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

Zhewang Ma, Hideyuki Suzuki, and Yoshio Kobayashi
Department of Electrical and Electronic Systems, Saitama University, Japan
Kei Satoh, Shoichi Narahashi, and Toshio Nojima
Wireless Laboratories, NTT DoCoMo Inc., Japan

***Abstract* — A novel low-loss high temperature superconductor (HTS) filter is proposed by using coplanar waveguide quarter-wavelength resonators. A 4-pole Chebyshev bandpass filter with a center frequency 5.0GHz and a 0.01dB-ripple fractional bandwidth 3.2% is designed and fabricated using a YBCO film deposited on a MgO substrate. The frequency response of the filter measured at 60K agrees very well with the theoretical prediction. The measured insertion loss is 0.22dB, the lowest reported so far for HTS coplanar waveguide filters.**

I. INTRODUCTION

Microwave filters using HTS films are attractive for a number of applications, like the base stations of mobile communication systems, because they are low-loss, small-size and own sharp skirt characteristics. Various types of HTS filters using microstrip lines have been reported. Compared with microstrip lines, coplanar waveguides (CPW) offer the advantages of cost-effective chip processing and easy integration with active devices because they do not require any backside film and via-hole processes. However, there are only a small number of publications on HTS CPW filters, and the reported insertion loss characteristics were poor. In [1]-[5], CPW filters using half-wavelength resonators were developed, but the insertion loss was unfavorably large. The loss was mainly attributed to the radiation occurred at curved parts of the filter, and to the loss caused by the metal air-bridges used to suppress the parasitic CPW modes.

In this paper, a novel HTS filter using CPW quarter-wavelength resonators is proposed, and a low insertion loss is realized. The filter, as shown in Fig. 1, consists of cascaded quarter-wavelength resonators that are aligned in a straight line. The resonators are coupled through capacitive gaps or short-circuited inductive stubs. The short-circuited stubs act also the role of air-bridges. The conductor loss of air-bridges and the radiation loss associated with curved structures are avoided thereby in this filter structure. The length of the filter is half that of the filter using half-wavelength resonators. A 4-pole Chebyshev band-pass filter (BPF) with a center frequency 5.0GHz and a 0.01dB-ripple fractional bandwidth 3.2% is designed and fabricated. The measured frequency response of the filter, without any post tuning, agrees quite well with the predicted one. An insertion loss of 0.22dB at 60K is realized.

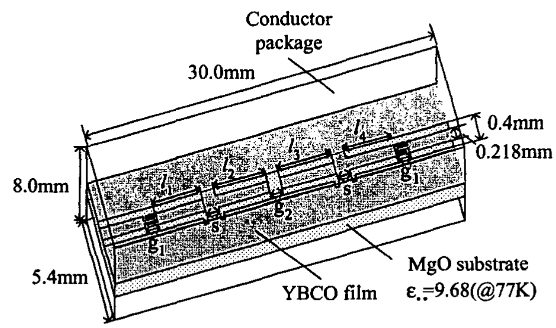


Fig. 1. Structure of a 4-pole BPF using CPW quarter-wavelength resonators.

II. FILTER STRUCTURE

The 4-pole BPF using CPW quarter-wavelength resonators, as shown in Fig. 1, is designed using a HTS YBCO film deposited on a MgO substrate. The thickness of the YBCO film is 0.5μm. The MgO substrate has a dielectric constant ε_r=9.68 at 77K and a thickness 0.5mm. The filter is shielded by a Copper box with cross sectional dimensions 5.4mm×8.0mm. The distance between the CPW film and the top of the package is 4.5mm, and is 3.0mm between the substrate and the bottom of the package. The dimensions of the shielding box are chosen to avoid package resonance in the frequency range of our interest.

The coplanar waveguide is designed to have a characteristic impedance Z_0=50 Ω. The central strip width is chosen as 0.218 mm, and the distance between the two grand planes is 0.400mm. The influence of the thickness and the kinetic inductance of the YBCO film are ignored in the design. The length l_i of each of the resonators is approximately one quarter-wavelength of the dominant CPW mode. One end of the resonator is terminated by an open gap and the other by a short-circuited stub. The

 2002 IEEE MTT-S Digest

relatively strong coupling between the resonator and the input/output feed line is realized by using inter-digital capacitive gaps, and the coupling between the second and the third resonators by a simple open-ended capacitive gap. The coupling between the first and the second resonators is controlled by using a short-circuited inductive stub.

