Design for transmit bandpass filter and trimming method using superconducting bulk ring resonator and dielectric rods

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Abstract. We designed transmit bandpass filters (BPFs) by using superconducting bulk ring resonators and dielectric trimming rods at a 5.0 GHz center frequency with a 100 MHz bandwidth. The filter with ring resonators was smaller than the filter with disk resonators, where the size was defined as the distance between the input/output ports. We found that the size contributes significantly to the miniaturization of multi-pole filters. A trimming mechanism was also evaluated. The frequency shift region of a single ring resonator reached more than 500 MHz after we moved a dielectric rod whose dielectric constant was 39 into the ring resonator. A 3-pole strip-line BPF was also designed using a Chebyshev function by using three pairs of ring resonators and dielectric trimming rods with the same dimensions and by adjusting the positions of the trimming rods. We obtained the optimal frequency response with a low loss and passband ripple for this BPF.

1. Introduction

High-temperature superconductor (HTS) filters are promising for efficiently using frequency resources. However, the power-handling capability of HTS filters is limited by the critical current of an HTS material and by the current concentration at the edges of HTS resonators [1]. Therefore, the superconducting properties (such as the critical current density \( J_c \)) and surface resistance \( R_s \)) must be enhanced, and the resonator structure must be improved to develop the power-handling capability of transmit filters. Numerous reports have addressed improving the power-handling capability of transmit bandpass filters (BPFs) by using structural improvements [2-8]. However, local and minute changes in the resonator make the current concentration rise at the changed area, so these resonators may not be effective for use as transmit BPFs. Therefore, a single-mode circular resonator with large critical current will be useful for improving the power-handling capability of HTS BPFs.

To increase the critical current of the resonator, we proposed using HTS bulk resonators and their BPFs. We fabricated modified quench-and-melt growth (QMG) HTS bulks and measured their \( R_s \) values [9]. The \( R_s \) values of optimized Dy-Ba-Cu-O and Gd-Ba-Cu-O bulks were low enough to be used for microwave filter applications. Additionally, a strip-line (SL) structure was enabled us to obtain a highly unloaded quality factor, \( Q_u \), for a circular resonator [10, 11].

We designed and fabricated 3-pole SL BPFs by using Dy-Ba-Cu-O bulk resonators on disk for the TM_{11} mode [11, 12]. A filtering response was clearly observed; however, a large insertion loss and a...
wide bandwidth were also observed in the actual measured response. These can be attributed to a deviation from the designed resonant frequency [12]. Therefore, a trimming mechanism is needed in the bulk BPFs to reduce the loss and bandwidth.

In this paper, we describe our design of SL BPFs that use superconducting bulk ring resonators and our evaluation of the trimming performance of the BPFs.

2. Design of filter that uses superconducting bulk ring resonator

2.1. Superconducting bulk ring resonator

The frequency responses and electromagnetic fields of a resonator and a BPF were simulated using an electromagnetic simulator (CST studio suits 2006B) based on the finite integral method and a perfect boundary approximation. Using SL resonators having a sandwich structure with two ground planes increased both the quality factor of the resonator and the coupling between the I/O ports and the resonators [11]. Figure 1 (a) illustrates a typical 3-dimensional simulation model of an SL single ring resonator. The microwave loss of the superconducting ring resonator and the I/O ports was neglected in this model. The superconducting ring resonator was 0.5-mm thick because of the fabrication limit. The thickness, the dielectric constant ($\varepsilon_r$), and the loss tangent of the dielectric substrate were 5.9 mm, 9.9, and $10^{-4}$. Both gaps $g_1$ and $g_2$ between the resonator and the I/O port were set to 6.0 mm to obtain a weak coupling. The center frequencies ($f_0$) of the ring resonators were simulated by varying the ratio of the internal and external radii ($r/R$). Figure 1 (b) shows the external radius ($R$) vs. the $r/R$ values for the single ring resonator corresponding to an $f_0$ of 5 GHz for the $TM_{11}$ mode. For a disk resonator, $r/R=0$. The external radius, $R$, decreases as $r/R$ increases. Fabricating a ring of less than 1 mm is too difficult, so we designed the ring using a resonator with $R=3.43$ mm and $r=2.43$ mm. The ring resonator can be miniaturized so that it is approximately 85% of the disk resonator's size. The unloaded quality factor, $Q_u$, of the SL ring-resonator with $R=3.43$ mm and $r=2.43$ mm is approximately $3\times10^5$, which is two orders of magnitude larger than that of a microstrip line ring-resonator [13].

