Elliptic-Disc Filters of High-T_c Superconducting Films for Power-Handling Capability Over 100 W

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***Abstract*—On the future digital communication system, distortion of transmitted signals should be eliminated as much as possible for high communication quality. However, the need to both minimize distortion of signal amplifiers and continue to provide good filtering protection can become difficult to achieve with conventional devices. In this paper, the RF coplanar circuit filter using elliptic-disc resonators is proposed and investigated, This proposition makes it possible to miniaturize power filter circuits and to realize high performance of power ability of high-temperature superconducting (HTS) filters. An end spread signal coupling electrodes is investigated in order to adjust the coupling degree between disc and feedline circuits and provide proper characteristic impedance of circuit. Two-mode coupling operation in the elliptic disc are then explained. Electromagnetic-field distribution change caused by this mode coupling can protect current and heat concentration, and realize power-handling capability over 100 W. Finally, the design principle of a multiple-disc filter is introduced for high performance of out-of-band rejection and passband flatness. It has been confirmed that an elliptic-disc resonator filter can bring out the excellent performance of HTS materials.**

***Index Terms*—Disc resonator, high-temperature superconductor, power filter, superconducting filters, thin film.**

I. Introduction

THE quality of the high-temperature (high-T_c) superconducting (HTS) films has been improved remarkably by recent progress in film preparation processes for oxide materials. Double-sided wafers with high performance are achieved in a size larger than 3 in in diameter [1]–[4]. Below the critical temperature of the HTS materials, their surface resistance at microwave frequency regions is lower than that of normal metals by one to three orders of magnitude. By using these materials as the thin-film circuits of microwave passive components, their conduction loss is dramatically reduced. High-Q resonators, low-loss filters, and other high-performance microwave devices can be achieved even by the microstrip or stripline thin-film configuration [5]–[7].

In this way, a new or future system of microwave communication is built by new digital technologies to provide an improved and more consistent quality of service for the users. These digital systems can provide a greater number of transmission channel allocations for their users and security of communication. On the digital communication system, distortion of the transmitted signal should be eliminated as much as possible for high communication quality. However, the need to both minimize distortion of signal amplifiers and continue to provide good filtering protection is difficult to satisfy with conventional high-power amplifiers and filters. For example, the frequency spectral regions allocated for mobile telecommunication systems are rather narrow and are certain to have a high density of communication channels. Thus, proper filtering of transmit and receive signals into the allocated bands and precise channelization of the multiple simultaneous signals within each band are essential in providing a high quality of communication service.

HTS filters are being expected on such microwave systems as the means to maximize such frequency use. At present, the filter for the band separation of the receiver of a high-frequency front end in the microwave communication systems becomes the main target of the application of the HTS devices [8]–[11]. In regard to those HTS filters, which treat small power signals at receiver circuits, a microwave coplanar circuit is generally constituted by the ground electrode and the thin-film circuit of the electric conducting thin films produced on both sides of a dielectric substrate. Since the structure of such a coplanar circuit can be interpreted as a two-and-one-half dimensional circuit in the middle of a three-dimensional microwave circuit and a concentrated constant circuit, it is difficult to design compared with the concentration constant circuit or the circuit constructed by the usual strip circuits. However, this coplanar circuit has the flexibility of a design. This coplanar circuit can realize a high function with a comparatively simple structure [12]–[14].

For high-power application of superconducting filters, a power-handling capability and precise design of circuit patterns are required [15], [16]. However, both the current concentration in the superconducting thin-film circuits and their critical current density, or critical magnetic field, cause the limit of the input signal power level in the HTS materials [13], [17]. To improve the power-handling capability, reducing the nonuniformity of current in the HTS resonator elements is much more effective. The disc resonator filter was proposed for the purpose of the miniaturization and improvement in an electric-power-proof performance of an HTS filter. Disc resonator filters using disc circuit patterns were designed by Nagai *et al.* [18]. From the viewpoint of current distribution, such a pattern is ideal because of smooth periphery, avoiding an extreme current concentration at a corner. When such a circuit pattern is

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applied for a superconducting filter, a current distribution can be made to equalize on a large area. Furthermore, it is enabled to reduce the maximum current density. Consequently, the improvement in an electric power-proof performance is highly expected.

In this paper, for the application of HTS power filters, thin-film circuit designs and power-handling capability of HTS multipole disc filters are discussed.

II. Superconducting Planar Filters

A. Disc Resonator Filter

As introduced in previous section, both the current concentration in the superconductors and their critical current density, or critical magnetic field, cause the limit of the input signal power level in the HTS materials. Due to such desperate problems, examination of the HTS filter generally does not progress for the high-power applications of electronics devices. To improve the power-handling capability, reducing the nonuniformity of the current in the HTS resonator elements is much more effective. Two typical filters for the transmitter were designed by using wide microstrip lines having low impedance and by polygonal circuit patterns. The former adopted the resonator configuration of lower characteristic impedance, i.e., wide linewidth of the resonator elements. From the viewpoint of current distribution, the later filter is advantageous because of a rather small concentration of the superconducting current at an obtuse angle. A disc pattern as the infinite polygonal pattern is especially and greatly advantageous because of smooth periphery, avoiding a current concentration at a corner.

