

TITLE

HIGH TEMPERATURE

SUPERCONDUCTOR-DIELECTRIC RESONATOR

5

FIELD OF THE INVENTION

This invention relates to microwave resonators formed of high temperature superconductor and dielectric materials as well as to electronic circuits that employ those microwave resonators.

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BACKGROUND OF THE INVENTION

Microwave resonators are known for use in time and frequency standards, frequency stable elements, as well as building blocks for passive devices such as filters and the like. The performance of the microwave resonator is gauged by its Q-value, expressed as

$$Q = 2\pi f_0 \cdot (\text{Storage energy} / \text{Loss power}), \quad (1)$$

where f_0 is the resonant frequency of the microwave resonator. (See Hayt, J. R., "Engineering Electromagnetics", 1981, p. 472). As shown in Equation (1), the Q-value of the microwave resonator can be increased by reducing the loss power associated with factors such as conductor loss, dielectric loss, and radiation loss.

Low temperature (T_c), such as 4 K, superconducting microwave resonators which employ a superconducting cavity made of Nb are known to have Q-values from about 10^6 to 10^9 . (See V. B. Braginskii, et al: "The Properties of Superconducting Resonators on Sapphire", IEEE Trans. on Magn. Vol. 17, No. 1, P355, 1981, as a reference.) Although low T_c Nb microwave resonators have high Q-values, they must operate at very low temperatures (below 9 K). These microwave resonators require use of curved cavity walls. Curved cavity walls

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of materials which have a high T_c , of for example 77 K, however, are difficult to produce. On the other hand, high Q-value microwave resonators formed merely from a dielectric without an associated conducting medium also have high Q-values (see D. G. Blair, et al: "High Q Microwave Properties of a Sapphire Ring Resonator", J. Phys. D: Appl. Phys., 15, P1651, 1982.) However, the problems associated with the far reaching evanescent fields make them very bulky and vulnerable to microphonic effect, which limits the applications.

The need therefore exists for microwave resonator made of high T_c , such as 77 K, superconductor that have Q-values comparable to low T_c superconducting microwave resonators made of Nb.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1(a) and 1(b) show a vertical cross section of superconducting microwave resonator and a holding device for that resonator.

Figure 2 is a schematic block diagram of a frequency stable element for oscillators that employs the microwave resonator of the invention.

Figures 3(a) and 3(b) show configurations of filters using superconducting microwave resonators according to the invention.

Figure 4 shows the Q-values of a superconducting microwave resonator of the invention that employ YBa_2Cu_3O superconductor and sapphire dielectric.

Figure 5 shows the Q-values of a superconducting microwave resonator of the invention that employs $TlBaCaCuO$ superconductor and sapphire dielectric.

Figure 6 shows the relationship of Q-value of the resonator to the size of the dielectric.

Figure 7 shows cross sectional views of an alternative embodiment of a device for holding the microwave resonators of the invention.

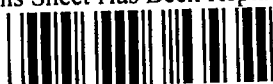


Figure 8 shows a vertical cross section of a further embodiment of a device for holding the microwave resonator of the invention.

Figure 9 shows a vertical cross section of a further alternative embodiment of a holding device for the microwave resonators of the invention.

Figure 10 shows a vertical cross section of a further embodiment of a holding device for the microwave resonators of the invention.

Figures 11(a)-11(d) show top views of alternative embodiments for coupling the microwave resonators of the invention to an electronic circuit.

Figure 12 shows a top view of a coupling mechanism that utilizes dual couplings for coupling the microwave resonators of the invention to an electronic circuit.

Figure 13 shows a top view of a coupling of the microwave resonator of the invention to an electronic circuit integrated onto the back side of the substrate.

Figure 14 shows a vertical cross section of an alternative embodiment of the microwave resonators of the invention.

SUMMARY OF THE INVENTION

The invention is directed to high temperature superconductor-dielectric microwave resonators, to holding devices for those resonators, coupling of those resonators to electronic circuits, and to their methods of manufacture. The superconducting microwave resonator of the invention employ a superconducting film on substrates positioned on a dielectric. The holding devices include a variety of configurations, such as, a spring loaded device. The microwave resonators can be readily coupled to electronic circuits. The superconducting microwave resonators have Q values that are as high as low temperature microwave resonators formed of Nb, but operate at much higher temperature.



In accordance with the invention, a high temperature superconducting microwave resonator comprising a dielectric and a plurality of substrates bearing a coating of high temperature superconducting material is provided. The substrates are positioned relative to the dielectric to enable the coating to contact said dielectric.

The invention also includes devices for retaining the configuration of the superconducting microwave resonator of the invention. These devices comprise means to retain the relative positions of the substrate and the dielectric during use of the microwave resonator in an electrical circuit. These devices further comprise means for coupling of the microwave resonator to electrical circuits.

The invention is further directed to a method for coupling the superconducting microwave resonator of the invention to an electric circuit by employing means positioned on the substrate for transferring electromagnetic energy between the dielectric of the superconducting microwave resonator and an electrical circuit via openings on the superconducting films and coupling lines.

The invention is still further directed to passive devices such as filters that are formed of a plurality of dielectrics positioned between a plurality of substrates bearing a coating of high temperature superconducting material, or wherein the dielectrics and substrates are in alternating positions relative to each other.

DETAILED DESCRIPTION OF THE INVENTION

Having briefly summarized the invention, the invention will now be described in detail by reference to the following specification and non-limiting examples. Unless otherwise specified, all percentages



are by weight and all temperatures are in degrees Kelvin.

Figure 1 shows superconducting microwave resonator and a holding device for that resonator. As shown in
5 Figures 1(a) and 1(b), a superconducting microwave resonator 100 with cavity 90 is provided in the form of substrates 20 bearing superconducting film 10 positioned on dielectric 30. Substrate 20 is a single crystal that has a lattice matched to superconductor
10 film 10. Preferably, substrates 20 are formed of LaAlO_3 , NdGaO_3 , MgO and the like.

Generally, superconductor film 10 may be formed from any high T_c superconducting material that has a surface resistance (R_s) that is at least ten times less
15 than that of copper at any specific operating temperature. T_c can be determined by the "eddy current method" using a LakeShore Superconductor Screening System, Model No. 7500. Surface resistance of superconducting film 10 can be measured by the method
20 described in Wilker et al., "5-GHz High-Temperature-Superconductor Resonators with High Q and Low Power Dependence up to 90 K", IEEE, Trans. on Microwave Theory and Techniques, Vol. 39, No. 9, September 1991, pp. 1462-1467. Generally, superconductor film 10 is
25 formed from materials such as YBaCuO (123), TlBaCaCuO (2212 or 2223), TlPbSrCaCuO (1212 or 1223), or the like.

Superconducting film 10 can be deposited onto substrate 20 by methods known in the art. See, for example, Holstein et al., "Preparation and
30 Characterization of $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ Films on 100 LaAlO_3 ", IEEE, Trans. Magn., Vol. 27, pp. 1568-1572, 1991 and Laubacher et al., "Processing and Yield of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ Thin Films and Devices Produced with a BaF_2 Process", IEEE, Trans. Magn., Vol. 27, pp. 1418-1421, 1991.

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Generally, the thickness of film 10 is in the range of 0.2 to 1.0 micron, preferably 0.5 to 0.8 micron.

Microwave resonator 100 is formed by positioning substrates 20 bearing superconducting film 10 on dielectric 30. Substrates 20 can be placed on the surface of dielectric 30, or, alternatively, low loss adhesive materials may be employed. Polymethyl methacrylate optionally may be deposited onto the surface of superconducting film 10 to more firmly bond dielectric 30, as well as to protect superconducting film 10.

Dielectric 30 may be provided in a variety of shapes. Preferably, dielectric 30 is in the form of circular cylinders or polygons. Dielectric 30 may be formed of any dielectric material with a dielectric constant $\epsilon_r > 1$. Such dielectric materials include, for example, sapphire, fused quartz, and the like. Generally, these dielectric materials have a loss factor ($\tan \delta$) of from 10^{-6} to 10^{-9} at cryogenic temperatures. The ϵ_r and $\tan \delta$ of the dielectric material can be measured by methods known in the art. See, for example, Sucher et al., "Handbook of Microwave Measurements", Polytechnic Press, Third Edition, 1963, Vol. III, Chapter 9, pp. 496-546.

The configuration of the microwave resonator 100, when in use, is maintained by holding device 25. The holding device can be any embodiment that maintains the relative positions of the components of the resonator during thermal cycling associated with use of the resonator. Figure 1(a) shows a first embodiment of a holding device that employs spring loading. As shown in Figure 1(a), the configuration of microwave resonator 100 is maintained by holding device 25. Holding device 25 includes sidewalls 45, bottom plate 50, top lid 60, pressure plate 70, and load springs 80. Load springs



80 are sufficiently strong to retain the configuration of the microwave resonator during thermal cycling. Load springs 80 preferably are formed of nonmagnetic material in order to prevent disturbing the radio frequency fields in the resonator to achieve the highest possible Q-values. Load springs 80 preferably are formed of Be-Cu alloys.

Parts 45, 50, 60 and 70 of holding device 25 are made of thermally and electrically conductive materials in order to reduce radio frequency loss as well as to enable efficient cooling of resonator 100. Parts 45, 50, 60 and 70 therefore may be formed of, for example, oxygen fired copper, aluminum, silver, preferably oxygen fired copper or aluminum.

The high T_c superconductor-dielectric microwave resonators of the invention are capable of attaining extremely high Q-values, due in part, to the ability of substrate 20 bearing film 10 to prevent axial radio frequency fields from extending beyond the London penetration depth of the superconducting film 10. This is accomplished where substrates 20 are substantially greater than the diameter of dielectric 30 so that radio frequency fields are confined within the cavity region between substrates 20.

The high Q-value superconducting microwave resonators provided by the invention have a variety of potential applications. Typically, these resonators may be employed in applications such as filters, oscillators, as well as radio frequency energy storage devices.

The microwave resonators of the invention also may be employed as frequency stable elements to reduce the phase noise for oscillators. As shown in Figure 2, circuit 51 employs a microwave resonator 100 of the invention that is inserted into a closed feedback loop



of, preferably, a low noise amplifier 15. Where the product of the gain of amplifier 15 and the insertion loss of resonator 100 is greater than one, and where the total phase of the closed loop, as adjusted by phase shifter 17, is a multiple of 2π , then, due to the extremely high Q-values of the superconducting microwave resonators of the invention, the oscillator can be made to oscillate at the microwave resonator's resonant frequency to yield lower phase noise in the oscillator.

10 The superconducting microwave resonators of the invention also may be employed to provide highly stable frequencies suitable for secondary standards for frequency or time. Since the microwave resonator has an extremely high Q-value and operates at a constant
15 cryogenic temperature, the microwave resonator has a very stable resonate frequency that makes the resonator useful for serving as a secondary standard.

The superconducting microwave resonators of the invention further may be employed as building blocks in
20 passive devices such as filters. Examples of such filters are shown in Figures 3(a) and 3(b). As illustrated in Figure 3(a), filter 110 is shown in the form of a series of dielectrics 30 sandwiched between substrates 20 bearing superconducting films 10.
25 Coupling between dielectrics 30 is achieved by the evanescent fields of dielectrics 30. Coupling of filter 10 to electronic circuits (not shown) can be achieved by coaxial cable 18 bearing coupling loop 21.

Figure 3(b) shows an alternative embodiment of a
30 filter. As shown in Figure 3(b), filter 120 employs a series of dielectrics 30. Coupling between dielectrics 30 is achieved by the evanescent fields of dielectrics 30 via openings (not shown) on substrates 20. Coupling of filter 120 to an electronic circuit (not shown) can
35 be achieved by couplings 13. Couplings 13 can be



coaxial lines, waveguides, or other transmission lines. In either of the embodiments of Figures 3(a) or 3(b), the high Q-values of the superconducting microwave resonators reduces the in-band insertion loss of the filter so as to make the skirt of the frequency response curve of the filter steeper.

An additional application of the superconducting, microwave resonators of the invention is to measure the surface impedance (Z_s) of superconductor materials and the complex dielectric constant $\epsilon_r = \epsilon_r' - j\epsilon_r''$ of dielectric materials, where Z_s and ϵ_r have been determined by measurement of f_0 and Q at two differing modes in accordance with methods known in the art.

Generally, high Q-values for the superconducting microwave resonators of the invention may be obtained by selecting the proper electromagnetic modes to prevent flow of radio frequency current across the edges of superconducting films 10. These proper modes are TE_{0in} modes where the radial mode index has a value of $i=1,2,3,\dots$ and the axial mode index has a value of $n=1,2,3,\dots$. All TE_{0in} modes have only circular radio frequency currents that do not cross the edge of films 10.

Having selected the specific electromagnetic mode of the microwave resonator, the Q and the resonant frequency f_0 for the microwave resonator can be calculated by solving Maxwell's Equations for the boundary conditions of the resonator, as is known in the art.

The loss power associated with parasitic coupling to low Q-value modes such as non- TE_{0in} modes or case modes may be minimized in the microwave resonators of the invention by assuring that substrates 20 are flat and parallel to within a tolerance of less than 1° . Loss power also may be minimized by ensuring that the



C-axis of anisotropic materials such as sapphire, when employed as dielectric 30, is perpendicular to substrate 20 to within $\pm 5^\circ$, preferably 1° .

As also is shown in Figure 1(a), microwave resonator 100 can be coupled to an electric circuit (not shown) by coaxial cable 18 that includes coupling loop 21 protruding into cavity 90 of microwave resonator 100. The orientation of coupling loop 21 and the depth of insertion of coaxial cable 18 into cavity 90 readily can be adjusted to ensure coupling to the electronic circuit.

In a preferred aspect of the invention, superconducting film is formed by epitaxially depositing 0.5 micron superconducting films of $Tl_2Ba_2Ca_1Cu_2O$ or YBa_2Cu_3O on 2 inch diameter substrates of $LaAlO_3$ positioned on cylindrical dielectrics of sapphire. The superconducting film is deposited so that the C-axis of the film is perpendicular to the surface of the substrate. The dielectrics of sapphire typically measure 0.625 inch diameter by 0.276 inch tall, 0.625 inch diameter by 0.552 inch tall, or 1.00 inch diameter by 0.472 inch tall. The substrates and dielectric are retained in position by a holding device formed of oxygen free copper. Coupling of the microwave resonator to an electrical circuit can be achieved by inserting two 0.087 inch diameter copper or stainless steel, 50 ohm coaxial cables with coupling loops made of extended inner conductor into the cavity of the resonator. The surface of the coupling loops is perpendicular to the vertical axis of the sapphire dielectric to enable selective coupling to the TE_{011} ($i=1$, $n=1$) mode of the dielectric.

The Q values of the above described microwave resonators, when employing YBa_2Cu_3O as the superconducting film, are shown in Figure 4. As shown



in Figure 4, Q values of 5 million, 1.5 million, and 0.25 million are found at temperatures of 4.2 K, 20 K and 50 K, respectively. The Q values of the above described microwave resonators, when employing

5 $\text{Ti}_2\text{Ba}_2\text{Ca}_1\text{Cu}_2\text{O}$ as the superconducting film, are shown in Figure 5. As shown in Figure 5, Q values of 6 million, 3 million, and 1.3 million are found at temperatures of 20 K, 50 K, and 77 K, respectively.

10 The dependence of Q values of the above described microwave resonators that employ $\text{Ti}_2\text{Ba}_2\text{Ca}_1\text{Cu}_2\text{O}$ as the superconducting film on the size of the sapphire dielectric is shown in Figure 6. As shown in Figure 6, the Q values increase from 3 million to 6 million with increasing size of the sapphire dielectric.

15 Device 25 shown in Figure 1(a) that employs spring loading is only illustrative. Other means for holding microwave resonator 100 are shown below.

Figures 7(a) and 7(b) show an alternative embodiment for holding the microwave resonators of the invention. As shown in Figure 7, the microwave resonator is held by holding device 27. Device 27 is identical to device 25 except that, as shown in Figure 7(a), spring loaded holding device 27 employs three dielectric rods 35 positioned 120° relative to each other to further support dielectric 30. Dielectric rods 25 35 are inserted through side walls 47 of holding device 27 into cavity 95. Dielectric rods 35 have a low loss and a dielectric constant less than that of dielectric 30. The tips of rods 35 are pointed to minimize contact area with dielectric 30 to minimize loss power. 30

A further embodiment of a device for holding the microwave resonators of the invention is shown in Figure 8. As set forth in Figure 8, the microwave resonator is retained in position by holding device 28. Holding device 28 is identical to holding device 25 except for 35



the additional use of retainer 77. As shown in Figure 8, substrate 20 bearing superconducting film 10 is positioned on bottom-plate 50. Dielectric 30 is positioned on substrate 20. Retainer 77 is positioned about dielectric 30. Retainer 77 contacts sidewalls 45 and superconducting film 10 on substrate 20. Retainer 77 and side walls 45 have openings for receiving coaxial cables 18. Cables 18 have loops 21 for coupling of the resonator to an electric circuit(not shown). Retainer 77 is formed of materials that have low dielectric constant of nearly 1 and low $\tan \delta$ of $<10^{-4}$. As shown in Figure 8, retainer 77 is hollow, and is solid near sidewalls 45 where the electrical fields are minimum. The wall thickness of retainer 77 is minimized to reduce the contact area between retainer 77 and dielectric 30 to minimize loss power.

