Superconducting Quasi-Lumped Element Filter on R-Plane Sapphire

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***Abstract*—Recent advancement in superconducting microwave technology has led to commercial deployment of high-temperature superconducting (HTS) subsystems for wireless communication applications. Commercialization of the HTS thin-film devices lies within, among other factors, the quality and consistency of the HTS film, as well as the overall cost and performance of the subsystem. In this paper, we present the design and performance of a quasi-lumped element filter on sapphire substrate. Centered at 1857 MHz with 0.8% fractional bandwidth, the six-pole Chebyshev filter has an insertion loss of less than 0.2 dB at 60 K, which translates into a realized unload Q of 35 000. This is an important step toward the commercialization of superconducting devices using industrial standard wafers. With the continuous improvement of the HTS film quality, YBCO film on sapphire could be an answer to the future.**

***Index Terms*—Applied superconducting, planar filter, sapphire, superconducting filter.**

I. INTRODUCTION

THE wireless communication industry has been growing at an impressive rate over the past decade. With the rapid development of new applications and an increasing demand from customers, service providers are facing simultaneous needs to increase capacity, extend coverage of base stations, and to improve data quality while reducing capital cost. A superconducting front-end subsystem provides a solution.

High-temperature superconducting (HTS) material has very small transmission loss. It has been applied to various radio-frequency (RF) passive and active devices [1]–[6]. The application of this material opened up an exciting avenue for future RF device technologies, most of which are under rapid development.

The superconducting thin-film filter is particularly attractive for the receiving applications due to the fact that HTS planar circuits with very small size and weight can be realized with an unloaded resonator Q equals to or better than those achieved by bulky waveguide cavities and dielectric resonators [7]–[12]. Of course, a cryogenic refrigerator is needed to keep the superconducting device below the critical temperature. However, for most system applications, a cooler can support a number of filters and other RF components, such as amplifiers, mixers, digital signal processing (DSP) chips, etc. The overall improvement in system performance and size reduction can be significant.

Due to its compatibility with the original HTS material $YBa_2Cu_3O_{7-\delta}$, lanthanum aluminate ($LaAlO_3$) is a widely used substrate in HTS thin-film devices. However, due to the rhombohedral structure of the $LaAlO_3$ at room temperature and below, twin boundaries with slightly different orientations are easily formed. Consequently, there is a spatial variation of dielectric constant as large as 2% [13], [14]. These twin formations also prohibit the design and reproducibility of very precise circuits such as a multipole ultra-narrow bandpass filter.

Alternatively, sapphire substrate is an attractive substitute for $LaAlO_3$ in microwave devices because of its low dielectric loss ($< 3 \times 10^{-8}$ at 77 K) [15] and availability of large twin-free single crystal wafers (3–5-in-diameter wafers are readily available). In addition, sapphire is one of the best thermal conductors, which minimizes the thermal gradient on a device operating at low temperatures. It is also sturdy, reliable, inexpensive, and offers the possibility of monolithic integration of silicon circuits. HTS film grown on M- and R-plane sapphire are routinely done [16]–[18] and various devices on sapphire substrate have been developed [19]–[21].

Present in this paper is a superconducting quasi-lumped element filter designed on an industrial standard wafer (sapphire) to improve the HTS film quality, as well as to reduce the wafer cost. The repeatedly realized unloaded quality factor of 35 000, together with the superior measured voltage standing-wave ratio (VSWR) of 1.12 : 1, indicated that our HTS film is consistent and of high quality. With the continuous improvement of the quality factor of the HTS film in the industry, the miniaturized HTS devices will be a solution to the increasingly complex communication requirements.

