PAPER Special Section on Superconducting Electronic Devices and Their Applications

Design and Measurement of a Miniaturized HTS Filter Using Microstrip Spiral Resonators

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SUMMARY A high temperature superconductor (HTS) filter is designed and measured at 1.93 GHz, using microstrip half-wavelength spiral resonators. Resonant and coupling characteristics of miniaturized microstrip spiral resonators are investigated first. Then a 4-pole Chebyshev bandpass filter with a very narrow passband (4.1 MHz) is designed and realized using microstrip spiral resonators. The filter is fabricated using HTS YBCO films deposited on a $LaAlO_3$ substrate. The measured frequency response of the filter agrees reasonably with the specifications, and shows that the filter owns excellent property of spurious resonance rejection over a wide frequency range.

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

1. Introduction

Although many types of miniaturized low-loss microstrip filters using high temperature superconductors (HTS) have been studied [1]–[5], there is always a strong demand for developing filters with smaller size and higher performance because of the rapid progress in various wireless communication systems. Recent studies [6]–[9] shown that the size of filters can be reduced significantly by using microstrip spiral resonators, particularly at the lower RF/microwave frequencies currently used by mobile communications. A three-pole bandpass filter (BPF) was developed in [6] using microstrip dual-spiral resonators. The spirals were interlaced to obtain mutual couplings. However, the resonant and coupling properties of spiral resonators were not investigated systematically, and the authors of [6] failed to provide a systematical design method for filters using spiral resonators. The same types of dual-spiral resonators were also used in filters reported in [7] and [8], but the authors employed different coupling structures compared with those of [6]. In [9], a very narrowband 4-pole Chebyshev BPF was designed by using spiral resonators with a simpler shape, and a design method based on the direct-coupled cavity theory [10] was also successfully established.

In this paper, a miniaturized 1.93 GHz bandpass filter (BPF) is developed by using HTS microstrip half-wavelength spiral resonators. Compared with the conventional microstrip straight-line resonator, the width of the spiral resonator is reduced to about one-tenth. A 4-pole Chebyshev BPF is designed by using an electromagnetic simulator Sonnet em [11], and is fabricated by using HTS YBCO films on a $LaAlO_3$ substrate. The measured frequency response agrees reasonably with the theoretical prediction.

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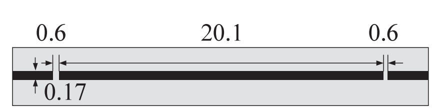
2. Design of the Filter

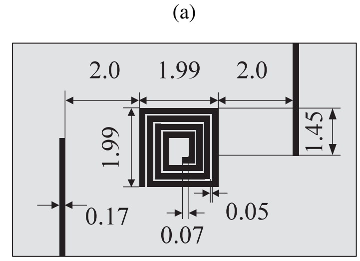
Figure 1 shows a comparison of the configuration and dimensions of a microstrip half-wavelength resonator in a straight-line and those of a spiral resonator at 1.93 GHz. A $LaAlO_3$ substrate is used which has a given dielectric constant of ε_r=23.87 at 77 K and a thickness of 0.5 mm. The line-width of the microstrip is chosen as 0.17 mm so that it owns a characteristic impedance Z_0=50 Ω. The thickness of the HTS YBCO films is 0.5 μm. The thickness and the kinetic inductance of the YBCO film are not considered in the design because our numerical computations show that their influences are minor and ignorable when the line-width of the resonator is 0.17 mm and the working frequency is as low as about 1.93 GHz.

The resonators, and also the filters discussed later, are shielded by a lossless conductor box when we execute the electromagnetic simulation using Sonnet em. The geometrical dimensions of the box are appropriately chosen so that the package resonance of the box will not occur in the frequency range of our interest. Influence of the conductor box on the resonators and/or filters are included in the simulation.

The variation of the resonant frequency f_0 versus the length L of the spiral resonator is computed by using Sonnet em, and is shown in Fig. 2. It is found that although the total length (18.23 mm) of the spiral resonator is roughly



(a)



(b)

Fig. 1 Configuration of microstrip half-wavelength resonators at 1.93 GHz. (a) Straight-line resonator, (b) spiral resonator.

