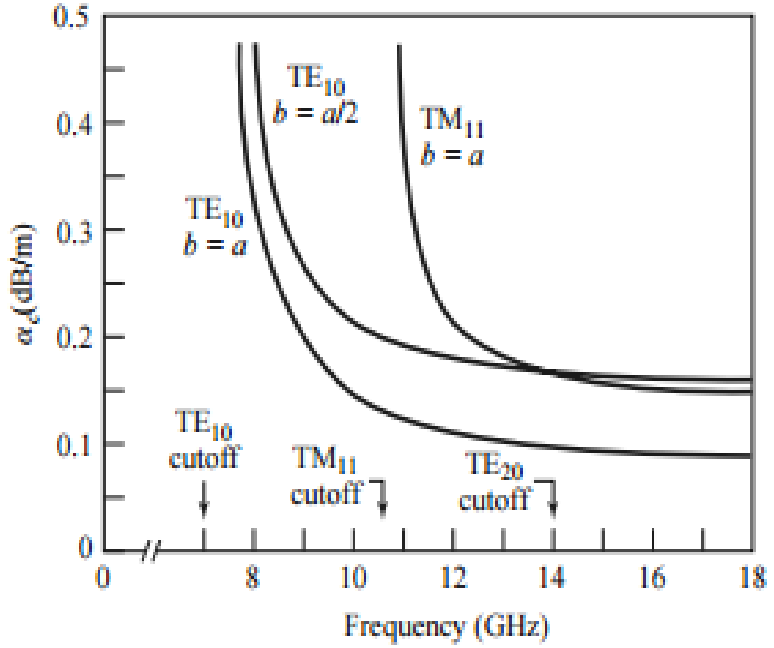
Options:

1. Hexagonal Cylinders
   - Discarded due to lack of sufficient literature to form a hypothesis

2. Rectangles
   - Easiest to construct
   - Resonant frequency too high

3. Cylinders
   - Low resonant frequencies possible

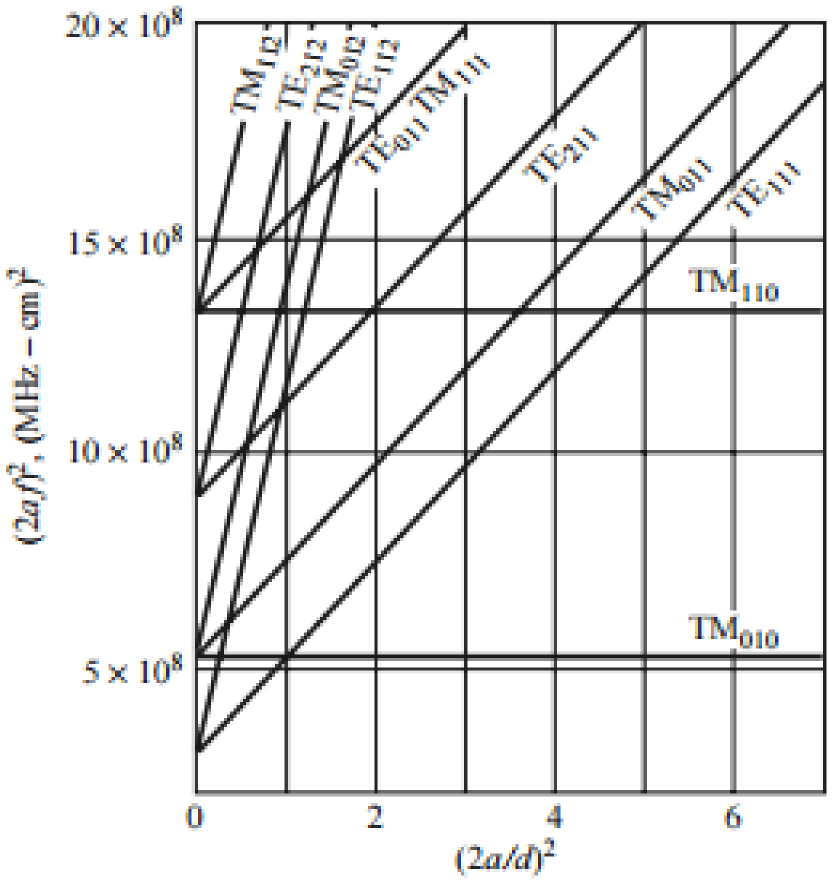
Rectangular Cavity Modes:

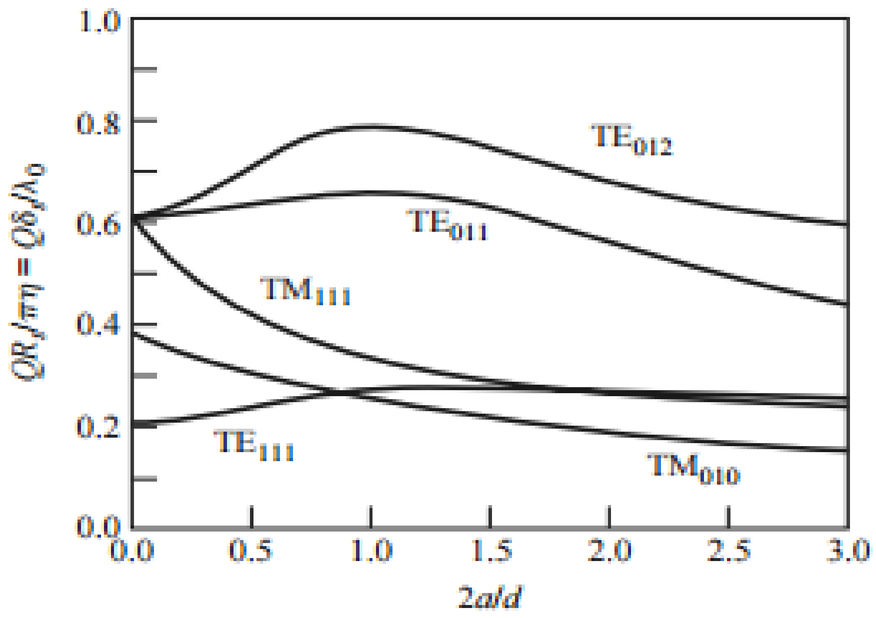


Choice of Resonant Mode

Choice of Resonant Mode

Cylindrical Cavity Q-Factor and Resonant Frequency:

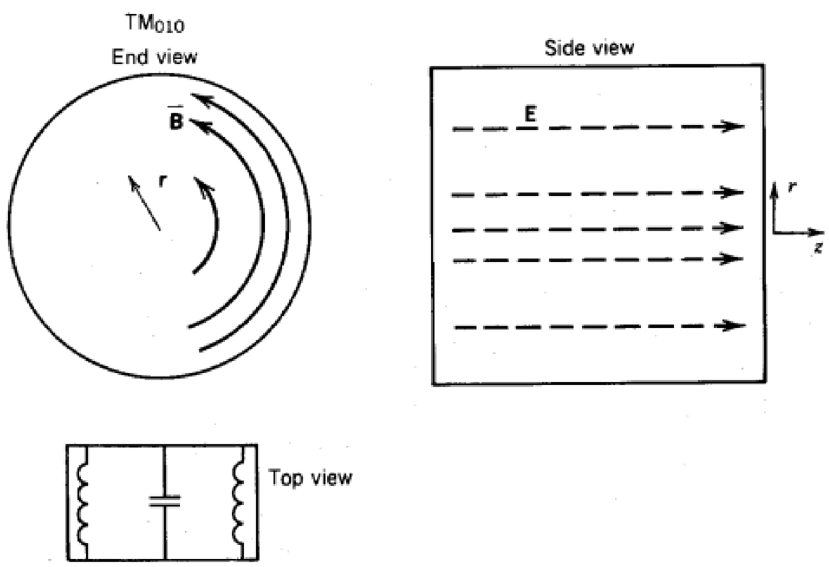




Choice of Resonant Mode

Field Lines:

TM 010



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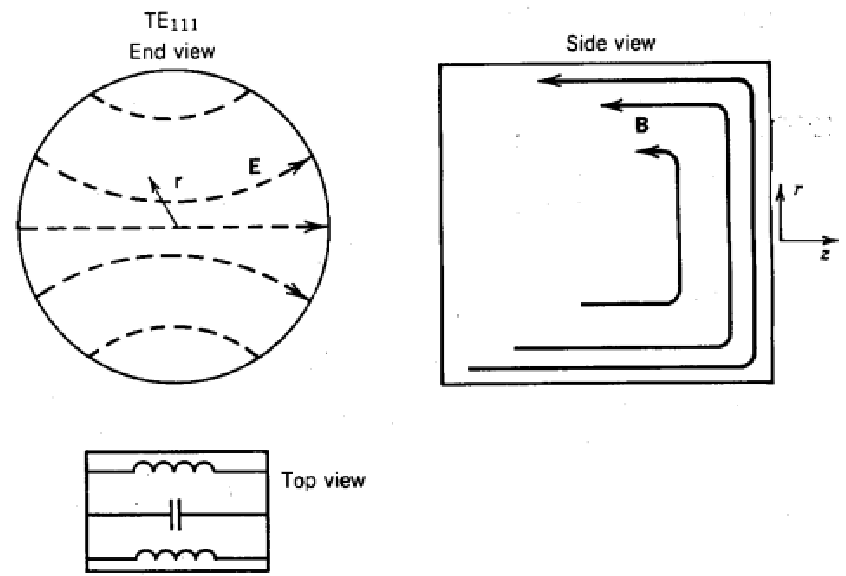


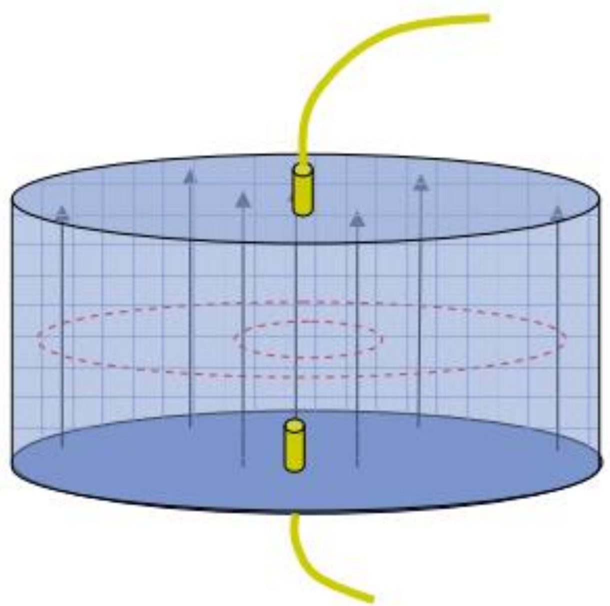
Choice of Resonant Mode

Advantages of TM 010:

- High Q-factor can be obtained
- Easy to couple to (see below)
- Straight field lines inside the cavity (E-field)

Coupling Setup:

- Wire/connector
- Couple E-field
- Capacitive coupling



Dielectric Material

Requirements:

- Easily moulded into a cylindrical shape
- Transparent to electric and magnetic fields
- Electrically insulating, but thermally conductive

