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IMPACT OF KINETIC INDUCTANCE EFFECT ON HIGH-T_c SUPERCONDUCTING COPLANAR WAVEGUIDE RESONATORS

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KEY TERMS

High-temperature superconductors, CPW resonators, phase velocity

ABSTRACT

High-Q transmission high-T_c superconducting coplanar waveguide resonators have been employed to make accurate measurements of the temperature dependence of the penetration depth via the change in phase velocity. Resonators made from several different film thicknesses are well described using a zero temperature penetration depth and a T-squared temperature dependence using a full-wave spectral-domain model of the coplanar waveguide transmission line. © 1993 John Wiley & Sons, Inc.

INTRODUCTION

Thin-film high-temperature superconductors have been employed to design and develop passive microwave components such as filters, delay lines, and resonators. Devices based on coplanar waveguide (CPW) geometries offer both an attractive means of fabrication and ease of experimental implementation. To accurately design superconducting microwave circuits it is necessary to be able to predict the effects of superconductivity on planar waveguiding structures. In particular, the internal inductance of the superconductor, consisting of both the internal magnetic inductance and the kinetic inductance [1], results in a temperature dependence of the phase velocity. This temperature dependence is most pronounced near the superconducting transition temperature T_c. The essence of the internal inductance effect is the temperature dependence of the superconducting penetration depth, λ.

Recently there has been debate as to the actual functional form of this temperature dependence for high-temperature superconductors [2]. Unlike many conventional type-II superconductors which exhibit a Gorter-Casimir type temperature dependence, HTS data are better described using a BCS weak-coupled temperature dependence or a T-squared dependence. This dependence is given by

$$\lambda = \lambda_0/(1 - (T/T_c)^2)^{1/2}, \tag{1}$$

where λ_0 is the zero temperature penetration depth and T_c is the critical temperature of the film. This T-squared dependence of λ and hence the phase velocity becomes a critical consideration when designing microwave components.

In conventional planar transmission line geometries using typical dimensions the phase velocity variation with temperature can be several percent. The primary benefit to be derived from the use of HTS in microwave circuits is the high quality factor that permits the design and construction of high-Q resonators and narrowband filters which are not possible with normal conductors. Obviously it is necessary to be able to predict the phase velocity to within 0.1% in order to accurately and reliably design a multipole filter of 1% or less bandwidth. These same considerations are also true for delay lines, as the time delay of the microwave signal is an important parameter of the delay line design. Therefore, when designing coplanar waveguide microwave components it is critical to be able to model and characterize this temperature-dependent phase velocity effect.

THEORY AND DESIGN

One of the most straightforward methods by which to characterize the impact of the kinetic inductance effect on the phase velocity of a coplanar waveguide is to characterize a half-wavelength resonator as a function of temperature. Although the phase velocity of the resonator depends on both the internal magnetic and kinetic inductances, only the kinetic inductance will have a characteristic temperature dependence associated with high-temperature superconductors. The phase velocity of such a resonant structure is given by

$$\nu_{\text{phase}}(T) = 2(l + K)F_0(T), \tag{2}$$

where l is the physical length of the half-wavelength resonator, $F_0(T)$ is the resonant frequency as a function of the temperature T, and K is a correction for end effects of the coplanar resonator. K simply adds an additional effective length to the length of the resonator.

In order to accurately model the observed behavior of $\nu_{\text{phase}}(T)$ the underlying physical properties of the HTS coplanar waveguide transmission line must be known. The phase velocity of any TEM or quasi-TEM transmission-line structure can be modeled by equivalent discrete circuit elements such that

$$\nu_{\text{phase}} = 1/(LC)^{1/2} \tag{3}$$

where L and C are the inductance and capacitance per unit length, respectively. It is the variation in L due to the internal (kinetic and magnetic) inductance effect that is responsible for $\nu_{\text{phase}}(T)$.

