Progress In Electromagnetics Research Letters, Vol. 76, 105–111, 2018

Design of Ultra-Narrowband Miniaturized High Temperature Superconducting Bandpass Filter

Liguo Zhou, Zhihe Long, Hui Li, Hang Wu, Tianliang Zhang*, and Man Qiao

Abstract—This paper proposes a novel clip-shaped meander-line resonator (CSMLR) to realize miniaturized ultra-narrowband (UNB) bandpass filter design. The main advantage is that it can achieve very weak coupling between adjacent resonators with keeping them very close and introduce transmission zeros (TZs). To further demonstrate the feasibility of using this configuration, a six-pole UNB filter with a fractional bandwidth (FWB) of 0.20% at the center frequency of 1915 MHz was designed on double-sided YBCO high temperature superconducting (HTS) thin films with a thickness of 0.5 mm and dielectric constant of 9.8. The measured responses agree rather well with the simulated ones. The measured results show a maximum insertion loss of 0.31 dB and return loss of 15.5 dB in the passband. Two TZs are generated to improve the passband selectivity, which causes the band-edge steepness better than 50 dB/MHz in both transition bands.

1. INTRODUCTION

In the past few years, plenty of efforts have been made for the design of narrowband bandpass filters, which are increasingly demanded for wireless personal communication services (PCS), global system for mobile communications (GSM) and satellite receiver links [1–7]. The ultra-narrowband (UNB) filters based on high temperature superconducting (HTS) films with very low microwave surface resistance and extremely high unloaded Q-factors can possess desirable low insertion loss, sharp selectivity, and high out-of-band rejection, which are greatly useful in the prevention of interference among wireless systems, especially in the systems with similar frequency bands. At the same time, it can also reduce the bandwidth of transition bands to improve the spectrum utilization.

As described in [8], UNB bandpass filters with a fractional bandwidth (FBW) less than 0.20% are still a challenge, because some difficult conditions must be satisfied to realize a UNB filter. Firstly, a very high unloaded Q-factors value is needed to reduce the loss to an acceptable level as it is well known that the narrower the bandwidth is, the higher the loss would be. Secondly, the UNB filter with extremely weak coupling between adjacent resonators is difficult to achieve within a limited layout area practically, because in order to decrease the coupling strength, increasing the distance between adjacent resonators is a frequently-used method, which is not beneficial for miniaturization. Thirdly, the extremely weak coupling between adjacent resonators would also magnify the influence of unwanted parasitic coupling. So there are a few published papers reporting filters with FBW less than 0.2%. In [9], a five-pole HTS microstrip filter shows a possible FBW of 0.014% at the center frequency of 700 MHz, but there is no transmission zero (TZ) located in transition bands. In [8], an HTS UNB bandpass filter with an FBW of 0.02% in C band is designed, but the measured minimum insertion loss is 3.8 dB. A two-pole HTS filter with FBW of 0.02% for the wireless industry applications is presented in [10], but the return loss and out-of-band rejection are not satisfying.

Received 10 February 2018, Accepted 9 April 2018, Scheduled 5 June 2018
* Corresponding author: Tianliang Zhang (ztl@uestc.edu.cn).
The authors are with the School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu 611731, China.

In this letter, a novel clip-shaped meander-line resonator (CSMLR) is proposed to solve the problems of weak coupling, compact size and TZs. A six-pole miniaturized and high-performance UNB filter with an FBW of 0.20% is achieved on the HTS film by utilizing CSMLRs. High selectivity is obtained due to the introduction of two TZs without any cross-coupling line and extracted-pole technology, and the performance of insertion loss and out-of-band rejection has obvious superiority.

2. DESIGN OF UNB FILTER

Two coupled CSMLRs are shown in Figure 1(a). It is well known that the coupling coefficient m_{ij} between the two adjacent resonators i and j can be calculated by their resonant peaks in Figure 1(b) through Equation (1) [3], and the coupling strength would decrease with the increase of the distance s between the two resonators, as exhibited in Figure 1(c). Besides tuning s, the coupling strength can also be conveniently changed by adjusting the dimension d with the distance s fixed at a small value in the proposed CSMLR configuration. Figure 1(d) shows the relationship between the coupling strength and d with s unchanged at 0.25 mm. It can be seen that with the increase of d, the coupling strength decreases first and then increases. Obviously, there exists an appropriate value d (about 2.57 mm) which can realize the expected weak coupling strength for the UNB filter design. More intuitive change of bandwidth can be seen from Figure 1(b), where when d is equal to 2.57 mm, the bandwidth is minimum. In addition, the resonant frequency f_0 of half-wavelength CSMLR can be roughly computed through Equation (2), where the value of 1.7 represents the total gap lengths; c is the speed of light in the vacuum environment; and ε_{eff} is the dielectric constant of substrate.

