Compact HTS bandpass filter employing CPW quarter-wavelength resonators with strongly-coupled open stubs

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Abstract. This paper presents a novel compact high temperature superconducting (HTS) bandpass filter (BPF) that employs a newly developed miniaturized coplanar–waveguide (CPW) quarter–wavelength resonators with strongly–coupled open stubs. The proposed resonator has a structure in which the open stubs are aligned close to the center conductor of the resonator. This is because strongly–coupled resonators have widely–split resonant frequencies, and the lowest resonant frequency is employed as the fundamental resonant frequency of the resonator in order to achieve miniaturization. The proposed resonator is 1.7 mm or less in length for use in the 5–GHz band, whereas the conventional straight resonator is approximately 6.4 mm long. A four–pole Chebyshev HTS BPF is designed and fabricated using the proposed CPW resonators. The entire length of the proposed four–pole filter is 15 mm. The frequency response of the fabricated filter agrees well with the electromagnetic simulation results. The proposed filter achieves a size reduction of at least 50% compared to previously reported filters without any degradation in the frequency characteristics.

1. Introduction
A high-temperature superconducting (HTS) filter is a strong candidate to attain efficient frequency utilization characteristics and improve the receiver-sensitivity in mobile communication base station receivers since it achieves a low insertion loss and has sharp cut-off characteristics [1-4]. There are several HTS filter configurations such as the microstrip line, stripline, and coplanar waveguide (CPW) configurations. The CPW configuration is not only advantageous in simplifying the fabrication process and in reducing the cost of the HTS filter but also facilitates establishing a quarter-wavelength resonator that is suited to miniaturizing filters [5], [6].

This paper proposes a novel CPW HTS filter which employs newly developed resonators that have strongly-coupled open stubs to miniaturize significantly the filter compared to the previously reported filters [7], [8]. A 5-GHz band four-pole CPW HTS filter is also fabricated to investigate experimentally the validity of the proposed method.

2. Resonator design concept
Figure 1 shows a schematic of the proposed miniaturized CPW quarter-wavelength resonator that has a structure where the open stubs are aligned close to the center conductor of the resonator. A quarter-wavelength resonator with open stubs has widely-split resonant frequencies because the open stubs couple electromagnetically with the center conductor. Thus, by employing the lowest resonant
frequency, the proposed resonator achieves a lower resonant frequency than that for a quarter-wavelength resonator without open stubs.

Figure 2 shows the split resonant frequencies versus the coupling spacing \( s \) between the center conductor and the open stubs as indicated in figure 1. The quarter-wavelength resonator without open stubs has the resonant frequency of 8.189 GHz. The narrower \( s \) becomes 0.20 mm to 0.01 mm and the wider resonant peaks \( (f_1 \) and \( f_2) \) separate. For example, the resonant frequency is split into 4.807 GHz and 11.99 GHz at spacing \( s \) of 0.08 mm. In other words, the proposed resonator is used as a 5-GHz band resonator, although the longitudinal length of the resonator is designed to have a resonant frequency in the 8-GHz band.

Figure 3 shows the center frequency \( f_0 \) and unloaded Q \( Q_u \) versus the resonant structure length, \( l \), as indicated in figure 1. The dimensions of the proposed resonator are approximately 1.68 mm long and 2.88 mm wide for the 5-GHz band filter. The simulated \( Q_u \) of the resonator is 40,000 or more.

3. Filter design
An overview of the design process for the proposed HTS BPF is given below. In the first step, the primary dimensions of the HTS BPF such as the resonator length, the distance between adjacent resonators, and the distance between the input/output line and the resonator are designed such that only the adjacent resonators are electromagnetically coupled. In the second step, all the filter dimensions are decided tentatively according to the parameters derived in the first step. Finally, the
tentative filter dimensions in the second step are tuned using the circuit simulator and electromagnetic simulator since undesired couplings essentially exist in the actual filter.

The specifications for the HTS BPF are summarized in Table 1. The filter to be designed is a four-pole Chebyshev BPF with a center frequency of 5 GHz, a 0.01-dB passband ripple, and a 3.2% (160 MHz) equal ripple bandwidth. The configuration of the four-pole BPF is shown in figure 4 where the CPW quarter-wavelength resonators with strongly-coupled open stubs are arranged serially. Here, symmetry is employed to facilitate electromagnetic analysis.

Figure 5 shows the original equivalent circuit of four-pole HTS BPF.