According to this guideline, two ideas are realized as the octagon resonator filter and the disc resonator filter. Recently, the maximum power-handling capability of 115 W at 6 GHz and 77 K was first achieved on the HTS filter using two coupled octagon resonators [19]. From this result, the higher power-handling capability should be expected for the disc type. The polygonal and disc shapes of resonators require a comparatively large wafer area, resulting in high refrigeration capacity and high cost. Recently, engineers can easily obtain the wafer of a diameter larger than 3 in. When $LaAlO_3$ is used as a substrate, the 2-GHz resonator requires the diameter of about 20 mm of disc. In this case, one 3-in wafer can supply seven resonator discs. Also, we can obtain high performance of the cryo-cooler, which has high cooling efficiency, long-life operation, and small size [20].

B. Device Fabrication Process

As the superconducting wafers, an $LaAlO_3$ substrate in which both surfaces are covered by $YBa_2Cu_3O_{7-x}$ thin films is used. A photolithography technique with Argon ion-beam etching was employed for the film patterning of planar circuits. The ground plane was fabricated by the gold film of about 1-μm thick or the superconducting film of 0.5∼0.8 μm thick deposited on the reverse side of a substrate. These two ground planes were compared with each other for investigating the loss factor of HTS substrates.

In the first place, the auxiliary gold film was deposited on the surface of superconducting film near the contact portions of electrodes, where signal coupling electrodes and signal feed-through connectors electrically contact each other. Such an auxiliary gold film can improve the reliability and electrical conductance of the contacts between a signal transfer electrode on the substrate and a core cable of signal feed-through connectors. The photo-resist of a negative type was spread and patterned on this substrate, coated by superconducting thin film and by additional gold films. After this, ion-beam etching of a superconducting film was performed and followed by oxygen plasma ashing of a photo-resist film. The filter substrate was mounted on a fixture and it was attached to a cold head of a Helium closed-cycle refrigerator.

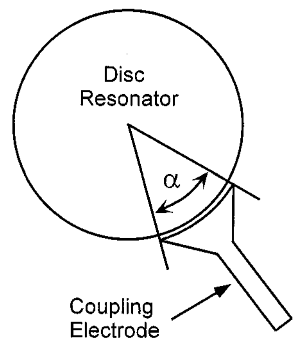


Fig. 1. Signal transfer circuit for high-power disc resonator.

C. Signal Coupling Electrodes

If the microstrip structure is employed for the filter configuration, discs and feedlines should be made of conductive films on a dielectric substrate with a ground plane on the reverse surface. The feedlines are coupled to the resonator on the periphery via gaps from the directions perpendicularly to each other so that the two-dipole modes are individually excited by the signals through the feedlines. Also, the design of the configuration of an input-and-output signal coupling or the coupling between each resonator circuit on a multipole filter is an important key for high performance of the filter devices. Especially when input-and-output signal coupling needs a comparatively high degree of coupling, these coupling designs become very important. However, in order to obtain the desired degree of coupling, only by capacitive coupling based on end coupling of a conventional traveling wave circuit, a coupling gap distance needs to be set up very narrowly. Also, in case it is a high electric-power operation, the danger of electric discharge arises. Therefore, the design of the coupling structure suitable for realizing the high degree of coupling is desired.

As shown in Fig. 1, the structure where circuit linewidth is expanded at the tip of a signal coupling electrode was used in the filter of this disc circuit structure. In this case, the coupling capacity of an end spread circuit and a disc resonator increases, and it is thought by changing angle α that the degree of signal coupling can be adjusted. However, when angle α is increased too much in this case, in connection with the increase in circuit linewidth, characteristic impedance must change a lot, and it must come conversely to take reflection of an unnecessary signal into consideration as the obstructive factor.

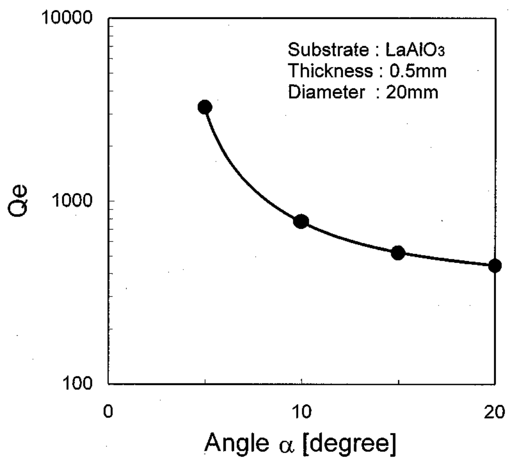


Fig. 2. Dependence of angle α on transfer signal coupling.

