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Miniaturized High-Temperature Superconductor Bandpass Filters Using Microstrip S-Type Spiral Resonators

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SUMMARY At frequencies currently used by mobile communications, many of the microstrip half-wavelength resonators are too large to realize miniaturized filters. For this reason, very small-sized microstrip spiral resonators and filters, using high-temperature superconductors (HTS), have been studied recently. In this paper, the resonant and coupling characteristics of microstrip G-type and S-type spiral resonators are investigated first by using an electromagnetic simulator. Then small-sized 4-pole, 8-pole, and 16-pole Chebyshev bandpass filters using S-type spirals are designed, respectively, with a midband frequency f_0 = 1.93 GHz. The frequency responses of the filters satisfy well the desired specifications, and the measured frequency response of the 8-pole HTS filter agrees well with the theoretical prediction.

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

1. Introduction

Recent years have seen rapid applications of various mobile communication systems. As a consequence, full and effective use of frequency resources is strongly demanded than ever been. One prospective approach to address this challenge is to employ low-loss and high-selective filters developed by using high-temperature superconductors (HTS). Although numerous small-sized HTS microstrip filters have been reported [1], [2], recent studies [3]–[6] shown that the size of filters can be further reduced significantly by using microstrip spiral resonators, particularly at the lower R F/microwave frequencies currently used by mobile communications. A three-pole bandpass filter (BPF) was developed in [3] using microstrip dual-spiral resonators, which are of the same shape as the S-type spirals of this paper. The spirals were transposed and interlaced to obtain mutual couplings. However, the resonant and coupling properties of spiral resonators were not investigated systematically, and the authors of [3] failed to provide a systematical design method for filters using spiral resonators. In [4] and [6], a very narrowband 4-pole Chebyshev BPF was developed, and a design method based on the direct-coupled cavity theory [7] was successfully established.

In this paper, miniaturized bandpass filters are developed by using microstrip S-type spiral resonators. In Section 2, a brief comparison of two types of microstrip half-wavelength spiral resonators, namely G-type and S-type spiral resonators, is made in view of their size and coupling characteristics. In Section 3, 4-pole, 8-pole, and 16-pole Chebyshev BPFs are designed, respectively, using microstrip S-type spiral resonators. The 8-pole filter is fabricated using HTS YBCO films on a $LaAlO_3$ substrate. The measured frequency response agrees satisfactorily with the theoretical prediction.

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2. Comparison of G-Type and S-Type Spiral Resonators

Microstrip half-wavelength resonators are widely used in developing microwave filters. However, filters using conventional half-wavelength resonators, like the straight-line resonators and hairpin-line resonators, are usually too large for many applications. On the other hand, it has been shown that we can get very small-sized spiral resonators and filters by winding the microstrip lines into small spirals [3]–[6].

Fig. 1 shows two types of microstrip half-wavelength spiral resonators, one is named as G-type, and the other S-type spiral resonator for convenience. A $LaAlO_3$ substrate is used which has a given dielectric constant of ε_r=23.40 at 77K and a thickness of 0.5 mm. The HTS YBCO film used has a thickness of 0.5 μm. However, its thickness and kinetic inductance are ignored in the design of the filter. The width of the microstrip is chosen as 0.17 mm so that it owns a characteristic impedance $Z_0 = 50\,\Omega$. Using the dimensions given in Fig. 1, the resonant responses of the G- and S-type spirals are computed by using Sonnet em [8], a commercial electromagnetic simulator, and the curves are given in Fig. 2. The results indicate that the dominant resonance of the G- and S-type spirals appear at about 1.93 and 2.65 GHz, respectively. This means that a single G-type spiral can be made smaller than the S-type spiral when they resonate at the same frequency.

