5 GHz High-Temperature-Superconductor Resonators with High Q and Low Power Dependence up to 90 K

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***Abstract*—We have fabricated high-temperature superconducting films made of TlBaCaCuO (2212) and YBaCuO (123) by postdeposition annealing techniques on (100) $LaAlO_3$ substrates. These films, especially the TlBaCaCuO (2212), exhibit a unique combination of microwave properties: high temperature operation, high Q (low surface resistance), and low power dependence. Both types of films have measured surface resistances which are better than 1/10 that of copper at 20 GHz. (These low surface resistance values are realized below 98 K for TlBaCaCuO (2212) and below 84 K for YBaCuO (123).) Microstrip resonators with a fundamental resonance frequency of 5 GHz were fabricated from these materials. The performance of our best resonator at 90 K (loaded $Q > 20\,000$ at 5 GHz) was 50 times better than an analogous copper resonator (also measured at 90 K) and can handle more than 10 W of peak power in the resonator with only a small degradation of the Q. In addition, the shift of the resonator frequencies with temperature was fit to a two-fluid model. The parameters for TlBaCaCuO (2212) were $T_c = 101.0$ K and $\lambda_0 = 4700$ Å and for YBaCuO (123) were $T_c = 91.1$ K and $\lambda_0 = 6800$ Å.**

I. Introduction

Good-quality thin films of YBaCuO (123) high-temperature superconductor have been grown by a variety of *in situ* deposition techniques.[1] All of these *in situ* techniques directly deposit the high-temperature superconductor at elevated substrate temperatures (550°–750°C) in an oxygen atmosphere. Some of these films have been shown to have excellent microwave properties.[2] We have fabricated high-temperature superconductor films made of YBaCuO (123) and TlBaCaCuO (2212) by postdeposition annealing techniques. These techniques consist of a room-temperature deposition of a precursor material followed by a high-temperature (800°–900°C) postanneal in an appropriate atmosphere to convert the film to the desired superconducting phase(s). The surface resistance of these films was measured at 20 GHz with an end-wall replacement TE_{011} copper cavity and found to be less than 1/10 that of oxygen-free copper at 77 K. Some microstrip resonators made from these films, especially the TlBaCaCuO (2212), exhibit a unique combination of microwave properties: high temperature operation (> 90 K), very high Q (> 20 000 at 5 GHz) and little power dependence (< 25% up to 10 W).

II. Film Preparation

We prepared TlBaCaCuO (2212) thin films by a two-step postanneal process.[3] A sputtering target was prepared by pressing a powder composed of prereacted barium copper oxide and calcium copper oxide with a nominal composition of Ba:Ca:Cu = 2:1:2. A precursor oxide film was deposited on a (100) $LaAlO_3$ substrate by off-axis RF magnetron sputtering at a rate of 1 to 2 Å/s. These films were then converted to TlBaCaCuO (2212) by heating in a covered alumina crucible (containing a powder mixture of TlBaCaCuO (2223) and Tl_2O_3 in air) at 800°–900°C for a few minutes to an hour. Film thickness increased by about 20% during thallination.

We prepared YBaCuO (123) thin films by the coevaporation of Y, Cu, and BaF_2.[4] A precursor film was deposited on (100) $LaAlO_3$ in a vacuum chamber with a base pressure of $< 8\times10^{-7}$ mbar and an oxygen pressure of 1×10^{-5} mbar. Y and Cu were e-beam evaporated from separate guns and BaF_2 was thermally evaporated from a covered Mo boat. The deposition rate varied from 0.5 Å/s to 1 Å/s. The two-stage annealing of these films took place in a quartz-lined tube furnace. The temperature was ramped at a rate of 10° to 25°C per minute up to between 850°C and 900°C in a flowing wet oxygen atmosphere. The peak temperature was then held for 30 min in wet oxygen to fully decompose the BaF_2. Finally, the furnace was slowly cooled at a rate of approximately 2°C per minute in dry oxygen.

X-ray diffraction analysis of the TlBaCaCuO (2212) and YBaCuO (123) films show them to be predominantly c-axis oriented. For TlBaCaCuO (2212), there was a small

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[1] See, for example, [1]–[4].
[2] For one of many compilations of the surface resistance of YBaCuO (123), see [5]. Surface resistance data for TlBaCaCuO (2212) are more difficult to find. See, for example, [6].
[3] For more detailed information on this process, see [7].
[4] For more detailed information on this process, see [8].