$$m_{ij} = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \tag{1}$$

$$f_0 \approx \frac{c}{2 \times [6(d+h) + 1.7] \times \sqrt{\varepsilon_{eff}}} \tag{2}$$

Figure 1(e) depicts the relationship between d and h under the case of f_0 unchanged. Due to the interaction of the electromagnetic fields inside the resonator, it can be observed that with the decrease of d, the value of $d+h$ decreases as well, so d chosen to be 2.57 mm is also beneficial to the miniaturization of resonators from this respect.

In order to verify the feasibility of CSMLR, a six-pole coupling coefficient matrix is synthesized in Table 1 with external quality factor $Q_{eS1} = Q_{e6L} = 456.7$ for a UNB filter design according to the Chebyshev theoretical prototype in [10].

The layout of the designed six-pole symmetrical UNB filter with CSMLR structure is shown in Figure 3. According to the previous discussion, the parameter d in all CSMLRs is fixed at 2.57 mm, and the distance s between adjacent CSMLRs is set to be variable for adjusting the coupling coefficient. If d is chosen as the variable, it would be detrimental to the circuit optimization, because the change of d in a CSMLR would affect the left and right adjacent coupling coefficients simultaneously. However,

Table 1. Coupling coefficient matrix of 6-pole filter.

	S	**1**	**2**	**3**	**4**	**5**	**6**	**L**
S	0	0	0	0	0	0	0	0
1	0	0	0.00172	0	0	0	0	0
2	0	0.00172	0	0.00125	0	0	0	0
3	0	0	0.00125	0	0.00121	0	0	0
4	0	0	0	0.00121	0	0.00125	0	0
5	0	0	0	0	0.00125	0	0.00172	0
6	0	0	0	0	0	0.00172	0	0
L	0	0	0	0	0	0	0	0

