DESIGN OF A FABRY-PEROT OPEN RESONATOR AT RADIO FREQUENCIES FOR AN MgB_2 TESTING PLATFORM

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Abstract

A proposal was written to begin R&D on the use of MgB_2, a high-T_c superconducting material that can be deposited onto metallic surfaces, for radiofrequency (RF) cavities. Materials Science Divisions at Argonne have been studying deposition techniques, including atomic layer deposition (ALD) to coat MgB_2 on sample 2" coupons. A Fabry-Perot open resonator is suggested as a cavity to test the quality of the coupons, while simulation software, Microwave Studios (MWS), is used to design and validate an open resonator model based on a previously reported cavity The MWS simulation will be used to scale open resonator designs to different- operating frequencies in the search for an optimal test structure. The results of the simulation are presented.

INTRODUCTION

Materials research over the past years has led to new developments for high-T_c superconducting materials. Research has been done to realize their feasibility for usage in superconducting radio frequency (SRF) cavities. A research proposal was written specifically to study the deposition of MgB_2 metallic cavities with the intent to operate at 8-12 K temperatures to allow cooling with cryocoolers for cryogen-free RF systems [1]. RF performance of these coated cavities is limited by impurities caused during cavity production and preparation, especially during deposition.

In a preliminary phase of this R&D project, a testing structure is needed to test the success of the MgB_2 thin films. The design chosen for the structure was that of an open resonator because it allows separate measurement of heat deposited on the test sample and the rest of the cavity structure. Successful Fabry-Perot open resonators exist [2, 3, 4] and provide insight into its functionality. Specifically, an article by Choi [5] provides a cavity design which can be used to scale to operating frequencies that might be more optimal for testing MgB_2 substrates deposited via Atomic Layer Deposition (ALD) and Hybrid Physical Chemical Vapor Deposition (HPCVD) methods.

BACKGROUND

The motivations for beginning this project stemmed from the positive outlook on new superconducting materials, such as MgB_2, and their possible relevance to storage rings and free-electron laser (FEL) light sources. However, the difficulties in developing innovative and complex technologies require techniques to start a testing program with small samples in a cost effective, and efficient, manner.

Superconducting Materials and Challenges Using MgB_2

The attractiveness of RF superconductivity lay in its low surface resistivity (R_s) with high magnetic field gradients. The ultimate goal is to achieve continuous wave operations, where the power dissipation is greatest in the walls [6], but without the use of liquid cryogens. The current project would build on studies with MgB_2 to achieve higher accelerating gradients than the 50MV/m limit set by Niobium and even at high power. [7].

Niobium is the usual material used for SRF cavities and can be easily fabricated or deposited onto copper for these purposes. The challenge for the use of MgB_2 films is to find a substrate material that has good thermal properties and will support the film without degradation. Furthermore, studies [7] have shown that a film of MgB_2 can have the same surface resistance at 8-12 K that Nb has at 4 K, deeming it worth investigation for its ability to be cooled with simply cryocoolers.

Fabry-Perot Open Resonator

The Fabry-Perot (FP) resonator consists of two end parallel plates that are reflecting mirrors and whose performance is analyzed based in terms of standing waves between the reflectors [8]. Therefore, the field constraints are placed upon the cavity solely by the end plates. Using spherical mirrors can result in focused waves without energy lost due to diffraction.

In this configuration, a sample plate is placed at the center location between the hemispherical mirrors, resulting in geometry with only one spherical mirror and a flat reflecting plate. Focusing by the spherical mirror makes the beam waist smaller on the sample plate. The resonant frequencies for the TEM modes can be found using the following equation [9]:

$$f_{lpq} = \frac{c}{2D}\left[q + 1 + \frac{2p+l+1}{\pi}\cos^{-1}(1 - D/R)\right] \quad (1)$$

The parameter D is the physical length of the full resonator complete with the second hemispherical mirror, it is therefore equal to 2L where L is the distance between the top spherical mirror and plane mirror at the center location, as shown in Figure 1. Meanwhile, q is the mode number corresponding to the full resonator (length D), and R is the radius of curvature of the hemispherical plate. The $TEM_{0,0,q}$ modes, found at f_{00q}, will induce magnetic fields onto the sample which result in heat loads that can be measured to test the quality of the coating. These tests help to determine which deposition technique to use for future cavities.

