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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 make the miniaturization of the filter possible. A 5-pole microstrip filter can be realized on 37 mm × 9 mm $LaAlO_3$ substrate, using double-sided high-temperature superconducting $YBa_2Cu_3O_{7-\delta}$ thin film. This filter shows 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;

1. Introduction

As the wireless communication market grows, the demand for high quality filter increases to lessen the interference problem. It is the superconducting filters that reduce this problem since they have good noise figures 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 receiver in 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 LNA is reduced by cooling it. The microstrip resonator made by superconducting thin film shows high unloaded Q-value at microwave frequency as a result of the low surface resistance of superconducting materials [4]. Due to this high Q-value, one can use many poles to get sharp skirt characteristics.

Many researchers have been presented various types of the superconducting microstrip filter such as the distributed element type or the lumped element one [4] - [9]. The distributed types are based on the half-wavelength or the quarter-wavelength resonator that has simple geometry whereas the lumped element types consist 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 the similar performance. The reduction of filter size had an advantage to save 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

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both the capacitance and the inductance. In spite of the ambiguous terminology, we call it "pseudo-lumped element". We have used a new filter sythesis method by cascading pseudo-lumped elements. Using this design concept, we have designed a 5-pole pseudo-lumped element filter with 1.78 GHz center frequency and 12 MHz bandwidth. We have fabricated the filter using a double-sided high-T_c superconducting $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film on a 37 mm $\times$ 9 mm $LaAlO_3$ substrate and measured its microwave characteristics at several temperatures.

2. Filter Design

The first step in the filter design is 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 Chebysev type is favorable [10]. In our design, we choose 5-pole Chebyshev filter to examine our synthesis method. The next thing to do is finding a low-pass prototype circuit that satisfies desired performance such as the bandwidth and the center frequency. It is well known to transform a lowpass circuit to a bandpass one [10]. There are several alternatives in selecting the circuit of a bandpass filter that can be transformed into the microstrip geometry. We present two possible cases in the Fig. 1. 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 of two circuits have equal transfer functions. Several authors often used former one [7] - [9], while we are using latter one.

We divide a circuit in Fig. 1 into several sections. Typical components of this circuit are an inductor with capacitors at both ends and the π-section of capacitors, as shown Fig. 1 (a) and Fig. 2 (a). We can also divide the capacitively coupled microstrip line into two kinds of section as Fig. 1 (b) and Fig. 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 by 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 as coupled patches. We also use an interdigit type capacitor

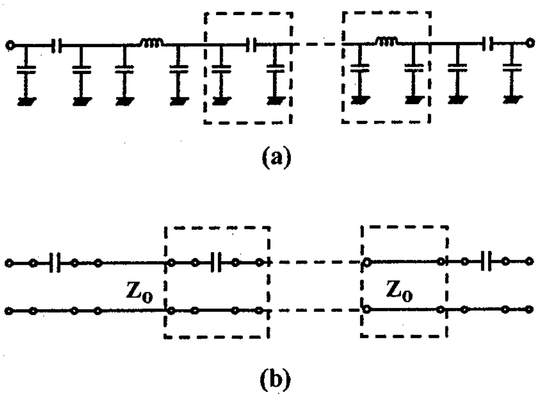

Fig. 1 Circuits of lumped-element bandpass filter. (a) Typical components of this circuit are the π-section of capacitors and an inductor with capacitors at both ends. (b) Capacitively coupled bandpass filter that consists of a capacitor with small bits of transmission line and a plain transmission line.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