Fig. 2 shows the degree of coupling of the end spread circuit illustrated in Fig. 1. As shown in this figure, angle α of a horizontal axis expresses the circumference angle of the coupling portion seen from the disc center, and a vertical axis expresses external $Q\,(Qe)$. The calculation was performed using the electromagnetic-field simulator. The dielectric constant of 24 and thickness of 0.5 mm of a substrate were set up as calculation conditions. A resonator is a microstrip-type disc resonator circuit, and it set the diameter to about 20 mm, which corresponds to about 2-GHz resonant frequency. Electrode width was set up so that the characteristic impedance of an end spread circuit might be set to 50 Ω. Calculation was performed under the condition that circuit strip lines are perfect conductors. In this case, the calculation error will be accompanied by the decrease of the unloaded Q value caused by conductive loss increasing. This error was prevented by this circuit condition. In this figure, it is shown that the large degree of coupling is corresponding to a small value of external Q.

The sophisticated specification, which can efficiently employ the low-loss nature of superconducting circuits, is obtained as frequency band ratio of, for instance, about 1% and amplitude change of about 0.01 dB or less in passband. When these design targets of filter performance are set up in this condition, several 100 or less values of external Q are needed. Under such a Q value condition used for such calculation, the gap distance value becomes considerably narrow for realizing the desired amount of coupling, and filter design becomes difficult. When a large electric-power signal is inputted into such a coupling circuit, the problem in stability and reliability of operation of the filter may arise, and the possibility of destruction of the filter by electric discharge becomes larger. In order to solve these problems, design parameters other than a gap distance need to be regulated pertinently. One of the solutions of such a problem is thickening a dielectric substrate, and a good result was confirmed by such a method in our experiments.

D. Filter Module Design

If 100 W of signal power is inputted to our high-power filters, about 0.1 dB of intrinsic filter loss generates heat of 2.3 W at the filter circuit. Therefore, a cryo-cooling system with power consumption of about 100 W, which will have a cooling ability greater than several watts at 77 K, can successfully cool down the HTS power filter. On a typical personal communication system (PCS) base station in the U.S., it is planned to design the tower top unit that eliminates the cable loss and is cooled by a Giford-Machmahon (G-M) type cooling unit. It seems to be confirmed that the signal transmission characteristic of their units satisfies a specification. However, they are supposed to require the continuous examination on the long-life durability, reliability, and price.

Filter devices treating high power signals need rather large area size, as shown in this paper. In case of use of a disc configuration, the size of the order of several millimeters $\sim$ several tens of millimeters diameter is required at the microwave frequency region. Among the proposed design methods for realizing multistage filter performance, a quasi-two-dimensional module structure was experimented for effective cooling and small package size in the early period. One example of such a structure was constructed with feed line conductors and plural disc resonators, which are placed in parallel order and patterned with a coupling hall on the HTS grand electrode. The packaging structure of this type realized high power-handling capability of up to 60 W at 4-GHz frequency band on the HTS filter constructed with a single-mode disc resonator [21].

However, the best thermal conductance can be obtained by direct contact between the filter substrate and cooling head. Our proposed dual-mode disc resonators can provide multistage filter performance of not less than four stages in planar circuits because of dual-mode operation of one disc. Actually, more than an eight-stage filter performance can be possible using one superconducting wafer of 3-in diameter of an $LaAlO_3$ substrate in the frequency range above 2 GHz.

III. Disc Resonator Filter

A. Elliptic-Disc Resonator

A dual-mode resonator can be realized by elliptic-disc shape [22]. An elliptic-disc resonator has two fundamental modes, and these are both the TM_{11} mode, which is suitable for high power handling because the current flows comparatively more uniformly. Fig. 3 shows a basic configuration of the dual-mode disc resonator filter. The conductive film of the disc and two feed lines are fabricated on a dielectric $LaAlO_3$ substrate with a ground plane on the reverse side. Fundamental TM_{11} dipole modes indicate their polarization directions parallel to the feed-line direction and have an orthogonal relation when the disc pattern is a genuine circle. These dipole modes are orthogonal in the resonator disc pattern with no feed lines. If the resonator disc is coupled to the feed lines, a small perturbation is generated in the disc. In case of a perfect circular disc, this perturbation has no influences on the coupling of these modes. Some distortion or deformation on the disc shape breaks this isolation between these two modes and induces the mode coupling.

Some examples of the structural perturbations have been demonstrated before [23]. One of those has a stub put on the periphery at a direction of 135° to the both feed lines. Other uses a notch at the same location as that of the stub in the former.

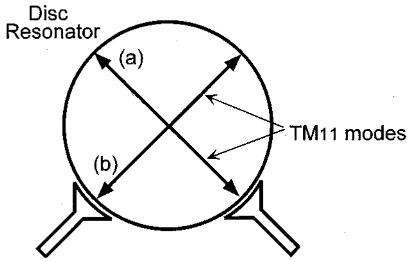


Fig. 3. (a) Circuit pattern of the dual-mode disc resonator. (b) Fundamental TM_{11} dipole modes.