Material	**Air**	**PTFE**	**FR4**
Relative Permeability	1	1	1
Relative Permittivity	1	2.1	4.5
Loss tangent (at 3 GHz)	0	0.0015	0.016
Thermal Conductivity (W/m-K)	0.024	0.25	0.25
Malleability	N/A	More	Less

Resonant Frequency

Calculating Resonant Frequency:

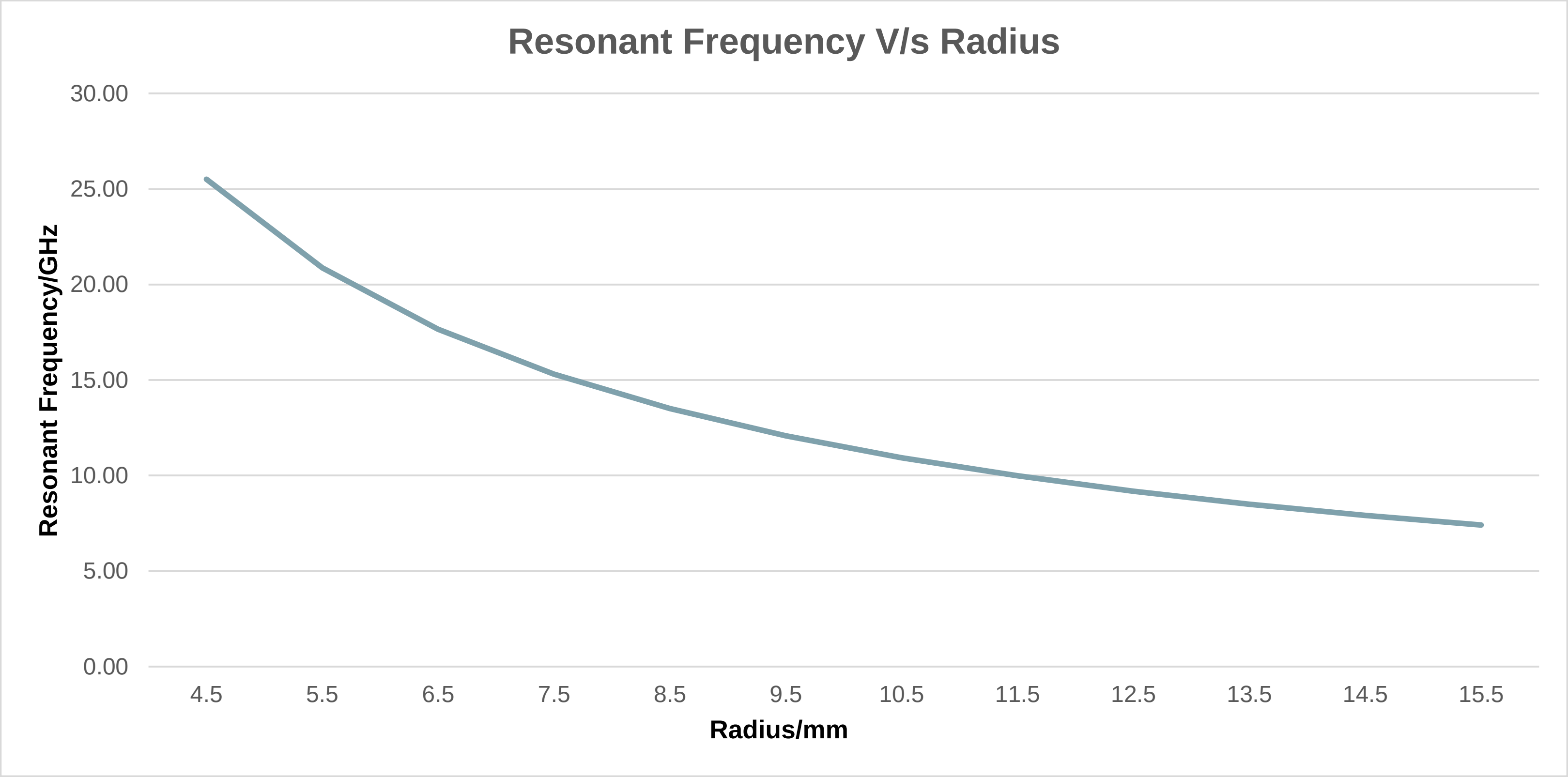
$$f_{nml} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{p_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2}$$

Radius required to get below 8 GHz:

Dielectric	**min{*a*} < 8 GHz (mm)**	***d* (mm)**
Air	14.5	29
PTFE	10	20
FR4	6.8	13.6

Resonant Frequency

Resonant Frequency as a function of Radius for Air:



Q-Factor

Overall Q-Factor:

$$Q_0 = \left(\frac{1}{Q_c} + \frac{1}{Q_d}\right)^{-1}$$

Cavity Q-factor:

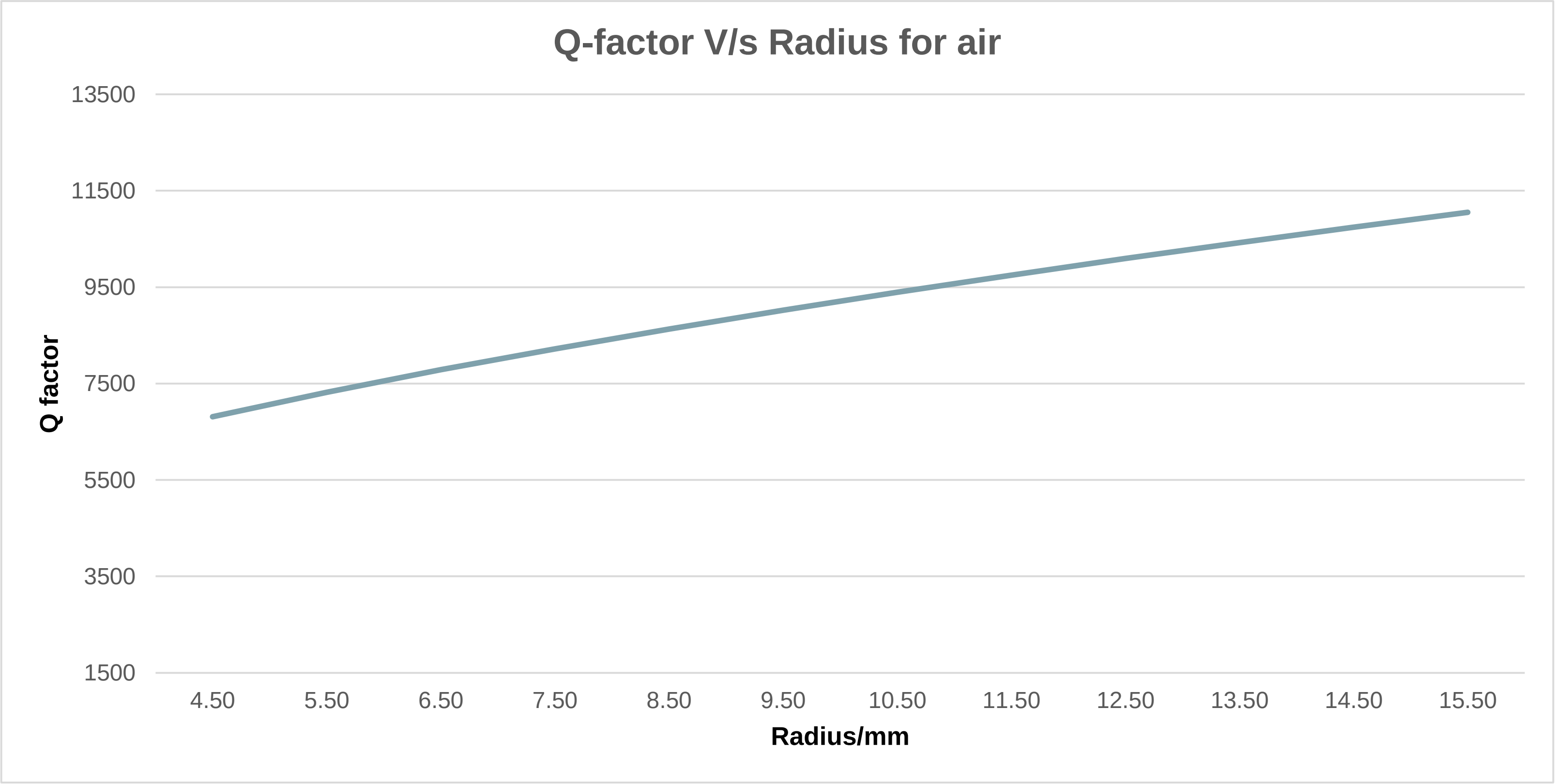
$$Q_c = \frac{ka\eta}{2R_s} \qquad Q_c = \frac{2V}{S\sqrt{\frac{2}{\omega\mu\sigma}}}$$

Intermediate Values:

$$R_s = \sqrt{\frac{\omega\mu}{2\sigma}} \qquad \eta = \sqrt{\frac{\mu}{\varepsilon}}$$

Q-Factor

Q-Factor as a function of Radius for Air:



Q-Factor

Q-factor comparison for various dielectrics:

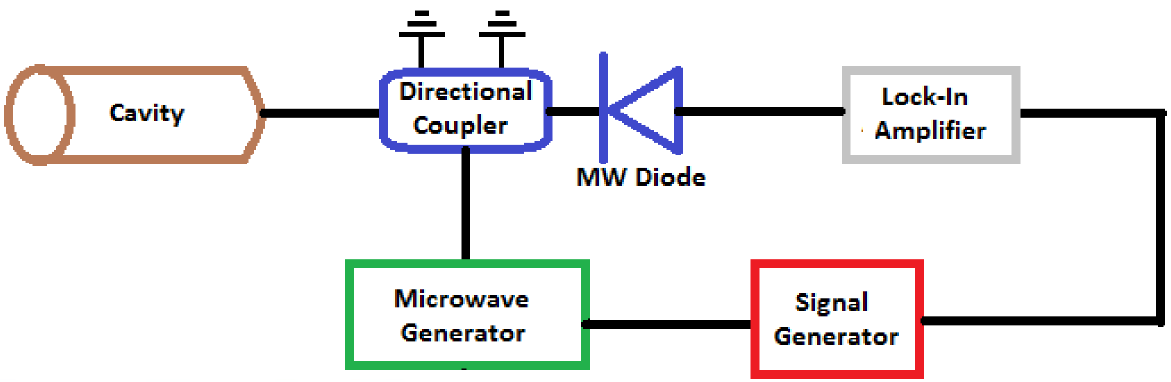
Material	**Dielectric**	**a (mm)**	**d (mm)**	**f (GHz)**	**Q-factor**
Copper	Air	14.5	29	7.9	16,000
Copper	PTFE	10	20	7.9	630
Copper	FR4	6.8	13.6	7.9	62