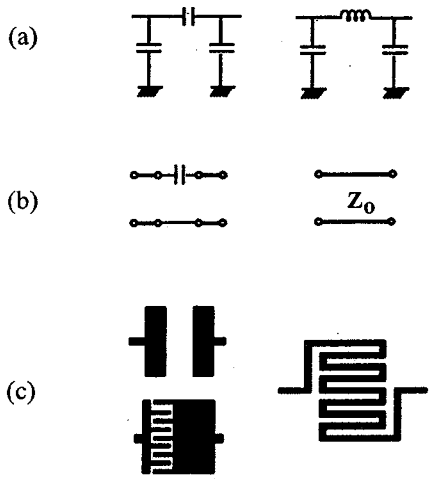

Fig. 2 Realization of the pseudo-lumped microstrip element from the lumped element circuit. (a) The π-section of capacitors and an inductor with capacitors at both ends, (b) a capacitor with small bits of transmission line and a plain transmission line, and (c) the pseudo-lumped microstrip elements;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

where the strong coupling is required. The inductor with capacitors at both ends and the fragment of the transmission line can be transformed to 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 the full-wave EM simulation software. The s-parameters of the pseudo-lumped microstrip elements are not exactly equal to those of lumped elements at every frequency. However, it is enough to compare the s parameters of both elements on the center frequency because we are dealing with very narrow filter. By comparing these s-parameters, we can determine the size of the microstrip element. The separation between the patches and the length of each patch mainly determine the strength of capacitive coupling. The length and the structure of the meander line define the inductance. After every pseudo-lumped element is determined, the remaining work is just cascading these elements. Sometimes, small corrections may be required to get better reflection and transmission properties.

As a result, we have designed the 5-pole filter that is to be fitted into a 37 mm × 9 mm substrate. The schematic of 5-pole pseudo-lumped element filter design is shown in Fig. 3.

3. 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 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 $2 \sim 3 \times 10^6$ 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 electrode was formed on the 50-ohm feed line by lift-off process for the electrical contact with SMA connector. The electrical contact between superconducting ground plane of the filter and the package was made 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 the flowing oxygen atmosphere.

Filter was packaged on the gold-coated brass structure. 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.

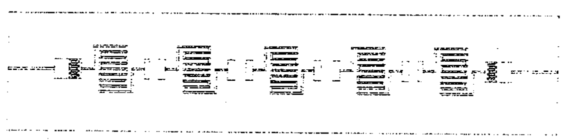

Fig. 3 Layout of a 5-pole pseudo-lumped element microstrip filter on 37mm × 9mm substrate.

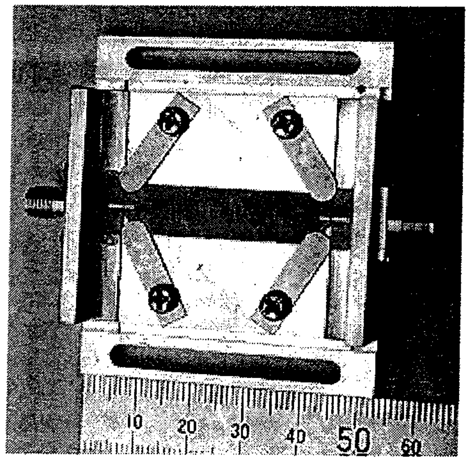

Fig. 4 A photograph of the packaged filter used in this experiment.

4. Filter Performance

We measured s-parameters of the filter using HP8714B network analyzer. The filter was installed at the cold end of a cryocooler in the vacuum chamber. To ensure the precise measurement of the filter characteristics, we calibrated the semi-rigid cable connections at room temperature. Then we measured s-parameters of a 1-cm-long, 50-ohm through-line made of superconducting film at low temperature to check the room temperature calibration. In 100 MHz passband around the filter center frequency, the reflection coefficient (S_{11}) was below -30 dB and the transmission coefficient (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 shown. We note that measurements were done without any tuning. In the measured data, the center frequency is 1.786 GHz, and passband width is 13 MHz (0.7 % fractional bandwidth). The minimum insertion loss and the ripple in the passband are 0.3 dB and 0.2 dB respectively. The filter also shows 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.

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 a perfect-conducting ground plane. 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 the simulated data. It was believed that this difference resulted from the fact that the initial estimation of dielectric constant was too high and the kinetic inductance effect of the superconducting film was completely missing in the simulation result. 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 were acquired from this consideration. In view of the overall frequency dependency, the simulation agrees well with the measured data.