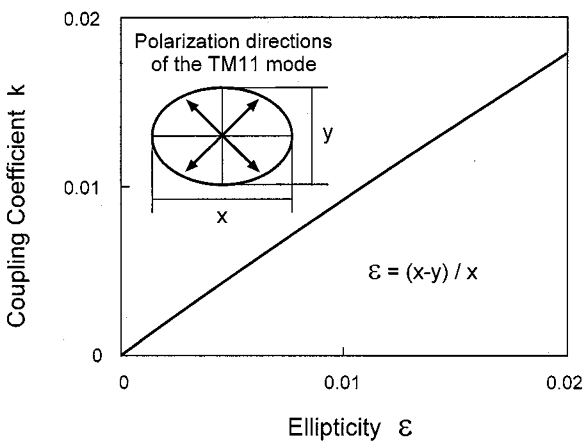
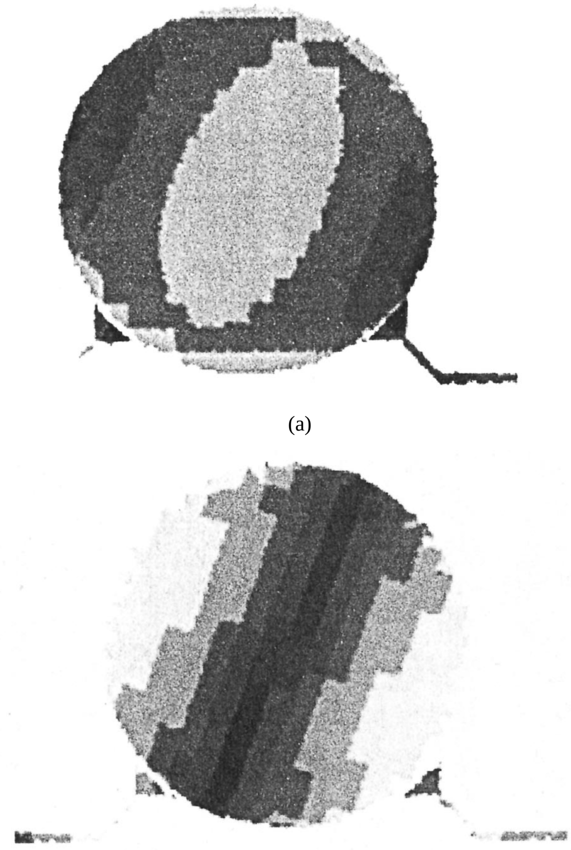


Fig. 4. Ellipticity dependence of the coupling coefficient between two dipole modes.

In these cases, an amount of the mode coupling approximately corresponds to an area size of the perturbations. In regard to the current distribution in the planar resonators, the microwave current flows along the edge near the periphery and shows the largest current density just at the edge. The perturbations of resonators produce sharp bends in the outline shape of the resonators. Such sharp bends, therefore, induce rapid changes of the flowing direction of the microwave currents and disturb the uniform current distribution in the conductor disc, which should cause the additional current concentration to reduce the power-handing capability.

An elliptical deformation is the most adequate for high power handling because of that smooth shape being free from the current concentration. Unless the ellipticity is too large, since the current distribution of the elliptic-disc resonator should be almost the same to that of a circular disc one, the current concentration would not increase additionally by the introduction of the elliptical distortion. The distortion is given by suitably adjusting the ellipticity of the disc shape where the symmetric axes are oriented at 45° to the polarization directions of the modes. The coupling coefficient between these dipole modes are calculated and shown in Fig. 4 as the function of ellipticity. Two lines with arrows correspond to the polarization directions of the TM_{11} mode in this figure.

The design of a two-dimensional planar circuit requires the three-dimensional electromagnetic-field calculation, including an axis toward the substrate. However, this takes a long time procedure of a typical computing tool. Recently, some commercial



(a)

(b)

Fig. 5. Schematic results of the simulation on the: (a) current density and (b) charge density distribution in the elliptic-disc filter.

software for planar circuit designs has made it easy to obtain an outline of the close solution, and can simulate the basic characteristics like frequency responses and charge density or current density distributions of the elliptic-disc resonator. Fig. 5(a) and Fig. 5(b) shows, respectively, the schematic results of the simulation on the current density and charge density distribution of TM_{11} resonating mode in the elliptic-disc filter at the center frequency of the filter passband. In this figure, the dark parts correspond to the low-density regions. In general, the current density pattern has the orthogonal relation with the charge density pattern, and this relation corresponds to the orthogonality between the electric and magnetic fields of the electromagnetic wave. Due to the slight difference between the two dipole modes of the elliptic resonator disc, the phase of the electromagnetic field changes as time passes. This phase change generates the rotation of the distribution pattern of the charge density. This rotation disperses the heat generation in the disc and the time average of the charge concentration becomes lower. It results in that the higher power can be handled by the two-mode operation.

