Helical resonators containing high T_c ceramic superconductors

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(Received 15 June 1989; accepted for publication 21 August 1989)

Resonators are the single most important ingredient in microwave and radio frequency circuits. We have produced some helical resonators using a bulk $\text{Ba}_2\text{YCu}_3\text{O}_7$ high T_c ceramic superconductor. These resonators, which operate at 77 K and cover the frequency range from 0.1 to 2.0 GHz, outperform their all copper counterparts by at least a factor of 5 in unloaded Q .

Without a doubt resonators are the single most important ingredient in microwave and radio frequency circuits. There are basically four types of resonators: (1) inductance-capacitance tuned circuits, (2) reentrant cavities such as sections of a coaxial transmission line, (3) cavity resonators of the waveguide type, and (4) a cavity consisting of a coil in a shield. This latter type is the so-called helical^{1,2} resonator and it operates as a slow-wave transmission line^{3,4} with a relatively high characteristic impedance. Traditionally such structures have had one end of the coil short circuited to the shield and the other end open.

These helical resonators have many applications in the rf through microwave spectrum. They are used extensively as preselection filters in receivers, as interstage filters in IF amplifiers and as resonant elements in oscillators. They are easy to construct, have good Q 's, and can be fairly small in size. At times their shape can be quite a distinct advantage. For example, a coaxial resonator at 400 MHz might typically have an 8:1 length to diameter ratio, while an equivalent helical resonator might have a 3:2 ratio.

A good description of the space saving advantage of a helical resonator has been given by Macalpine and Schildknecht.² As they point out, a helical resonator for 10 MHz with an unloaded $Q = 1000$ is about 6 in. in diameter by 8 in. long. In contrast, a coaxial resonator would be 25 ft long and 3 in. in diameter. An equivalent inductance-capacitance tuned circuit would approach the size of a large trash can.

In principle, we should be able to improve the performance of a helical resonator by making it from high T_c ceramic superconductors. In the past it was not possible to fabricate a helix out of high quality material. Recently, a method was developed by I. C. I. Advanced Materials⁵ to form ceramic parts for electronic equipment⁶ by a viscous processing method which enabled quite complex shapes to be made because the green body, with its polymer carrier, is truly plastic. Extrusion of rods, wires, pipes, and helices poses no problem for Y-Ba-Cu-O superconductors and theoretical density is achieved after firing. The superconductor has a critical current density of 2000 A/cm², a very smooth surface, and a flexural strength of 2000 MPa. The smooth surface leads to low rf loss and the high flexural strength permits strong, reliable components to be made. A critical current density of 2000 A/cm² is satisfactory for many rf applications.

As mentioned before, the usual configuration of a helical resonator has one end of the helix short circuited to the shield. To make optimum use of the superconductor, it is wise to make a resonator with both ends open to eliminate any losses associated with a solder or other joint. No design data seem to be available for such a resonator, even using copper.

To design a helical resonator using a ceramic superconductor we need an expression for the surface impedance as a function of frequency. We would expect that the real part of the surface impedance should increase as f^2 . However, we usually find that for long lengths of ceramic superconductor (> 6 in.), the frequency dependence is $\sqrt{f}$, just as in a normal metal.^{7,8} This means that the long ceramic wire, on average, is acting like a normal metal but with a reduced surface impedance. Typically, this ranges from a value near that of copper (at 77 K) to one-tenth that of copper. The average surface impedance of the long wire is thus many orders of magnitude larger than one would obtain using a normal metallic superconductor.⁹

It is interesting to note that Gyorgy and co-workers¹⁰ have conclusively demonstrated persistent currents in single-phase $\text{Ba}_2\text{YCu}_3\text{O}_7$ and set an upper limit of 3×10^{-18} Ω cm on the dc resistivity of this material at 77 K with $J > 100$ A/cm². Their measurements were for path lengths of only a few centimeters, however. We believe that the losses we are experiencing are largely due to grains and other phases of the material, which are difficult to control over longer path lengths. However, we do find that shorter lengths of material have a frequency response lying somewhere between f and $\sqrt{f}$. Because of the difficulty in finding a correct expression for the surface impedance of the superconductor, we decided to design on the basis of copper and ascertain where in the structure the impact of adding a superconductor is greatest.

In general, a copper coil in a close fitting shield has a distributed inductance L modified by the presence of the shield. Thus^{11,12}

$$L = 0.025N^2d^2[1 - (d/D)^2]\mu\text{h/in.} \quad (1)$$

Here N = turns/in., d = mean diameter of turns in inches, and D = mean shield diameter in inches. Likewise, there is a distributed capacitance C given by²

$$C = 0.75/\log_{10}(D/d)\text{pF/in.} \quad (2)$$

This formula approximates the capacitance of the structure by two simple coaxial cylinders. The resonant frequency f_0 for a helix with both ends open can be written as

$$f_0 = 2/b \sqrt{LC}. \quad (3)$$

Here b is length of the helix in inches. The impedance Z_0 can be expressed as

$$Z_0 = 1000(L/C)^{1/2}. \quad (4)$$

As an example, consider a copper helix 0.4 in. in diameter and 1.455 in. long with 12.37 turns per inch. These dimensions are the same as a typical ceramic superconducting helix. Figure 1 shows the result of evaluating Eqs. (1)–(4) at room temperature for these dimensions as a function of the shield diameter D . We note that a closely spaced shield has a significant effect. A typical shield diameter used in our experiments is 1.5 in. For this case, we calculate Z_0 to have the relatively high value of 660 Ω and f_0 to be 375 MHz. An experimental measurement of f_0 for this case gives 360 MHz in good agreement with theory. The theory works well for other dimensions as well.

