High Q Dielectric Resonators using $\text{YBa}_2\text{Cu}_3\text{O}_x$ Thick Films and Polycrystalline Dielectrics

Stuart J. Penn and Neil McN. Alford
EEIE, South Bank University, London, SE1 0AA, UK

Tim W. Button
IRC in Materials, University of Birmingham, B15 2TT, UK

Abstract — The combination of high Q dielectric resonators and high temperature superconducting (HTS) films offer many advantages in the area of cellular and satellite communications. The high cost of single crystal dielectrics and HTS thin films may be unattractive in certain applications. Superconducting thick films and polycrystalline ceramic dielectrics offer a high performance, low cost alternative to high Q thin film/single crystal dielectric resonators. Results on polycrystalline dielectrics show that Q 's well in excess of 10^5 at 10 GHz and 77 K can be achieved in a design made compact by the use of a HTS thick film shield.

B. Dielectric Ceramics

Alumina discs were produced from commercial high purity alumina powders. The powders were pressed in a die press and sintered in air at about 1500°C to form discs of nominal diameter 10 mm and height 4.5 mm. The fired discs were close to 100% theoretical density (> 97%). Room temperature material Q 's ($1/\tan \delta$) of 37,000 at 9 GHz have been achieved [5]. Room temperature Q 's of 50,000 have been achieved by doping the alumina with titania, TiO_2 [5]

I. INTRODUCTION

The growth of microwave communications has led to the requirement for compact high Q resonators. Sapphire and HTS thin films have been used to construct dielectric resonators which have shown very high Q 's [1,2]. A single filter requires several such resonators. The high cost of single crystal sapphire and thin films may make this type of filter too expensive to be economically feasible. Cheaper alternatives are HTS thick films and ceramic dielectrics. Results for $\text{YBa}_2\text{Cu}_3\text{O}_x$ thick films and alumina (Al_2O_3) ceramics are presented here. Alumina was chosen as it is the polycrystalline equivalent of sapphire. Alumina and sapphire have a dielectric constant, ϵ_r , of about 10. The size of a dielectric resonator can be reduced by using a dielectric with a higher ϵ_r , such as $\text{Ba}(\text{Mg}_{1/3}, \text{Ta}_{2/3})\text{O}_3$, $\epsilon_r = 24$.

II. MATERIAL PREPARATION

A. $\text{YBa}_2\text{Cu}_3\text{O}_x$ Thick Films

The preparation of $\text{YBa}_2\text{Cu}_3\text{O}_x$ thick films has been presented in detail elsewhere [3,4]. Briefly an ink made from $\text{YBa}_2\text{Cu}_3\text{O}_x$ powder, polymers and solvents is doctor bladed on to a polycrystalline yttria stabilised zirconia substrate. The film is then fired above the peritectic temperature to form a melt textured film with spherulitic morphology. The films produced by this method have shown a surface resistance of 1.5 m Ω at 7.5 GHz and 77 K.[4].

III. MEASUREMENT AND RESULTS

A. Surface Resistance

The surface resistance of the $\text{YBa}_2\text{Cu}_3\text{O}_x$ thick film was measured using a dielectric resonator technique with a single crystal sapphire dielectric as shown in Fig. 1. The sapphire had a diameter and height of 11.90 mm and 5.50 mm respectively and the gap between the sapphire and the top thick film plate was 2 mm. The quality factor Q of the $\text{TE}_{01\delta}$ mode was measured on a HP8719C Vector Network Analyser. The resonator was cooled by a closed cycle cryostat.

The resonance was weakly coupled. The Q of a resonator is given by

$$\frac{1}{Q} = \frac{1}{Q_d} + \frac{1}{Q_s} \quad (1)$$

Fig. 1. Schematic diagram of dielectric resonator

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Fig. 2. The surface resistance of YBa₂Cu₃O_x thick films at 10.47 GHz..

where Q_d is the dielectric Q ($=1/\tan \delta$, where $\tan \delta$ is the dielectric loss tangent) and Q_s is the Q of the superconducting plates. For sapphire $Q_d \gg Q$, therefore $Q \approx Q_s$. The surface resistance of the thick film was calculated from a variational method based on the Itoh and Rudokas model using routines based on those in [6]. The temperature dependence of the R_s of the thick film at 10.47 GHz is shown in Fig. 2.

B. Q of YBa₂Cu₃O_x Thick Film and Alumina Resonator

A dielectric resonator was constructed as in Fig.1 using the same thick film plates as above. The sapphire was replaced with a sintered alumina (Al₂O₃) ceramic, diameter 10.70 mm and height 5.38 mm. The gap between the top of the alumina and top thick film was 1.5 mm. The alumina was doped with 0.5% TiO₂ to increase the Q [5]. The effective Q of the thick films, Q_s , in this configuration was calculated using the data for R_s above corrected for the small difference in frequency, f , by assuming an f^{-2} dependence. The Q of the alumina was then calculated using (1). The Q , Q_d and Q_s at 11.05 GHz are shown in Fig. 3. The dielectric constant of the alumina was calculated to be 9.48.

