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High Temperature Superconducting Pseudo-Lumped Element Bandpass Filter

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Abstract

A high-temperature superconducting 1.78 GHz bandpass filter, designed for PCS applications, is presented. The structure consists of microstrip pseudo-lumped elements, which enables miniaturization of the filter. A 5-pole microstrip filter could be realized on *a* 37 mm × 9 mm $LaAlO_3$ substrate, using double-sided high-temperature superconducting $YBa_2Cu_3O_{7-\delta}$ thin film. This filter showed 0.7 % fractional bandwidth, 0.3 dB insertion loss, and 12 dB return loss in the passband at 60 K.

Keywords: Microwave Filter, High Temperature Superconductor, Thin Film

I. Introduction

As the wireless communication market grows, demands for high quality filters increase to lessen the interference problem. It is the superconducting filters that reduce this problem since they have low insertion losses and steep skirt characteristics [1] - [4]. The insertion loss of a filter and the noise figure of a low noise amplifier (LNA) are two important parts that determine the total noise figure of a RF front-end of a receiver in a wireless communication system. These can be enhanced using a superconducting filter and a cooled LNA, because the superconducting filter has a low insertion loss and the noise of an LNA is reduced by cooling. A microstrip resonator fabricated with superconducting thin films shows high unloaded Q at microwave frequency due to the low surface resistance of the superconducting films [4]. Due to this, one can use many poles to get sharp skirt characteristics.

Many researchers have reported various types of superconducting microstrip filters such as the distributed element type or the lumped element one [4] - [9]. The distributed type is based on the half-wavelength or the quarter-wavelength resonator that has a simple geometry. Meanwhile the lumped element type consists of inductors and capacitors that have more complex geometry. The lumped element type has the merit that the size is generally much smaller than the distributed one with similar performance. Here it is noted that reduction in filter size enables saving the cooling capacity of the cryocooler.

Though the design rule for lumped element filter is well established, it is not easy to realize the lumped element as a microstrip waveguide. It is due to the fact that the microstrip lumped element actually has both the capacitance and the inductance. Henceforth, the microstrip lumped element is called the "pseudo-lumped element". Here we used a new filter synthesis method of cascading pseudo-lumped elements. Using this design concept, we designed a 5-pole pseudo-lumped element filter with 1.78 GHz center frequency and 12 MHz bandwidth. We fabricated the filter using a double-sided high-T_c superconducting $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film on a 37 mm × 9

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mm $LaAlO_3$ substrate and measured its microwave characteristics at several temperatures.

II. Filter Design

The first step in the filter design was to decide the type of transfer function and the number of poles. If one wants a flat response in the passband, the most desirable type is the Butterworth response. If one wants an equal ripple and sharp skirts, the Chebyshev type is favorable [10]. Here we chose a design for a 5-pole Chebyshev filter to examine our synthesis method. The next step was to find a low-pass prototype circuit that satisfies the desired performance such as the bandwidth and the center frequency. The process for transforming a lowpass circuit to a bandpass one is well known [10].

There are several alternatives in selecting the circuit of a bandpass filter that can be transformed into the microstrip geometry. We presented two possible cases in Fig. 1, where one consists of inductors and the π-type section of capacitors and the other consists of transmission lines with capacitor type couplings at each end. Both circuits have equal transfer functions. Several authors often used the former one [7] - [9], while we are using the latter.

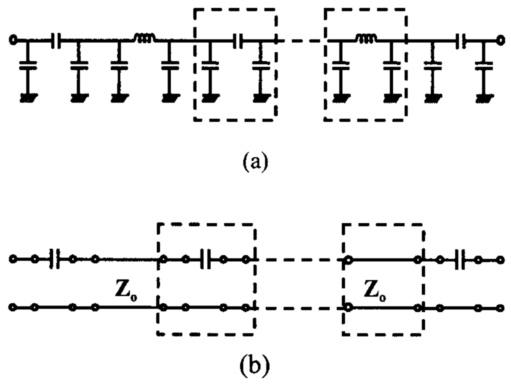

Fig. 1. Circuits of lumped-element bandpass filters. (a) Typical components of this circuit are the π–section of capacitors and an inductor with capacitors at both ends. (b) A capacitively coupled bandpass filter that consists of a capacitor with small bits of transmission line and a plain transmission line. Z_0 means the characteristic impedance of the line.

