

TITLE

HIGH POWER HIGH-TEMPERATURE SUPERCONDUCTIVE FILTERS

FIELD OF THE INVENTION

5 This invention relates to filters made of high-temperature superconductors designed to handle high power and to the structures which effect the combination of these filters.

BACKGROUND OF THE INVENTION

10 Filters are an important microwave component with widely spread applications in commercial and military microwave systems, such as telecommunication, instruments, radar and electronic warfare systems. High performance bandpass filters require narrow bandwidth with sharp skirts, high rejection in the off-band, low
15 insertion loss in the passing band, high power handling capability all in a compact and light package. The conventional filters made of normal conductors, such as copper, silver, gold, aluminum and the like, have limited conductivity which cause unacceptable high
20 inband insertion loss and are unable to satisfy all the requirements for high performance.

The discovery of high temperature superconductors (HTS) with a transition temperature, T_c , above the liquid nitrogen temperature (77 K) provided the
25 opportunity to produce HTS filters with orders of magnitude better performance in a compact package. In the microwave frequency range, the Q-value of HTS thin film materials are 10 to 1,000 times higher than copper under the same conditions, which directly translates
30 into extremely low insertion loss in the passing band of multi-pole bandpass filters. Many HTS filters have been reported with unprecedented high performance. But despite the success of HTS filters, the power handling capability of known HTS filters is still far less than
35 desired. Unlike the common metals, the HTS materials

show nonlinear behavior at relatively low power levels. This has decreased their capability of handling high power, therefor limiting the application of HTS filters.

According to the known configurations, HTS filters can be classified into three categories: the one dimensional, the two dimensional and the three dimensional. The conventional one dimensional filter is made of a series of coupled half-wave-length transmission line resonators. The rf current distribution in the resonator is in a standing-wave form along its length with the maximum current density at the center. Along the line width direction, the current also has an uneven distribution with maximum current density at the two edges. The critical current density, J_c , is defined as the maximum current density for which the HTS materials can carry without significant degradation of its conductivity. When the power increases in an HTS filter, the current density increases accordingly until the maximum current density exceeds the J_c , which determines the maximum power handling capability of the HTS filter.

As an example, C. Walker et al., IEEE-Trans MTT., Vol. 39, 1462-1467 (1991) described a 5 GHz HTS half-wave-length resonator. This resonator has a section of HTS microstrip line. In this particular case, it is a $Tl_2Ba_2CaCu_2O_8$ microstrip line with 500 μm width deposited on a 20-mil thick $LaAlO_3$ substrate. At operating temperature (77 K), the resonator has a loaded Q-value of 7,000-8,000 at input power below 1 mW and it begins to drop above 1 mW. At 32 mW of input power, the loaded Q-value reduced to 6,000. If this resonator is a part of HTS filter, which requires a minimum loaded Q-value of 6,000, then it will not handle input power more than 32 mW without significant performance degradation. Moreover, the 500- μm -wide HTS line on 20-mil $LaAlO_3$

substrate is not a 50-ohm line. The 50-ohm microstrip line on a 20-mil LaAlO_3 substrate has a width of only 165 μm , which handles much lower power than the 500 μm line. Thus, the power handling capability of this resonator is in the range of milliwatts and is limited by narrow line width. It is desirable to have HTS filters with a higher power handling capability for many applications.

The building block of the two dimensional HTS filters is in two dimensional planar forms wherein the dimensions along both directions are comparable to the wave length. The most commonly used form of two dimensional filters is the "dual mode" cut-corner square form, as described by A. Curtis et al. 1991 IEEE MTT-S International Microwave Symposium Digest, Vol. 2, pp. 443-446. Figure 6a shows a typical layout of an 8-pole (a pole represents a resonance) dual mode HTS filter. The building block of such a filter is an HTS cut-corner square pattern deposited on a substrate. Each cut-corner square represents two modes, therefore, the four cut-corner squares in Figure 6a represent 8 poles instead of just four. The two dimensional HTS filters handle more power than the one dimensional HTS filters because the rf current is distributed over a large area. However, the planar layout of known two dimensional HTS filters, such as the one shown in Figures 6a and 6b, have a problem of occupying too much substrate area and require a very large package to house the filter circuit. This problem becomes severe as the number of poles increases and the operating frequency decreases. For example, for a filter operating at 0.5 GHz, the size of the HTS square needed would be approximately 7 cm x 7 cm on a LaAlO_3 substrate with a dielectric constant, $\epsilon_r = 24$. The total area for a dual mode 8-pole filter such as shown in Figure 6a would be

at least 20 cm x 20 cm, which is unacceptably large. Moreover, such large substrates require an even larger enclosure which creates severe cryogenic problems.

