High-temperature superconducting coplanar-waveguide quarter-wavelength resonator with odd- and even-mode resonant frequencies for dual-band bandpass filter

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Abstract. This paper presents a high-temperature superconducting coplanar-waveguide quarter-wavelength resonator that has two different resonant modes for use in a dual-band bandpass filter (DBPF). An RF filter with multiple passbands such as the DBPF is a basic element that is expected to achieve broadband transmission by using separated frequency bands aggregately and simultaneously in future mobile communication systems. The proposed resonator has a folded center conductor and two open stubs that are aligned close to it. The odd- and even-mode resonant frequencies are configured using the space between the folded center conductor and the open stubs. It is easy to configure the odd- and even-mode coupling coefficients independently because the two resonant modes have different current density distributions. Consequently, a DBPF with two different bandwidths can be easily designed. This paper presents three design examples for a four-pole Chebyshev DBPF with different combinations of fractional bandwidths in order to investigate the validity of the proposed resonator. This paper also presents measured results of the DBPF based on the design examples from the standpoint of experimental investigation. The designed and measured frequency responses confirm that the proposed resonator is effective in achieving DBPFs not only with two of the same bandwidths but also with two different bandwidths.

1. Introduction

In future mobile communication systems, wideband transmission technologies will be required to achieve high-capacity data transmission capabilities. It is, however, difficult to reserve a broad frequency band in order to achieve wideband transmission because most frequency bands suitable for radio communication systems have already been assigned to various systems such as TV broadcasting, mobile communications, and Wireless LANs. Frequency reallocation is one solution to reserve a broad frequency band. However, this approach is very time consuming. Spectrum aggregation technology, which aims at using different frequency bands aggregately and simultaneously, has been investigated as a solution to attain wideband transmission [1]. A multiband filter that has multiple passbands is a basic device that supports spectrum aggregation technology.

Dual-band bandpass filters (DBPFs) have been reported as the first step in configuring multiband filters [2], [3]. In [2], Sun et al. reported on a DBPF based on half wavelength stepped-impedance
resonators. This DBPF is suitable for configuring the same fractional bandwidths (BW) in two passbands. The coupling configuration in the DBPF increases the latitudinal length of the filter when the two passbands have two different fractional BWs. In [3], Guan et al. reported on a DBPF that achieves two passbands, 1.8 GHz and 2.4 GHz bands, based on quarter wavelength resonators and J-inverters. A transmission zero at approximately 2.1 GHz produces sharp and large attenuations between the two passbands. However, this filter requires a large area because of its structural property of open stubs, which makes it difficult to reduce the size of the DBPF.

Radio communication system specifications are specified based on not only its own system requirements but also on the circumstance of the other wireless systems such as the assignment of each base station, transmission power of each base station transmitter, and frequency spacing between two radio communication systems. Accordingly, a multiband filter is required to have sharp-skirt characteristics at the band-edge, high degree of attenuation in the stopbands, and low insertion losses in the passbands. A high temperature superconducting (HTS) filter is one of the candidates to satisfy these requirements for configuring a multiband filter.

A cryogenic receiver front-end (CRFE) [4-8], which comprises a HTS filter, a cryogenic low noise amplifier (CLNA), and a cryostat, is proposed to enhance mobile communication systems from the perspective of efficient frequency utilization and improving the base station receiver sensitivity. From the standpoint of easy installation, the CRFE must be small because the CRFE is located directly under the base station antenna. The HTS filter, cryogenically cooled by the cryostat, must also be compact in order to reduce the size of the cryostat. This is because reducing the cooling capability of the cryostat leads to miniaturization of the CRFE. It is not appropriate to construct compact HTS multiband filters based on the design method in [2] since the filter size becomes large if the multiband filter has two passbands with different fractional BWs. It is difficult to design compact HTS multiband filters with the method in [3] because the structure is characterized such that open stubs are assigned vertically with respect to the input-output line.

This paper presents a design method for a DBPF and compact HTS-DBPF that uses a new coplanar-waveguide (CPW) quarter-wavelength (λ/4) resonator with open stubs [9-11], which generates two resonant frequencies: one is odd- and the other is the even-mode frequency. The proposed HTS-DBPF is almost half the size compared to those designed by the conventional method [2] for not only the same but also different fractional BWs. This paper evaluates the validity of the proposed method by designing a DBPF with the same fractional BWs and two kinds of different fractional BWs in two passbands, by fabricating a 4-pole Chebyshev 2.0-/3.5-GHz band DBPF using a YBCO thin film deposited on a MgO substrate, and by measuring the frequency responses of the fabricated DBPF. This paper also discusses the difference in the frequency responses between electromagnetic simulation and measured results.