B. Power-Handling Capability

In order to examine the power-handling capability of the HTS filter, the transmission power dependence of the insertion loss of two kinds of elliptic-disc resonator filters was measured. These two kinds of samples were prepared and measured in a dif-

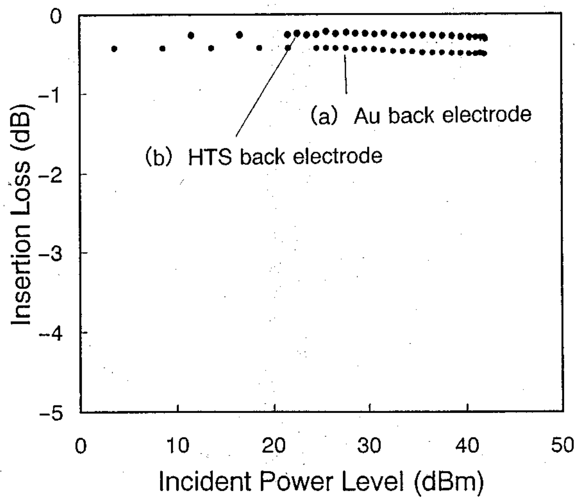


Fig. 6. Incident power dependence of passband insertion loss of the HTS elliptic-disc filter of 5.1-GHz center frequency measured at 20 K. Back side electrode is formed by: (a) Au or (b) HTS film.

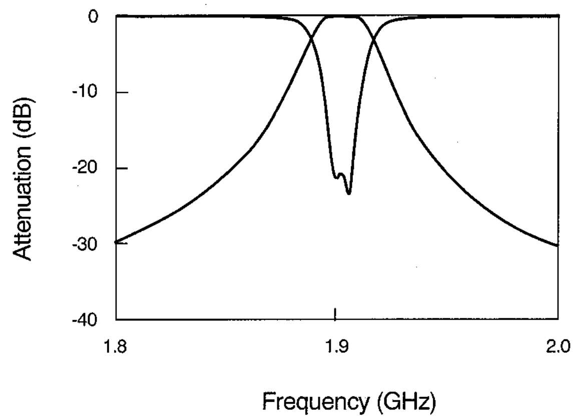


Fig. 7. Frequency response of high-power HTS filter at 77 K.

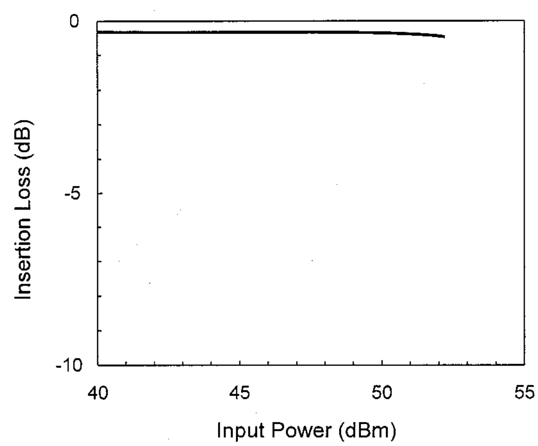


Fig. 8. Power dependence of insertion loss of 1.9 GHz filter measured at 20 K using pulse-modulated signals of 10-μs width.

ferent experimental setup of power-handling systems, which are the continuous and pulsed RF network analyzer systems. In the pulse system, the RF power signal modulated by a pulse of 10 μs $\sim$ 10-ms width was used so that a resonator element portion might not be influenced by generation of heat in the signal feed cable or a connection part of signal feed lines. The critical current density data of thin films of those substrates is evaluated as greater than 1×10^6 A/cm^2 in all area of the 1-in HTS wafer at 77K. The samples with the dual-mode disc resonator configuration were designed for a Chebyshev bandpass filter according to the standard design procedure using a low-pass prototype filter [24].

The center frequency of 5.1 GHz was designed for the filter sample of the first kind. The disc resonator has an elliptical shape of 2% ellipticity for the required mode-coupling coefficient, and the diameter along to the major axis is 7 mm. The disc film pattern was fabricated with a 0.7-μm-thick HTS thin film. The incident power dependence of the passband insertion loss is shown in Fig. 6 for these samples of an elliptic-disc resonator filter constructed by an Au [see Fig. 6(a)] or HTS [see Fig. 6(b)] backside electrode. In this measurement, the maximum power level of the continuous RF signal was limited to 46 dBm (around 40 W) by the maximum handling power of the experimental setup. The insertion loss of 0.38 and 0.21 dB is obtained for the samples [see Fig. 6(a)] and [see Fig. 6(b)] at the low power level and 20 K, respectively. A clear difference of the passband attenuation between these disc filters can be observed. The simulation for the loss of the backside electrode successfully estimates this difference. In this case, insertion loss improvement of about 0.2 dB is confirmed at the power level over 40 dBm. This figure shows that the insertion loss was constant at input levels below +30 dBm, but it slightly increased over +30 dBm. At the maximum power level, it is about 15% higher than that of the small-signal levels. In simplicity, this slight increase may attribute to an increase of the dissipation loss according to the supernormal transition of the HTS film. However, the surface resistance of HTS films at the normal state is much higher than that at the superconducting state by several orders of magnitude [17]. Therefore, the insertion loss caused by the supernormal transition even in part should increase much more drastically than those shown in Fig. 6. The greater part of these loss values should attribute to the contribution of connectors, cables, RF radiation, and some measurement setup errors rather than dissipation loss.