Referring the Figure 6a, the basic building block of such a filter is a cut-corner square HTS resonator 51a, 51b, 51c or 51d deposited on a substrate 54 with HTS ground plane 55 on the back side. The HTS square can support two resonance modes as shown in Figures 7a-7c. Referring to Figures 7a-7c, the TE_{10} mode has a current flowing along the x direction, and the TE_{01} mode has a current flowing along the y direction. In Figure 7c, both TE_{10} mode and TE_{01} mode co-exist and are coupled to one another by the cut-corner. The coupling can be adjusted by varying the size of the cut-corner. Therefore, each cut-corner square in Figure 6a represents two modes and the filter has eight poles. The inter-square coupling is provide by HTS line sections 53a, 53b and 53c and the gaps between cut-corner squares 51a, 51b, 51c, and 51d and the HTS line sections 53a, 53b and 53c. The input and output coupling are provided by HTS line section 52a and 52b and the gap between 52a and 51a and the gap between 52b and 51d. This two dimensional HTS filter can handle more power than the one dimensional HTS filter. But a problem remains in that the two dimensional HTS filter requires a large substrate area, especially when the number of poles is large and the frequency is low, because the side of each square is approximately equal to a half wavelength. The two dimensional HTS filters have moderate power handling capability in the low watts.

For one dimensional HTS filters, the present invention provides an unique method to make them in low characteristic impedance with broader line width and to

combine them to increase the power handling capability significantly.

For two dimensional HTS filters, the present invention provides a structure which greatly reduces the substrate size and makes its package more compact. This structure is particularly suitable for low frequency, multi-pole high power HTS filters.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1a, 1b, 2a, 2b, 3a and 3b are schematic drawings of structures in accordance with this invention of the HTS converted impedance junctions for combining the HTS filters including the microstrip line version shown in Figures 1a and 1b, the strip line version shown in Figures 2a and 2b and the coplanar line version shown in Figure 3a and 3b.

Figures 4a and 4b are a schematic drawing of a parallel low impedance HTS filter pair in the microstrip line configuration in accordance with this invention combined by two converted impedance junctions to handle high power.

Figures 5a and 5b are schematic drawings of a combined parallel low impedance HTS filter, i.e., 5a, the single pair configuration; 5b, the multi-pair configuration.

Figures 6a and 6b are a schematic drawing of a layout of a planar HTS 8-pole dual mode bandpass filter.

Figures 7a-7c illustrate the rf (radio frequency) current distributions in HTS planar resonators having a square circuit pattern: 7a, TE_{10} mode; 7b, TE_{01} mode; 7c, TE_{10} mode and TE_{01} mode co-exist and are coupled to each other by the cut-corner.

Figure 8 schematically represents a structure in accordance with this invention of a stacked configuration 8-pole dual mode HTS bandpass filter and its separated different parts.

Figures 9a to 9f depict the individual parts of the stacked configuration 8-pole dual mode HTS bandpass filter of Figure 8: 9a, an unpatterned HTS ground plane; 9b, the layout of the input/output section with coupling to a TE_{10} mode HTS cut-corner dual mode square resonator; 9c, the layout of the input/output section with coupling to a TE_{01} mode HTS cut-corner dual mode square resonator; 9d, the layout of the HTS ground plane with a coupling slot for the TE_{01} modes on both sides; 9e, the layout of the HTS ground plane with a coupling slot for the TE_{10} modes on both sides; 9f, the layout of a HTS dual mode square resonator with a cut-corner.

Figures 10a-10c are schematic drawings of a structure in accordance with this invention and the mechanism of the E-field coupling for the dual mode filter: 10a, an HTS ground plane with a rectangular opening for the E-field coupling for the TE_{01} mode; 10b, an HTS ground plane with a rectangular opening for the E-field coupling for the TE_{10} mode; 10c, a cross section view of an HTS dual mode 4-pole bandpass filter with the E-field coupling and the E-field distribution showing the coupling mechanism.

Figures 11a and 11b are a cross section view of an assembled 4-pole HTS dual mode bandpass filter in accordance with this invention with tuning rods for fine tuning of the resonant frequencies of the resonators and the grounding mechanism for connecting separate ground planes.

Figures 12a-g are the parts for a stacked HTS dual mode filter with round shape configuration according to this invention. Figure 12a shows an HTS ground plane for use in a stacked round shape HTS dual mode filter.

Figures 12b and 12c show alternate circuit patterns for use in the resonator components of the filters of the present invention: 12b shows a round pattern with a

rectangular notch coupling mechanism for coupling two distinct modes: TE_{01} and TE_{10} . 12c shows a round pattern with a rectangular stub coupling mechanism for coupling two distinct modes: TE_{01} and TE_{10} .

5 Figure 12d shows the layout of a round HTS ground plane with a coupling slot for the TE_{01} mode on both sides.

10 Figure 12e shows the layout of a round HTS ground plane with a coupling slot for coupling the TE_{10} mode on both sides.

Figure 12f shows an alternative round HTS ground plane with an elliptical opening E-field coupling mechanism for coupling the TE_{01} mode on both sides.

15 Figure 12g shows an alternative round HTS ground plane with an elliptical opening E-field coupling mechanism for coupling the TE_{10} mode on both sides.

SUMMARY OF THE INVENTION

20 The present invention comprises various HTS filters having increased power handling capability which include:

(a) new structures to combine HTS low impedance filters in parallel to increase power handling capability by means of a converted impedance junction; and

25 (b) new structures for stacked HTS dual mode resonators to form a very compact filter with higher power handling capability.

In particular the present invention comprises a structure for combining filters in parallel comprising
30 1) at least two filters each comprising one or two substrates each having a high temperature superconductor ground plane and a patterned high temperature superconductor circuit, 2) an input splitting converted impedance junction connecting said filters in branches
35 arranged symmetrically to an output combining converted

impedance junction, and 3) input and output lines which are impedance matched with the high temperature superconductor circuit.