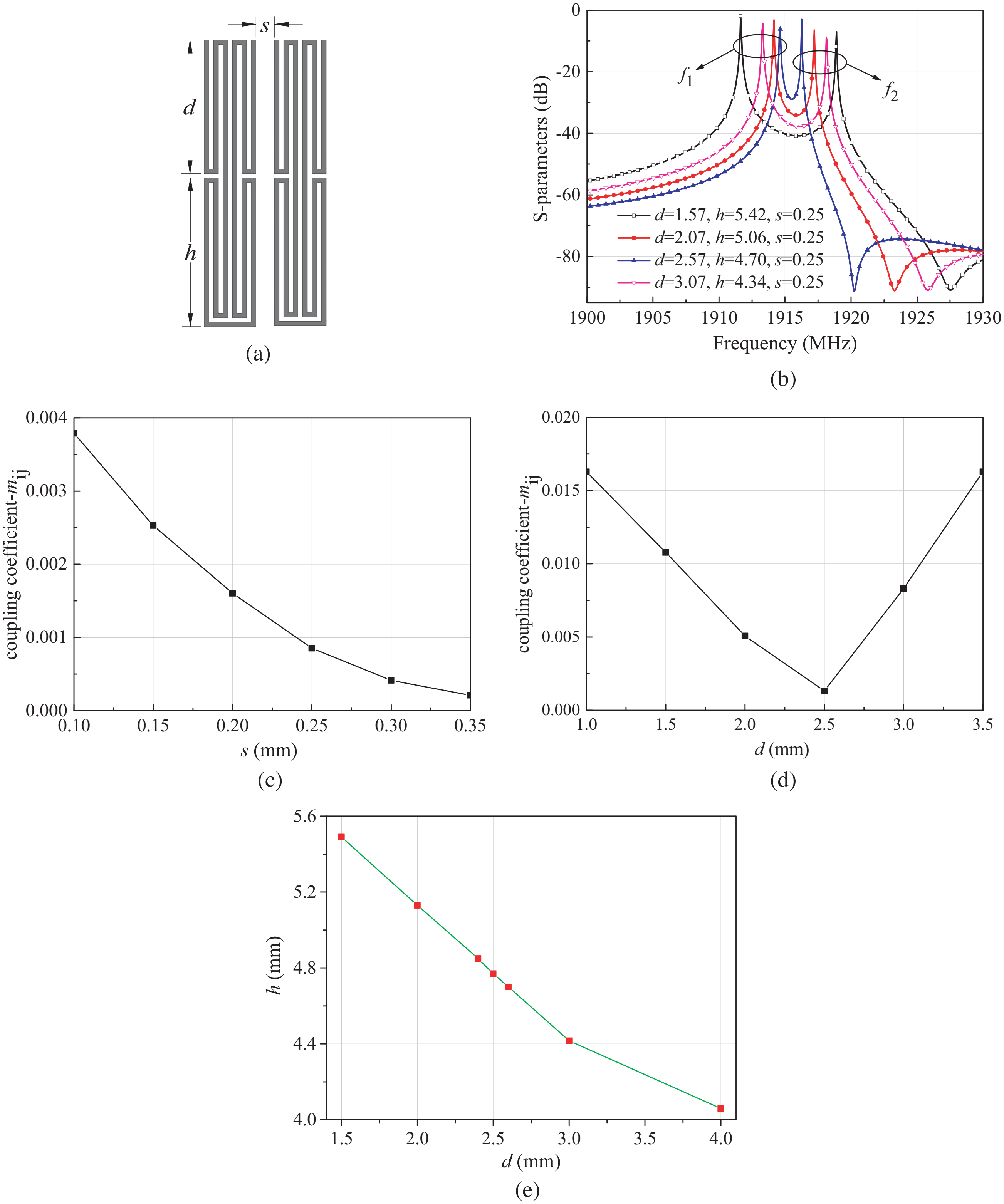


Figure 1. Proposed CSMLR configuration. (a) Layout of two CSMLRs. (b) Relationship between coupling strength and d with $s = 0.25$ mm. (c) Relationship between coupling coefficient and s. (d) Relationship between coupling coefficient and d. (e) Relationship between d and h with f_0 unchanged.

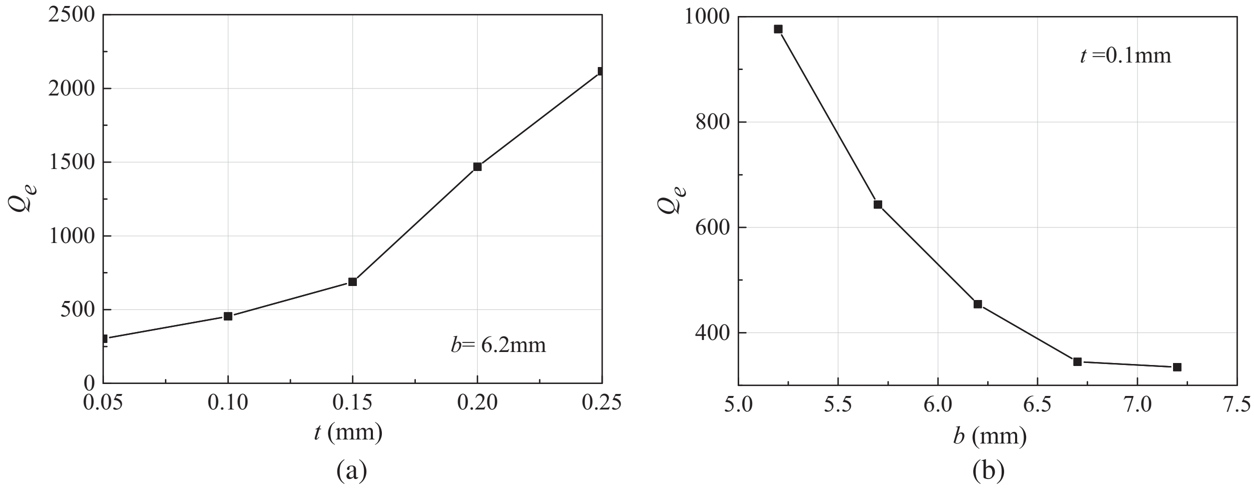


Figure 2. Relationship between the external quality factor Q_e and t or b. (a) t with $b = 6.2$ mm. (b) b with $t = 0.1$ mm.