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amount of other randomly oriented material present, while for YBaCuO (123), there was some a-axis-oriented material present. XRD ϕ scans for both types of films show a high degree of in-plane epitaxial alignment with the (100) $LaAlO_3$ substrate. The dc transition temperature was 91 K for YBaCuO (123) with a transition width of < 2 K and was 106 K for TlBaCaCuO (2212) with a transition width of ~ 5 K.

III. Microwave Film Characterization

All measurements were made in specially modified 60 l He storage Dewars with glass-epoxy inserts. The insert is equipped with a vacuum interlock, which facilitates high sample throughput and prevents atmospheric condensation, especially water, on the films. The packages are mounted on a copper plate at the end of a stainless steel probe which is then evacuated and finally lowered into the insert. The temperature is controlled over a range of 4 to 150 K with a pair of 100 W heaters. The scattering parameter, S_{21}, was measured with an HP8510B network analyzer. Prior to the measurements, a through response calibration as a function of temperature was performed on the probe and saved in an external computer. The calibrated insertion loss of the device could then be calculated at every measurement temperature and measurement frequency.

The surface resistance of 1 in. square unpatterned films was measured at 20 GHz by end-wall replacement in a TE_{011} oxygen-free copper cavity.[5] First, a 1 in. by 1 in. piece of polished oxygen-free copper was held in place at one end of the cavity by an arrangement of Cu–Be springs. The loaded Q, Q_m(Cu), was measured as a function of temperature. Then a superconducting film replaced the copper standard and the loaded Q, Q_m(SC), was again measured as a function of temperature. The unloaded Q, Q_0, was calculated, assuming coupling coefficients, $\beta_1 = \beta_2$:

$$Q_0 = Q_m(1+\beta_1+\beta_2) = Q_m(1+2\beta)$$

where

$$(1+2\beta) = \frac{1}{(1-10^{(-IL/20)})}$$

and where IL is the calibrated insertion loss of the cavity. The ratio of the surface resistance of copper to the surface resistance of the superconducting film was then calculated.

The Q of any closed cavity made of a good conductor is proportional to the energy stored in the electric and magnetic fields within the cavity divided by the losses caused by the surface currents in the walls of the cavity:

$$Q = \frac{2\pi f E_{st}}{(L_{sw}+2L_{ew})}$$

where f is the resonant frequency, E_{st} is the stored energy, L_{sw} is the loss in the sidewall, and L_{ew} is the loss in the end wall. For an all-copper cylindrical cavity with one sidewall and two end walls, the unloaded Q, Q_0(Cu), is given by

$$Q_0(\mathrm{Cu}) = \frac{2\pi f E_{st}}{(L_{sw}(\mathrm{Cu})+2L_{ew}(\mathrm{Cu}))}$$

where L_{sw}(Cu) is the loss in a copper sidewall and L_{ew}(Cu) is the loss in a copper end wall. If one end wall of the cavity is replaced by a superconducting film, then the unloaded Q, Q_0(SC), is

$$Q_0(\mathrm{SC}) = \frac{2\pi f E_{st}}{(L_{sw}(\mathrm{Cu})+L_{ew}(\mathrm{Cu})+L_{ew}(\mathrm{SC}))}$$

where L_{ew}(SC) is the loss in the superconducting end wall. The ratio of the unloaded Q's of an all-copper cavity and the same cavity with one end wall replaced with a superconducting film is

$$\frac{Q_0(\mathrm{Cu})}{Q_0(\mathrm{SC})} = \frac{(L_{sw}(\mathrm{Cu})+L_{ew}(\mathrm{Cu})+L_{ew}(\mathrm{SC}))}{(L_{sw}(\mathrm{Cu})+2L_{ew}(\mathrm{Cu}))}.$$

Adding and subtracting L_{ew}(Cu) in the numerator yields

$$\frac{Q_0(\mathrm{Cu})}{Q_0(\mathrm{SC})} = 1+\frac{L_{ew}(\mathrm{SC})}{(L_{sw}(\mathrm{Cu})+2L_{ew}(\mathrm{Cu}))} - \frac{L_{ew}(\mathrm{Cu})}{(L_{sw}(\mathrm{Cu})+2L_{ew}(\mathrm{Cu}))}.$$