Figs. 3(a) and (b) illustrate two coupled microstrip G-type and S-type spiral resonators, respectively. Their coupling coefficients are computed by using Sonnet em. In

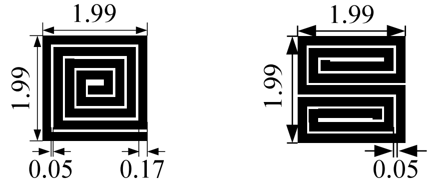

Fig. 1 Microstrip, (a) G-type and (b) S-type, spiral resonators.

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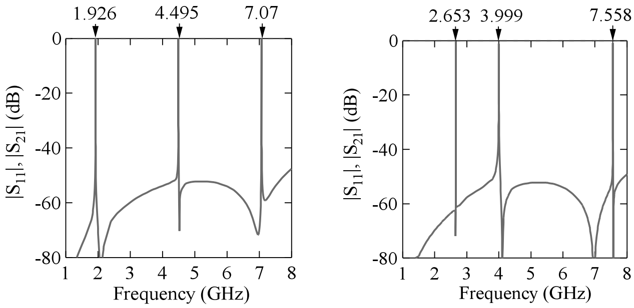


Fig. 2 Resonant curves of microstrip G-type and S-type spiral resonators.

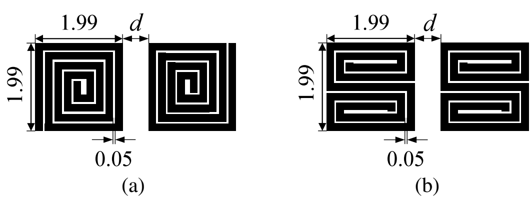


Fig. 3 Coupled microstrip, (a) G-type and (b) S-type, spiral resonators.

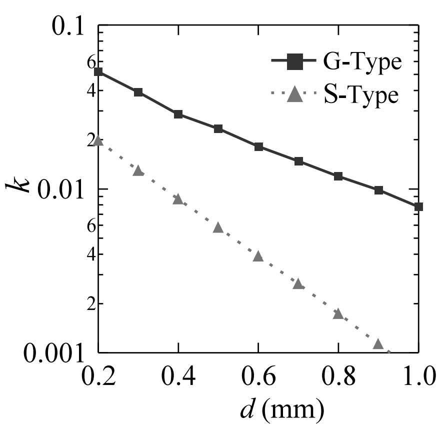


Fig. 4 Variation of the coupling coefficient k versus the distance d between two coupled resonators.

Fig. 4, the variation of coupling coefficient k versus the distance d between two resonators is drawn by solid and dashed lines for G- and S-type spiral resonators, respectively. It is seen that S-type spiral resonators own smaller k than G-type resonators do. This can be explained by the following fact: Both the G-type and S-type spiral resonators have electric and magnetic couplings, but the magnetic couplings are dominant. The G-type spiral resonator is winded in one direction, while the S-type spiral resonator is winded into two opposite directions. As a result, magnetic fields in space around the G-type spiral resonator are stronger than fields of the S-type spiral resonator. Therefore, a stronger coupling occurs between two neighboring G-type spiral resonators.

This conclusion means that although a single S-type spiral is larger than a G-type spiral, two neighboring S-type spirals can be arranged closer than G-type spirals in a filter configuration. Therefore, both the size and the coupling property of a resonator, as well as the specifications of a filter, need to be considered in the choice of the spirals. Roughly speaking, if a wideband filter is designed, the G-type spiral resonators are preferred; if a narrowband filter is required, we may choose the S-type spiral resonators.

3. Bandpass Filter Using S-Type Spirals

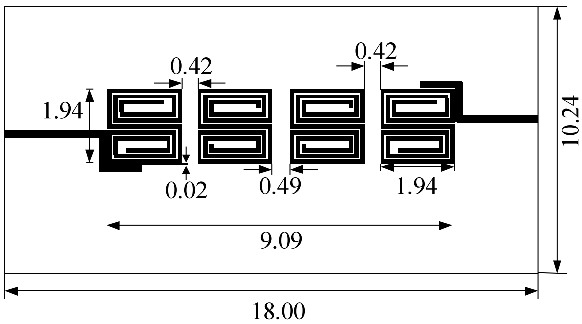
By using microstrip G-type spiral resonators, we had designed and fabricated a very narrowband 4-pole Chebyshev BPF with a midband frequency f_0=1.93 GHz, a passband ripple of 0.01 dB, and an equal-ripple fractional passband width of 0.212% (4.1 MHz). The measured frequency response of the filter agreed favourably with the theoretical simulation [6].