Still yet another embodiment of a holder device for the microwave resonators of the invention is shown in Figure 9. Holding device 29 shown in Figure 9 is identical to holding device 25 except for the use of additional dielectric 65. As shown in Figure 9, cavity 91 between dielectric 30 and the interior surface of sidewall 45 of device 25 is filled with dielectric material 65. Dielectric material 65 has a $\tan \delta$ of less than 10^{-5} . Examples of dielectric material 65 include styrofoam, porotic teflon, and the like.

Figure 10 shows a further embodiment of a holding device suitable for use with the superconducting microwave resonators of the invention. Holding device 24 shown in Figure 10 is identical to holding device 25 except for additional use of holding pins 71. As shown in Figure 10, pins 71, formed of low $\tan \delta$ dielectric materials such as sapphire, quartz, polymers, polytetrafluoroethylene ("teflon"), "Delrin", registered trademark of E. I. du Pont de Nemours and Company, and



the like are inserted into substrate 20 bearing superconducting film 10 and into dielectric 30.

Figures 11(a) to 11(d) show alternative embodiments for coupling of the microwave resonators of the invention to an electronic circuit (not shown). Generally, the embodiments shown in Figures 11(a)-11(c) entail use of substrates that bear superconducting films on the surfaces of the substrate that directly contacts dielectric 30. Openings are provided on the superconducting film on the side which directly contacts dielectric 30. A coupling device is located over the opening on surface of the substrate that does not contact dielectric 30.

Figure 11(a) shows a microstrip line coupling mechanism for coupling of the microwave resonators of the invention to an electronic circuit (not shown). In Figure 11(a), microstrip line 15 is formed by depositing superconducting film material on that surface of substrate 20 that is remote to dielectric 30. Microstrip line 15 serves as the lead to an electronic circuit (not shown). Opening 12 is provided in film 10 on the surface of substrate 20 that contacts dielectric 30. Opening 12 extends through film 10 but not through substrate 20. Opening 12 does not contact dielectric 30 in order to minimize the effects of magnetic fields on dielectric 30. Opening 12 is parallel to the local magnetic field. Coupling is achieved by magnetic field leakage through opening 12 to line 15. Microstrip line 15 extends over opening 12 by a distance of $\lambda/4$, where λ is the wavelength of the radio frequency field at the operating frequency of the resonator.

Figure 11(b) shows a coplanar line coupling mechanism for coupling the microwave resonators of the invention to an electronic circuit (not shown). The coplanar line coupling is formed by depositing



superconducting film material on that surface of substrate 20 that is remote to dielectric 30 to form center line 19 and ground plane 21. The coplanar line coupling serves as the lead to an electronic circuit (not shown). The coplanar line coupling extends over opening 12. Opening 12 is provided by film 10 on the surface of substrate 20 that contacts dielectric 30. Opening 12 extends through film 10 but not through substrate 20. Opening 12 does not contact dielectric 30.

In the coplanar line coupling of Figure 11(b), center line 19 is short circuited to ground plane 21. Center line 19 extends across opening 12. Opening 12 is parallel to the local magnetic field. Coupling is achieved by magnetic field leakage through slot 12 to center line 19.

Figure 11(c) shows a parallel line coupling mechanism for coupling dielectric 30 to an electronic circuit(not shown). The parallel line coupling includes parallel lines 31 and loop 32. The parallel line coupling is formed by depositing superconducting film material on that surface of substrate 20 that is remote to dielectric 30. The parallel line coupling mechanism serves as the lead to an electronic circuit (not shown). Parallel lines 31 and loop 32 extend over opening 12. Opening 12 is provided in film 10 on the surface of substrate 20 that contacts dielectric 30. Opening 12 extends through film 10 but not through substrate 20. Opening 12 does not contact dielectric 30. Coupling is achieved by leakage of magnetic field through opening 12 which is captured by loop 32.

Figure 11(d) shows a coupling mechanism useful for microwave resonators such as those used for a filter as shown in Figure 3(b). As shown in Figure 11(d), the coupling mechanism employs identical, congruent slots 12



through film 10 of both surfaces of substrate 20. Slots 12 extend through films 10 but terminate at the surfaces of substrate 20. Slots 12 on each surface of substrate 20 may be the same or different in size. Coupling is
5 achieved by leakage of evanescent magnetic field through slots 12.

Coupling of the microwave resonator also may be achieved through dual couplings. Figure 12 shows a dual coupling mechanism that utilizes dual identical coupling
10 microstrip lines 44(a) and 44(b) that cross slots 12(a) and 12(b) on film 10. Slots 12(a) and 12(b) are provided in film 10 on that surface of the substrate 20 that contacts dielectric 30. Slots 12(a) and 12(b) terminate at the surface of substrate 20. Couplings
15 44(a) and 44(b) are connected by lead line 41 that is divided into equal length branches 42(a) and 42(b). Lines 44(a) and 44(b) and lead line 41 are formed by depositing superconductive material onto substrate 20. Coupling is achieved by leakage of evanescent magnetic
20 field through slots 12(a) and 12(b). The dual coupling mechanism shown in Figure 12 enables selective coupling to the TE₀₁₁ mode and suppresses competing electromagnetic field modes that have antisymmetrical magnetic field distribution.

25 The coupling mechanisms of the invention also provide for ease of connection to circuits integrated onto substrate 20. As shown in Figure 13, a circuit is integrated onto the side of substrate 20 that bears coupling mechanisms 55(a) and 55(b). Couplings 55(a)
30 and 55(b) may be formed by depositing superconductive film material onto substrate 20 over slots 12(a) and 12(b). Slots 12(a) and 12(b) are provided in the superconducting film (not shown) on that side of substrate 20 that contacts dielectric 30. Slots 12(a)
35 and 12(b) extend through the superconductor film but



terminate at the surface of substrate 20. Coupling is achieved by leakage of magnetic field through slots 12(a) and 12(b).

5 Integration of circuits onto substrate 20 as shown in Figure 13 may be achieved by well known thin film printed circuit technology. If the circuit is a hybrid circuit that employs, for example, transistors, then the transistors can be integrated into the circuit by conventional wire bonding.

10 Figure 14 shows an alternative embodiment of the superconducting microwave resonator of the invention that is retained by holding device 25. As shown in Figure 14, rings 61 with a dielectric constant much less than that of dielectric 30 are inserted between
15 dielectric 30 and superconducting film 10. Rings 61, by placing dielectric 30 further from superconducting film 10, enable the microwave resonator to handle greater power levels.

20 From the foregoing description, one skilled in the art can easily ascertain the essential characteristics of this invention, and without departing from the spirit and scope thereof, can make various changes and modifications of the invention to adapt it to various uses and conditions.

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CLAIMS

What is claimed is:

- 5 1. A high temperature superconducting microwave resonator comprising a dielectric and a plurality of substrates bearing a coating of high temperature superconducting material, wherein said substrates are positioned relative to said dielectric to enable said
10 coating to contact said dielectric.
2. The high temperature superconducting microwave resonator of Claim 1 wherein said dielectric is selected from the group of sapphire and quartz.
- 15 3. The high temperature superconducting microwave resonator of Claim 2 wherein said dielectric is sapphire.
- 20 4. The high temperature superconducting microwave resonator of Claim 1 wherein said substrates are single crystals that are lattice matched to said superconducting material.
- 25 5. The high temperature superconducting microwave resonator of Claim 4 wherein said substrates are selected from the group of LaAlO_3 , NdGaO_3 and MgO .
- 30 6. The high temperature superconducting microwave resonator of Claim 1 wherein said superconducting material has a surface resistance at least ten times less than copper.
- 35 7. The high temperature superconducting microwave resonator of Claim 6 wherein said superconducting

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material is selected from the group of YBaCuO (123), TlBaCaCuO(2212), TlBaCaCuO(2223), TlPbSrCaCuO(1212) or TlPbSrCaCuO(1223).

5 8. The high temperature superconducting microwave resonator of Claim 1 further comprising dielectric rings positioned between said dielectric and said substrate.

10 9. A filter comprising a plurality of dielectrics positioned between a plurality of substrates bearing a coating of high temperature superconducting material, wherein said substrates are positioned relative to said dielectric to enable said coating to contact said dielectric.

15

10. The filter of Claim 9 wherein said dielectrics and said substrates are in alternating positions relative to each other.

20 11. A device for retaining the configuration of a superconducting microwave resonator, said microwave resonator comprising a dielectric and a plurality of substrates bearing a coating of high temperature superconducting material, wherein said substrates are
25 positioned relative to said dielectric to enable said coating to contact said dielectric,

said device comprising means to retain the relative positions of said substrate and said dielectric during use of said microwave resonator in an electrical
30 circuit.

12. The device of Claim 11 wherein said device is formed of conductive materials selected from the group of copper, aluminum, silver.

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13. The device of Claim 11 wherein said means is springs formed of non magnetic material.

14. The device of Claim 11 wherein said device
5 includes an additional dielectric material between said substrate and said dielectric of said microwave resonator, wherein said dielectric material is different from said dielectric of said microwave resonator.

10 15. The device of Claim 11 wherein said device further comprises a retainer positioned between said substrates and contacting said dielectric.

16. The device of Claim 11 further comprising a
15 coupling means for transferring electromagnetic energy between said dielectric to an electrical circuit.

17. The device of Claim 16 wherein said coupling
means comprises a coaxial cable with coupling loops
20 formed of extended inner conductor of said cable, said cable positioned between said substrates of said microwave resonator.

18. The device of Claim 13 wherein plurality of
25 spaced rods of dielectric material contact said dielectric of said microwave resonator, wherein said dielectric material of said rods is different from said dielectric of said microwave resonator.

19. A method for coupling a superconducting
30 microwave resonator to an electric circuit, said resonator comprising a dielectric and a plurality of substrates bearing a coating of high temperature superconducting material wherein said substrates are
35 positioned relative to said dielectric to enable said

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coating to contact said dielectric and wherein said
substrates have at least one opening therein for passing
electromagnetic fields generated by said dielectric,
said method comprising employing a means positioned on
5 said substrate for transferring said electromagnetic
fields passing through said at least one opening to an
electrical circuit.

20. The method of Claim 19 wherein said means is a
10 microstrip line.

21. The method of Claim 19 wherein said means is a
coplanar line.

15 22. The method of Claim 19 wherein said means is a
parallel line.

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AMENDED CLAIMS

[received by the International Bureau on 23 April 1993 (23.04.93);
original claim 10 cancelled; original claim 9 amended;
other claims unchanged (1 page)]

material is selected from the group of YBaCuO (123),
TlBaCaCuO(2212), TlBaCaCuO(2223), TlPbSrCaCuO(1212) or
TlPbSrCaCuO(1223).

5 8. The high temperature superconducting microwave
resonator of Claim 1 further comprising dielectric rings
positioned between said dielectric and said substrate.

10 9. A filter comprising a plurality of dielectrics
positioned between a plurality of substrates bearing a
coating of high temperature superconducting material,
wherein said substrates are positioned relative to said
dielectric to enable said coating to contact said
dielectric, and said dielectrics and said substrates are
15 in alternating positions relative to each other.

11. A device for retaining the configuration of a
superconducting microwave resonator, said microwave
resonator comprising a dielectric and a plurality of
20 substrates bearing a coating of high temperature
superconducting material, wherein said substrates are
positioned relative to said dielectric to enable said
coating to contact said dielectric,

25 said device comprising means to retain the relative
positions of said substrate and said dielectric during
use of said microwave resonator in an electrical
circuit.

12. The device of Claim 11 wherein said device is
30 formed of conductive materials selected from the group
of copper, aluminum, silver.



ABSTRACT

HIGH-TEMPERATURE SUPERCONDUCTOR-DIELECTRIC RESONATOR

The invention is directed to superconducting microwave resonator, to holding devices for those resonators, and to their methods of manufacture. The superconducting microwave resonators employ a superconducting film on substrates positioned on a dielectric. The holding devices include a variety of configurations, such as, a spring loaded device. The superconducting microwave resonators have Q values of as high as microwave resonators formed of Nb, but operate at much higher temperature.

Fig. 1a



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FIG. 1a

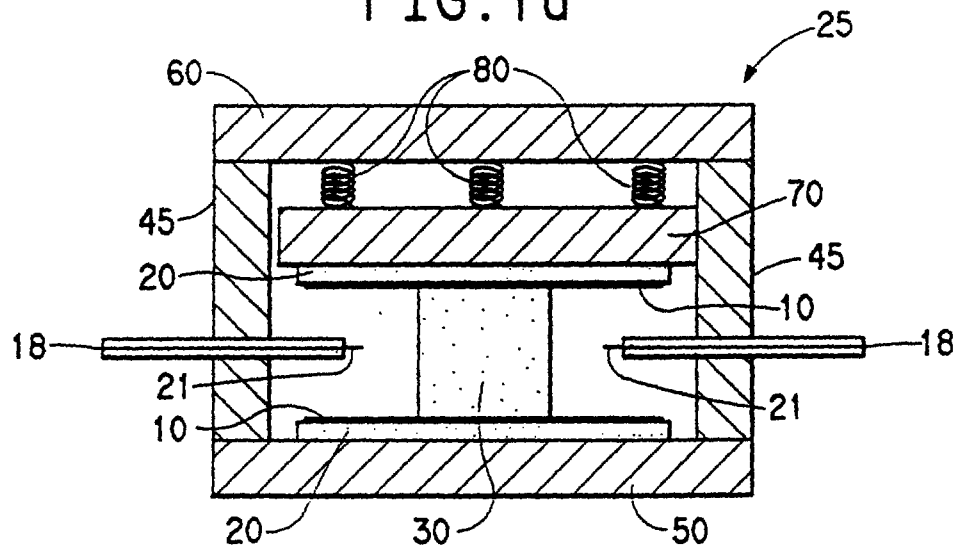


FIG. 1b

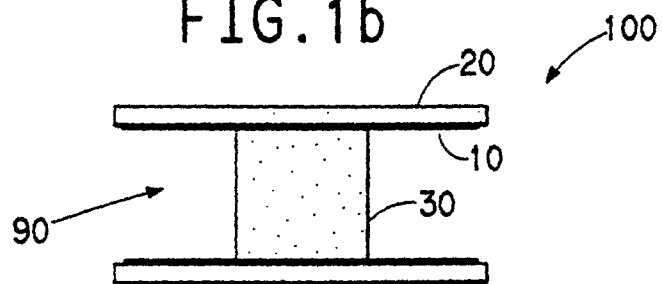
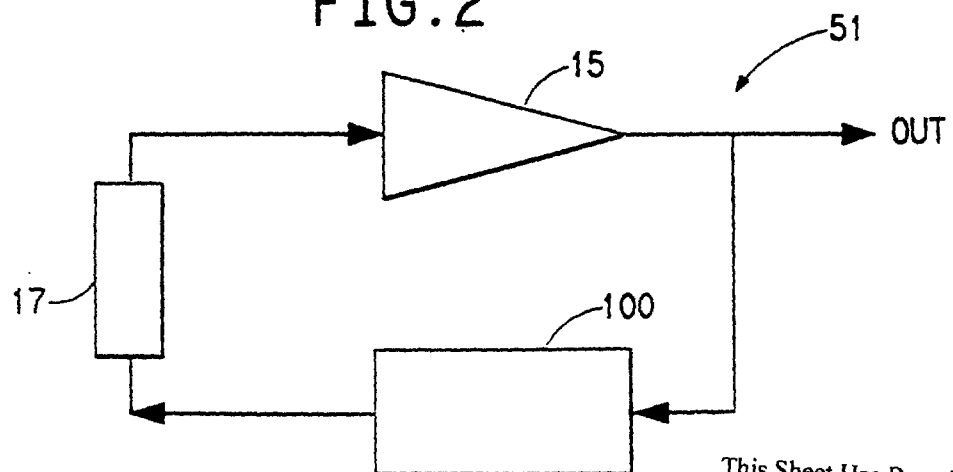


