PRESENT AND PROJECTED PERFORMANCE OF HIGH-TEMPERATURE SUPERCONDUCTING FILTERS

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ABSTRACT

Microwave planar high-temperature superconducting (HTS) filterbanks will find application in radar and communications. Because of difficulties of growing HTS films on both sides of a substrate, it is convenient to use normal-conducting ground planes to fabricate HTS microstrip filters. The insertion losses in a filter have been estimated from a calculation of the effect of a normal-conducting ground plane on the losses of an HTS microstrip line. It is shown that, even with a gold ground plane, the performance of current filters could be limited by mismatch losses rather than conductor losses, and that, above Ka-band, the benefits of using an HTS ground plane are only marginal.

1. INTRODUCTION

Microwave planar high-temperature superconducting (HTS) filters will find application in radar and communications where high-performance, low-loss, compact filterbanks are needed. Microstrip is, for now at least, the preferred and simplest structure. The initial phases in the realization of HTS microstrip filters have been successfully completed by several groups (1-3). These filters have been made both with a superconducting ground plane or a normal-metal ground plane. Among those of the first type there are results using a post-deposition annealing approach (2) to grow $YBa_2Cu_3O_7$ (YBCO) on both sides of a $LaAlO_3$ substrate. There are also results with a separate substrate for the ground plane, for which YBCO epitaxial films grown in-situ were used (1). This approach, however, is not likely to yield results close to design because of inevitable air gaps between the substrate holding the patterned film and the ground plane (1). The use of double-sided YBCO films is, therefore, very desirable.

Alternatively, although high-quality epitaxial films grown on both sides of a substrate will soon become available, a normal-metal could be used for the ground plane. The reason is that in a microstrip structure most of the losses occur in the strip, not in the ground plane. Thus, in this initial phase in HTS filter work, for bandwidths between 1 and 2%, very encouraging results can be obtained with normal-conducting ground planes (1-3).

2. INSERTION LOSS ESTIMATE

The effect of a normal-metal ground plane on the loss of a microstrip filter was evaluated. It was assumed that the filter is made up of identical half-wavelength long 50Ω coupled resonators. This is approximately true for practical microstrip designs. Furthermore, it was assumed that a $LaAlO_3$ substrate of nominal thickness 0.043 cm was used ($\epsilon_r = 23.4$), and that the operating temperature was 77K (liquid nitrogen). An expression for an equivalent surface resistance R_{seq} as a function of frequency was developed [see below, (2.5)], assuming an f^2 dependence for the HTS surface resistance R_s. The loss estimate obtained was compared with similar calculations for all-YBCO and all-normal-metal microstrip filters. The incremental inductance rule (4,5) and Wheeler's characteristic impedance expressions (5) were used in this analysis.

From classic filter design equations, the insertion loss in dB at mid-band of a coupled-resonator filter is approximately given by (6)

$$A_n \simeq \frac{434}{BW(\%)} \sum_{k=1}^{n} \frac{g_k}{Q_{uk}} \text{ (dB)} \qquad (2.1)$$

Here, n is the number of poles, g_k are the normalized series inductance and shunt capacitance values of the low-pass prototype filter (6), Q_{uk} is the unloaded quality factor for the k-th resonator, and BW is the percent fractional bandwidth of the filter. Assuming a Chebychev six-pole filter with 0.1 dB equal amplitude ripple and that it can be made up of identical resonators, this expression becomes,

$$A_6 \simeq \frac{3863}{Q_u \bullet BW(\%)} \text{ (dB)} \tag{2.2}$$

We now derive an analytical expression for Q_u which can be substituted in (2.2) to obtain an estimate of the filter loss as a function of the microstrip dimensions, the surface resistances of the strip and the ground plane and the substrate dielectric characteristics. The microstrip line is presumed to be housed in a metallic box with dimensions of a waveguide below cut-off so that there is no radiated power from the microstrip. The loss contribution from the microstrip rf fields fringing into the walls of the housing will be neglected. The unloaded Q, Q_u, is then determined from contributions from the conductor (Q_c) and dielectric (Q_δ) losses, i.e.