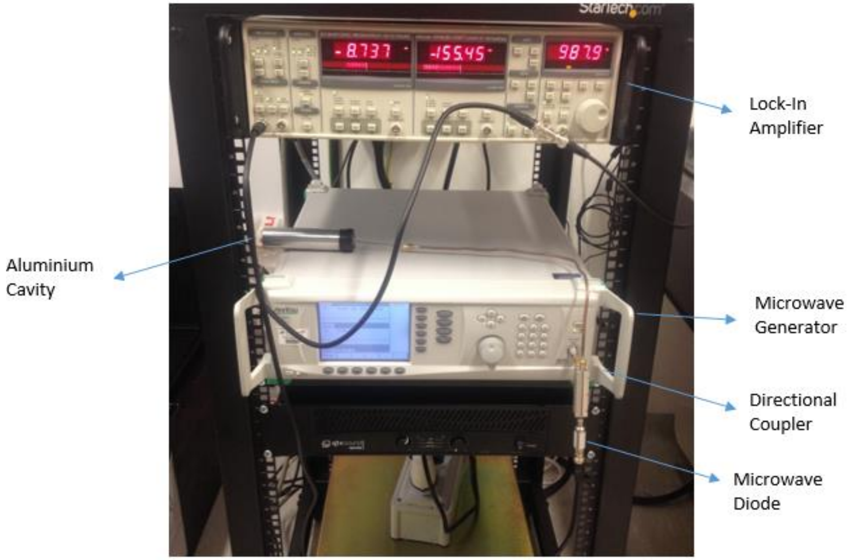
Conclusions:

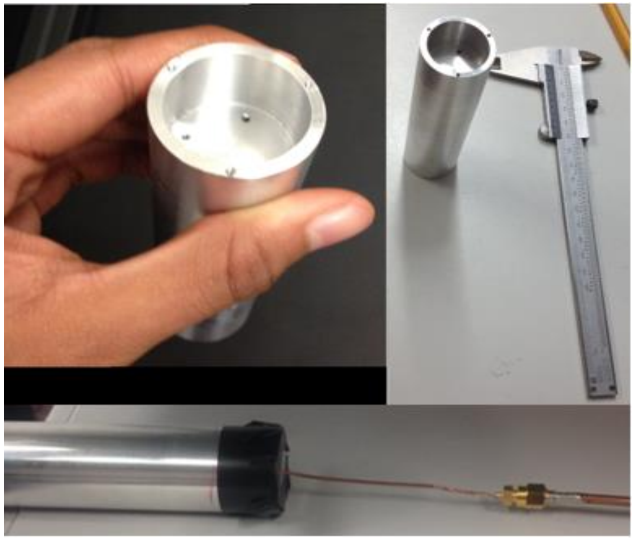
- FR4 gives a much lower Q-factor as it has a large loss tangent
- Air gives the highest Q-factor
- Losses will typically be a percentage of the theoretical Q-factor
- Therefore, we chose air as our dielectric

Aluminium Cavity

Experimental Setup:

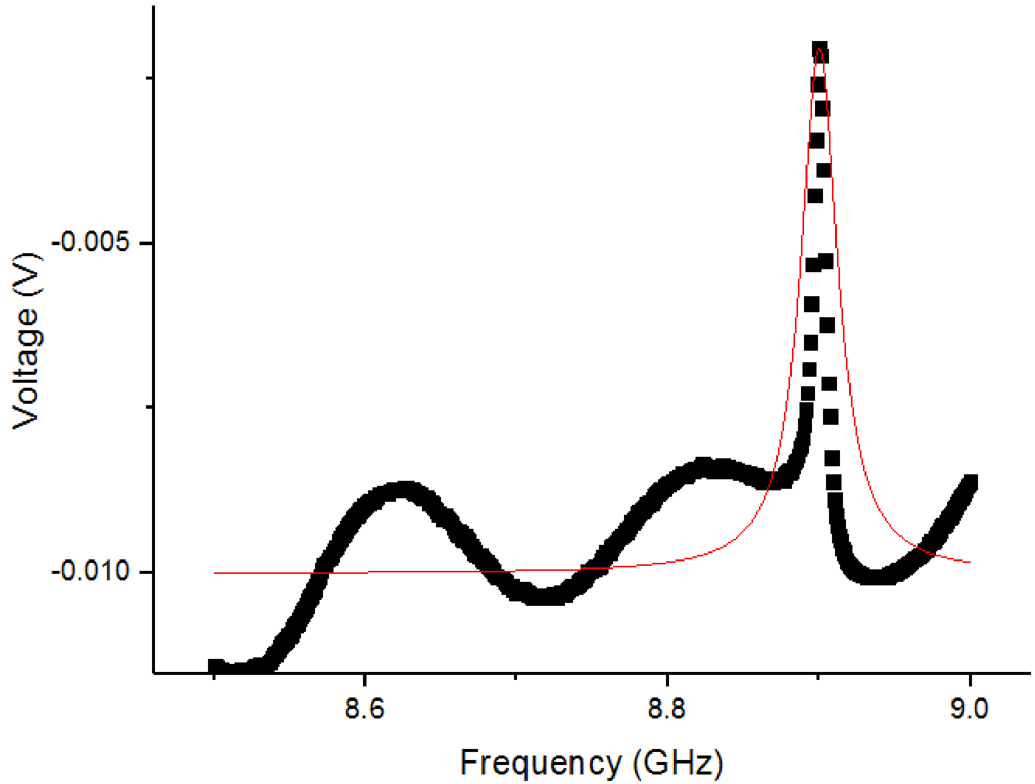






Aluminium Cavity

Al Cavity Response between 8.5 – 9 GHz:



