INVITED PAPER *Special Section on Recent Technologies of Microwave and Millimeter-Wave Devices*

Miniaturized High-Temperature Superconducting Microstrip and Coplanar Waveguide Filters

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SUMMARY Two types of miniaturized high-temperature superconducting filters are described in this paper. The first type is developed by using small-sized microstrip spiral resonators, and the second type by coplanar waveguide quarter-wavelength resonators. The filters have significantly reduced size compared with many previous HTS filters. They are designed by employing an electromagnetic simulator in combination with appropriately chosen equivalent circuits. Their measured frequency responses agree well with theoretical predictions, and show low insertion losses in spite of their small sizes.

key words: *high-temperature superconductor, microstrip spiral resonator, coplanar waveguide, bandpass filter*

1. Introduction

Microwave filters using high temperature superconducting (HTS) films are attractive for a number of applications, like the base stations of mobile communication systems, because they enable great increases in the sensitivity and selectivity of the systems due to the extremely low losses in the materials [1], [2].

In this paper, we report two types of miniaturized HTS filters. The first type is microstrip bandpass filter (BPF) developed by using small-sized microstrip spiral resonators [3]–[10]. Although there have been numerous publications on microstrip HTS filters having various shapes of resonators [1], [2], recent studies show that the dimensions of HTS filters can still be significantly reduced by using microstrip spiral resonators [3]–[10]. In Sect. 2, after a comparison of six types of microstrip spiral resonators in terms of their size, higher order resonance frequencies, and unloaded Q-factors, a 4-pole and an 8-pole BPF using microstrip G-type and S-type spiral resonators are described, respectively.

The second type of HTS filter given in this paper is coplanar waveguide (CPW) BPF developed by using CPW quarter-wavelength resonators [11]–[20]. Compared with microstrip lines, CPWs have generally larger conductor losses. However, they offer the advantages of cost-effective HTS film processing and easy integration with active devices, because they do not require any backside film and via-hole processes. In Sect. 3, a 4-pole BPF using cascaded in-line CPW quarter-wavelength resonators, and a 5-pole CPW interdigital BPF are described. In contrary to most previous CPW filters, no air-bridges are used in CPW filters of this paper, and low insertion losses are realized.

An electromagnetic simulator is used in the design of these filters, in combination with appropriately chosen equivalent circuits. A diagnosis program using a circuit-based optimization algorithm is employed to make accurate and efficient adjustment of the filters [16]. The designed filters are fabricated by using HTS YBCO films deposited on $LaAlO_3$ or MgO substrates, and their measured frequency responses agree well with theoretical predictions.

2. Microstrip Filters Using Small-Sized Spiral Resonators

2.1 Comparison of Six Types of Microstrip Spiral Resonators

Figure 1 shows six types of microstrip spiral resonators [6], [9]. The strip length of each of the spirals equals approximately one half-wavelength of the microstrip line. For convenience, these spiral resonators are named as G-type, S-type, B-type, C-type, rewound, and meander line resonator, respectively. They are designed to resonate at 1.93 GHz by using Sonnet em, a commercial electromagnetic (EM) simulator [21].

Table 1 provides a comparison of the size, higher order resonance frequencies, and unloaded Q-factors of these resonators. A $LaAlO_3$ substrate is used which has a permittivity of 23.84, a loss tangent of 5.3×10^{-7} and a thickness of 0.5 mm. The deposited HTS YBCO film has a thickness of 0.5 μm, a surface resistance of $6.1 \times 10^{-6}\,\Omega$, but its thickness and kinetic inductance are ignored in the design. The strip width of all the resonators is chosen as 0.17 mm, which corresponds to a characteristic line impedance of 50 Ω, and

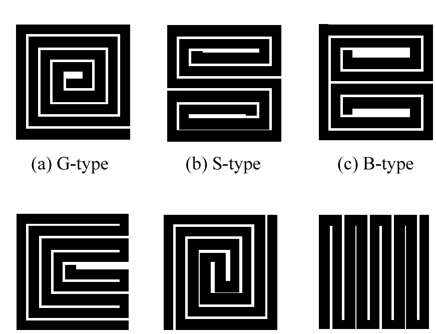

Fig. 1 Six types of microstrip spiral resonators.

Manuscript received March 15, 2005.

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DOI: 10.1093/ietele/e88–c.7.1406

Table 1 Comparison of six types of spiral resonators resonating at f_0=1.93 GHz.

