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Superconducting Compact Coplanar Waveguide Filters Based on Quarter-Wavelength Spiral Resonators with Suppressed Slot-Line Mode

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Abstract *Quarter-wavelength superconducting spiral resonators have been used to realize a coplanar waveguide bandpass filter and bandstop filter around the center frequency of 6 GHz. These compact coplanar waveguide filters have been made from 300-nm-thick NbTiN thin film on a 525-μm-thick silicon substrate. The bandpass filter is a six-pole Chebyshev filter with two zero transmissions due to nonadjacent coupling in its structure. Accurately microfabricated air-bridges have been used to suppress the undesired slot-line mode in this filter. The bandstop filter is a very simple two-pole structure that used wire bonding to suppress the slot-line mode. Measurements have been done at a temperature of 4.2 K in liquid helium. Good agreement between simulation and measurement results has been found.*

Keywords compact microwave filter, coplanar waveguide filters, spiral resonators, superconducting filters, slot-line mode suppressed

1. Introduction

Superconducting microwave filters have been used frequently for different goals. Very low insertion loss, good sharpness, and small size are the advantageous properties of superconducting filters, which motivate scientists toward this kind of microwave filter. One novel type of compact planar microwave filters is the spiral filter, which uses single spiral resonators, and can be realized in the forms of microstrip structure made by superconductors (Zhang et al., 2005, 2006) or normal conductors (Luo et al., 2010; Roshanmanesh & Javadzadeh, 2012) and coplanar waveguides (CPWs) (Ma et al., 2006). Although superconducting filters may show nonlinear behaviors in relatively high input powers (Xu et al., 1995), it is mostly irrelevant and can be predicted accurately (Javadzadeh et al., 2013).

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CPW microwave filters are the best choice for realizing microwave integrated circuits (MICs) and on-chip microwave signal conditioning. A common drawback of CPW filters is the excitation of the slot-line mode. The best solution for suppressing the slot-line mode is to electrically connect the two grounds on both sides of the center line of the CPW to equalize their potential. For this purpose, wire bonding can be employed, but a more accurate and reproducible method is through the implementation of lithographed air-bridges. Moreover, compared with microstrip structures, the CPW is more suitable for quarter-wavelength resonator filters, because, by having the ground planes on the same substrate surface as the signal line, grounding of CPW circuits requires no vias. Using a single-side deposited film on the substrate also simplifies the fabrication process.

In this article, the design, fabrication, and measurements of two kinds of superconducting CPW spiral filters are presented. The first is a six-pole quasi-elliptic bandpass filter (BPF) with a 400-MHz bandwidth around 6 GHz, which, because of non-adjacent coupling, shows quasi-elliptic frequency response. This BPF uses accurate air-bridges to suppress the slot-line mode. These air-bridges are made of aluminum and are realized by e-beam lithography. The overall occupied area for this filter is less than 5 mm × 3.6 mm, which is very small in this frequency band.

The second is a two-pole bandstop filter (BSF), around 6-GHz center frequency, which uses wire bonding to suppress the slot-line mode. In both cases, quarter-wavelength resonators are used, which leads to more compact structures. As it is difficult to obtain accurate explicit equations for resonance and coupling coefficients of spiral resonators, the full-wave electromagnetic simulation by Sonnet EM (Sonnet Software Inc., 2012) is used in this study.