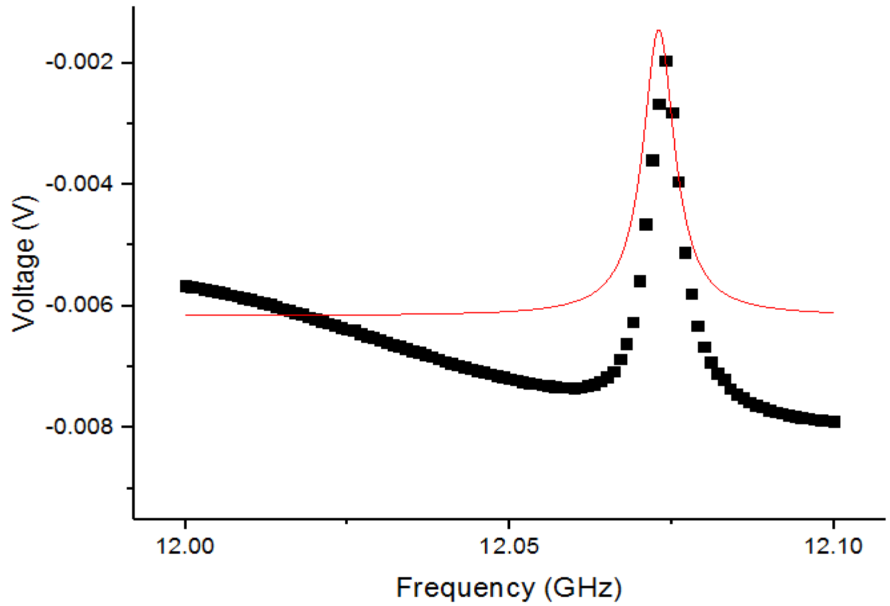
Q = Resonant frequency/FWHM

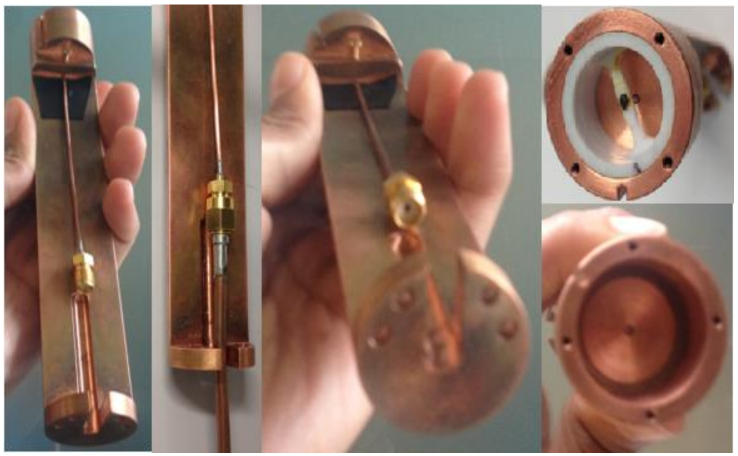
Q = 300

Resonant frequency = 9 GHz

Copper Cavity

Cu Cavity Response between 11.5 – 12.5 GHz:





Q = 2,000
Resonant frequency = 12 GHz

Al vs. Cu Comparison and Simulations

Cavity Comparison:

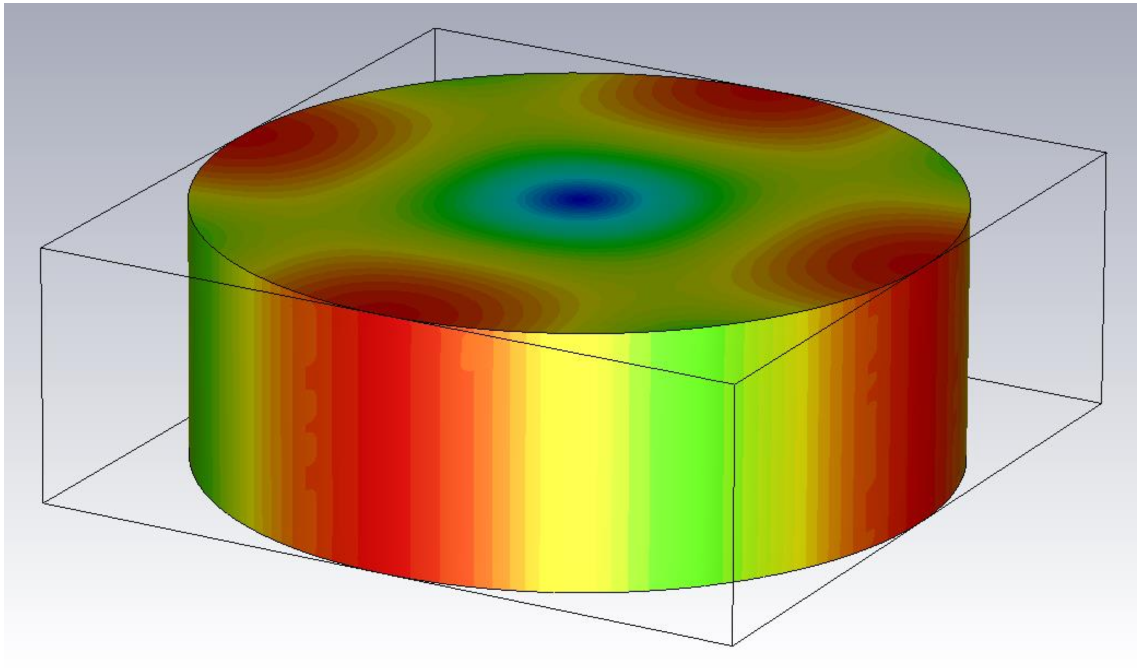
Material	**Copper (Cu)**	**Aluminium (Al)**
Cost	More expensive	Cheaper/Less expensive
Oxidisation	Both similar	Both similar
Resonant Frequency	12 GHz	9 GHz
Q factor	2000	300

Simulation Dimensions:

a (mm)	**d (mm)**	**f (GHz)**	**Q-factor**
14.5	50	7.9	15,300
14.5	29	7.9	13,160
14.5	10	7.9	8,000