Spiral resonators	Size (mm²)	Second resonance (GHz)	Third resonance (GHz)	Q_u
G-type	3.96	4.51 (2.3f_0)	7.15 (3.7f_0)	94000
S-type	5.52	2.96 (1.5f_0)	5.81 (3.0f_0)	100000
B-type	5.52	2.80 (1.5f_0)	5.44 (2.8f_0)	51000
C-type	8.45	2.85 (1.4f_0)	3.51 (1.8f_0)	40000
Rewound	5.34	2.92 (1.5f_0)	5.99 (3.1f_0)	48000
Meander	10.16	3.47 (1.8f_0)	4.57 (2.4f_0)	40000

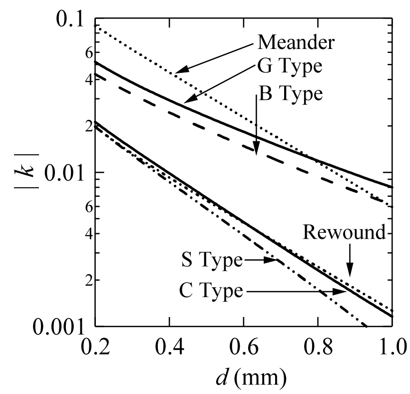


Fig. 2 Variation of the coupling coefficient k versus the distance d between two coupled resonators.

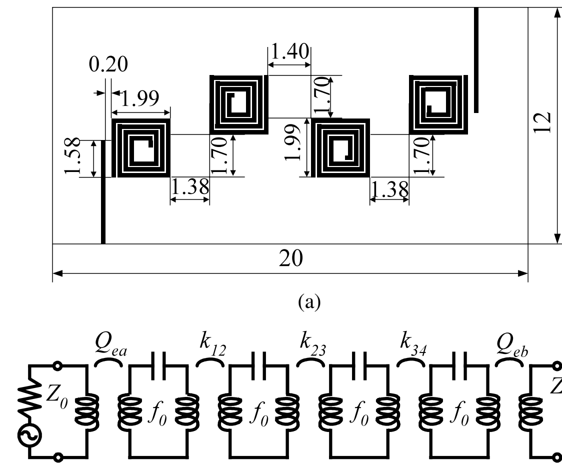


Fig. 3 (a) Configuration of a 4-pole BPF using microstrip G-type spiral resonators. (b) Equivalent circuit of the filter.

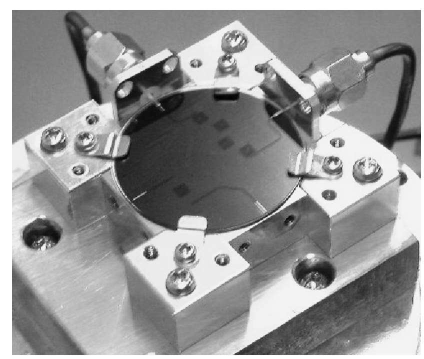


Fig. 4 Photograph of the 4-pole BPF in a test fixture. Microstrip G-type spiral resonators are used in the BPF.

the gap between two neighboring strips is 0.05 mm. Table 1 reveals that the G-type spiral owns the smallest size and widest spurious-free bandwidth. Both the G- and S-type spirals have much larger Q_u values than other four types of spirals.

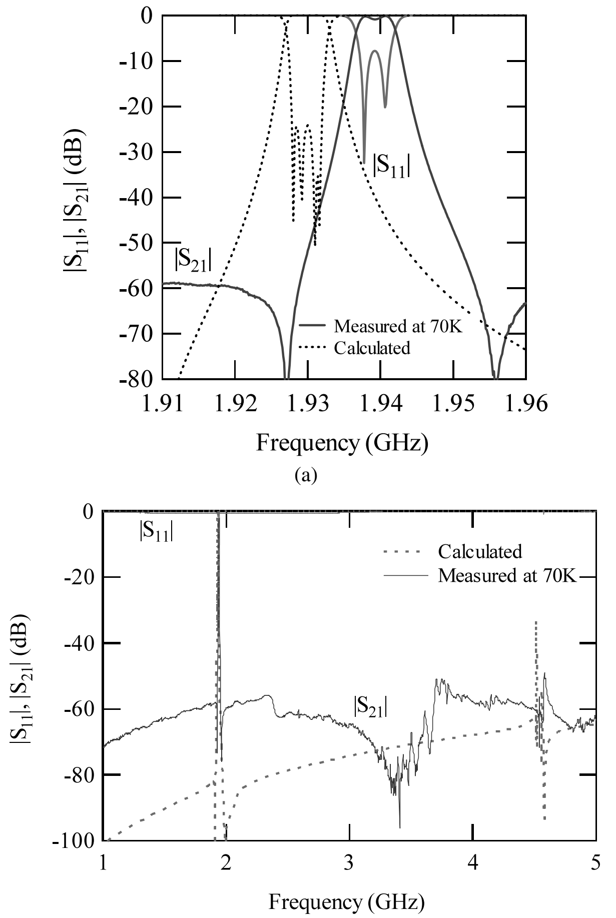
Figure 2 shows a comparison of the coupling coefficients of these resonators. The coupling coefficients are computed as a function of the distance d between two coupled resonators [6], [9]. It is seen that the coupling coefficient of S-type spiral is significantly smaller than that of the G-type spiral.