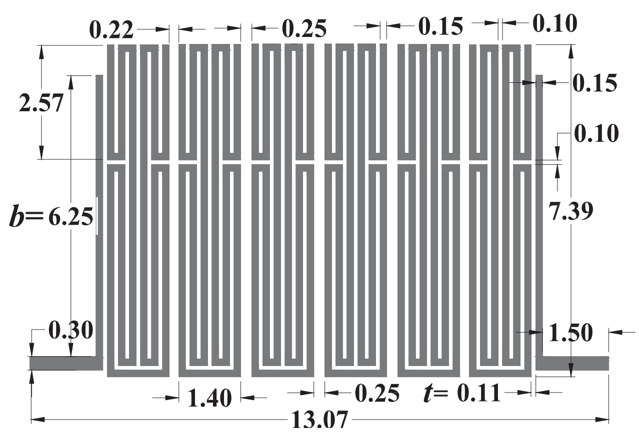


Figure 3. Layout of the proposed six-pole UNB filter (unit: millimeter).

by tuning s in a small range, required coupling coefficients can be obtained without influencing other ones, and compact filter size would also be guaranteed.

Indirect coupling ports are adopted to flexibly adjust the value of external quality factor for achieving the suitable external coupling strength. Figure 2(a) and Figure 2(b) show the simulated external quality factor Q_{e} as a function of the distance t between the input (output) port and the first (last) resonator, and a function of the height b of ports, respectively. It can be seen that as t increases, Q_{e} increases to a huge value very quickly, and with the increase of b, Q_{e} drops to a small value rapidly. So by repeatedly optimizing the distance t and height b, correct external coupling strength can be achieved. Finally, when $t = 0.11$ mm, $b = 6.25$ mm, Q_{e} is equal to 456.7.

Through the optimization of the full-wave electromagnetic simulation software IE3D, the final associated dimensions of the filter can be determined, and they are marked in Figure 3. It can be observed from Figure 4(b) that a pair of TZs is introduced, however no cross-coupling line is loaded between non-adjacent resonators, or extracted-pole technology is adopted. According to Reference [14], due to the controllable electric and magnetic mixed coupling between adjacent CSMLRs, the TZs (TZ_1 and TZ_2) are introduced. In [14], the authors designed some equivalent circuits of bandpass filters to investigate the electric and magnetic mixed coupling and gave Equations (3), (4) and (5) to present the relationship among inductive/capacitive coupling coefficient (M_C/E_C), odd- and even-mode resonant frequencies (ω_{od} and ω_{ev}) and the TZ frequency (ω_m).

$$M_C = \frac{\omega_{\mathrm{od}}^2 - \omega_{ev}^2}{\omega_{\mathrm{od}}^2 + \omega_{ev}^2 - 2\omega_m^2} \tag{3}$$

$$E_C = \frac{\omega_m^2\left(\omega_{\mathrm{od}}^2 - \omega_{ev}^2\right)}{2\omega_{\mathrm{od}}^2\omega_{ev}^2 - \omega_m^2\left(\omega_{\mathrm{od}}^2 + \omega_{ev}^2\right)} \tag{4}$$

$$m_{ij} = M_C - E_C = \frac{\omega_{\mathrm{od}}^2 - \omega_{ev}^2}{\omega_{\mathrm{od}}^2 + \omega_{ev}^2} \tag{5}$$

On the basis of the definition of electric and magnetic mixed coupling, Equation (6) is presented below [14]. It can be found that the ratio of the inductive and capacitive coupling coefficients determines the relative position of the TZs. The closer the capacitive coupling and inductive coupling are, the closer the TZs are to the self-resonant frequency (ω_0). Equation (7) can be used to more obviously explain the relationship between TZs and the ratio of the inductive and capacitive coupling coefficients through the simplification of Equation (6) [14].