If we define K to be

$$K = \frac{L_{ew}(\mathrm{Cu})}{(L_{sw}(\mathrm{Cu})+2L_{ew}(\mathrm{Cu}))}$$

then, substituting, we find

$$\frac{Q_0(\mathrm{Cu})}{Q_0(\mathrm{SC})} = 1-K+K\frac{L_{ew}(\mathrm{SC})}{L_{ew}(\mathrm{Cu})}.$$

Since the electric and magnetic field distribution is the same for both configurations of the cavity, the loss in any wall is proportional to the surface resistance; therefore,

$$\frac{Q_0(\mathrm{Cu})}{Q_0(\mathrm{SC})} = 1-K+K\frac{R_s(\mathrm{SC})}{R_s(\mathrm{Cu})}$$

or, rearranging

$$\frac{R_s(\mathrm{Cu})}{R_s(\mathrm{SC})} = \frac{K}{\left(K+\dfrac{Q_0(\mathrm{Cu})}{Q_0(\mathrm{SC})}-1\right)}.$$

The value of K was found by comparing a polished copper end wall with a Nb thin film at 6 K. For our cavity, this value was 0.25. It should be noted that this formula only breaks down when the surface resistance of the superconductor becomes very much worse than copper.

Since the reproducibility of our Q measurement is better than 1%, this allows us to measure surface resistance ratios up to 10. The absolute surface resistance can be found by calculating the surface resistance of the

[5]For a review of cavity techniques, see [9].

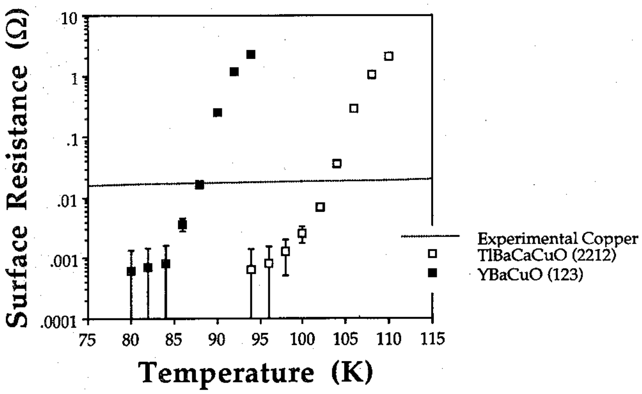

Fig. 1. Surface resistance versus temperature for TlBaCaCuO (2212) and YBaCuO (123) measured in a 20 GHz TE_{011} end-wall replacement copper cavity.

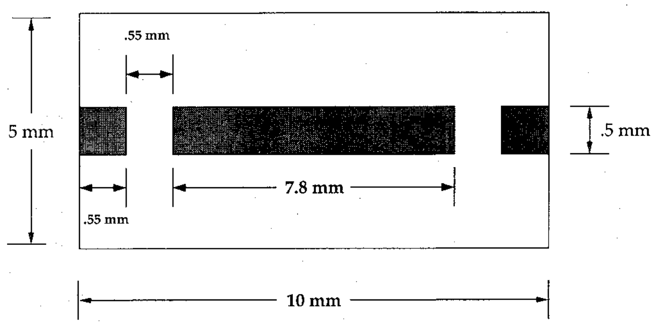

Fig. 2. Design of 30 Ω microstrip resonator with a resonant frequency of 5 GHz on a 20 mil $LaAlO_3$ substrate.

all-copper cavity from well-known formulas.[6] The surface resistances of YBaCuO (123) and TlBaCaCuO (2212) films measured by this technique are shown in Fig. 1. The sensitivity limit of the cavity is approximately 1.5 mΩ, the 10× limit. For our best TlBaCaCuO (2212) films, this limit is reached at ~98 K. For our best YBaCuO (123) films, this limit is reached at ~84 K.

IV. Device Design, Fabrication, and Packaging

The microstrip resonator was designed with EESOF Touchstone and verified by Hewlett-Packard MDS and is shown in Fig. 2. For our design on 20 mil $LaAlO_3$ (dielectric constant, $\epsilon_r = 24.5$), the characteristic impedance is 30 Ω, the effective dielectric constant, ϵ_{eff}, is 16 and the fundamental resonance frequency is approximately 5 GHz. Eight resonators were patterned from a film that had been deposited on a 1 in. by 1 in. substrate. Standard photolithographic patterning techniques were followed by ion beam milling of the superconductor. This substrate (and a second substrate to be used for a ground plane) was coated with PMMA and diced to size. The PMMA was then stripped by a reactive ion etch. Silver contact pads were applied through an etched metal shadow-mask and annealed for 1 h at 530°C in oxygen. The substrate "sandwich" was then placed in the package and held

[6]For example, we used [10].

