# NOVEL SUPERCONDUCTING RING FILTER

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**Abstract**

A novel planar filter composed of ring resonators with open gaps is proposed. The coupling intensity between the adjacent resonators can be controlled by changing the relative direction of the gaps. Very weak coupling can be obtained so that the narrow bandwidth filter is realized in a compact size. A 5-pole filter at 3 GHz center frequency with 1 % bandwidth and an 8-pole filter at 2 GHz with 0.25 % bandwidth were demonstrated by using niobium films on 50 mm diameter MgO substrates.

## Introduction

Planar filters using high temperature superconducting films for cellular applications have been reported [1-6]. It is highly advantageous to fabricate narrow-band filters with superconducting materials because of its high unloaded quality factor. However, it is not easy to achieve narrow bandwidth (BW) less than 1 % in a compact size by using conventional design such as parallel-coupled or end-coupled layouts. In the case of parallel-coupled arrays, large spaces between adjacent resonators are required for weak coupling. On the other hand, in the case of end-coupled arrays, longitudinal direction size becomes longer even if weak coupling can be realized. To surmount this problem, we focused on ring resonators to achieve weak coupling in quite close space. This paper presents a novel planar filter composed of half-wavelength ring resonators with open gaps and proposes a special layout featuring weak coupling. Based on the design concept presented in this paper, very narrow-band filters can be realized easily in a compact size. To demonstrate the performance, a 5-pole filter with 1 % BW and an 8-pole filter with 0.25 % BW using niobium films on MgO substrates were fabricated and measured at 4.2 K. The layout pattern of the 8-pole filter is illustrated in Fig. 1. In this work, niobium films were used because high uniformity of superconductivity all over wafer surface were required for high-Q applications such as 0.25% BW. The undesirable coupling between input and output terminal resonators has to be considered [7], because they were close to each other as shown in Fig. 1. Electromagnetic shields in the package were employed to obstruct the interference between the input and output resonators. The effect of the shields on the filter response was also examined.

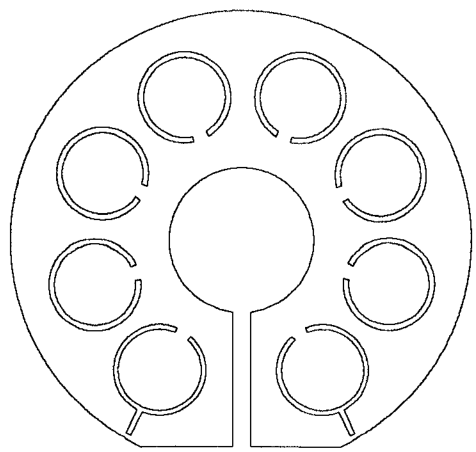

Figure 1. Layout of an 8-pole ring filter at 2 GHz with 0.25% BW on 50 mm diameter MgO wafer.

## Fitler Design

The coupling coefficients between ring resonators were computed numerically by using EM simulator "momentum" provided by Hewlett Packard. As discussed in the references [1,2,8], the coupling coefficients can be derived from the open-circuit admittance matrix Y with reference to ports $\alpha$ and $\beta$ in Fig. 2 (a). The circuit in Fig. 2 (a) is transformed to an equivalent circuit in Fig. 2 (b). The admittance inverter parameter $J_{\alpha\beta}$ and the resonator susceptance $jB_\alpha$ and $jB_\beta$ relate to Y-matrix as

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$$J_{\alpha\beta} = \left| y_{\alpha\beta} \right| \quad (1)$$

$$jB_\alpha = y_{\alpha\alpha} \quad (2)$$

$$jB_\beta = y_{\beta\beta} \quad (3)$$

Parameters $y_{\alpha\alpha}$ and $y_{\beta\beta}$ represent diagonal and off-diagonal elements of Y-matrix respectively. Then the coupling coefficient $k_{\alpha\beta}$ is expressed as follows

$$k_{\alpha\beta} = \frac{J_{\alpha\beta}}{\sqrt{b_\alpha b_\beta}} \quad (4)$$

where

$$b_i = \frac{f}{2}\frac{dB_i}{df}\bigg|_{f=f_0} \quad (5)$$

is the resonator slope parameter at the center frequency $f_0$ .

Several types of ring resonator arrays have been examined. Coupling coefficients between ring resonators depend on not only the distance between ring centers but also the open gap angle of each ring. Typical arrays with reference to the open gap directions and their coupling coefficients calculated by Eqs. (1)-(5) are shown in Fig. 3. The values of the coupling coefficient are so small as to be applied to narrow-band filters. For example, in the case of the BW less than 1 %, the required coupling coefficient is less than 1E-2. The results also indicate that the intensity of the coupling coefficient can be controlled in the wide range shown in Fig. 3 without changing the distance between ring centers. It can be controlled only by turning the each ring around its center. These interesting characteristics suggest that the ring resonator has excellent potential to be applied to narrow-band filters. However, a great number of combinations of ring arrays can be considered when a filter is composed of more than three ring resonators. That indicates the ring filter design to be complicated.

