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A 15-pole high temperature superconductor filter for radar applications

Xiao Yu[1,2], **Weibin Xi**[1] **and Songtao Wu**[1,2]

[1] Institute of Plasma Physics, Chinese Academy of Science, Hefei, Anhui, 230031, People's Republic of China

[2] University of Science and Technology of China, Hefei, Anhui, 230026, People's Republic of China

E-mail: xiwb@ipp.ac.cn

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Abstract

This paper presents a compact and high first harmonic frequency resonator. The characteristics of this resonator are theoretically analyzed. A highly selective 15-pole Chebyshev high temperature superconducting ultra-high frequency narrowband filter for radar applications was fabricated by using this resonator. The filter has a center frequency of 495 MHz and a fractional bandwidth of 1%. The first harmonic frequency is more than 3.3 times the fundamental frequency. The measured filter shows excellent selectivity, better than 85 dB/1 MHz skirt slopes, and more than 85 dB of rejection at 497.5 MHz from the band edge. The filter was fabricated on a 2 inch YBCO thin film with a 0.5 mm thick MgO substrate. The experimental results are consistent with the simulations.

Keywords: HTS filter, high selective, high first harmonic frequency, interdigital structure resonator

(Some figures may appear in colour only in the online journal)

1. Introduction

High temperature superconducting (HTS) film has a very small microwave surface resistance, which is more than 1000 times smaller than that of normal metal film in an ultra-high frequency (UHF) band. HTS filters can therefore get high out-of-band rejection and more steep edges with very low insertion loss by increasing the number of resonators [1, 2]. Compared with ordinary metal filters, HTS filters can further improve the sensitivity and selectivity of microwave systems, thereby increasing their coverage and anti-jamming ability. HTS filters have been widely developed in those fields using microwave systems such as medical instruments, satellites, military communication and aerospace, etc [3, 4].

Half-wavelength resonators are mostly used in the design of HTS filters, but it is difficult to design high order HTS filters at low frequency for larger sizes of resonators. In addition, a half-wavelength bandpass filter contains spurious bands centered at double frequencies above the fundamental frequency, thus impairing the out-of-band performance of the filter. The first spurious band problem is more pronounced in low frequency filters [5]. For many applications, higher selectivity filters are still required. Hattori W *et al* [6] developed a 21-pole HTS filter for IMT-2000 base stations with steep attenuation to avoid interference from signals in the personal cell phone system band. Zhang *et al* [1] presented a 24-pole HTS filter for mobile communication applications with a skirt slope of 17 dB MHz^{-1} and an out-of-band rejection level of 90 dB. Li C *et al* [7] designed a steep skirt slope ultra-narrow bandpass HTS filter for wind-profiler radars in urban areas to prevent a crowded frequency spectrum. Li *et al* [8] presented a 12-pole highly selective HTS filter for third-generation wireless communication applications to reduce the interference of the intermodulation products from co-channels or adjacent channels. Kawaguchi *et al* [9] developed a high-selectivity HTS filter for weather radar receivers to reduce interference between adjacent channels. Zhang *et al* [10–13] developed a series of HTS filters for the Jodrell Bank Radio Observatory to prevent interference from TV signals. An 8-pole HTS filter with a passband of 607–613 MHz has been tested and the field results showed that the TV signals at 605.25 MHz and 615.25 MHz can be effectively suppressed. The radar with dielectric-resonator filters can barely receive the signal due to a tightness of

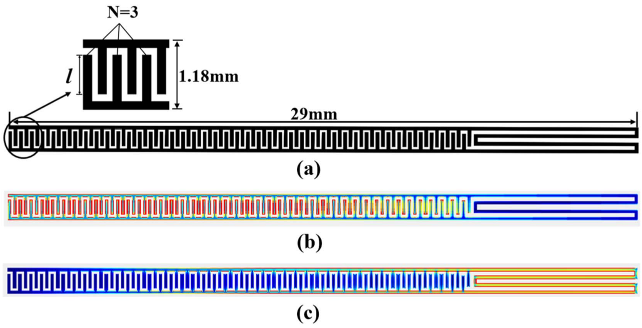

Figure 1. (a) Layout of proposed the resonator with a 0.15 mm line width. (b) Charge distribution of the proposed resonator. (c) Current distribution of the proposed resonator.