In this paper, 4-pole, 8-pole, and 16-pole Chebyshev BPFs are designed, respectively, using microstrip S-type spiral resonators. The filter has a midband frequency f_0=1.93 GHz, a passband ripple of 0.1 dB, and an equal-ripple fractional passband width of 1.04% (20 MHz). Fig. 5(a) shows the configuration of the 4-pole filter, and Fig. 5(b) its equivalent circuit. The external Q-factors and the coupling coefficients in Fig. 5(b) are calculated by using the well-known formulas in [7], together with the specifications of the filter. We get $Q_{ea} = Q_{eb} = 107$, $k_{12} = k_{34} = 8.61 \times 10^{-3}$, and $k_{23} = 6.81 \times 10^{-3}$.

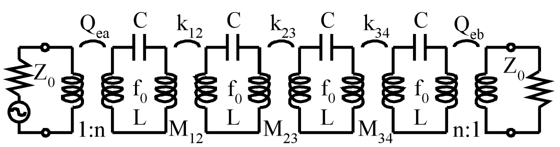
To reduce the size of the spiral resonators, the strip width of all the spirals is reduced from 0.17 mm to 0.1 mm, but the width of the input and output feed lines is remained as 0.17 mm to keep a characteristic impedance Z_0=50 Ω.

The external coupling between the resonator and the input/output feed line is controlled by changing the length of the coupling strip, as is shown in Fig. 6. The variation of external Q_e and resonant frequency f_0 versus Δt is depicted in Fig. 6. Because of the coupling with external circuits, the resonant frequencies of the 1st and 4th resonators in Fig. 5(a) decreased to about 1.909 GHz, as indicated by Fig. 6. To compensate for this frequency reduction, the strip lengths of the 1st and 4th spirals are reduced a little from their inner sides of the spirals. The final dimensions of the filter are shown in Fig. 5(a). In Fig. 7, the solid line represents the simulated frequency response of the filter using Sonnet em, and the dashed line is the ideal Chebyshev response calculated from the equivalent circuit. The agreement is quite well.

In order to get filters with higher frequency selectivity, 8-pole and 16-pole filters using S-type spiral resonators are designed, respectively, in a similar way described above. After the first-round of design, the frequency responses of the 8-pole and 16-pole filters do not agree well with the desired specifications. Then, diagnosis and adjustment of the filters are made, using a circuit-based optimization algorithm [9]. The final axial lengths of the 8-pole and 16-pole filters are only about 19 mm and 39 mm, respectively. The frequency responses of the 8-pole and 16-pole filters are shown in Figs. 8(a) and (b), respectively. The solid lines are simulated by Sonnet em, and they agree well with the ideal



(a)



(b)

Fig. 5 (a) Configuration of a 4-pole BPF using microstrip S-type spiral resonators, and (b) its equivalent circuit.