The model used here is a full-wave spectral domain analysis based on a resistive boundary condition employed to simulate the superconducting qualities of the coplanar waveguide [3]. Because the current in a superconductor is composed of both a superconducting component and a normal component, the resistivity used in the boundary condition is necessarily a complex quantity. The model numerically solves for the complex propagation constant β_z of the wave traveling in the **z** direction. Thus

$$\nu_{\mathrm{phase}}(T) = 2\pi f/\beta_z(T), \qquad (4)$$

where f is the frequency of interest. The use of the resistive boundary condition is only rigorous in the thin film limit, where the thickness of the superconductor is much less than the penetration depth. However, it is possible to extend the applicability of this approach by using a generalized form of the boundary condition into the regime where the superconductor thickness is on the order of a penetration depth. The use of a $\coth(t/\lambda)$ (where t is the thickness of the superconductor) modification to the boundary condition allows for the internal damping of the fields associated with the penetration depth [4, 5]. This approximation can be used to successfully model planar transmission lines of many geometries.

The overall layout of the resonator is given in Figure 1. The 20-mil-thick lanthanum aluminate substrate is 0.7 × 0.7 in. The coplanar waveguide resonator is designed to be an end-coupled in-line device such that the transmission characteristics, S_{21}, can be measured. Constant impedance coplanar waveguide tapers were used to transform the center conductor width from 400 down to 200 μm. The 400-μm input width was used to facilitate the connection of the resonator to a Wiltron K connector. The constant impedance taper was designed using well-known impedance equations for coplanar waveguide [6]. The resonators were 8.54 mm long with a center conductor width of 200 μm and a transverse gap width of 370 μm. This is nominally 50 Ω on a lanthanum aluminate substrate of dielectric constant 26. The coupling gap is 15 μm.

The high-temperature superconductor used in these experiments was $YBa_2Cu_3O_{7-x}$ (YBCO). The YBCO was deposited using a pulsed laser ablation deposition technique [7].

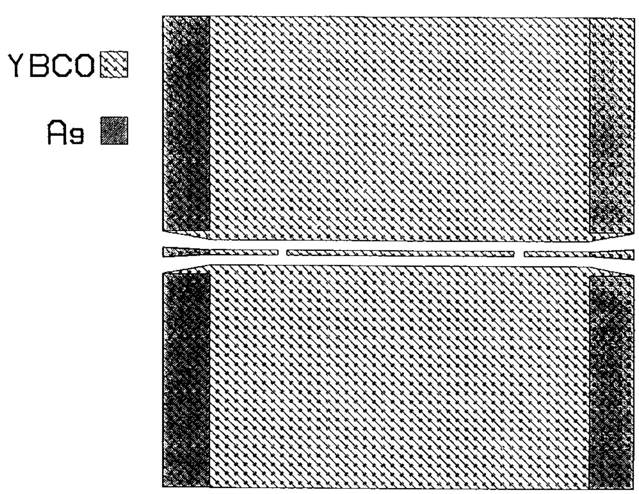

Figure 1 The layout of the coplanar waveguide resonator. The lanthanum aluminate substrate is 0.7 × 0.7 in. in area. The tapers are 50-Ω constant impedance center conductor width transformers to facilitate connection to K connectors. The coupling gap to the resonator is 15 μm

After the YBCO was patterned using standard photolithographic techniques and ion milling in an Ar atmosphere, a layer of silver was deposited, ex situ, on the taper and the surrounding ground plane to facilitate contact to the K connector. After the silver was deposited, the entire wafer was annealed at 450 C in an oxygen-rich atmosphere for 1 h. This promotes excellent contact resistance between the HTS and the silver while still maintaining the HTS integrity.

For microwave testing the device was placed on a Teflon block 0.50 in. thick and enclosed in an aluminum box to which the K connectors were attached. The center pin of the connector was attached to the center conductor of the CPW using silver paint. The Teflon block provides enough separation between the backside of the wafer and the bottom of the aluminum box to minimize the effect of changing the characteristic impedance of the CPW due to ground-plane proximity. A lid was then placed on top of the box such that a channel cutout measuring 0.250 in. wide by 0.100 in. deep by 0.700 in. long was centered directly above the resonator. The lid was then made to make contact to the CPW ground plane on either side of the resonators close to the launch point of the K connector, through the use of spring-loaded contact machined into the lid. In addition, a cryogenic thermometer was inserted into the Teflon block in such a way as to not effect the performance of the resonator while yielding accurate temperature data. The entire test structure was mounted on a coaxial probe and inserted into a liquid helium dewar. The coaxial leads were then connected to an HP 8720A network analyzer. The entire length of the leads from the network analyzer to the device under test is approximately 2.5 m. Because of the length of the coax leads an accurate and stable calibration of the reflection coefficient S_{11} was not possible. Therefore, only S_{21} measurements were conducted.