There are three sources of loss that must be considered in the design of a helical resonator. They are (1) dielectric loss in the support for the helix, (2) surface resistance loss in the helix, and (3) shield loss. By making the dielectric support for the helix from thin walled, high quality fused quartz tubing the support loss can be made extremely small.

For a copper helix, the surface loss is due to skin and proximity effects. The loss resistance R_c at room temperature can be expressed approximately as¹³

$$R_c = (0.083 \times 10^{-3}) (\phi/d_0) N \pi d f^{1/2} \Omega/\text{in.} \quad (5)$$

Here d_0 is the diameter of the conductor in inches. The factor ϕ depends on the ratio of the coil length to diameter and the closeness of the windings. This function is tabulated in Ref. 13 and we use bilinear interpolation to find intermediate values. The loss in the copper shield can be expressed by a loss resistance R_s .¹¹ Thus

$$R_s = \frac{(9.37) N^2 b^2 (d/2)^4 (1.724 f_0)^{1/2}}{b [D^2(b+d)/8]^{4/3}} \Omega/\text{in.} \quad (6)$$

The unloaded Q of the resonator is given by

$$Q = 2\pi f_0 L / (R_c + R_s). \quad (7)$$

Evaluating Eqs. (5)–(7) for the same parameters as before leads to Fig. 2. We see that R_c is always larger than R_s . For

FIG. 1. f_0 , Z_0 , C , and L values for a helical resonator with $d = 0.4$ in., $b = 1.455$ in., and 12.37 turns/in. The horizontal axis is D , the diameter of the shield.

FIG. 2. Q , R_s , and R_c values for a helical resonator with $d = 0.4$ in., $b = 1.455$ in., and 12.37 turns/in. The horizontal axis is D , the diameter of the shield.

$D > 1.5$ in., R_s can be essentially neglected. We also note that Q drops sharply for $D < 1.0$ in. For $D = 1.5$, Q is calculated to be 1150. This is almost exactly what we find experimentally at room temperature.

From the analysis just presented it should be clear that if we replace the copper helix with a superconducting helix the Q should improve. In fact, unless one wishes to reduce D , it is not necessary to replace the copper shield with a superconducting shield to obtain a significant improvement.

To make a practical helical resonator the liquid-nitrogen coolant must not be allowed to get inside the cavity. The bubbling causes the dielectric constant to fluctuate and the resonant frequency of the cavity to vary in a random manner. Thus the cavity must be sealed. In addition, the condensation of liquid oxygen must be avoided. Otherwise, as it moves about in the cavity, it too causes frequency shifts. Also, the connectors that couple power in and out of the cavity must not leak liquid nitrogen. Finally, the resonator must be economical in its use of liquid nitrogen and this requires low thermal loss cable.

Figure 3 shows a practical resonator. The helix is inside a thin walled, high quality fused quartz support tube. Usually it is held in place by glass (silica) wool. The seal on each end has ground metal joints, much like copper pipe unions, to allow disassembly but prohibit the influx of liquid nitrogen. The coax is made from stainless-steel tubing and a stainless-steel rod with a thin layer of copper plated on it. The

FIG. 3. Practical helical resonator. Note that it is totally sealed.

FIG. 4. Equivalent circuit for a resonator.

coax passes into the resonator through compression fittings which also prohibit liquid-nitrogen leakage into the cavity. The coupling to the resonator is adjusted by either rotating the coupling loops or by moving them in or out of the cavity. The resonator is tuned by means of copper slugs which also pass into the cavity through compression fittings. Before cooling, the cavity is blown out with nitrogen gas, to eliminate the possibility of condensation of liquid oxygen.

In general, resonators may be one, two, or multiport and may have a variety of coupling schemes. Ours are, for the most part, two port with loop couplings. Figure 4 shows the equivalent circuit for such a cavity. Coupling is considered in the form of an ideal transformer of $N:1$ turns ratio while losses are represented by R_{eq} . The quantities R_{eq} , L_{eq} , and C_{eq} should be considered as intrinsic parameters of the cavity proper, whereas N^2 reflects the effect of the coupling. It is not difficult to show^{14,15} that the voltage transmission coefficient T can be expressed as

$$T = 1 - Q_L/Q_u. \quad (8)$$

Here Q_L and Q_u are the loaded and unloaded Q 's of the cavity, respectively. Thus by measuring the voltage transmission coefficient and the loaded Q we can obtain the unloaded Q and Q_u . We also note that Eq. (8) is a linear relationship which makes analysis particularly easy. We can determine Q_u by measuring Q_L for a number of values of T and extrapolating to $T = 0$.

We have made and evaluated a substantial number of helical resonators over the frequency range from 100 to 2000 MHz and all have performed better than their all copper counterparts at 77 K, as far as Q is concerned. Figure 5 shows data taken on a typical helical resonator whose resonance frequency is 360 MHz. The lower curve is for a copper helix at 77 K, while the upper one is for the ceramic superconductor. The dimensions are the same as before. We note the improved performance of the ceramic superconductor over the copper helix. As expected, replacing the copper shield with a superconducting shield had essentially no effect.

FIG. 5. Experimental data taken at 355 MHz and 77 K on the helical resonators made of copper and ceramic high T_c superconductor. Note that the superconductor outperforms the copper.

In conclusion, it is possible to make high T_c helical resonators that perform better than their all copper counterparts over the frequency range from 100 to 2000 MHz by at least a factor of 5 at 77 K. In fact, on occasion we have had helices that outperformed copper by a factor of 10.

We would like to express our appreciation to A. E. White, C. S. Saunders, and L. Watkins.

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