CRITICAL DESIGN ISSUES IN IMPLEMENTING A YBCO SUPERCONDUCTOR X-BAND NARROW BANDPASS FILTER OPERATING AT 77 K

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ABSTRACT

New design parameters were considered in the successful implementation of a narrow band (0.5%) high-T_c filter operating at X-band and 77K. This article addresses the effects of HTS film thickness on the loss performance; kinetic and mutual inductance contributions to the center frequency drift with temperature; and nonlinearities associated with the generation of intermodulation distortion.

STATEMENT OF THE PROBLEM

High temperature superconductors (HTS) are the basis for a rapidly expanding technology that is well suited for microwave applications. There are significant practical advantages to operate at liquid-nitrogen rather than liquid-helium temperatures. To maximize the performance attained from these low-loss HTS films, additional design parameters must be evaluated. In developing the narrow-bandpass (0.5%), X-band filter operating at 77K, shown in Fig. 1, we had to address fundamental design problems unique to HTS superconductors [1]. Film thickness, kinetic inductance, and nonlinearity had to be assessed due to their significant effect on performance when operating close to the transition temperature (T_C). Details of the conventional as well as new critical design issues follow.

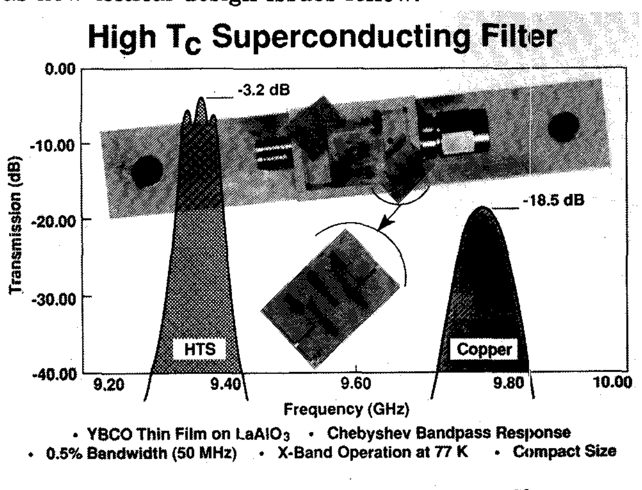

Fig. 1. Performance details of HTS and copper filters.

CONVENTIONAL DESIGN ISSUES

We have concentrated our efforts on the realization of very-narrow-bandpass filters to demonstrate the superiority of experimental HTS films. Achieving both low-loss and narrow-band performance is dependent on realizing very high Q resonators, as the insertion loss is inversely proportional to Q and is approximately given by [2]

$$(L_A)_0 \cong 4.343\, n/(\omega\, Q_u) \text{ dB} \qquad (1)$$

where Q_u is the unloaded Q of the coupled resonators of the bandpass filter, ω is the fractional bandwidth, n is the number of resonators, and $(L_A)_0$ is the midband insertion loss in dB.

We selected a narrow bandpass filter design using pseudo interdigital stripline. A 0.1 dB ripple Chebyshev filter with a 50-MHz bandwidth using an interdigital line structure was designed and built. The filter is centered around 9.5 GHz, with a bandwidth of approximately 0.5%. Conventional filters with bandwidth values of 10% or more can be fabricated using microstrip structures without excessive losses, whereas very-narrow-bandpass filters require large waveguide structures or dielectric resonators to attain reasonable losses. It is in applications requiring very narrow-band filters in a small volume where superconductivity becomes an enabling technology.

The interdigital bandpass filter structure consists of TEM-mode stripline resonators located between parallel ground planes. Each resonator is a quarter-wavelength long at midband frequency and has an open circuit at one end, and a short circuit on the other. Coupling is achieved through the fringing fields of adjacent resonator elements. We limited the number of sections to three for both space restrictions and ease of tuning (if needed). The filter structure was defined in an area less than 10.6 mm x 7.6 mm to accommodate the size of available laser-deposited films.

The three resonators are slightly staggered-tuned around the center frequency. Mistuning results in the presence of displaced peaks in transmission. The interdigital line filter structure also has open-end discontinuities and proximity effects to the side walls that cause additional capacitive loading affecting the filter response.

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In copper stripline filter structures, ground plane spacings of 2.5 to 5 mm are common in order to achieve reasonable Q factors. Filters with smaller ground-plane spacings require narrower lines to maintain the same values of mutual coupling and impedance. These designs lead to high insertion loss values due to increased conductor losses. Miniaturized filter designs can, however, be obtained with reasonable Q when using superconducting lines. The use of the high ε_r material helps in reducing the physical length of the quarter-wavelength sections (filter width).