EXPERIMENTAL RESULTS AND DISCUSSION

Figures 2–4 show the temperature variation in the $\nu_{\mathrm{phase}}(T)$ of the 100-, 200-, and 300-nm-thick films, respectively. The phase velocity is normalized to the speed of light in a vacuum, c. The zero temperature penetration depths that provided the best model fits were 200, 250, and 225 nm for Figures 2–4, respectively. The 100- and 300-nm films were processed at the same time, while the 200-nm film was processed 6 months later using a different YBCO target. It is important to note

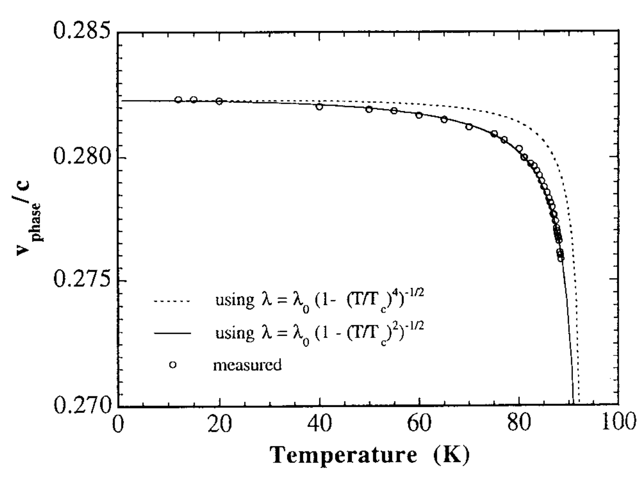

Figure 2 Phase velocity versus temperature for the 100-nm-thick film. The model used here assumes a zero temperature penetration depth of 200 nm and a T-squared penetration depth temperature dependence

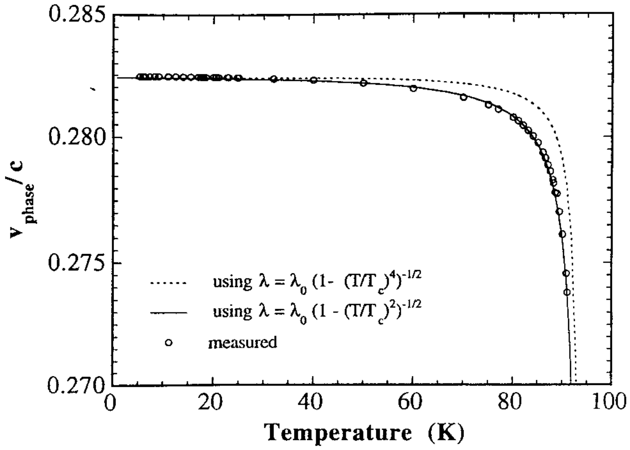

Figure 3 Phase velocity versus temperature for the 200-nm-thick film. The model used here assumes a zero temperature penetration depth of 250 nm and a T-squared penetration depth temperature dependence

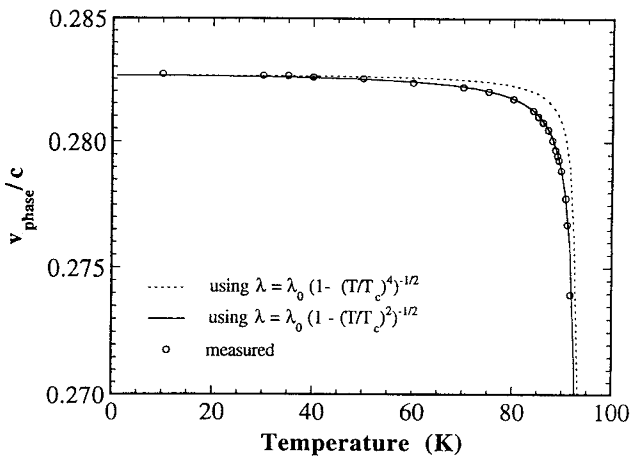

Figure 4 Phase velocity versus temperature for the 300-nm-thick film. The model assumes a zero temperature penetration depth of 225 nm and a T-squared penetration depth temperature dependence