The measured data show smaller transmission loss compared to that of computed data at low frequency side from passband. It can be explained by the effect of filter package [12]. The minimum return loss of measured data in the passband is worse than that of computed data. It is believed that the over-etching of the pattern degraded the impedance matching. To improve the matching, the tuning was performed with five screws positioned on top of the resonator.

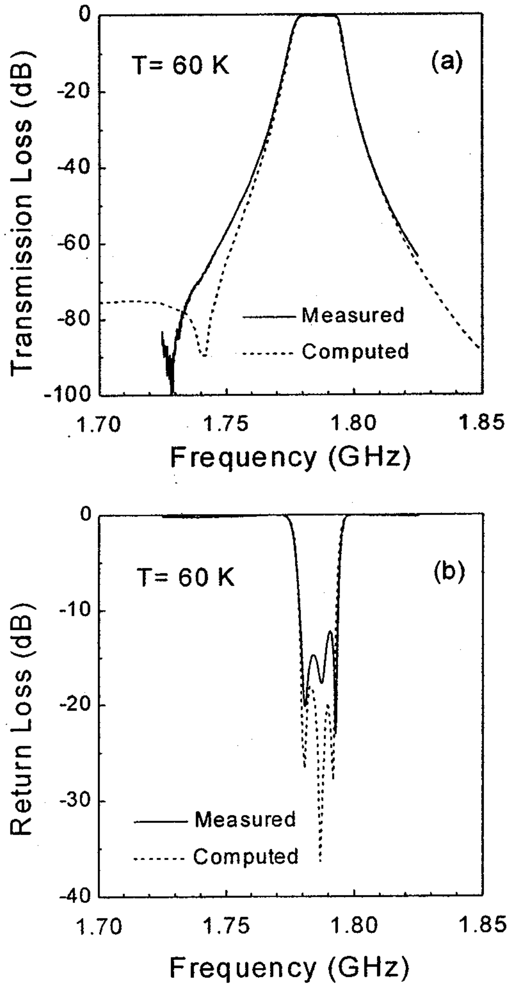

Fig. 5 Measured and computed frequency response of the 5-pole pseudo-lumped element microstrip filter at 60 K; (a) the transmission loss, S_{21} and (b) the return loss, S_{11}. The solid line for measured data and the dashed line for computed ones.

After tuning, the return loss was improved to 18 dB from 12 dB and the ripple was decreased considerably whereas the insertion loss was slightly increased. Fig. 6 shows the enhanced ripple characteristics.

5. Conclusions

A high-temperature superconducting pseudo-lumped element bandpass filter was designed for PCS applications by new design method. Using the double-sided high-temperature superconducting $YBa_2Cu_3O_{7-\delta}$ thin film, a 5-pole microstrip filter was fabricated on 37 mm × 9 mm $LaAlO_3$ substrate. This compact size could be possible 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 measurement data and the simulated result were in good agreement. It was shown that the appropriate tuning was needed to enhance ripple characteristics. The pseudo-lumped element band pass filter is a good candidate for PCS wireless communication application.

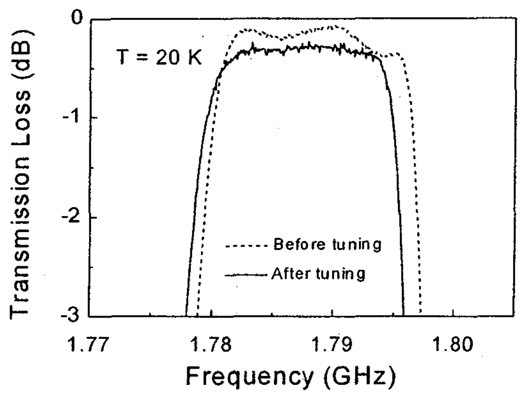

Fig. 6 Ripple details of the filter response at 20 K (dashed line). Enhanced ripple characteristics after tuning (solid line).

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