2. Filter Design

The first filter is a six-pole BPF with bandwidth of 400 MHz around 6 GHz. To design a microwave BPF, a prototype low-pass filter (LPF) must first be designed, and the coupling coefficients matrix calculated. The computed internal coefficient matrix for a six-pole Chebyshev filter with a bandwidth of 400 MHz around 6 GHz is given as

$$K = \begin{bmatrix} 0 & 0.052 & 0 & 0 & 0 & 0 \\ 0.052 & 0 & 0.0392 & 0 & 0 & 0 \\ 0 & 0.0392 & 0 & 0.0377 & 0 & 0 \\ 0 & 0 & 0.0377 & 0 & 0.0392 & 0 \\ 0 & 0 & 0 & 0.0392 & 0 & 0.052 \\ 0 & 0 & 0 & 0 & 0.0052 & 0 \end{bmatrix}.$$

An external coupling (the coupling between ports and resonators) of $K_e = 0.057$ is calculated for this filter structure. Additionally a nonadjacent coupling, for example, between resonators 2 and 5, leads to having two transmission zeros in the filter frequency-response and gives rise to a quasi-elliptic filter.

The next step of the filter design is to choose a suitable resonator structure; quarter-wavelength spiral resonators are selected herein. Spiral resonators are not only very compact, but they have interesting properties, such as a high Q-factor, high power capability, and insensitivity to the fabrication process. Moreover, quarter-wavelength resonators, in addition to their more compact size compared to their half-wavelength counterparts, have the capability of a second passband and do not have a passband at twice the center frequency. Each resonator has an area of 0.74 mm × 0.57 mm with a line width and gap between adjacent lines of 30 μm.

To realize the external coupling, the structure shown in Figure 1(a) is considered. The external coupling is equal to the ratio of 3-dB bandwidth to the center frequency in the scattering parameter diagram of S_{21} (Roshanmanesh & Javadzadeh, 2012). By changing length L_p, the amount of external coupling can be controlled. Figure 1(b) shows the diagram of external coupling versus the parameter of L_p. Hence, with determination of L_p, the desirable amount of external coupling can be achieved. It is important to consider air-bridges in the simulation procedure.

The internal coupling coefficients should then be realized by determining the distance between resonators in a similar manner (Roshanmanesh & Javadzadeh, 2012). In each case, the suitable internal coupling diagram should be obtained, and then the desirable value can be found. Finally, a global optimization over all parameters must be done. Figure 2 shows the general configuration of the designed quasi-elliptic BPF. The input and output transmission line is a 50-Ω CPW transmission line with linewidth of 30 μm and gap of 20 μm. To shift the transmission zeros near the passband and have sharp skirt selectivity, resonators 3 and 4 should be changed slightly. That means it is not necessary that all resonators be exactly the same and sometimes using unequal resonators can improve the frequency response of the filter. Usually with this asymmetrically technique, the frequency of transmission zeros can be controlled.

An important note in the design of superconducting filters is that kinetic inductance has to be estimated and considered in the simulations. From the measured critical temperature and normal state resistivity of the 300-nm-thick NbTiN films, $Ls = 0.8$ pH/sq was calculated, and this value was used in the definition of superconductor in Sonnet. The resulting filter geometry lead to a spectral response perfectly centered at 6 GHz, as desired.

Another filter structure is a BSF. This notch filter is also based on a quarter-wavelength CPW spiral resonator. For simplicity, this filter contained bonding wires to suppress the slot-line mode. Obviously, using accurate air-bridges can lead to better results.