III. FILTER DESIGN

The equivalent circuit of the filter is shown in Fig. 2(a), which is drawn half only in consideration of the symmetry of the filter structure. Each of the resonators is represented by an uniform transmission line of electrical length θ_i (i=1, 2, 3, 4). The open gaps are represented by equivalent Π-type circuits of capacitors, and the short-circuited stubs by T-type circuits of inductors. By adding uniform transmission lines of electrical length $\phi_i/2$ to both sides of the Π-type or T-type circuits, we can realize J- or K-inverters [6]. The equivalent circuit of the filter with J- and K-inverters is shown in Fig. 2(b).

When the specifications of a Chebyshev filter, i.e., the centre frequency f_0, the ripple width RW, and the equal-ripple fractional pass-band width $\Delta f/f_0$ are given, the values of the J- and K-inverters in Fig. 2(b) are calculated readily by using the well-known formulas in [6]. From the J and K values of the inverters, we determine the geometrical dimensions of the coupling gaps and the short-circuited stubs. Fig. 3 shows the configuration of an open-ended gap and the variation of J/Y_0 ($Y_0=1/Z_0$) and ϕ versus the gap width g_2. The results are obtained by calculating the scattering matrix [S] or admittance matrix [Y] at the reference planes T_1 and T_2 shown in the figure, using the electromagnetic simulator SONNET em [7]. From the computed [S] or [Y] matrix, we get the element values B_a and B_b of the equivalent Π-type circuit. Then the values of J/Y_0 and ϕ of the J-inverter are calculated from B_a and B_b by using the well-known formulas in [6].

The above open-ended gap is used to realize the inverter J_{23} between the second and the third resonators. Compared with J_{23}, the values of J_{01} and J_{45} (represent coupling between the resonator and the input/output feed lines) are about 10 times larger. To realize this strong coupling, inter-digital gaps with fixed finger spacing 0.025mm and 0.018mm are used as shown in Fig. 4. As the inter-digital gap is an asymmetric structure, the left and right shunt capacitances of the equivalent Π-type circuit are not equal. Then the formulas relating B_a, B_b with J/Y_0 and ϕ, provided in [6] for symmetrical circuits, can not be used directly. To obtain a symmetrical equivalent Π-type circuit, we fix the reference plane T_2 at the location indicated in Fig. 4, and then move the reference plane T_1 by a distance calculated from the following expression:

$$T_1 = T_2 - \frac{\angle(S_{11}) - \angle(S_{22})}{8\pi}\lambda_g, \qquad (1)$$

where λ_g is the wavelength of the dominant CPW mode at f_0. The variation of J/Y_0 and ϕ is calculated as a function of the finger length g_1, and the result is drawn in Fig. 4.

The short-circuited stub shown in Fig. 5 is used to realize K-inverters, K_{12} and K_{34}, in the filter. The stub has a fixed slot width 0.100mm, and a depth 0.090mm. In a

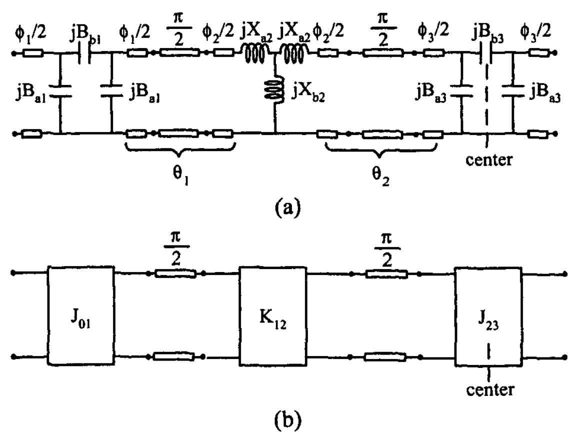


Fig. 2. Equivalent circuits of the 4-pole filter with quarter-wavelength resonators.

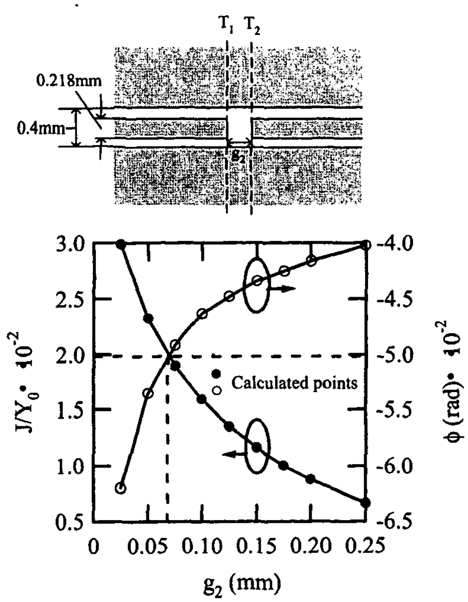


Fig. 3. Configuration of the open-ended gap and the variation of J/Y_0 and ϕ versus the gap width g_2.