DESIGN AND SIMULATION

Design

The first simulation tests comprised of a FP open resonator matched to the parameters described by Choi that would become the validation model. A simplified version of equation (1) is shown below to calculate the resonant frequencies of only $TEM_{0,0,q}$ modes:

$$f_r = \frac{c}{2D}\left[q + 1 + \frac{1}{\pi}\cos^{-1}(1 - D/R)\right] \quad (2)$$

The parameters of the validation model from Choi at ~28GHz are stated in Table 1 along with dimensions scaled to achieve a resonant frequency of 8 GHz. When these scaled dimensions were placed into equation (2), with q=34 to account for the length D of the resonator, the resonant value of ~8GHz was predicted.

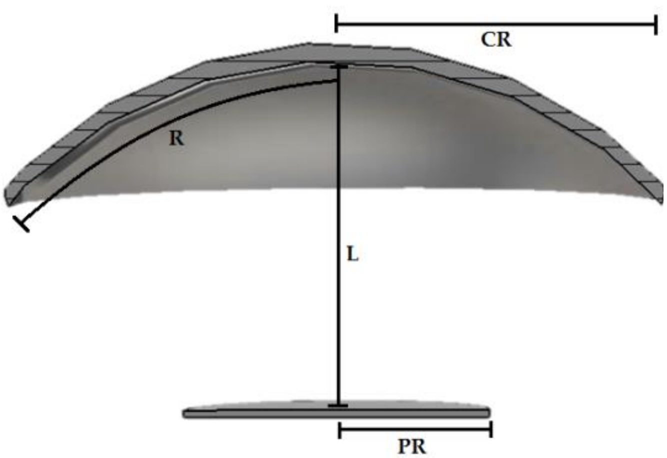

Figure 1: Cross-section view of the Fabry-Perot open resonator design in MWS for the validation model.

Table 1: Dimensions for both the 28GHz validation model and the dimensions for the model scaled to 8GHz.

Description	28GHz Dimensions	8GHz Dimensions
Concave mirror radius of curvature (R)	12.5cm	42.78cm
Concave mirror radius (CR)	9.15cm	31.32cm
Length between plates (L)	9.83cm	33.64cm
Plane mirror radius (PR)	4.23cm	18.10cm

Simulation

Simulation software is needed in order to visualize the modal patterns at the resonant frequencies to match them as $TEM_{0,0,17}$ modes. While the Choi paper uses High Frequency Simulation Software (HFSS), MWS was the available software at the time of modeling so that it was used for the design and excitation of the valuation model. There are multiple solvers available for representing these modes. While the Eigenmode solver would display the modal properties within a closed resonator, it would not allow for these calculations to take place in an open resonator such as the FP. Therefore, the Transient solver was used to help determine if the electric field peaks for the $TEM_{0,0,17}$ modes found with HFSS were in fact the same predicted modes obtained by MWS.

Probes were placed at locations within the y–z plane that would correspond to the expected modal pattern where the electric field peaks would be at their maximum. These would result in a plot of probe value in V/m (magnitude of peaks in dB~log$\left(\frac{V_n}{V_{n-1}}\right)$) versus frequency in GHz as shown in Figure 2. Furthermore, monitors were placed on a second round of simulations at resonant peaks obtained with the first pass by the probes. These monitors displayed the 1-D electric field pattern in terms of magnitude along axial distance between plates.

A current source between plates was used with the MWS simulation to excite modes rather than a waveguide as was done with the Choi model. There are expected deviations from the exact signal received relative to Choi, but the pattern of field generated is of consequence and the resonant frequencies are expected to have approximately the same values.

PRELIMINARY SIMULATION RESULTS

The resonant frequencies obtained are found in Figure 2 and are comparable to those shown in Figure 3 from Choi. The four resonant peaks discovered for the validation model, from a range of 2-29GHz, are found at 27.317, 27.933, 28.396, and 28.769GHz, respectively. As for those found for the Choi model, the four peaks within the same frequency range are located at 27.39, 28, 28.44, and 28.89GHz, respectively. Clearly, the frequencies are quite close to one another in value and some of these slight inconsistencies could be due to the differences in excitation and boundary conditions used due to the different abilities of the HFSS and MWS simulation software.

However, the value of electric field magnitude versus axial position should, according to the Choi paper, display 18 peaks to be classified as the $TEM_{0,0,17}$ mode at 27.39GHz whereas we have only 17 peaks at 27.317GHz. The same inconsistency occurs at the $TEM_{0,0,18}$ mode where 18 peaks are found rather than the expected 19.

