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Barium strontium titanate dielectric helical resonators

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Abstract

This paper presents the processing, modelling and results of a resonant element made from ultra high permittivity dielectric material shaped into a helix. The ceramic helix was made from bulk barium strontium titanate and was produced by viscous plastic processing (VPP). A 1.2 turn and 1.75 turn helix was produced and measured to validate the electromagnetic modelling results. Some of the helices studied in this work are very compact. An optimised device may possess moderate Q factors, due to the low filling factors. The dielectric loss and permittivity of the bulk barium strontium titanate were also measured at microwave frequencies. The quality factors achieved in this paper with dielectric helical resonators, made from barium strontium titanate, are the highest so far attained.

Keywords: Dielectric properties; Functional Applications; Communications; Helices

1. Introduction

High performance resonators are needed at microwave frequencies for use in communications filters. Such filters are typically designed to operate at a wide variety of centre frequencies, e.g. 900, 1800, 2400 or 5600 MHz, but only over a fairly narrow range of frequencies. The resonators themselves need to be small, temperature stable and have a fairly high quality factor (Q). The earliest resonators used for communication filters were very simple air filled cavity resonators supporting a standing electromagnetic wave along its length.[1] More contemporary filters are often based on some form of quarter wave resonator.

Conventional quarter wave resonators (sometimes referred to as combline resonators), Fig. 1, have an inner metal finger and metal outer, and can achieve Q's on the order of 5000. Recent work by Wang et al.[2] has introduced a new type of combline resonator called a dielectric combline resonator (DCR). In this design the inner metal finger is replaced by a high permittivity dielectric rod and can achieve Q's on the order of 10,000 in the same volume. Several papers have now been published on this type of resonator.[3] The principle behind the DCR is illustrated in Fig. 2, which considers the electric field perpendicular to an air/ceramic interface. For this configuration the electric flux density D, is conserved across the boundary. Hence $D_0 = D_1$ where D_0 and D_1 are the electric flux densities in the air and inside the ceramic respectively. Consequently the size of the electric field inside the ceramic, E_1 is given by $E_1 = (\varepsilon_0 E_0)/\varepsilon_1$. Therefore in principle the amount of electric field inside the ceramic can be made extremely small providing a sufficiently large permittivity is used. Thus the DCR is based upon the principle that a ceramic material, with sufficiently high permittivity, can exclude the electric field from within the rod and hence behave rather like a metal.[2] The key advantage is that conductor losses on the inner of the combline resonator are eliminated with a corresponding increase in Q.

The principle behind the dielectric helical resonator (DHR) shares some similarities with that behind a dielectric combline resonator (DCR) introduced by Wang et al.[2] Previous work[4] has shown that a relatively thick dielectric helix can act as a resonant structure and that the mode was very similar to that found in a dielectric combline resonator.[2] However that early work was concerned with relatively low permittivities in the region of 40–100. This work is concerned with dielectric helical resonators (DHR) made from very high permittivity materials such as barium strontium titanate (BST) which can have permittivities on the order of 500–6000 depending upon the composition.[5] A

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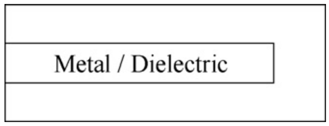

Fig. 1. Schematic of a quarter wave resonator.

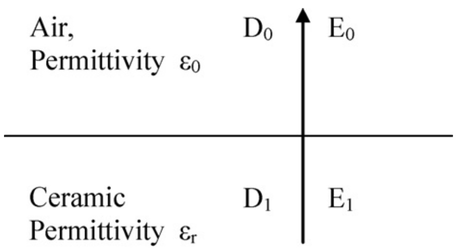

Fig. 2. Schematic of the electric field at an air/ceramic boundary.

conventional metallic helical resonator has an even smaller volume than a combline resonator but its Q is limited to 1000–2000. This paper examines the possibility of using a dielectric helix as a resonator. In principle it may be possible using a DHR to achieve the same Q as that of a conventional metallic combline resonator, but in a volume that is at least an order of magnitude smaller.

2. Experimental arrangement and design simulation

For this work it was desired to use a material with high permittivity and the material available that seemed most appropriate was barium strontium titanate (BST). The BST powder supplied by Power Wave contained ∼2.0 wt% organic binder that was subsequently burnt out at 500 °C for 3 h prior to use, and had a composition of 70% ($Ba_{0.55}Sr_{0.45}TiO_3$) 30 mol% MgO. BST is far from an ideal material due to its very high value of TC_ε, as well as its high dielectric loss. Therefore several groups have tried to use MgO doping, to reduce both TC_ε, as well as $\tan\delta$. In this work a paraelectric composition of $Ba_{55}Sr_{45}TiO_3$ was used with a doping level of 30 mol% MgO, giving a T_c of −55 °C. Small doping levels of MgO tended to shift T_c fairly linearly, from about −11 to −55 °C at 0.1 and 1.0 mol% respectively. Doping levels larger than 1.0 mol% failed to shift T_c significantly. The BST used in previous work[6] was doped with only 0.002 mol% MgO and had produced a DHR with a very low Q of 142. However with a doping level of only 0.002 mol% MgO it had a T_c of −26 °C, although still in the paraelectric state at room temperature.