similar way described above, we calculate the [S] or [Z] matrix at the reference planes T_1 and T_2 shown in the figure, with different stub width s. From the computed [S] or [Z] matrix, we obtain the element values X_a and X_b of the equivalent T-type circuit. The values of K/Z_0 and ϕ of

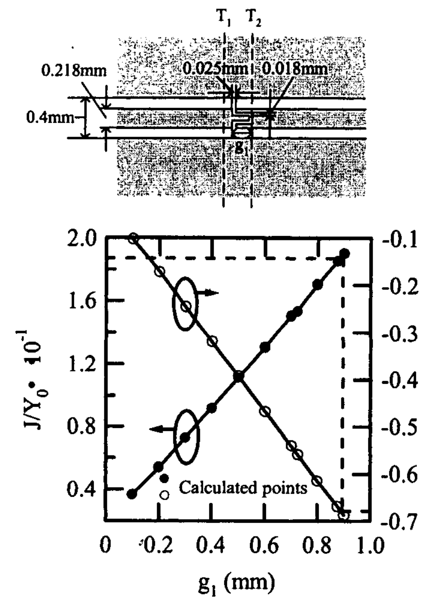


Fig. 4. Configuration of the inter-digital gap and the variation of J/Y_0 and ϕ versus the finger length g_1.

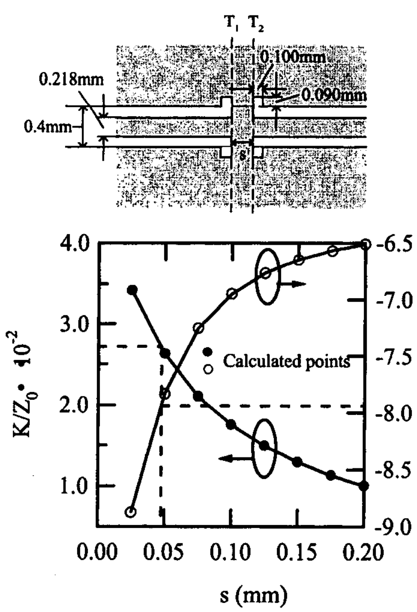


Fig. 5. Configuration of the short-circuited stub and the variation of K/Z_0 and ϕ versus the stub width s.

the K-inverter are calculated by formulas provided in [6]. These values are calculated as a function of the stub width s, and are shown in Fig. 5.

The lengths of the CPW resonators are finally determined by the following expressions [6]:

$$l_i = \frac{\lambda_g}{2\pi}\theta_i, \qquad \theta_i = \frac{\pi}{2} + \frac{1}{2}(\phi_i + \phi_{i+1}), \tag{2}$$

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

A 4-pole Chebyshev bandpass filter is designed with f_0=5.0GHz, RW=0.01dB and $\Delta f/f_0$=3.2%. The values of the J- and K-inverters of this filter are: $J_{01}/Y_0=J_{45}/Y_0=$ 0.187764, $K_{12}/Z_0=K_{34}/Z_0=0.0271679$, and $J_{23}/Y_0=$ 0.019956. From the calculated results provided above, we obtained the dimensions of the filter: g_1=0.885mm, g_2= 0.070mm, s=0.045mm, $l_1=l_4$=4.985mm, and $l_2=l_3$= 6.290mm. The dimensions of the filter pattern are illustrated in Fig. 6.

In Fig 7(a), the solid line is the frequency response of the filter simulated by SONNET em using the dimensions in Fig. 6. It agrees well with the broken line, which is the ideal Chebyshev response calculated from the equivalent circuit shown in Fig. 2(b). The wideband frequency response calculated by SONNET em and the equivalent circuit is shown in Fig 7(b). As expected, the second passband appears at about $3f_0$, which corresponds to the three-fourth-wavelength resonance. No extra package resonance is observed because of our appropriately chosen package dimensions.

IV. Filter Farication and Measurement

The filter designed above is fabricated by using a photolithography and dry etching process. The photograph of the filter is shown in Fig. 8. The frequency response of the filter, without any post tuning, is measured by using a pair of coplanar microprobes and a network analyzer. The measured response at 60K is shown in Fig. 9 by the solid line, and it agrees very well with the predicted one in dashed line. The measured center frequency f_0=5.02GHz with I.L.=0.22dB at 60K, and f_0=5.00GHz with I.L.=0.32dB at 77K. The equivalent unloaded Q_u of the resonators of the filter with I.L.=0.22dB is about 4300.