The present invention further comprises a converted
5 impedance junction comprising a) a common port, b) two branch ports connected to said common port combining or splitting circuits in parallel, and c) a matching impedance transformer at the common port.

The present invention further comprises a dual mode
10 filter comprising a) alternating stacked ground planes and dual mode resonators, b) a high temperature superconducting transmission line connected to two of said resonators, c) coupling means comprising a mode
15 selective coupling mechanism on each internal ground plane oriented 45° with respect to a coupling mechanism on each resonator adjacent to each internal ground plane, d) tuning rods between adjacent ground planes, and e) grounding links connected to said ground planes.

In particular the ground planes and resonators in
20 the dual mode filter each comprise a substrate having a high temperature superconducting film deposited thereon and are arranged in a stacked formation comprising a) two end ground planes, (b) two resonators, one adjacent to each end ground plane and coupled to said
25 high temperature superconducting transmission line, and c) additional internal alternating ground planes and resonators each having a coupling mechanism.

The coupling means comprises

(a) a mode selective coupling mechanism on
30 each internal ground plane comprising an opening which is oriented 45° with respect to

(b) a coupling mechanism on each resonator adjacent to each internal ground plane comprising a discontinuity in the perimeter of the patterned high
35 temperature superconducting film of said resonator.

The coupling mechanism on each ground plane provides coupling between two like resonant modes, while the coupling mechanism on each resonator provides coupling between two distinct resonant modes. The required orientation of the coupling mechanisms provides the mode selection function and permits coupling to a particular desired resonant mode at a particular location within the filter.

DETAILED DESCRIPTION OF THE INVENTION

One way to increase the power handling of one dimensional filters is to combine N , where N is an integer, identical HTS filters in parallel which has N times more power handling capability than the individual one. A second way to increase the power handling capability is to increase the line width of the HTS lines in the filter which can carry more current and much more power, since power is proportional to the square of the current. It would be even better by using a combination of these two methods, i.e., to combine N identical filters with wider line width in parallel. But a simple combination does not work, because these two methods have contradictory requirements. On the one hand, the input and output require 50-ohm matching which translates into a $N \times 50$ ohm characteristic impedance for the filters in a parallel combination. On the other hand, the increase of the line width in the filter translates into a lower characteristic impedance.

The present invention provides a converted impedance junction as shown in Figures 1a, 1b, 2a, 2b, 3a and 3b to combine the wide line filters in parallel as shown in Figures 4a and 4b to solve the problem and thereby to increase the power handling capability of the one dimensional HTS filters significantly (10 to 25 times compared to a conventional single 50-ohm filter).

Another way to further increase the power handling capability is to use two dimensional HTS filters. This invention provides a compact structure for two dimensional dual mode HTS filters by stacking the individual dual mode resonators as shown in Figures 8, 9a-9f, 10a-10c, and 11a-11b.

The present invention comprises three basic elements. The first is a combination of a plurality of one dimensional low impedance HTS filters with broader line width formed by using a converted impedance junction. The second is the converted impedance junction used to combine the one dimensional filters in parallel. The third is an HTS two dimensional dual mode filter formed by stacking a plurality of HTS coated substrates with coupling means, tuning mechanism and grounding connections.

Converted Impedance Junction

Figures 1(a)-3(b) show three versions of the converted impedance junction of the present invention, which is used for combining HTS filters in accordance with the structures of this invention. The converted impedance junction comprises a) a common or sum port, b) two branch ports connected to said common port combining or splitting circuits in parallel, and c) a matching impedance transformer at the common port. The converted impedance junction serves two purposes: one is as a one-to-two splitter or a two-to-one combiner for microwave signals; the other is as an impedance converter to convert the characteristic impedance Z_c at the sum port or common port to the characteristic impedance $Z_c/2$ at the two branch ports and vice versa.

Figures 1a and 1b show the microstrip line version. It comprises a substrate 4, an HTS ground plane 5 on the back side of 4 and a patterned HTS circuit on the front side of 4. Figure 1a shows a top view of the HTS

circuit. HTS microstrip line 1 with a characteristic impedance Z_c serves as the sum port. The two branch HTS microstrip lines 2 with a characteristic impedance of $Z_c/2$ serve as the branch ports. HTS microstrip line 3 with a characteristic impedance $Z_c/2$ and a length of $\lambda/4$, serves as an $\lambda/4$ impedance converter where λ represents the guided wavelength at the center frequency of the filters to be combined.

A $\lambda/4$ impedance converter having a characteristic impedance Z_3 matches two impedances Z_1 and Z_2 at its input and output, respectively, when

$$Z_3 = (Z_1 Z_2)^{1/2} \quad (1)$$

In this case, $Z_1 = Z_c$, $Z_3 = Z_c/2$, and $Z_2 = Z_c/4$ due to the parallel splitting, so (1) is satisfied. The curved corners in the junction compensate for the discontinuities introduced by the junction and to optimize the matching. In essence, the impedance converted junctions provide a way to combine the two low impedance branch lines in parallel with the sum line and maintains impedance matched at the sum port, which satisfies the requirement for combining two low impedance filters in parallel.