that no a priori quantitative temperature dependence of the penetration depth nor zero temperature penetration depth values were assumed. The T_c at $R = 0$ of all the films was 92 K with a transition region of 2 K. To establish the validity of such a model the same temperature dependence was used in Figures 2–4. The figures clearly indicate that a T-squared temperature dependence accurately models the variation of $\nu_{phase}(T)$ with the film thickness as a controlled parameter. In all cases the measured $\nu_{phase}(T)$ had to be multiplied by an additional 3% ($K = 0.03$) to compensate for the end effects of the resonator. This additional compensation should be on the order of 1 to 2 linewidths of the resonator. Given the measured dimensions of the resonator, the K factor should be on the order of 2–5%, well within the predicted model's compensation value. The predicted value of 225 ± 25 nm for the zero temperature penetration depth is also very close to previous independently determined values (done at the same time) based on a parallel plate method of determining the penetration depth [8].

Figure 5 is a plot of the measured Q of the resonators as a function of temperature. Notice that the measured Q is only a weak function of the film thickness. In particular the measured Q of the 300-nm film degrades much more slowly than does that of the 100-nm film as T approaches T_c. This difference in Q degradation is similar to that predicted for microstrip resonators of different film thicknesses [9]. The shape of the curves is also an important consideration. The measured Q is inversely proportional to the surface resistance of the HTS film. As one would expect, the model surface resistance is lowest at low T (128 $\mu\Omega$) and increases as T approaches T_c. The method used to calculate the surface resistance is outlined in [10].

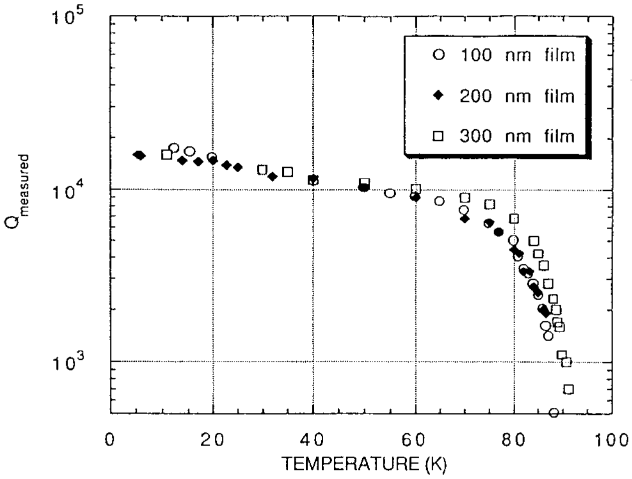

Figure 5 The measured Q versus the temperature as a function of film thickness. The effect of the thickness on the Q appears to be only a second-order effect. Notice the Q values at low temperature are around 16,000 for all thicknesses

Finally, Figure 6 is a plot of the resonance frequency of the resonator versus the film thickness at both 20 and 77 K. Notice in all cases the resonance frequency increases with film thickness. This indicates that for a given temperature the phase velocity increases with film thickness. This implies that slow-wave coplanar waveguide structures require thinner superconductor films. In addition the phase velocity decreases with increasing temperature for the same film thickness.