The above examinations indicate that although a single S-type spiral is larger than a G-type spiral, two neighboring S-type spirals may be arranged closer than G-type spirals in a filter configuration. Therefore, when we try to design a filter with given specifications, we need compare carefully the sizes, Q-factors, as well as the resonant and coupling properties of the spirals in order to choose an appropriate type of spiral.

2.2 BPF Using G-type Spiral Resonators

A 4-pole Chebyshev BPF with a midband frequency of 1.93 GHz, a passband ripple of 0.01 dB, and an equal-ripple fractional bandwidth of 0.212% is designed by using microstrip G-type spiral resonators [7], [8]. The pattern and dimensions of the filter are shown in Fig. 3(a), where the spiral can be made as small as $1.99 \times 1.99\,\text{mm}^2$. The equivalent circuit of the filter is given in Fig. 3(b), where the values of the external Q-values, Q_{ea} and Q_{eb}, and the coupling coefficient $k_{i,i+1}$ $(i = 1, 2, 3)$ are calculated readily using the well-known formulas in [22]. In the design, the midband frequency of the filter is adjusted by varying the lengths of the spirals, and the coupling between two neighboring resonators is adjusted by varying the distance between two spirals. The coupling between the spiral resonator and the input or output line is controlled by adjusting the width of the coupling gap [7], [8].

The filter is fabricated by using HTS YBCO films deposited on a $LaAlO_3$ substrate, and a photograph of it in a test fixture is shown in Fig. 4. The measured narrowband response at 70K is shown in Fig. 5(a). The maximum reflection loss in the passband is about 10 dB. This value is reasonable and satisfactory in view of the inadequate calibration made in the measurement [7], [8]. The transmission zeroes at both sides of the passband are caused by cross-couplings among the spiral resonators. The measured midband frequency of the filter is 1.938 GHz, which is 8 MHz higher than the designed value. From the measured midband frequency, we estimated that the dielectric constant of the



(a)

(b)

Fig. 5 Comparison of the measured and simulated frequency response of the 4-pole BPF using microstrip G-type spiral resonators. (a) Narrowband response. (b) Wideband response.

LaAlO$_3$ substrate is approximately 23.67, 0.8% smaller than its nominal value of 23.87 used in the filter design [7], [8]. Taking into account of the fact that the dielectric constants of LaAlO$_3$ or MgO substrates usually deviate in a range of about 1% [23], the discrepancy between the designed and measured midband frequencies is difficult to avoid. Such a frequency discrepancy is also observed in the following HTS filters of this paper. Therefore, in the development of narrow band HTS filters, frequency-tunable mechanisms are usually required [8], [24].

The wideband response of the filter is measured over 1–5 GHz at 70K, and is depicted in Fig. 5(b). Only a very weak spurious resonance is observed at about 4.6 GHz. This indicates that the filter using G-type spirals owns an excellent property of spurious resonance rejection over a wide frequency range.

2.3 BPF Using S-Type Spiral Resonators

In [9], [10], a 4-pole, an 8-pole, and a 16-pole Chebyshev BPF using microstrip S-type spiral resonators are designed, respectively. The specifications are: midband frequency f_0=1.93 GHz, passband ripple RW=0.1 dB, and equal-ripple fractional bandwidth 1.04% (passband width Δf=20 MHz). Figure 6 shows the configuration of the 8-pole filter. To reduce the size of the spiral resonators, the strip width of all the spirals is reduced from 0.17 mm to 0.1 mm, but that of the input and output feed lines is remained as 0.17 mm to keep a characteristic impedance of 50 Ω. The design process is the same as described above, and the obtained dimensions of the filter are shown in Fig. 6.

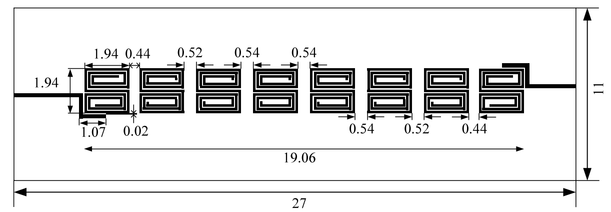


Fig. 6 Configuration of an 8-pole BPF using microstrip S-type spiral resonators.

