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Compact ultra-narrowband superconducting filter using N-spiral resonator with open-loop secondary coupling structure*

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A novel N-spiral resonator with open-loop secondary coupling structure (OLSCS) is proposed to realize a compact ultra-narrowband high temperature superconducting (HTS) filter. The coupling strength and polarity between the resonators can be significantly reduced and changed by introducing OLSCS, thus the required weak coupling can be achieved in a very compact size. A six-pole superconducting filter at 1701 MHz with a fractional bandwidth of 0.19% is designed to validate this method. The filter is fabricated on MgO substrate with a compact size of 15 mm × 10 mm. The measured insertion loss is 0.79 dB, and the return loss is better than 17.4 dB. The experimental results show a good agreement with the simulations.

Keywords: bandpass filters, high temperature superconducting (HTS), microstrip, ultra-narrowband

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1. Introduction

In the current wireless communication scenario, the development of innovative hardwire devices is necessary to support the rapid growth of new functions and complex services. Modern microwave structures have to satisfy increasingly stringent requirements for their performance, as well as compactness and ease of integration with other systems. The ultra-narrow bandpass filter has the advantage of improving the utilization of spectrum resources and system sensitivity, which plays an important role in microwave communication and detection systems. Since the insertion loss of a bandpass filter of a given order is inversely proportional to its fractional bandwidth (FBW),[1] it is difficult to achieve the ultra-narrowband filters using normal metals (especially FB$W < 1\%$). Compared with normal metal conductors, superconducting thin films have extremely low microwave surface resistance, which help high temperature superconducting (HTS) microstrip resonators present very high quality factors ($> 10^4$)[1] and consequently make possible the fabrication of compact ultra-narrowband filters with high performances in terms of very low insertion in-band loss, high out-of-band rejection, and high selectivity.

For a given application, the miniaturization of an HTS ultra-narrowband filter is one of the most important research issues since it reduces the cost related to the necessary superconducting area, relaxes the cryogenic burden for the cryo-cooler, and facilitate the integration with other systems. Miniaturization requires the resonators in a filter to be in weak coupling conditions with small distances, and people have made great efforts to achieve that. Resonator design is a very important point for compact filter construction. Various resonator structures have been employed to develop compact HTS ultra-narrowband filters in recent years. Li and Huang *et al.*[2] proposed a multiloop resonator to design a quasi-elliptic filter with an FBW of 0.23%. Li *et al.*[3,4] presented a clip-shape resonator and a dual-spiral resonator to design quasi-elliptic function ultra-narrowband HTS filters with FBWs of 0.02% and 0.35%. Huang *et al.*[5] designed a resonator consisting of a microstrip spiral, with a reversal in winding direction and developed a 0.1% bandwidth filter. In addition, stepped impedance resonators are widely used in ultra-narrowband filters design.[6–8] Kawaguchi *et al.*[6] developed a quasi-elliptic filter with an FBW of 0.25% using stepped impedance resonators and separation filter package. Kwak *et al.*[7] presented a filter with a bandwidth of 17 MHz and a center frequency of 1760 MHz using meander line resonators with stepped impedance structures. Jin *et al.*[8] proposed a stepped impedance spiral resonator and developed an HTS filter with a bandwidth of 0.3%. Twin-spiral and twin spiral-in-spiral-out resonators have been employed to design filter with ultra-narrow bandwidth.[9–16] Tao *et al.* proposed modified twin-spiral and twin spiral-in-spiral-out resonators to realize weak couplings and designed two compact ultra-narrowband filters with FBWs of 0.08%[12] and 0.18%[14] in S band. Moreover, another inspiring method that adding secondary coupling structures between resonators to reduce coupling has also been investigated.[10,17] Lu *et al.*[10] presented a double U-type secondary coupling structure to reduce the coupling between twin-spiral resonators and realize a filter at 600 MHz with an FBW of 0.083%. Among the previous re-

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ports, bandwidth and compactness are often not well balanced, and the miniaturization of ultra-narrowband filters is still a challenging problem.

In this paper, in order to achieve a very compact ultra-narrowband filter configuration, we propose a novel N-spiral resonator surrounded by an open-loop secondary coupling structure (OLSCS). By introducing OLSCS, the coupling strength and polarity can be effectively weakened and controlled artificially. Consequently, a sufficiently weak coupling is obtained within a relatively small coupling distance. Furthermore, the interaction between OLSCS and N-spiral resonator, and the effect of OLSCS on the coupling are investigated and discussed. A six-pole ultra-narrowband filter with an FBW of 0.19% in L band is designed and fabricated to validate this method.

