RAPID COMMUNICATION

A high-temperature superconducting filter with controllable transmission zero*

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This paper presents a novel microstrip feedline structure to introduce an extra and controllable transmission zero (TZ) with high rejection for a narrowband filter. This structure loads a reconfigurable capacitor at the end of the input feedline without changing the main structure of the filter. The capacitor is recognized by a 2-bit inter-digital capacitor array. The asymmetrical microstrip feedline structure is suitable for multiple-pole filter designs. A low-loss six-pole high-temperature superconducting bandpass filter with a reconfigurable TZ is designed and fabricated. The center frequency of the filter is 5.22 GHz with TZ at the lower stopband. The TZ can be tuned among four different states. The out-of-band rejection at the TZ frequency is higher than 90 dB, and the insertion loss is lower than 0.92 dB. The measured results are consistent with the simulations.

Keywords: superconducting, narrowband filter, transmission zero

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1. Introduction

Filters are playing an important part in modern communication systems. More and more articles focus on different kinds of filters.[1–6] Introducing transmission zeros (TZs) at the rejection band can raise the selectivity of a filter without increasing its complexity and order. Thus, filter design with TZs is an important research topic.[7–14]

In order to work in the increasingly complicated electromagnetic environment, a TZ of the filter should be not only deep but also reconfigurable or tunable. A reconfigurable TZ with high rejection is useful in resisting changeable out-of-band interferences. However, only a few articles have paid attention to reconfigurable or tunable TZs. Zhang and Chen[15] proposed two bandpass filters with one or two tunable TZs. Some varactors combined with tapped $\lambda/4$ stubs were utilized to introduce and tune TZs. Some microstrip bandpass filters with one or more TZs were presented in Refs. [16]–[18]. The TZs were controlled by certain parameters in the simulation phase. However, the TZs of the fabricated filters cannot really be tuned. Chiou and Rebeiz[19] presented a three-pole tunable filter with TZ and bandwidth control. One of the TZs could be tuned from 1.37 GHz to 1.64 GHz by using varactor diodes. Zhou *et al.*[20] presented two bandpass filters with tunable center frequency and reconfigurable TZs. Tapped stubs combined with varactors were utilized to reconfigure the TZ positions. Yang and Rebeiz[21] proposed a four-pole bandpass filter with two TZs that can be moved from the upper to the lower stopband by tuning the varactor diodes.

Some of the tunable TZs cannot be flexibly controlled, because the fabricated filters do not contain turning elements. Whereas the filters with real reconfigurable TZs always have two disadvantages. The insertion losses in the passband are high, and the rejections in the stopband are not sufficiently high at the frequencies of TZs. High-temperature superconducting (HTS) filters have the advantage of low insertion loss. However, significantly few HTS filters have reconfigurable TZs, because common varactor diodes that can tune the TZ will degrade the insertion loss of the HTS filter. Sekiya *et al.*[22] proposed an HTS three-pole filter. Some π-shaped waveguides were used to tune the bandwidth of the filter between two different states. A TZ besides the passband was simultaneously tuned.

This study presents a novel asymmetrical microstrip feedline structure to realize a reconfigurable TZ with high rejection for a low-loss bandpass filter. A reconfigurable capacitor is loaded at one end of the input feedline in order to introduce a controllable TZ at arbitrary frequencies without changing the major structure of the filter. The capacitor is recognized by an N-bit inter-digital capacitor (IDC) array. A six-pole bandpass filter with a reconfigurable TZ is designed and fabricated. The center frequency of the filter is 5.22 GHz with a TZ in the lower stopband. The TZ has four states with frequencies in the range from 4.84 GHz to 4.95 GHz. The out-of-band re-

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jections of the four states at the frequencies of TZ are higher than 95 dB. The insertion loss is also maintained at less than 0.95 dB. The measurements are in good agreement with the simulations.