frequency resources and the problem of increasing interference from out-of-band signals. A very high first harmonic is also required to prevent adjacent-channel interference, especially at low frequencies. Therefore, it is significant for the low frequency filters to design a compact structure with a very high out-of-band rejection and first harmonic. In recent years, various kinds of HTS filters with excellent performances have been constructed successfully [14]. Many highly selective filters [1, 2, 6, 15, 16] have been developed with more than 20 poles. But high order filters usually have a high center frequency and have little influence on the adjacent channel. For a low frequency filter, Dustakar and Berkowitz [17] presented a 5-pole HTS ultra-narrowband filter with a center frequency of 700 MHz. Jin *et al* [18] designed an 8-pole ultra-narrowband HTS filter with a central frequency of 650 MHz, where the measured skirt slope exceeded 70 dB MHz^{-1}. Lu *et al* [19] presented a 6-pole HTS ultra-narrowband filter with double U-type secondary coupling structures at 600 MHz with a 70 dB out-of-band rejection. Wang *et al* [5] designed a 6-pole HTS filter with a center frequency of 700 MHz and a 55 dB out-of-band rejection by using interdigital structure resonators. But the orders of most UHF band filters are less than 10 and only a few filters have a high first harmonic, which cannot meet the requirements of higher selectivity.

According to the frequency response specifications, the filter for a radar receiver should have a 495 MHz center frequency and a 5 MHz passband. The insertion loss should be less than 0.5 dB and the ripple should be less than 0.2 dB. The out-of-band rejection should be more than 80 dB at 500 MHz and 490 MHz to reduce interference between adjacent channels. A wide stopband is also needed to avoid interference from various kinds of noise sources, especially at low frequency. In this article we present an interdigital structure resonator which has a high first harmonic frequency. The characteristics of this resonator are theoretically studied and explained. Considering the requirements, a 15-pole narrowband HTS filter with a 1% fractional bandwidth is designed based on this resonator. The measured filter shows excellent selectivity and suitably matches the simulations.

2. Design and analysis of the resonator

The proposed resonator consists of an interdigital structure and a meander-line structure, as shown in figure 1. Sonnet software is used to acquire the charge and current distribution of proposed resonator.

The interdigital structure has a high first harmonic frequency. The resonant frequency of half-wavelength resonator can be expressed as follows:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

where L and C denote the self-capacitance and self-conductance of the resonator. When the half-wavelength resonator resonates at the fundamental frequency, the charges of adjacent interdigital fingers are opposite and the self-capacitance is large. When the half-wavelength resonator resonates at the first harmonic frequency, the charges of adjacent interdigital fingers are the same and the self-capacitance is small. According to equation (1), under the same fundamental frequency, the larger the interdigital fingers capacitance, the higher harmonic frequency is.

The equivalent capacitance of interdigital fingers can be expressed by the expression [20]:

$$C_{\rm I} = 3.937 \times 10^{-5} l(\varepsilon_r + 1)[0.11(N - 3) + 0.252] \qquad (2)$$

where ε_r denotes the relative dielectric constant, l denotes the depth of the interdigital fingers and N denotes the number of interdigital fingers as shown in figure 1. According to the equation (2), we can get a larger interdigital fingers capacitance by increasing the number of interdigital fingers at the same depth of interdigital fingers. A larger interdigital fingers capacitance can also make the resonator more compact according to equation (1). Figure 2 shows the simulation results from the Sonnet software. Figure 2(a) shows that under the same depth of interdigital fingers, the more interdigital fingers there are, the higher the ratio k (f_1/f_0) is, where f_1 denotes the first harmonic frequency and f_0 denotes the fundamental frequency. Figure 2(b) shows that for the same number of interdigital fingers, the deeper they are, the higher the ratio k is. Figures 2(c), (d) show that compared with a spiral resonator, the interdigital structure resonator is more compact and has a high first harmonic frequency, which is consistent with theoretical analysis.

