RADIATION EFFICIENCY MEASUREMENTS OF A THIN-FILM Y-BA-CU-O SUPERCONDUCTING HALF-LOOP ANTENNA AT 500 MHZ

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ABSTRACT

A 500 MHz half-loop antenna and matching network has been fabricated from a 2-cm by 2-cm thin film of the high temperature superconductor YBaCuO. The antenna demonstrates a radiation efficiency of 20 percent, compared to 7 percent for a comparable copper antenna.

INTRODUCTION

Cryogenically-cooled antennas made from superconductors (and from normal metals) have been the objective of several theoretical and experimental studies (1-3). All of these studies demonstrate that cooling can be of considerable benefit when (or if) the antenna is electrically small (dimensions much less than the wavelength λ). Cooling reduces the loss resistance R_L relative to the low radiation resistance R_r found in electrically small antennas, yielding a larger radiation efficiency η:

$$\eta = \frac{R_r}{R_r + R_L} \qquad (1)$$

In addition, as a receiving antenna, the signal-to-noise-ratio is increased (1). However, practical issues associated with the obvious problems in cooling an antenna below the typical 20°K transition temperatures of (pre-1987) metallic superconductors prevented any applications of such antennas.

In 1987 high temperature superconductors (HTS) were discovered, prompting renewed interest in superconducting antennas. The 90 to 125°K range of transition temperatures for HTS considerably eases the problems of providing cooling, since compact, cheap, and reliable open- and closed-cycle coolers are available, as is liquid nitrogen. Several recent papers have reviewed the potential applications of HTS antennas (4,5).

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This paper describes a thin-film antenna fabricated from YBaCuO that has been used to transmit and receive signals at a frequency of 512 MHz. To our knowledge, this is the first *thin-film* HTS antenna demonstrated below 2 GHz. The antenna and its matching circuit, fabricated on a 2-cm by 2-cm $LaAlO_3$ substrate, form a very small antenna ($L/\lambda \sim 0.03$).

ANTENNA AND MATCHING NETWORK DESIGN

The input reactance of electric antennas such as monopoles becomes increasingly more negative (capacitive) with decreasing size, whereas the input reactance of a magnetic antenna such as a loop approaches zero with decreasing size. To make the impedance matching problem more tractable, then, we chose to develop a magnetic antenna (Figures 1 and 2).

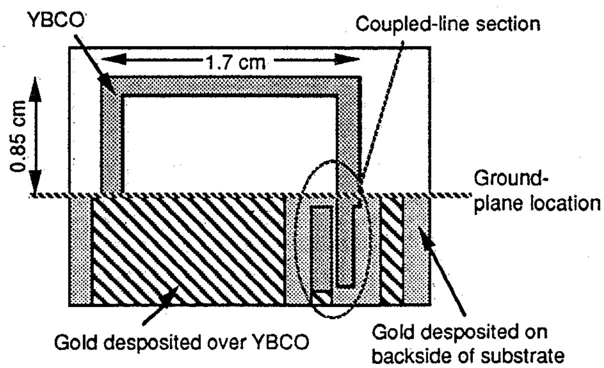

FIGURE 1. Layout of HTS Antenna

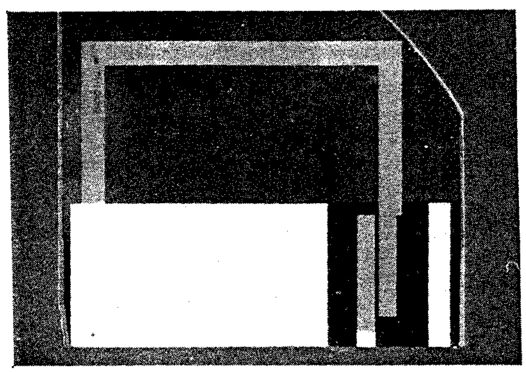

FIGURE 2. YBaCuO Antenna

A half-loop over a groundplane, rather than a full loop antenna, was selected for several reasons:

- The matching network can be placed behind the groundplane, and thereby not interfere or complicate the radiation pattern;

- The closed-cycle refrigerator can also be placed behind the groundplane;

- The configuration is more useful for applications, since isolated full loop antennas are difficult to realize.