FIG. 2



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FIG. 3a

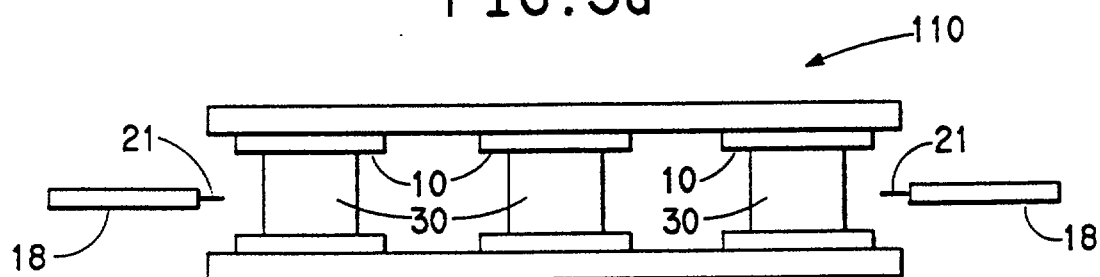
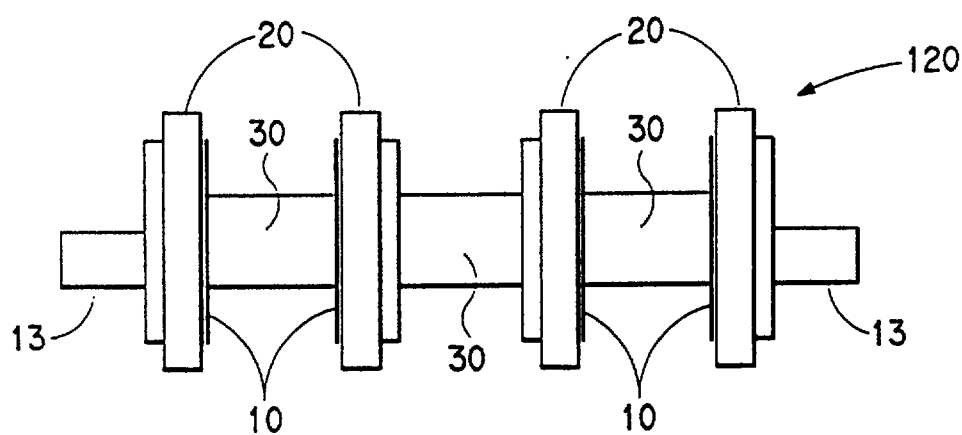


FIG. 3b

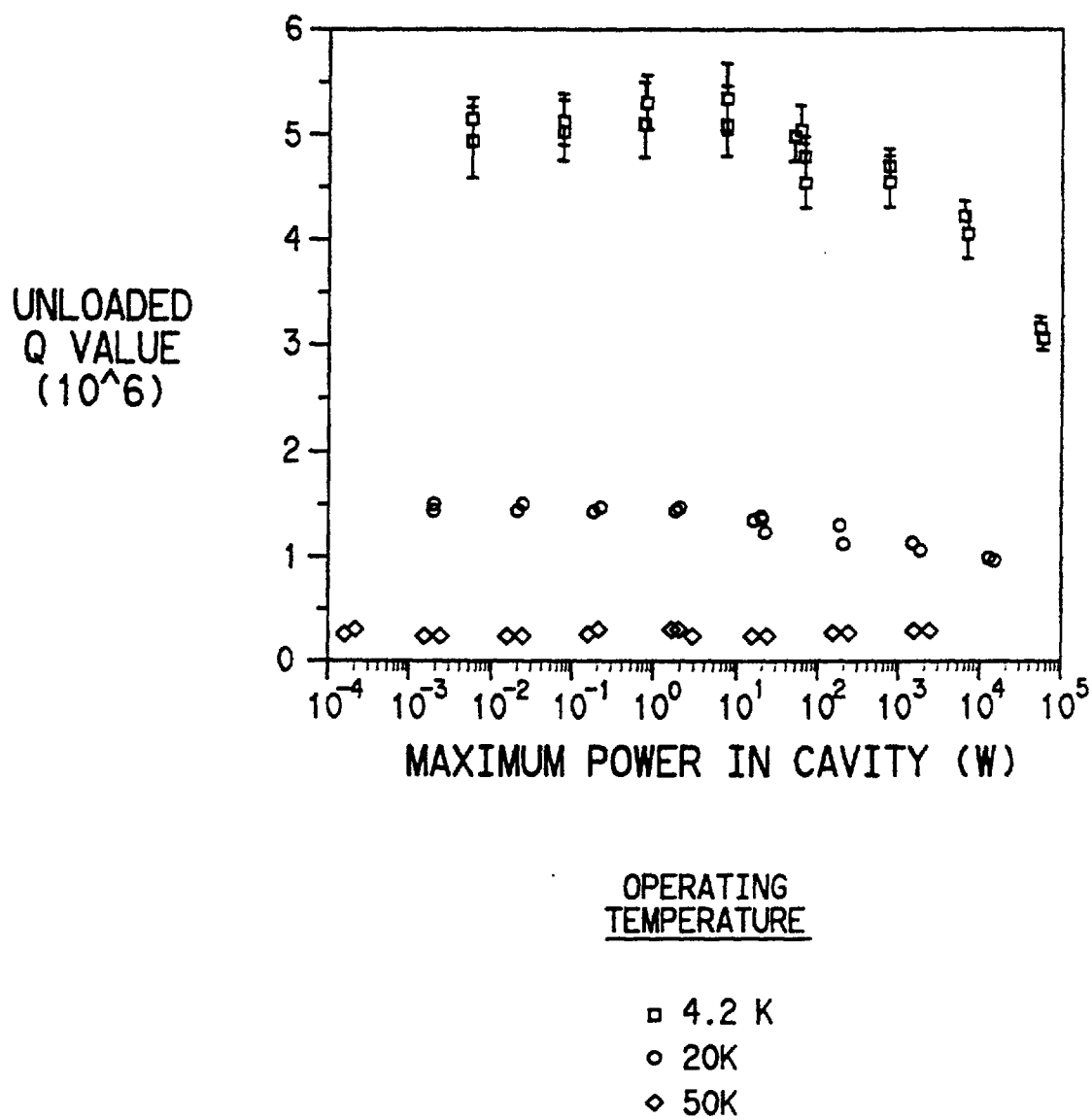


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FIG. 4

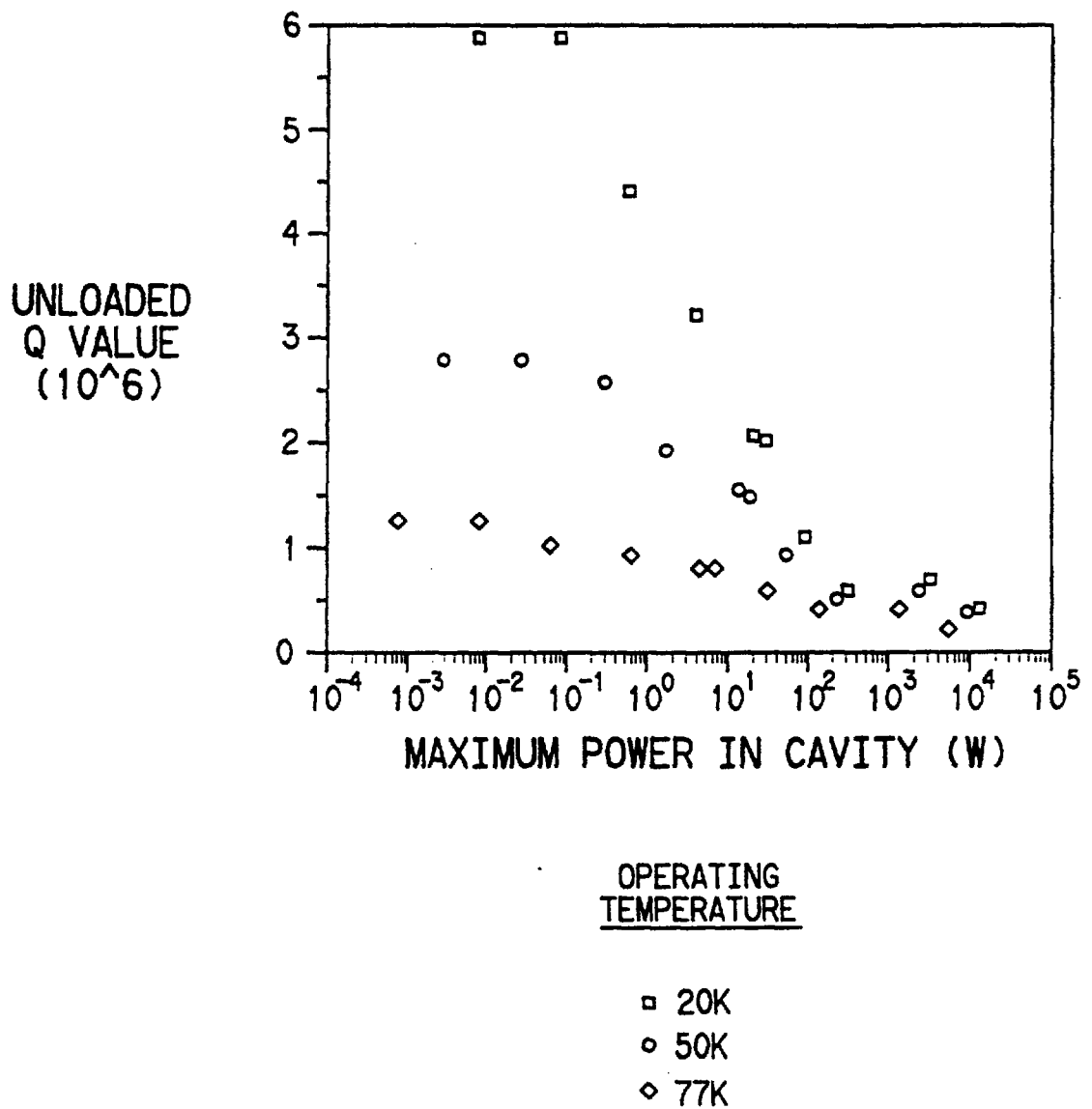


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FIG. 5

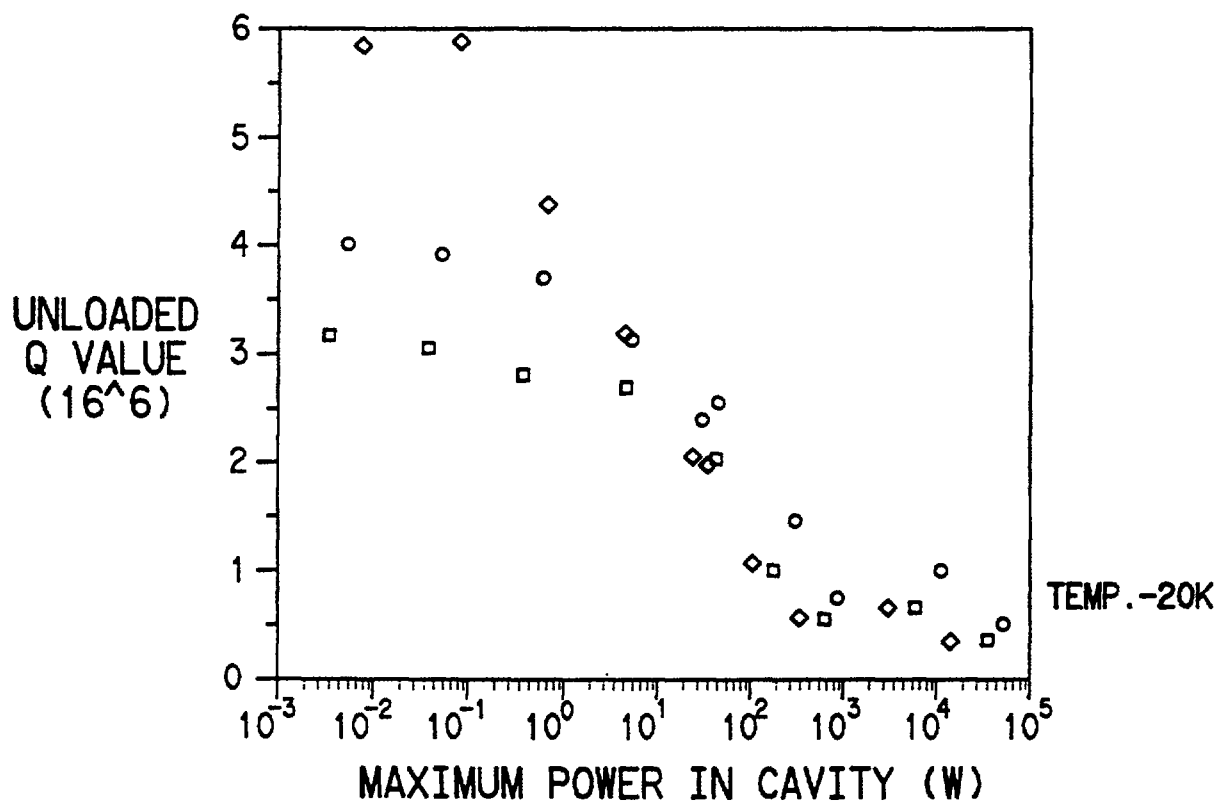


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FIG. 6

SAPPHIRE SIZE

- .625" DIA. BY .276" HGT
- .625" DIA. BY .552" HGT
- ◇ 1" DIA. BY .472" HGT

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6/11
FIG. 7a

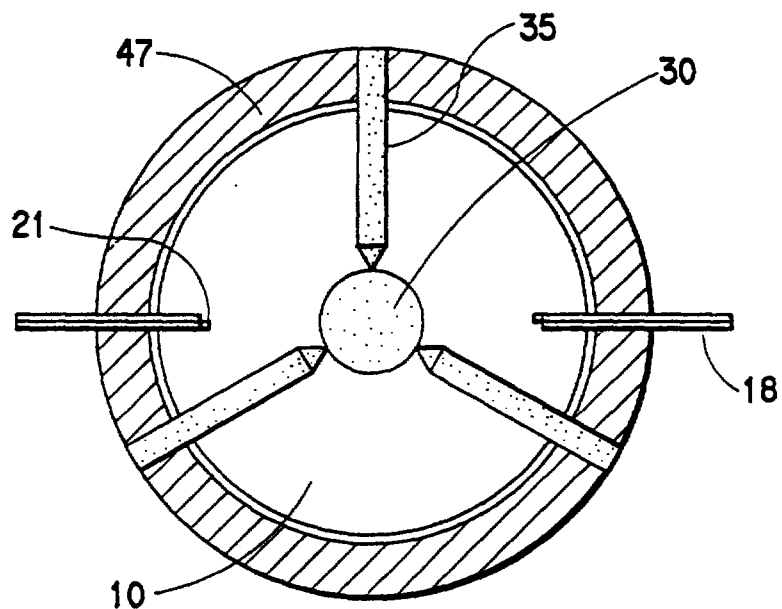
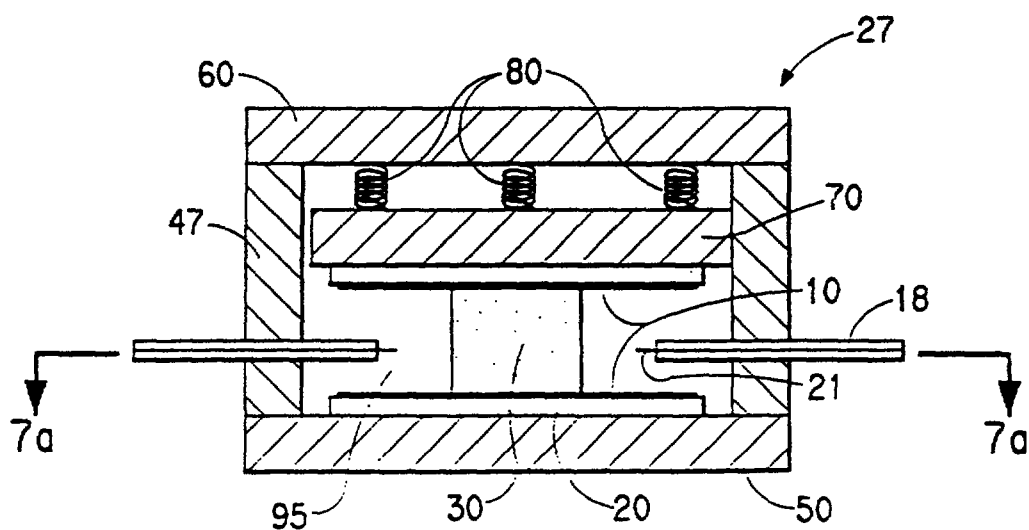
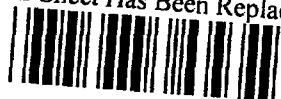


FIG. 7b



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FIG. 11a

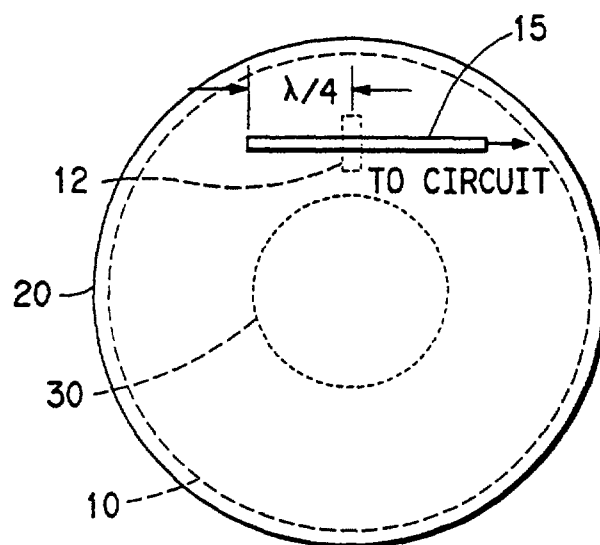
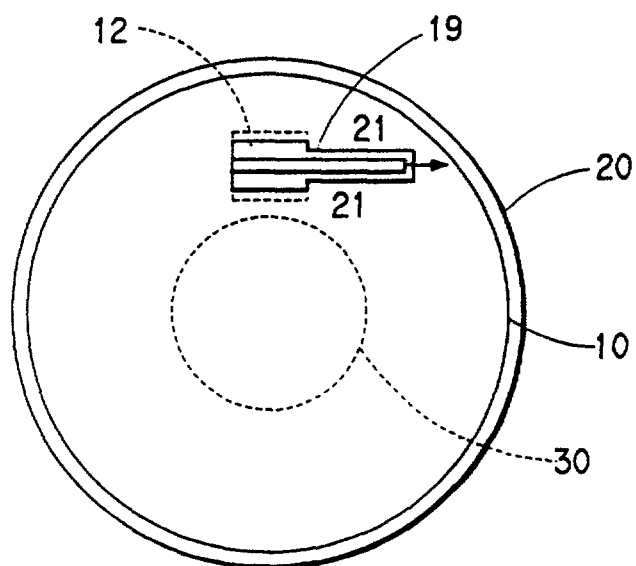


