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A Low-Loss 5 GHz Bandpass Filter Using HTS Quarter-Wavelength Coplanar Waveguide Resonators

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SUMMARY A new structure of a low-loss high temperature superconducting (HTS) filter is proposed by using quarter-wavelength coplanar waveguide (CPW) resonators. A 4-pole Chebyshev band-pass filter with the center frequency 5.0 GHz and the 0.01 dB-ripple fractional bandwidth 3.2% is designed based on the theory of direct-coupled resonator filters using K- and J-inverters. This filter is fabricated by using a high-T_c superconductive YBCO film deposited on a MgO dielectric substrate. The frequency response of the filter measured at 60 K agrees very well with the theoretical one. The insertion loss is 0.22 dB. The insertion loss of this filter is the lowest in HTS-CPW filters presented so far.

key words: *superconductor, coplanar waveguide, quarter-wavelength resonator, band-pass filter, microwave*

1. Introduction

The microwave filters using HTS film have the advantages of low-loss, small-size and steep skirt slope characteristics. They are expected to be useful for applications to base stations of mobile communication systems. Many HTS microstrip filters have been developed so far. Compared to these microstrip filter structures, coplanar waveguide (CPW) filter structures are expected to offer the advantages of cost-effective chip processing and easy integration with active devices, because the CPW structure has a HTS film on only one side of the substrate. A High-Q CPW half-wavelength resonator has been reported in [1]. Few papers have been published for HTS filters using CPW half-wavelength resonators [2]–[4]. For these filters, however, low loss characteristics have not been realized, because of radiation loss from the curve sections and excess loss by the conductor airbridges used to suppress the parasitic even mode of CPW.

In this paper, a new structure using HTS CPW quarter-wavelength resonators is proposed to realize low insertion loss. In this filter structure, we do not use airbridges which cause the excess conductor loss and curve sections which cause the radiation loss. The quarter-wavelength resonators are available to realize multi-stage filters because they have half length compared with the half-wavelength resonators. A 4-pole Chebyshev band-pass filter with the center frequency 5.0 GHz and the 0.01 dB-ripple fractional bandwidth 3.2% is designed based on the theory of direct-coupled resonator filters using K- and J-inverters. The validity of the design theory will be verified by frequency characteristics measured for the fabricated filter.

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2. Filter Structure

A structure of a 4-pole BPF using CPW quarter-wavelength resonators is shown in Fig. 1. This filter is constructed by using a high-T_c superconductive YBCO film with the thickness 0.5 μm deposited on a MgO dielectric substrate. The MgO substrate has a dielectric constant $\varepsilon_r = 9.68$ at 77 K and the thickness $h = 0.5$ mm. This filter is inserted into a Cu conductor package, where the cross sectional dimensions are 5.4 mm × 8.0 mm to construct a TE_{10} mode cutoff waveguide. The distances between the CPW and the top of the package, and between the substrate and the bottom of the package are 4.5 mm and 3.0 mm, respectively.

The influence of thickness and kinetic inductance of a YBCO film is neglected in this design. The width of the center line is 0.218 mm and the distance between the two grand planes is 0.400 mm, so that the characteristic impedance Z_0 is 50 Ω. Each of the lengths l_1 to l_4 is approximately one quarter wavelength for the CPW dominant mode. One end of the resonator is terminated by an open gap and the other end is terminated by a short-circuited stub. Couplings between the input port

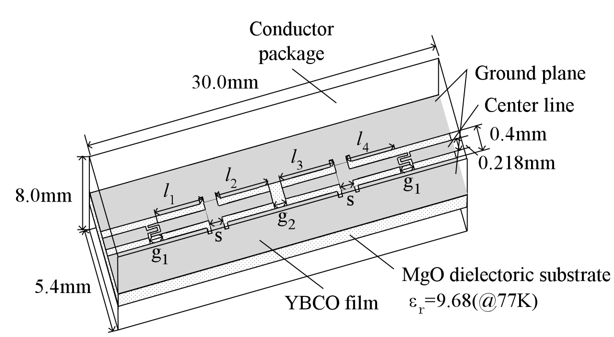


Fig. 1 Structure of 4-pole BPF using CPW quarter-wavelength resonators.