Table 1. Four-pole Chebyshev BPF specifications.

| Specification                  | Value                  |
|-------------------------------|------------------------|
| Center frequency              | 5.0 GHz                |
| Equal ripple bandwidth        | 3.2% (160 MHz)         |
| Ripple                        | 0.01 dB                |
| Substrate Relative dielectric constant | 9.68                  |
| Thickness                     | 0.5 mm                 |
| Superconductor Thickness      | 0.5 µm                 |

Figure 4. Circuit pattern for compact HTS BPF employing CPW quarter-wavelength resonators with strongly-coupled open stubs.

Figure 5. Original equivalent circuit of four-pole HTS BPF.
decided theoretically as $Q_{e1} = Q_{e4} = 22.3$, $k_{12} = k_{34} = 3.46\%$, and $k_{23} = 2.54\%$, if there is no undesired coupling such as $k_{13}$, $k_{24}$, and $k_{14}$ [9].

Figure 6 shows the variation in the external Q ($Q_e$) and resonant frequency ($f$) versus the open-end gap ($g$). From the figure, $g_1$ and $g_4$ in figure 4 are set to 0.08 mm and the resonant frequency is almost 4.8 GHz. Figure 7 shows the coupling coefficient versus the distance between two resonators ($d$). Distances $d_{12}$, $d_{34}$, and $d_{23}$ in figure 4 are set to 0.30 mm, 0.30 mm, and 0.60 mm, respectively.

In the actual design, however, there exist undesired couplings, $k_{13}$, $k_{34}$, or $k_{14}$. Taking these into account, all the dimension parameters of the HTS BPF are repeatedly tuned until the frequency responses obtained by the electromagnetic simulator satisfy the design specifications. As a result, the final dimensions $d_{12}$, $d_{34}$, $d_{23}$, $l_1$, and $l_2$ in figure 4 are set to 0.33 mm, 0.33 mm, 0.54 mm, 1.54 mm and 1.64 mm, respectively. In figure 4, the longitudinal length is 15 mm for the proposed four-pole HTS BPF while it is 30 mm for the conventional filter where the straight quarter-wavelength resonators are assigned serially.
4. Filter fabrication and test results

Figure 8 is a photograph of the fabricated HTS BPF. This filter is fabricated on Yttrium Barium Copper Oxide (YBCO) film on a Magnesium Oxide (MgO) substrate with a relative dielectric constant of 9.68 and thickness of 0.5 mm. The details of the filter fabrication procedure are described in [5].

Table 2, figure 9, and figure 10 show the frequency responses of the fabricated HTS BPF at 60 K. The solid lines in figures 9 and 10 represent the measured characteristics of $|S_{11}|$ and $|S_{21}|$. The dashed lines represent the calculated results from the electromagnetic simulator. The measured characteristics agree
well with the simulated characteristics. The upward shift in the center frequency of 11 MHz is considered to originate from the difference in the dielectric constant between the MgO substrate used in fabricating the proposed filter and the computer simulation design.

5. Conclusion
A CPW quarter-wavelength resonator with strongly-coupled open stubs was proposed in order to miniaturize the HTS BPF. A 5-GHz band four-pole CPW HTS BPF was designed and fabricated for the purpose of investigating the validity of the proposed resonator. The CPW HTS BPF achieved over 50% reduction in the longitudinal length compared to the conventional filter without any degradation in frequency characteristics.

References
[1] Narahashi S, Satoh K, Kawai K, Koizumi D and Nojima T 2006 Supercond. Sci. Technol. 19 S416-S422
[2] Simon R W, Hammond R B, Berkowitz S J and Willemsen B A 2004 Proc. of the IEEE 92 1585-1596
[3] Nojima T, Narahashi S, Mimura T, Satoh K and Suzuki Y 2000 IEICE Trans. Commun. E83-B 1834-43
[4] Klauda M, Kässer T, Mayer B, Neumann C, Schnell F, Aminov B, Baumfalk A, Chaloupka H, Kolesov S, Piel H, Klein N, Schornstein S and Bareiss M 2000 IEEE Trans. Microwave Theory Tech. 48 1227-39
[5] Tsujiguchi T, Mathsumoto H and Nishikawa T 1998 IEEE MTT-S Int. Microwave Symp. Dig. 829-832
[6] Ma Z, Suzuki H, Kobayashi Y, Satoh K, Narahashi S and Nojima T 2002 IEEE MTT-S Int. Microwave Symp. Dig. 1967-70
[7] Kawai K, Satoh K, Narahashi S, Ma Z and Kobayashi Y 2004 Proc. 34th European Microwave Conf. (Amsterdam The Netherlands) 1109-12
[8] Koizumi D, Satoh K and Narahashi S 2006 Proc. IEEE Radio and Wireless Symp. 583-586
[9] Maataei G, Young L and Jones E M T 1980 Microwave Filters, Impedance-Matching Networks, and Coupling Structures (Norwood, MA: Artech House)