The passband attenuation of the bandpass filter depends on an inverse value of the unloaded Q factor of the elliptic-disc resonator. That attenuation expected theoretically from the Q value and the design parameters differs from the measured value [24]. Such difference is attributable to unexpected losses included between the reference planes in the S–parameter measurement, such as connection losses between the connector and feed line. The Q value larger than about 8000 was obtained by S–parameter measurement at 77 K. The intrinsic loss of this HTS filter calculated from this Q value is lower than the measured loss value, and unexpected loss can be estimated larger than 0.2 dB.

The filter sample of the second kind shows the center frequency of 1.9 GHz and is constructed by a double-sided HTS substrate [25]. The diameter along to the major axis is 19.6 mm. The thickness of 1 mm of an $LaAlO_3$ substrate was assumed as a design parameter. In this case, since ellipticity of disc

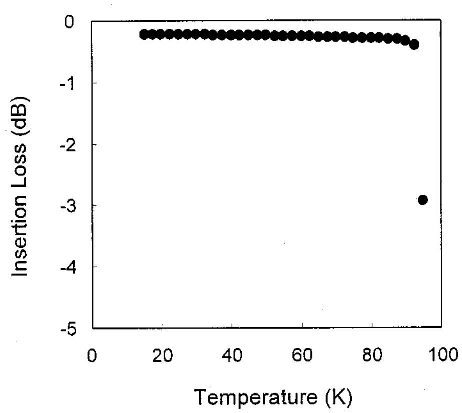


Fig. 9. Temperature dependence of the insertion loss of 1.9-GHz filter.

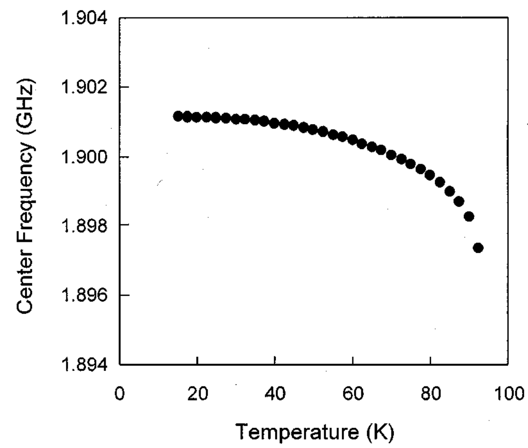


Fig. 10. Temperature dependence of the center frequency of 1.9-GHz filter.

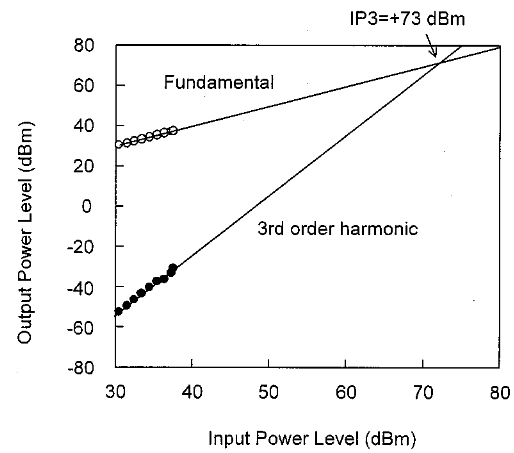


Fig. 11. Nonlinear responses of dual-mode resonator at 50 K. Fundamental signals: 1.905 and 1.910 GHz. Third-order harmonic signals: 1.900 and 1.915 GHz.

shape is merely as few as 1%, which is mostly seemingly a true circle. Fig. 7 shows the frequency response of this elliptic-disc filter measured at 77 K. Two-pole filter performance is clearly obtained, and reflection loss of over 20 dBm is confirmed at the center frequency. Fig. 8 also shows the incident power dependence of the passband insertion loss measured at 20 K. In this case, the maximum power level of the pulse-modulated RF signal was limited to 150 W (52 dBm) by the improved experimental setup. When the RF signal modulated by s 10-μs pulse is inputted, there is no fluctuation for higher power incident up to 100 W and the insertion loss less than about 0.3 dB is obtained. From these incident power data and discussion in the previous paragraph, the intrinsic filter loss of this sample can be estimated less than about 0.1 dB, and current flow in the microstrip planar circuit can be considered to be lower than the value of critical current density. Moreover, Figs. 9 and 10 express temperature dependence of the insertion loss and center frequency, respectively.

Form these results, it is confirmed that disc resonator can disperse RF current flow effectively to the wide area of a disc pattern, and can operate normally without the destruction caused by the high electric field of a high power signal. Low-loss performance of such a disc filter was shown experimentally to the continuous signal input up to about 40 W. Thus, it is confirmed that this superconducting filter can demonstrate the high power-handling performance beyond 100 W if the influence of heat generation caused by loss of the RF signal can be eliminated.