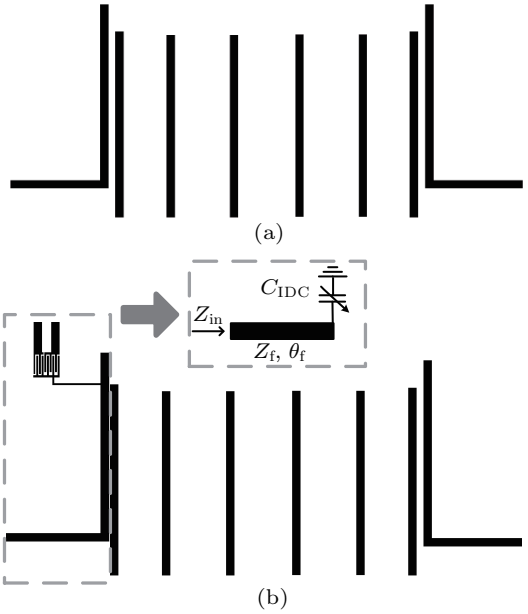


Fig. 1. (a) Layout of a common six-pole filter without TZ. (b) Layout of the proposed six-pole filter with a reconfigurable TZ.

2. Design of the asymmetrical feedline and the filter with a reconfigurable TZ

Figure 1(a) shows the layout of a common six-pole Chebyshev bandpass filter without TZ. An asymmetrical feedline structure is proposed in this study to introduce an additional TZ without changing the main body of the filter. The feedline structure and its simplified model are shown in Fig. 2. The structures and models are about the input feedline without requiring a special design in the output feedline. Therefore, the feedline is asymmetrical. Figure 2(a) demonstrates the simplified equivalent circuit model of the input feedline. Figure 2(b) shows the basic microstrip model of the input feedline. The final layout of the input feedline has been slightly optimized to a smaller size, as shown in Fig. 2(c). The main part of the input feedline (L_1 in Fig. 2(b)) is equivalent to the microstrip (Z_f, θ_f) shown in Fig. 2(a). The characteristic impedance of the feedline (Z_f) should be 50 Ω to meet the requirements of impedance match. The feedline width W is set to 0.48 mm based on the calculation in Ref. [23]. Instead of common high-loss variable capacitors, a two-bit IDC array is loaded at the end of the input feedline, which is equivalent to the lumped C_{IDC} in Fig. 2(a). This distributed structure has a minimal effect on the insertion loss of the HTS reconfigurable filter.[24,25]

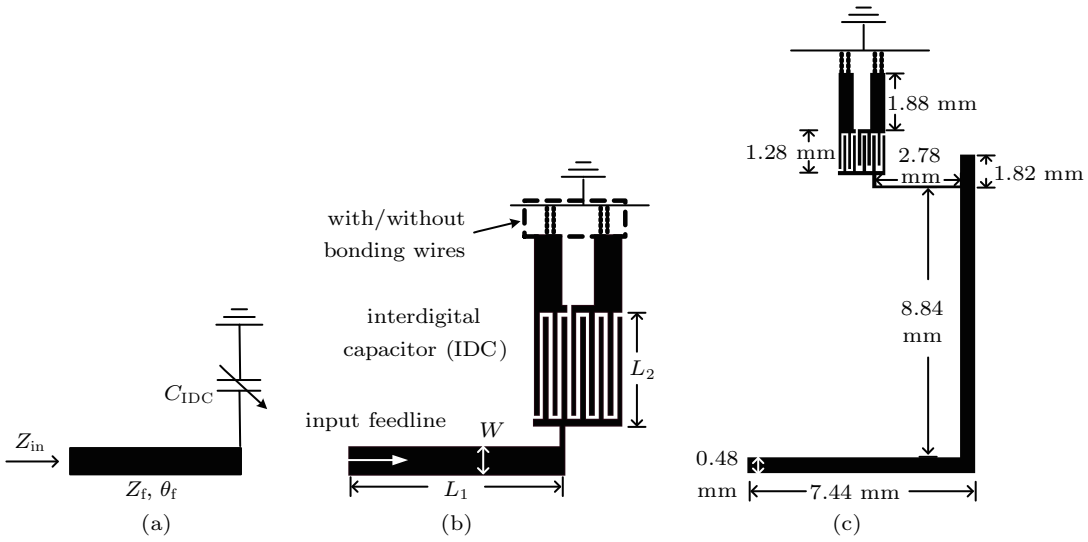


Fig. 2. (color online) (a) Simplified equivalent circuit model of the input feedline. (b) Basic microstrip input feedline model. (c) Layout of the input feedline in the filter.