SUMMARY

Though the validation model is simplified, its results are similar to those found in Choi in values for resonant frequencies. However, the electric field magnitude peaks are not the exact same in comparison. This suggests that there is an unknown variation resulting in a change in only the modal patterns, though the resonant frequencies are comparable. The results are inconclusive as per whether the criteria are met for the validation model created through MWS to be scaled up. However, an attempt was made to run simulations at the calculated design parameters for the 8GHz model. The 1D electric field magnitude plot of these results are shown in Figure 6 and when compared to Figure 4, they have the same 17 peaks. This could state that the differences between the validation model and Choi's may be systematic.

As a future outlook, a re-visit to the validation model should be made to try and excite the same modes through coupled waveguides as was done by Choi rather than a current source as was used in this case. This is to be certain that the difference in field magnitude near the axis is purely due to the use of a current source, or another factor yet to be determined. The next phase would then be to scale up the dimensions to optimize the resonator for a given sample plate size.

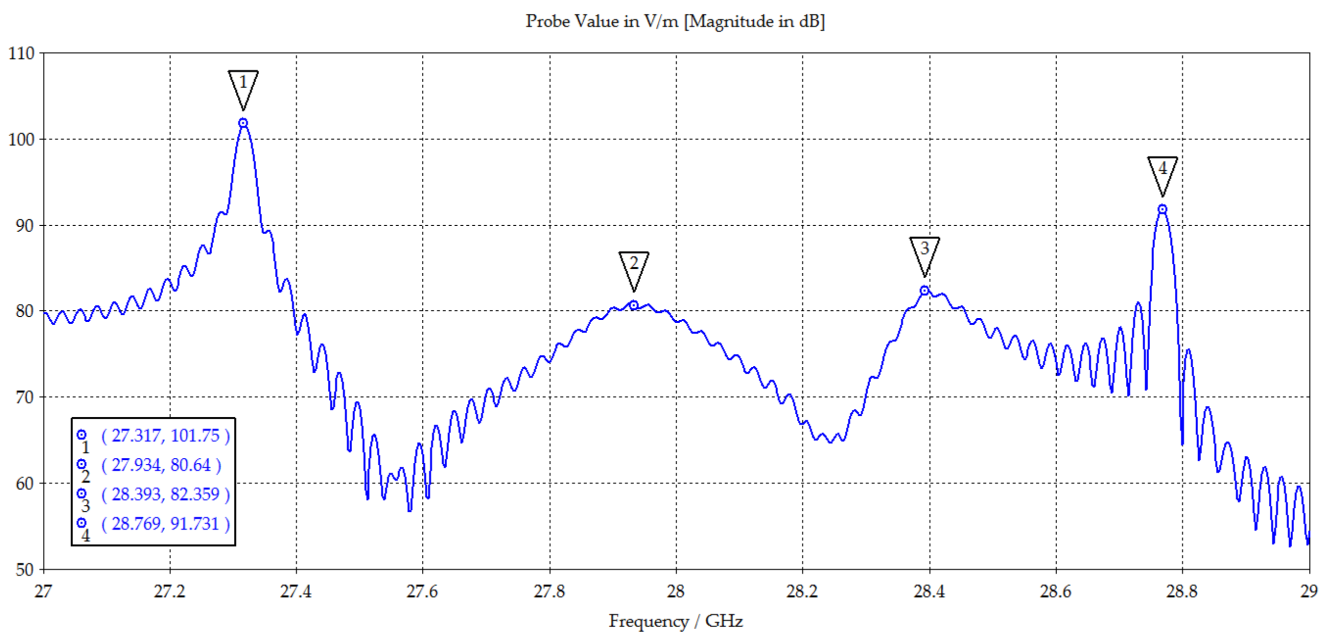

Figure 2: Graph of probe value (V/m, magnitude of peak in dB) versus frequency (GHz).