2. Proposed filter

Figure 1 shows a CPW-λ/4 resonator with open stubs. The open stubs (denoted by a and b) are aligned close to the folded center conductor (denoted by c) of the λ/4 resonator. The proposed resonator has two mode resonant frequencies: one is the odd mode frequency for the lower passband of the two

![Figure 1. CPW-λ/4 resonator with open stubs.](image-url)
passbands, and the other is the even mode frequency for the upper passband (hereinafter referred to as a dual-band resonator (DBR)). These two resonant modes have different current flows (denoted by $i_o$ and $i_e$ for the odd and even modes, respectively) on the short stub (denoted by $d$). It is easy to configure independently the coupling coefficients for the lower and upper passbands when the short sides of the resonators face each other.

Figure 2 shows the equivalent circuit of the four-pole DBPF. Adjacent resonators are coupled with the appropriate strength as denoted by $k_{A12}$, $k_{A23}$, and $k_{A34}$ for lower passband $A$, and $k_{B12}$, $k_{B23}$, and $k_{B34}$ for upper passband $B$. Consequently, a coupled-resonator structure requires that each coupling coefficient ($k_{Aij}$ and $k_{Bij}$) be configured independently. The input/output (I/O) line and resonator are also coupled with the appropriate strength as defined by the external $Q$ ($Q_{Ae1}$, $Q_{Ae2}$, $Q_{Be1}$, and $Q_{Be2}$).

In general, it is difficult to set only one coupling coefficient for dual passbands in coupled DBRs. Figure 3(a) shows the relationship between the coupling coefficients for the lower passband ($k_{A23}$) and the upper passband ($k_{B23}$) regarding the distance between the two resonators ($d_{23}$) and the length of the short stub ($y$) when the short sides of the DBRs face each other. Parameter $y$ represents the design freedom of the coupling coefficients because parameter $k_A$ decreases with an increase in parameter $k_B$ as represented by the solid line with filled circle plots and dashed-dotted line with filled triangle plots in figure 3(a).

Figure 3(b) shows the relationship between coupling coefficients $k_{A12}$ ($= k_{A34}$) and $k_{B12}$ ($= k_{B34}$) regarding the distance between the two resonators, $d_{12}$, and the space between the center conductor and the open stubs ($x$) when the open sides of the DBRs face each other. The solid line with the filled circle plots and the dashed-dotted line with the filled triangle plots in figure 3(b) indicate a similar tendency compared to those in figure 3(a).

Figure 3. Relationship between coupling coefficients $k_A$ and $k_B$ (a) When the short sides of the DBRs face each other (b) When the open sides of the DBRs face each other.
Figures 3(a) and 3(b) determine the dimension parameters of a part of the DBPFs such as the distance between the two resonators. The DBPFs constructed based on the results from figures 3(a) and 3(b) are optimized using an electromagnetic simulator. This is because undesired coupling occasionally occurs when the DBRs and I/O coupling section are arranged serially.

Table 1. Summary of calculated frequency responses for 2.0-/3.5-GHz DBPFs.

| Parameter                  | 2.0/3.9%-BW DBPF | 3.0/2.1%-BW DBPF | 3.1/3.0%-BW DBPF |
|----------------------------|------------------|------------------|------------------|
| Center frequency           | 1.95/3.45 GHz    | 1.94/3.49 GHz    | 1.95/3.62 GHz    |
| Equal ripple bandwidth     | 2.0/3.9% (39/133 MHz) | 3.0/2.1% (59/75 MHz) | 3.1/3.0% (60/109 MHz) |
| Minimum insertion loss     | 0.13/0.03 dB     | 0.22/0.03 dB     | 0.21/0.03 dB     |
| Average insertion loss     | 0.24/0.07 dB     | 0.74/0.04 dB     | 0.63/0.13 dB     |