Figures 2a and 2b show the strip line version. It comprises a substrate 14, a superstrate 16, two HTS ground planes 15 on the back side of 14 and 16, and a patterned HTS circuit 17 between the substrate 14 and the superstrate 16. Figure 2a shows a top view of the circuit 17. HTS strip line 11 with a characteristic impedance Z_c serves as the sum port. The two branch HTS strip lines 12 with a characteristic impedance of $Z_c/2$ serve as the branch ports. HTS strip line 13 with a characteristic impedance $Z_c/2$ and a length of $\lambda/4$, which serves as an $\lambda/4$ impedance converter. According to the same principle described above for the microstrip line

version, this arrangement serves the same purpose as the microstrip line version in a strip line configuration.

Figures 3a and 3b show the coplanar line version of the converted impedance junction. It comprises a substrate 34, and a patterned HTS circuit 37 on the front side of 34. Figure 3a shows a top view of the circuit 37. The HTS center line 31 with a characteristic impedance Z_0 serves as the sum port. The two branch HTS center lines 32 with a characteristic impedance of $Z_0/2$ serve as the branch ports. The HTS center line 33 with a characteristic impedance $Z_0/2$ and a length of $\lambda/4$, serves as an $\lambda/4$ impedance converter. The ground planes 35 are on the same side of the substrate 34 as the center lines and are divided into three pieces, as show in Figure 3a. Two air bridges 36 are used to link the three ground planes to suppress the unwanted odd mode which is generated by the junction. According to the same principle described for the microstrip line version, this arrangement serves the same purpose as the microstrip line version in a coplanar line configuration.

Parallel Combined One Dimensional Low Impedance HTS Filters

The present invention further comprises a structure for combining filters in parallel comprising 1) at least two filters each comprising one or two substrates each having a high temperature superconductor ground plane and a patterned high temperature superconductor circuit, 2) an input splitting converted impedance junction connecting said filters in branches arranged symmetrically to an output combining converted impedance junction, and 3) input and output lines which are impedance matched with the high temperature superconductor circuit. The ground plane and the patterned circuit can be on the same side of the substrate or on

opposite sides of the substrate, or when two substrates are present they can be on the same side in one and on the opposite sides in another. The compositions of the substrates when more than one is present can vary, but preferably the compositions of multiple substrates in each filter are the same. Likewise, the high temperature superconductor compositions can vary, but preferably are the same for a particular filter.

Figures 4a and 4b show an example of two HTS low impedance filters 6 and 6a combined by two converted impedance junctions 7a and 7b at the input and the output in a microstrip line form. It comprises a substrate 4 with HTS ground plane 5 on the back side and patterned HTS circuit 8 on the front side. The two identical 3-pole HTS filters 6 and 6a are combined by two converted impedance joints 7a and 7b at the input and output, respectively. In this particular case, the input and output line 1 has a characteristic impedance $Z_c = 50$ ohm. The other lines 2 and 3 have a characteristic impedance of $Z_c/2 = 25$ ohm. According to the principle described previously, this circuit is impedance matched at both input and output.

For a conventional 50 ohm HTS microstrip line on 20-mil LaAlO_3 substrate, the line width is only 165 μm , which limits the power handling capability of a filter made of such lines. On the other hand, the 25 ohm HTS microstrip line has a line width of 830 μm on the same substrate, which is 5 times wider than the 50 ohm line. If the current distribution does not change with line width, the 830 μm wide 25 ohm line can carry 5 times more current than the 165 μm wide 50 ohm line with the same current density. In the traveling wave case, the power P carried by a transmission line with characteristic impedance Z_c can be expressed as

$$P = I^2 Z_c \quad (2)$$

where I is the total current carried by the line.

Therefore, the 25 ohm HTS line has 12.5 times higher power handling than the 50 ohm HTS line. Since there are two 25 ohm filters 6 and 6a in the circuit shown in Figure 4a, comparable to a regular 50-ohm HTS filter, this HTS circuit has 25 times higher power handling capability, which is a significant improvement.

However, because the current tends to concentrate at the edges of the HTS lines, the increase in current carrying capacity may not be proportional to the increase of the line width. This factor reduces the power handling capability advantage of the 25 ohm HTS filter compared to the 50-ohm filter, i.e., the power handling capability improvement may not be as high as 25 times. Fortunately, a power test on HTS lines indicated that the "current concentrated at edges" effect is eased at a high power level. Therefore, compared to the regular 50-ohm HTS filter, the HTS filter circuit shown in Figure 4a still has a significant improvement of power handling capability ranging from about 10 to about 25 times.

The two branches in the circuit shown in Figure 4a are preferably identical, i.e., the upper half and the lower half of the circuit are preferably in a mirror image symmetry with respect to the center line. Deviations from symmetry will result in a performance degradation due to either the amplitude or the phase difference between these two branches.