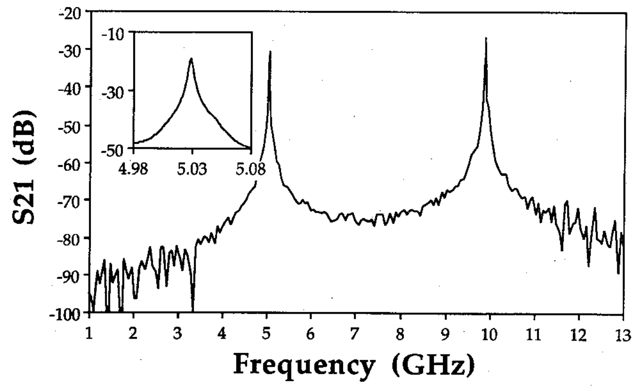

Fig. 3. Insertion loss of a packaged YBaCuO (123) device. The fundamental resonance is shown in the inset.

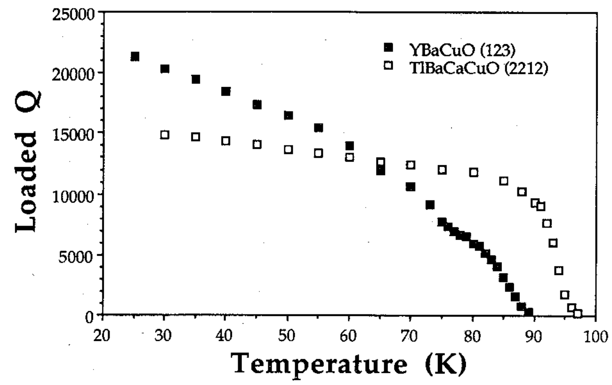

Fig. 4. Loaded Q versus temperature for 5 GHz resonators of TlBaCaCuO (2212) and YBaCuO (123).

together by a Cu–Be spring on one side and two pieces of Delrin on the other. The spring ensures a good pressure fit between the circuit and the sliding contact of the coaxial connector. The device package was then hermetically sealed and tested.

V. Device Testing and Analysis

The uncalibrated S_{21} of a packaged device is shown in Fig. 3. When packaged correctly, the fundamental and the first two harmonics remain uncluttered by any packaging modes. The loaded Q data for resonators fabricated from TlBaCaCuO (2212) and YBaCuO (123) films are shown in Fig. 4. Both of these resonators are very lightly loaded ($\beta < 0.01$) so that the measured Q and the unloaded Q are almost identical. By comparison, a resonator fabricated from gold had an unloaded Q of 300 at 77 K. These superconducting resonators perform 40 times better than gold. The internal average RF magnetic field in these resonators is at most 0.1 G. Several resonators were repackaged with increased coupling and hence increased internal average RF magnetic field. The power dependence of one of the TlBaCaCuO (2212) resonators is shown in Fig. 5. Up to an internal average field of approximately 10 G, or an average power of approximately 20 W inside of the resonator, there is only a 25% degradation of Q.

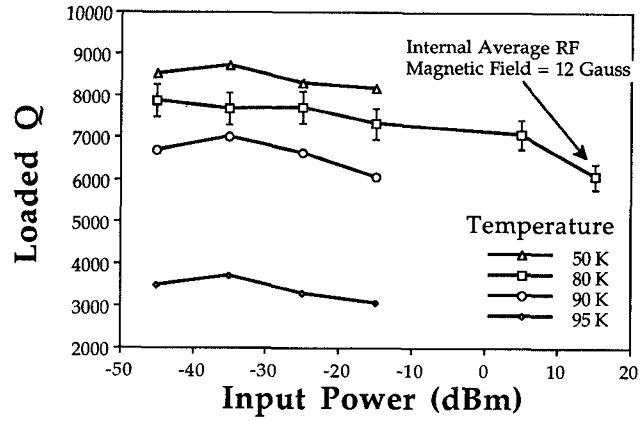

Fig. 5. Loaded Q versus input power for a TlBaCaCuO (2212) resonator at several temperatures.

