

A Closed Slot-Line Resonator Filter

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Abstract—A microwave bandpass filter made from three-dimensional (3-D) slot-line resonators is described. This structure readily lent itself to the design and realization of a 16-pole filter. By concentrating the losses on the resonant element, very high Q can be achieved by using low surface resistance material, such as high temperature superconductor, for the slot-line resonator. The filter is five to ten times smaller than previous generation 3-D filters made using high temperature superconductors.

Index Terms—Filters, high temperature superconductors, inter-modulation distortion, slot line.

I. INTRODUCTION

HIGH-PERFORMANCE RF and microwave filters benefit from high resonator Q because the reduced loss of each resonator allows the designer to design higher order filters. Three-dimensional (3-D) high Q filters have been successfully realized by coating the conductive surfaces with high temperature superconductive (HTS) thick films [1]. Any attempt to optimize Q by maximizing the volume to surface area ratio will put 3-D filters at the disadvantage of having very large size. HTS thick film technology has been used to minimize the volume of 3-D filters by applying the thick films to structures which confine the current to a small surface area. After coating the high current region with HTS material, the volume of the 3-D housing can then be reduced while keeping the Q high.

This paper reports the most recent development in HTS thick film filter miniaturization. This work was done at 1900 MHz, with third generation UMTS wireless communication base stations as the intended application. Over the past several years the volume of filters using HTS thick films has been reduced significantly. The 16-pole 1900 MHz 3-D filters using HTS thick film and built by our group had a volume of 2.4 l in 1997, 1.5 l in 1999 and, most recently, 0.3 l in 2001 using the development reported here.

II. CLOSED SLOT-LINE RESONATOR

Three-dimensional cavity filters are necessarily bulky in comparison to some other filter technologies, such as thin film microstrip, and at the frequency of this work, 1900 MHz, are usually comparable in size to dielectric resonator filters. As a general rule, the Q of a 3-D filter varies directly with the volume,

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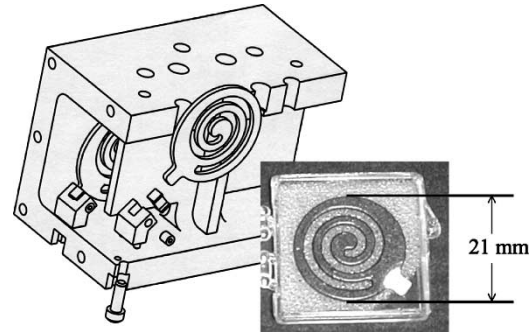


Fig. 1. Closed slot-line spiral resonators in their cavities, depicting also the mounting scheme. The photo in the inset shows the HTS coated resonator with the bare mounting tab.

V , according to the general scaling expression, $Q \propto V/(AR_S)$, where A is the conductive surface area and R_S is the surface resistance.

Previously, 3-D cavity filters have been made using high temperature superconducting resonant elements, [2] and [3]. The individual resonator cavities at 1900 MHz had volumes ranging from 53 cm³ for resonators in [2] to 110 cm³ for resonators in [3]. In this work, a slot-line spiral resonator with the same Q at 1900 MHz as in [2] and [3] was developed that has a cavity volume of 9.8 cm³.

The resonator is shown in Fig. 1. The resonator substrate is cut from a 1 mm thick sheet of polycrystalline yttria stabilized zirconia (TTZ) with a pulsed sapphire laser. The laser is also used to cut the spiral slot in the interior of the 21-mm diameter round piece. For the purpose of mounting, a tab is also formed on the exterior of the substrate.

The finished substrate is coated with an ink loaded with unreacted precursors of superconducting YBa₂Cu₃O_{7-x} and sintered at 1050 °C in pure oxygen, then slow cooled to room temperature, allowing for sufficient time to anneal. The process and its applications are described in [4] and [5]. A superconductive coating is essential for high Q in this structure. When this resonator is made out of copper and operated at room temperature, it has a Q factor less than 100. The mounting tab was deliberately left uncoated to avoid a superconductor/metal electrical interface with the aluminum mounting post. There is very little current in the region of the tab, but enough current to affect Q if there is a bad contact.