FIG. 11b



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FIG. 11c

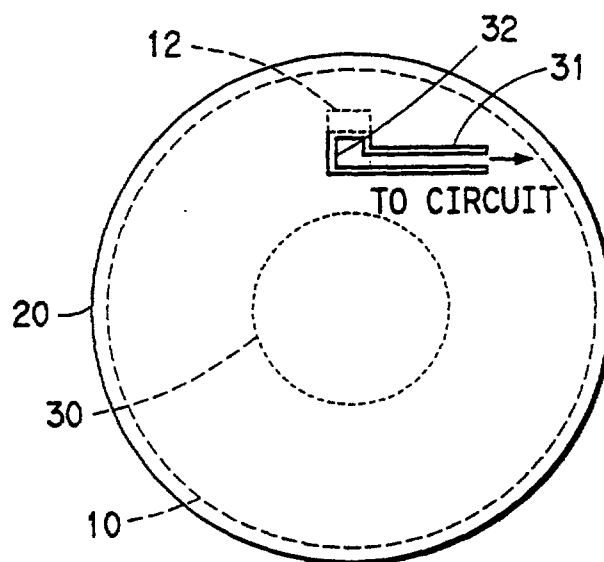
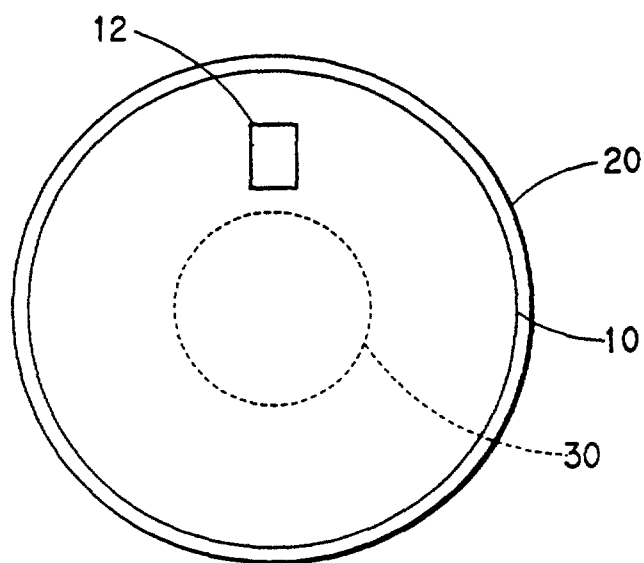


FIG. 11d



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FIG. 12

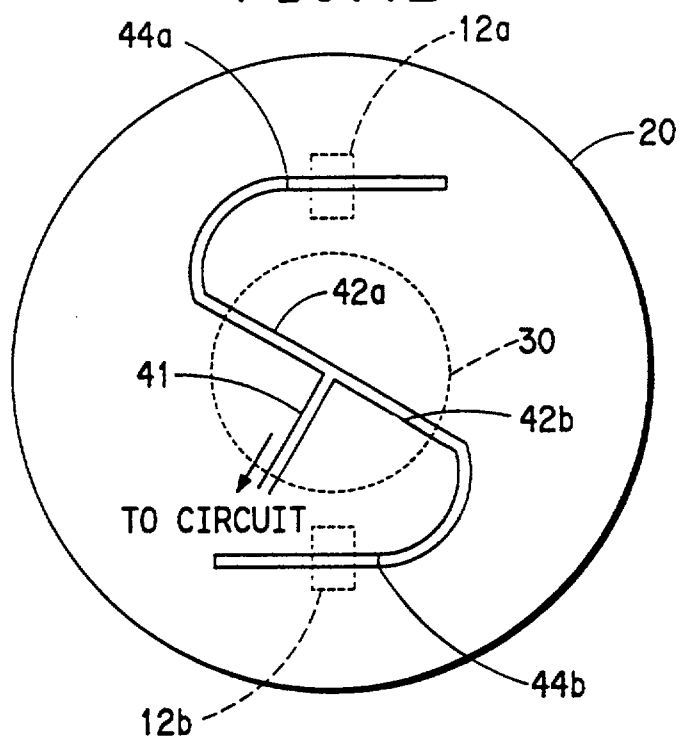
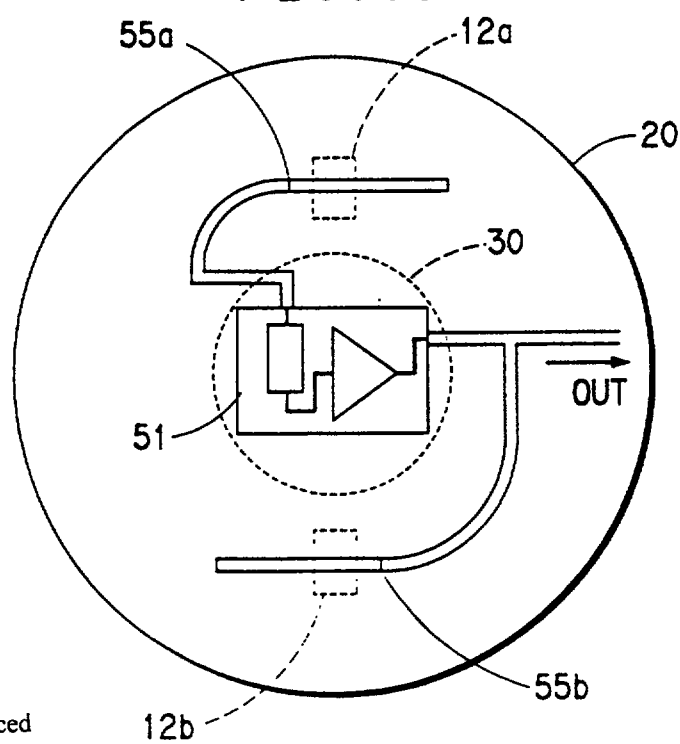


FIG. 13

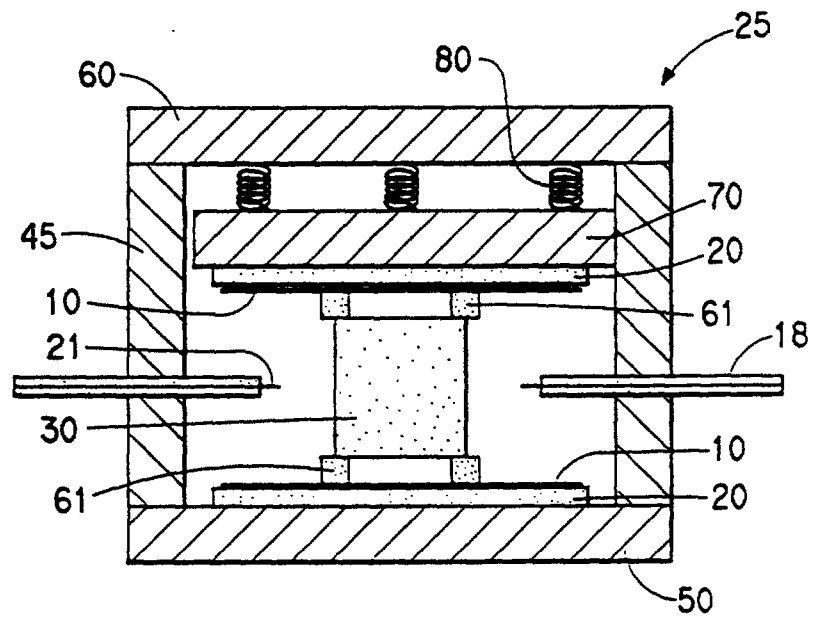


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11/11

FIG. 14



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of materials which have a high T_c , of for example 77 K, however, are difficult to produce. On the other hand, high Q-value microwave resonators formed merely from a dielectric without an associated conducting medium also have high Q-values (see D. G. Blair, et al: "High Q Microwave Properties of a Sapphire Ring Resonator", J. Phys. D: Appl. Phys., 15, P1651, 1982.) However, the problems associated with the far reaching evanescent fields make them very bulky and vulnerable to microphonic effect, which limits the applications.

Curtis, J. A. et al., 1991 IEEE MTT-S International Microwave Symposium Digest, Vol. 2, pp. 447-450, June 10-14, 1991, Boston, MA, U.S. discloses hybrid dielectric/high temperature superconductor resonators and filter configurations using these resonators. For the TE_{011} mode resonators disclosed the Q-value is about 200,000 at 20 K. Pao, C. et al., 1988 IEEE MTT-S International Microwave Symposium Digest, Vol. 1, pp. 457-458, May 25-27, 1988, New York, NY, U.S. disclose a superconductor-dielectric resonator based on a sapphire tube loaded with two plates of Y-Ba-Cu oxides wherein a Q-factor of 10^5 to 10^6 may be achieved using a $H_{01\delta}$ or H_{015} mode. Kogami, Y. et al., 1991 IEEE MTT-S International Microwave Symposium Digest, Vol. 3, pp. 1345-1348, June 10-14, 1991, Boston, MA, U.S. teaches a bandpass filter using two $TM_{01\delta}$ mode dielectric rod resonators oriented axially in a high temperature superconductor cylinder having a Q value of 150,000 at 20 K. St. Martin, J. et al., Electronics Letters, Vol. 26, No. 24, November 22, 1990, pp. 2015-2016 discloses a dielectric resonator antenna consisting of a $HEM_{11\delta}$ mode circular dielectric resonator fed by a microstrip feedline through a coupling aperture in the ground plane between them.

The need therefore exists for microwave resonator made of high T_c , such as 77 K, superconductor that have

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SUBSTITUTE SHEET

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Q-values comparable to low T_c superconducting microwave resonators made of Nb.

5 BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1(a) and 1(b) show a vertical cross section of superconducting microwave resonator and a holding device for that resonator.

Figure 2 is a schematic block diagram of a
10 frequency stable element for oscillators that employs the microwave resonator of the invention.

Figures 3(a) and 3(b) show configurations of filters using superconducting microwave resonators according to the invention.

15 Figure 4 shows the Q-values of a superconducting microwave resonator of the invention that employ $\text{YBa}_2\text{Cu}_3\text{O}$ superconductor and sapphire dielectric.

Figure 5 shows the Q-values of a superconducting microwave resonator of the invention that employs
20 TlBaCaCuO superconductor and sapphire dielectric.

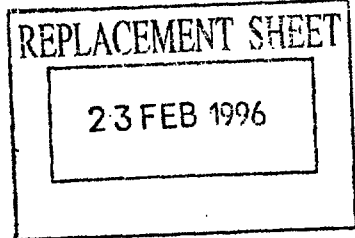
Figure 6 shows the relationship of Q-value of the resonator to the size of the dielectric.

Figure 7 shows cross sectional views of an alternative embodiment of a device for holding the
25 microwave resonators of the invention.

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SUBSTITUTE SHEET

CLAIMS

What is claimed is:

1. A high temperature superconducting microwave resonator comprising a dielectric having a loss factor
5 (tan δ) of from 10^{-6} to 10^{-9} at cryogenic temperature, and a plurality of substrates bearing a coating of high temperature superconducting material, wherein said substrates are positioned relative to said dielectric to enable said coating to contact said dielectric, said
10 resonator contained within a holding device having a top, bottom and sidewalls wherein a clearance gap exists between the device sidewalls and a plate positioned in contact with at least one substrate and perpendicular to side sidewalls, said resonator having a Q value of at
15 least 0.25 million at 50 K and a TE_{0in} mode wherein i and n are each integers of at least 1.

2. The high temperature superconducting microwave resonator of Claim 1 wherein said dielectric is selected from the group of sapphire and quartz.

20 3. The high temperature superconducting microwave resonator of Claim 2 wherein said dielectric is sapphire.

4. The high temperature superconducting microwave resonator of Claim 1 wherein said substrates are single
25 crystals that are lattice matched to said superconducting material.

5. The high temperature superconducting microwave resonator of Claim 4 wherein said substrates are selected from the group of $LaAlO_3$, $NdGaO_3$ and MgO .

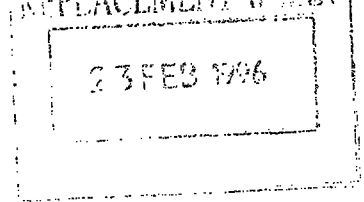
30 6. The high temperature superconducting microwave resonator of Claim 1 wherein said superconducting material has a surface resistance at least ten times less than copper.

7. The high temperature superconducting microwave
35 resonator of Claim 6 wherein said superconducting

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material is selected from the group of YBaCuO (123), TlBaCaCuO(2212), TlBaCaCuO(2223), TlPbSrCaCuO(1212) or TlPbSrCaCuO(1223).

8. The high temperature superconducting microwave resonator of Claim 1 further comprising dielectric rings positioned between said dielectric and said substrate.

9. A filter comprising a plurality of dielectrics having a loss factor ($\tan \delta$) of from 10^{-6} to 10^{-9} at cryogenic temperature, positioned between a plurality of substrates bearing a coating of high temperature superconducting material, wherein said substrates are positioned relative to said dielectric to enable said coating to contact said dielectric and wherein said dielectrics and said substrates are in alternating positions relative to each other, said filter contained within a holding device having a top, bottom and sidewalls wherein a clearance gap exists between the device sidewalls and a plate positioned in contact with at least one substrate and perpendicular to said sidewalls, said filter having a Q value of at least 0.25 million at 50 K and a TE_{0in} mode wherein i and n are each integers of at least 1.

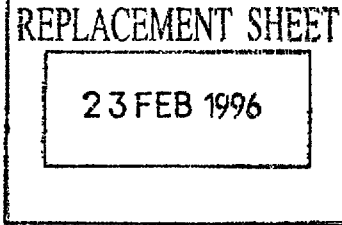
11. A device for retaining the configuration of a superconducting microwave resonator, said microwave resonator comprising a dielectric having a loss factor ($\tan \delta$) of from 10^{-6} to 10^{-9} at cryogenic temperature, and a plurality of substrates bearing a coating of high temperature superconducting material, wherein said substrates are positioned relative to said dielectric to enable said coating to contact said dielectric, said resonator having a Q value of at least 0.25 million at 50 K and a TE_{0in} mode wherein i and n are each integers of at least 1,

said device comprising means having a top, bottom and sidewalls wherein a clearance gap exists

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between said sidewalls and a plate positioned in contact with at least one substrate and perpendicular to said sidewalls, said means retaining the relative positions of said substrate and said dielectric during use of said microwave resonator in an electrical circuit.

12. The device of Claim 11 wherein said device is formed of conductive materials selected from the group of copper, aluminum, silver.

13. The device of Claim 11 wherein springs formed of non magnetic material are positioned between and in contact with the device top and said plate.

14. The device of Claim 11 wherein said device includes an additional dielectric material between said substrate and said dielectric of said microwave resonator, wherein said dielectric material is different from said dielectric of said microwave resonator.

15. The device of Claim 11 wherein said device further comprises a retainer positioned between said substrates and contacting said dielectric.

16. The device of Claim 11 further comprising a coupling means for transferring electromagnetic energy between said dielectric to an electrical circuit.

17. The device of Claim 16 wherein said coupling means comprises a coaxial cable with coupling loops formed of extended inner conductor of said cable, said cable positioned between said substrates of said microwave resonator.

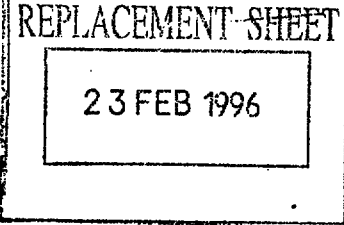
18. The device of Claim 13 wherein plurality of spaced rods of dielectric material contact said dielectric of said microwave resonator, wherein said dielectric material of said rods is different from said dielectric of said microwave resonator.

19. A method for coupling a superconducting microwave resonator to an electric circuit, said resonator comprising a dielectric having a loss factor

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(tan δ) of from 10^{-6} to 10^{-9} at cryogenic temperature, and a plurality of substrates bearing a coating of high temperature superconducting material wherein said substrates are positioned relative to said dielectric to enable said coating to contact said dielectric, said resonator contained within a holding device having a top, bottom and sidewalls wherein a clearance gap exists between the device sidewalls and a plate positioned in contact with at least one substrate and perpendicular to said sidewalls, said resonator having a Q value of at least 0.25 million at 50 K and a TE_{0in} mode wherein i and n are each integers of at least 1, and wherein said substrates have at least one opening therein for passing electromagnetic fields generated by said dielectric, said method comprising employing a means positioned on said substrate for transferring said electromagnetic fields passing through said at least one opening to an electrical circuit.

