Performance of a Four-Element Ka-Band High-Temperature Superconducting Microstrip Antenna

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***Abstract*—Superconducting four-element microstrip array antennas operating at 30 GHz have been designed and fabricated on a lanthanum aluminate ($LaAlO_3$) substrates. The experimental performance of these thin film Y–Ba–Cu–O superconducting antennas is compared with that of identical antenna patterned with evaporated gold. Efficiency measurements of these antennas show an improvement of 2 dB at 70 K and as much as 3.5 dB at 40 K in the superconducting antenna over the gold antenna.**

I. Introduction

SINCE the advent of high-temperature superconductors (HTS), many superconducting electronics applications have been projected at liquid nitrogen temperatures [1]. More recently, HTS devices such as resonators, delay lines, filters, and phase shifters have been fabricated and tested at X-band frequencies and below [2]. Experimental results have shown that HTS devices typically exhibit significantly better performance than that of identical metallic circuits. Experimental work with Ka-band superconducting ring resonators [3] has shown a factor of 3 improvement in circuit "Q" at 35 GHz over an identical circuit fabricated with evaporated gold. Such results have encouraged the investigation of potential HTS applications in microstrip antenna systems.

To date, experimental investigation of HTS antennas has been very limited in scope, consisting mainly of work done on electrically small antennas at frequencies less than 1 GHz [4]. Analytical work by Dinger [5] has shown that HTS may be most beneficial when used in the feed and matching networks for microwave and millimeter-wave microstrip arrays. This is due to the fact that metal microstrip transmission lines have high ohmic losses which, in the feed network of an antenna array, act to limit the maximum obtainable gain. This problem is especially profound at Ka-band and higher frequencies. With the use of HTS, however, the conductor losses in the feed network are reduced dramatically. According to Dinger [5], an HTS 100 element linear array at 35 GHz could experience a gain increase of 8 to 10 dB over an identical copper array.

To experimentally investigate the advantages of HTS in such array antennas we have designed and fabricated a 30 GHz four-element superconducting microstrip array on a lanthanum aluminate ($LaAlO_3$) substrate. Efficiency measurements are presented and compared with identical gold antennas.

II. The Antennas

The four-element antenna arrays were designed for a lanthanum aluminate substrate. This material was chosen in spite of its high relative permittivity (ϵ_r) because it allows the growth of high quality YBCO thin films. The design for the antenna consists of four microstrip patches spaced $\lambda_0/2$ apart in both directions and fed in-phase by a microstrip corporate feed network. The patch feedpoints are inset by approximately 28% and fed via 100-Ω quarter-wave transformers to match the high-patch input impedance. A substrate thickness of 0.25 mm is used to minimize substrate modes and radiation. The YBCO thin film was deposited by a laser ablation process and had a relatively low critical temperature (T_c) of 84 K. The patterning of the circuit was done by standard photolithography using a wet chemical etchant. An evaporated gold ground plane of 100-Å titanium followed by 1 μm of gold was used. An identical circuits was made using 1 μm of evaporated gold as metallization for comparison purposes.

The antennas are assembled into a brass test fixture with a 50-Ω gold microstrip feed line patterned on an alumina substrate separating the coax-to-microstrip transition from the antenna (Fig. 1). Wire bonds connect the feed line on the alumina substrate to the antenna. To test the devices, each test fixture was in turn mounted at the second stage of a two-stage closed-cycle helium refrigerator that has a high-density polyethylene (HDPE) cap serving as both a vacuum jacket and a radome [6].

The efficiency of the HTS antenna relative to the gold antenna was found measuring the power received by the antenna under test at boresight and applying the Friis transmission formula. The antenna under test is used in the receive mode in the presence of a transmitting horn, while S_{21} and the reflection coefficient (S_{11}) of each antenna under test are in turn measured (Fig. 2). With all other factors being equal for the two antennas under test, the efficiency of the HTS antenna

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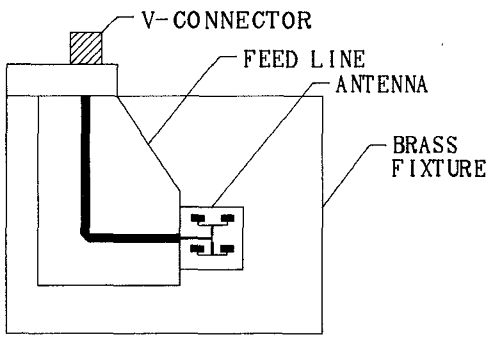

Fig. 1. Four-element array with feedline mounted in test fixture.

relative to the gold may be found as

$$\frac{\eta_{\mathrm{HTS}}}{\eta_{Au}} = \frac{\frac{|S_{21}|^2_{\mathrm{HTS}}}{1-|S_{11}|^2_{\mathrm{HTS}}}}{\frac{|S_{21}|^2_{Au}}{1-|S_{11}|^2_{Au}}}. \quad (1)$$

III. Results and Discussion

The measured E- and H-plane patterns of the gold array at 31 GHz are shown in Fig. 3. The perturbations in the patterns are due to effects such as feed radiation, surface waves, and scattering from the test fixture. As can be seen in Fig. 4, the efficiency of the HTS antenna increases dramatically at the onset temperature but tends to level off at lower temperatures. The efficiency of the four-element arrays can be approximated as

$$\eta_{(\mathrm{dB})} = \alpha_c L - \alpha_o L + \eta_{(\mathrm{dB})_{\mathrm{misc}}}. \quad (2)$$

Here, α_c is the conductor attenuation constant (dB/unit length), α_o is the attenuation constant due to other effects such as substrate losses and feedline radiation losses, L is the total feedline length, and η_{misc} is any remaining efficiency term including such effects as aperture and surface wave efficiencies. Of the terms involved in (2), to a very good approximation only α_c is affected by a change in either conductor metallization or ambient temperature. Thus, the relative efficiency as given in (1) is a measure of the difference in metal losses found in the feed network and patches of the two antennas. Loss calculations predict the HTS antenna to have approximately 1.3 dB of increase in gain over the gold antenna at 77 K. Measured relative efficiency data shows 2 dB increase at 70 K and as much as 3.5 dB improvement at 40 K. The better than expected performance at the lower temperatures may be attributed to higher than expected losses in the very narrow (2.8-μm width) 100-Ω gold lines.

