Superconducting Microstrip Bandpass Filter on $LaAlO_3$ with High Out-of-Band Rejection

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***Abstract*—A superconducting eight-pole narrow-band filter on lanthanum aluminate substrate material $(\varepsilon_r \approx 24)$ is introduced. The filter has a center frequency of 1.8 GHz and a fractional bandwidth of 0.84%. Steep filter skirts (∼20 dB at 700 kHz) and high out-of-band rejection (∼60 dB at 5 MHz) have been achieved by a quasi-elliptic filter design with two transmission zero pairs. The measured high-quality factor of ∼60 000 at 70 K results in an insertion loss of less than ∼0.3 dB in the passband and ∼0.5 dB at the band edges.**

***Index Terms*—High out-of-band rejection, high-temperature superconductivity, lanthanum aluminate, quasi-elliptic filter design, superconducting bandpass filter.**

I. Introduction

HIGH-TEMPERATURE superconductors (HTS's) offer a way to develop planar bandpass filters with extremely high selectivity but still maintain low insertion losses [1], [2]. The low surface resistance R_s of superconducting materials like $YBa_2Cu_3O_{7-\delta}$ (YBCO) deposited as thin films [3] on compatible high-permittivity substrates allows the building of planar resonators with high unloaded quality factors ($Q_0 \geq 50\,000$ at 2 GHz) at cryogenic temperatures ($T \leq 80$ K). The compatible substrate materials usually employed are magnesium oxide (MgO, $\varepsilon_r \approx 10$), CeO_2 buffered sapphire ($\varepsilon_r \approx 10$), and lanthanum aluminate ($LaAlO_3$, and $\varepsilon_r \approx 24$).

As a high permittivity leads to a significant size reduction, lanthanum aluminate is very attractive for high-order filters at frequencies below ∼5 GHz. Furthermore, $LaAlO_3$ is not as brittle as MgO and is isotropic unlike sapphire. However, previous works on HTS filters [1], [4] have shown that due to the high permittivity, disturbing box modes can strongly be excited and parasitic coupling increases. This may lead to a degraded filter performance and has significant effect on the out-of-band rejection of a microstrip filter.

To demonstrate a high out-of-band rejection with high-order filters on lanthanum aluminate substrates, the introduced quasi-elliptic eight-pole filter has been designed, fabricated, and tested. Such highly selective filters are in discussion as receive filters in base transceiver stations (BTS's) of future mobile communication systems, e.g., UMTS, as future systems may face strong interference problems.

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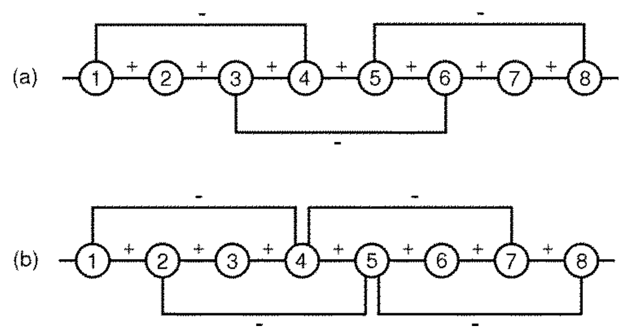

Fig. 1. Two filter models for a quasi-elliptic eight-pole filter. Both models result in an identical response with respect to the S-parameters, but filter model (b) yields more favorable values for the cross-couplings. The minus signs mark the different phase of the cross-couplings with respect to the main couplings.

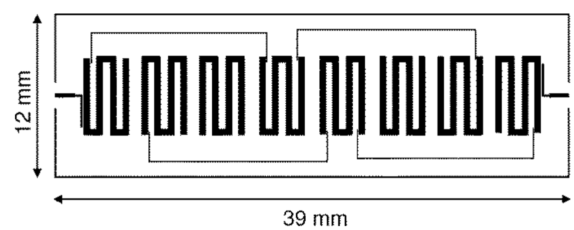

Fig. 2. Layout of the developed eight-pole filter for 0.5-mm-thick lanthanum aluminate substrate (black represents the superconductor).

II. Filter Design

In order to achieve a high selectivity, an eight-pole filter with quasi-elliptic filter response was chosen for realization. Two symmetric filter models with different positions of the required cross-couplings as shown in Fig. 1 were investigated. With respect to the S-parameters, both models result in an identical filter response with two symmetric transmission zero pairs. The required values of the coupling coefficients of the filter models were determined with the help of circuit model software [5], and as the actual values of the cross-couplings of model (b) were more favorable to the realization compared to case (a), filter model (b) was chosen.

As one specification of the filter was a high out-of-band rejection, the parasitic transmission through a housing with a high-permittivity substrate was investigated with the help of full-wave analysis software [6]. It was found that this parasitic transmission could significantly be reduced with a long and narrow housing.

With the latter fact in mind, filter model (b) was transfered into a microstrip structure with meander line resonators as depicted in Fig. 2. For a quasi-elliptic filter response, the

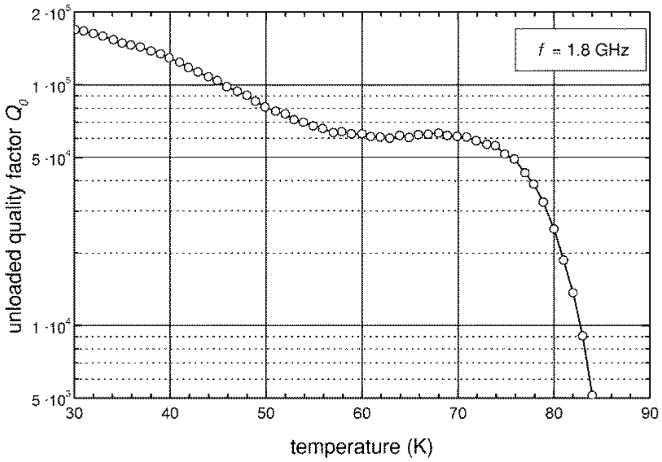

Fig. 3. Measured unloaded quality factor $Q_0(T)$ for a single resonator.