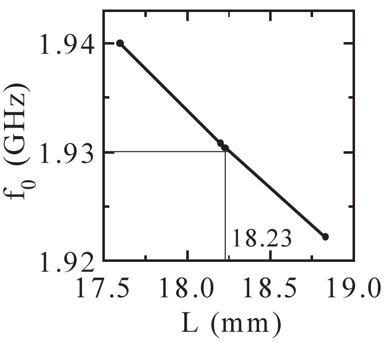
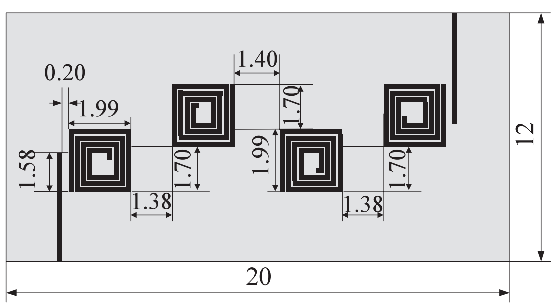
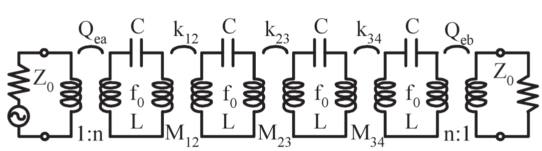


Fig. 2 Variation of the resonant frequency f_0 versus the length L of the spiral resonator.



(a)

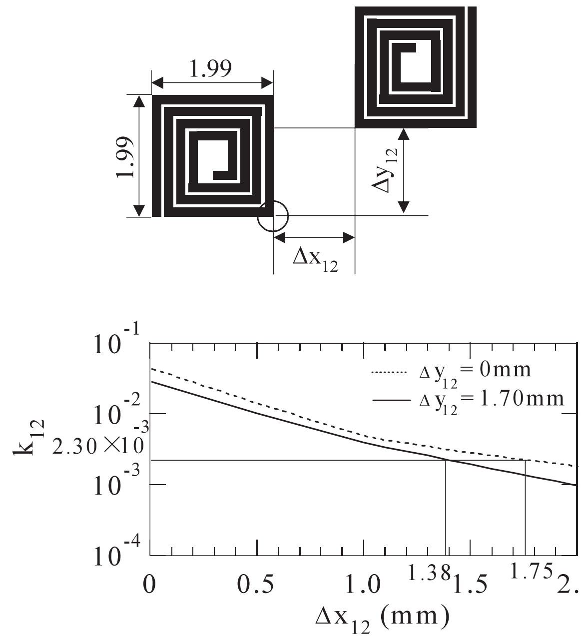


(b)

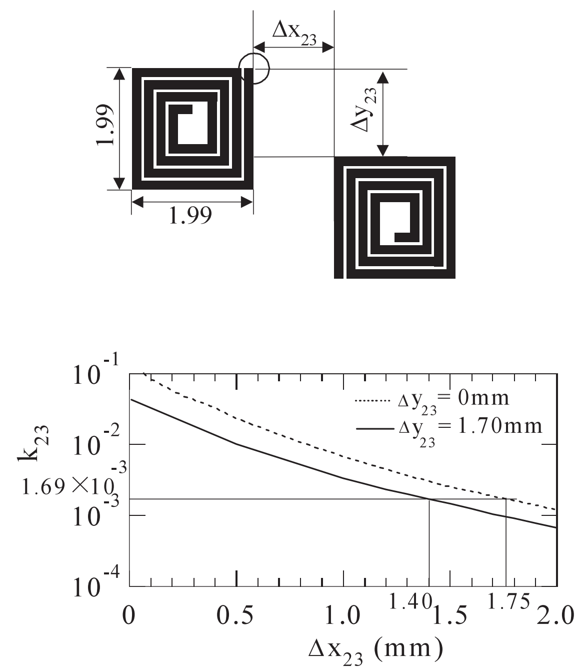
Fig. 3 (a) Configuration of a 4-pole BPF using microstrip spiral resonators, and (b) its equivalent circuit.