The resonator can also bind the electric field energy in the interdigital fingers, which can weaken the coupling of adjacent resonators. The weak coupling is beneficial for reducing the size of the narrowband filter. Figure 3 shows that the interdigital structure can weaken the coupling of adjacent resonators effectively and make the filter more compact.

3. Filter design

The circuit designed in this work is based on the Chebyshev filter prototype. The equivalent circuit model of the 15-pole filter is shown in figure 4. The preliminary external Q factor and coupling coefficient $k_{i,i+1}$ between resonators of the

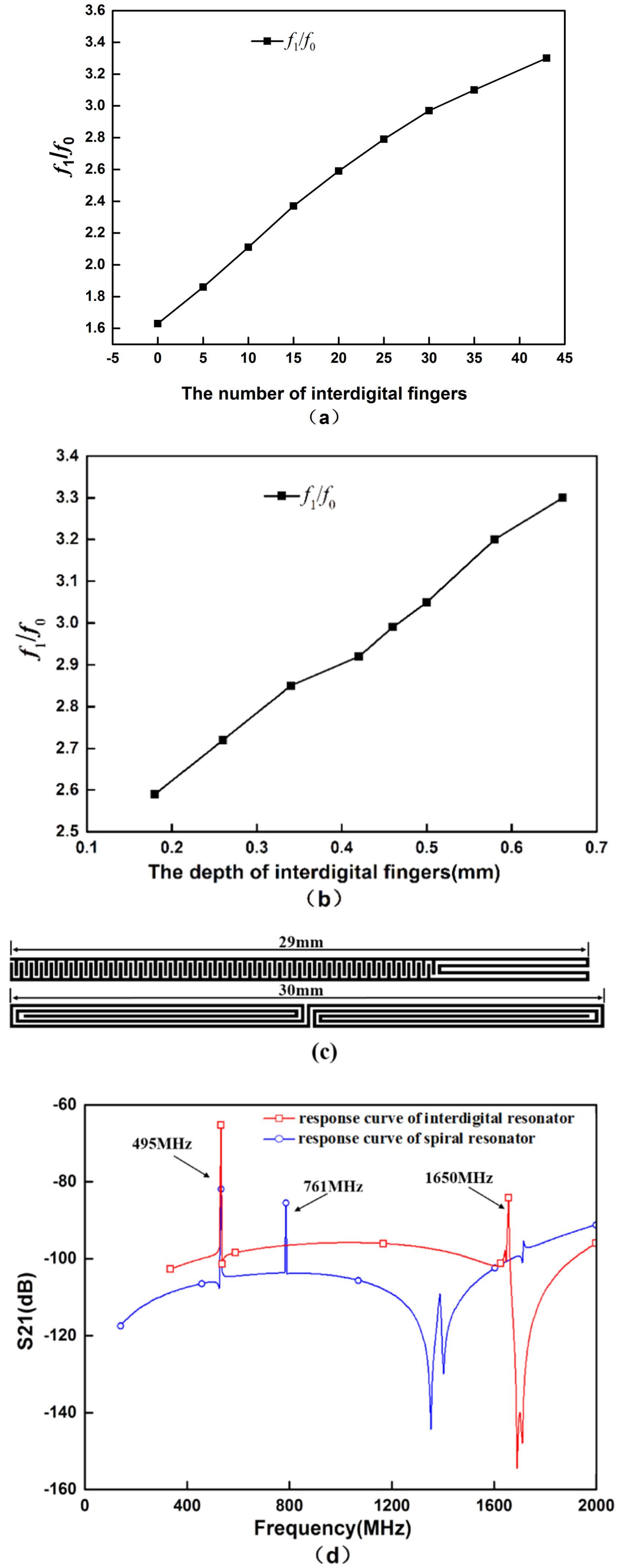

Figure 2. (a) The ratio k (f_1/f_0) of the first harmonic frequency (f_1) and fundamental frequency (f_0) changes with the number (N) of interdigital fingers. (b) The ratio k changes with the depth of interdigital fingers. (c) The interdigital structure resonator and the spiral resonator. (d) The frequency response curve of the interdigital structure resonator and spiral resonator.