This paper proposes a special ring resonator array to improve the problems. In the proposed array, the ring resonators are arranged in a circle with the radius $R$ as shown in Fig. 4, where the open gap of each ring is turned round toward the radius vector of the circle. The coupling coefficient can be controlled by the angle $\theta$ between two radius vectors of neighboring rings. This idea can be expanded easily into filter layout: the centers of all resonators are arranged in a circle where the open gap of each ring is turned round toward the radius vector of the circle. On the condition that the $R$ is fixed, the coupling coefficient is controlled only by one parameter $\theta$. Introducing the proposed ring arrays, the design of ring filters is simplified. Figure 5 shows the relationship between the angle $\theta$ and the coupling coefficient $k$ calculated in two cases shown in Fig. 4. The results indicate that the configuration Fig. 4 (b) can realize weaker coupling compared with the configuration (a). So the configuration (b) is suitable for very narrow-band filters less than 1 % BW. Based on the design concept, a 5-pole filter with 1 % BW and an 8-pole filter with 0.25 % BW was designed by using the configurations (a) and (b) respectively. The layout patterns and design parameters are shown in Fig. 6 and Table. The positions of the input and output taps were calculated according to the reference [1].

As mentioned above, the undesirable coupling between input and output terminal resonators has to be considered, especially in the case where two terminal resonators are close to each other as the 8-pole filter. It can be thought that the background level at the rejection band increases as a result of the undesirable couplings. To decrease the background level, the package with electromagnetic shields composed of a partition wall and a column employed for the 8-pole filter as shown in Fig. 7. The key-hole pattern as illustrated in Fig. 1 was cut off from the substrate by laser beam cutting machine to assemble it into this package.

## Measurement Results

(A) 5-pole filter at 3 GHz with 1 % BW

The 5-pole filter was fabricated by using niobium films on a half size of 50-mm diameter MgO wafer to confirm the performance of the ring filter proposed in this paper. The measured transmission response at 4.2 K in liquid helium and the simulation result are shown in Fig. 8 (a) and (b) respectively. The cable loss reduction from calibration at room temperature has not been corrected in the measurement. The results indicate that narrow-band performance of the ring filter has been confirmed although the measured response is somewhat different compared with the simulation. The measured bandwidth is a little wider and the center-frequency is a little lower than the simulation. It is considered that they are caused by the difference of some physical parameters (i.e., dielectric constant and substrate thickness) between simulation and an actual device.

(B) 8-pole filter at 2 GHz with 0.25 % BW

The 8-pole filter was fabricated by using niobium films on a 50-mm diameter MgO wafer. To examine the effect of the shields, the filter responses were measured for two cases: (a) assembled the shields into the package and (b) removed the shields from the package. The measured transmission response at 4.2 K in liquid helium for each case is shown in Fig. 9. The background level at the rejection band was higher about 20 dB and the passband skirt was widened when the shields were removed. The results indicate that these phenomena are caused by the direct coupling between the first resonator and the eighth resonator. Therefore the shields should be assembled when the terminal resonators are close to each other.

## Conclusions

In conclusion, we have proposed and demonstrated novel filters composed of ring resonators. It has been confirmed that narrow-band filters can be realized easily in a compact size based on the design concept presented herein. The effect of the shields assembled into the package has been examined. The results indicate that the shields should be assembled when the terminal resonators are close to each other.

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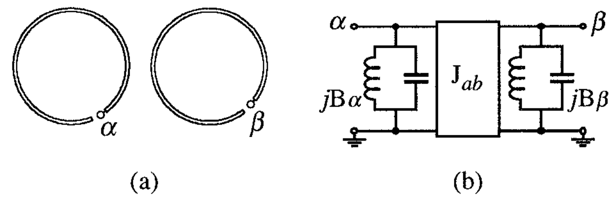


Figure 2. (a) Coupled ring resonators with open gap. (b) Transformed equivalent circuit of (a) .

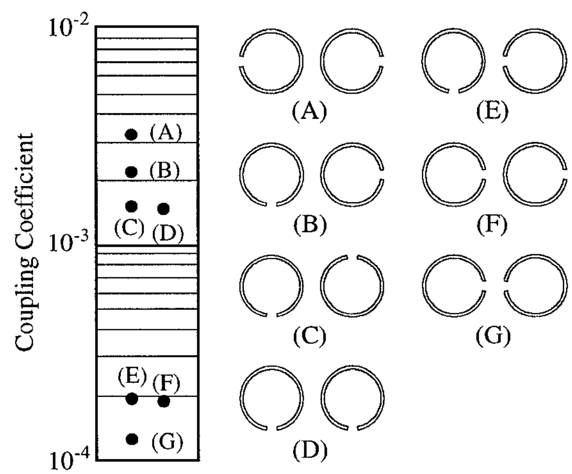


Figure 3. Typical ring arrays with reference to the open gap directions and their coupling coefficients.