The same principle and configuration are not restricted to the microstrip line version shown in Figure 4a. The configuration can be in a strip line version and a coplanar line version by using the converted impedance junctions shown in Figures 2a and 2b

and Figures 3a and 3b, respectively, and obtain the same advantages. A general form of the HTS filter combination of the present invention is shown in Figure 5a, in which 42 is any form of one dimensional HTS filter with any number of poles, and 41 is the converted impedance junction as shown in Figures 1a and 1b, 2a and 2b or 3a and 3b. A more general configuration of filters of the present invention is shown in Figure 5b, in which the input splitting network and the output combining network are constructed by a two-stage cascade of the converted impedance junctions, which has four branches with a characteristic impedance of $Z_c/4 = 12.5$ ohm. In this case, the input power is split equally into four channels with four HTS filters in parallel, which increases the power handling capability. More importantly, the 12.5 ohm line has a much wider line width than the 25 ohm line which further increases the power handling capability. Of course, the cascade is not restricted to 2-stage. It can have multiple stages to increase the number of filters in parallel and to further increase the power handling capability. However, there are two factors which limit the number of filters in parallel. One factor is that the required substrate area increases with the number of filters, which is restricted by the available substrate wafer size. The other is that the characteristic impedance of the branch lines decreases with the increasing number of filters, which requires increasing line width. A line with an impedance which is too low requires an unacceptably wide line width. In fact, by definition, a one dimensional filter should not have a line width as large as a half-wave length.

The HTS thin film materials useful in the practice of this invention include superconductors with a T_c greater than 77 K. Preferred materials include

YBa₂Cu₃O₇, TlBaCaCuO (2212, or 1223), (TlPb)SrCaCuO (1212, or 1223). The substrate materials suitable for use herein include any dielectric material with close lattice match to the HTS thin film deposited on it and with a loss tangent of less than 0.0001. Preferred are

Stacked Two dimensional Dual Mode HTS Filters

The present invention further comprises a dual mode filter comprising a) alternating stacked ground planes and dual mode resonators, b) a high temperature superconducting transmission line connected to two of said resonators, c) coupling means comprising a mode selective coupling mechanism on each internal ground plane oriented 45° with respect to a coupling mechanism on each resonator adjacent to each internal ground plane, d) tuning rods between adjacent ground planes, and e) grounding links connected to said ground planes.

Each ground plane comprises a substrate having a high temperature superconducting film deposited thereon, and each resonator comprises a substrate having a patterned high temperature superconducting film deposited thereon. The substrate and film compositions can vary, but preferably in a particular filter the substrates all have the same composition and preferably the films all have the same composition. The ground planes and dual mode resonators are arranged in a stacked formation comprising a) two end ground planes, b) two resonators, one adjacent to each end ground plane and coupled to said high temperature superconducting transmission line, and c) additional alternating internal ground planes and resonators each having a coupling mechanism.

In particular the dual mode filter of the present invention differs from conventional filters in having a selective coupling means. The coupling means comprises

a) a mode selective coupling mechanism on each internal ground plane comprising an opening which is oriented 45 degrees with respect to b) a coupling mechanism on each resonator adjacent to each internal ground plane comprising a discontinuity in the perimeter of the patterned high temperature superconducting film of said resonator. Preferably the coupling mechanism on the ground plane comprises an opening located at the edge of the ground plane or an opening in the form of a slot located at the center of the ground plane, and the coupling mechanism on the resonator comprises a discontinuity in the perimeter of the high temperature superconducting film in the form of a notch, cut corner or stub. Each ground plane has two distinct modes on each side thereof, e.g., TE_{10} and TE_{01} . The mode selective coupling mechanism on the ground plane couples two like resonance modes, such as TE_{01} and TE_{01} , or TE_{10} and TE_{10} , on either side of the ground plane. The coupling mechanism of the resonator couples two distinct resonance modes, such as TE_{01} and TE_{10} . The required 45 degree orientation of the two coupling mechanisms provides the mode selection function and permits coupling to a particular desired resonant mode at a particular location within the filter.

Figures 8 and 9a-9f show a stacked two dimensional dual mode 8-pole HTS filter and its parts. Figure 8 shows the subassembly. The HTS parts are shown in Figures 9a, 9b, 9c, 9d, 9e, and 9f. The combination of HTS filters shown in Figure 8 is not restricted to eight poles. There can be any number of poles. Figure 8 shows the sub-assembly 67, in which 60 is an unpatterned HTS film deposited on a substrate. There are two of them used as two end ground planes. There are two in-between HTS circuits 63 and two end HTS circuits 61 serving as the dual mode resonators to form the 8-pole

filter. Although the circuits are shown as a square pattern having a cut-corner coupling mechanism, other patterns are suitable as discussed hereinafter in reference to Figures 12a-12g. The resonators 61 also include a section of HTS line coupled to the cut-corner square as the input or output. HTS ground planes 62 and 62a each having a coupling slot are placed between the adjacent HTS resonators 63 and 61 to isolate them and to provide the mode selective couplings. The slot 64 in the HTS ground plane 62 as shown in Figure 9d cuts the current of the TE_{01} mode shown in Figure 7b, which provides the coupling of TE_{01} modes on both sides of the ground plane 62. The slot 64a in the HTS ground plane 62a as shown in Figure 9e cuts the current of the TE_{10} mode as shown in Figure 7a, which provides the coupling of TE_{10} modes on both sides of ground plane 62a. The mode sequence in the sub-assembly shown in Figure 8 is TE_{10} -(by the cut-corner on the resonator 61)- TE_{01} -(by the slot 64 in ground plane 62)- TE_{01} -(by the cut-corner on the resonator 63)- TE_{10} -(by the slot 64a in ground plane 62a)- TE_{10} -(by the cut-corner on the resonator 63)- TE_{01} -(by the slot 64 in ground plane 62)- TE_{01} -(by the cut-corner on the resonator 61)- TE_{10} . The slot coupling is highly mode selective due to the fact that it cuts only the current perpendicular to it of one mode and it does not cut the current parallel to it of the other mode. Thus, the same mode is maintained on both sides. Use of the cut-corner coupling mechanism results in a change of mode.