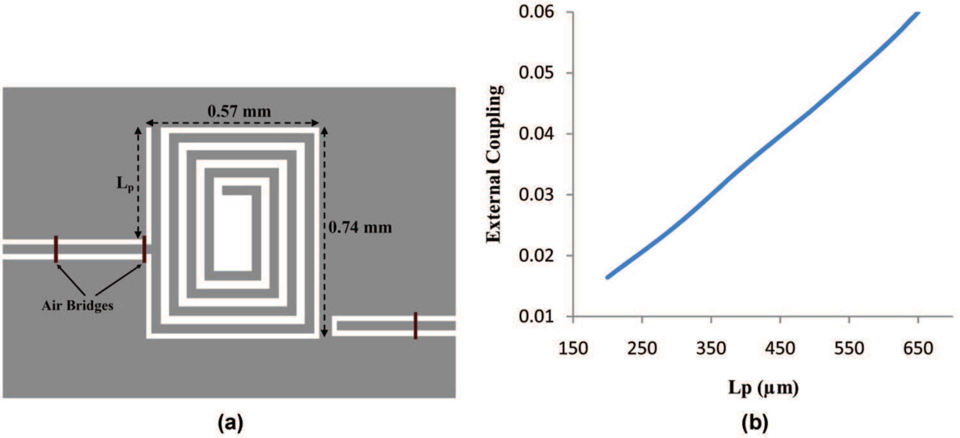

Figure 1. (a) Single spiral resonator; this structure can be used to compute the external coupling; small brown sections represent air-bridges and (b) value of calculated external coupling versus L_p; in this case, $L_p = 0.63$ mm leads to desirable external coupling of $K_e = 0.057$.

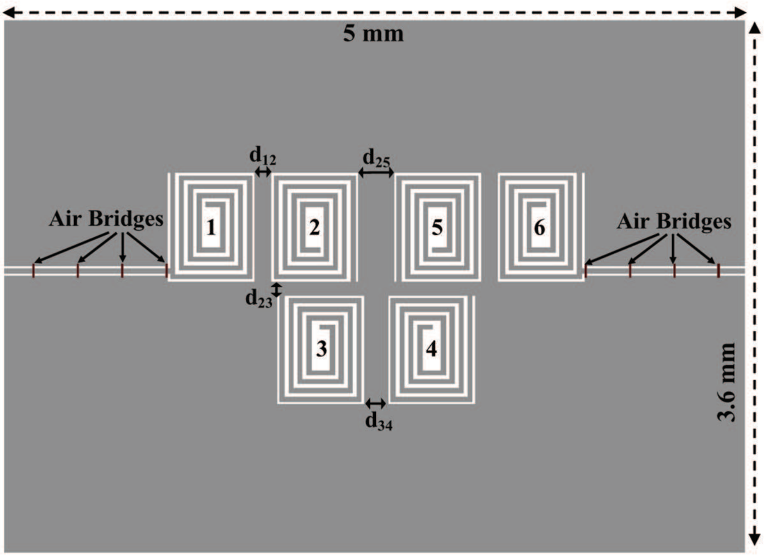

Figure 2. Configuration of the designed quasi-elliptic six-pole BPF. Nonadjacent coupling between resonators 2 and 5 causes two transmission zeros in the filter frequency response. The area considered for the simulation in Sonnet is 5 mm × 3.6 mm; $d_{12} = 110\ \mu$m, $d_{23} = 70\ \mu$m, $d_{34} = 160\ \mu$m, and $d_{25} = 240\ \mu$m. Air-bridges are shown, and their position and number must be considered in the simulations.

3. Fabrication Procedure

Test samples of the filters were realized on a 20 mm × 4 mm silicon substrate having a thickness of 525 μm. The superconducting layer is sputter deposited in a 3-mTorr Ar/N_2 atmosphere (Iosad et al., 2000, 2002). For patterning the structure, an electron beam pattern generator (EBPG) is used in combination with a polymethyl methacrylate (PMMA) resist. Reactive ion etching was employed in order to etch the patterned structure. The realization of the air-bridges required a single PMMA layer, exposed at variable doses: a full dose (of about 1,300 μC/cm^2) for the ground contacts and a gradient of lower doses for the bridged sections. Careful choice of the development time allowed the resulting PMMA structure to be capable of lifting off a subsequent evaporation of a Ti/Al bilayer. The titanium layer was necessary to improve the adhesion and its electrical conductivity is 2.38×10^6.

Figure 3 shows a scanning electron microscope (SEM) picture of one of the fabricated air-bridges. Each air-bridge has the length of 75 μm, width of 10 μm, and approximate height of 2 μm at its waist.