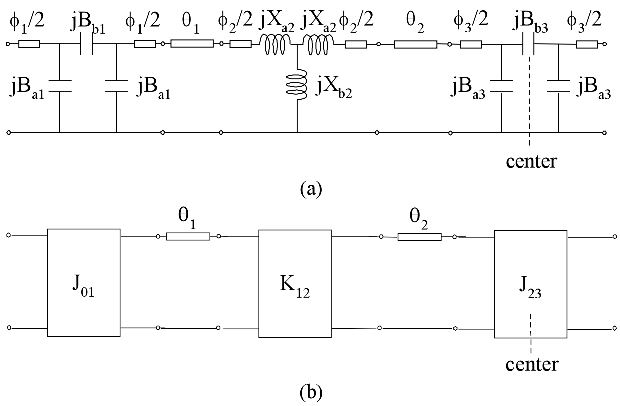


Fig. 2 Equivalent circuits of 4-pole quarter-wavelength resonator filter.

and the first resonator and between the second and the third resonator are performed capacitively. Coupling between the first and the second resonator is performed inductively.

The equivalent circuit is shown in Fig. 2(a), which indicates only a half because of the symmetrical structure. Each of the resonators in the equivalent circuit is represented by a uniform transmission line of electrical length $\theta_i = \pi/2$ $(i = 1, 2, 3, 4)$. The open gaps are represented by the equivalent Π-type circuits of the capacitances. Following the design method of direct-coupled resonator filters [5], we can realize J-inverters by adding the uniform transmission lines of electrical length ϕ_i to both sides of the Π-type circuits. The short-circuited stubs are represented by equivalent T-type circuits of inductances. K-inverters are realized in a similar way to the J-inverters. The equivalent circuit is transformed as shown in Fig. 2(b) by using J_{01}, J_{23}, J_{45} inverters and K_{12}, K_{34} inverters.

3. Design of 4-Pole Filter

When a center frequency f_0, a ripple width RW, and a fractional ripple pass-band width $\Delta f/f_0$ are given as this 4-pole filter specification, the design procedure is given as follows:

(A) Design of open gap

An open gap structure for J_{23} is shown in Fig. 3(a). Reference planes T_1 and T_2 shown in the figure correspond to the input and the output port of the equivalent Π-type circuit, respectively. The scattering parameters with different gap width g_2 are computed at T_1 and T_2, by using 2.5 dimensional electromagnetic simulator SONNET em [7]. From the computed scattering parameters, we obtain element values B_a and B_b of the equivalent Π-type circuit from

$$jB_a = \frac{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21} - 2S_{12}}{\Delta} \tag{1}$$

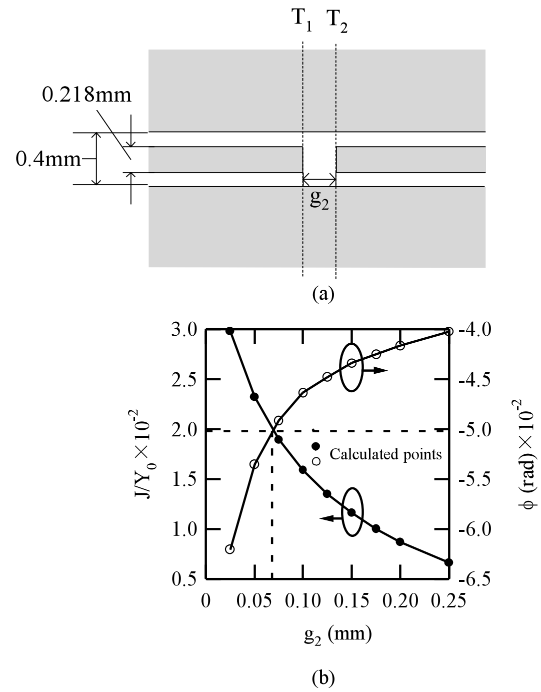


Fig. 3 (a) Structure of open gap. (b) J/Y_0 and ϕ vs. gap width g_2.