Three loss mechanisms contribute to the intrinsic Q_0 of a resonator: conductor loss, Q_c, dielectric loss, Q_d, and radiation loss, Q_r:

$$\frac{1}{Q_0}=\frac{1}{Q_c}+\frac{1}{Q_d}+\frac{1}{Q_r}.$$

The conductor loss is proportional to the surface resistance of the superconductor. This loss can be calculated from well-known formulas [11]. Assuming that the surface resistance is 1/10 that of copper at 20 GHz, that the film has not degraded during patterning, and that the ω^2 dependence of the two-fluid model holds[7] yields a $Q_c >$ 30000. This means that the performance of our resonators is limited not by the conductor loss but rather by the loss tangent, $\tan\delta$, of the $LaAlO_3$ substrate or the radiation losses.

Some additional information can also be garnered from the frequency response versus temperature of the resonators. As the temperature approaches the critical temperature, T_c, the kinetic inductance of the superconductor increases, and so the phase velocity and resonant frequency decrease. This shift of the resonator frequency with temperature was fit to a two-fluid model and the critical temperature and zero degree penetration depth, λ_0, were calculated. The parameters for TlBaCaCuO (2212) were $T_c = 101.0$ K, $\lambda_0 = 4700$ Å, and TCE = 19 ppm; for YBaCuO (123) they were $T_c = 91.1$ K, $\lambda_0 =$ 6800 Å, and TCE = 26 ppm.[8] These data for TlBaCaCuO (2212) and YBaCuO (123) resonators are shown in Figs. 6 and 7, respectively.

The normalized frequency, f^*, is the fractional frequency shift normalized to the frequency at the lowest measurement temperature:

$$f^* = \frac{(f-f_0)}{f_0}$$

where f is the measured frequency at temperature T and

[7]There are many papers that address this issue. See, for example, [12].
[8]A value of 20 ppm for the thermal expansion coefficient, TCE, of $LaAlO_3$ at 77 K has been reported [15].

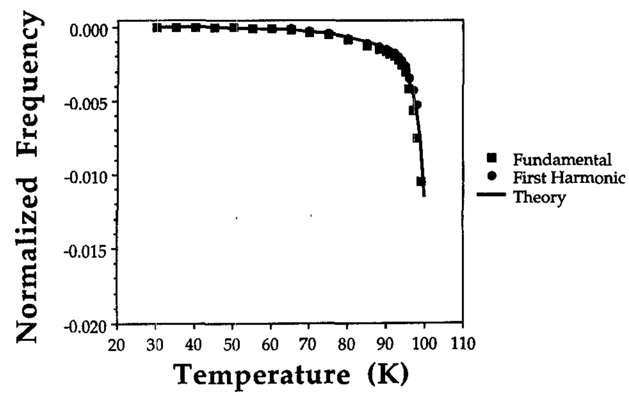

Fig. 6. Normalized frequency versus temperature at 5 GHz (fundamental) and 10 GHz (first harmonic) for a TlBaCaCuO (2212) resonator. The solid line is the theoretical fit to the data with TCE = 19 ppm, $T_c = 101.0$ K, and $\lambda_0 = 4700$ Å.

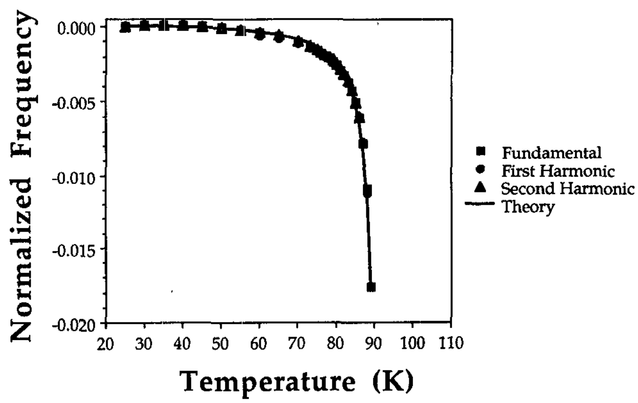

Fig. 7. Normalized frequency versus temperature at 5.5 GHz (fundamental), 10.7 GHz (first harmonic), and 15.7 GHz (second harmonic) for a YBaCuO (123) resonator. The solid line is the theoretical fit to the data with TCE = 26 ppm, $T_c = 91.1$ K, and $\lambda_0 = 6800$ Å.