4. Experimental Results

Figure 4(a) shows the measured results of the six-pole quasi-elliptic filter in comparison with simulation results from Sonnet EM. Measured results have good agreement with simulation results. Insertion loss of the filter is very small due to using superconductor resonators. Figure 4(b) depicts the simulated and measured amount of insertion loss of the BPF.

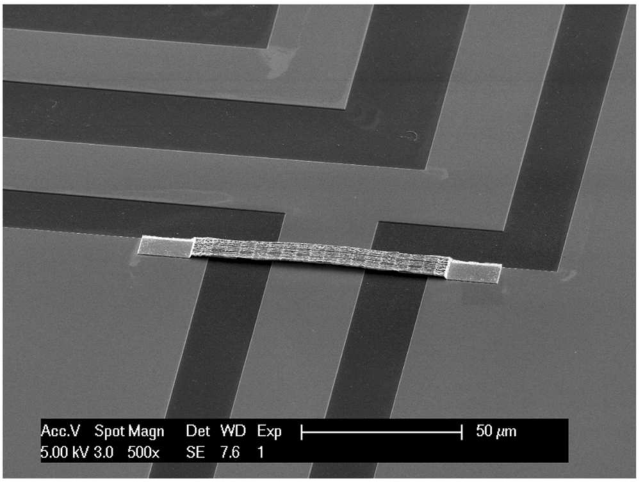

Figure 3. SEM picture of the realized air-bridge for the six-pole BPF. Each air-bridge has the length of 75 μm and width of 10 μm and is made of a titanium/aluminum bilayer.

Figure 5 displays wide band frequency response of the fabricated BPF. Both filters are mounted in the gold-plated copper boxes. Sub-multi-assembly (SMA) connectors are mounted on the boxes, which are soldered on interface boards, and the interface boards wire bonded to the superconducting structure. The interface board is a suitable transition between the microstrip to the CPW. Because of the special kind of spiral resonator in which the ground is placed just around the resonator, it is important that there is an air gap behind the CPW structure. Therefore, the floor of the box was machined to suspend the substrate. Despite the high thickness of substrate layer, existence of a ground plane behind it would have lead to changing of resonance frequency of the resonators.

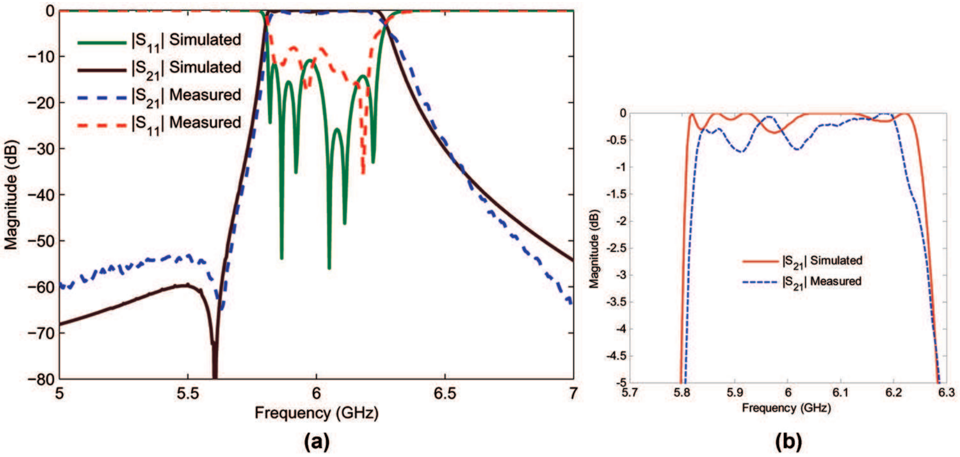

Figure 4. (a) Comparison simulation and measurement results of the scattering parameters of the six-pole BPF; due to using superconducting material, insertion loss in the passband of the filter is very small and (b) comparison simulation and measurement result of the insertion loss of the six-pole BPF.