![Fig. 1. (a): Typical 3-dimensional simulation model of SL single ring-resonator. (b): R vs. r/R of single ring-resonator corresponding to $f_0$ of 5 GHz.](image)

2.2. Design of 3-pole BPF using ring resonators

A 3-pole Chebyshev BPF was designed to incorporate a 0.5-mm-thick ring resonator with $R=3.43$ mm and $r=2.43$ mm for the $TM_{11}$ mode. The other conditions used for the simulation were the same as the single ring resonator described in section 2.1. We designed the filter based on these specifications; an $f_0$ of 5.0 GHz, a bandwidth of 100 MHz, and a passband ripple of 0.1 dB. We derived the theoretical values of the external quality factor ($Q_e$) and the coupling coefficient ($k_{12}=k_{23}$) as $Q_e=51.58$.
and $k_{12}=k_{23}=1.838\times10^{-2}$ to design the filter. Figure 2 (a) shows the dependence of $Q_e$ on $g_1$ for $g_2=6.0$ mm. We found that $Q_e$ is mostly proportional to $g_1$, and we easily achieved the required $Q_e$ value for the filter design. Figure 2 (b) shows the dependence of the coupling coefficient, $k$, on the distance ($s$) from two ring resonators for $g_1=g_2=6.0$ mm. We found that $k$ was inversely proportional to $s$, and we achieved the required $k_{12}$ and $k_{23}$ values for the filter design. We designed the 3-pole BPF by using the theoretical $g_1$, $g_2$, $s_1$, and $s_2$ obtained from Fig. 2.

Figure 3 (a) illustrates a 3-dimensional BPF model optimized so that $R$, $r$, $g$, and $s$ meet the specifications of the frequency response. Figure 3 (b) shows the simulated response of the 3-pole SL BPF that uses the ring resonator. The solid and dashed lines represent the propagation ($S_{21}$) and the reflection ($S_{11}$) properties. The $f_0$, the bandwidth, the insertion loss, the passband ripple, and the maximum return loss of the 3-pole SL BPF were 5.00 GHz, 98 MHz, 0.096 dB, 0.04 dB, and 20.97 dB. For comparison, the sizes of the external diameters (2R), the $g$ values, and the $s$ values of the filters using the ring and disk resonator are listed in Table 1. The variable $x$ is defined as the distance between the I/O ports. The $x$-value of the filter with the ring resonator is smaller than that of the filter with the disk resonators. Therefore, increasing the number of resonators contributes significantly to miniaturizing the multi-pole BPFs.

![Fig. 2. (a): External quality factor ($Q_e$) vs. gap between resonator and I/O port ($g_1$). (b): coupling coefficient ($k$) vs. space between resonators.](image1.png)

![Fig. 3. (a): Three-dimensional simulation model of strip-line 3-pole bulk ring-filter. (b): Simulated response of strip-line 3-pole bulk ring-filter.](image2.png)
Table 1. Comparison of size of 3-pole filters with ring and disk resonators

| Resonator type | External diameter 2R [mm] | g1, g2 [mm] | s1, s2 [mm] | x [mm] |
|----------------|---------------------------|-------------|-------------|--------|
| Ring           | 6.84                      | 6.90        | 1.50        | 6.20   | 35.98  |
| Disk           | 8.40                      | 8.44        | 1.20        | 5.80   | 39.24  |

3. Design of BPF using superconducting bulk ring resonator and trimming rod

3.1. Trimming properties of a single ring resonator

To improve the bulk filter, we need to use a trimming mechanism and the effective dielectric constant of the substrate. [12] We developed such a trimming mechanism and evaluated its trimming and tuning capabilities. Figure 4 (a) shows the side view of the simulated model of a single ring resonator attached to the substrate with a dielectric trimming rod.