In practice, increased conductor losses and higher mechanical sensitivity limit the scaling down in size of these filter structures. Narrow lines have higher losses, are very sensitive to pinholes and metalization defects, and are difficult to connect to the external circuitry. Meanwhile, air gaps between substrates can mistune these high Q resonators, especially when hard substrates, such as lanthanum aluminate, are used.

FILTER REALIZATION

If an all-superconductor-stripline filter were implemented, it would require three separate films stacked on top of each other. Since the effect of using normal conductor ground planes on the performance of the superconducting filter is minimal, we need only the filter pattern to be superconducting.

The interdigital filter requires short circuit terminations to alternate ends of its coupled fingers. Short circuits carry high currents, and their performance can limit the Q and compromise the overall performance of the filter structure. The use of normal ground connections would reduce the Q of the superconductor resonators. Instead, virtual grounds consisting of open-ended quarter-wavelength resonators are added to replace these shorts. It is important to mention that addition of these resonant quarter-wavelength transformers reduces the overall bandwidth, which must be included in the design considerations.

Models of circuits using high-dielectric-constant material have not yet been adequately developed. Approximate formulas are normally valid only for $\varepsilon_r < 12$, and the validity of most available discontinuity models is also questionable for high ε_r. In addition, the use of high-dielectric-constant materials tends to require transmission lines to be extremely narrow, where their impedance levels are sensitive to a change of a few microns in line width. The filter was designed assuming a superconducting material with a surface resistance better than copper by an order of magnitude at 10 GHz.

Air gaps at the top, center, and bottom dielectric/conductor interfaces are minimized, although not completely eliminated, through the use of a pressure plate that holds the two substrates firmly together. Both $LaAlO_3$ substrates are lapped and polished flat and careful attention to package mechanical tolerances are necessary steps to ensure even pressure across the dielectric sandwich. The high dielectric constant of these substrates makes this structure particularly sensitive to air gaps.

The copper version of the filter design was constructed and measured. Figure 1 shows the measured passband insertion loss of the copper filter at a minimum value of 18.5 dB at 77K. At 300K, the loss was 29 dB. The best HTS filter tested exhibited a minimum passband insertion loss of 3.2 dB, as shown in Fig. 1, while typical values of 4 to 6 dB were observed at 77K [1]. The theoretical minimum loss for this structure, if all conductors had a 10 times lower surface resistance than copper, is 2 dB. The additional loss is attributed to the housing and input/output connectors as well as input and output mismatches.

Mutual and kinetic inductances change as a function of temperature. Therefore, a more complete model must be used in order to investigate the temperature-dependent propagation characteristics of the superconducting coupled lines. The distribution of currents and fields along coupled superconducting lines is different than that of normal metal coupled-line structure, and the next logical step in the analysis is the development of such a model.

CRITICAL DESIGN ISSUES

Mutual and Kinetic Inductance Effects

The filter's center frequency is temperature-dependent. A major fraction of the measured 300-MHz frequency drift occurs between 80K and 85K, and is related to the temperature sensitivity of the kinetic and mutual inductance. In this filter, mutual inductance effects are not significant, as estimated by our modified copper coupled line model. The circuit was modeled by assuming temperature-dependent effective widths and spacings between the coupled lines. Calculations showed that the drift in frequency is only a few tens of megahertz. We assumed that the effective width w_{eff} and the effective spacing s_{eff} are given by

$$s_{eff} = s + 2\lambda, \text{ and } w_{eff} = w - 2\lambda \qquad (2)$$

where the spacings "s" and widths "w" of the lines (used in the filter) are much larger than the zero-temperature London's penetration depth, λ_o, and the temperature dependence of λ, according to the Gorter and Casimir two-fluid model, is given by

$$\lambda = \lambda_o / \sqrt{1-(T/T_c)^4}. \qquad (3)$$

Kinetic inductance effects, on the other hand, are dominant. Significant frequency drift occurs near the transition (T > 80K). To simulate this temperature dependence, the length of the different resonators are represented by an equivalent temperature dependent length "l_{eff}" given by

$$l_{eff} = l\,(1 + \kappa\lambda/h \coth t/\lambda)^{1/2} \qquad (4)$$

where κ is a geometry factor. A comparison between measured and predicted values for the center frequency drift with temperature was made, and excellent agreement is seen in Fig. 2, which is indicative of the dominance of the kinetic inductance effects. Operating at temperatures away from the transition temperature will reduce this frequency sensitivity.