Figure 9a shows the unpatterned HTS film 60 used as a ground plane. Figure 9b shows an HTS pattern of an HTS cut-corner square 61 serving as a dual mode resonator and a section of HTS line coupled to the HTS cut-corner square via a gap serving as the input or output circuit for the TE_{10} mode. Figure 9c shows an

HTS pattern of an HTS cut-corner square serving as a dual mode resonator and a section of HTS line coupled to the HTS cut-corner square via a gap serving as the input or output circuit for the TE_{01} mode. Figure 9d shows an HTS ground plane with a horizontal slot 64, which serves as a coupling apparatus for the TE_{01} modes on both sides of the ground plane. The coupling mechanism is that the slot cuts the current of the TE_{01} mode and provides the current/H-field coupling for the TE_{01} mode on both sides of the ground plane. Figure 9e shows an HTS ground plane with a vertical slot 64a, which serves as a coupling apparatus for the TE_{10} modes on both sides of the ground plane. The coupling mechanism is that the slot cuts the current of TE_{10} mode and provides the current/H-field coupling for the TE_{10} mode on both sides of the ground plane. Figure 9f shows a cut-corner square serving as a dual mode resonator. The HTS patterns in all the parts in Figure 9a-9f are deposited on a lattice matched substrate comprising a dielectric material having a loss tangent of less than 0.0001. Preferred substrates include $LaAlO_3$, MgO , $LiNbO_3$, $LiTaO_3$, sapphire ($\alpha-Al_2O_3$) quartz, and the like.

For example, if the eight-pole stacked dual mode HTS filter has a center frequency of 0.5 GHz, the cut-corner HTS square resonator would have a size of 6 cm x 6 cm deposited on a 8 cm x 8 cm square 20 mil thick substrate with an $\epsilon_r = 24$, such as $LaAlO_3$. The entire subassembly shown in Figure 8 would have a size of 7 cm x 7 cm x 0.5 cm, which will fit in a slightly larger outer enclosure, say 8 cm x 8 cm x 2 cm, which is very compact and easy for maintenance at cryogenic temperature. Compared to the usual 20 cm x 20 cm substrate in a conventional dual mode 8-pole filter as shown in Figure 6a at the same frequency, the savings in

the overall size for the stacked version in accordance with this invention is clear.

The stacked dual mode HTS filter in accordance with this invention also has a higher power handling capability than a conventional dual mode HTS filter. The conventional filter shown in Figures 6a and 6b has only one substrate and one ground plane. Due to the high dielectric constant of the substrate, the electromagnetic fields of the filter are primarily located between the cut-corner squares 51a, 51b, 51c and 51d, and the ground plane 55. The rf current is primarily located on the inner side of the cut-corner square resonators and ground plane facing the substrate 54. On the other hand, the stacked dual mode HTS filter of this invention, shown in Figure 8, has two ground planes per each section and the electromagnetic fields are spread on both sides of the cut-corner square resonators. The rf current is also spread between the two sides of the cut-corner square resonators as well as between the two ground planes. Therefore, for the same input power, the current density in the HTS films is approximately reduced to one half for the stacked version compared to the conventional version, which translates into a 4-times higher power handling capability under the same conditions.

Figures 10a-10c show another way in accordance with this invention to provide the E-field coupling between adjacent HTS resonators. Figure 10a shows a HTS ground plane 65 with a rectangular opening 66 located at the maximum E-field of the TE_{01} mode which lets the E-field go through it, and which provides coupling for the TE_{01} modes on both sides of the ground plane. Figure 10b shows a HTS ground plane 65a with a rectangular opening 66a located at the maximum E-field of the TE_{10} mode which lets the E-field go through it, and which provides

coupling for the TE_{10} modes on both sides of the ground plane. Figure 10c shows a 4-pole dual mode HTS filter with E-field coupling as an example. It comprises two end HTS ground planes 60, two dual mode HTS resonators 61a, and a ground plane 65a in between the resonators with an E-field coupling opening 66a. The dual mode HTS resonator 61a on top acts as an input and excites a TE_{01} mode in the dual mode square. It is coupled to a TE_{10} mode via a cut-corner in 61a. The cross section E-field distribution pattern is shown in Figure 10c. The E-field on the right side goes through the coupling opening 66a on ground plane 65a from the top section into the bottom section to excite the TE_{10} mode with the E-field as shown. The TE_{10} mode in the bottom section excites the TE_{01} mode via the cut-corner coupling mechanism in dual mode HTS resonator 61a and provides the output. The E-field coupling opening 66a on ground plane 65a does not provide coupling for the TE_{01} mode, because there is virtually no E-field of the TE_{01} mode at the opening 66a. For the same reason, the opening 66 on 65 provides coupling for the TE_{01} mode only. Therefore, this E-field couplings are also mode selective because of the location of the openings. Moreover, the E-field coupling can handle more power than a slot coupling due to the fact that the opening is large and is not located at the rf current peak, as the slot is.