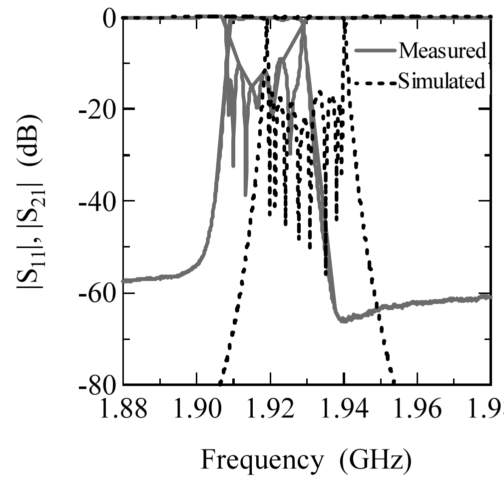


Fig. 7 Comparison of the measured and simulated frequency response of the 8-pole BPF using microstrip S-type spiral resonators.

The measured narrowband response at 70K is shown in Fig. 7, and we get f_0=1.92 GHz, RW=0.4 dB, and a passband width Δf=19 MHz. The minimum insertion loss is 0.07 dB, which indicates that the unloaded Q_u of the spiral resonator reaches a value of about 80,000 [22]. The maximum reflection loss in the passband is about 10 dB. This value is satisfactory, because the reflections occurred between the SMA connectors and the microstrip feed lines of the filter are not removed in the simplified calibration process [9]. The measured midband frequency of the filter is 1.92 GHz, 10 MHz lower than the designed value. The reason is probably that the actual dielectric constant of the LaAlO$_3$ substrate is a little bit larger than 23.40 used in the design. The wideband response of the filter at 70K is measured over 1–6 GHz, and the first spurious resonance appears at about 3 GHz as expected by the EM simulation [10].

3. CPW Filters Using Quarter-Wavelength Resonators

Figure 8(a) shows a 4-pole BPF using CPW in-line quarter-wavelength resonators [15]–[17]. It is designed using an HTS YBCO film deposited on an MgO substrate. The specifications of the 4-pole Chebyshev BPF are: midband frequency f_0=5.0 GHz, passband ripple RW=0.01 dB, and equal-ripple fractional bandwidth 3.2%. The MgO substrate has a dielectric constant ε_r=9.68 at 70K and a thickness 0.5 mm. The filter is shielded by a copper box with cross sectional dimensions 5.4 mm × 8.0 mm. The dimensions of the shielding box are chosen to avoid package resonance in the frequency range of our interest [15].

The length l_i of each of the resonators in Fig. 8(a) 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 relatively strong coupling between the resonator and the input/output feed line is realized by using interdigital capacitive gaps, and the coupling between the second and the third resonator by a simple open-ended capacitive gap. The coupling between the first and second resonator is controlled by using a short-circuited inductive stub, which acts also the role of an air-bridge.

This filter can also be designed by using the equivalent circuit shown in Fig. 3(b). However, a much more efficient design approach is to use the equivalent circuit shown in Fig. 8(b), which is drawn half only in consideration of the symmetry of the filter structure. Each of the in-line resonators is represented by a 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. The filter is then represented by an equivalent circuit having J- and K-inverters as shown in Fig. 8(b) [22]. The final dimensions of the filter are shown in Fig. 8(a) [15]–[17].

The fabricated filter is measured by using a pair of coplanar microprobes and a network analyzer. Without any tuning of the filter, the measured response at 60K is indicated in Fig. 9 by the solid lines, and it agrees very well with the predicted result in dashed lines. At 60K, the measured f_0=5.02 GHz and $I.L.$=0.22 dB, and at 77K, f_0=5.00 GHz and $I.L.$=0.32 dB. When $I.L.$=0.22 dB, the equivalent unloaded Q_u of the resonators of the filter is approximately 4300.

The CPW filter shown in Fig. 8(a) consists of cascaded quarter-wavelength resonators aligned in a straight line. When we want to get steeper passband skirt by increasing the number of resonators of the filter, the size (the length) of the filter will become too large.