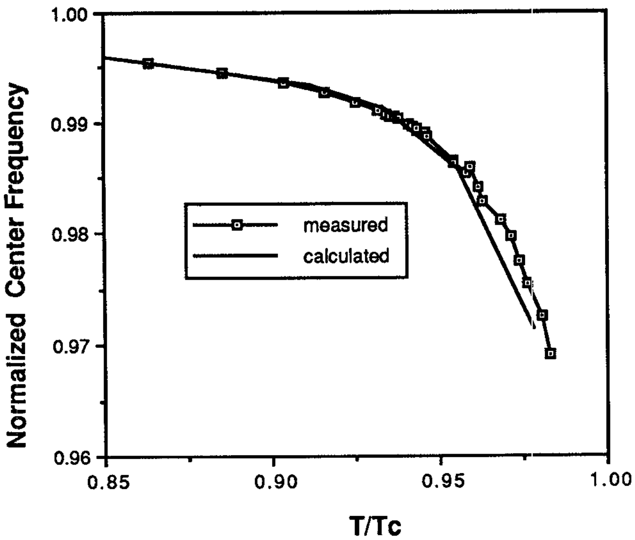

Figure 2. Shift in center frequency of filter response vs normalized temperature.

Film Thickness Effects

The thickness of the HTS thin film affects Q and the power handling capability of the circuit. Thinner films with higher surface resistance exhibit lower Q values. We use film thicknesses (t) that vary from 2000 Å to 4000 Å and thus are comparable with λ_o. We calculated the Q of these lines as function of their thickness and temperature. Taking the surface impedance boundary conditions into account, a function, G(T,t), given by

$$G(T,t)=(\coth t/\lambda+t/(\lambda \sinh^2 t/\lambda))/(1+\kappa \lambda/h \coth t/\lambda) \quad (5)$$

was derived and normalized to its value at T = 0K and $t > 10\ \lambda_o$. This normalized function represents a deterioration factor for the Q when using lines comparable with λ_o. Figure 3 shows this Q deterioration factor vs the normalized temperature (T/T_c) for a family of different superconducting films whose thicknesses are multiples of λ_o. As predicted, the deterioration factor is greatest near T_c, and approaches 1 at lower temperatures. In general, it is recommended that films be at least two to three times thicker than λ_o to avoid this deterioration.

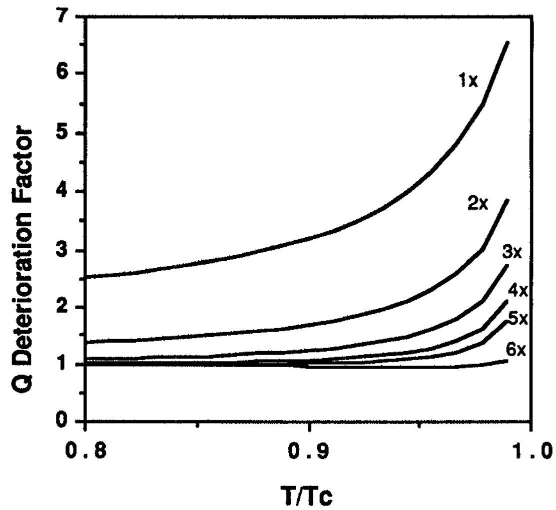

Figure 3. Deterioration factor of resonator Q value vs film thickness as a multiple of λ_o.

INTERMODULATION DISTORTION

The superconducting filter exhibits nonlinear performance. Power in vs power out was measured at different temperatures. Compression at higher power levels is indicative of power dependence. This non-linearity results in the generation of intermodulation products.

The measurement of intermodulation distortion (IMD) in this filter is limited to evaluation of third-order product levels at various combinations of input power and temperature. Since this is a narrow-bandpass filter, second-order products fall outside the passband and are therefore greatly attenuated. The two carrier frequencies for the measurement are located very near the center of the filter passband and are spaced 5 MHz apart. The filter ripple in this region is less than 1 dB. This choice of frequencies places the third-order products at 5 MHz below the lower frequency tone and 5 MHz above the higher frequency tone, clearly measurable within the passband.

The tones are generated with HP-8671B and HP-8340B synthesizers and fed through 40-dB isolators to a 3-dB Wilkinson coupler. A variable attenuator and 20-dB isolator follow. The two-tone test signal is fed to the filter located in a variable temperature cryostat, and the filter output is monitored with an HP-8566B spectrum analyzer. All measured powers are single-tone values. The results of these measurements are plotted in Fig. 4.