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_\delta} \tag{2.3}$$

where

$$Q_\delta \simeq (\tan \delta)^{-1} \tag{2.4}$$

Assuming that the conductor thicknesses are at least three times the rf field penetration depth, the conductor losses can be obtained from the incremental inductance rule expressed in terms of the impedance of the microstrip line with the substrate removed, Z_{LO} (5), i.e., when $\epsilon_r = 1$:

$$\alpha_c = \frac{1}{2Z_L\eta_o} \sum_{j=1}^{n} R_{sj} \frac{\partial Z_{L0}}{\partial x_j} \text{ (Nepers/unit length)}$$

where the summation is over all n conductor surfaces and ∂x_j is an infinitesimal change in one of the dimensions of the transmission line related to conductor j. R_{sj} is the surface resistance of conductor j. If Z_L is the microstrip characteristic impedance, then

$$Z_{L0} = Z_L \sqrt{\epsilon_{eff}}$$

With reference to the insert in Figure 1 (top left-hand quadrant), the attenuation expression given above can be written for a microstrip line as,

$$\alpha_c = \frac{1}{2Z_L\eta_o} \left[R_{s1} \left(\frac{\partial Z_{L0}}{\partial h} - 2\frac{\partial Z_{L0}}{\partial w} - 2\frac{\partial Z_{L0}}{\partial t} \right) + R_{s2} \frac{\partial Z_{L0}}{\partial h} \right]$$

with $\eta_o = 120\ \pi\Omega$, the characteristic impedance of free space. R_{s1} and R_{s2} are the surface resistances of the strip and the ground plane, respectively.

From Wheeler's characteristic impedance for $0.16 \leq w/h \leq 3.3$ (5),

$$Z_{L0} = 60 \left[\ln(4x) + \sqrt{16x^2 + 2} \right]$$

In this expression,

$$x \equiv h/w_e$$

with

$$w_e = w + \frac{t}{\pi} \left(1 + \ln \frac{2h}{t} \right)$$

Evaluating the various terms in the expression for α_c we find

$$\alpha_c = \frac{dZ_{L0}/dx}{2\eta_o Z_L w} \left[R_{s1}(G - 1) + R_{s2} \right]$$

with

$$G = 2 + 2x + \left(\frac{2x}{\pi}\right) \ln \left(\frac{2h}{t}\right)$$

The conductor loss α_c could now be rewritten in terms of an equivalent surface resistance R_{seq},

$$R_{seq} = \frac{R_{s1}(G - 1) + R_{s2}}{G} \tag{2.5}$$

This is the equivalent surface resistance for the case $R_{s1} \neq R_{s2}$; it reduces to R_s for $R_{s1} = R_{s2} = R_s$. The attenuation can now be written as

$$\alpha_c = \frac{dZ_{L0}/dx}{2\eta_o Z_L w} G\, R_{seq}$$

The Q due to conductor loss, Q_c, for a microstrip line of these characteristics (i.e., $0.16 \leq w/h \leq 3.3$) can be readily obtained from this expression:

$$Q_c = 2\pi f \frac{\eta_o}{c_o} \frac{w}{\frac{1}{Z_{L0}}\left(\frac{dZ_{L0}}{dx}\right)} \frac{1}{R_{seq}\, G} \tag{2.6}$$

Equations (2.4) and (2.6) can be substituted into (2.3) to find the microstrip unloaded Q.

3. RESULTS AND DISCUSSION

Figure 1 is a three-way composite plot that summarizes the analytical results obtained for a 50Ω microstrip line on a 0.043-cm thick (0.017 inch) $LaAlO_3$ substrate. The cases of YBCO and gold microstrip and that of a YBCO strip with a gold ground plane are included in the figure. On the top right-hand quadrant is a plot of the mid-band filter loss A_6 [expression (2.2)] as a function of Q_u, with the filter bandwidth as a parameter. On the quadrant immediately below, Q_u is plotted versus frequency for 50Ω microstrip lines for the three cases mentioned. On the bottom left-hand quadrant R_{seq} [expression 2.5)] is plotted as a function of frequency for the same three cases. Thus it is possible to compare, in one diagram, the various parameters which affect filter loss performance and their variation with frequency. The surface resistances used in these calculations for YBCO and gold at 77K were, respectively, $R_s = 5$ μΩ at 1 GHz (i.e., $R_s(f) = 0.005 f^2$ mΩ) and $R_s \simeq 5(f)^{0.5}$ mΩ. The value of R_s chosen for YBCO is typical (not the lowest) of our samples, which were measured using a slight modification of the technique given in reference (7). This R_s value is consistent with those observed in other laboratories (8).