To overcome this problem, a novel compact CPW interdigital BPF is proposed [19]. Figure 10 shows the configuration of a 5-pole CPW BPF using interdigital quarter-wavelength resonators. The specifications of the filter are the same as those of the filter in Fig. 8(a). By using Sonnet em, we investigated the resonant property and external Q of the resonator, and the coupling coefficient between two resonators. The final dimensions of the filter are shown in Fig. 10. Figure 11 is the simulated frequency response of the 5-pole CPW interdigital filter. The design specifications

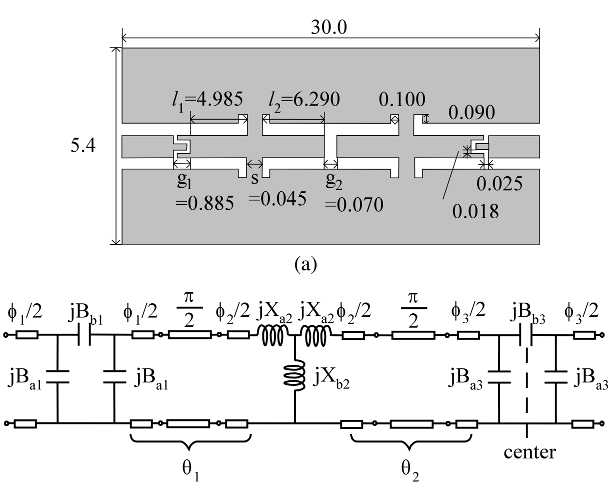


Fig. 8 (a) Configuration of a 4-pole BPF using CPW quarter-wavelength resonators. (b) Its equivalent circuit.

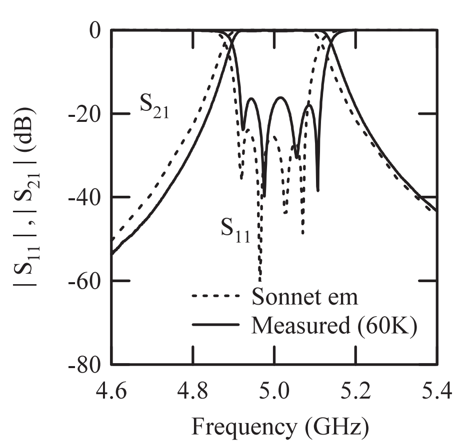


Fig. 9 Comparison of the measured and simulated frequency response of the 4-pole CPW filter.

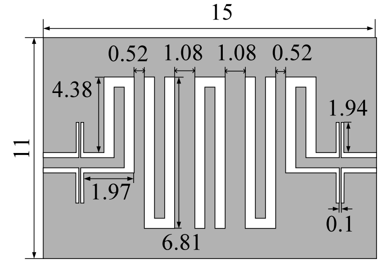


Fig. 10 Configuration of a 5-pole CPW BPF using interdigital quarter-wavelength resonators.

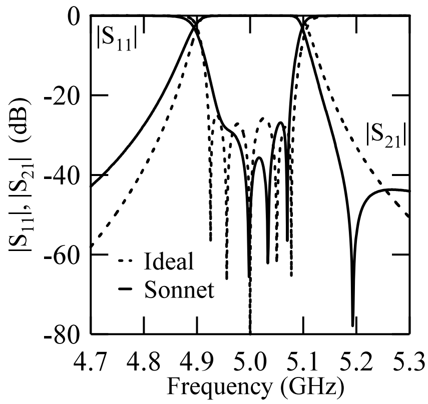


Fig. 11 Frequency response of the 5-pole CPW interdigital filter. The solid lines are simulated by an EM solver, and the broken lines are ideal Chebyshev response.

are satisfied well.

A four-pole and an eight-pole CPW combline BPFs using quarter-wavelength resonators are proposed and designed in [20]. These filters are also compact in size.

4. Conclusions

This paper described two types of HTS filters developed by using miniaturized microstrip spiral resonators and CPW quarter-wavelength resonators. It was shown that these filters are small-size and low loss. By taking advantage of both the circuit-based and EM-based simulators, the design and diagnosis of the filters were made efficient and accurate. Because of the deviations of substrate materials, discrepancies between the designed and measured midband frequencies occurred. As a result, frequency-tuning mechanisms were usually wanted in narrow band HTS filters.

Acknowledgments

The authors would like to thank Dr. H. Kayano of Toshiba Corporation, Mr. K. Kawai, Mr. D. Koizumi, Mr. K. Satoh, and Mr. S. Narahashi of NTT DoCoMo Inc., for their assistance in the works related to this paper. This paper is supported in part by the Grant-in-Aid for Scientific Research (KAKENHI 17560303) from the Japan Society for the Promotion of Science.

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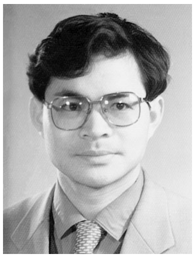

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