A sufficiently accurate equation for determining the input reactance of the half-loop antenna in Figure 1 is

$$X_{in} = (\mu_o c/\lambda) [L_1 \cosh^{-1}(L_2/d) + L_2 \cosh^{-1}(L_1/d)] \quad (2)$$

where d = w/1.15. A number of copper-on-alumina antennas were fabricated to confirm the degree to which Eq. (2) can predict X_{in}. The factor of 1.15 gave better agreement between analysis and experiment. The input resistance of the antenna is given by $R_{in} = R_r + R_L$. The radiation resistance R_r is given in ohms by

$$R_r = 10 [(2\pi/\lambda)^2 L_1 L_2]^2 \quad (3)$$

and the loss resistance R_L is given by

$$R_L = (2/\pi d) R_s (L_1 + L_2) \quad (4)$$

where R_s is the surface resistance of the conductor. The radiation efficiency of the antenna plus matching network (i.e., the radiation efficiency defined at the terminals of the matching network) is

$$\eta = R_r/(R_r + R_L + R_{match}) \quad (5)$$

where R_{match} accounts for any losses in the matching network. Figure 3 is a plot of Eqs (2-4). We emphasize that Eqs (2-4) do not take the substrate into account, and therefore give approximate values only.

At the operating frequency of 500 MHz, Figure 3 shows that an impedance of Z_{in} = 0.1 + j80 Ω must be matched to the 50-Ω impedance of the feedline. Most matching networks using transmission line distributed elements require lines at least λ/4 in length. However, on an $LaAlO_3$ substrate with relative dielectric constant $\varepsilon_r \approx$ 24, this condition would require a λ/4-transmission line approximately 3.7 cm in length--much larger than any available HTS thin film area. To avoid this problem, we designed the coupled-line matching network shown in Figure 1.

The analysis makes use of the odd and even mode impedances--Z_{oo} and Z_{oe}, respectively--of the coupled lines. The width of the lines are chosen to give a

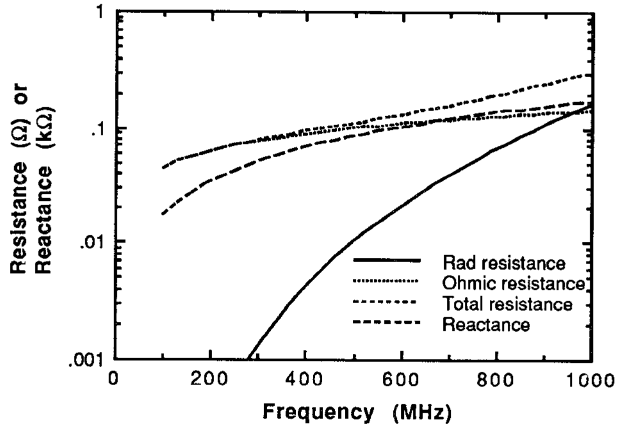

FIGURE 3. Calculated Input Resistance and Reactance for the YBaCuO Antenna Shown in Figures 1 and 2

Z_o = 50-Ω impedance. The real part of the impedance looking into the coupled line section from the antenna side can be written as

$$R_m = Z_o (Z_{oo} - Z_{oe})^2/(Z_{oo} + Z_{oe})^2 \quad (6)$$

R_m can be selected by adjusting the difference between Z_{oo} and Z_{oe}. For a fixed line width this difference depends principally on the separation between the lines. For the low value of R_m required in the present case (0.2Ω), $Z_{oo} \approx Z_{oe}$. The imaginary part of the impedance is given by

$$X_m = \frac{Z_+ \cot\theta_m (4 Z_o^2 \sin^2\theta_m + Z_+^2 \cos^2\theta_m - Z_-^2)}{2 (4 Z_o^2 \sin^2\theta_m + Z_+^2 \cos^2\theta_m)} \quad (7)$$

where $\theta_m = 2\pi L_m/\lambda$, $Z_+ = Z_{oo} + Z_{oe}$, and $Z_- = Z_{oo} - Z_{oe}$. However, since $Z_{oo} \approx Z_{oe}$ for this matching circuit, $Z_- \approx$ 0 and Eq. (7) becomes

$$X_m \approx (Z_+ \cot\theta_m)/2 \quad (8)$$

Hence, the reactive part of the antenna impedance can be matched mainly by adjusting the length of the coupled line sections. Fortunately, for the 500 MHz frequency and Z_{in} to be matched in the present case, the length (and width) of the matching section can be accommodated within the area available on the YBaCuO thin film. The coupled-line length turns out to be substantially less than λ/4 in length because a portion of the capacitance needed to cancel the antenna inductance is provided by the large *lumped-element* capacitance of the coupled-line structure. That is, the coupled-line structure resembles a capacitor at 500 MHz.

Eqs (6) and (8) are convenient for a preliminary analysis, but the final tweaking of the design was carried out using Touchstone microwave analysis software. Without an exact knowledge of R_s for the YBaCuO at 500 MHz and some specified temperature, and without more accurate equations for X_a, R_a, and R_L, we decided (somewhat arbitrarily) to design the matching network using R_s parameters appropriate for copper at room temperature. The fact that the YBaCuO antenna turned out to have the best match at about 75°K (as shown in the data below) is in part fortuitous.