The dielectric loss in $LaAlO_3$ corresponds to $\tan \delta \simeq 3 \times 10^{-5}$ at 77K and limits the total unloaded Q to about 3×10^4 at low frequencies.

Notice from Figure 1 that above Ka-band it may not be worthwhile to have a superconducting ground plane because its benefits are only marginal.

Figures 2(a) and 2(b) show the return and insertion losses of an X-band, 1.5% bandwidth, six-pole microstrip superconducting filter with a gold ground plane deposited on the back of the $LaAlO_3$ substrate. An epitaxial YBCO film was grown by off-axis sputtering on the front surface. It was then patterned by standard photolithographic techniques. This filter is similar to those discussed in reference (1). The return losses have minima at about 8 dB and the minimum insertion loss is 1.4 dB. Comparing this experimental result with Figure 1 it can be concluded that the insertion loss in the filter is limited by the input/output mismatch and not by conductor losses. According to these figures the insertion loss should be at most 1 dB provided the input/output matching can be improved to a minimum return loss of 10 or 12 dB. A 20 dB return loss is desirable, however, in order to meet amplitude and phase design requirements. Indeed, matching has become a challenging aspect of HTS filter work since the low conductor loss and the stringent packaging assembly considerations have made it difficult so far to fabricate filters with high return losses. Future work will concentrate on careful processing and improved design of coaxial-to-microstrip transitions. The possibility of slight de-tuning of the parallel-coupled resonators that make up the filter due to the random twinning in the $LaAlO_3$ substrates has also been suggested as the reason for the relatively low return losses (9) obtained. Other, twin-free, substrates could in principle be used, provided their dielectric losses can be shown to be small. Examples are $NdGaO_3$ and $PrGaO_3$ (10).

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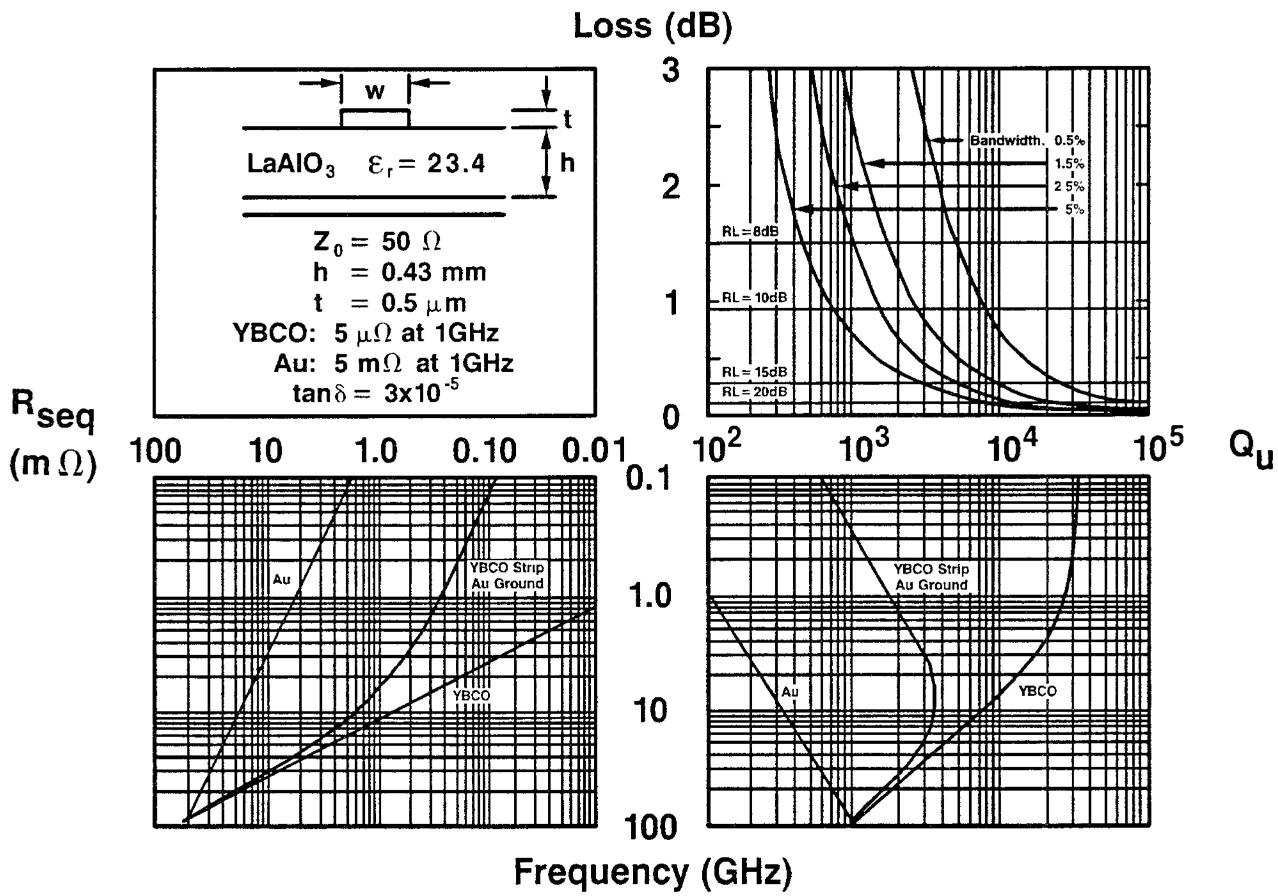