The utility of this exercise is to predict the spur-free dynamic range (SFDR) of the filter. Using the definition of SFDR as the difference, expressed in dB, between the thermal noise level and the two-tone signal level that will produce IMD products equal to the noise level [3], we calculate

$$SFDR_3 = (2/3)\,[\,IP_3 - NF + 179.7 - 10 \log (B)\,] \quad (6)$$

where, $SFDR_3$ = spur-free dynamic range for third-order products (dB), IP_3 = third-order intercept point (dBm), B = filter bandwidth (Hz), and NF = the noise figure (loss) of the filter (dB). These calculations, using the 66K and 78.4K measurements, show a $SFDR_3$ of 81 and 75.8 dB, respectively.

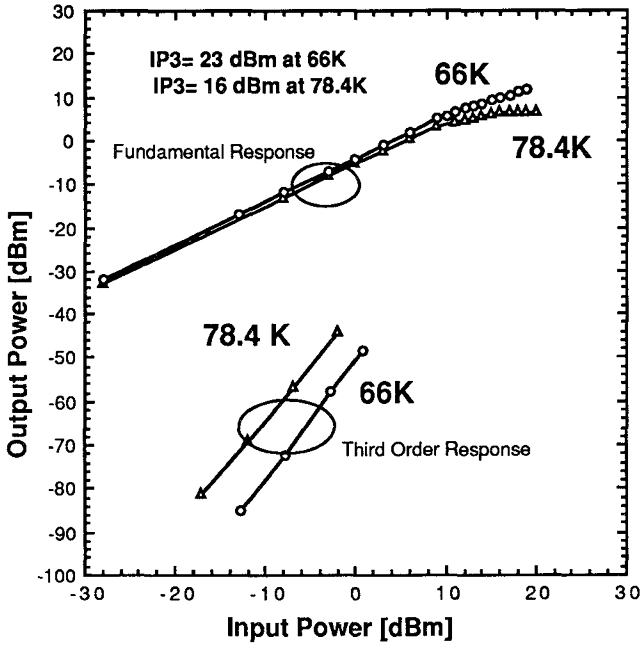

Figure 4. Output level of fundamental and third-order products vs Input power for the filter at different temperatures.

There are two possible sources of the non-linearity, namely, the junction to the gold contact pads deposited on the HTS material and the narrow (25 μm) lines in the filter structure. We have modeled the filter network to estimate the peak currents neglecting current crowding in each finger of the filter structure and the current density at the contact pads. Maximum peak current was predicted at the center finger, and the current as function of frequency is shown in Fig. 5.

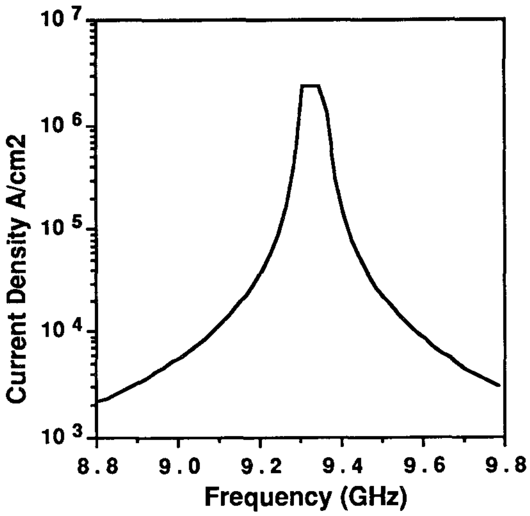

Figure 5. Current density in the center finger of the filter vs frequency for a 10-dBm input.

For an input power level of 10 dBm, the current density in the center element exceeds 10^6 A/cm^2, which causes this nonlinear performance [4]. The large area of the contact pads makes it unlikely they are the source of the non-linearity. The dynamic range of the filter can be increased by reducing temperature or using wider lines in the filter design.

CONCLUSIONS

Going beyond the usual design considerations for interdigital filters and trying to take advantage of the performance benefits possible with HTS materials has led us into a new design arena. While it is possible to design high-performance circuits with these materials, several new parameters must be evaluated in the design process. Kinetic inductance effects and the generation of intermodulation products must be controlled. Film thickness and uniformity are key parameters to low-loss performance. This work is the first step in predicting and designing more complicated, higher-order filters with high power handling, lower intermodulation levels, and frequency accuracy commensurate with performance goals.

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