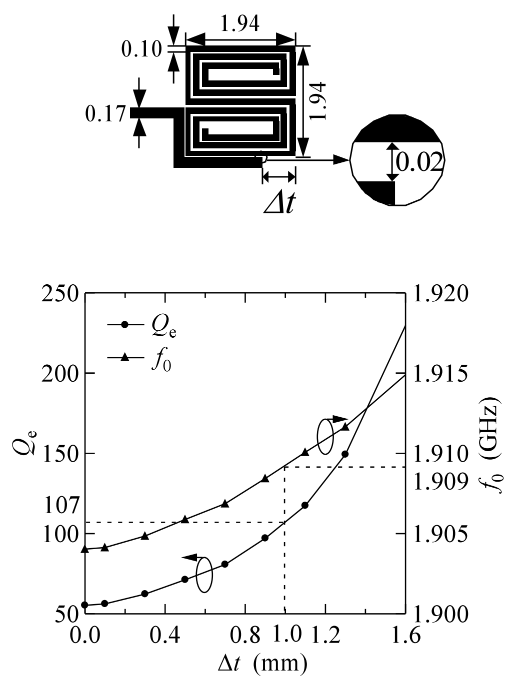


Fig. 6 Variation of the external Q_e and resonant frequency f_0 versus the coupling strip length.

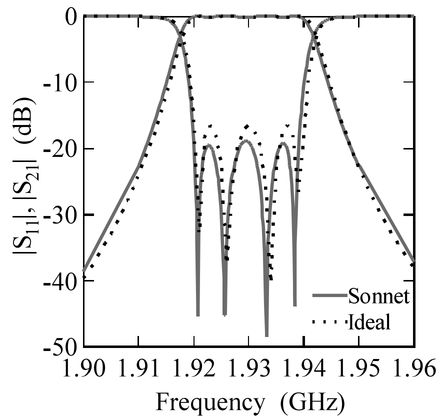
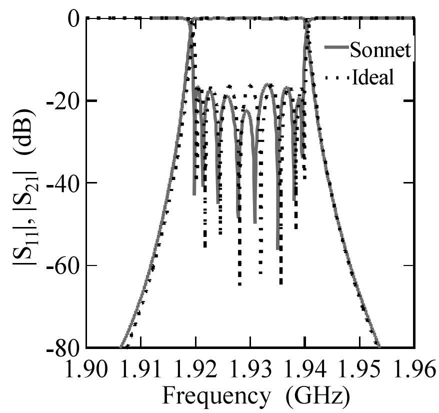
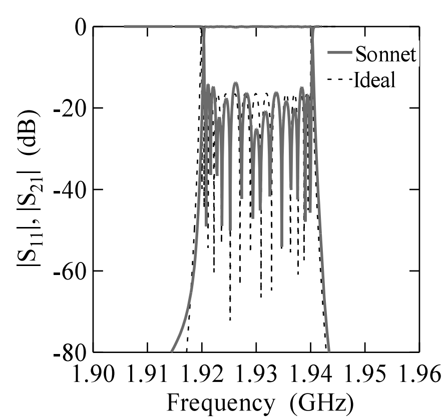


Fig. 7 Simulated narrowband frequency response of the 4-pole BPF using microstrip S-type spiral resonators.



(a)



(b)

Fig. 8 Simulated frequency response of, (a) an 8-pole, and (b) a 16-pole BPF, using microstrip S-type spiral resonators.

Chebyshev responses depicted by the dashed lines.

If the filters above are designed using G-type spiral resonators of the same size, $1.94 \times 1.94\,\mathrm{mm}^2$, it is found that because of the stronger mutual couplings, the interval distance between two neighboring resonators will increase from about 0.45 mm in the case of S-type spirals to about 0.95 mm in the case of G-type spirals. As a result, in the case of a 4-pole filter, the axial length of the filter will increase from about 9 mm when using S-type spirals, to about 10.5 mm when using G-type spirals, a nearly 17% increase in length. In the case of an 8-pole filter, the length of the filter will increase from about 19 mm when using S-type spirals, to about 22.5 mm when using G-type spirals, an increase in length larger than 18%. For filters with narrower bandwidth, the size reduction will be more significant when using S-type spirals than G-type spirals.