We divided a circuit in Fig. 1 into several sections. Typical components of this circuit include an inductor with capacitors at both ends and the π–section of capacitors, as shown in Figs. 1(a) and 2(a). We can also divide the capacitively coupled microstrip line into two kinds of section as in Figs. 1(b) and 2(b). One is a capacitor with small bits of transmission lines and the other is a plain transmission line. Each section can be transformed into a pseudo-lumped microstrip geometry as depicted in Fig. 2 (c). The π–type section of capacitors and the capacitor with small bits of lines are transformed into coupled patches. We also used an interdigit type capacitor when strong couplings are required. The inductor with capacitors at both ends and the fragment of the transmission line can be transformed into a meander type inductor. We can obtain the S-parameters of pseudo-lumped microstrip elements such as coupled patches and a meander-type inductor by a full-wave EM simulation software. The S-parameters of the pseudo-lumped microstrip elements are not exactly equal to those of lumped elements. However, it is enough to compare

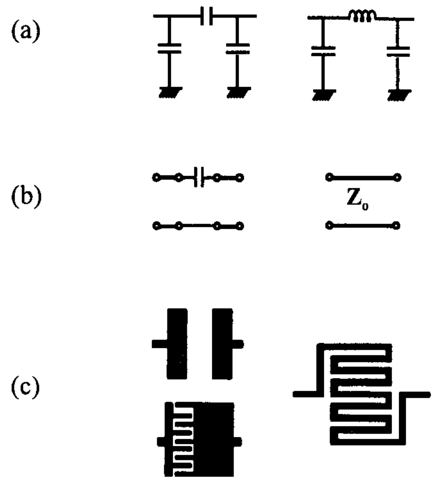

Fig. 2. Realization of the pseudo-lumped microstrip element from the lumped element circuit. (a) The π-section of capacitors and an inductor with capacitors at both ends, (b) a capacitor with small bits of transmission line and a plain transmission line, and (c) the pseudo-lumped microstrip elements; a coupled patch, an interdigit capacitor, and a meander line inductor.

the S-parameters of both elements at the center frequency because we are dealing with a very narrow filter. By comparing these S-parameters, we can determine the size of the microstrip element. The gap between the patches and the length of each patch mainly determines the strength of the capacitive coupling. Meanwhile, the length and the structure of the meander line determine the inductance. After every pseudo-lumped element is determined, the remaining work was just cascading these elements. ometimes, small corrections may be required to get better frequency responses.

The above-mentioned process describes how we designed the 5-pole filter that is fitted into a 37 mm × 9 mm substrate. A schematic of the 5-pole pseudo-lumped element filter design is shown in Fig. 3.

III. Filter Fabrication

The filter was fabricated from a double-sided YBCO film deposited on a 50-mm-diameter, 0.5-mm-thick $LaAlO_3$ substrate. The YBCO material was simultaneously deposited on both sides of the substrate by the 90° off-axis pulsed laser deposition method [11]. The substrate was heated by thermal radiation from a heating element surrounding the substrate. Both sides of the film have almost the same transport properties and morphology. The typical thickness, the transition temperature, and the critical current density of the YBCO film were 0.4 μm, 88 ~ 90 K, and 2 ~ 3 $\times 10^6$ A/cm^2, respectively. The thickness uniformity of the film was about 10 %. The surface resistance of the film was 1.01 mΩ measured at 77 K, 19.56 GHz.