II. SAPPHIRE

Although M-plane sapphires have been successfully used in superconducting microwave devices, R-plane sapphire attracts more attention because of its availability as a standard industrial wafer. However, because of the anisotropy in the permittivity tensor, microstrip designs in R-plane sapphire has been extremely difficult. Excellent theoretical treatment of the anisotropy can be found in the literature [22]–[25]. However, it would be impractical to apply these techniques to such a complex circuit as presented here. Instead, a simple approximation

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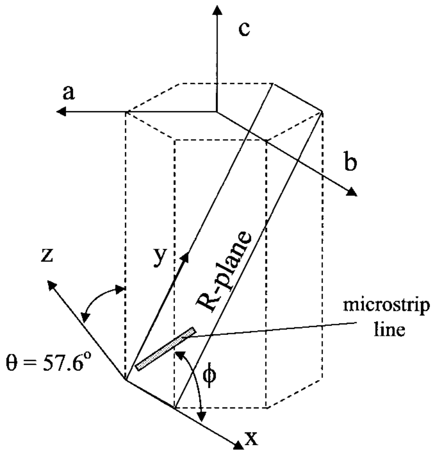

Fig. 1. Conventional unit cell of a single crystal sapphire with crystal axes labeled as a, b, and c. Also shown is the definition of the angle ϕ on the R-plane substrate.

is chosen to treat the anisotropy in this particular design, yet provides satisfactory results.

The principal axis permittivity of the crystalline sapphire is given by $\varepsilon_{//} = 11.6$, $\varepsilon_{\perp} = 9.4$ [26], [27], and its general permittivity tensor in the R-plane can be obtained by performing two consecutive rotational transformations, i.e.,

$$\varepsilon_R = U_2 U_1 \varepsilon^0 U_1^{-1} U_2^{-1}$$

where

$$\varepsilon^0 = \begin{pmatrix} 9.4 & 0 & 0 \\ 0 & 9.4 & 0 \\ 0 & 0 & 11.6 \end{pmatrix}$$

$$U_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

$$U_2 = \begin{pmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ is the angle between the crystal c-axis and the normal vector to the R-plane, which is equal to 57.6°, and ϕ is the angle measured from the x-axis on the R-plane, as illustrated in Fig. 1. For instance, a microstrip line along the x-axis would experience a permittivity tensor of

$$\varepsilon_R(\phi = 0^0) = \begin{pmatrix} 9.4 & 0 & 0 \\ 0 & 10.97 & -0.99 \\ 0 & -0.99 & 10.03 \end{pmatrix}$$

and a 45° microstrip line would experience a

$$\varepsilon_R(\phi = 45^\circ) = \begin{pmatrix} 10.18 & 0.78 & -0.70 \\ 0.78 & 10.18 & -0.70 \\ -0.70 & -0.70 & 10.03 \end{pmatrix}.$$

It was suggested by Vendik *et al.* [28] that this permittivity tensor ε_R could be approximated by an isotropic dielectric constant with a correction term containing all the angular dependence or, equivalently, a function of w/h, where w is the width of the transmission line and h is the thickness of the substrate. In the case of $\phi = 45^\circ$, the angular dependence of the effective isotropic dielectric constant is very weak. It ranges from $\varepsilon_{\text{eff}}^{\text{iso}} = 10.080$ for $w/h = 0.125$ to $\varepsilon_{\text{eff}}^{\text{iso}} = 10.044$ for $w/h = 4.0$. Therefore, the simplest and most natural approximation for this orientation is to replace the anisotropic permittivity tensor with an effective isotropic dielectric constant of 10.06.

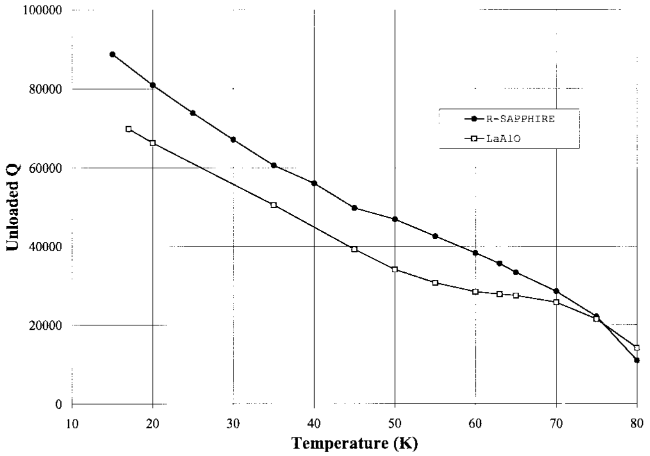

Fig. 2. Unloaded Q of HTS resonators on R-sapphire and $LaAlO_3$.