Figures 11a and 11b show a cross section view of an assembled dual mode 4-pole HTS filter with the invented stacked structure. The filter subassembly comprises two end HTS ground planes 60, two cut-corner HTS square resonators with input and output couplings 61, and HTS ground plane 62 or 65 with coupling slot 64 (not shown) or rectangular opening 66 (not shown) depending upon the coupling mechanism chosen. All the HTS films are

deposited on four substrates as shown. The subassembly is placed in and held by a metal case or outer enclosure, which includes a top cover 70a, a bottom cover 70b and a case body or sidewalls 70. 71 and 71a are the input and output connectors.

Bandpass filters require the resonant frequency for each of the resonators in the filter to be accurate. Since the resonant frequency of the HTS cut-corner resonators is determined by many factors including the shape, dimension of the HTS square and the cut-corner as well as the dielectric constant of the substrate, it is impractical to expect that the real resonant frequencies of the resonators will all meet the specifications. Therefore, tuning is a necessity for the filter to perform properly. Tuning rods 72 and 72a are used for tuning as shown in Figure 11a. Two tuning rods 72 are used for tuning the two TE_{10} modes: one in the top section and the other one in the bottom section. The other two tuning rods 72a are used for tuning the two TE_{01} modes: also one in the top section and the other one in the bottom section. The tuning rods are made of dielectric materials with high dielectric constant and low loss tangent such as sapphire, quartz, ceramic, and the like. The dielectric constant of the tuning rod material preferably is within 50% of the highest dielectric constant of any substrate material employed in a ground plane or resonator of the filter. The tuning rod is placed at the maximum E-field of the mode to be tuned. Since the maximum E-field of the TE_{01} mode is located at the minimum E-field of the TE_{10} mode and vice versa, the tuning can be done separately for each mode without interference.

There are three HTS ground planes in the filter shown in Figures 11a and 11b: two end ground planes 60 and one in-between ground plane 62. These three ground

planes must be well connected electrically for the filter to perform properly. This can be achieved by the metal (gold or silver) wrap arounds or contacts on the edge of each ground plane and a gasket as shown in the exploded view in Figure 11b, in which two metal wraparound contacts 73 are deposited on top of HTS grounds 60, 62 and extended to the edges of the two substrates. A gasket 74 is placed against the left side wall of the case 70, which provides secure electrical contacts between the case and the ground planes as shown in the exploded view.

The stacked dual mode multi-pole filter shown in Figures 11a and 11b is not restricted to four poles. It can be as any number of poles. The HTS thin film materials can include any superconductor with a T_c greater than 77 K and preferably is $YBa_2Cu_3O_7$, $TlBaCaCuO$ (2212, or 1223), $(TlPb)SrCaCuO$ (1212, or 1223). The substrate materials can be any dielectric material with close lattice match to the HTS thin film deposited on it and with a loss tangent of less than 0.0001, and preferably is $LaAlO_3$, MgO , $LiNbO_3$, $LiTaO_3$, sapphire, or quartz.

In the filters of the present invention such as those of Figure 8, 10c or 11a, the HTS ground planes and the HTS dual mode resonators are not necessarily confined to the square shape. In fact, since most available substrates are round in shape, the round shape configuration of the HTS ground planes and the HTS dual mode resonators is more favorable for taking advantage of the largest physical area of the substrate. Figures 12a-g show some examples. Figure 12a shows an unpatterned round shaped HTS ground plane 86 deposited on a substrate (not shown), which can be used as an end plane of a stacked HTS dual mode filter, such as to replace the end planes 60 in Figure 8. Figure 12b shows

a round shaped circuit 80(a) having an HTS dual mode resonator 85(a) deposited on a substrate 84(a). The dual mode resonator 85(a) supports two modes: TE_{01} and TE_{10} similar to the square version with the current distributions shown in Figure 7. A rectangular notch 81(a) provides the coupling mechanism for these two modes. Figure 12c show a round shaped circuit 80(b) having an HTS resonator 85(b) deposited on a substrate 84(b). The dual mode resonator 85(b) supports two modes: TE_{01} and TE_{10} similar to the square version with the current distributions shown in Figure 7. A rectangular stub 81(b) provides the coupling mechanism for these two modes. Both circuits 80(a) and 80(b) can be used as the dual mode resonators in a stacked HTS dual mode filter, such as to replace the dual mode resonators 63 shown in Figure 8.

Figure 12d shows an HTS ground plane 87(a) with a horizontal coupling slot 82(a) providing coupling for the TE_{01} modes on both sides of the ground plane. Ground plane 87(a) can be used as an internal ground plane in a stacked HTS dual mode filter such as to replace the ground plane 62 in Figure 8. Figure 12e shows an HTS ground plane 87(b) with a vertical coupling slot 82(b) providing coupling for the TE_{10} modes on both sides of the ground plane. Ground plane 87(b) can be used as an internal ground plane in a stacked HTS dual mode filter, such as to replace the ground plane 62a in Figure 8.