Helices, were prepared from ceramic dough formed through a viscous processing route.[7] The dough, incorporating the BST powder, polymer binder and solvent mixed and de-agglomerated on a twin-roll mill, was extruded through a circular die to form a flexible wire. The wire was wound onto a former of the appropriate diameter to form a helix, and then dried at room temperature to harden the dough and fix the shape of the helix. The dried helices were then carefully transferred onto alumina bars wrapped in Pt foil and heated to 1450 °C for 2 h to burnout the binder and sinter the BST. A 1.2 turn sintered helix is shown in Fig. 3.

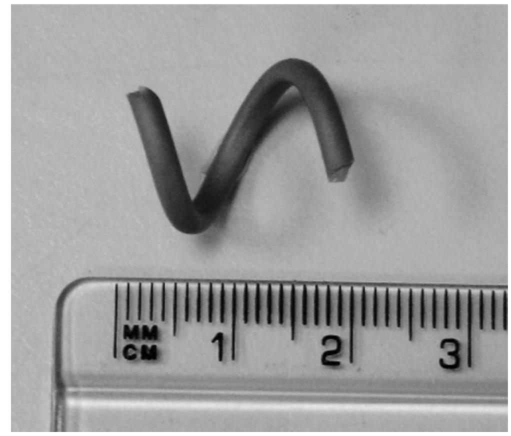

Fig. 3. Picture of the 1.2 turn BST helix.

Each BST helix was measured in a cylindrical copper cavity supported by a PTFE (polytetrafluoroethylene) rod. The cavity was manufactured from copper and was 70 and 45 mm in length and diameter respectively. The PTFE support maintained the helix co-axially within the cylindrical cavity, and kept the helix midway between the ends. Therefore the helical resonator considered here was principally a half wavelength resonator. The PTFE support had an outer diameter of approximately 20 mm. The BST helix was approximately 1.2 turns in size and with a pitch and minor radius of 15 and 1.25 mm respectively.

Coupling loops were fed into the cavity near the centre where the helix was placed. The coupling loops were connected to the two ports of a network analyser (Agilent 8753E). The network analyser was used to investigate resonances in the spectrum by measuring the Q factor in transmission. The frequencies and quality factors associated with each of the resonances were measured.

CST Microwave Studio™ software package was used for numerical modelling of the structures. Firstly, CST's eigenmode solver was used to calculate the resonance frequencies and the corresponding electromagnetic field patterns (eigenmodes) for closed loss free structures. Finally, the Q factor for each individual mode can be calculated by computing its surface losses using the perturbation method as well as dielectric losses using the same software. The conductive surfaces were all assumed to be copper (resistivity, $\rho = 1.7 \times 10^{-8}\ \Omega$m). The modelling assumed a complex relative permittivity for PTFE of $\varepsilon_r = 2.08$ and $\tan\delta = 2.4 \times 10^{-4}$ as reported by Krupka et al.[8] at 10 GHz. For BST the real part of the permittivity is assumed not to be frequency dispersive but the loss tangent is assumed to be proportional to frequency.

In addition to the helix, straight rods of BST were also extruded by the same processing route. These rods of BST were produced, from the same batch of powder, to enable the measurement of its permittivity and loss tangent. They were measured in a modified Hakki–Coleman resonator developed by Geyer et al.[9] as shown in Fig. 4. Essentially a BST rod is inserted down the centre of a high permittivity dielectric ring resonator (DRR) and the change in resonant frequency and Q permits the calculation of the permittivity and loss tangent of the BST respectively.

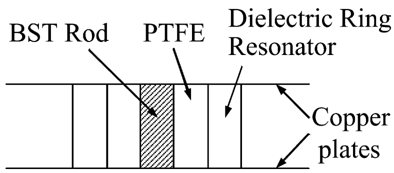

Fig. 4. Cross-section schematic of the modified Hakki–Coleman resonator developed by Geyer et al.

In this case the DRR was made of Zirconium Tin Titanate (ZTS) and the end plates on each face were made of copper.

In a dielectric helical resonator (DHR) the total losses of the structure can be divided into a series of contributions from different loss mechanisms. Hence the overall unloaded Q, Q_u can be divided up as in Eq. (1), where Q_c represents the conductor losses in the metal cylindrical walls and end plates, Q_D represents the dielectric losses in the BST, and Q_{DPTFE} represents the losses due to the dielectric loss of the PTFE support.