The circuit in Fig. 2(a) produces a TZ by analyzing the impedance looking into the input feedline. The common impedance transforming equation[23] is used to obtain the relationship between the frequency of the TZ and the parameters of the circuit elements, as shown below:

$$f_{TZ} = \frac{1}{2\pi Z_f C_{IDC} \tan\theta_f}, \tag{1}$$

where θ_f is the electrical length of the feedline at the frequency of TZ (f_{TZ}). f_{TZ} depends on the length of the feedline and the equivalent capacitance of the IDC (C_{IDC}). That is, f_{TZ} decreases with the increase of the two parameters. Thus, f_{TZ} can be set at any required frequency.

Two bonding blocks exist between the IDC and the ground, as shown in Fig. 2(b). By separately connecting different bonding blocks to the ground, four different states of the input feedline are recognized, namely, states (00), (01), (10), and (11). The different states represent various C_{IDC} in Fig. 2(a). Among them, state (00) has the smallest C_{IDC},

whereas state (11) has the largest.[24] Figure 3 shows the simulated S_{21} curves of the four states. The dimensions are as follows: $L_1 = 14.8$ mm, $L_2 = 1.4$ mm, and $W = 0.48$ mm. The TZ introduced by the asymmetrical feedline can be flexibly reconfigured from 3.349 GHz to 2.86 GHz. The frequency of the TZ decreases with the increase of $C_{\rm IDC}$ from state (00) to state (11), which agrees with Eq. (1). The rejection at $f_{\rm TZ}$ of any state is higher than 110 dB.

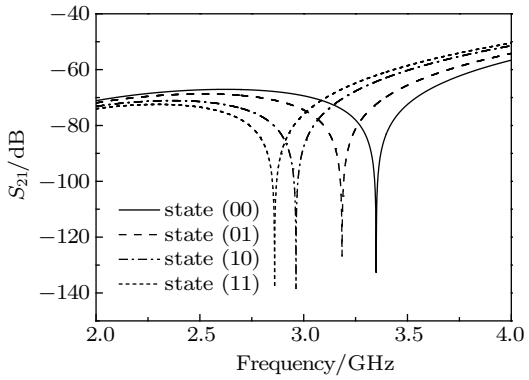


Fig. 3. Simulated S_{21} curves of the four states in Fig. 2(b).

The entire structure of the filter is fabricated by lossless HTS materials, except for the bonding wires in Fig. 2(b), to decrease the insertion loss of the filter. The bonding wires are composed of ordinary metals and they are necessary to tune the TZ. Figure 4 shows the dependence on the resistance of the bonding wire. The responses of the reconfigurable TZ is analyzed and simulated using Sonnet EM. Given the resistance of the bonding wire increasing from 0 Ω to 20 Ω, the rejection of the TZ becomes low from $>$ 120 dB to 80 dB, whereas its frequency becomes high. In order to reduce the effect to the rejection of the TZ, the resistance of the bonding wire should be less than 3 Ω.

The gray lines in Fig. 5 show the simulated responses of a common six-pole HTS parallel combline filter, whose layout is shown in Fig. 1(a). The filter has no TZ in the stopband. After the application of the proposed feedline structure, a filter with a reconfigurable TZ is designed, as shown in Fig. 1(b).

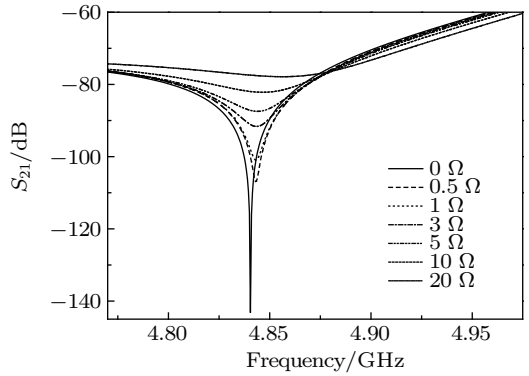


Fig. 4. Different rejections at the frequency of TZ under different resistances of the bonding wires.