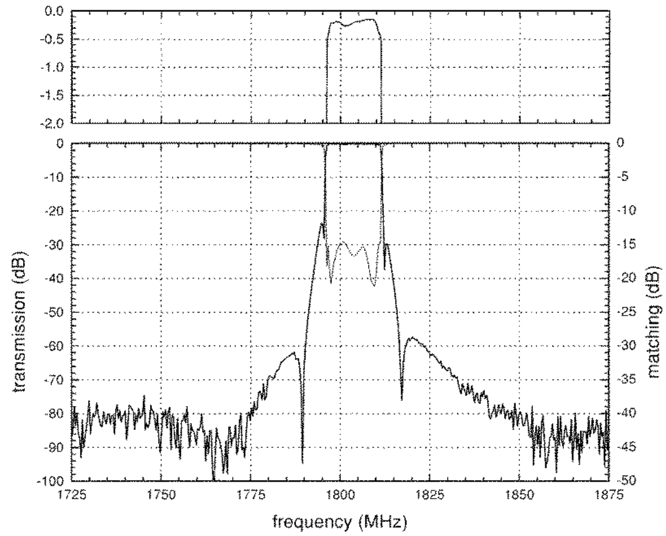

Fig. 4. Measured frequency response of the quasi-elliptic eight-pole filter. (YBCO on 39 × 12 × 0.5 mm^3 $LaAlO_3$ substrate at 70 K. Solid line: $|S_{21}|$; dotted line: $|S_{11}|$).

cross-couplings had to be of different phases with respect to the main couplings. This was achieved by cross-coupling the corresponding resonators at specific locations with transmission lines as shown in the figure, i.e., the ends of the lines were capacitively coupled to the resonators. The strength of the cross-couplings was mainly determined by the gap between these lines and the resonators, but was also influenced by the characteristics (e.g., length and width) of the transmission lines. With this approach, it was made possible to keep the width of the filter structure narrow.

The required geometric parameters (distances between the resonators) were also determined with the full-wave analysis software. First, only resonator pairs were considered, and finally the whole filter structure was simulated. The simulation results showed good agreement with the filter model but are not further discussed here.

III. Filter Fabrication and Material Properties

The filter was fabricated from a double-sided YBCO thin film with a critical temperature of $T_c \approx 92$ K, a surface resistance of $R_s \approx 12\ \mu\Omega$ ($f = 2$ GHz, $T = 77$ K), and a critical dc current density of $J_c \approx 5 \cdot 10^6$ A/cm^2 ($T = 77$ K) on a 39 × 12 × 0.5 mm^3 $LaAlO_3$ wafer with a gold-plated ground plane [3]. The structure was patterned using standard photolithography (with a chromium mask) and ion-milling processes. The gold contacts of the feed lines were deposited with a liftoff procedure. To avoid thermal stress, the filter was bonded onto a gold-plated steel carrier, which was fixed into a copper housing. The connections between the contacts and sub-miniature-A (SMA) connectors were made with ultrasonic wire bonding using 25-μm aluminum wires.

IV. Experimental Results

First, the unloaded quality factor Q_0 of a single resonator was determined with a one-port measurement for temperatures T between 30–84 K and an input power of -15 dBm. The measurement result is depicted in Fig. 3. At ~76 K, Q_0 reaches 50 000 and exceeds 60 000 at ~71 K. The highest value at $T = 30$ K is ~170 000. The relatively constant Q_0 of ~60 000 (plateau) between ~56–70 K derives mainly from a loss tangent maximum of specific $LaAlO_3$ crystals at this temperatures [7] from which the used substrate was cut.

The filter response was measured at a temperature of $T = 70$ K with an HP 8510C vector network analyzer. After tuning with sapphire tuning screws, the result shown in Fig. 4 was achieved. Within the passband, an insertion loss of less than 0.3 dB was measured, and at the band edges, the insertion loss was ~0.5 dB. From these values, the quality factor can be deduced to be on the order of 60 000, which agrees well with the measurement of the single resonator. Because of the quasi-elliptic design and the high Q-value, steep filter skirts have been achieved. Within 700 kHz from the band edge, the insertion loss increases to ~20 dB and reaches 60 dB within ~5 MHz.

Compared with the filter model, the center frequency was higher than designed but specified bandwidth of 15 MHz was met. Furthermore, the cross-couplings were stronger than simulated, which caused a slight mismatch of the filter. Instead of the design goal of 20-dB return loss, a value of ~15 dB was experimentally found.

V. Conclusion

A highly selective superconducting bandpass filter on $LaAlO_3$ has been designed, fabricated, and tested. The experimental results showed low insertion loss, steep skirts, and high out-of-band rejection. The good agreement with the theoretic filter model demonstrates that parasitic effects in superconducting filters on $LaAlO_3$ can be minimized with the introduced layout.

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