C. Q of Ba(Mg_{1/3}Ta_{2/3})O₃

In order to reduce the size of a dielectric resonator it is necessary to increase the dielectric constant of the material used. Unfortunately, generally speaking the higher a material's dielectric constant the lower its Q . Very few results are available for the properties of dielectric ceramics at cryogenic temperatures. Reference [7] suggests that the Q of Ba(Mg,Ta)O₃ increases as the temperature is reduced whereas [8] suggests that it decreases.

To determine the Q of Ba(Mg,Ta)O₃ from room temperature to 12 K a dielectric resonator was constructed as in Fig. 4. The spacer was a 4 mm thick disc of low loss quartz. The R_s of the copper cavity was determined from room

Fig. 3. Quality Factor of an alumina and YBa₂Cu₃O_x thick film dielectric resonator at 11.04 GHz. The figure shows the measured Q of the resonator and the Q 's of its constituent parts.

temperature down to 10 K by measuring the Q of the TE₀₁₁ mode of the empty cavity. The R_s was used to remove the effect of the copper on the measured Q . The results for a disc of commercially available Ba(Mg,Ta)O (Murata), diameter 7.69 mm and height 3.04 mm, at 8.34 GHz are shown in Fig. 5. It can be seen from Fig. 5 that due to the spacing of the dielectric from the copper walls the measured Q is very close to the Q of the dielectric.

IV. DISCUSSION

The results above can be used to calculate the Q of cryogenic dielectric resonators using Ba(Mg,Ta)O₃ and YBa₂Cu₃O_x thick films. It is necessary to scale the results for the R_s of the thick film and Q of the dielectric with frequency. The R_s of a superconductor scales as f^{-2} and for the Q of the dielectric the $Q \times f$ product is assumed to be constant. These are reasonable assumptions over the range of frequencies considered here.

If the Ba(Mg,Ta)O disc measured above is formed into a resonator by placing it between the thick film plates without a gap, the resonator would have a Q of 17,933 at 77 K and

Fig. 4. Schematic of resonator used to measure Q of Ba(Mg,Ta)O₃ Ceramics

Fig. 5. The Q of a commercial Ba(Mg,Ta)O dielectric as a function of temperature at 8.34 GHz. The measured Q and the Q of the dielectric with the loss in the copper cavity removed are shown.

23,134 at 60 K and the resonant frequency would be 12.56 GHz. However, this geometry may not give the optimum performance. There is a balance between the size and Q of a resonator. Increasing the gap between the dielectric and the thick film plates increases the Q of the resonator at the expense of size and weight. Also, increasing the gap reduces the frequency of the resonator. To recover the frequency of resonator the size of the dielectric must be reduced. The reduction in the size of the dielectric is not enough to compensate for the gap so there is still a net increase in size. Placing a gap between the superconductor and dielectric may be important for high power devices because as the gap increases the r.f. field seen by the superconductor reduces.

To show the effect of the gap on the Q of a resonator a target frequency of 10 GHz was chosen. The Q of the resonator was calculated for different gaps with the dielectric size adjusted to keep the resonant frequency 10 GHz. The gap between the top plate and the resonator and the bottom plate

Fig. 6. Effect of gap size on the Q of a 10 GHz dielectric resonator constructed from a Ba(Mg,Ta)O dielectric and YBaCuO thick films. The resonator height is defined as the thickness of the dielectric plus the top and bottom gaps. The curves show a gap variation from 0 mm to 3 mm.

Fig. 7 Effect of gap size on the Q of a 10 GHz dielectric resonator constructed from an alumina dielectric and YBaCuO thick films. The resonator height is defined as the thickness of the dielectric plus the top and bottom gaps. The curves show a gap variation from 0 mm to 5 mm.

and the resonator were set to the same value. The ratio of the dielectric's height to diameter was fixed to 0.4. The R_s and dielectric Q used in the modelling were taken from the data above. The results are plotted as resonator Q against resonator height, where the resonator height is taken to be the thickness of the dielectric plus the top and bottom gap. The results for a Ba(Mg,Ta)O - YBa₂Cu₃O_x thick film resonator are shown in Fig. 6 and the results for an alumina - YBa₂Cu₃O_x thick film resonator are shown in Fig. 7. As expected as the gap is increased the Q rises asymptotically towards the Q of the dielectric.

A summary of the material properties at 20 K, 60 K and 77 K normalised to 10 GHz is shown in Table 1.

V. CONCLUSION

Sintered alumina and Ba(Mg,Ta)O dielectrics show very high Q 's at low temperature. The use of high quality YBa₂Cu₃O_x thick films offers an attractive combination of material properties for the manufacture of microwave components such as filters at low cost. The use of the superconductors allows maximum advantage to be taken of the dielectrics' high Q without sacrificing the small size.

TABLE 1
SUMMARY OF MATERIAL PROPERTIES AT 20 K, 60 K AND 77 K
NORMALISED TO 10 GHz

Material	20 K	60 K	77 K
Alumina, Q	704,990	340,614	269,576
Ba(Mg,Ta)O, Q	87,820	43,192	36,892
YBaCuO Thick film, R_s (mΩ)	0.544	0.945	1.45

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