Ninety resonators were fabricated under nearly identical conditions. The untuned resonant frequencies, measured in a single cavity housing, were nominally 1989 MHz with a range of ± 4 MHz. At 77 K, the average Q was 44 000, the highest Q was 63 800, and 67% of the resonators had $Q > 40 000$. When building a filter, the higher Q resonators are used in the center of the filter, where there is high sensitivity to Q . Low Q

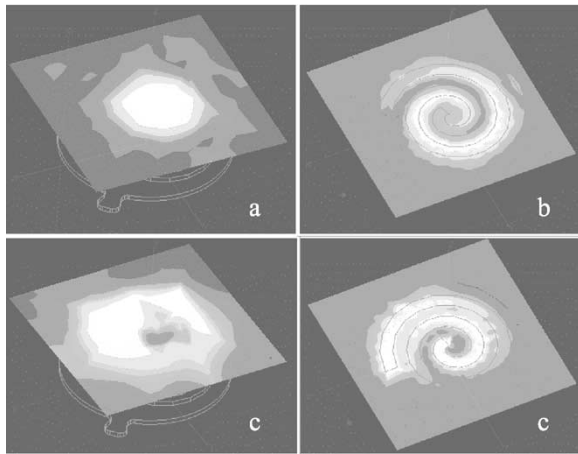


Fig. 2. Magnitude of (a) the electric field on the aperture wall of the cavity, (b) the electric field on the surface of the resonator, (c) the magnetic field on the aperture wall of the cavity, and (d) the magnetic field on the surface of the resonator.

resonators are used near the input and output cells, where there is very little sensitivity to Q .

The resonator was simulated using the finite element high frequency structure simulator (HFSS), Version 8 from Ansoft Corporation. With a realistic surface resistance of $160 \mu\Omega$ at 77 Kelvin and 1.95 GHz, the Q is expected to be 56 500. Later process improvements resulted in an average Q of 58 000. This high Q with such a significant reduction in size is possible because this design efficiently confines the current to the low loss superconductive slot-line resonant element.

The spiral slot-line resonators in this work resonated around 1950 MHz. The electric and magnetic fields were computed using HFSS and are shown in Fig. 2. Although a slot line propagates a nearly transverse electric mode [6], the slot-line resonance nevertheless has two magnetic field maxima and one electric field maximum along the slot similar to a half wave TEM mode. The slot length is approximately commensurate with half the TE guide wavelength of the slot [7].

The resonant frequency is tuned by a screw which passes into the high electric field region. A nylon stud is mounted on the end of the brass screw, and a small copper cylinder is on the end of the nylon. In compliance with Slater's theorem, the frequency could be driven down about 10 MHz by introducing this perturbation into the high electric field region. After 10-MHz of de-tuning, the screw which drives the tuner in and out starts to load the resonator and additional, lossy de-tuning is available for about 70 MHz.

III. RESONATOR COUPLING

Magnetic (positive) inter-resonator coupling is achieved with an aperture in the wall between two neighboring resonators. A 20-MHz wide filter was made in this work, so 10 to 16 MHz is the range of adjacent resonator coupling values that need to be available for the practical realization of filters. Suitably strong magnetic coupling was accomplished with an aperture that follows the edge of the wall, as seen in Fig. 3. This is the optimum aperture shape, because the electric field in Fig. 2(a) is strongest in the middle of the wall, so for magnetic coupling, the middle of

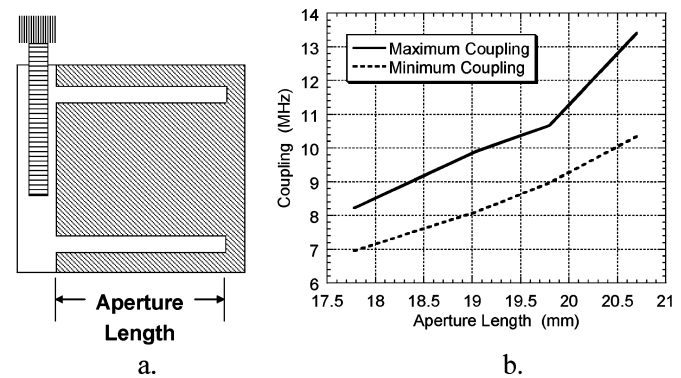


Fig. 3. (a) Positive coupling is varied by adjusting the length of the aperture in (b) the wall. The screw tunes the coupling strength. The results are experimental.