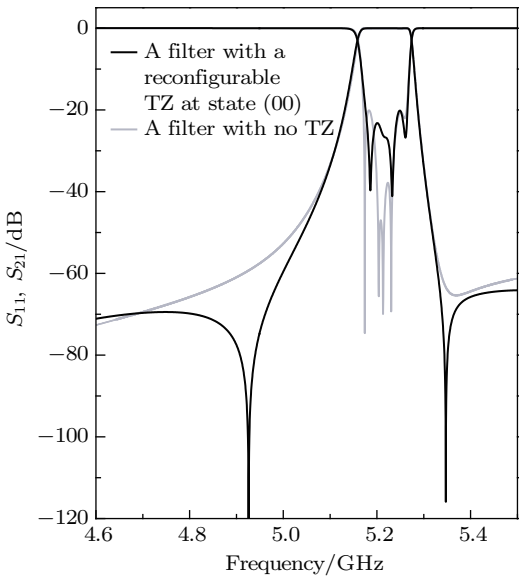


Fig. 5. Simulated responses of the common parallel combline filter without TZ (Fig. 1(b)) and the filter with the asymmetrical feedline structure (Fig. 1(a)).

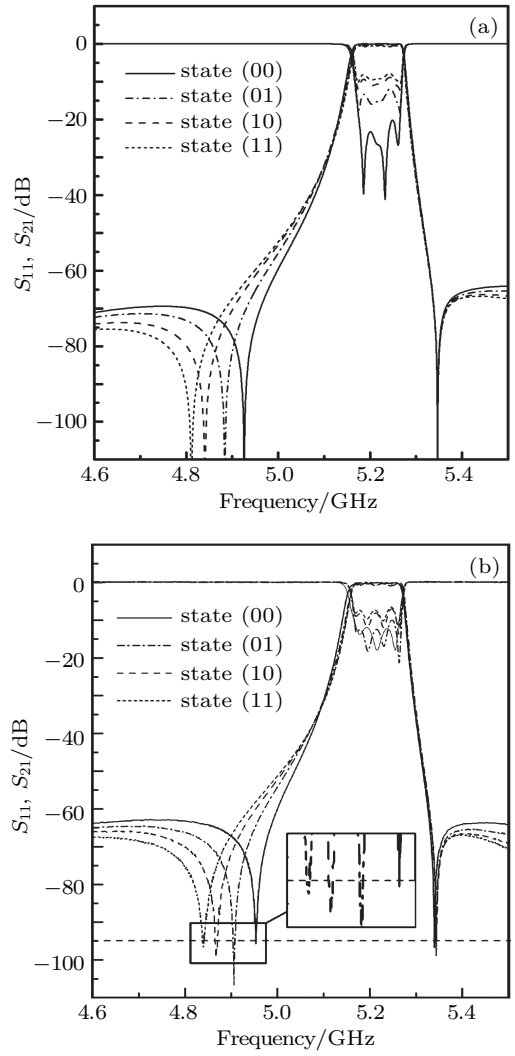


Fig. 6. (a) Simulated responses of the filter with a reconfigurable TZ. (b) Measured responses of the filter with a reconfigurable TZ.

The major filter structure remains virtually unchanged. Only the distance between the input feedline and the first resonator

is changed. Figure 5 shows that the TZ introduced by the feedline structure sharpens the rejection skirt of the passband. The rectangle coefficient decreases from 3.7 to 2.7. Moreover, the rejection at the TZ frequency increases over 30 dB. The in-band insertion loss maintains at less than 0.1 dB, which is as good as the filter without TZ. This comparison proves that the proposed asymmetrical feedline structure can recognize a reconfigurable high-rejection TZ and increase the selectivity of a low-loss filter.