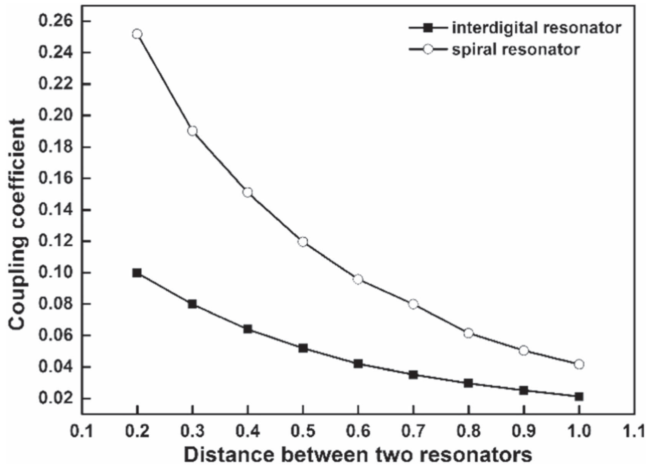

Figure 3. The coupling coefficients varies with the distance of two resonators of interdigital structure and spiral structure.

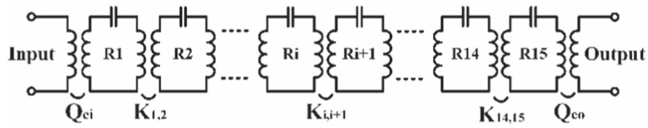

Figure 4. The equivalent circuit model of the 15-pole filter. R denotes the resonator.

bandpass filter can be obtained as follows [21]:

$$k_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}}, \tag{3}$$

$$Q_{ei} = Q_{eo} = \frac{g_i}{FBW} \tag{4}$$

where FBW denotes the fractional bandwidth and g_i is defined as the conductance parameters of the Chebyshev low pass prototype.

Through integrated optimizing using software according to the equivalent circuit model, the final coupling coefficient and external Q factor is shown as follows:

$$\begin{aligned} k_{1,2} &= k_{14,15} = 0.009\,073 \\ k_{2,3} &= k_{13,14} = 0.006\,081 \\ k_{3,4} &= k_{12,13} = 0.005\,526 \\ k_{4,5} &= k_{11,12} = 0.005\,331 \\ k_{5,6} &= k_{10,11} = 0.005\,245 \\ k_{6,7} &= k_{9,10} = 0.005\,203 \\ k_{7,8} &= k_{8,9} = 0.005\,186 \\ Q_{ei} &= Q_{eo} = 83.20. \end{aligned} \tag{5}$$

The proposed resonators have two coupling patterns as shown in figure 5. The coupling coefficient varies with the distance between the adjacent resonators. The coupling pattern aligned in the same direction was selected in this design to get a more compact structure. The distance between adjacent resonators is modified to agree with the theoretical coupling coefficient.

The external Q factor is determined by the feed lines, the first and the last resonators. The first and the last resonators with feed lines are modified to agree with the theoretical external Q factor. Due to the inevitable parasitic effect, the geometrical configuration of the filter still needs optimization

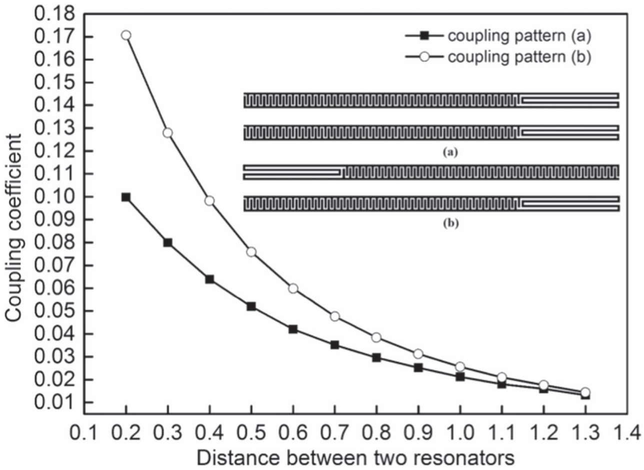

Figure 5. Coupling coefficient of two coupling patterns.