Figure 12f shows an HTS ground plane 88(a) with an elliptical shaped opening 83(a) providing the E-field coupling for the TE_{01} modes on both sides of the ground plane. Figure 12g shows an HTS ground plane 88(b) with an elliptical shaped opening 83(b) providing the E-field coupling for the TE_{10} modes on both sides of the ground plane. Ground plane 88(b) can be used as an internal

ground plane in a stacked HTS dual mode filter, such as to replace the ground plane 65a in Figure 10c.

All the filters of the present invention are useful as frequency selectors in microwave components having
5 widespread applications in commercial and military microwave systems. Examples include telecommunication, instruments as well as radar and electronic systems.



What is claimed is:

1. A structure for combining filters in parallel comprising

1) at least two filters each comprising one or two substrates each having a high temperature superconductor ground plane and a patterned high temperature superconductor circuit,

2) an input splitting converted impedance junction connecting said filters in branches arranged symmetrically to an output combining converted impedance junction, and

3) input and output lines which are impedance matched with the high temperature superconductor circuit.

2. The structure of Claim 1 wherein for said filters

(a) the ground plane and the patterned circuit are on the same side of the substrate,

(b) the ground plane and the patterned circuit are on the opposite sides of a substrate, or

(c) a combination of (a) and (b).

3. The structure of Claim 1 wherein for said filters each high temperature superconducting film is has a T_c of greater than 77 K.

4. The structure of Claim 3 wherein each high temperature superconducting film is independently selected from the group consisting of $YBa_2Cu_3O_7$, $Tl_2Ba_2CaCu_2O_8$, $TlBa_2Ca_2Cu_3O_9$, $(TlPb)Sr_2CaCu_2O_7$ or $(TlPb)Sr_2Ca_2Cu_3O_9$.

5. The structure of Claim 3 wherein each film is deposited on a substrate comprising a dielectric material having a loss tangent of less than 0.0001.

6. The structure of Claim 5 wherein each film is deposited on a substrate independently selected from the



group consisting of LaAlO_3 , MgO , LiNbO_3 , LiTaO_3 , sapphire or quartz.

7. The structure of Claim 1 wherein said filters are in microstrip line form, strip line form or coplanar line form.

8. The structure of Claim 1 further comprising a multistage cascade of input and output converted impedance junctions.

9. A converted impedance junction comprising

- a) a common port,
- b) two branch ports connected to said common port combining or splitting circuits in parallel, and
- c) a matching impedance transformer at the common port.

10. A dual mode filter comprising

- a) alternating stacked ground planes and dual mode resonators,
- b) a high temperature superconducting transmission line connected to two of said resonators,
- c) coupling means comprising a mode selective coupling mechanism on each internal ground plane oriented 45° with respect to a coupling mechanism on each resonator adjacent to each internal ground plane,
- d) tuning rods between adjacent ground planes, and
- e) grounding links connected to said ground planes.

11. The filter of Claim 10 wherein each ground plane comprises a substrate having a high temperature superconducting film deposited thereon, and each resonator comprises a substrate having a patterned high temperature superconducting film deposited thereon.

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12. The filter of Claim 11 wherein said ground planes and dual mode resonators are arranged in a stacked formation comprising

- a) two end ground planes,
- 5 b) two resonators, one adjacent to each end ground plane and coupled to said high temperature superconducting transmission line, and
- c) additional alternating internal ground planes and resonators each having a coupling mechanism.

10 13. The filter of Claim 10 wherein said coupling means comprises

- a) a mode selective coupling mechanism on each internal ground plane comprising an opening which is oriented 45 degrees with respect to
- 15 b) a coupling mechanism on each resonator adjacent to each internal ground plane comprising a discontinuity in the perimeter of the patterned high temperature superconducting film of said resonator.

14. The filter of Claim 13 wherein the coupling
20 mechanism on the ground plane comprises an opening located at the edge of the ground plane or an opening in the form of a slot located at the center of the ground plane.

15. The filter of Claim 13 wherein the coupling
25 mechanism on the resonator comprises a discontinuity in the perimeter of the high temperature superconducting film in the form of a notch, cut corner or stub.

16. The filter of Claim 11 wherein each high
30 temperature superconducting film has a T_c greater than 77 K.

17. The filter of Claim 16 wherein each high
temperature superconducting film is independently
selected from the group consisting of $\text{YBa}_2\text{Cu}_3\text{O}_7$,
 $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$, $\text{TlBa}_2\text{Ca}_2\text{Cu}_3\text{O}_9$, $(\text{TlPb})\text{Sr}_2\text{CaCu}_2\text{O}_7$, or
35 $(\text{TlPb})\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_9$.



18. The filter of Claim 16 wherein each high temperature superconducting film has the same composition.

5 19. The filter of Claim 11 wherein each substrate is independently selected from the group consisting of LaAlO_3 , LiNbO_3 , LiTaO_3 , MgO , sapphire or quartz.

20. The filter of Claim 19 wherein each substrate has the same composition.

10 21. The filter of Claim 11 wherein said tuning rod comprises a dielectric material, having a dielectric constant within about 50% of the highest dielectric constant of any substrate of the ground planes or the resonators.

15 22. The filter of Claim 11 wherein said grounding links comprise

a) a metallic contact on the edge of each ground plane, and

b) a metallic gasket connected to each said metallic contact and to an outer enclosure containing
20 the filter.

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