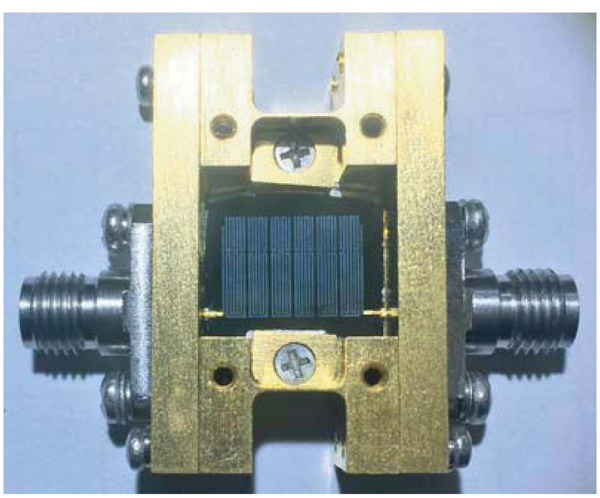
$$\frac{M_C}{E_C} = \frac{L_m/L}{C/C_m} = \frac{L_m C_m}{LC} = \frac{\omega_0^2}{\omega_m^2} \tag{6}$$

$$f_m = f_0\sqrt{\frac{E_C}{M_C}} \tag{7}$$

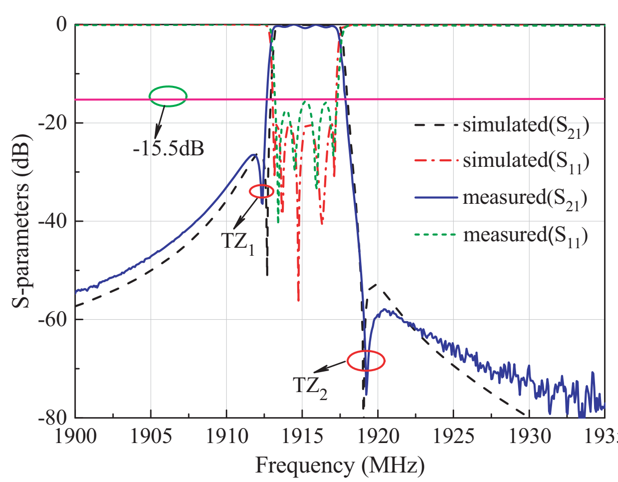
According to Equation (5), when E_C is close to M_C in proposed coupled CSMLRs, and the total coupling m_{ij} would be minimum, which is suitable for UNB design. According to Equation (7), when M_C/E_C in coupled CSMLRs is less than 1, TZ willabove ω_0. Because M_C is very close to E_C in the coupled CSMLRs ($m_{ij} \approx 0$), M_C/E_C less or more than 1 can be easily realized by adjusting the parameter d slightly in Figure 1(a), so that the control of TZs can be achieved in the proposed UNB filter design.

3. FABRICATION AND MEASUREMENT OF UNB FILTER

The UNB filter was fabricated on a 0.5-mm thick MgO wafer with double-sided YBCO HTS thin films. The relative dielectric constant of MgO is 9.8. One side of the HTS films is patterned into the filter



(a)



(b)

Figure 4. Photograph and results of fabricated UNB filter. (a) Photograph of fabricated six-pole HTS UNB filter. (b) Measured and simulated S-parameters of the filter.

circuit by the standard procedure of photolithography, the other side is used for grounding. The eventual circuit size is 13.07 mm × 7.39 mm ($0.26\lambda_g \times 0.15\lambda_g$, λ_g is the wavelength in the dielectric).

A physical photograph of the fabricated HTS UNB filter is displayed in Figure 4(a). The packaged HTS UNB filter was cooled down to a temperature of 77 K in a cryogenic cooler and measured by HP8753 network analyzer, after the full two-port calibration for reflection and transmission measurements was performed at ambient temperature, and Figure 4(b) illustrates the simulated and measured frequency responses. It can be observed that the FWB is 0.20% at the center frequency of 1915 MHz, the same as the simulated one. And due to the existence of TZs, the passband selectivity is improved effectively. The band-edge steepness reaches over 50 dB/MHz in both transition bands, and the out-of-band rejection is better than 70 dB at the frequency of 1919 MHz. The maximum in-band insertion loss is 0.31 dB with corresponding unloaded Q-factors about 67000. The return loss is better than 15.5 dB within the passband. In general, the measured results are in good agreement with simulated ones. Table 2 is the comparison between the proposed UNB filter with the reported ones.

Table 2. Performance comparison with reported UNB filters.