the same as that (20.1 mm) of the straight-line resonator, the width (1.99 mm) of the spiral resonator is reduced to about one-tenth of that (20.1 mm) of the straight-line resonator. Numerical results also indicate that the second resonance of the spiral resonator appears at about 4.50 GHz, larger than that (3.85 GHz) of the straight-line resonator. This may be accounted by the fact that compared with the straight-line resonator, the magnetic flux passing through the spiral resonator is reduced much because of the opposite flowing directions of currents on the spiral at the second resonance, and the distributed inductance is reduced thereby more significantly.

The filter to be designed is a 4-pole Chebyshev BPF with a midband frequency f_0=1.93 GHz, a passband ripple of 0.01 dB, and an equal-ripple fractional passband width $\Delta f/f_0$=0.212% (Δf=4.1 MHz). The configuration of the BPF using microstrip spiral resonators is shown in Fig. 3(a), and its equivalent circuit in Fig. 3(b). The values of the external Q, Q_{ea} and Q_{eb}, and the coupling coefficient $k_{i,i+1}$ (i=1, 2, 3) in the equivalent circuit of Fig. 3(b) can be calculated readily by using the well-known formulas in [10]. The resonant frequencies of the spiral resonators are adjusted by varying their lengths, and the coupling between two neighbouring resonators is adjusted by changing the distance between two resonators.



(a)



(b)

Fig. 4 (a) Variation of the coupling coefficient k_{12} with the distance Δx_{12}, and (b) variation of the coupling coefficient k_{23} with the distance Δx_{23}.

The variation of the coupling coefficient k_{12} with the distance Δx_{12} between the first and second resonator, and the variation of k_{23} with Δx_{23} between the second and third resonator are shown in Figs. 4(a) and (b), respectively. All the curves are computed by using the electromagnetic simulator, Sonnet em. The dashed lines are obtained with Δy_{12}=0 mm or Δy_{23}=0 mm, which means that the coupled spiral resonators are aligned in a straight line in the horizontal direction. In this case, we get Δx_{12}=Δx_{23}=1.75 mm to realize the required k_{12} and k_{23}. In order to reduce the distances between two neighbouring spiral resonators, we staggered them in the vertical direction by a distance 1.7 mm. In this case, the calculated coupling coefficients are drawn in Figs. 4(a) and (b) by solid lines, and we get Δx_{12}=1.38 mm and Δx_{23}=1.40 mm, respectively, which are reduced by 20% compared with the case when Δy_{12}=0 mm or Δy_{23}=0 mm.

The coupling between the resonator and the input or output line is controlled by changing the width g of the coupling gap shown in Fig. 5, and the variation of external Q_e with the gap width g is also depicted in Fig. 5.

From Figs. 4 and 5, we determine the structural dimensions of the 4-pole filter. By using a circuit-based optimization algorithm [10], we made diagnosis and minor adjustment of the dimensions of the filter. The final dimensions of the filter are given in Fig. 3(a). From these dimensions, the frequency response of the filter is computed again by using Sonnet em. In Fig. 6, the solid line represents the simulated result using Sonnet em, and the dashed line is the ideal frequency response calculated from the equivalent circuit in Fig. 3(b). The agreement is found quite well.

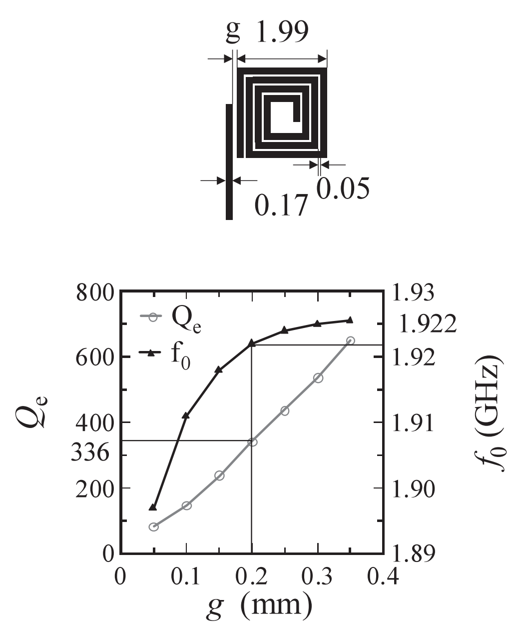


Fig. 5 Variation of the external Q_e with the coupling gap width g.