The film was patterned by the conventional photolithography and argon ion-milling method. Gold electrodes were formed on the 50 Ω feed lines by the lift-off process for making electrical contacts with the SMA connectors. The electrical contact between the superconducting ground plane of the filter and the package was provided by 1-μm-thick gold film deposited on top of the bottom YBCO. After the gold deposition, the filter was annealed at 480 °C in an oxygen atmosphere.

The filter was packaged into a gold-coated brass fixture. The electrical connection between the filter and the SMA connector was provided by wire bonding. Fig. 4 shows a photograph of the packaged filter used in this experiment.

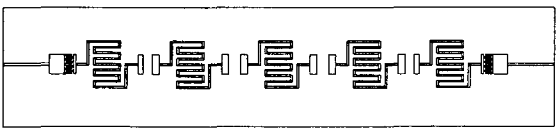

Fig. 3. Layout of a 5-pole pseudo-lumped element microstrip filter on a 37mm × 9mm substrate.

IV. Filter Performance

We measured the S-parameters of the filter using HP8714B network analyzer. The filter was mounted on the cold end of our cryostat in vacuum. To ensure precise measurements of the filter characteristics, we calibrated the semi-rigid cable connections at room temperature. Then we measured the S-parameters of a 1 cm-long, 50 Ω through-line made of a superconducting film at low temperature to check the room temperature calibration. Within the 100 MHz passband around the filter center frequency, the return loss (S_{11}) was more than 30 dB and the insertion loss (S_{21}) was about 0.1 dB for the calibration setup. So the error was almost negligible in the measured data.

The filter characteristics measured at 60 K are shown in Fig. 5, where the computed results are also displayed. We note that measurements were done

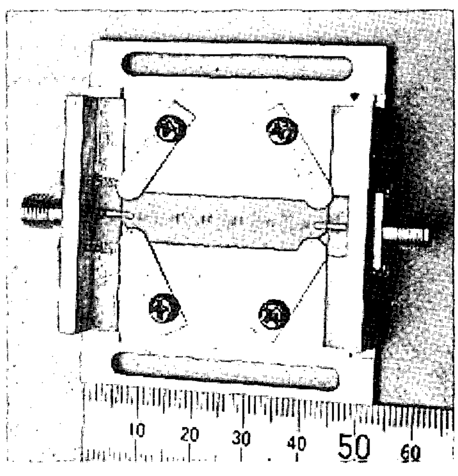

Fig. 4. A photograph of the packaged filter used in this experiment.

without tuning. In the measured data, the center frequency is 1.786 GHz, and passband width (3dB) is 13 MHz (0.7 % fractional bandwidth). The maximum insertion loss and the ripple in the passband are 0.3 dB and 0.2 dB respectively. The filter also showed skirt characteristics of ~3 dB/MHz at the edge of the passband. The out-of-band rejection is about 70 dB at the frequencies of ±50 MHz away from the center frequency.