Ref.	f (MHz)	FBW (%)	Q-factors	VSWR	TZs	Pole	Size ($\lambda_g \times \lambda_g$)
[6]	9900	0.65	24000	1.58	No	6	1.81 × 0.27
[11]	900	0.27	10800	1.20	No	5	No
[12]	1968	0.25	48000	1.38	Yes	8	0.78 × 0.27
[13]	1967.5	0.76	17000	1.9	Yes	18	1.23 × 0.27
This work	1915	0.2	67000	1.40	Yes	6	0.26 × 0.15

4. CONCLUSION

A novel CSMLR is proposed to reach very weak coupling between adjacent resonators for miniaturized UNB filter design. A pair of TZs can be produced to realize sharp passband selectivity in the design of the six-pole HTS UNB filter. The simulated six-pole UNB filter was fabricated finally to verify the correctness and feasibility of this structure. The experimental results show the filter possesses high performance, which can be applied to modern wireless communication systems.

REFERENCES

1. He, Y., G. Wang, and L. Sun, "Direct matrix synthesis approach for narrowband mixed topology filters," *IEEE Microwave and Wireless Components Letters*, Vol. 26, No. 5, 301–303, 2016.
2. Zhou, J. F., M. J. Lancaster, F. Huang, R. Neil, and G. Dave, "HTS narrow band filters at UHF band for radio astronomy applications," *IEEE Transactions on Applied Superconductivity*, Vol. 15, No. 2, 1004–1007, 2005.
3. Liu, H. W., F. Liu, F. Qin, B. P. Ren, P. Wen, and X. H. Guan, "Compact dual-band HTS bandpass filter using spirally asymmetric stepped-impedance resonators," *IEEE Transactions on Applied Superconductivity*, Vol. 26, No. 7, 1–5, 2016.
4. Gao, T. Q., B. Wei, B. S. Cao, D. Wang, and X. B. Guo, "A low loss superconducting filter with four states based on symmetrical interdigital-loaded structure," *Physica C: Superconductivity and Its Applications*, 48–51, 2016.
5. Sekiya, N., "Design of high-order HTS dual-band bandpass filters with receiver subsystem for future mobile communication systems," *Physica C: Superconductivity and Its Applications*, 91–97, 2016.
6. Wang, X., B. Wei, T. N. Zheng, B. S. Cao, L. N. Jiang, and J. B. Chen, "Design and implementation of a narrow-band superconducting X-band diplexer with high isolation," *Physica C: Superconductivity and Its Applications*, 9–13, 2016.

7. Liu, H. W., B. P. Ren, S. X. Hu, X. H. Guan, P. Wen, and J. M. Tang, "High-order dual-band superconducting bandpass filter with controllable bandwidths and multitransmission zeros," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 65, No. 10, 3813–3823, 2017.
8. Li, C. G., T. Yu, Y. B. Bian, Y. Wu, J. Wang, X. Q. Zhang, L. Sun, H. Li, and Y. S. He, "An ultra-narrowband high-temperature superconducting bandpass filter with a fractional bandwidth of 0.02%," *IEEE Transactions on Applied Superconductivity*, Vol. 26, No. 7, 1–4, 2016.
9. Dustakar, K. and S. Berkowitz, "An ultra-narrowband HTS bandpass filter," *IEEE MTT-S International Microwave Symposium digest*, 1881–1884, 2003.
10. Hejazi, Z. M., M. C. Scardelletti, F. W. Van Keuls, A. A. Omar, and A. Al-Zayed, "EM full-wave analysis and testing of novel quasi-elliptic microstrip filters for ultra narrowband filter design," *Progress In Electromagnetics Research*, Vol. 85, 261–288, 2008.
11. Zhang, D., G. C. Liang, C. F. Shih, M. E. Johansson, and R. S. Withers, "Narrowband lumped-element microstrip filters using capacitively-loaded inductors," *IEEE Transactions on Microwave Theory and Techniques*, 3030–3036, 1995.
12. Hong, J. S., E. P. Mcerlean, and B. Karyamapudi, "Narrowband high temperature superconducting filter for mobile communication systems," *IEE Proceedings — Microwaves, Antennas and Propagation*, 491–496, 2005.
13. Hong, J. S., E. P. Mcerlean, and B. Karyamapudi, "High-order superconducting filter with group delay equalization," *IEEE MTT-S International Microwave Symposium Digest*, 1467–1470, 2005.
14. Chu, Q. X. and H. Wang, "A compact open-loop filter with mixed electric and magnetic coupling," *IEEE Transactions on Microwave Theory* & *Techniques*, 431–439, 2008.