20. The method of Claim 19 wherein said means is a microstrip line.

21. The method of Claim 19 wherein said means is a coplanar line.

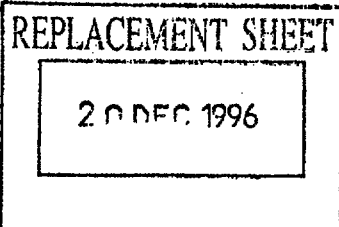
22. The method of Claim 19 wherein said means is a parallel line.

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TITLE
HIGH TEMPERATURE
SUPERCONDUCTOR-DIELECTRIC RESONATOR

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FIELD OF THE INVENTION

This invention relates to microwave resonators formed of high temperature superconductor and dielectric materials as well as to electronic circuits that employ those microwave resonators.

10

BACKGROUND OF THE INVENTION

Microwave resonators are known for use in time and frequency standards, frequency stable elements, as well as building blocks for passive devices such as filters and the like. The performance of the microwave resonator is gauged by its Q-value, expressed as

$$Q = 2\pi f_0 \cdot (\text{Storage energy} / \text{Loss power}), \quad (1)$$

where f_0 is the resonant frequency of the microwave resonator. (See Hayt, J. R., "Engineering Electromagnetics", 1981, p. 472). As shown in Equation (1), the Q-value of the microwave resonator can be increased by reducing the loss power associated with factors such as conductor loss, dielectric loss, and radiation loss.

25

Low temperature (T_c), such as 4 K, superconducting microwave resonators which employ a superconducting cavity made of Nb are known to have Q-values from about 10^6 to 10^9 . (See V. B. Braginskii, et al: "The Properties of Superconducting Resonators on Sapphire", IEEE Trans. on Magn. Vol. 17, No. 1, P355, 1981, as a reference.) Although low T_c Nb microwave resonators have high Q-values, they must operate at very low temperatures (below 9 K). These microwave resonators require use of curved cavity walls. Curved cavity walls

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✓ Description : pages 1 to 1	pages 1 to 1
✓ Claim(s) : page 1	to page 1
✓ Drawing(s) : page 1	to page 1
✓ Abstract : page 1	to page 1
DATE OF RECEIPT 20/12/96	

of materials which have a high T_c , of for example 77 K, however, are difficult to produce. On the other hand, high Q-value microwave resonators formed merely from a dielectric without an associated conducting medium also have high Q-values (see D. G. Blair, et al: "High Q Microwave Properties of a Sapphire Ring Resonator", J. Phys. D: Appl. Phys., 15, P1651, 1982.) However, the problems associated with the far reaching evanescent fields make them very bulky and vulnerable to microphonic effect, which limits the applications.

The need therefore exists for microwave resonator made of high T_c , such as 77 K, superconductor that have Q-values comparable to low T_c superconducting microwave resonators made of Nb.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1(a) and 1(b) show a vertical cross section of superconducting microwave resonator and a holding device for that resonator.

Figure 2 is a schematic block diagram of a frequency stable element for oscillators that employs the microwave resonator of the invention.

Figures 3(a) and 3(b) show configurations of filters using superconducting microwave resonators according to the invention.

Figure 4 shows the Q-values of a superconducting microwave resonator of the invention that employ YBa_2Cu_3O superconductor and sapphire dielectric.

Figure 5 shows the Q-values of a superconducting microwave resonator of the invention that employs $TlBaCaCuO$ superconductor and sapphire dielectric.

Figure 6 shows the relationship of Q-value of the resonator to the size of the dielectric.

Figure 7 shows cross sectional views of an alternative embodiment of a device for holding the microwave resonators of the invention.

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Figure 8 shows a vertical cross section of a further embodiment of a device for holding the microwave resonator of the invention.

Figure 9 shows a vertical cross section of a further alternative embodiment of a holding device for the microwave resonators of the invention.

Figure 10 shows a vertical cross section of a further embodiment of a holding device for the microwave resonators of the invention.

Figures 11(a)-11(d) show top views of alternative embodiments for coupling the microwave resonators of the invention to an electronic circuit.

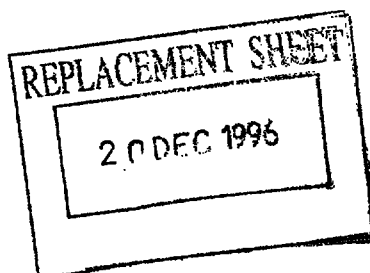
Figure 12 shows a top view of a coupling mechanism that utilizes dual couplings for coupling the microwave resonators of the invention to an electronic circuit.

Figure 13 shows a top view of a coupling of the microwave resonator of the invention to an electronic circuit integrated onto the back side of the substrate.

Figure 14 shows a vertical cross section of an alternative embodiment of the microwave resonators of the invention.

SUMMARY OF THE INVENTION

The invention is directed to high temperature superconductor-dielectric microwave resonators, to holding devices for those resonators, coupling of those resonators to electronic circuits, and to their methods of manufacture. The superconducting microwave resonator of the invention employ a superconducting film on substrates positioned on a dielectric. The holding devices include a variety of configurations, such as, a spring loaded device. The microwave resonators can be readily coupled to electronic circuits. The superconducting microwave resonators have Q values that are as high as low temperature microwave resonators formed of Nb, but operate at much higher temperature.



In accordance with the invention, a high temperature superconducting microwave resonator comprising a dielectric and a plurality of substrates bearing a coating of high temperature superconducting material is provided. The substrates are positioned relative to the dielectric to enable the coating to contact said dielectric.

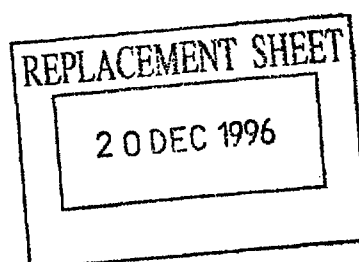
The invention also includes devices for retaining the configuration of the superconducting microwave resonator of the invention. These devices comprise means to retain the relative positions of the substrate and the dielectric during use of the microwave resonator in an electrical circuit. These devices further comprise means for coupling of the microwave resonator to electrical circuits.

The invention is further directed to a method for coupling the superconducting microwave resonator of the invention to an electric circuit by employing means positioned on the substrate for transferring electromagnetic energy between the dielectric of the superconducting microwave resonator and an electrical circuit via openings on the superconducting films and coupling lines.

The invention is still further directed to passive devices such as filters that are formed of a plurality of dielectrics positioned between a plurality of substrates bearing a coating of high temperature superconducting material, or wherein the dielectrics and substrates are in alternating positions relative to each other.

DETAILED DESCRIPTION OF THE INVENTION

Having briefly summarized the invention, the invention will now be described in detail by reference to the following specification and non-limiting examples. Unless otherwise specified, all percentages

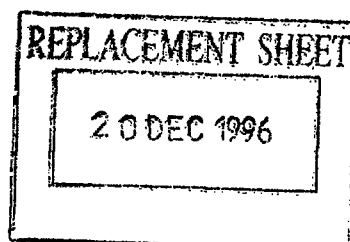


are by weight and all temperatures are in degrees Kelvin.

Figure 1 shows superconducting microwave resonator and a holding device for that resonator. As shown in Figures 1(a) and 1(b), a superconducting microwave resonator 100 with cavity 90 is provided in the form of substrates 20 bearing superconducting film 10 positioned on dielectric 30. Substrate 20 is a single crystal that has a lattice matched to superconductor film 10. Preferably, substrates 20 are formed of LaAlO₃, NdGaO₃, MgO and the like.

Generally, superconductor film 10 may be formed from any high T_c superconducting material that has a surface resistance (R_s) that is at least ten times less than that of copper at any specific operating temperature. T_c can be determined by the "eddy current method" using a LakeShore Superconductor Screening System, Model No. 7500. Surface resistance of superconducting film 10 can be measured by the method described in Wilker et al., "5-GHz High-Temperature-Superconductor Resonators with High Q and Low Power Dependence up to 90 K", IEEE, Trans. on Microwave Theory and Techniques, Vol. 39, No. 9, September 1991, pp. 1462-1467. Generally, superconductor film 10 is formed from materials such as YBaCuO (123), TlBaCaCuO (2212 or 2223), TlPbSrCaCuO (1212 or 1223), or the like.

Superconducting film 10 can be deposited onto substrate 20 by methods known in the art. See, for example, Holstein et al., "Preparation and Characterization of Tl₂Ba₂CaCu₂O₈ Films on 100 LaAlO₃", IEEE, Trans. Magn., Vol. 27, pp. 1568-1572, 1991 and Laubacher et al., "Processing and Yield of YBa₂Cu₃O_{7-x} Thin Films and Devices Produced with a BaF₂ Process", IEEE, Trans. Magn., Vol. 27, pp. 1418-1421, 1991.

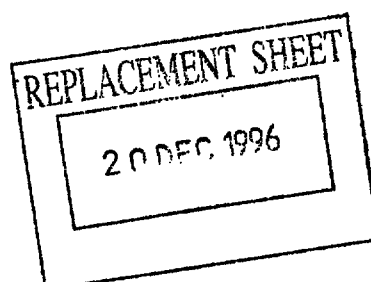


Generally, the thickness of film 10 is in the range of 0.2 to 1.0 micron, preferably 0.5 to 0.8 micron.

Microwave resonator 100 is formed by positioning substrates 20 bearing superconducting film 10 on dielectric 30. Substrates 20 can be placed on the surface of dielectric 30, or, alternatively, low loss adhesive materials may be employed. Polymethyl methacrylate optionally may be deposited onto the surface of superconducting film 10 to more firmly bond dielectric 30, as well as to protect superconducting film 10.

Dielectric 30 may be provided in a variety of shapes. Preferably, dielectric 30 is in the form of circular cylinders or polygons. Dielectric 30 may be formed of any dielectric material with a dielectric constant $\epsilon_r > 1$. Such dielectric materials include, for example, sapphire, fused quartz, and the like. Generally, these dielectric materials have a loss factor ($\tan \delta$) of from 10^{-6} to 10^{-9} at cryogenic temperatures. The ϵ_r and $\tan \delta$ of the dielectric material can be measured by methods known in the art. See, for example, Sucher et al., "Handbook of Microwave Measurements", Polytechnic Press, Third Edition, 1963, Vol. III, Chapter 9, pp. 496-546.

The configuration of the microwave resonator 100, when in use, is maintained by holding device 25. The holding device can be any embodiment that maintains the relative positions of the components of the resonator during thermal cycling associated with use of the resonator. Figure 1(a) shows a first embodiment of a holding device that employs spring loading. As shown in Figure 1(a), the configuration of microwave resonator 100 is maintained by holding device 25. Holding device 25 includes sidewalls 45, bottom plate 50, top lid 60, pressure plate 70, and load springs 80. Load springs



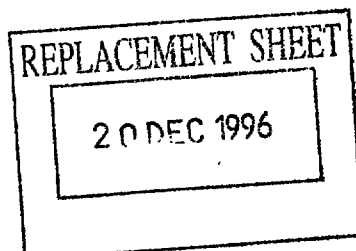
80 are sufficiently strong to retain the configuration of the microwave resonator during thermal cycling. Load springs 80 preferably are formed of nonmagnetic material in order to prevent disturbing the radio frequency fields in the resonator to achieve the highest possible Q-values. Load springs 80 preferably are formed of Be-Cu alloys.

Parts 45, 50, 60 and 70 of holding device 25 are made of thermally and electrically conductive materials in order to reduce radio frequency loss as well as to enable efficient cooling of resonator 100. Parts 45, 50, 60 and 70 therefore may be formed of, for example, oxygen fired copper, aluminum, silver, preferably oxygen fired copper or aluminum.

The high T_c superconductor-dielectric microwave resonators of the invention are capable of attaining extremely high Q-values, due in part, to the ability of substrate 20 bearing film 10 to prevent axial radio frequency fields from extending beyond the London penetration depth of the superconducting film 10. This is accomplished where substrates 20 are substantially greater than the diameter of dielectric 30 so that radio frequency fields are confined within the cavity region between substrates 20.

The high Q-value superconducting microwave resonators provided by the invention have a variety of potential applications. Typically, these resonators may be employed in applications such as filters, oscillators, as well as radio frequency energy storage devices.

The microwave resonators of the invention also may be employed as frequency stable elements to reduce the phase noise for oscillators. As shown in Figure 2, circuit 51 employs a microwave resonator 100 of the invention that is inserted into a closed feedback loop



of, preferably, a low noise amplifier 15. Where the product of the gain of amplifier 15 and the insertion loss of resonator 100 is greater than one, and where the total phase of the closed loop, as adjusted by phase shifter 17, is a multiple of 2π , then, due to the extremely high Q-values of the superconducting microwave resonators of the invention, the oscillator can be made to oscillate at the microwave resonator's resonant frequency to yield lower phase noise in the oscillator.

10 The superconducting microwave resonators of the invention also may be employed to provide highly stable frequencies suitable for secondary standards for frequency or time. Since the microwave resonator has an extremely high Q-value and operates at a constant
15 cryogenic temperature, the microwave resonator has a very stable resonate frequency that makes the resonator useful for serving as a secondary standard.

The superconducting microwave resonators of the invention further may be employed as building blocks in
20 passive devices such as filters. Examples of such filters are shown in Figures 3(a) and 3(b). As illustrated in Figure 3(a), filter 110 is shown in the form of a series of dielectrics 30 sandwiched between substrates 20 bearing superconducting films 10.
25 Coupling between dielectrics 30 is achieved by the evanescent fields of dielectrics 30. Coupling of filter 10 to electronic circuits (not shown) can be achieved by coaxial cable 18 bearing coupling loop 21.

Figure 3(b) shows an alternative embodiment of a
30 filter. As shown in Figure 3(b), filter 120 employs a series of dielectrics 30. Coupling between dielectrics 30 is achieved by the evanescent fields of dielectrics 30 via openings (not shown) on substrates 20. Coupling of filter 120 to an electronic circuit (not shown) can
35 be achieved by couplings 13. Couplings 13 can be

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coaxial lines, waveguides, or other transmission lines. In either of the embodiments of Figures 3(a) or 3(b), the high Q-values of the superconducting microwave resonators reduces the in-band insertion loss of the filter so as to make the skirt of the frequency response curve of the filter steeper.

An additional application of the superconducting, microwave resonators of the invention is to measure the surface impedance (Z_s) of superconductor materials and the complex dielectric constant $\epsilon_r = \epsilon_r' - j\epsilon_r''$ of dielectric materials, where Z_s and ϵ_r have been determined by measurement of f_0 and Q at two differing modes in accordance with methods known in the art.

Generally, high Q-values for the superconducting microwave resonators of the invention may be obtained by selecting the proper electromagnetic modes to prevent flow of radio frequency current across the edges of superconducting films 10. These proper modes are TE_{0in} modes where the radial mode index has a value of $i=1,2,3,\dots$ and the axial mode index has a value of $n=1,2,3,\dots$. All TE_{0in} modes have only circular radio frequency currents that do not cross the edge of films 10.

Having selected the specific electromagnetic mode of the microwave resonator, the Q and the resonant frequency f_0 for the microwave resonator can be calculated by solving Maxwell's Equations for the boundary conditions of the resonator, as is known in the art.

The loss power associated with parasitic coupling to low Q-value modes such as non- TE_{0in} modes or case modes may be minimized in the microwave resonators of the invention by assuring that substrates 20 are flat and parallel to within a tolerance of less than 1° . Loss power also may be minimized by ensuring that the

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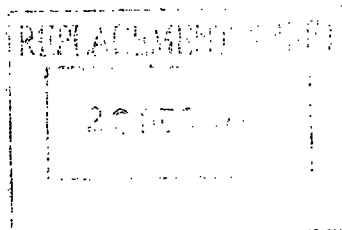
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C-axis of anisotropic materials such as sapphire, when employed as dielectric 30, is perpendicular to substrate 20 to within $\pm 5^\circ$, preferably 1° .

As also is shown in Figure 1(a), microwave resonator 100 can be coupled to an electric circuit (not shown) by coaxial cable 18 that includes coupling loop 21 protruding into cavity 90 of microwave resonator 100. The orientation of coupling loop 21 and the depth of insertion of coaxial cable 18 into cavity 90 readily can be adjusted to ensure coupling to the electronic circuit.

In a preferred aspect of the invention, superconducting film is formed by epitaxially depositing 0.5 micron superconducting films of $Tl_2Ba_2Ca_1Cu_2O$ or YBa_2Cu_3O on 2 inch diameter substrates of $LaAlO_3$ positioned on cylindrical dielectrics of sapphire. The superconducting film is deposited so that the C-axis of the film is perpendicular to the surface of the substrate. The dielectrics of sapphire typically measure 0.625 inch diameter by 0.276 inch tall, 0.625 inch diameter by 0.552 inch tall, or 1.00 inch diameter by 0.472 inch tall. The substrates and dielectric are retained in position by a holding device formed of oxygen free copper. Coupling of the microwave resonator to an electrical circuit can be achieved by inserting two 0.087 inch diameter copper or stainless steel, 50 ohm coaxial cables with coupling loops made of extended inner conductor into the cavity of the resonator. The surface of the coupling loops is perpendicular to the vertical axis of the sapphire dielectric to enable selective coupling to the TE_{011} ($i=1$, $n=1$) mode of the dielectric.