2. Resonator design and coupling analysis

To realize a miniaturized ultra-narrowband filter, novel resonators with compact structures and weak coupling characteristics need to be satisfied. Figure 1 shows the configurations and dimensions of two half-wavelength resonators.

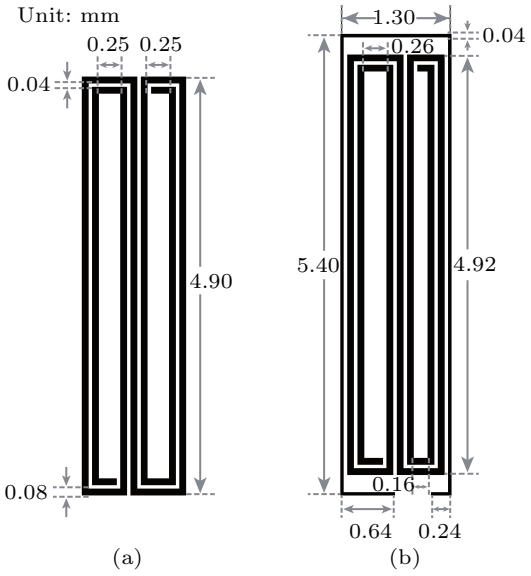


Fig. 1. (a) N-spiral resonator. (b) Modified N-spiral resonator with OLSCS.

Figure 1(a) is an N-spiral resonator consisting of two spirals wound in opposite directions and the two ends of the microstrip line located inside. At the resonance of fundamental frequency, the currents mainly distribute along the outer spiral while the charges accumulate on the inner ends of microstrip line. The currents on the two spirals in opposite directions decrease the mutual inductance. The charges wrapped inside reduce the mutual capacitance. Therefore, the electric and magnetic fields would have comparative distributions, so that the coupling can be referred to as mixed coupling. When two N-spiral resonators are in symmetric coupling structure, the electric and magnetic coupling between them will cancel each other, as proved later. To further weaken the resonator coupling, we propose an open-loop secondary coupling structure (OLSCS) with a modified N-spiral resonator for the ultra-narrowband filter, as shown in Fig. 1(b). The proposed N-spiral resonator and OLSCS are considered as a whole resonant element to realize weak coupling property in the filter design, different from the reported split-ring resonator as a junction of two channel filters.[18,19]

Figure 2 shows the frequency response of the proposed resonator in Fig. 1(b). The fundamental frequencies of the N-spiral resonator and OLSCS are 1705 MHz and 4755 MHz, which are far from each other, despite the spurious frequency.

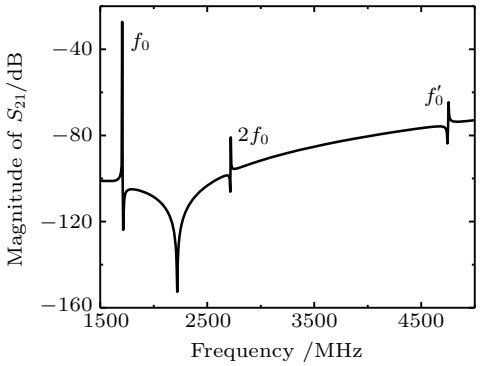


Fig. 2. The frequency response of the proposed resonator in Fig. 1(b).

There is a capacitive coupling between the OLSCS and N-spiral resonator, resulting in a reduction in electric coupling. To explain the interaction between OLSCS and N-spiral resonator, as well as understand the effect of OLSCS on coupling, the coupled resonators are represented with a lumped element equivalent circuit as shown in Fig. 3. It can be seen from Fig. 3(a) that the inductive charges are accumulated on both sides of the OLSCS which are closed to the N-spiral resonator at the resonant frequency, so the interaction between the OLSCS and N-spiral resonator can be regarded as capacitive coupling, which is represented by C_2 in Fig. 3(b). L_1 and C_1 represent the self-inductance and the self-capacitance of N-spiral resonator. L_m and C_m denote the mutual inductance and the mutual capacitance between the coupled resonators. The formula of coupling coefficient for mixed coupling[1,20] can be derived as the difference between the magnetic coupling, k_m, and the electric coupling, k_e.