$$jB_b = \frac{2S_{21}}{\Delta}, \tag{2}$$

where

$$\Delta = (1 + S_{11})(1 + S_{22}) - S_{12}S_{21} \tag{3}$$

From these values, values of ϕ and J/Y_0 in the J-inverter are calculated from [5]

$$\phi = -\tan^{-1}\left(\frac{2B_b}{Y_0} + \frac{B_a}{Y_0}\right) - \tan^{-1}\left(\frac{B_a}{Y_0}\right) \tag{4}$$

$$\frac{J}{Y_0} = \left|\tan\left\{\frac{\phi}{2} + \tan^{-1}\left(\frac{B_a}{Y_0}\right)\right\}\right| \tag{5}$$

where $Y_0 = 1/Z_0$. These values calculated as a function of the gap width g_2 are shown in Fig. 3(b). The solid and open dots in the figure indicate the calculated points.

(B) Design of interdigital gaps

We require coupling values for J_{01} and J_{45} about 10 times greater, compared with one for J_{23}, as mentioned below. Then, interdigital gaps with fixed finger spacing 0.025 mm and 0.018 mm were used as shown in Fig. 4(a) to realize the greater coupling values for J_{01} and J_{45}. In the interdigital gaps, right and left shunt capacitances of the equivalent Π-type circuit are not equal, because of the asymmetrical structure of left and right hand sides. We first put the reference plane T_2 at the location indicated in Fig. 4(a). Then, to obtain the symmetrical equivalent Π-type circuit, the reference plane

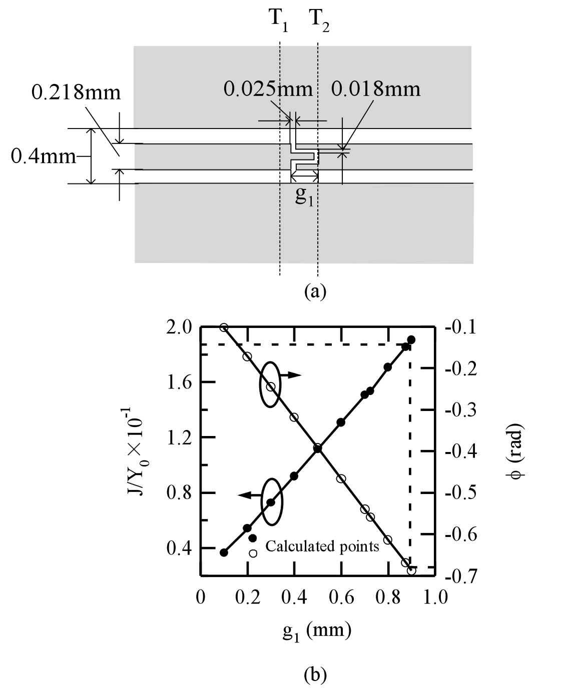


Fig. 4 (a) Structure of interdigital gap. (b) J/Y_0 and ϕ vs. gap width g_1.