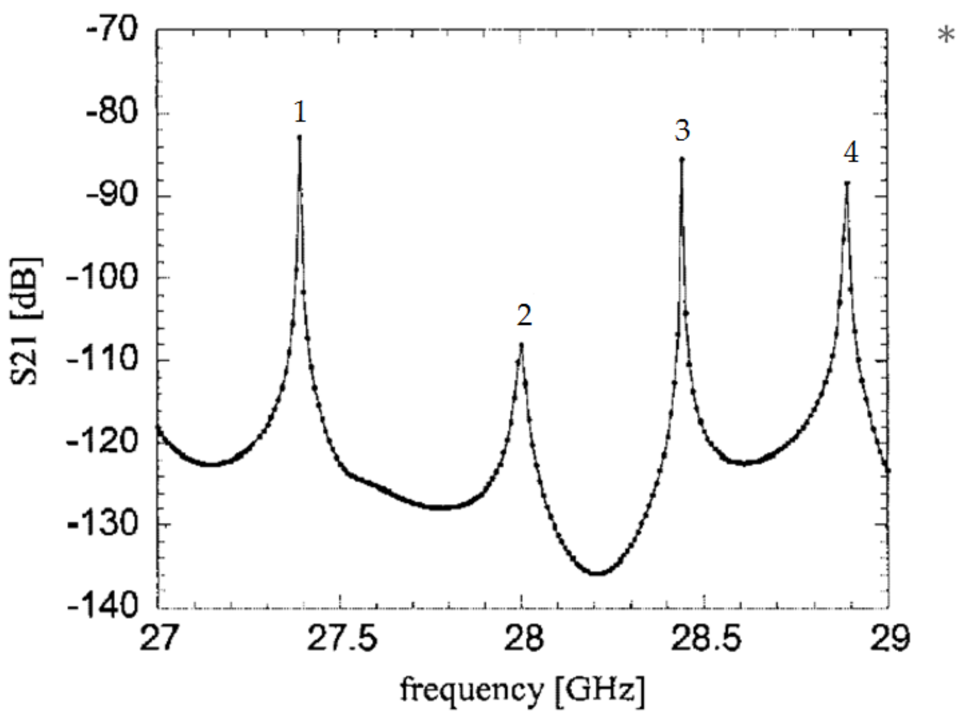

Figure 3: Graph of forward transmission in dB versus frequency in GHz. Peaks 1-4 are located at 27.39, 28, 28.44, and 28.89GHz, respectively.[5]

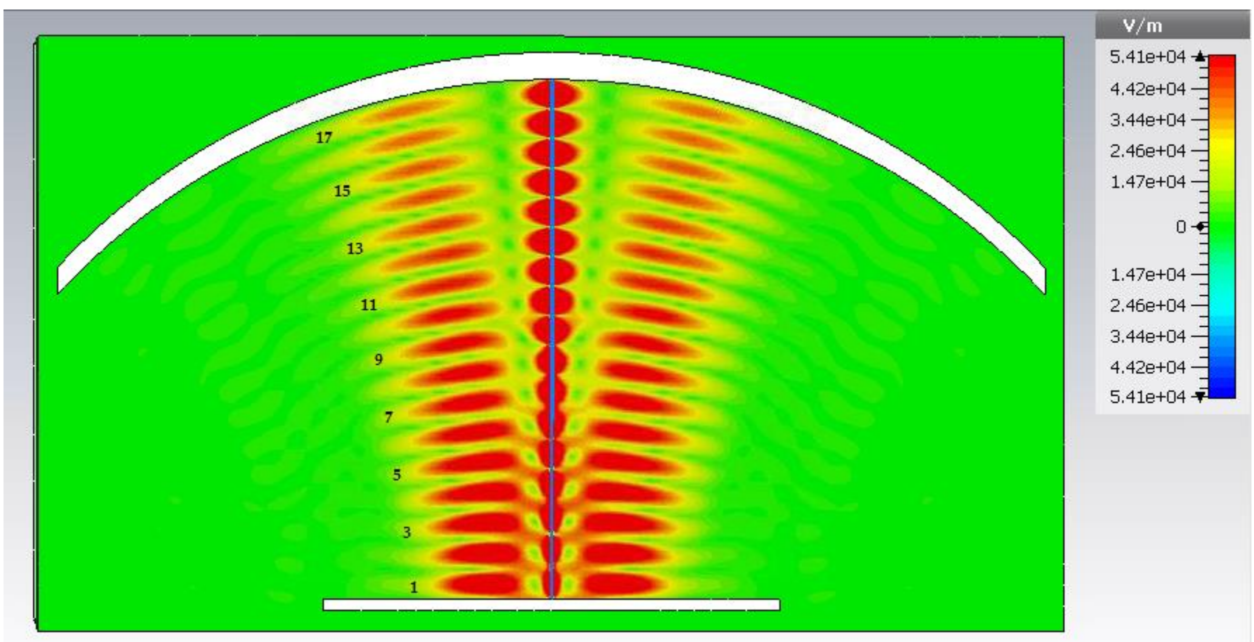

Figure 4: 1-D magnitude of electric field shown at 27.317GHz, the supposed $TEM_{0,0,17}$ mode.