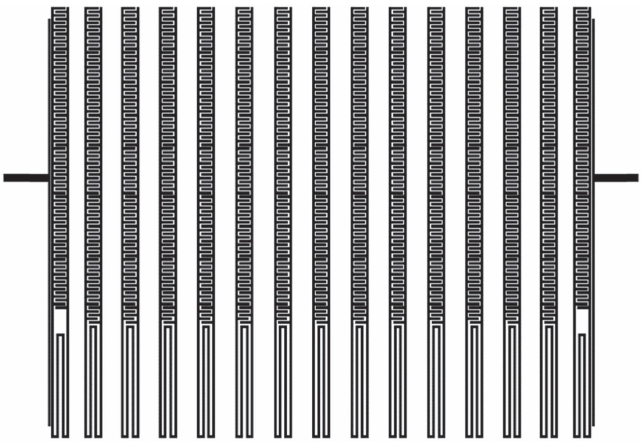

Figure 6. Layout of the HTS filter.

after the preliminary design. The final layout of the HTS filter is shown in figure 6. The results of the simulation are represented in figure 7(b).

4. Fabrication and experiment

The 15-pole filter is fabricated with a double-sided YBCO thin film on a 2 inch diameter, 0.5 mm thick MgO wafer using photolithography and ion etching technology. The overall HTS circuit size is only 36.98 × 29.15 mm without the feed lines. The HTS filter circuit is assembled into a gold-plated metal shield box. The photograph of the HTS filter is shown in figure 8.

The filter is mounted in a high vacuum multi-layer insulated dewar, cooled by liquid nitrogen and measured with a network analyzer. Figure 7(a) presents the measured responses of the HTS filter from 470–520 MHz. The test results show that the center frequency of the filter is 494.8 MHz and the 1 dB bandwidth is 5 MHz, which is 1% fractional bandwidth. The return loss of the measured filter is better than 15 dB. The slope of the filter was about 85 dB MHz^{-1} at the band edge of the filter. Figure 7(b) presents the comparison between the experimental