$$k = k_m - k_e = \frac{L_m}{L_1} - \frac{C_m}{C_1 + C_2}. \tag{1}$$

The contribution of OLSCS is contained in the expression of electric coupling coefficient above. It demonstrates that the electric coupling decreases as the capacitive coupling increases. When the electric coupling is reduced to less than the magnetic coupling, the magnetic coupling will become dominant between the coupled resonators. Therefore, when the electric coupling is weakened to be close to the magnetic coupling, very weak coupling can be realized using N-spiral resonators and OLSCSs without large resonator distance.

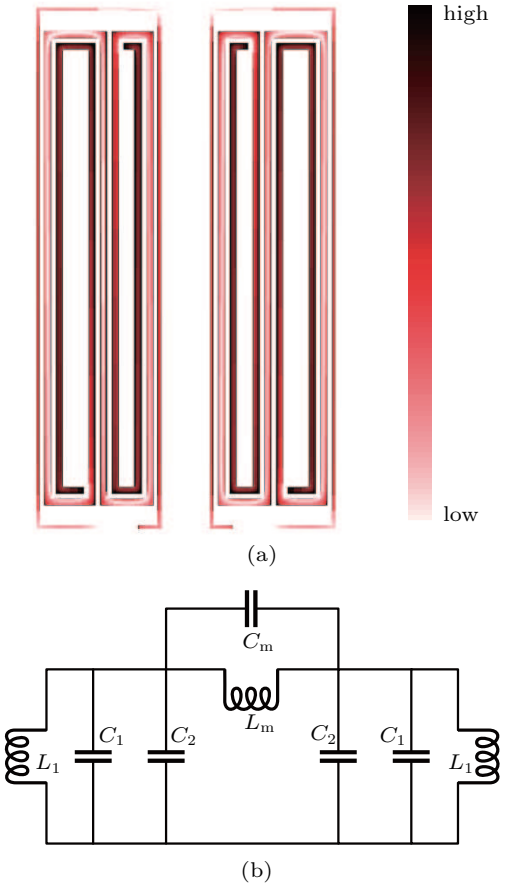


Fig. 3. (a) Charge density distribution of coupled N-spiral resonators with OLSCSs. (b) The equivalent circuit.

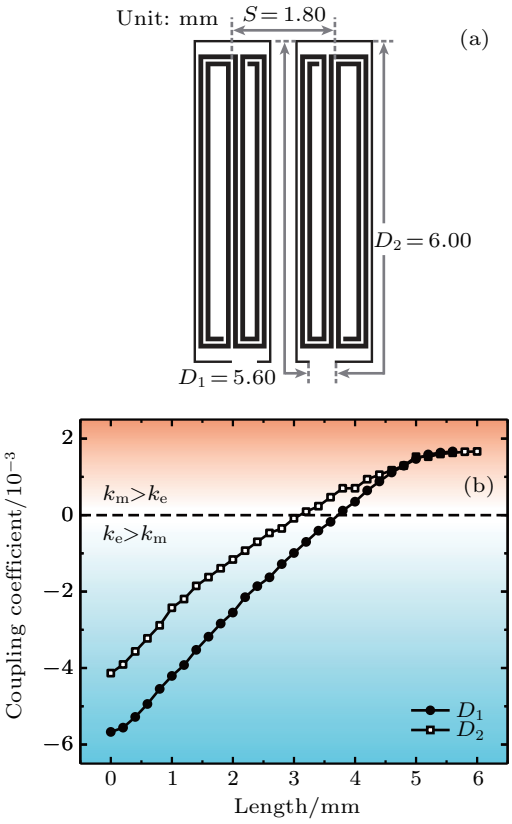


Fig. 4. (a) Coupled N-spiral resonators with OLSCSs ($S = 1.80$ mm, $D_1 = 5.60$ mm, $D_2 = 6.00$ mm). (b) Coupling coefficient *versus* the lengths of D_1 and D_2 of the OLSCSs ($S = 1.80$ mm).