Figure 4. Comparison of calculated frequency responses between 2.0/3.9%-BW DBPF, 3.0/2.1%-BW DBPF, and 3.1/3.0%-BW DBPF.
Table 1, figure 4, and figure 5 show the three examples of the designed four-pole Chebyshev DBPFs. The first has the center frequencies of 1.95/3.45 GHz, 0.33/0.12-dB passband ripples, and 2.0/3.9% (39/133 MHz) equal ripple BWs (as denoted by 2.0/3.9%-BW DBPF). The second example has the center frequencies of 1.94/3.49 GHz, 1.13/0.01-dB passband ripples, and 3.0/2.1% (59/75 MHz) equal ripple BWs (as denoted by 3.0/2.1%-BW DBPF). The third example has the center frequencies of 1.95/3.62 GHz, 1.35/0.23-dB passband ripples, and 3.1/3.0% (60/109 MHz) equal ripple BWs (as denoted by 3.1/3.0%-BW DBPF). The total length and width of the DBPFs are 35.5 mm and 5.4 mm, respectively. The proposed 4-pole DBPF has an area of 192 mm², whereas the conventional 2-pole DBPF has an area of 366 mm².

3. Filter fabrication and measured results

3.1. Fabrication

To investigate the validity of the proposed filter, a four-pole Chebyshev DBPF with 2.0/3.9% BWs was fabricated [4]. Figure 6 is a photograph of the 2.0/3.9%-BW DBPF using an Yttrium Barium Copper Oxide (YBCO) film deposited on a 0.5-mm-thick Magnesium Oxide (MgO) substrate. Photolithography and ion milling are used in the fabrication process. The details of the filter fabrication procedure are described in [12].

Figure 5. Configuration of 2.0-/3.5-GHz DBPFs.

Figure 6. Photograph of 2.0/3.9%-BW DBPF.
3.2. Frequency responses

Figures 7(a), 7(b), 7(c), and table 2 show the frequency responses of the fabricated four-pole DBPF compared to the electromagnetic simulation results with the relative dielectric constant of 9.68. The measured values are obtained without any tuning procedures after the fabrication. In the 2.0- and 3.5-GHz bands, the upward shift in each center frequency of 5% 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. Figures 8(a), 8(b), and 8(c) show the electromagnetic simulation results with the relative dielectric constant of 9.58 compared to the measured frequency responses as a parameter. The measured values agree well with the calculated ones with a relative dielectric constant of 9.58 [8]. The minimum insertion losses are 0.31 and 0.32 dB in the 2.0- and 3.5-GHz bands, respectively. The proposed DBPF achieves these low insertion losses by using HTS materials even though the proposed resonator comprises a narrow center conductor and narrow open stubs.

**Figure 7.** Measured frequency responses for 2.0/3.5%-BW DBPF at 60 K (\(\varepsilon_r = 9.68\)).

**Figure 8.** Measured frequency responses for 2.0/3.9%-BW DBPF at 60 K (\(\varepsilon_r = 9.58\)).
4. Conclusion
This paper presented a compact 4-pole Chebyshev 2.0-/3.5-GHz band HTS-DBPF based on the proposed design method and proposed CPW-λ/4 resonator with open stubs. The proposed DBPF achieved low insertion losses by using HTS materials, although the proposed resonator comprises a narrow center conductor and narrow open stubs. The DBPF is approximately half the size of the conventional DBPF. A DBPF having fractional BWs of 2.0-/3.9% was fabricated using a YBCO-deposited MgO substrate. Measured frequency responses of the DBPF agreed well with the simulation results using an appropriate dielectric constant for the substrate, which confirms the effectiveness of the proposed filter and method in achieving a multipole DBPF. Our next research targets are to investigate the frequency stability against cooling temperature deviation, the linearity to input signals, and the power-handling capabilities of the proposed DBPF from a practical-use perspective.

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Table 2. Summary of frequency responses for 2.0-/3.9%-BW DBPF at 60 K.

| Parameter                     | 2.0-GHz band | 3.5-GHz band |
|-------------------------------|--------------|--------------|
|                               | Measured/Simulated | Measured/Simulated | |
| Center frequency              | 1.96/1.95 GHz  | 3.47/3.45 GHz  | |
| Equal ripple bandwidth        | 2.0/2.0% (40/39 MHz) | 3.9/3.9% (134/133 MHz) | |
| Minimum insertion loss        | 0.31/0.13 dB   | 0.32/0.03 dB   | |
| Average insertion loss        | 0.63/0.24 dB   | 0.39/0.07 dB   | |