Cross-Coupled Dual-Spiral High-Temperature Superconducting Filter

C. Y. Tan, Linfeng Chen, Jian Lu, X. S. Rao, and C. K. Ong

***Abstract*—A microstrip bandpass filter implemented with dual-spiral resonators is described in this letter. The dual-spiral resonators make the filter compact and allow implementation of positive and negative inter-resonator couplings. Implementation of the positive and negative couplings is used to introduce a pair of finite frequency transmission-zeros in the filter response. The two zeros are designed to be close to the passband, thus improving the selectivity of the filter. As an example, a four-stage cross-coupled dual-spiral filter is designed and fabricated using superconducting $YBa_2Cu_3O_{7-\delta}$ thin films deposited on $LaAlO_3$ substrate.**

***Index Terms*—Cross coupling, dual-spiral resonators, high-temperature superconductor, microstrip bandpass filter, miniaturization.**

I. Introduction

COMPACT, high selectivity filter with low passband insertion loss is desirable in many applications. Generally, to achieve higher selectivity, it is necessary to use more resonators in the filter design, which have the undesired effects of increasing insertion loss and filter size. Cross coupling of resonators can be used to introduce finite frequency transmission-zeros near the passband so that higher selectivity can be obtain without using more resonators [1]–[3]. Cross-coupled filters are traditionally realized using waveguide cavities or dielectric resonators, which are bulkier than planar structures. When using cross-coupled resonators to implement filter with finite frequency transmission-zeros, both positive and negative couplings are required. The difficulty with using planar structures to implement cross-coupled filter is finding resonator structures that allow suitable inter-resonator coupling. Previously proposed microstrip cross-coupled filters are mostly based on open-loop resonators [3].

In this letter, we present a superconducting cross-coupled dual-spiral microstrip bandpass filter. In addition to being compact, the dual-spiral resonators allow easy implementation of the positive and negative couplings required in cross-coupled filters. The use of high-temperature superconducting (HTS) thin film as conductive layers in a planar filter allows miniaturization with low insertion loss as HTS thin film has very low surface resistance.

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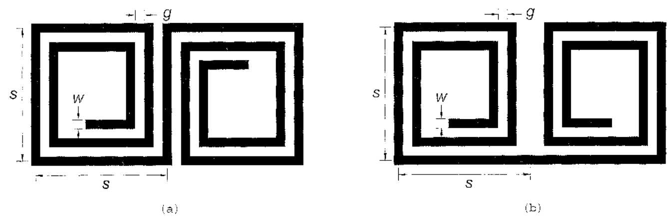

Fig. 1. Layout of dual-spiral resonators with the spirals wound in the same (a) and opposite (b) direction.

II. Dual-Spiral Resonators

A. Dual-Spiral Resonators

A dual-spiral resonator consists of two spirals connected in series with the spirals wound in the same or opposite direction as in Fig. 1. Dual-spiral resonators have been used for non cross-coupled filters in [4]–[6]. As it is difficult to obtain accurate explicit equations for resonance and coupling of dual-spiral resonators, IE3D, a full-wave electromagnetic simulator was used in our studies.

In our simulations, the substrate was defined as 0.5 mm thick, with $\varepsilon_r = 23.8$ and $\tan\delta = 10^{-5}$, corresponding to $LaAlO_3$. The conductive layers were defined as 450 nm thick HTS thin film with penetration depth of 150 nm.

The dual-spiral resonators are defined by s, w, g and l (the length of the path about center of the track through the dual-spiral). $s = 2.9$ mm, $w = 0.2$ mm and $g = 0.2$ mm were used in our design. For the dual-spiral geometry in Fig. 1(a) and Fig. 1(b), $l = 41.84$ mm and 44.12 mm respectively, will give a resonant frequency of 1 GHz.

B. Coupling Between Dual-Spiral Resonators

When designing cross-coupled filters, both the magnitude and phase of the inter-resonator coupling must be correct. An inter-resonator coupling is positive (also called inductive or magnetic) when a positive phase shift is observed at the split resonance frequencies whereas a negative phase shift indicates a negative (also called capacitive or electric) coupling [7].

For dual-spiral resonators, when only one spiral from each resonator is adjacent to the other resonator, the inter-resonator coupling sign is determined by the relative winding direction of these two adjacent spirals, i.e. when the two spirals are wound in the opposite direction as in Fig. 2(a), the coupling is positive whereas when the spirals are been wound in the same direction as in Fig. 2(b), the coupling is negative.

In cases where all four spirals are in close proximity as in Fig. 2(c), the inter-resonator coupling is dependant on the resultant interaction of all four spirals. In some cases, the coupling sign will change when separation between the resonators are varied.