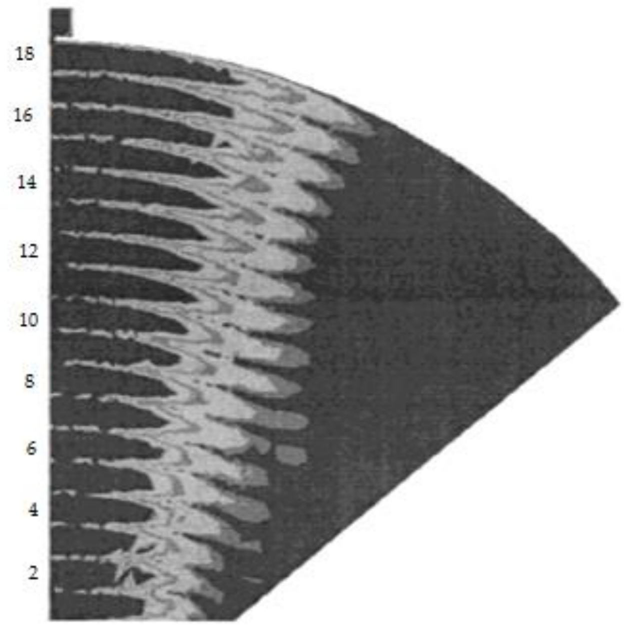

Figure 5: Magnitude plot of the electric field at 27.39GHz, the 18 field peaks indicate that the mode is $TEM_{0,0,17}$. [5]

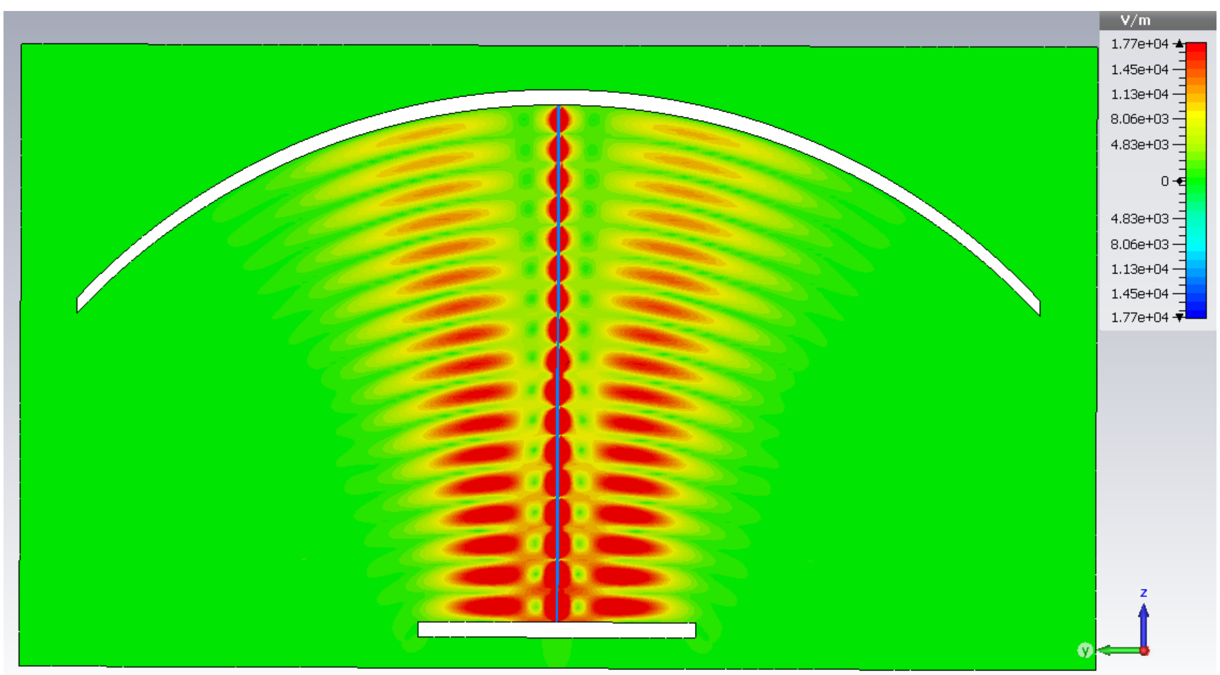

Figure 6: 1D electric field magnitude with respect to axial position of the scaled cavity at 7.848GHz, the 17 peaks represent the same mode found in the validation model.

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