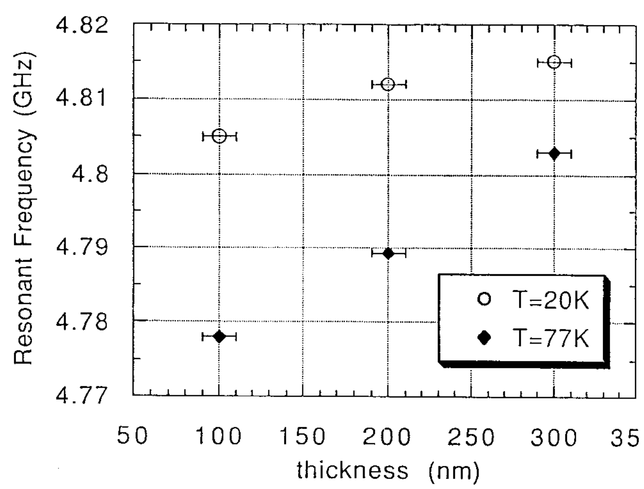

Figure 6 The resonance frequency versus film thickness at 20 and 77 K. The data are from Figures 2–4. The phase velocity increases as film thickness increases, and the phase velocity decreases with increased temperature

CONCLUSION

We have designed, fabricated, and tested high-T_c superconducting end-coupled in-line coplanar waveguide resonators to determine the impact of the kinetic inductance effect. A model was developed based on a resistive boundary condition incorporated into a full-wave spectral domain analysis of the tested structures. The model reveals a zero temperature penetration depth of 225 ± 25 nm for the 100–300-nm-thick films. The measured data are consistent with a T-squared temperature dependence of the penetration depth. Using a T-squared temperature dependence provides enough accurate phase velocity information for such components as high-T_c superconducting CPW delay lines, filters, and slow-wave structures to be designed.

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AN ULTRA-LOW-NOISE MILLIMETER-WAVE OSCILLATOR USING A SAPPHIRE DISK RESONATOR AND HIGH-TEMPERATURE SUPERCONDUCTOR GROUND PLANES

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KEY TERMS

Oscillator, HTS, sapphire, millimeter wave, phase noise, cryogenic electronics

ABSTRACT

The first fully integrated HTS millimeter-wave oscillator operating at 77 K with a phase noise improvement of 20 dB over conventional oscillators is reported. A loaded Q of 59,000 at 36.5 GHz obtained from a sapphire resonator shielded by HTS ground planes is almost 100 times greater than ceramic resonators. © 1993 John Wiley & Sons, Inc.

INTRODUCTION

Utilization of high-temperature superconducting (HTS) thin films in the development of high-performance microwave circuits has been demonstrated and shows promise of being included in commercial and military electronics in the very near future. HTS oscillators, filters, and delay lines are likely to be the first components integrated into existing or new systems. This article presents the results of the first fully integrated HTS millimeter-wave oscillator and reports a phase noise improvement of 20 dB over conventional oscillators which use ceramic dielectric resonators and operate at room temperature. This oscillator was built for a dual mode seeker demonstration, where infrared- and millimeter-wave electronics are combined on one small cryogenic platform operating at 80 K. The purpose of this project was to demonstrate high performance and small size in an integrated package.

An extremely high loaded quality factor (Q) of 59,000 at 36.5 GHz was obtained from a sapphire disk resonator shielded by two HTS ground planes operating at 77 K. This resonator result is almost 100 times higher than that obtained from conventional dielectric resonators shielded by normal metals at room temperature, and is consistent with other reports using this method [1, 2]. This approach also produces Qs that far exceed those of patterned HTS resonators, which are limited by substrate and radiation losses, thereby providing a means to improve upon earlier HTS oscillators [3]. Microstrip circuitry including a bandpass filter, coupler, and transmission lines were also designed and made from HTS thin film to reduce loss. Circuit components become significantly smaller at millimeter-wave frequencies, which permitted the use of a parallel feedback configuration in a package size comparable to conventional oscillators which use series feedback.

The thallium-based HTS films $Tl_2Ba_2Ca_2Cu_2O_8$ (TBCCO) used in this oscillator assembly were prepared by laser ablation deposition of a mixed oxide target on a 2-in.-diameter $LaAlO_3$ wafer, followed by a postdeposition thermal process [4]. The wafer was then diced into 1-cm^2 substrates. Typical film properties include transition temperature greater than 100 K, as measured by AC susceptibility at 50% amplitude and 10-GHz surface resistance less than 0.25 mΩ per square