Figure 1 Composite plot showing calculations of mid-band six-pole filter loss vs. Q_u, Q_u vs. frequency and R_{seq} vs. frequency for 50Ω all-YBCO, all-gold and YBCO microstrip with gold ground plane, respectively. The insert shows the microstrip structure studied. In the calculation of R_{seq}, R_{s1} and R_{s2} are the surface resistances of the strip and ground plane, respectively.

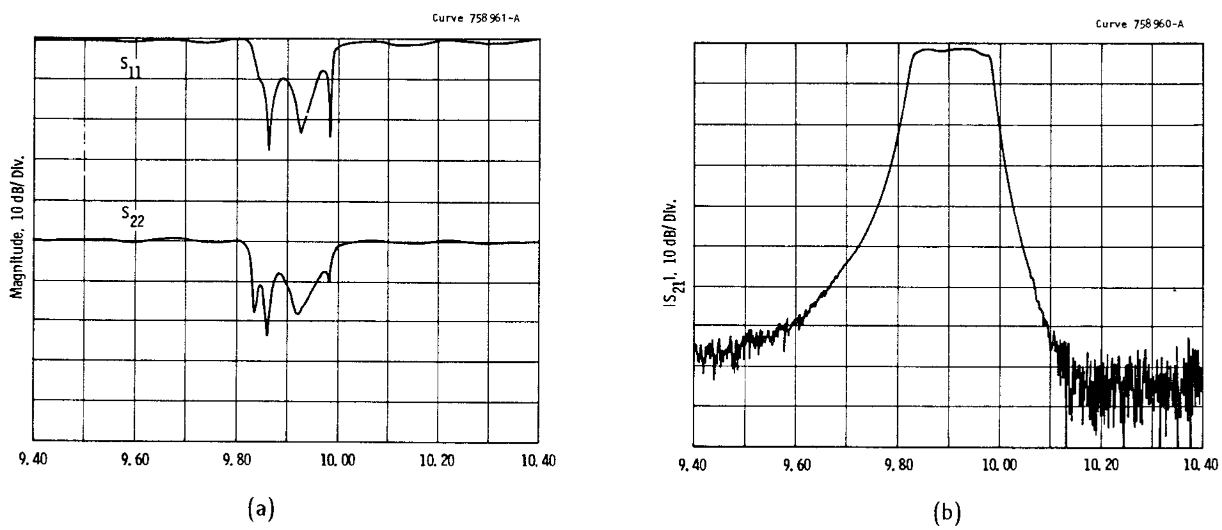

Figure 2 (a) Return and (b) insertion loss of a six-pole YBCO microstrip filter with gold ground plane.