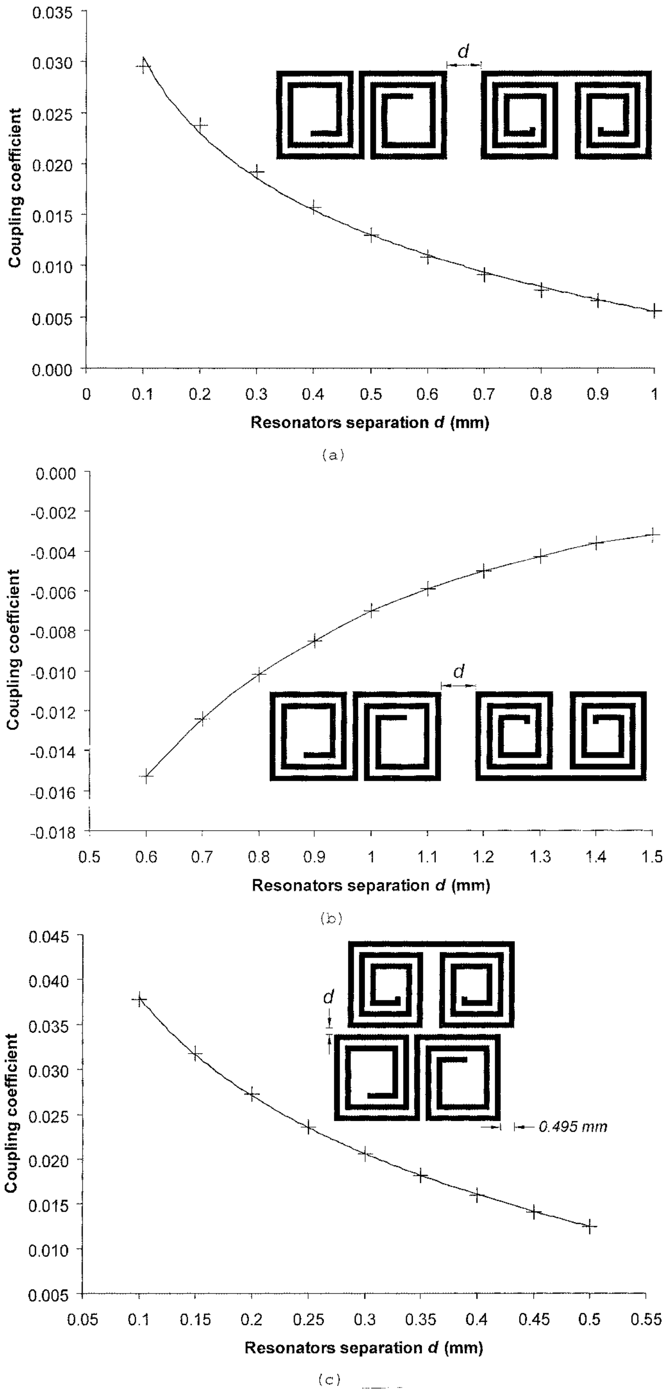

Fig. 2. (a)–(c) Variation of coupling coefficient with resonators separations for selected dual-spiral resonator pairs with different configuration.

The coupling coefficient between two frequency synchronous resonators can be calculated from the split resonant frequencies [7]. The variation of coupling coefficient with resonators separation, obtained from simulation for selected resonator pairs are shown in Fig. 2.

III. Dual-Spiral Filter

A. Filter Design

As an example, a four-stage cross-coupled filter with the following specification was designed: $\text{Center frequency} = 1$ GHz, 3 dB $\text{bandwidth} = 3.5\%$, and 45 dB $\text{bandwidth} = 6\%$. The required selectivity can be satisfied with transmission zeros at 0.97 GHz and 1.03 GHz. Using the synthesis equations in [3], $M_{x,y}$, the required coupling coefficient between resonator x and y are: $M_{1,2} = M_{3,4} = 0.030$, $M_{2,3} = 0.028$, and $M_{1,4} = -0.009$. $Q_{ei} = Q_{eo} = 27.5$ are the external quality factor of resonator 1 and 4's input/output. The cross coupling must be out of phase with the main path couplings, as indicated by the negative sign of $M_{1,4}$.

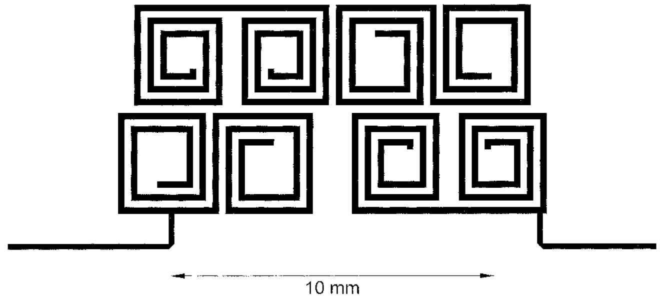

Fig. 3. Layout of the cross-coupled dual-spiral filter.