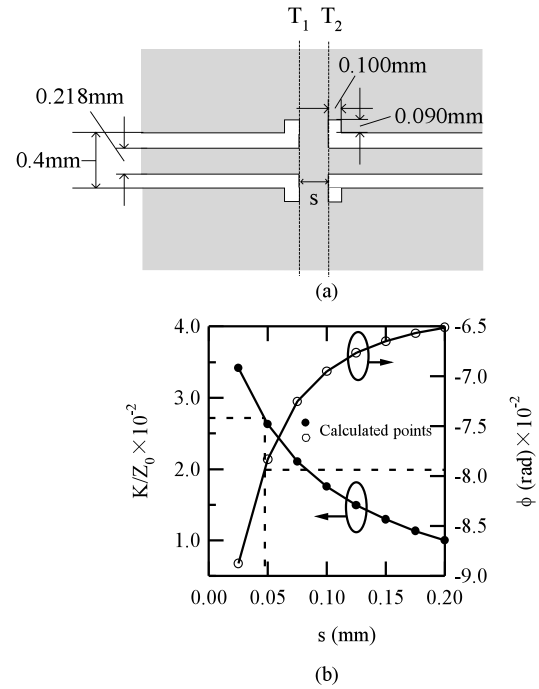


Fig. 5 (a) Structure of short-circuited stub. (b) K/Z_0 and ϕ vs. stub width s.

T_1 is determined from

$$T_1 = T_2 - \frac{\angle(S_{11}) - \angle(S_{22})}{8\pi}\lambda_{eff}, \tag{6}$$

where λ_{eff} is an effective wavelength in the CPW at f_0. Values of ϕ and J/Y_0 are calculated from (1)–(5). These values calculated as a function of the gap width g_1 are shown in Fig. 4(b).

(C) Design of short-circuited stubs

Short-circuited stub for K_{12} and K_{34} are shown in Fig. 5(a). The stub has a fixed slot with its width 0.100 mm and depth 0.090 mm to obtain a greater K/Z_0 value. Reference planes T_1 and T_2 shown in the figure correspond to the input and the output port of the equivalent T-type circuit. The scattering parameters with different stub width s are computed at T_1 and T_2. From the computed scattering parameters, we obtain element values X_a and X_b of the equivalent T-type circuit from

$$jX_a = \frac{(1+S_{11})(1-S_{22}) + S_{12}S_{21} - 2S_{12}}{\Delta} \tag{7}$$

$$jX_b = \frac{2S_{21}}{\Delta}, \tag{8}$$

where

$$\Delta = (1-S_{11})(1-S_{22}) - S_{12}S_{21} \tag{9}$$

From these values, values of ϕ and K/Z_0 in the K-inverter are calculated from [5]

$$\phi = -\tan^{-1}\left(\frac{2X_b}{Z_0} + \frac{X_a}{Z_0}\right) - \tan^{-1}\left(\frac{X_a}{Z_0}\right) \tag{10}$$

$$\frac{K}{Z_0} = \left|\tan\left\{\frac{\phi}{2} + \tan^{-1}\left(\frac{X_a}{Z_0}\right)\right\}\right| \tag{11}$$

These values calculated as a function of the stub width s are shown in Fig. 5(b).

(D) Determination of resonator length

Actual lengths of the CPW resonators are determined from [5]

$$\theta_i = \frac{\pi}{2} + \frac{1}{2}(\phi_i + \phi_{i+1}), \quad l_i = \frac{\lambda_{eff}}{2\pi}\theta_i \tag{12}$$

where the electrical length ϕ_i is obtained from Figs. 3(b), 4(b) and 5(b), using the J/Y_0 and K/Z_0 values calculated from the filter specifications.

4. Design of 4-Pole Filter Pattern at 5 GHz

A 4-pole Chebyshev bandpass filter is designed with $f_0 = 5.0$ GHz, $RW = 0.01$ dB and $\Delta f/f_0 = 3.2\%$. Using element values g_i of the prototype Chebyshev lowpass filter [5], we determined the J- and K-inverter values in this filter to be $J_{01}/Y_0 = J_{45}/Y_0 = 0.187764$, $K_{12}/Z_0 = K_{34}/Z_0 = 0.0271679$ and $J_{23}/Y_0 = 0.019956$ [5], [6]. Based on the calculated results mentioned above, we obtain $g_1 = 0.885$ mm, $g_2 = 0.070$ mm, $s = 0.045$ mm, $l_1 = l_4 = 4.985$ mm, and $l_2 = l_3 = 6.290$ mm. Dimensions of the filter pattern are shown in Fig. 6.