III. Superconducting Film on Sapphire

Double-sided 250-nm-thick YBCO films were grown on 2-in-diameter 17-mil-thick R-plane sapphire substrates using reactive thermal evaporation [29] with CeO_2 as buffer layers. The films were found to be of high quality. The patterned film had a resistivity of 200 $\mu\Omega \cdot$ cm and a critical temperature (T_C) of 87 K, indicating slight oxygen overdoping. Scanning electron microscopy revealed a small amount of 0.2-μm-wide copper–oxide boulders over a smooth matrix of YBCO.

The unloaded quality factor (Q_u) of a resonator similar to those used in the filter is measured over the temperature range of 15–80 K. The result is compared with that of the $LaAlO_3$ in Fig. 2. Due to the local maximum in the loss tangent of $LaAlO_3$ [27], [30], the Q_u of the YBCO/$LaAlO_3$ resonator exhibits a plateau around 60 K, whereas the sapphire's monotonically increases as temperature decreases. At 60 K, the unloaded Q of the sapphire resonator is about 37 000 and the lanthanum's is around 28 000. Our films are optimized to operate at 60 K as evidenced from the relatively low T_C. Consequently, the insertion loss of the filter is expected to be higher at 77 K.

IV. Filter Design

The filter chosen for this experiment is a six-pole Chebyshev prototype with a 0.01-dB equal-ripple passband at 1850–1865 MHz, as shown in Fig. 3. To take full advantage of the small size of superconducting planar design, we use a quasi-lumped element realization of a tubular topology, whose equivalent circuit is illustrated in Fig. 4. The standard design procedure is commonly used and documented [31]–[33].[1]

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[1] SFILSYN, DGS Associates, Santa Clara, CA.

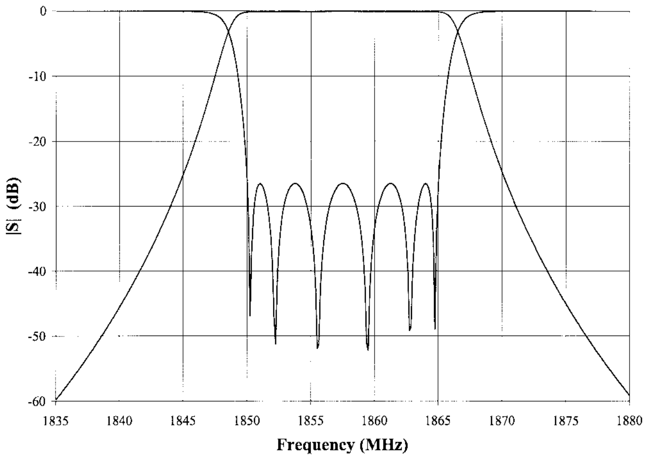

Fig. 3. Design response of a six-pole Chebyshev bandpass prototype with a 0.8% fractional bandwidth.

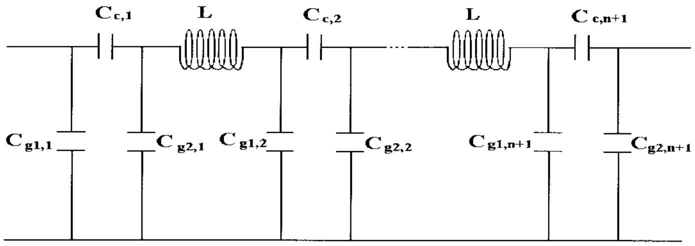

Fig. 4. Equivalent circuit representation of a tubular design.

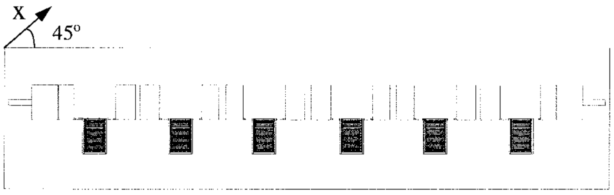

Fig. 5. Physical layout of a six-pole bandpass filter on a 17-mil R-plane sapphire. The substrate is 1.7-in × 0.4-in along the 45-° direction on the x–y plane.

The filter is laid out along the 45°, as illustrated in Fig. 5, such that the relative permittivity tensor can be approximated by an isotropic dielectric constant of 10.06. This simple approximation is very effective, as supported by the experimental data presented in Section V.