The superconducting ring-resonator was 0.5-mm thick with R=4.1 mm and r=2.4 mm. The thickness, dielectric constant (εr) [12], and loss tangent of the dielectric substrate were 5.5 mm, 8.1, and 10^-4. Both gaps (g1 and g2) between the resonator and the I/O port were set to 6.0 mm to obtain the weak coupling. The trimming rod had an εr value of 39, a diameter of 4.8 mm, and a height of 3.4 mm. The ideal value was used for the conductivity of the Cu material at 20 K.

The f0 of the ring resonators was simulated by varying the height (h) of the dielectric rod above the bottom of the resonator. Figure 4 (b) shows the f0 for the TM11 mode vs. the h characteristic. The value of f0 gradually increases as h increases. The frequency shift can be changed more than 500 MHz by moving the trimming rod into the ring resonator. These results will enable us to trim the filter responses. Moreover, they may be useful for tuning with a large frequency shift.

3.2. Design of 3-pole filter with trimming rods

To evaluate the feasibility of our composed filter, we designed the 3-pole Chebyshev BPF by using three pairs of SL superconducting bulk ring-resonators and dielectric rods with the same dimensions. Figure 5 illustrates a typical 3-dimensional view of the simulation model. We could not precisely define the microwave loss for the superconducting materials, so we used a conductivity value of the superconducting materials that was two orders of magnitude larger than that of the Cu metal at 20 K.
Figure 6 shows the simulated responses of the 3-pole bulk ring-filter models. Here, we defined \( h_1 \), \( h_2 \), and \( h_3 \) as the heights of the dielectric rods above the bottoms of the resonators. Fig. 6 (a) shows the response of the filter for \( h_1 = h_3 = 1.65 \) mm and for \( h_2 = 1.25 \) mm. The \( f_0 \), bandwidth, insertion loss, passband ripple, and maximum return loss of the filter were 5.041 GHz, 93.2 MHz, 0.045 dB, 0.994 dB, and 6.90 dB. The passband ripple and maximum return loss did not meet the specifications, so we adjusted the heights of the trimming rods to decrease the return loss to less than 20 dB. Fig. 6 (b) shows the response of the filter after adjusting it for the parameters \( h_1 \) and \( h_3 \) (1.52 mm) and \( h_2 \) (0.96 mm). After the trimming, the \( f_0 \), bandwidth, insertion loss, passband ripple, and maximum return loss of the filter were 5.016 GHz, 92.3 MHz, 0.04 dB, 0.004 dB, and 33.3 dB. Finally, we investigated the relationship between the loss tangent of the trimming rods and insertion loss of the frequency response. Figure 7 shows the simulated response of the optimised 3-pole BPF with the loss tangent of the trimming rods varied from \( 10^{-4} \) to \( 10^{-2} \). A low insertion loss of less than 0.1 dB was obtained by...
assuming that the loss tangent of rods was smaller than 10^{-3}. These results demonstrate that the superconducting bulk ring filters with the added trimming mechanisms are useful in adjusting the BPF properties to apply the transmit BPFs. An experimental evaluation of the frequency response, the turning properties, and the power-handling capability of the actual filter will be done in future work.

4. Conclusion

A 3-pole BPF was designed using superconducting bulk ring resonators and dielectric trimming rods with the same dimensions. A filter response that met prescribed specifications was obtained by adjusting the height of each trimming rod setting into the ring resonators.

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