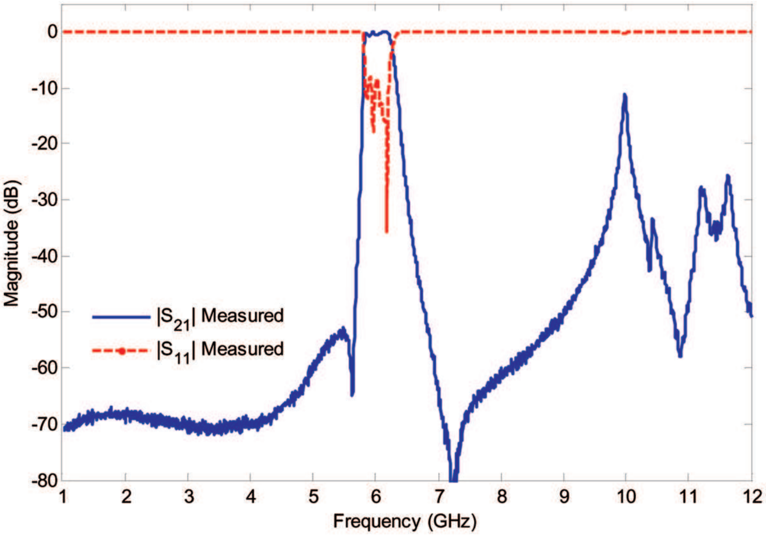

Figure 5. Wideband frequency response of the fabricated BPF. This filter has sharp skirt selectivity, which is important in many applications. Additionally, because of using quarter-wavelength resonators, there is no passband at twice the center frequency.

Figure 6 displays the measured results of the two-pole BSF in comparison with simulation obtained by Sonnet EM. The right inset shows the fabricated BSF in a gold-plated copper box with SMA connectors, and the left inset displays an image of the etched BSF, obtained by optical microscopy. In this filter, wire bonding was used to suppress the slot-line mode. Measurement results have good accordance with simulation results obtained by Sonnet EM.

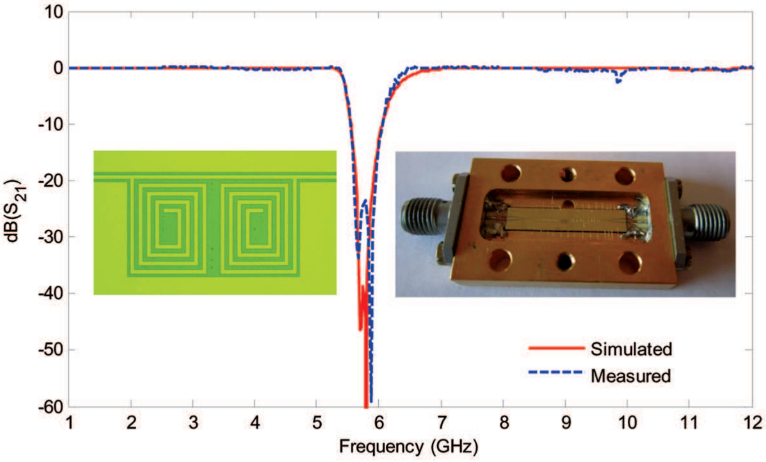

Figure 6. Comparison simulation and measurement results of the scattering parameters of the realized BSF. Right inset shows the fabricated BSF mounted in the gold-plated copper box with SMA connector and pdb transitions, while left inset displays microscope picture of the etched BSF.

5. Conclusion

In this work, two superconducting compact CPW spiral filters were reported. A 300-nm thickness of NbTiN thin film on silicon substrate were used for both filters. The first filter is a six-pole quasi-elliptic BPF that has precise air-bridges to suppress the slot-line mode. The second is a simple two-pole BSF for which bonding wires are used to suppress the slot-line mode. Measurement results of both filters show good agreement with the simulation results of Sonnet EM. These filters can easily be integrated to superconducting microwave devices to provide on-chip signal conditioning.

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