Frequency responses of the designed filter are

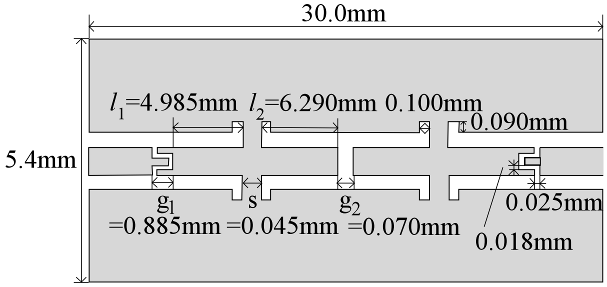


Fig. 6 Dimensions of filter pattern designed.

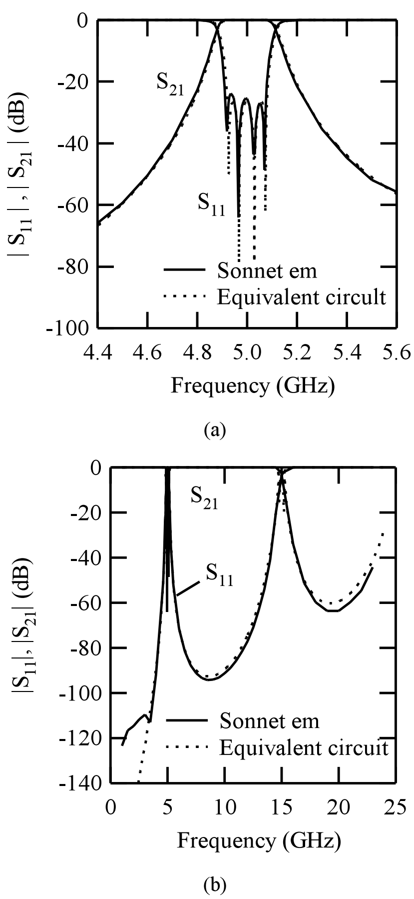


Fig. 7 Simulated frequency responses. (a) Filter response of 4-pole Chebyshev bandpass filter with $f_0 = 5.0$ GHz, $RW = 0.01$ dB and $\Delta f/f_0 = 3.2\%$. (b) Spurious response.

shown in Fig. 7(a). The solid curve indicates the frequency response simulated from the filter pattern shown in Fig. 6 by using SONNET em [7] and the broken curve indicates one calculated from the equivalent circuit shown in Fig. 2(b). The simulated frequency response agrees very well with one calculated from the equivalent circuit. The spurious frequency responses calculated from SONNET em and the equivalent circuit are shown in Fig. 7(b). The second passband appears about $3f_0$, which corresponds to the resonant frequency of the three-fourth-wavelength resonance. No

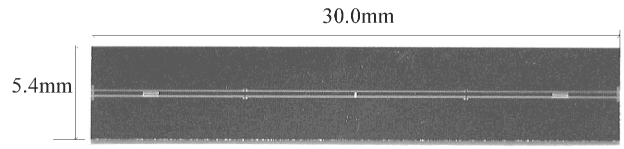


Fig. 8 Photograph of filter pattern fabricated.

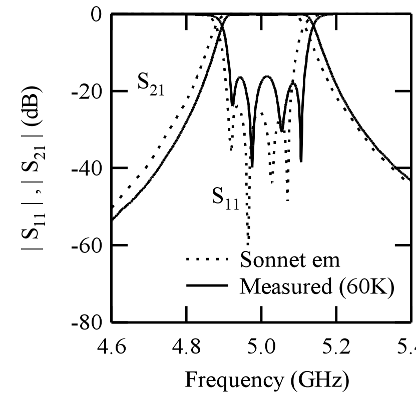


Fig. 9 Measured frequency response.

extra waveguide mode is observed because of the TE_{10} mode cutoff waveguide constructed by the conductor package.