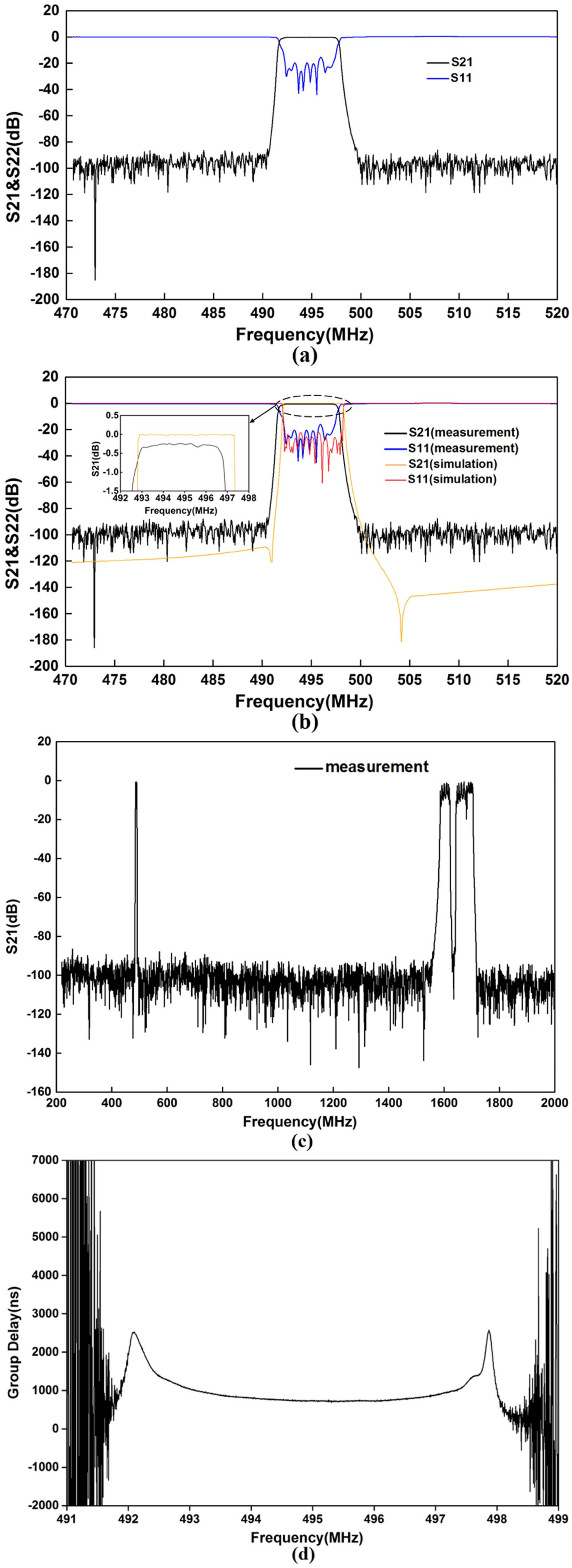

Figure 7. Photograph of the fabricated filter.

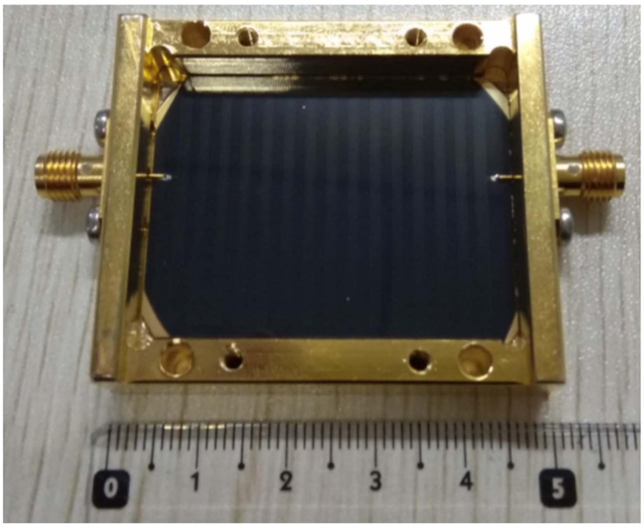

Figure 8. (a) Measured responses of the filter. (b) Simulated (by Sonnet software) and measured results of the filter. (c) Wideband response of the filter. (d) Measured group delay of the filter.

and simulation data using Sonnet software. The zoomed-in view shows that the measured filter has an insertion loss of less than 0.3 dB. Figure 7(c) presents the wideband response of the filter. The out-of-band rejection is higher than 85 dB, which reaches the limit of the instrument noise. The center frequency of the first harmonic is about 1640 MHz, which is 3.3 times higher than the fundamental frequency. Figure 7(d) presents the measured group delay of the filter. The steep out-of-band rejection characteristic introduces an inevitable uneven group delay, especially at the passband edge. However, the usable frequencies concentrate in the vicinity of central frequency and the group delay is relatively even, which can meet the needs of applications. Equalization of the group delay deviation will be studied in future work.

5. Conclusion

A 15-pole UHF band HTS filter with a high first harmonic is developed based on an interdigital structure resonator. The resonator is compact and very suitable for weak coupling. The circuit size is only 36.98 × 29.15 mm. The center frequency of the filter is 494.8 MHz and the 1 dB bandwidth is 5 MHz, which is 1% fractional bandwidth. The measured filter shows an excellent selectivity, the out-of-band rejection is higher than 85 dB, which reaches the limit of the instrument. At the band edge of the filter, the slope was about 85 dB MHz^{-1}. The measurements suitably match the simulations.

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ORCID iDs

Xiao Yu https://orcid.org/0000-0002-9251-9373

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