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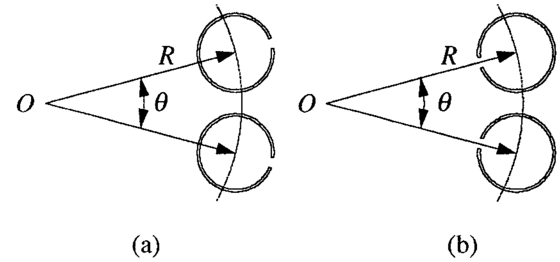


**Figure 4.** Proposed ring resonators arrays: (a) The open gap of each ring faces opposite direction toward the center of the imaginary circle, *O*. (b) Each open gap faces toward the center *O*.

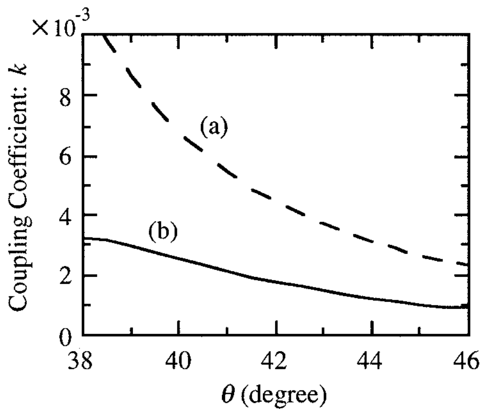


**Figure 5.** The relationship between the angle $\theta$ and the coupling coefficient $k$ calculated in two cases (a) and (b) in Fig. 4.

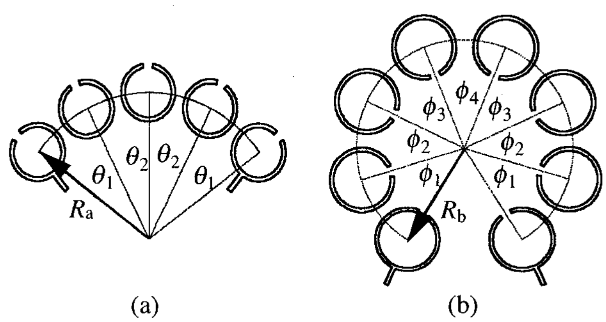


**Figure 6.** Design layout: (a) The 5-pole filter at 3 GHz with 1 % BW. (b) The 8-pole filter at 2GHz with 0.25 % BW.

**Table** The angles (degree) between rings and the radii (mm) of the imaginary circle in Fig. 6.

| $R_a$ | $\theta_1$ | $\theta_2$ | $R_b$ | $\phi_1$ | $\phi_2$ | $\phi_3$ | $\phi_4$ |
|---|---|---|---|---|---|---|---|
| 18.0 | 25.96 | 27.09 | 17.0 | 40.80 | 42.70 | 43.07 | 43.14 |

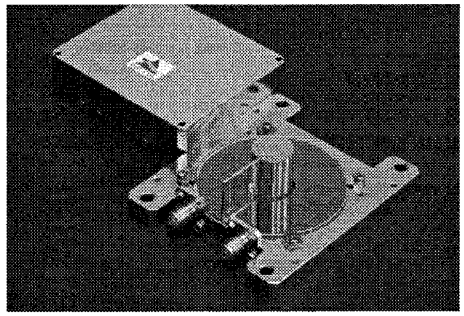

**Figure 7.** Photograph of the package assembled with shields for the 8-pole filter.

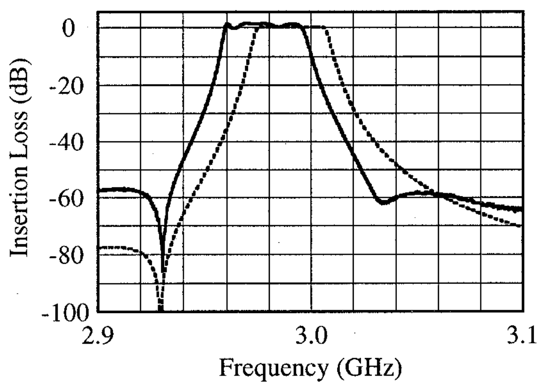


**Figure 8.** The responses of the 5-pole ring filter with 1% BW. (a) The solid line shows the measured response at 4.2 K. (b) The dashed line shows the simulation result.

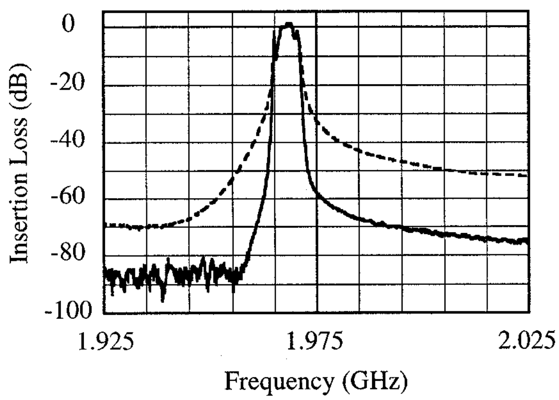


**Figure 9.** The measured responces at 4.2 K of the 8-pole ring filter. (a) The solid line shows the response when the shields were assembled into the package. (b) The dashed line shows the response when the shields were removed from the package.

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