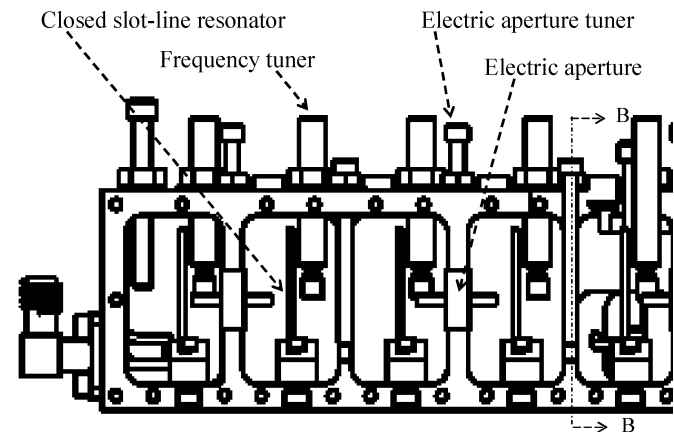


Fig. 4. Sketch of the 16-pole filter showing all of the features involved in realizing a complete filter including the resonators, the tuners and the apertures. Section B-B is shown in Fig. 3(a).

the wall should be blocked. The magnetic coupling is adjusted with a screw that is driven through one leg of the three-legged aperture.

Magnetic coupling for two co-planar resonators is achieved with a wire loop, both ends of which are terminated in the wall of the housing. Because a loop can be placed in close proximity of the resonators, stronger coupling is achieved this way than with an aperture.

Significant electric (negative) coupling is only realized by placing a probe between the two resonators. The negative coupling mechanism between resonators is seen in Fig. 4. The probe is mounted in a hole in the wall between the resonators at the point where the electric field is strongest, according to the HFSS simulation in Fig. 2(a). Electric coupling between two co-planar resonators is similarly achieved by placing a probe between the resonators.

IV. SIXTEEN-POLE FILTER

A detailed sketch of the first five resonators of the 16-pole filter is shown in Fig. 4. There are two negative cross-couplings, to provide a quasielliptic response. The first attempt to realize a filter failed due to very strong nonadjacent resonator coupling. The problem was particularly acute between resonators 2 and 4, and between 3 and 5, and so on (where cavities 1 and 16 are the input and output resonators). The solution to this nonadjacent

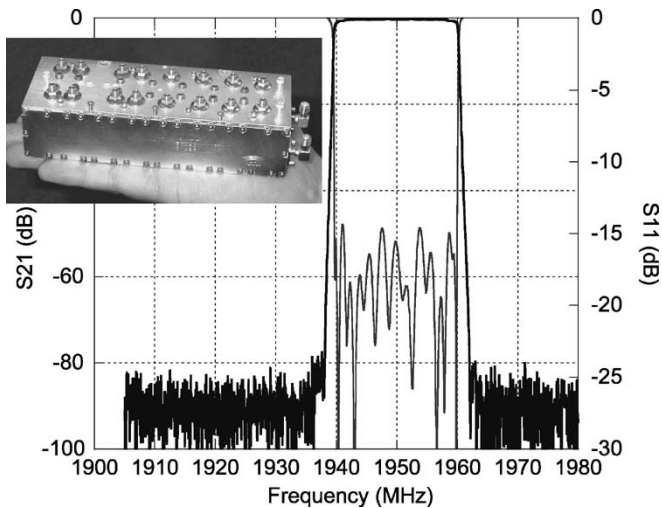


Fig. 5. S-parameter response of the 16-pole filter. The filter is shown in the inset.

coupling, which rendered the filter un-tunable, was to alternate the sign of the coupling between positive and negative, rather than making all the primary couplings positive. This alternated coupling type is visible in the drawing of Fig. 4.

Fig. 5 shows the filter response of the 20 MHz wide filter centered at 1950 MHz. The mid-band insertion loss is approximately -0.3 dB, and at 1940 and 1960 MHz is approximately -1.3 dB, corresponding to an effective Q of 35 000. The Q and the absolute values of insertion loss were determined by matching the roll-off characteristic with that predicted using Genesys Version 7.52 from Eagleware Corp., Norcross, GA. Some Q degradation results from the resonator coupling structures and from frequency tuning. The inset of Fig. 5 shows a photograph of the 16-pole filter. The rejection was 80 dB at 1938 MHz and at 1962 MHz.

Intermodulation distortion (IMD) is generated by this filter because the superconductor is nonlinear. The IMD was measured using two tones in the middle of the filter passband at 1950 and 1951 MHz, as described in [1]. For two input carriers

of -40 dBm, the third order IMD tone was -120 dBm. This is about 10 dB higher than a 1900 MHz filter built using the split toroidal resonators described in [2].

V. CONCLUSION

Compact, high Q 3-D filters have been realized using slot-line spiral resonators. A Q as high as 63 800 was realized in the small 9.8 cm^3 cavity at 1900 MHz. Aperture, loop and probe mechanisms were used to realize inter-resonator coupling, and the precise placement of these couplers was determined by finite element analysis. A 16-pole filter was built and tuned, yielding a 20-MHz wide filter with less than 0.5-dB mid-band insertion loss, and 80-dB rejection 2 MHz out of band.

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