The Q values of the above described microwave resonators, when employing YBa_2Cu_3O as the superconducting film, are shown in Figure 4. As shown.



in Figure 4, Q values of 5 million, 1.5 million, and 0.25 million are found at temperatures of 4.2 K, 20 K and 50 K, respectively. The Q values of the above described microwave resonators, when employing
5 $\text{Tl}_2\text{Ba}_2\text{Ca}_1\text{Cu}_2\text{O}$ as the superconducting film, are shown in Figure 5. As shown in Figure 5, Q values of 6 million, 3 million, and 1.3 million are found at temperatures of 20 K, 50 K, and 77 K, respectively.

10 The dependence of Q values of the above described microwave resonators that employ $\text{Tl}_2\text{Ba}_2\text{Ca}_1\text{Cu}_2\text{O}$ as the superconducting film on the size of the sapphire dielectric is shown in Figure 6. As shown in Figure 6, the Q values increase from 3 million to 6 million with increasing size of the sapphire dielectric.

15 Device 25 shown in Figure 1(a) that employs spring loading is only illustrative. Other means for holding microwave resonator 100 are shown below.

Figures 7(a) and 7(b) show an alternative embodiment for holding the microwave resonators of the
20 invention. As shown in Figure 7, the microwave resonator is held by holding device 27. Device 27 is indential to device 25 except that, as shown in Figure 7(a), spring loaded holding device 27 employs three dielectric rods 35 positioned 120° relative to each
25 other to further support dielectric 30. Dielectric rods 35 are inserted through side walls 47 of holding device 27 into cavity 95. Dielectric rods 35 have a low loss and a dielectric constant less than that of dielectric 30. The tips of rods 35 are pointed to minimize contact
30 area with dielectric 30 to minimize loss power.

A further embodiment of a device for holding the microwave resonators of the invention is shown in Figure 8. As set forth in Figure 8, the microwave resonator is retained in position by holding device 28. Holding
35 device 28 is identical to holding device 25 except for

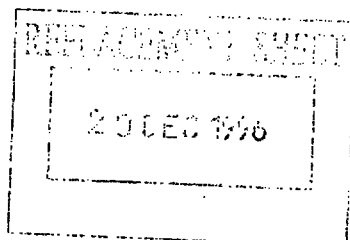
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the additional use of retainer 77. As shown in Figure 8, substrate 20 bearing superconducting film 10 is positioned on bottom-plate 50. Dielectric 30 is positioned on substrate 20. Retainer 77 is positioned about dielectric 30. Retainer 77 contacts sidewalls 45 and superconducting film 10 on substrate 20. Retainer 77 and side walls 45 have openings for receiving coaxial cables 18. Cables 18 have loops 21 for coupling of the resonator to an electric circuit(not shown). Retainer 77 is formed of materials that have low dielectric constant of nearly 1 and low $\tan \delta$ of $<10^{-4}$. As shown in Figure 8, retainer 77 is hollow, and is solid near sidewalls 45 where the electrical fields are minimum. The wall thickness of retainer 77 is minimized to reduce the contact area between retainer 77 and dielectric 30 to minimize loss power.

Still yet another embodiment of a holder device for the microwave resonators of the invention is shown in Figure 9. Holding device 29 shown in Figure 9 is identical to holding device 25 except for the use of additional dielectric 65. As shown in Figure 9, cavity 91 between dielectric 30 and the interior surface of sidewall 45 of device 25 is filled with dielectric material 65. Dielectric material 65 has a $\tan \delta$ of less than 10^{-5} . Examples of dielectric material 65 include styrofoam, porotic teflon, and the like.

Figure 10 shows a further embodiment of a holding device suitable for use with the superconducting microwave resonators of the invention. Holding device 24 shown in Figure 10 is identical to holding device 25 except for additional use of holding pins 71. As shown in Figure 10, pins 71, formed of low $\tan \delta$ dielectric materials such as sapphire, quartz, polymers, polytetrafluoroethylene ("teflon"), "Delrin", registered trademark of E. I. du Pont de Nemours and Company, and

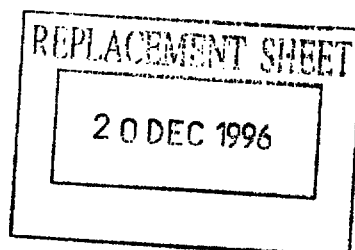


the like are inserted into substrate 20 bearing superconducting film 10 and into dielectric 30.

Figures 11(a) to 11(d) show alternative embodiments for coupling of the microwave resonators of the invention to an electronic circuit (not shown). Generally, the embodiments shown in Figures 11(a)-11(c) entail use of substrates that bear superconducting films on the surfaces of the substrate that directly contacts dielectric 30. Openings are provided on the superconducting film on the side which directly contacts dielectric 30. A coupling device is located over the opening on surface of the substrate that does not contact dielectric 30.

Figure 11(a) shows a microstrip line coupling mechanism for coupling of the microwave resonators of the invention to an electronic circuit (not shown). In Figure 11(a), microstrip line 15 is formed by depositing superconducting film material on that surface of substrate 20 that is remote to dielectric 30. Microstrip line 15 serves as the lead to an electronic circuit (not shown). Opening 12 is provided in film 10 on the surface of substrate 20 that contacts dielectric 30. Opening 12 extends through film 10 but not through substrate 20. Opening 12 does not contact dielectric 30 in order to minimize the effects of magnetic fields on dielectric 30. Opening 12 is parallel to the local magnetic field. Coupling is achieved by magnetic field leakage through opening 12 to line 15. Microstrip line 15 extends over opening 12 by a distance of $\lambda/4$, where λ is the wavelength of the radio frequency field at the operating frequency of the resonator.

Figure 11(b) shows a coplanar line coupling mechanism for coupling the microwave resonators of the invention to an electronic circuit (not shown). The coplanar line coupling is formed by depositing

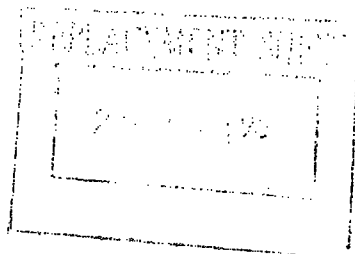


superconducting film material on that surface of substrate 20 that is remote to dielectric 30 to form center line 19 and ground plane 21. The coplanar line coupling serves as the lead to an electronic circuit (not shown). The coplanar line coupling extends over opening 12. Opening 12 is provided by film 10 on the surface of substrate 20 that contacts dielectric 30. Opening 12 extends through film 10 but not through substrate 20. Opening 12 does not contact dielectric 30.

In the coplanar line coupling of Figure 11(b), center line 19 is short circuited to ground plane 21. Center line 19 extends across opening 12. Opening 12 is parallel to the local magnetic field. Coupling is achieved by magnetic field leakage through slot 12 to center line 19.

Figure 11(c) shows a parallel line coupling mechanism for coupling dielectric 30 to an electronic circuit(not shown). The parallel line coupling includes parallel lines 31 and loop 32. The parallel line coupling is formed by depositing superconducting film material on that surface of substrate 20 that is remote to dielectric 30. The parallel line coupling mechanism serves as the lead to an electronic circuit (not shown). Parallel lines 31 and loop 32 extend over opening 12. Opening 12 is provided in film 10 on the surface of substrate 20 that contacts dielectric 30. Opening 12 extends through film 10 but not through substrate 20. Opening 12 does not contact dielectric 30. Coupling is achieved by leakage of magnetic field through opening 12 which is captured by loop 32.

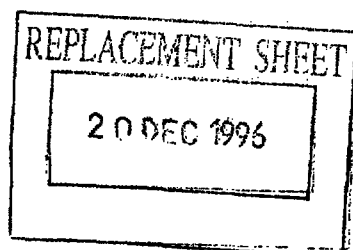
Figure 11(d) shows a coupling mechanism useful for microwave resonators such as those used for a filter as shown in Figure 3(b). As shown in Figure 11(d), the coupling mechanism employs identical, congruent slots 12



through film 10 of both surfaces of substrate 20. Slots 12 extend through films 10 but terminate at the surfaces of substrate 20. Slots 12 on each surface of substrate 20 may be the same or different in size. Coupling is
5 achieved by leakage of evanescent magnetic field through slots 12.

Coupling of the microwave resonator also may be achieved through dual couplings. Figure 12 shows a dual coupling mechanism that utilizes dual identical coupling
10 microstrip lines 44(a) and 44(b) that cross slots 12(a) and 12(b) on film 10. Slots 12(a) and 12(b) are provided in film 10 on that surface of the substrate 20 that contacts dielectric 30. Slots 12(a) and 12(b) terminate at the surface of substrate 20. Couplings
15 44(a) and 44(b) are connected by lead line 41 that is divided into equal length branches 42(a) and 42(b). Lines 44(a) and 44(b) and lead line 41 are formed by depositing superconductive material onto substrate 20. Coupling is achieved by leakage of evanescent magnetic
20 field through slots 12(a) and 12(b). The dual coupling mechanism shown in Figure 12 enables selective coupling to the TE_{011} mode and suppresses competing electromagnetic field modes that have antisymmetrical magnetic field distribution.

25 The coupling mechanisms of the invention also provide for ease of connection to circuits integrated onto substrate 20. As shown in Figure 13, a circuit is integrated onto the side of substrate 20 that bears coupling mechanisms 55(a) and 55(b). Couplings 55(a)
30 and 55(b) may be formed by depositing superconductive film material onto substrate 20 over slots 12(a) and 12(b). Slots 12(a) and 12(b) are provided in the superconducting film (not shown) on that side of substrate 20 that contacts dielectric 30. Slots 12(a)
35 and 12(b) extend through the superconductor film but

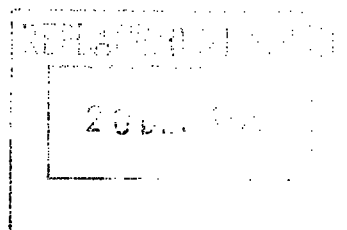


terminate at the surface of substrate 20. Coupling is achieved by leakage of magnetic field through slots 12(a) and 12(b).

Integration of circuits onto substrate 20 as shown in Figure 13 may be achieved by well known thin film printed circuit technology. If the circuit is a hybrid circuit that employs, for example, transistors, then the transistors can be integrated into the circuit by conventional wire bonding.

Figure 14 shows an alternative embodiment of the superconducting microwave resonator of the invention that is retained by holding device 25. As shown in Figure 14, rings 61 with a dielectric constant much less than that of dielectric 30 are inserted between dielectric 30 and superconducting film 10. Rings 61, by placing dielectric 30 further from superconducting film 10, enable the microwave resonator to handle greater power levels.

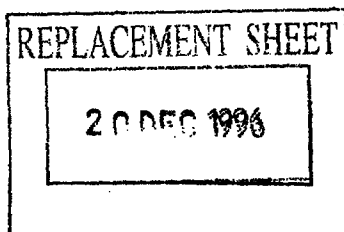
From the foregoing description, one skilled in the art can easily ascertain the essential characteristics of this invention, and without departing from the spirit and scope thereof, can make various changes and modifications of the invention to adapt it to various uses and conditions.



CLAIMS

What is claimed is:

- 5 1. A high temperature superconducting microwave resonator comprising a dielectric and a plurality of substrates bearing a coating of high temperature superconducting material, wherein said substrates are positioned relative to said dielectric to enable said
10 coating to contact said dielectric.
2. The high temperature superconducting microwave resonator of Claim 1 wherein said dielectric is selected from the group of sapphire and quartz.
- 15 3. The high temperature superconducting microwave resonator of Claim 2 wherein said dielectric is sapphire.
- 20 4. The high temperature superconducting microwave resonator of Claim 1 wherein said substrates are single crystals that are lattice matched to said superconducting material.
- 25 5. The high temperature superconducting microwave resonator of Claim 4 wherein said substrates are selected from the group of LaAlO_3 , NdGaO_3 and MgO .
- 30 6. The high temperature superconducting microwave resonator of Claim 1 wherein said superconducting material has a surface resistance at least ten times less than copper.
- 35 7. The high temperature superconducting microwave resonator of Claim 6 wherein said superconducting



material is selected from the group of YBaCuO (123), TlBaCaCuO(2212), TlBaCaCuO(2223), TlPbSrCaCuO(1212) or TlPbSrCaCuO(1223).

5 8. The high temperature superconducting microwave resonator of Claim 1 further comprising dielectric rings positioned between said dielectric and said substrate.

10 9. A filter comprising a plurality of dielectrics positioned between a plurality of substrates bearing a coating of high temperature superconducting material, wherein said substrates are positioned relative to said dielectric to enable said coating to contact said dielectric.

15

10. The filter of Claim 9 wherein said dielectrics and said substrates are in alternating positions relative to each other.

20 11. A device for retaining the configuration of a superconducting microwave resonator, said microwave resonator comprising a dielectric and a plurality of substrates bearing a coating of high temperature superconducting material, wherein said substrates are positioned relative to said dielectric to enable said coating to contact said dielectric,

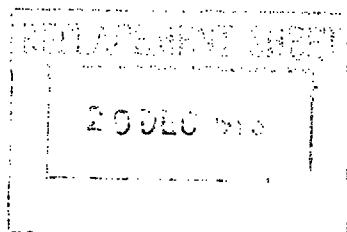
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said device comprising means to retain the relative positions of said substrate and said dielectric during use of said microwave resonator in an electrical circuit.

30

12. The device of Claim 11 wherein said device is formed of conductive materials selected from the group of copper, aluminum, silver.

35



13. The device of Claim 11 wherein said means is springs formed of non magnetic material.

14. The device of Claim 11 wherein said device
5 includes an additional dielectric material between said substrate and said dielectric of said microwave resonator, wherein said dielectric material is different from said dielectric of said microwave resonator.

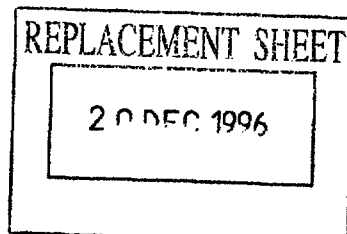
10 15. The device of Claim 11 wherein said device further comprises a retainer positioned between said substrates and contacting said dielectric.

16. The device of Claim 11 further comprising a
15 coupling means for transferring electromagnetic energy between said dielectric to an electrical circuit.

17. The device of Claim 16 wherein said coupling
means comprises a coaxial cable with coupling loops
20 formed of extended inner conductor of said cable, said cable positioned between said substrates of said microwave resonator.

18. The device of Claim 13 wherein plurality of
25 spaced rods of dielectric material contact said dielectric of said microwave resonator, wherein said dielectric material of said rods is different from said dielectric of said microwave resonator.

30 19. A method for coupling a superconducting microwave resonator to an electric circuit, said resonator comprising a dielectric and a plurality of substrates bearing a coating of high temperature superconducting material wherein said substrates are
35 positioned relative to said dielectric to enable said



coating to contact said dielectric and wherein said
substrates have at least one opening therein for passing
electromagnetic fields generated by said dielectric,
said method comprising employing a means positioned on
5 said substrate for transferring said electromagnetic
fields passing through said at least one opening to an
electrical circuit.

20. The method of Claim 19 wherein said means is a
10 microstrip line.

21. The method of Claim 19 wherein said means is a
coplanar line.

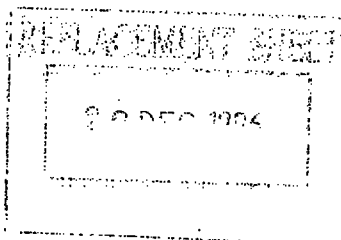
15 22. The method of Claim 19 wherein said means is a
parallel line.

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AMENDED CLAIMS

[received by the International Bureau on 23 April 1993 (23.04.93);
original claim 10 cancelled; original claim 9 amended;
other claims unchanged (1 page)]

material is selected from the group of YBaCuO (123),
TlBaCaCuO(2212), TlBaCaCuO(2223), TlPbSrCaCuO(1212) or
TlPbSrCaCuO(1223).

5 8. The high temperature superconducting microwave
resonator of Claim 1 further comprising dielectric rings
positioned between said dielectric and said substrate.

10 9. A filter comprising a plurality of dielectrics
positioned between a plurality of substrates bearing a
coating of high temperature superconducting material,
wherein said substrates are positioned relative to said
dielectric to enable said coating to contact said
dielectric, and said dielectrics and said substrates are
15 in alternating positions relative to each other.

11. A device for retaining the configuration of a
superconducting microwave resonator, said microwave
resonator comprising a dielectric and a plurality of
20 substrates bearing a coating of high temperature
superconducting material, wherein said substrates are
positioned relative to said dielectric to enable said
coating to contact said dielectric,

25 said device comprising means to retain the relative
positions of said substrate and said dielectric during
use of said microwave resonator in an electrical
circuit.