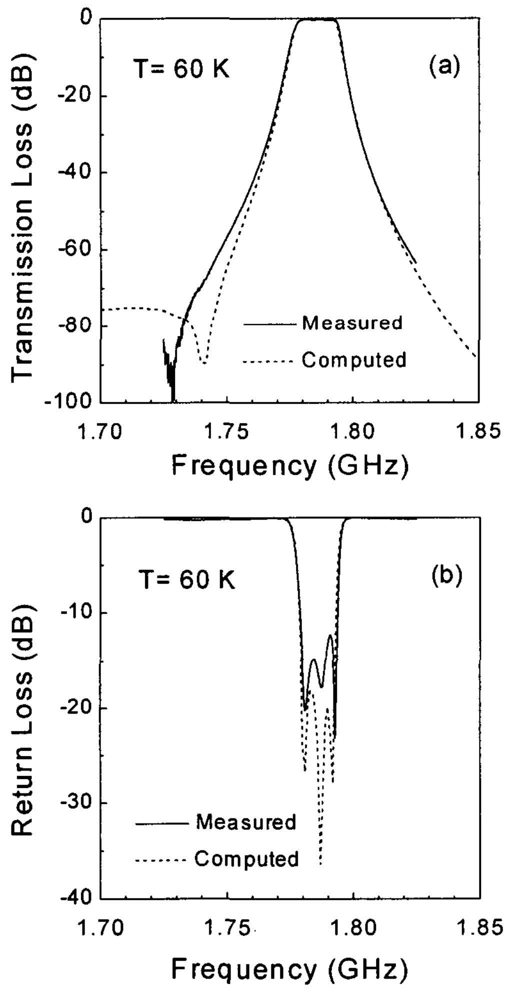

Fig. 5. The measured and computed frequency responses of the 5-pole pseudo-lumped element microstrip filter at 60 K; (a) the insertion loss, S_{21} and (b) the return loss, S_{11}. The solid and dashed lines represents the measured and computed data, respectively.

At the designing stage, all the resonators were assumed as perfect conductors patterned on 0.5 mm-thick $LaAlO_3$ substrates (dielectric constant = 23.7) with perfect-conducting ground planes. The designed value of the center frequency was 1.775 GHz. But there was a small difference in the center frequency between the measured and simulated ones. It is believed that this difference results from the fact that the initial estimation of dielectric constant was too high and the kinetic inductance effect of the superconducting film was completely ignored during the simulation process. To fit the center frequency of the simulated result to the experimental one, we changed the dielectric constant from 23.7 to 23.3, and took the effect of the kinetic inductance into consideration. The computed results shown in Fig. 5 reflect these changes. It is noted here that the simulated results agree well with the measured data for most frequency ranges. The measured data show smaller insertion loss compared to that of computed data at frequencies lower than the passband, which can be due to the effect of filter package [12]. The maximum return loss of the measured data in the passband is worse than that of the computed data. It is believed that the over-etching of the pattern degraded the impedance matching. To improve the matching, tuning was performed with five screws positioned on top of the resonator. After tuning, the return loss improved from 12 dB to 18 dB and the ripple decreased considerably. Meanwhile, the insertion loss showed a slight increase. Fig. 6 shows the improved ripple characteris-

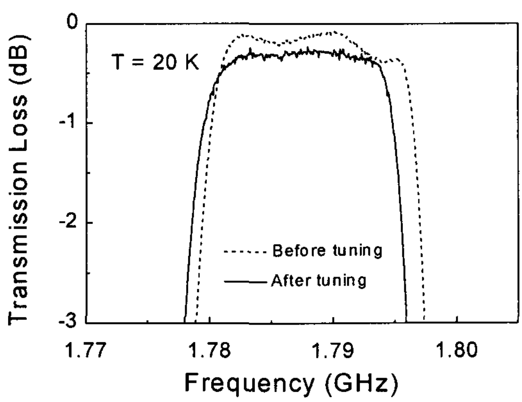

Fig. 6. Ripple details of the frequency response at 20 K (dashed line) with improved ripple characteristics after tuning (solid line).

tics.

V. Conclusions

A high-temperature superconducting pseudo-lumped element bandpass filter was designed for PCS applications by a new design method. Using *a* double-sided high-temperature superconducting $YBa_2Cu_3O_{7-\delta}$ thin film, a 5-pole microstrip filter was fabricated on a 37 mm × 9 mm $LaAlO_3$ substrate. This compact size could be realized by taking advantage of the pseudo-lumped elements. This filter showed 0.7 % fractional bandwidth, 0.3 dB insertion loss, and 12 dB return loss in the passband at 60 K. The measured and simulated results were in good agreement. It was shown that appropriate tuning was needed to improve ripple characteristics. Usefulness of the pseudo-lumped element band pass filter as a device for PCS wireless communication systems are described.

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