f_0 is the frequency at the lowest measurement temperature, T_0. This represents the residual frequency shift obtained after also accounting for the small contribution from the contraction of the substrate as a function of temperature. This is usually expressed as the temperature coefficient of expansion, α, which we choose to write as

$$f(T) = \frac{f_m}{(1+\alpha(T-T_0))}$$

where f_m is the measured resonant frequency. For each resonator, the TCE was found by fitting the temperature behavior below $T_c/2$, where the penetration depth, λ, can be expressed as a linear function of temperature. The normalized frequency shift can be attributed to the change in the inductance per unit length of the line that occurs as a consequence of the change of the penetration depth. Since the phase velocity is inversely proportional to the square root of the inductance, the resonant frequency is expected to increase with decreasing temperature. We can express the frequency of the resonator as

$$f = \frac{v_p}{(2l_r)}$$

where v_p is the phase velocity and l_r is the effective length of the resonator, which is slightly longer that the physical length owing to the coupling capacitance. The phase velocity, v_p, of a microstrip transmission line can be expressed as [13]

$$v_p = \frac{c}{\sqrt{\epsilon_{\text{eff}}}}\left[1+\frac{2\lambda}{d}\coth\left(\frac{b}{\lambda}\right)\right]^{-0.5}$$

where c is the velocity of light, ϵ_{eff} is the effective dielectric constant, d is the substrate thickness, and b is the film thickness. The temperature dependence of λ, assuming the two-fluid model, can be expressed as

$$\lambda = \lambda_0\left[1-\left(\frac{T}{T_C}\right)^4\right]^{-0.5}$$

where λ_0 is the penetration depth at 0 K and T_c is the critical temperature of the superconductor. A nonlinear fit of the data is also shown in Figs. 6 and 7.

The penetration depth, λ_0, for single-crystal YBaCuO (123) has been reported in the range of 1600 Å for the best crystals and up to 8000 Å for poor crystals [14]. Our value of 6100 Å falls within this range and compares to a value of 4500 Å reported for a coevaporation YBaCuO (123) ring resonator at 10 GHz [15]. This measured "effective" penetration depth is an average over the entire film surface including grain boundaries, a-axis-oriented material, edges of the microstrip that may have been degraded during patterning, etc. To date, we are unaware of any analogous values for the penetration depth of TlBaCaCuO (2212).

VI. Conclusions

We have fabricated both TlBaCaCuO (2212) and YBaCuO (123) thin films by postdeposition annealing techniques. The measured surface resistances of these films are better than 1/10 that of oxygen-free copper at 20 GHz; for TlBaCaCuO (2212) this occurs below 98 K and for YBaCuO (123) below 84 K. Our best microstrip resonator, made from TlBaCaCuO (2212), exhibits a unique combination[9] of microwave properties: high temperature operation, very high Q, and little power dependence. These resonators can be operated at temperatures up to 90 K without significant degradation of the Q. The performance of our best resonator is 50 times better than an analogous copper resonator (both measured at 90 K and 5 GHz). Also, the superconducting resonator can handle a peak power of more than 20 W in the resonator with only a 25% degradation of the Q.

[9]For some high-quality YBaCuO (123) resonators at other frequencies and made by other techniques, see [16]–[18]. For TlBaCaCuO (2212) resonators, see [19].

Acknowledgment

The authors wish to acknowledge and thank R. J. Small for making the YBaCuO (123) films; L. A. Parisi for making the TlBaCaCuO (2212) films; R. D. Nicholls and M. S. Warrington for patterning the devices; W. Rewa for dicing the substrates; L. D. Gardenhour for designing the packages; M. S. Brenner and C. F. Carter for the electrical characterization of the films and devices; R. Riegert for the electromagnetic modeling of the cavity; and T. Cooper for helping with the Touchstone simulation.

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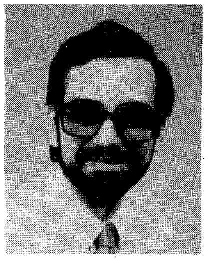

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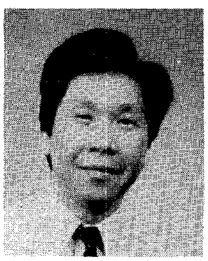

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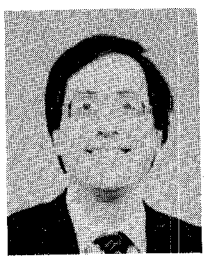

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