The effect of the OLSCS on the coupling is simulated and shown in Fig. 4. The center distance of the resonators is fixed at 1.80 mm, while the lengths of OLSCS, D_1 and D_2, change independently in the simulations. Figure 4(b) indicates that the coupling coefficients decrease as the lengths increase. Furthermore, the coupling can be reduced to zero and change from electric coupling to magnetic coupling. Therefore, the coupling strength and polarity can be effectively weakened and controlled by adjusting the lengths of OLSCS. In addition, due to the asymmetry of the resonator, the coupling is differently sensitive to the changes in D_1 and D_2.

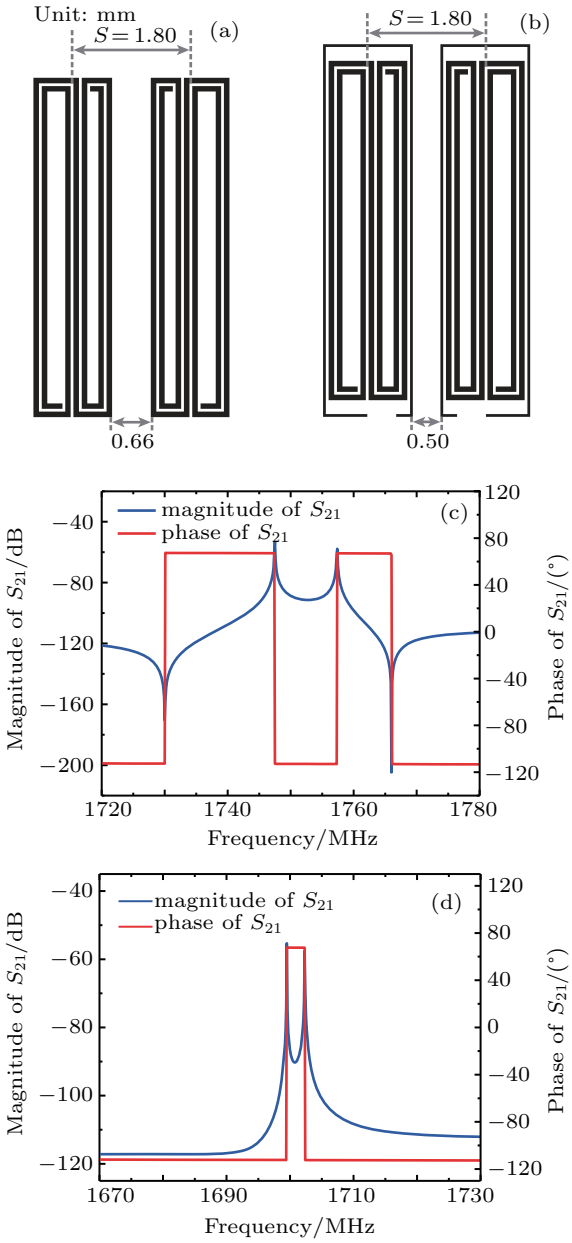


Fig. 5. (a) Coupled N-spiral resonators. (b) Coupled N-spiral resonators with OLSCSs. (c) Simulated response of coupled N-spiral resonators in panels (a). (d) Simulated response of coupled N-spiral resonators with OLSCSs in panel (b).

In order to identify the influence of OLSCS, we investigate the coupling behavior in the modified N-spiral resonator shown in Fig. 1(b) with and without OLSCS. The coupling

strength and polarity can be obtained from the simulated response at the resonant frequency. In Figs. 5(a) and 5(b), the center distances of the two pairs of coupled resonators are both set to 1.80 mm, considering both the size of the resonator itself and the coupling distance. It can be seen that the phase response in Fig. 5(c) is out of phase with that in Fig. 5(d), showing the opposite signs of the two couplings. The electric coupling is dominant for the N-spiral resonators without OLSCSs, whereas the magnetic coupling becomes dominant when the OLSCSs are added. Obviously, by introducing the OLSCS, the coupling polarity is changed from electric coupling to magnetic coupling, and the coupling strength is also weakened, which is in consistent with the previous analysis. Furthermore, the result can also indicate us that there will be a transition zero point from electric coupling to magnetic coupling, which means we can obtain extremely weak coupling.