Simulation: Design 1

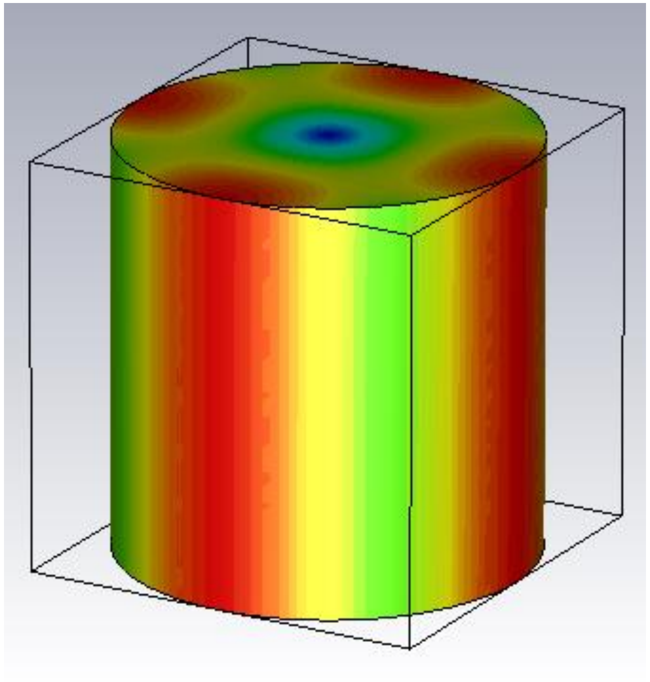
Radius: 14.5 mm, Height: 10 mm



Mode	Q factor	Resonant Frequency (GHz)
TM 010	7590.3	7.310

Simulation: Design 2

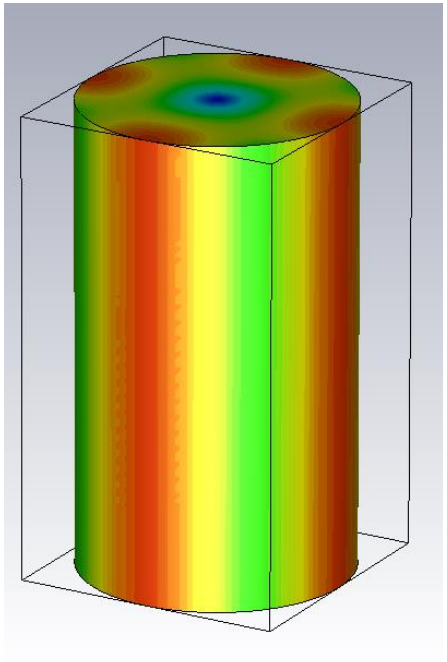
Radius: 14.5 mm, Height: 29 mm



Mode	Q factor	Resonant Frequency (GHz)
TM 010	12302	7.310

Simulation: Design 3

Radius: 14.5 mm, Height: 50 mm



Mode	**Q factor**	**Resonant Frequency (GHz)**
TM 010	14254	7.310

Simulation Results: Conclusion

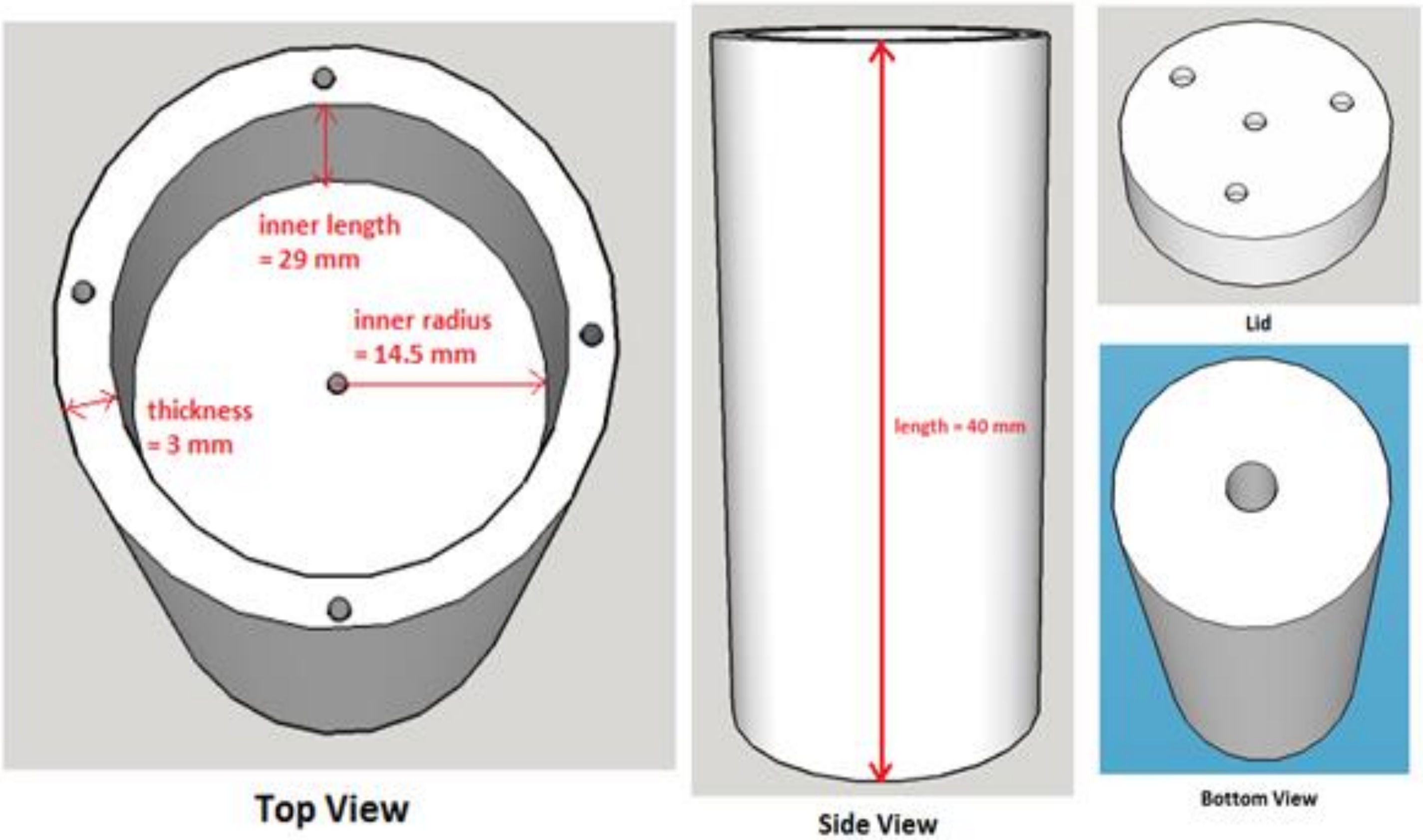
Comparison of Predictions vs. Results:

Height (mm)	Expected Q-factor	Obtained Q-factor	Expected Resonant Frequency (GHz)	Obtained Resonant Frequency (GHz)
10	8,000	7,590	7.9	7.3
29	13,160	12,302	7.9	7.3
50	15,300	14,254	7.9	7.3

- ✓ Simulation results discussion
- ✓ High Q-factor, 2 -8 GHz resonant frequency, strong E/M fields

Final Cavity Design

Final Cavity Model:



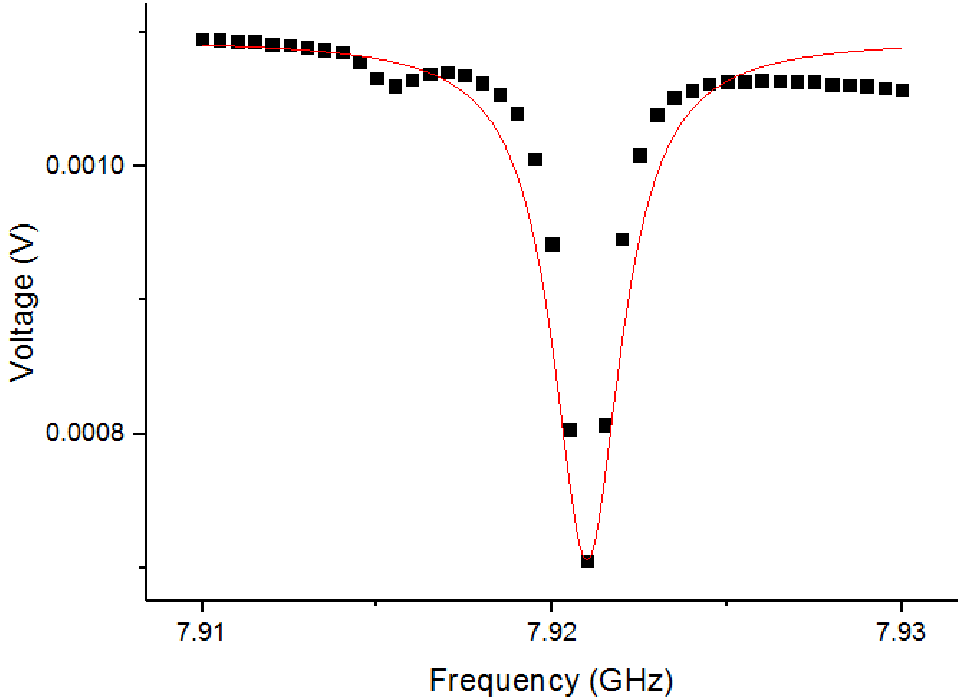
Final Cavity Characteristics

Table of key parameters:

Parameter	Value
Material	Copper (Cu)
Shape	Cylinder
Resonant Mode	TM 010
Dielectric	Air
Length (mm)	29
Radius (mm)	14.5
Wall Thickness (mm)	3
Predicted Q-Factor	13,160
Predicted Resonant Frequency (GHz)	7.9

Final Cavity Performance

Cavity Response between 7.91 – 7.93 GHz:



Cavity Version	Q-factor	Resonant Frequency (GHz)
Original	2,000	12
New Predicted	13,160	7.9
New Actual	3,340	7.9

Production Delays

- Significant delay in the production of the upgraded Microwave Cavity
- Unable to conduct experiments on time to validate our hypothesis
- New cavity arrived this week and we were able to include new results for the purpose of this presentation

Discrepancies

Predicted Q-factor:

13,160

Actual Q-factor:

3,340

Q-factor for existing Copper Cavity:

2,000

Reasons for discrepancy:

- Oxidation of Copper
- Imperfect Coupling
- Assumed ideal conditions during simulations

Accurate Predictions

- Simulations were in line with theoretical predictions throughout

Predicted Resonant Frequency:

7.9 GHz

Actual Resonant Frequency:

7.9 GHz

Resonant Frequency of existing Copper Cavity:

12 GHz

Reflection

Goal achieved:

- Design an optimal microwave to provide accurate detections of spin dynamics in thin-film samples

Final cavity design:

- Depicted the desired characteristics
- Higher Q-factor
- Resonant Frequency within the target range

Issues:

- Production delay
- Lack of time due to the delay did not allow us to conduct enough experiments

Further Work

Q-Factor:

- Reduce discrepancy between the idealized and actual Q-factor

FMR:

- FMR experiment using the new cavity
- Experiments to measure the ferromagnetic resonance of the Copper and Aluminum Cavities
- Wholesome comparison between old and new cavities