30 12. The device of Claim 11 wherein said device is
formed of conductive materials selected from the group
of copper, aluminum, silver.



ABSTRACT**HIGH-TEMPERATURE SUPERCONDUCTOR-DIELECTRIC RESONATOR**

The invention is directed to superconducting microwave resonator, to holding devices for those resonators, and to their methods of manufacture. The superconducting microwave resonators employ a superconducting film on substrates positioned on a dielectric. The holding devices include a variety of configurations, such as, a spring loaded device. The superconducting microwave resonators have Q values of as high as microwave resonators formed of Nb, but operate at much higher temperature.

Fig. 1a

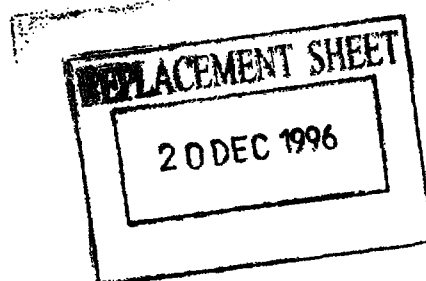


FIG. 1a

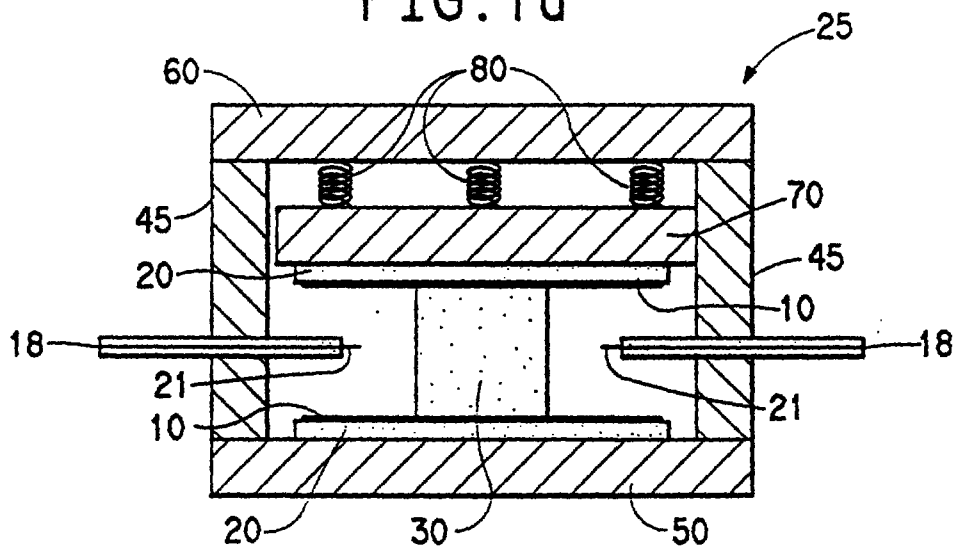


FIG. 1b

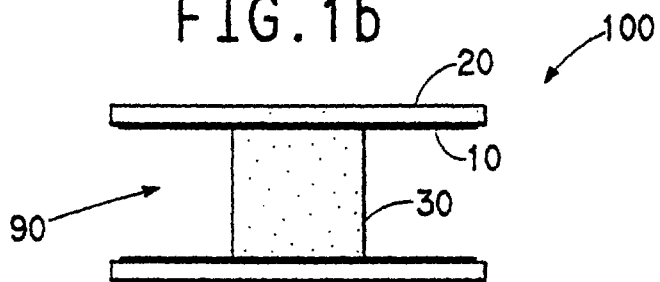
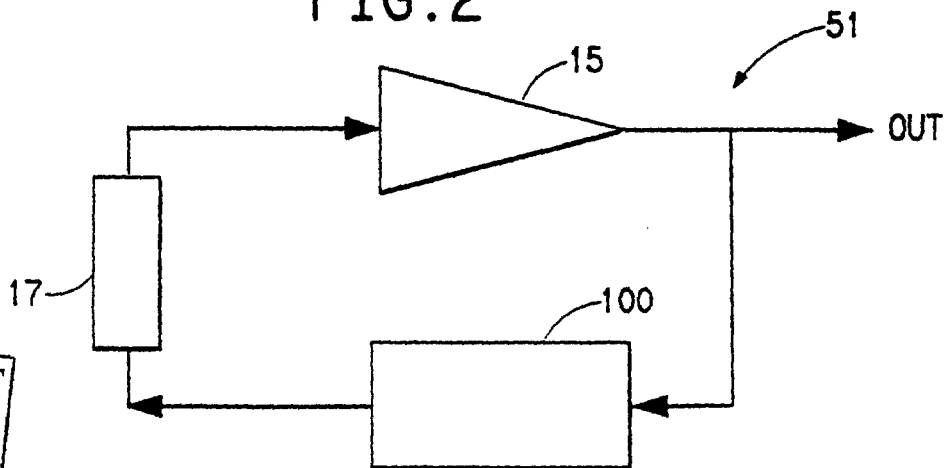


FIG. 2



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FIG. 3a

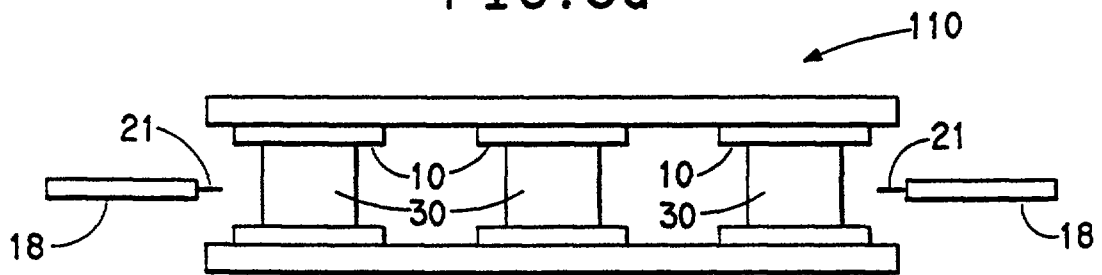


FIG. 3b

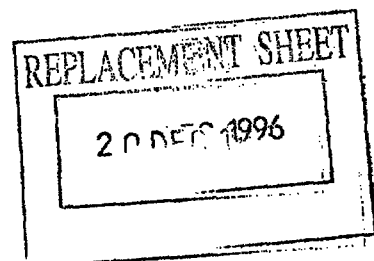
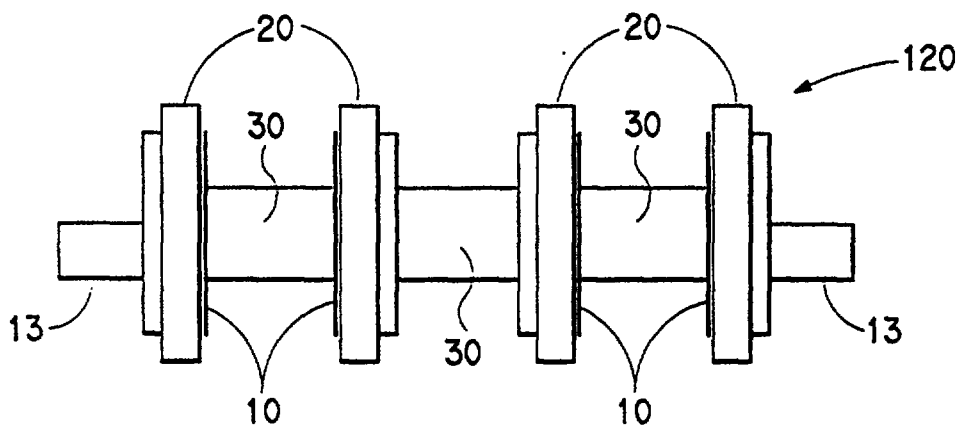
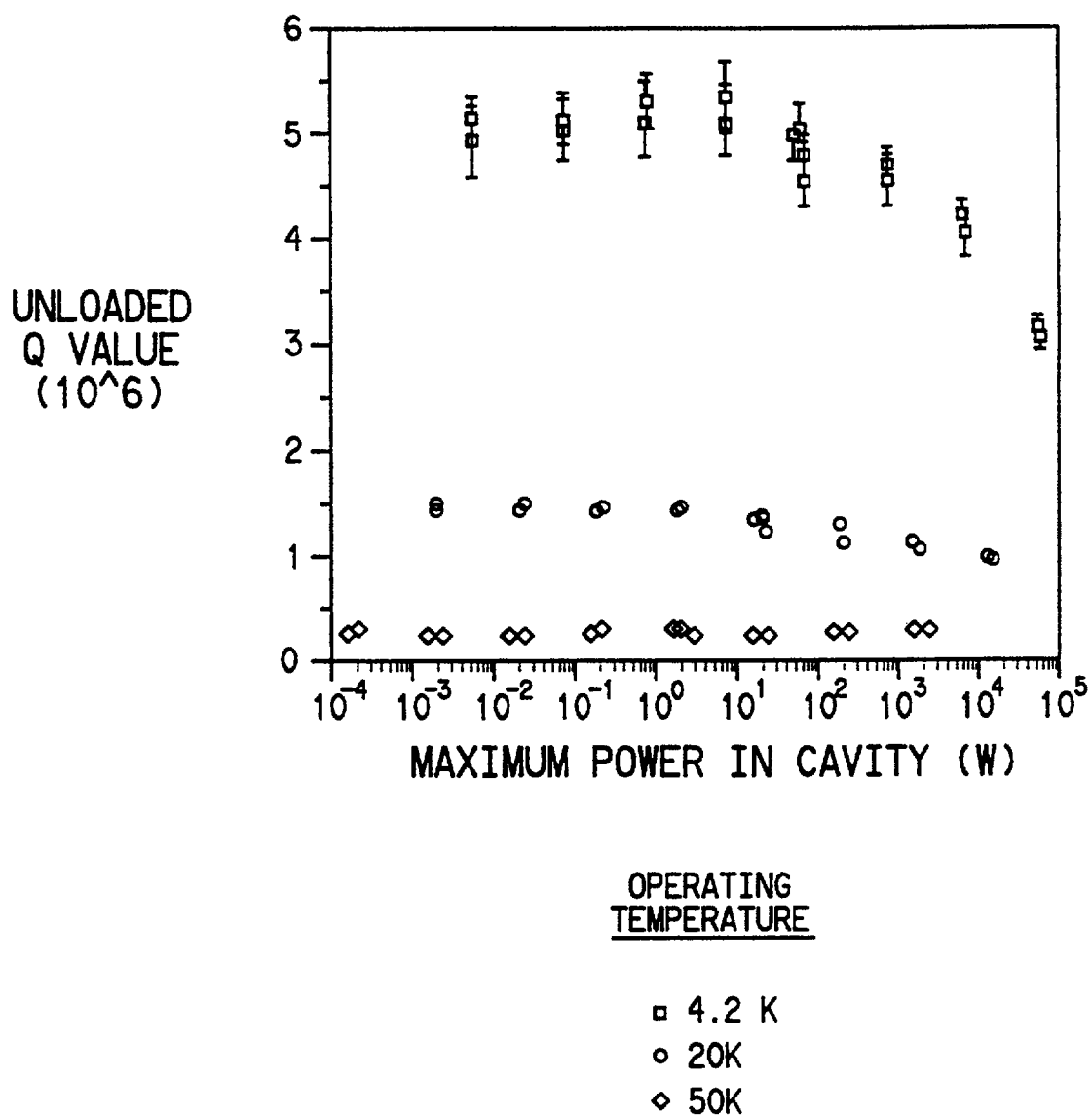


FIG.4



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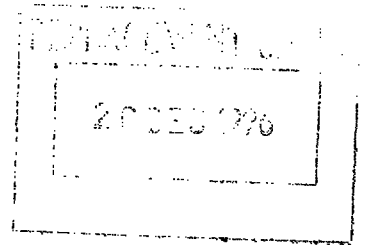
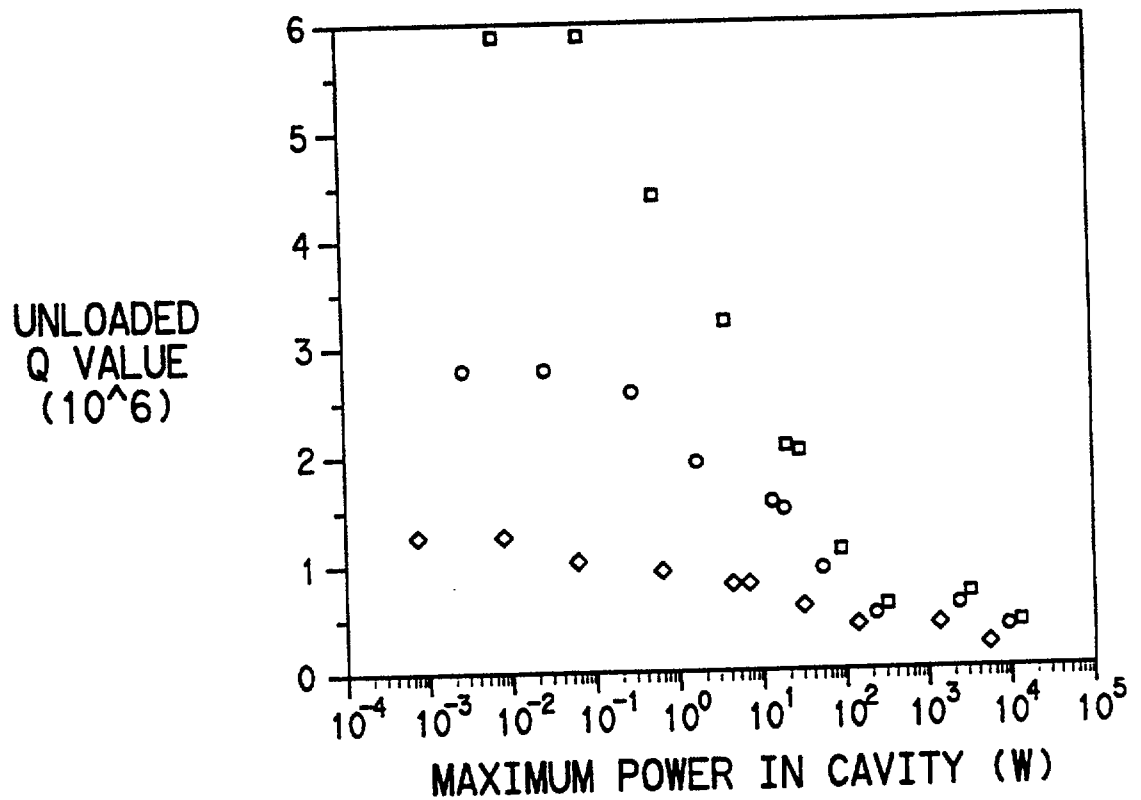
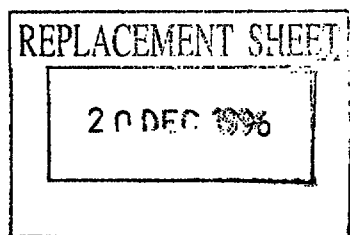