V. EXPERIMENTS

Two filters were fabricated on separate wafers of the same batch. Packaged filter performance measured in liquid nitrogen are shown in Figs. 6–8 with different frequency spans. The measured passband is expectedly 50 MHz lower than the design value due to the loading of liquid nitrogen ($\varepsilon_r = 1.45$), the temperature variation in dielectric constant, and the differential thermal expansion of the substrate from the target temperature. A 25-dB return loss, corresponding to a VSWR of 1.12 : 1 is measured, although the equal-ripple fractional bandwidth is about 0.97%, which is higher than the design value of 0.81%. A simulated response is generated from matching the measured center frequency and bandwidth of

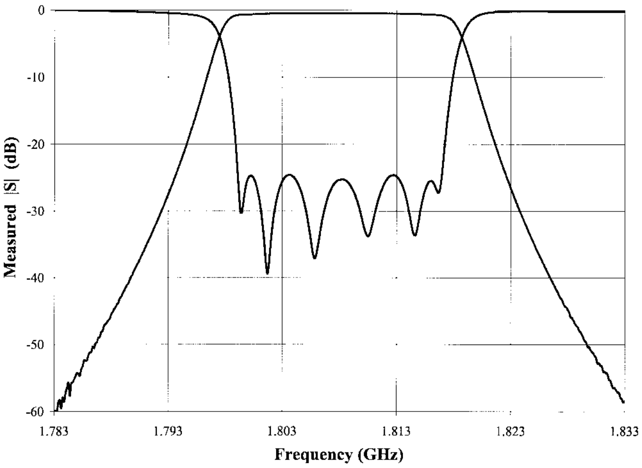

Fig. 6. Measured $|S_{11}|$ and $|S_{21}|$ of Filter 1 in liquid nitrogen.

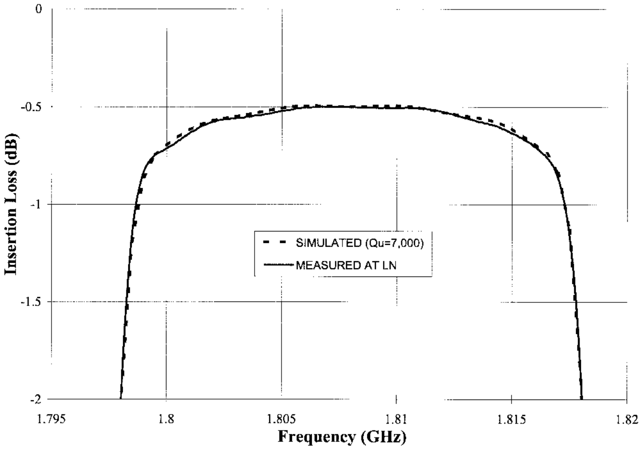

Fig. 7. Measured and simulated passband of the filter shown in Fig. 6, indicating that the unloaded Q of the filter is 7 000 in liquid nitrogen.

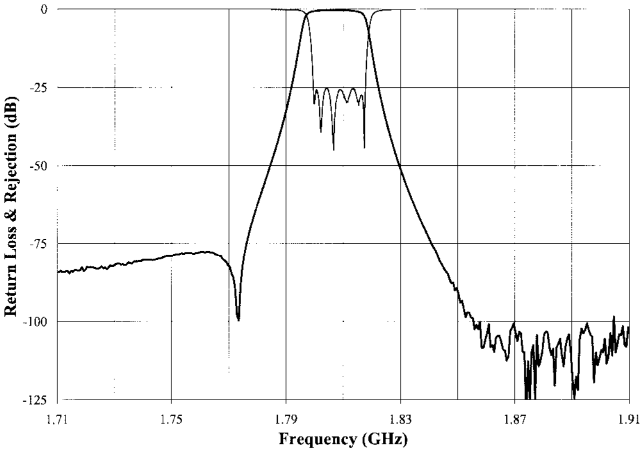

Fig. 8. Measured return loss and rejection of Filter 2 fabricated from a different wafer of the same batch.