C. Nonlinear Response at High-Power Input

Nonlinear responses are the most important problem for high reliable communication systems, such as digital telecommunication systems. Those become serious when a high current is supplied to superconducting materials, and is caused by the heterogeneous characteristic of material structures or the intrinsic characteristic peculiar to an HTS [26], [27]. The harmonic signals generated as a result of these nonlinear responses may affect on the signals assigned to the neighboring frequency band. Thus, evaluation of this characteristic is very important for HTS power filter application. Here, the evaluation of such nonlinear performance was performed based on a two-tone method on the developed high-power filters using a dual-mode disc resonator. In measurement, the superconducting filter was cooled down at a temperature of 50 K, and two signals of the frequency of 1.905 and 1.910 GHz in the frequency band were simultaneously inputted to the filter element. These two input signals were prepared using two sets of synthesized sweep oscillator that attached to the high-power pulsed-RF network analyzer. The intensity of those signals were amplified to a maximum of +37.3 dBm by a microwave power amplifier, and mixed by a 3-dB coupler. The electric power of the two signals generated as third-order harmonic wave component at 1.915 or 1.900 GHz was investigated.

In Fig. 11, the relation between the electric power input signal and the third-order harmonic wave component is shown, and this figure also shows the relation between the electric power of fundamental output signal and the input signal. Since an approximate straight line can be fitted to measurement data, as shown in this figure, it is confirmed that the third-order harmonic component generated in an HTS filter element is proportional to the third power of the input signal power. In general, the fundamental output and the third-order harmonic component have the intersection at a certain point, as shown in this figure. Such a point is called the third-order intercept point (IP3), and is used as an index evaluating nonlinear performance of RF components.

The IP3 value of +73 dBm (20 kW) is derived on this superconducting filter. This is quite a high value and proves a very excellent response in the linearity of our HTS filter.

IV. MULTICOUPLING ELLIPTIC-DISK FILTER

When a receiving and transmitting band are arranged adjacently on a communication RF system, the harmonic distortion signals and noise signals, which are generated outside the frequency passband by the transmitting power amplifier, negatively affect the receiving circuit. Even if the filter characteristic of signal suppression is designed ideally for the receivers, disturbing signals, which are generated by the unnecessary response, such as the cross modulation, intermodulation and others at the receiving systems, need to be taken into consideration. Thus, the steep skirt characteristic is also desired for a transmitting filter. The steep skirt characteristic can be obtained by increasing the number of resonant stages of the resonator-type filter. In a previous section, it was shown that the elliptic-disc resonator has a two-resonance mode corresponding to two poles of filter performance. In this section, a multipole filter using plural elliptic-disc resonators are newly proposed and the fundamental coupling characteristic are introduced in order to realize a steep bandpass filter with high performance of out-of-band signal suppression.

A. Mode Coupling Among Two Elliptic-Disc Resonators

An increase in the number of resonant stages enlarges filter size, and the large wafer of the superconducting substrate should be desired. Our elliptic-disc resonator has a two-pole performance, which is in contrast with a conventional disc resonator showing monopole performance. Thus, the elliptic disc has a great advantage on the wafer size. In other words, an elliptic-disc filter can realize the same frequency response in the half size of wafer of a conventional disc filter. Also, as described in the previous section, recent progress in thin-film technology will solve this problem as far as the filter will be designed at the frequency above gigahertz band.

In order to constitute the multipole filter using a coupling between plural disc resonators that have multiresonance modes, the coupling among those resonance modes should be simultaneously controlled. However, such coupling control has been difficult because of the luck of principle for microwave circuit design up to now. Fig. 12 shows the basic construction of a four-stage bandpass filter using two elliptic-disc resonators. In this construction, the coupling between input and output signals is successfully controlled by the suitable design for the elliptic-disc resonator. The signal introduced from Port-1 drives Mode-1 first, then successively each mode can be driven in turns as the Mode-1→Mode-2→Mode-3→Mode-4, and finally, the signal comes out from Port-2. The directions of electromagnetic fields of Mode-1 and Mode-3 are in an orthogonal relation to each other. Mode-2 and Mode-4 are also in the same orthogonal relation. This orthogonal relation corresponds to weak coupling between two modes that can be neglected on a mode coupling design.

The coupling between Mode-2 and Mode-3 is designed by controlling an ellipticity of Disc-2. The mode coupling between Mode-1 and Mode-2 ($K12$) is designed by controlling the space (d) between two resonator discs, and the coupling between Mode-3 and Mode-4 ($K34$) are also designed in the same manner. The coupling coefficient of the space (d) dependent is shown in Fig. 13. Coupling of two disc resonators of almost 14-mm diameter are designed on an $LaAlO_3$ substrate of 1-mm thickness. When the space d is set to almost 3 mm, the condition of $K12 = K34$ is obtained. Under such a condition, a symmetrical frequency response of the passband can be realized. Fig. 14 shows the frequency response that was simulated by a commercial electromagnetic-field simulator and was designed as the filter of a 0.01% ripple in the passband and of a 1% bandwidth. This result has certified that an appropriate design based on the design principle proposed here can realize the flat passband performance peculiar to a multistage filter.

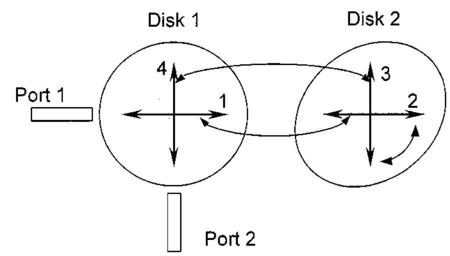


Fig. 12. Coupling principle among two dual modes of two-disc resonators.