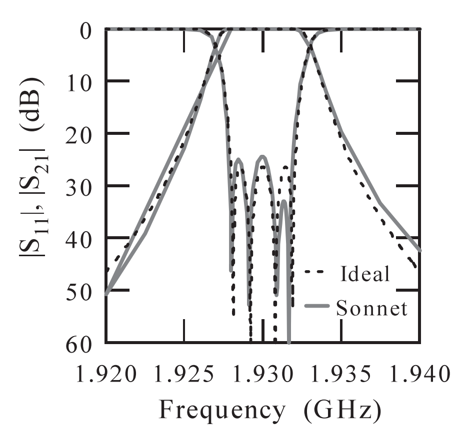


Fig. 6 Frequency response of the 4-pole microstrip filter. The solid line is simulated by using an electromagnetic solver, and the dashed line is the ideal response calculated from the equivalent circuit.

3. Measurement of the Filter

The 4-pole filter designed above is fabricated by using HTS YBCO films on a $LaAlO_3$ substrate with a photolithography and dry etching process. The photograph of the filter in a test fixture is shown in Fig. 7. The inner conductor of the SMA connector is pressed on the input and output microstrips of the filter directly, and the reflections occurred there are not removed from the measured results because the calibration of the measurement is made at the room-temperature (25°C) by using standard coaxial calibration kits.

The frequency response of the filter is measured, without any tuning of the filter, by using a network analyzer. The measured narrowband response at 70 K is shown in Fig. 8. The maximum reflection loss in the passband is about 10 dB. This value is satisfactory and reasonable in view of the inadequate calibration process described above. 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 about 1.938 GHz, 8 MHz higher than the designed 1.930 GHz. Several factors can be considered which may cause the shift of the midband frequency of the filter. They include (1) influence of the kinetic inductance of the HTS films, (2) variation of the thickness of the substrate, and (3) variation of the dielectric constant of the substrate. As stated at the beginning of Sect. 1, the thickness and the kinetic inductance of the HTS YBCO film are not considered in the design, because our numerical computations show that their influences are minor and ignorable when the line-width of the spiral resonators is as wide as 0.17 mm and the working frequency is as low as about 1.93 GHz. We simulated also the frequency responses of the filter with a number of different thicknesses of the substrate. The results show that the mid-

Fig. 7 Photograph of the 4-pole BPF filter in a test fixture.

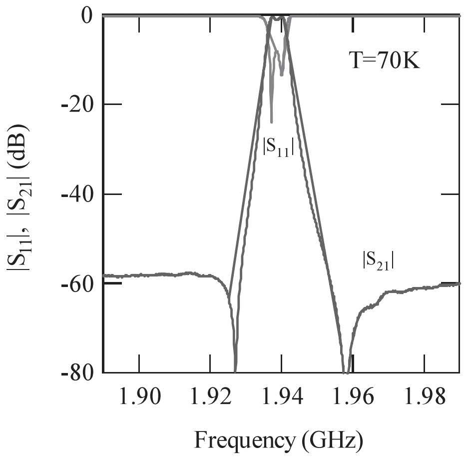


Fig. 8 Measured narrowband frequency response of the 4-pole BPF.