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_D} + \frac{1}{Q_{DPTFE}} \tag{1}$$

Finally Q_D can be related to the filling factor, *ff*, and the dielectric loss tangent of the BST, tan δ, via Eq. (2). The filling factor, *ff*, represents the fraction of the electric field energy inside the BST.

$$Q_D = \frac{1}{ff \tan \delta} \tag{2}$$

In all the cases examined here the dielectric losses in the PTFE were typically two orders of magnitude smaller than those in the BST. Therefore Eq. (1) reduces down to

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_D} \tag{3}$$

3. Results and discussion

The standard BST rods were measured at a frequency of 2.52 GHz in a dielectric ring resonator made from zirconium tin titanate (ZTS). As a check, on the accuracy of the measurement system developed by Geyer et al., the resonant frequency and unloaded Q were measured with no sample present, these results are displayed in Table 1. The agreement between the measured and simulated resonant frequency is excellent and the measured Q is approximately 91% of the theoretical value, which also agrees well. The measured values for the BST rods, of permittivity and loss tangent, were found to be 1075 ± 15 and 0.0035 ± 0.0005 respectively. These values were then used in the CST modelling to predict the resonant frequency and Q factor of the BST helix. Measurements had also been taken of the permittivity of the BST at a frequency of 1 kHz using a precision LCR meter, giving a value of 1150 ± 50.

The measured and simulated resonant frequency and unloaded Q of the DHR are shown in Table 2 for both a 1.2 and 1.75 turn helix. The error between the simulated and measured resonant frequency is about 1–2%, which is very good, considering that the BST helix has some minor deviations from the profile of a perfect helix. However the agreement between measured and simulated Q is not as good, with an error of about 12–24%. But this is not surprising, as the error in the tan δ value alone, used in the modelling, is about 15%. For this helix, approximately 55% of the electric field energy is confined within the BST helix, which helps to explain its rather low Q. In all cases the conductor Q was on the order of several hundred thousand, so the unloaded Q is overwhelmingly dominated by the dielectric loss of the BST.

At 2.52 GHz this BST, in the paraelectric state, had a loss tangent of 0.0035 ± 0.0005. Assuming a linear dependence for the loss tangent, then extrapolating down to 1 GHz this BST should have a loss tangent of 0.0014. Previous work on the same BST composition,[6] but with an MgO doping of 0.002 mol%, had a loss tangent of 0.005 at 1 GHz. The BST used in this work had a T_c of −55 °C whereas the T_c of the 0.002 mol% MgO doped material had a T_c of −26 °C. This might explain the significant difference in the dielectric loss between the two compositions. As the 30 mol% MgO-alloyed BST was much further from its T_c it would be expected to have lower dielectric losses. So the BST material used in this work therefore represents an improvement in the loss tangent of a factor of 3 over previous work.

Table 1
Comparison of the frequency and Q for the empty ZTS DRR operating at 2.5 GHz.

	Measured	Simulated
Freq (GHz)	2.588 ± 0.002	2.588
Unloaded Q	10290 ± 50	11,363

Table 2
Comparison of the measured and simulated properties of the BST helices.

	Freq (GHz)	Unloaded Q
1.2 turn helix		
Measured	2.661 ± 0.01	560 ± 50
Simulated	2.691	442
1.75 turn helix		
Measured	2.045 ± 0.01	730 ± 50
Simulated	2.092	819

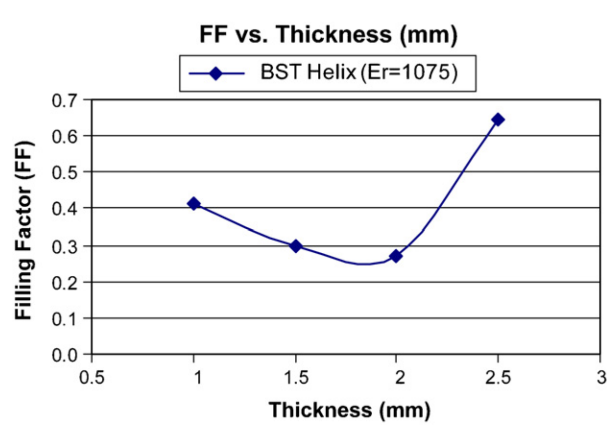

Fig. 5. Filling factor for an optimised DHR.

With proper optimisation of the design it would be possible to achieve much lower filling factors on the order of 0.25, with a significant increase in the Q. This is illustrated in Fig. 5 where the filling factor for a DHR with a permittivity of 1075 is shown vs. minor radius. The minor radius is the radius of the ceramic wire from which the helix is formed. With a more optimised design and a $\tan\delta$ of 0.0035 an unloaded Q of approximately 1100 could be achieved.

4. Conclusion

Measurements have been taken, of the dielectric loss of the same BST composition with 30 mol% MgO doping, showing considerable reduction in the losses compared to 0.002 mol% MgO doping. If measurements were extrapolated to an identical frequency then the losses with the 30 mol% MgO doping would be approximately 3 times lower than with the 0.002 mol%. Good agreement has been achieved between the modelled and measured results for a 1.2 and 1.75 turn dielectric helical resonator. With a proper optimised design and the loss tangent measured in this work a dielectric helical resonator could be produced with a Q of over 1100. Since in this work the dielectric loss is dominant, future work will look at the use of titania as the dielectric which should give significantly lower dielectric losses and consequently much higher Q's.

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