The coupling strengths between N-spiral resonators with and without OLSCSs are compared in Fig. 6, as a function of the resonator center distance S. The coupling strengths decrease monotonically as S increases from 1.5 mm to 2.5 mm. The coupling strength of N-spiral resonators with OLSCSs is significantly weaker than that of N-spiral resonators without OLSCSs, which verifies that OLSCS can effectively weaken the coupling strength and is significant to the miniaturized design of ultra-narrowband filters. Moreover, when the center distance S is around 7.5 mm, the coupling polarity of N-spiral resonators without OLSCSs is reversed, which proves the previous statement about the electromagnetic coupling cancellation between symmetrically coupled N-spiral resonators.

The capacitive coupling between the OLSCS and the N-spiral resonator will pull down the resonator frequency, which is a critical issue for ultra-narrowband filter design. To eliminate the effect of resonant frequency shift, the OLSCS and the N-spiral resonator are considered as a whole resonant element to facilitate the filter design.

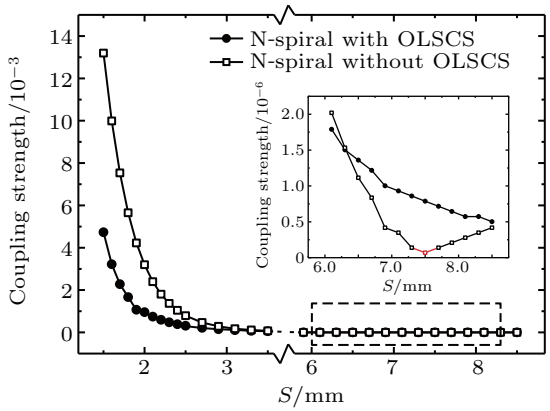


Fig. 6. The coupling strengths between N-spiral resonators with and without OLSCSs as a function of the resonator center distance S.

3. Filter design, fabrication, and measurement

A six-pole ultra-narrowband HTS filter with an FBW of 0.19% at 1701 MHz is designed using the N-spiral resonator with OLSCS to have a Chebyshev response.[1] The required coupling coefficients k_{ij}, $(i = 1,\ldots,5, j = i+1)$, and external quality factors Q_e are determined as

$$\begin{aligned} k_{12} &= k_{56} = 00016354, \\ k_{23} &= k_{45} = 00011855, \\ k_{34} &= 00011318, \quad Q_e = 513.2890287. \end{aligned} \tag{2}$$

The full-wave electromagnetic simulator Sonnet is used to simulate and extract the coupling coefficients and external quality factors. In Fig. 7(a), an open-circuit coupled line is presented to provide capacitive coupling to the resonator. The coupling strength is determined by the length of the feedline, D_4, the length of the OLSCS, D_6, and the distance between the feedline and the N-spiral resonator, D_7. The resonant frequency is compensated by adjusting D_3. As OLSCS can reduce the electric radiation from the resonator, the capacitive coupling between the feedline and the resonator is not strong enough to meet the requirement. To enhance the external coupling, D_6 should be shortened significantly. As shown in Fig. 7(b), the external quality factor Q_e decreases with the shortening of D_6, and the curve tends to be flat when D_6 is relatively small. By reducing the distance D_7, Q_e can be further decreased to the desired value.

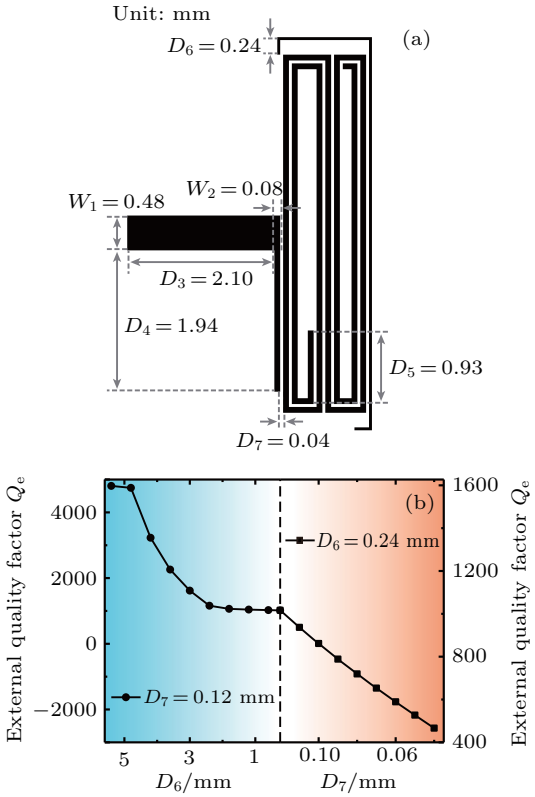


Fig. 7. (a) Configuration of the feeding structure. (b) External quality factor Q_e *versus* D_6 and D_7.