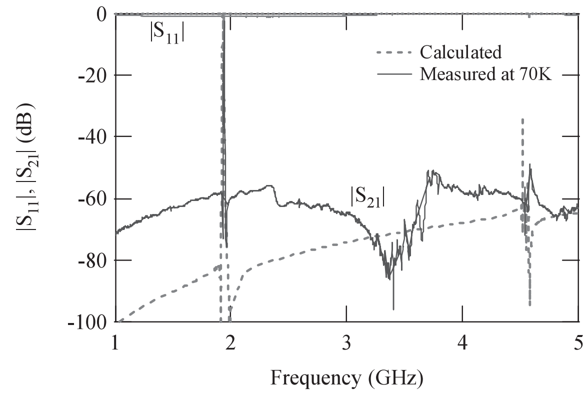


Fig. 9 Measured wideband frequency response of the 4-pole BPF.

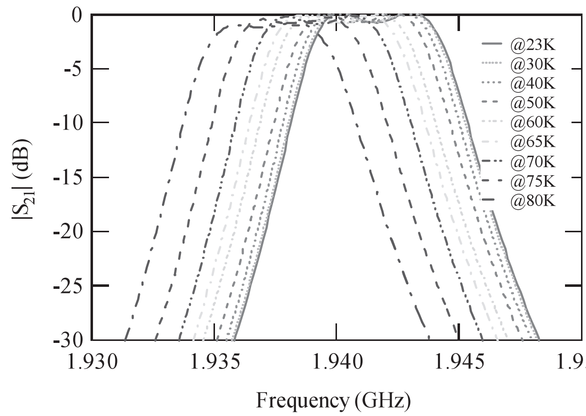


Fig. 10 Variation of the transmission characteristics of the filter measured at different temperatures.

band frequency varies less than 1 MHz when the substrate thickness is increased or reduced by 5 μm (1% of 0.5 mm of the nominal substrate thickness). We measured next the thickness of a number of $LaAlO_3$ substrates and found that the average error is only 1 μm. Then we can conclude that the variation of the substrate thickness will cause minor shift of the midband frequency of the filter. Therefore, the most possible reason for the variation of the midband frequency is that the actual dielectric constant of the $LaAlO_3$ substrate is smaller than the given nominal value, ε_r=23.87 at 77 K. To confirm this, we measured the dielectric constant of one other $LaAlO_3$ substrate provided by the manufacturer, using a circular empty cavity method. We got ε_r =23.42 at 77 K. The frequency response of the filter is recomputed with ε_r=23.42, and it is found that while the passband characteristics remained almost the same, the midband frequency is moved up to about 1.945 GHz. From the measured midband frequency of the filter, we estimated that the dielectric constant of the filter substrate is approximately 23.67, only 0.8% smaller than its nominal value. Therefore, prior to the design and fabrication of the filter, accurate measurements of the substrate (its thickness and dielectric constant) are necessary and important.

The wideband response of the filter is measured over 1-5 GHz at 70 K. As shown in Fig. 9, the measured response in solid lines agrees well with the simulated response in dashed lines. It can be seen from Fig. 9 that only a very weak spurious resonance appeared at about 4.6 GHz in the measured frequency range, and this spurious resonance is caused by the second resonance of the spiral resonators. This indicates that the filter using microstrip spiral resonator owns excellent property of spurious resonance rejection over a wide frequency range.

Figure 10 provides the variation of transmission characteristics of the filter measured at different temperatures. It is seen that with the increase of temperature, the midband frequency of the filter moves downwards while the insertion loss in the passband becomes larger gradually.

4. Conclusion

By using microstrip spiral half-wavelength resonators, a very small 4-pole HTS BPF was designed and measured at 1.93 GHz. The design is succeeded after careful investigation of the resonant and coupling characteristics of microstrip spiral resonators. The measured frequency response of the filter agreed reasonably with the prediction, and validated that microstrip spiral resonators and filters have good spurious resonance rejection over a wide frequency range.

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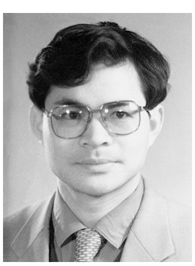

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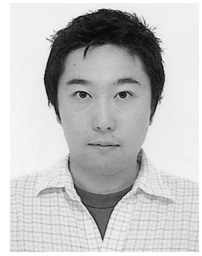

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