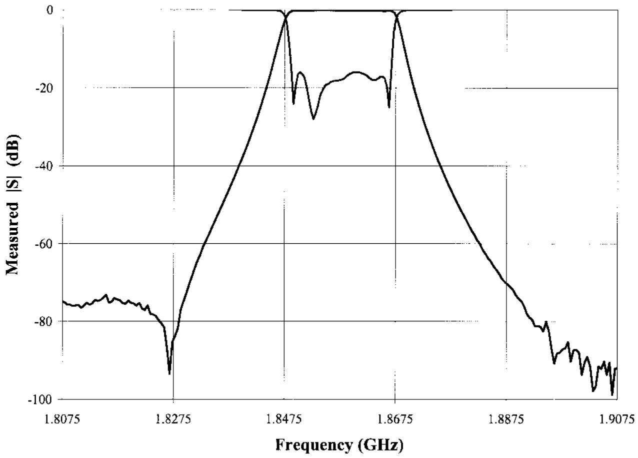

Fig. 9. Measured return loss and rejection of Filter 1 in 60-K vacuum.

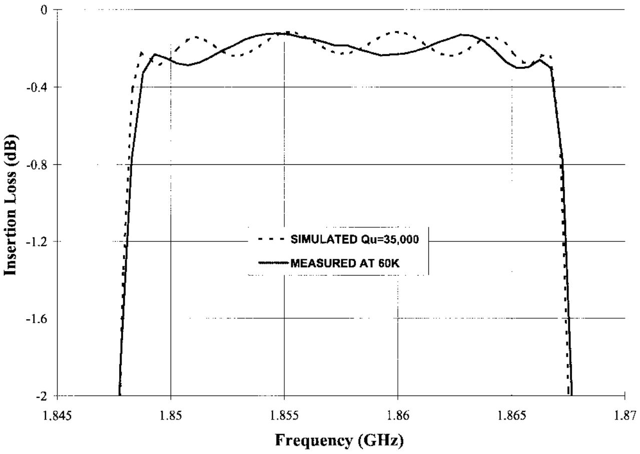

Fig. 10. Measured and simulated passband of Filter 1 in 60-K vacuum, indicating the realized unloaded Q of the filter is about 35 000.

the filter, which are different from the design prototype shown in Fig. 3. Fig. 7 compares the measured insertion loss to the simulated passband with an unloaded Q of 7 000 to match not only the absolute insertion loss, but also the rounding at the band edges. The unloaded Q value obtained from this method is consistent with the single resonator measurement at liquid nitrogen. The performance of the second filter is presented in Fig. 8 with a broader frequency range. Similar to the first filter shown in Fig. 6, a 25-dB return loss is obtained. This is an important indication that our film growth process is well controlled and the quality of the HTS is very uniform and repeatable. The finite transmission zero below the passband is introduced from the nonadjacent coupling, mainly due to the fringing field above the substrate, as indicated from preliminary electromagnetic and circuit simulations.

The same filters were then cooled to 60 K in vacuum without further adjustment, and the measured frequency response of the first one are shown in Figs. 9 and 10. Note that the passband is shifted to the desired frequency, although the bandwidth is still too wide. However, the insertion loss measured at the same input power of 10 dBm has improved by a significant amount, indicating that the realized unloaded Q of the filter is about 35 000, as shown in Fig. 10. Consider the unloaded Q of a single resonator is only about 37 000, this experiment implied that our overall structure and packaging do not degrade the performance of the HTS resonators significantly.

VI. CONCLUSION

A simple approximation approach for designing a lumped-element filter on an anisotropic substrate is presented in this paper. The superior performance of the prototypes (judging from the measured return loss and unloaded Q) indicated that such a procedure is applicable to the R-plane sapphire design. Implications of this experiment are: 1) the YBCO film on R-plane sapphire is of good quality, consistent, and suitable for manufacturing; 2) the current packaging effect on RF performance of the HTS filter is negligible; and 3) the thin-film superconducting filters can be realized on an industrial standard substrate without sacrificing their performance. With the continuous improvement of the HTS film quality, cryogenic cooling technology, and reliable cryo-packaging, HTS film on sapphire would provide a new avenue to many communication applications.

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Dr. Liang is an active member of the IEEE (co-chair for MTT-1 8 Technical Committee, MTT-S technical coordinator, member of Technical Program Committee, a member of the MTT-S editorial board and chairman of the Santa Clara IEEE Communication Society.