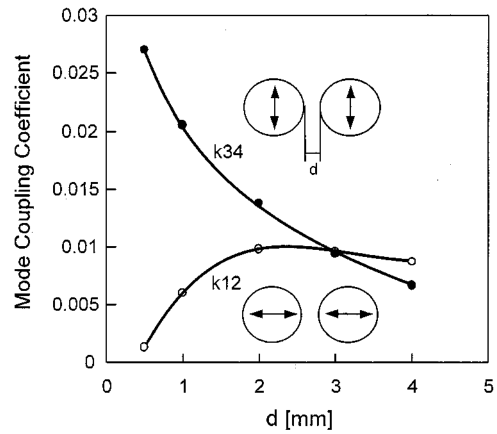


Fig. 13. Relation between the mode-coupling coefficient and space d between two-disc resonators.

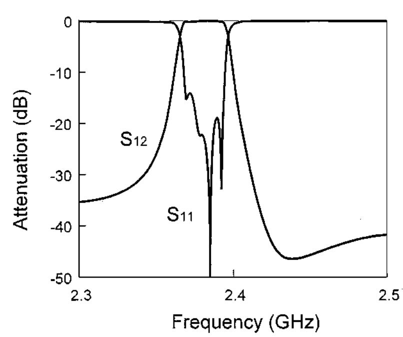


Fig. 14. Simulated frequency response of a four-pole disc resonator filter. Design parameters are a 0.01% ripple in the passband and 1% in the bandwidth.

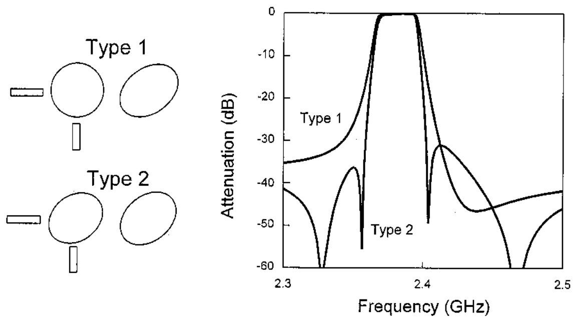


Fig. 15. Disc filter patterns for input–output mode coupling and the notch response simulation.

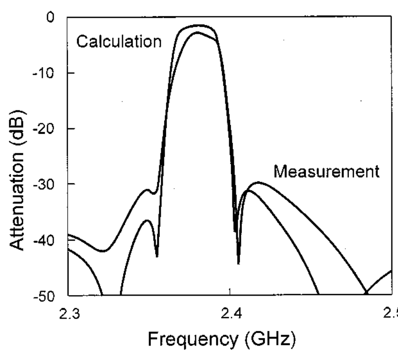


Fig. 16. Calculated and measured frequency responses of elliptic-disc filter using Au thin-film patterns.

B. Notch Responses of Elliptic Function Type

The proposed design principle can realize the frequency response of the elliptic function type. In this case, a notch response can be designed on the outside of the passband. The specific pattern of a device is shown in Fig. 15 as type-2, which is constructed by two elliptic-disc resonators and utilizes direct coupling between Mode-1 and Mode-4. Simulation and experiment for this notch response were performed on an Au thin-film device. Fig. 16 shows both the calculated and measured results of a clear notch performance. In this figure, measured result could not be exactly simulated by calculated results. The commercial two-and-one-half-dimensional electromagnetic-field simulator was used for this simulation. The unexpected coupling caused by three-dimensional electromagnetic-field distribution in a package or the undesired coupling of resonance modes should be investigated for this discrepancy. As can be easily supposed, this design principle has great advancement because of its flexible design using an elliptic function for an example. Many efforts on simulation and experiment in the future will establish the optimum design of disc filter structures proposed here.

V. SUMMARY

Microwave power devices had not expected the possibility of their application in the early stage because of poor capability of HTS thin-film materials on high superconducting current performance. At this stage, many researchers recognize the high-power ability of HTS thin-film devices. The reason for this situation should be caused by great technical improvement on crystal substrates with low dielectric loss, high-quality HTS thin-film fabrication, and electromagnetic simulation tools. The RF coplanar circuit filter using elliptic-disc resonators, which were proposed and investigated in this paper, makes it possible to miniaturize filter circuits and to realize high performance of the power ability of HTS filters.

In the first place, end spread signal coupling electrodes were investigate for effective input and output coupling to a disc resonator and in order to adjust the coupling degree and proper characteristic impedance of the circuit. Two-mode coupling in the elliptic disc was then explained. It was shown that electromagnetic-field distribution changes every moment. This change results in current dispersion that can protect current and heat concentration. Thus, this two-mode operation realized power-handling capability over 100 W.

The design principle of a multiple-disc filter was introduced for high performance of out-of-band rejection and passband flatness. For a future information communication field, the high reliability of communication must be secure. The HTS microwave devices that will be adopted on both a receive and transmit pass can satisfy this serious request and should be able to take on this important role. The elliptic-disc resonator filter can bring out the excellent performance of HTS materials.

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