The 8-pole filter designed above using S-type spiral resonators is fabricated by using HTS YBCO films on a $LaAlO_3$ substrate with a photolithography and dry etching

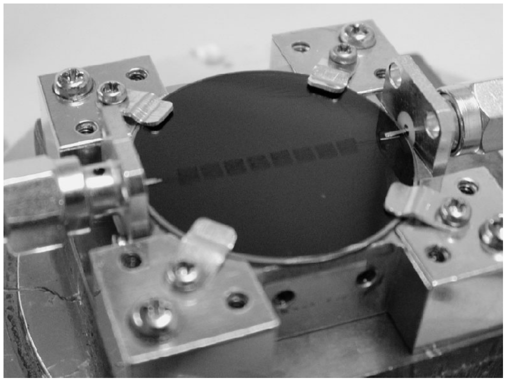
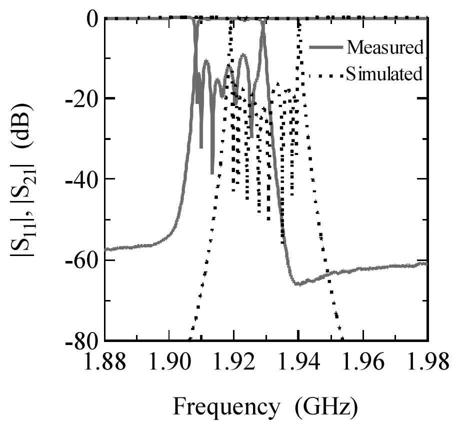
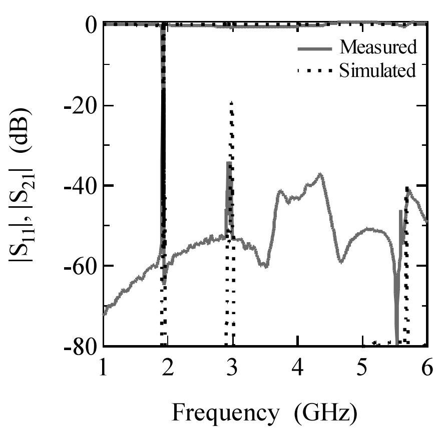


Fig. 9 Photograph of the 8-pole spiral resonator filter in a test fixture.



(a)



(b)

Fig. 10 Comparison of the simulated and measured frequency response of the 8-pole BPF using microstrip S-type spiral resonators. (a) Narrowband response. (b) Wideband response.

process. The photograph of the filter in a test fixture is shown in Fig. 9.

The measurement of the filter is made by using a vector network analyzer. A simple calibration of the measurement is taken 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. The measured narrowband response at 70K is shown in Fig. 10(a), and we find a midband frequency of 1.92 GHz, passband ripple of 0.4 dB, and a passband width of 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. The maximum reflection loss in the passband is about 10 dB. This value is satisfactory, because the reflections occurred between the SMA connector and the microstrip feed lines of the filter are not removed in the simplified calibration process mentioned above. The measured midband frequency of the filter is about 1.92 GHz, 10 MHz lower than the designed value. The reason is that the actual dielectric constant of the $LaAlO_3$ substrate is a little bit larger than the given nominal value, ε_r =23.4 at 77K. From the measured midband frequency of the filter, we estimated that the dielectric constant of the filter substrate is approximately 23.6, only about 0.9% larger 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 very important.

The wideband response of the filter at 70K is measured over 1 to 6 GHz. As can be seen from Fig. 10(b), the first spurious resonance appeared at about 3 GHz, which agreed with the simulated one.

4. Conclusions

After careful investigations of the resonant and coupling characteristics of microstrip G-type and S-type spiral resonators, very small-sized HTS bandpass filters were designed using S-type spiral resonators. With diagnosis and adjustment of the filters using a circuit-based optimization algorithm, the frequency responses of the designed filters satisfied well the desired specifications. The 8-pole spiral filter was fabricated and its frequency response was measured without any post-tuning. Favourable agreement was found between the measured result and the theoretical prediction.

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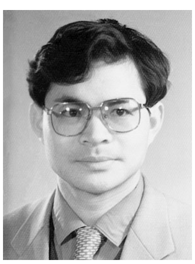

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