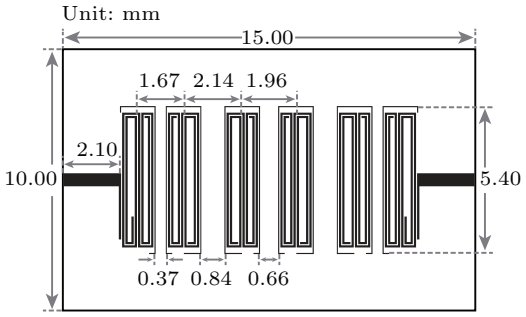


Fig. 8. Layout of the six-pole ultra-narrowband filter.

Figure 8 shows the filter layout with an overall size of 15 mm ×10 mm, including margins to the box wall. The filter is fabricated on the upper side of a double-side coated $YBa_2Cu_3O_{(7-x)}$ thin film deposited on a MgO substrate. The relative dielectric constant of the substrate is 9.75. The YBCO film is patterned by photolithography and ion etching, and the substrate is packaged in a metal shield box. The filter is measured by an Agilent Vector Network Analyzer and tuned by dielectric screws at 65 K with an input power of −10 dBm. The experimental performance shows a good agreement with the simulation, as shown in Fig. 9. The center frequency is located at 1700.98 MHz. The measured 1-dB bandwidth is 2.89 MHz, thus the FBW is 0.17%, which is slightly narrower than the simulated result. The insertion loss is 0.79 dB, and the return loss is better than −17.4 dB. The quality factor of the resonator is about 4×10^4.

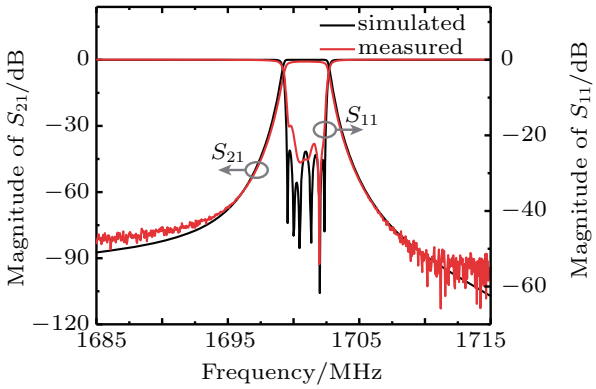


Fig. 9. Simulated and measured response of the filter.

Table 1 shows the comparison of the proposed filter with other reported filters. A compact size and low insertion loss are achieved in the proposed filter.

Table 1. Comparison of the proposed filter with other reported filters.

Ref.	Filter order	Center frequency/MHz	FBW/%	Insertion loss/dB	Relative size /$\lambda_g \times \lambda_g$ [21]	Real size /mm×mm
[7]	8	1760	0.97	0.4	0.657 × 0.103	32 × 5
[8]	6	650	0.3	0.3	0.190 × 0.150	38 × 30
[12]	6	2795	0.08	1.5	0.453 × 0.194	21 × 9
[14]	6	2258	0.18	1	0.327 × 0.139	18.8 × 8
[15]	6	3300	0.1	0.62	0.687 × 0.255	27 × 10
Proposed filter	6	1701	0.19	0.79	0.197 × 0.131	15 × 10

4. Conclusion

In this paper, we proposed a novel N-spiral resonator with open-loop secondary coupling structure (OLSCS) to design a compact ultra-narrowband filter. The capacitive coupling between OLSCS and N-spiral resonator leads to the reduction of electric coupling. As the coupling between the N-spiral resonators without OLSCSs is mixed electromagnetic coupling and dominant by electric coupling, the coupling strength can be effectively reduced by introducing OLSCS, as well as the polarity can be changed to magnetic coupling with a transition zero point. Therefore, the required weak coupling can be achieved without large resonator distance using N-spiral resonator with OLSCS, which realizes the miniaturization. To demonstrate the novel structure, a six-pole HTS ultra-narrowband filter with an FBW of 0.19% has been designed and fabricated in a compact size of 15 mm ×10 mm. The measured results show a good agreement with the simulations.

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