5. Filter Fabrication and Measured Result

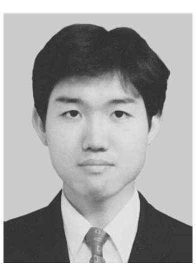
Photo lithography and dry etching processes are used to make the filter pattern. A photograph of the filter is shown in Fig. 8. A pair of air coplanar probes is used in the measurement. The frequency response of the filter measured at 60 K is shown in Fig. 9. The measured frequency response agrees very well with the simulated one. The measured results are $f_0 = 5.02$ GHz and the insertion loss (IL) 0.22 dB at 60 K and $f_0 = 5.00$ GHz and $IL = 0.32$ dB at 77 K. The equivalent unloaded-Q (Q_u) of the resonators calculated from $IL = 0.22$ dB is 4,300, which is much lower, compared with $Q_u = 80{,}000$ reported for 2 GHz microstrip bandpass filter [8]. The following two points are considered as cause of the Q degradation: 1) Surface resistance (R_s) of the superconductor at 5 GHz increases to about 6 times compared with one at 2 GHz because of f^2 characteristic of R_s. Thus, Q_u decrease to one-sixth. 2) Excess loss occur at the edges of the grand planes in the CPW structure.

6. Conclusion

A new structure of a low-loss HTS filter was proposed by using quarter-wavelength CPW resonators. A 5 GHz Chebyshev band-pass filter was designed based on the theory of direct-coupled resonator filters using K- and J-inverters. This filter is fabricated by using a high-T_c superconductive YBCO film deposited on a MgO dielectric substrate. The measured frequency response agrees very well with the theoretical one, and the validity of the design theory was verified. The insertion loss of this filter was the lowest in HTS-CPW filters presented so far. Finally, the 5 GHz bandpass filter of this structure can be constructed up to a 10-pole filter on a 3-in-diamter YBCO film.

References

[1] T. Konaka, M. Sato, H. Asano, S. Kubo, and Y. Nagai, "High-T_c supercoducting high-Q coplanar resonator made on MgO," IEEE MTT-S Int. Microwave Symp. Dig., vol.3, no.RR-4, pp.1337–1340, June 1991.
[2] K. Yoshida, K. Sashiyana, S. Nishioka, H. Shimakage, and Z. Wang, "Design and performance of miniaturized superconducting coplanar waveguide filters," IEEE Trans. Appl. Supercond., vol.9, no.2, pp.3905–3908, June 1999.
[3] R. Weigel, M. Nalezinski, A.A. Valenzuela, and P. Russer, "Narrow-band YBCO superonducting parallel-coupled coplanar waveguide band-pass filters at 10 GHz," IEEE MTT-S Int. Microwave Symp. Dig., vol.3, no.LL-5, pp.1285–1288, June 1993.
[4] J.K.A. Everard and K.K.M. Cheng, "High performance direct coupled bandpass filters on coplanar waveguide," IEEE Trans. Microwave Theory & Tech., vol.41, no.9, pp.1568–1573, Sept. 1993.
[5] G.L. Matthaei, L. Young, and E.M.T. Jones, Microwave Filters, Impedance-Matching Networks, and Coupling Structures, pp.97–104, pp.464–472, McGraw-Hill, New York, 1964.
[6] Z. Ma, Y. Takiguchi, H. Suzuki, and Y. Kobayashi, "Design of two types of millimeter wave filters using coplanar waveguide structures," Asia-Pacific Microwave Conference Proceedings (APMC'2000), pp.516–519, Dec. 2000.
[7] Em, Electromagnetic Analyzing Software, Sonnet Software Inc., ver.6.0, Liverpool, NY, 1998.
[8] G. Tsuzuki, M. Suzuki, and N. Sakakibara, "Superconducting filter for IMT-2000 band," IEEE Trans. Microwave Theory & Tech., vol.48, no.12, pp.2519–2525, Dec. 2000.



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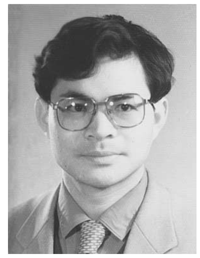

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