To verify the shape of the efficiency curve found in this work, data from measured microstrip ring resonators patterned on identical YBCO thin films [3] was used to find the attenuation constant, α, as a function of temperature. By assuming this loss to be the only loss in the array, the shape of the gain-versus-temperature curve may be found as

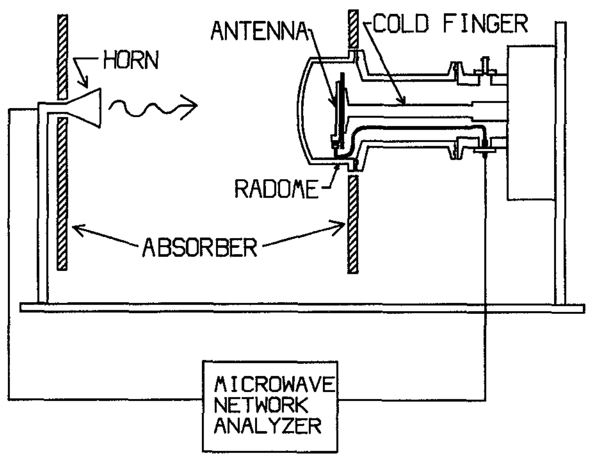

Fig. 2. Antenna efficiency measurement setup.

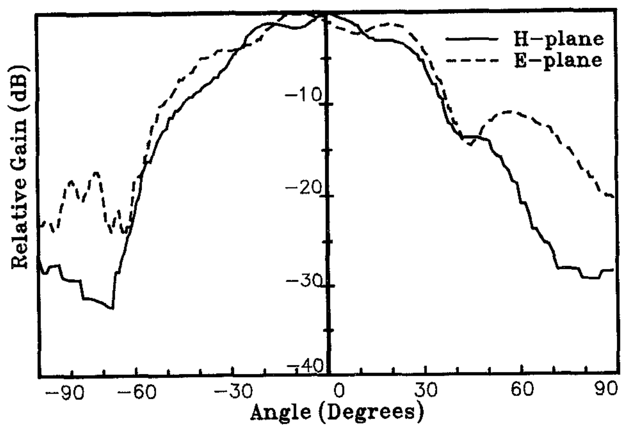

Fig. 3. E- and H-plane patterns of the gold array.

$$G = 10\log_{10}\frac{(4\pi A)}{\lambda_0} - \alpha L, \quad (3)$$

where L is the total feed line length (1.5 cm). These values are plotted in Fig. 5 along with the experimental antenna received power quantity

$$\frac{|S_{21}|^2}{1-|S_{11}|^2} \quad (4)$$

and show the same behavior as measured in the array. Similarity of these curves confirms the shape of the experimentally-found efficiency curve and validates the assumption that conductor loss is the only parameter of the antenna efficiency which changes significantly with temperature.

IV. Conclusion

A superconducting Ka-band microstrip array on lanthanum aluminate has been demonstrated. Efficiency measurements show a distinct improvement in performance over an identical gold circuit at temperatures below 75 K. Comparison with measured data from ring resonators confirm the general shape of the measured efficiency curve.

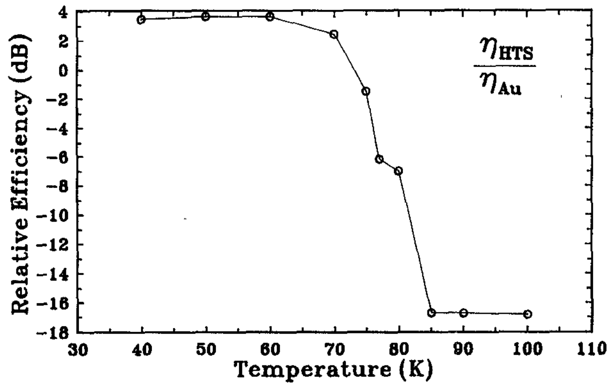

Fig. 4. Relative efficiency of HTS antenna with respect to gold antenna versus temperature.

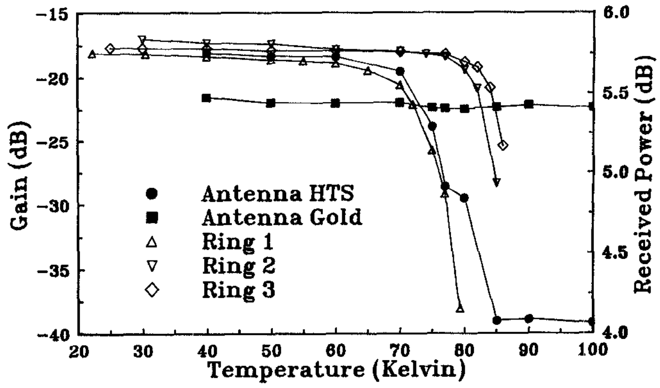

Fig. 5. Gain curves using data from HTS ring resonators compared to received power data.

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