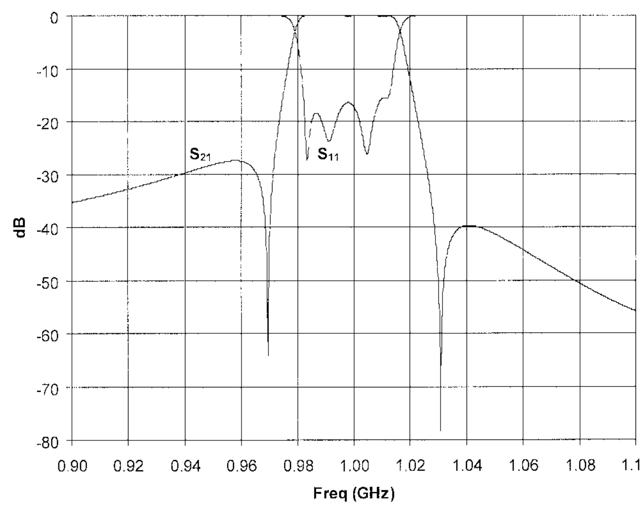

Fig. 4. Simulated responses of the dual-spiral filter.

The resonator pairs in Fig. 2(a) and Fig. 2(b) were used to realize the couplings $M_{2,3}$ and $M_{1,4}$, respectively. The couplings $M_{1,2}$ and $M_{3,4}$ were realized using the resonator pair in Fig. 2(c). The resonators separations used in the initial design filter were obtained from Fig. 2. The geometry for the tapped-line input/output used to provide the required Q_{ei} and Q_{eo} was also obtained from simulation. The filter design after optimization using simulation is shown in Fig. 3 with the simulated filter responses shown in Fig. 4.

B. Filter Fabrication and Measurement

The filter was fabricated using epitaxial $YBa_2Cu_3O_{7-\delta}$ thin films deposited by pulsed laser ablation [8] on both sides of a 15 mm $\times$ 20 mm $\times$ 0.5 mm $LaAlO_3$ substrate with $\langle 100 \rangle$ surface orientation. The surface resistance of the $YBa_2Cu_3O_{7-\delta}$ thin films were measured using dielectric resonator method [9] and found to be 0.7 mΩ at 10.66 GHz and 77 K. The filter was patterned using contact photolithography and wet etching. The filter was housed in a hermetic brass casing with SMA input/output.

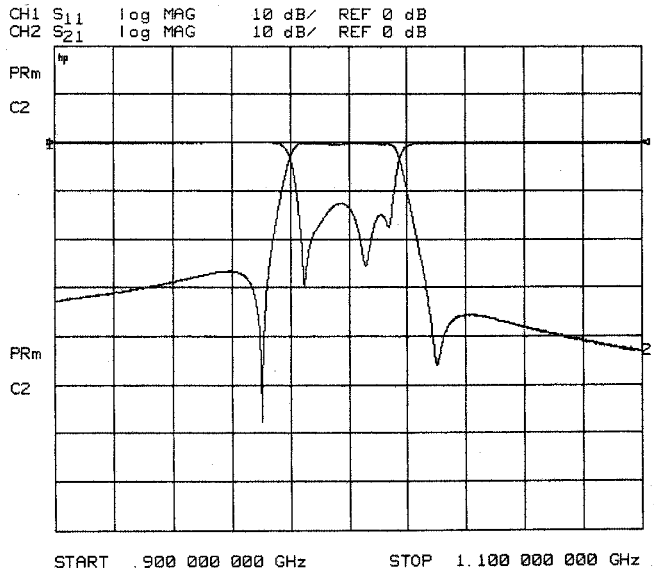

Fig. 5. Measured responses of the dual-spiral filter at 77 K.

Measurement of the packaged filter's responses at 77 K was carried out using HP8722D vector network analyzer. As shown in Fig. 5, the measured responses closely matched the simulated results, with passband insertion loss and ripple both at less than 0.2 dB.

IV. Conclusion

In this letter, we showed that the highly compact dual-spiral resonator when used with superconductor allows miniaturization of filter without sacrificing performance. In addition, dual resonators allow easy implementation of positive and negative coupling in filter design.

Although only results for a cross-coupled quadruplet filter with a pair of finite frequency transmission zeros are presented here, other types of cross-coupled filter, such as Cascaded Quadruplet (CQ) filter with flat group delay or Cascaded Trisection (CT) filter with finite frequency transmission zeros are also suitable for dual-spiral resonator implementation.

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