FIG.5



OPERATING
TEMPERATURE

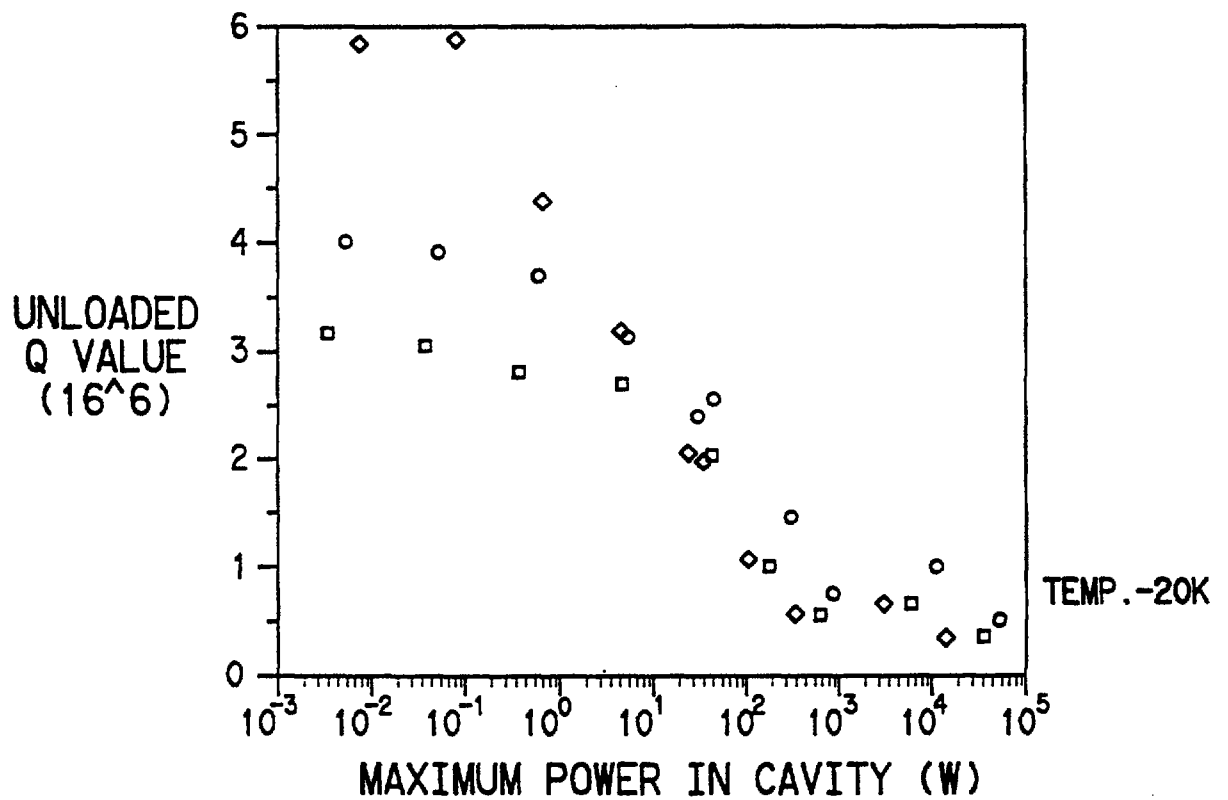
- 20K
- 50K
- ◇ 77K



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FIG.6



SAPPHIRE SIZE

- .625" DIA. BY .276" HGT
- .625" DIA. BY .552" HGT
- ◇ 1" DIA. BY .472" HGT

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FIG. 7a

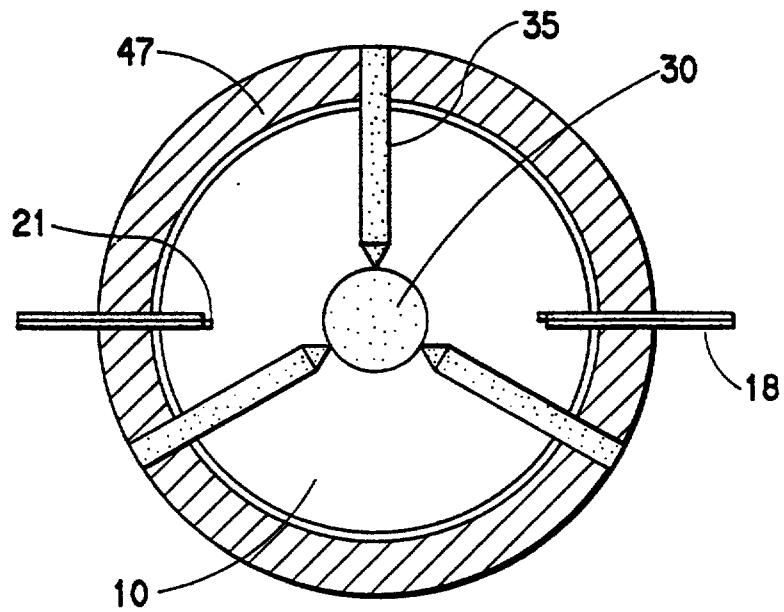
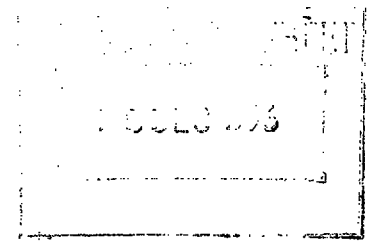
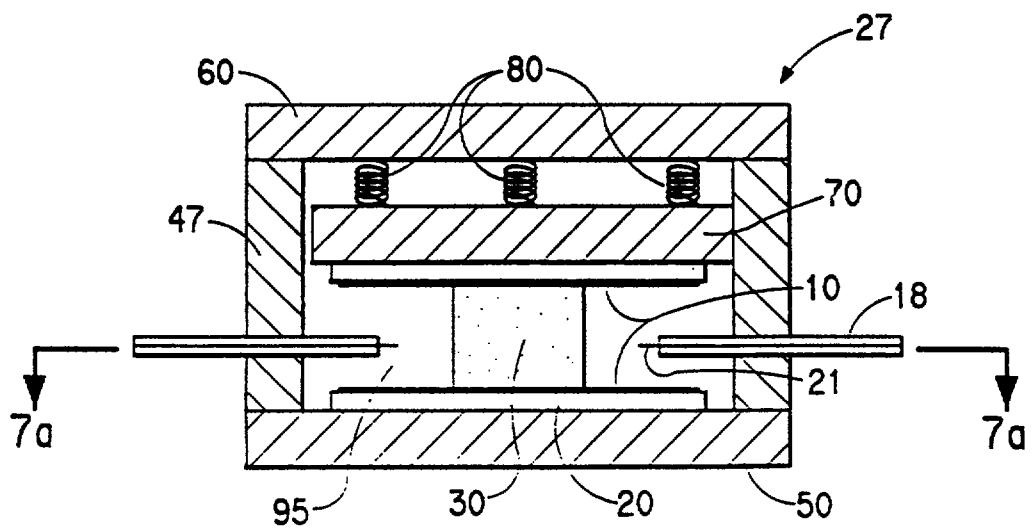


FIG. 7b



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FIG. 8

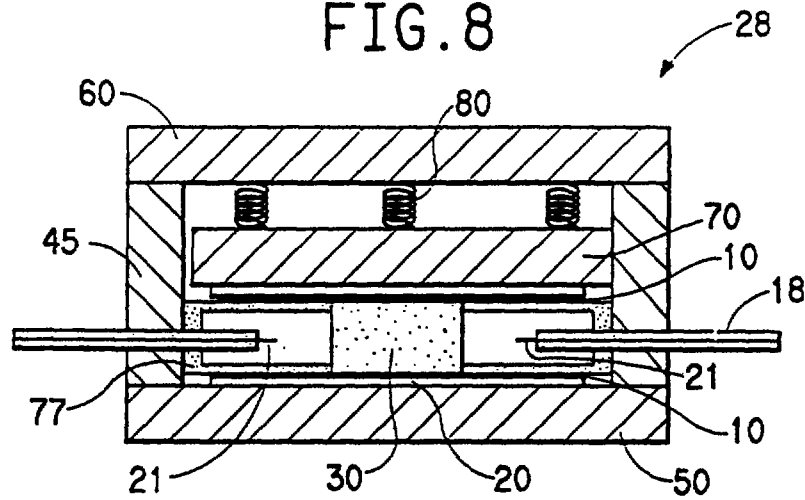


FIG. 9

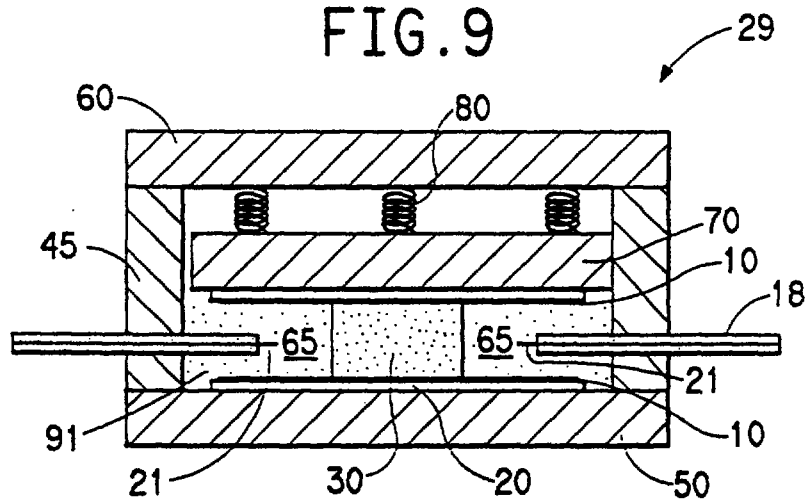
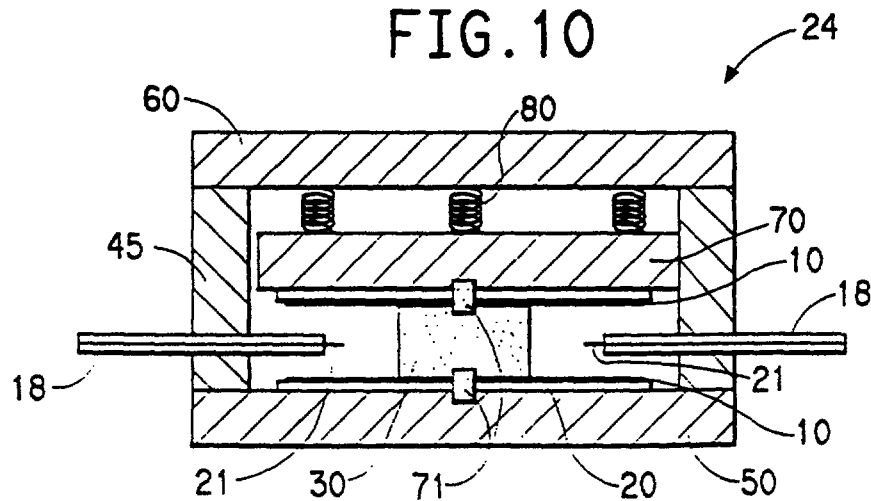


FIG. 10



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FIG. 11a

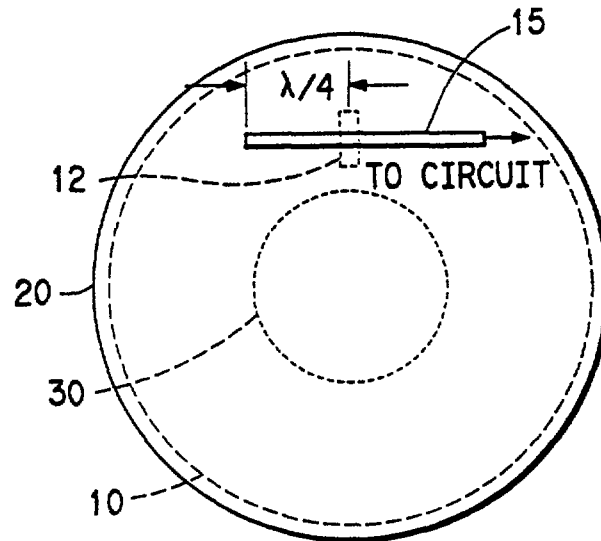
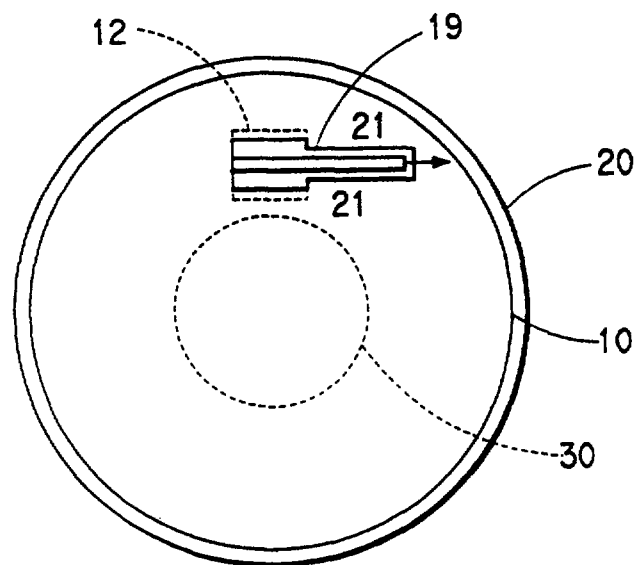


FIG. 11b



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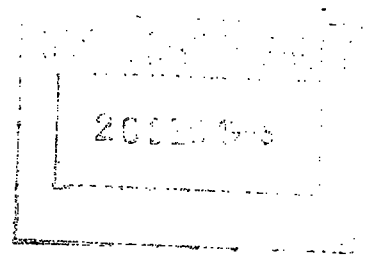


FIG.11c

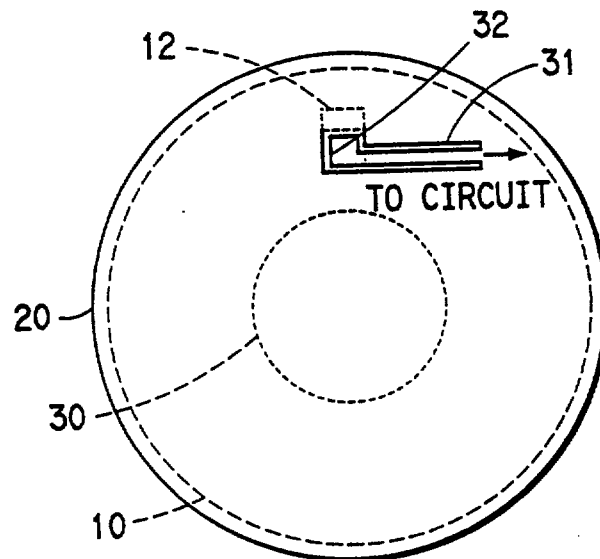
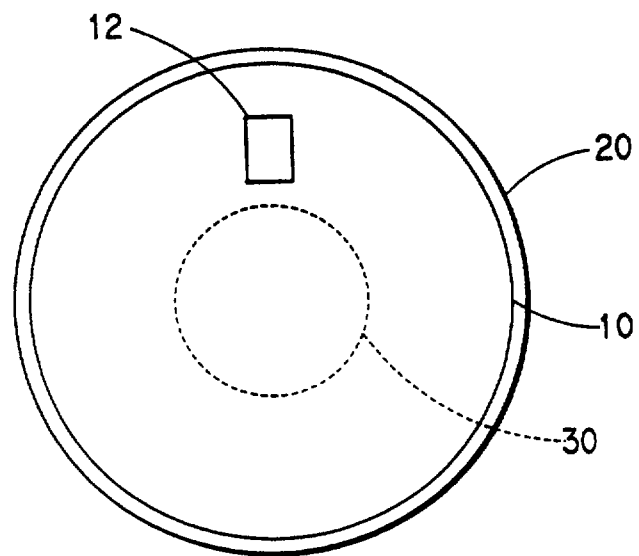


FIG.11d



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FIG. 12

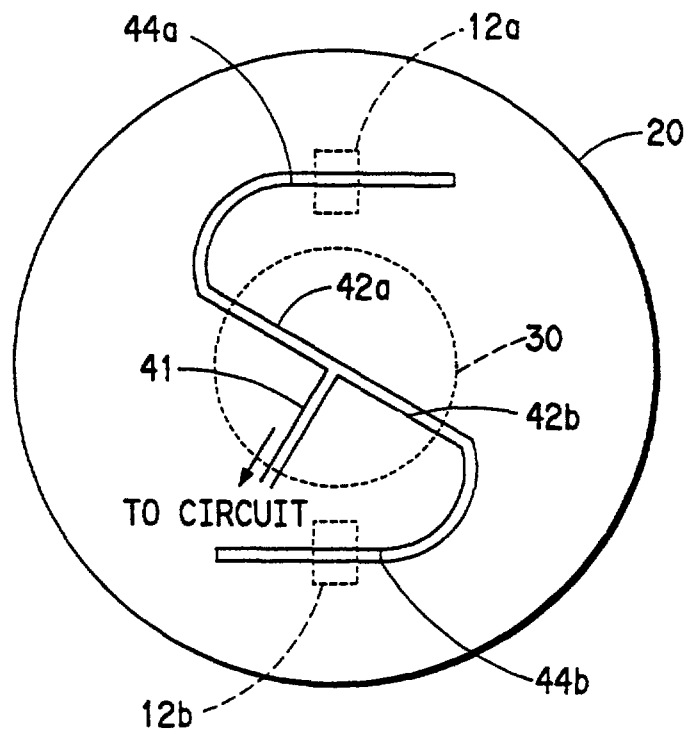


FIG. 13

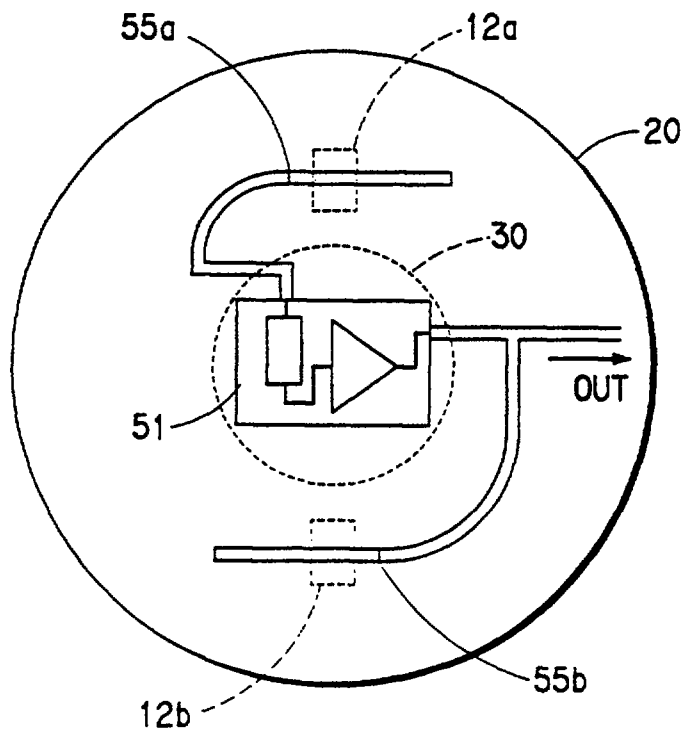


FIG. 14