Figure 6(a) and Table 1 present the simulated filter performance of the four states. The center frequency of the filter is approximately 5.22 GHz with a bandwidth of approximately 110 MHz. The reconfigurable TZ in the lower stopband, which is introduced by the proposed asymmetrical feedline, can be tuned discretely from 4.93 GHz to 4.81 GHz. Different states have different TZ locations. Thus, the skirt slope at the low-frequency edge is reconfigurable. The other TZ in the upper stopband is due to self-coupling.[26]

Table 1. Simulated and measured responses of the filter at the four states.

Filter states		(00)	(01)	(10)	(11)
Center frequency/GHz	simulated	5.22	5.22	5.22	5.22
	measured	5.21	5.22	5.22	5.22
Bandwidth/MHz	simulated	116	112	110	110
	measured	118	115	114	112
TZ frequency/GHz	simulated	4.93	4.88	4.84	4.81
	measured	4.95	4.91	4.87	4.84
Rejection at the TZ frequency/dB	simulated	>120	>120	>120	>120
	measured	95	107	99	97
Insertion loss/dB	simulated	0.04	0.29	0.6	0.78
	measured	0.28	0.32	0.81	0.92

3. Fabrication and measurement of the filter

The proposed six-pole HTS filter is fabricated on the upper side of a double-sided 500-nm-thick YBCO thin film deposited on a 0.5-mm-thick MgO substrate. The relative dielectric constant is approximately 9.7. The overall circuit size is 32 mm $\times$18 mm. A photograph of the filter at state (00) (Fig. 1(b)) is patterned using photolithography and ion etching technology. The entire circuit is then mounted on a gold-plated metal carrier assembled into a shield box. Different states are manually realized by connecting different IDC groups to the shield box using metal bonding wires. The filter is cooled down to 65 K by a Stirling cooler and measured with an Agilent N5230A network analyzer.

Figure 6(b) and Table 1 show that the measured results suitably match the simulations. The frequencies of the lower TZ can be reconfigured from 4.84 GHz to 4.95 GHz with minimal effect on the filter responses. The rejections at the TZ frequencies are maintained at higher than 95 dB, and the insertion losses are maintained at less than 0.92 dB in the four states. The comparison of the TZ rejection between Fig. 6(b) and Fig. 4 shows that the resistance of the bonding wire is less than 1 Ω. Therefore, the bonding wire can be set as lossless during simulation.

Table 2 compares the proposed filter with other filters. The proposed filter has similarly low insertion loss, as well as the other HTS filters. However, a reconfigurable TZ with the highest rejection is achieved in the proposed filter.

Table 2. Comparison between the presented filter and other filters with tunable TZs.

Ref.	Filter order	Center frequency/GHz	Tuning range of TZ/GHz	Insertion loss/dB	Rejection at the frequency of TZ/dB
[15]	2	0.9	0.83–0.99	$\sim$3	$\sim$25–35
[19]	3	1.5–2.2	1.37–1.64	3–6	$\sim$25–55
[20]	2	0.68–1.02	$\sim$0.6–1.2	3.2–6.1	$\sim$25–40
[21]	4	1.25–2.1	$\sim$1.5–2.0	3.5–8.5	$\sim$40–70
[14]	HTS, 8	2.0	cannot tune	$\sim$0.3	$\sim$40–60
[22]	HTS, 3	5–5.09	$\sim$5.5–5.7	$\sim$0.8–1.6	$\sim$60–75
Proposed filter	HTS, 6	5.2	4.84–4.95	0.28–0.92	95–107

4. Conclusion

A novel asymmetrical feedline structure is proposed and analyzed. The structure introduces a reconfigurable and high-rejection TZ for a filter at any required frequency, and increases filter selectivity. A low-loss six-pole HTS filter with a reconfigurable TZ is designed, fabricated, and measured based on the structure. High rejection at the frequency of TZ and low insertion loss are achieved simultaneously. The measurements are in good agreement with the simulations. This structure can be further used when designing filters with multiple poles and increased number of TZs.

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