DEVICE FABRICATION

The antenna and matching network were patterned from a YBaCuO thin film fabricated by off-axis sputtering. The circuit was patterned by conventional wet-etch techniques. As indicated by Figure 1, the groundplane of the matching section was evaporated gold. Measurements on an antenna with an HTS matching section groundplane will be carried out in the very near future.

Measurements of R_s on films grown under the same conditions at a frequency of 22 GHz have given values around 6 mΩ. Scaling by the square of the frequency predicts R_s = 3 μΩ at 500 MHz. However, an R_s value for the particular film used in this antenna was not measured.

An identical copper antenna was fabricated, also on an $LaAlO_3$ substrate, for comparison with the YBaCuO antenna. We emphasize that the comparison is actually biased towards the copper antenna, since the design was optimized for copper (see previous section).

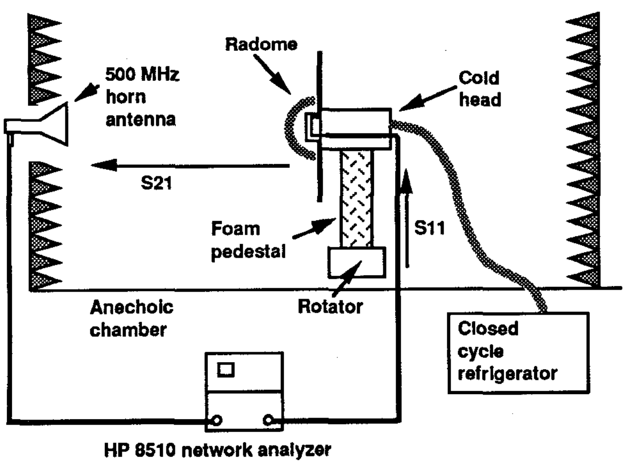

FIGURE 4. Measurement Setup

MEASUREMENT APPARATUS

To cool the antenna, we used a 14-W closed-cycle refrigerator, as diagrammed in Figure 4. The $LaAlO_3$ substrate and circuit, mounted within a copper can attached to a cold finger, can be seen protruding through the groundplane in Figure 5; a hemispherical evacuated radome in turn covers this antenna. An automatic network analyzer measured both the transmission coefficient (S_{21}) between a horn antenna and the HTS antenna, and the reflection coefficient at the input to the antenna (S_{11}). Using the Friis transmission equation, it is easy to show that the radiation efficiency as defined by Eq. (1) is given by

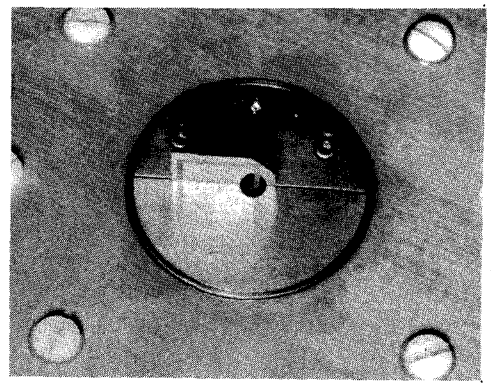

FIGURE 5. YBaCuO Antenna Protruding Through Copper Groundplane

$$\eta = \frac{|S_{21}|^2 (4\pi R)^2}{\lambda^2 G_t G_r} \tag{9}$$

where R is the distance from transmitting to receiving antenna, and G_t and G_r are the directive gain of the transmitting and receiving antennas, respectively.

If one wishes to compare the *transfer radiation efficiency* η_t of the copper and YBaCuO antenna/matching network, Eq. (9) is modified to give

$$\eta_t = \frac{|S_{21}|^2 (4\pi R)^2}{(1 - |S_{11}|^2)\, \lambda^2 G_t G_r} \tag{10}$$

The transfer radiation efficiency divides out the residual mismatch of the matching network, and permits a more direct comparison of the losses in the YBaCuO and copper devices. Of course, at the temperature at which the devices are matched, $S_{11} \to 0$, and the two definitions of efficiency are identical. We made all measurements in an anechoic chamber.

RESULTS

Measurements of S_{11} and S_{21} were taken as the antenna cooled down from room temperature to 20°K, the lowest temperature that the refrigerator was capable of. Figure 6 is a plot of the radiation efficiency as a function of temperature, showing the transition of the antenna to the superconducting state at a temperature of approximately 78°K (Because of the location of the temperature sensor on the copper enclosure, there may be a difference of as much as 5°K in the actual antenna temperature and the indicated temperature). The YBaCuO antenna produces, at the lowest temperature, a transfer radiation efficiency three times higher than the copper antenna and a radiation efficiency twice that of the copper antenna. Figure 7 is a Smith chart display of the S_{21} data as a function of temperature and indicates that the antenna is matched at about 75°K. The 3-dB bandwidth is approximately 8.0 MHz at 50°K.