V. Conclusion

A new structure of a low-loss HTS filter was proposed by using quarter-wavelength CPW resonators. A 5GHz Chebyshev BPF was designed based on the theory of direct-coupled resonator filters using K- and J- inverters. The filter is fabricated by using a YBCO film on a MgO substrate. The measured frequency response agrees very well with the theoretical one. The 0.22 dB insertion loss of this filter is the lowest reported so far for HTS CPW filters. A 10-pole 5GHz BPF of this structure was designed and is now under fabrication. Applications of this type of CPW filter at higher frequencies are also expected.

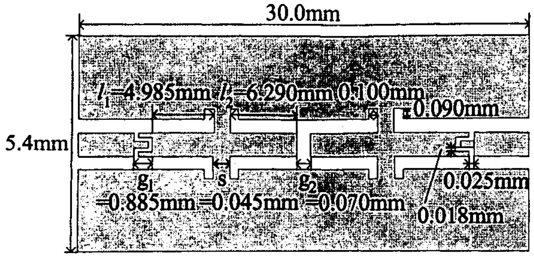
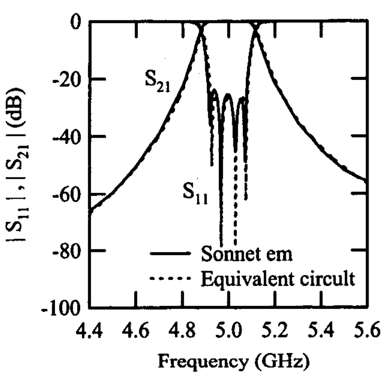
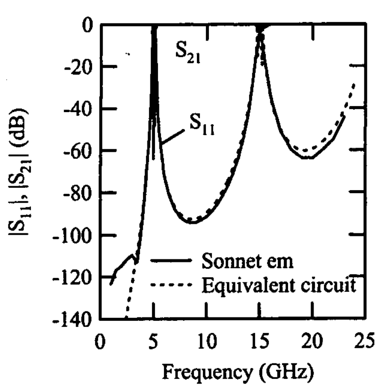


Fig. 6. Dimensions of the 4-pole CPW filter designed.



(a)



(b)

Fig. 7. Simulated frequency response of the filter. (a) Filter response near the pass-band, and (b) wideband response.

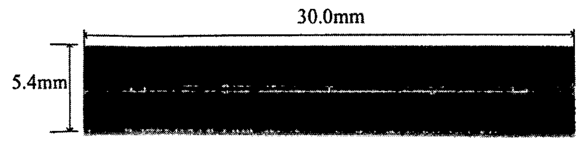


Fig. 8. Photograph of the fabricated HTS CPW filter.

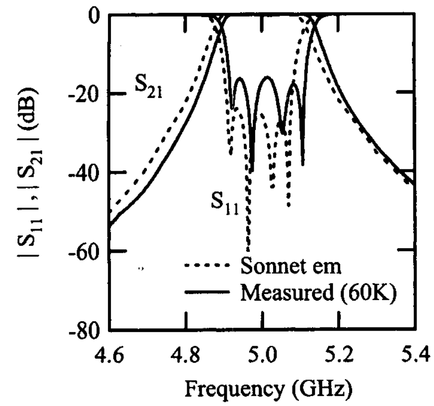


Fig. 9. Comparison of the measured and simulated frequency response of the CPW filter.

REFERENCES

[1] T. Konaka, M. Sato, H. Asano, S. Kubo, and Y. Nagai, "High-Tc supercoducting high-Q coplanar resonator made on MgO," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1337-1340, June 1991.

[2] J. K. A. Everard and K. K. M. Cheng, "High performance direct coupled bandpass filters on coplanar waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-41, pp. 1568-1573, Sept. 1993.

[3] R. Weigel, M. Nalezinski, A. A. Valenzuela, and P. Russer, "Narrow-band YBCO superconducting parallel-coupled coplanar waveguide band-pass filters at 10GHz," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1285-1288, June 1993.

[4] K. Yoshida, K. Sashiyana, S. Nishioka, H. Shimakage, and Z. Wang, "Design and performance of miniaturized superconducting coplanar waveguide filters,• •*IEEE Trans. on Appl. Supercond.*, vol. 9, pp.3905-3908, June 1999.

[5] Z. Ma, Y. Takiguchi, H. Suzuki, and Y. Kobayashi, "Design of two types of millimeter wave filters using coplanar waveguide structures," *2000 Asia-Pacific Microwave Conference Proceedings*, pp. 516-519, Dec. 2000.

[6] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, New York: McGraw-Hill, pp. 97-104, pp. 464-472, 1964.

[7] Sonnet Suite, Release 6.0, Sonnet Software, Inc., Liverpool, NY, 1999.