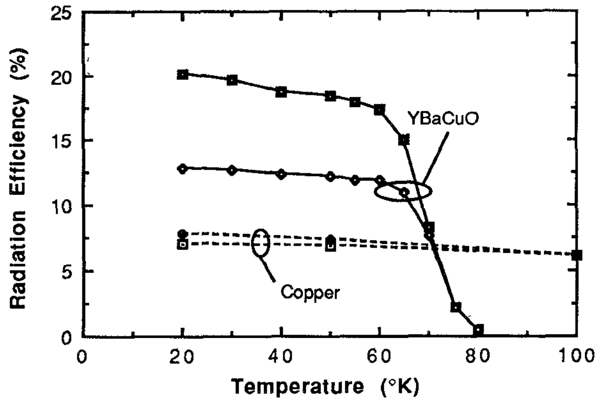

FIGURE 6. Radiation Efficiency vs Temperature. For each pair of curves, the upper curve is η_t (Eq. 10) and the lower curve is η (Eq. 9)

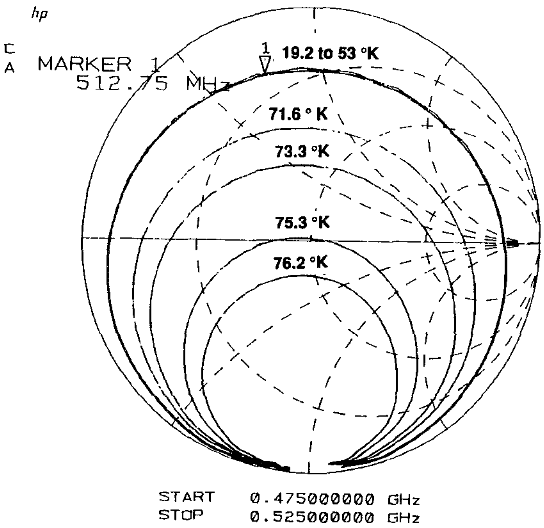

FIGURE 7. S_{11} as a Function of Temperature and Frequency

In Figure 8, we plot the measured efficiency versus the input power at a temperature of 50°K. As the input power increases, the efficiency decreases because of the dependence of R_s on the current density, an effect observed in other HTS microwave devices. We observed that the dependence on input power was most pronounced at a temperature near 75°K, i.e. at the matched condition, where the largest standing waves are set up in the coupled-line matching section.

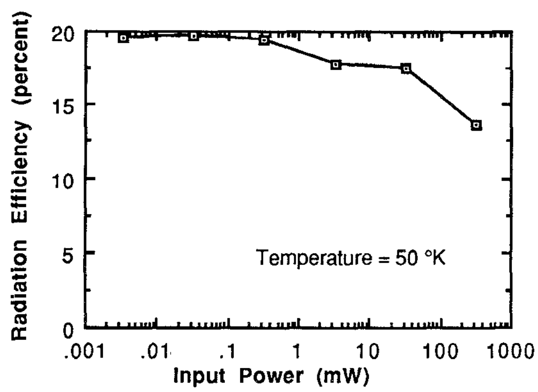

FIGURE 8. Dependence of Radiation Efficiency η on Input Power

CONCLUSIONS AND CONTINUING WORK

An improved version of the antenna using a matching section with a somewhat larger gap and adjusted overlap length has been designed to match the antenna at a lower temperature (goal of 50°K) to take advantage of a lower R_s value. Efforts are currently underway to identify the sources of dissipation in the antenna and improve the efficiency. The principal remaining reducible source of dissipation is the gold groundplane in the coupled-line matching section. Measurements are in progress both on a double-sided YBaCuO antenna and on a sandwich structure with a YBaCuO groundplane. *Preliminary* measurements on the sandwich structure have yielded a transfer radiation efficiency of 49 percent; however, the matching circuit was excessively undercoupled to the antenna, so that the radiation efficiency was lower.

Contact losses between the coaxial input line and the matching section input may also contribute to a reduction in efficiency. An irreducible source of dissipation are the "image losses" in the copper antenna groundplane. These losses cannot be reduced and set a fundamental limit to the achievable efficiency of about 70 percent.

REFERENCES

1. L. H. Hoang and M. Fournier, *IEEE Trans Ant. Propagation*, **AP-20**, 509-511 (1972).

2. J. D. Moore and D. N. Travers, *IEEE Trans. Ant. Propagation*, **AP-14**, 246 (1966).

3. G. B. Walker and C. R. Haden, *J. Applied Physics*, **40**, 2035-2039 (1969).

4. R. C. Hansen, *IEEE Trans on Aerospace and Electronic Systems*, **AES-26**, 345-355 (1990)

5. R. J. Dinger, *J. Superconductivity*, **3**, 287-296 (1990).