HIGH-TEMPERATURE SUPERCONDUCTING MATCHING NETWORKS FOR ELECTRICALLY SHORT MONOPOLE ANTENNAS

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ABSTRACT

The benefits of using thin film high-temperature superconducting (HTS) matching networks for electrically short monopole antennas were demonstrated. Their performance was compared with similar matching networks made with gold, showing an efficiency improvement of 2 dB. A two-element array was also designed, fabricated and tested using HTS matching networks and short monopoles. The matching networks were configured as microstrip single stubs. This is the first demonstration of its type using thin film HTS material.

INTRODUCTION

Electrically short antennas in the UHF and L-band regions are desirable whenever the platform to be used cannot support resonant radiating structures because of size constraints. High radiation efficiency cannot be achieved in most cases, however, because of the large mismatch between source and radiator and the resulting Q demanded of the matching network. High-temperature superconductors (HTS) provide a unique opportunity for high-Q matching networks using planar waveguiding structures such as microstrip.

The work presented here is a preliminary result which demonstrates the use of HTS technology for this application. A two-element array using normal-conductor, electrically short monopoles and superconducting microstrip matching networks was fabricated and tested. The microstrip structure for the matching networks consisted of high-temperature superconducting $YBa_2Cu_3O_7$ (YBCO) thin films deposited on both sides of 0.05-cm-thick dielectric $LaAlO_3$ substrates. The 77K operating temperature required by the matching networks was achieved by immersion in a liquid nitrogen bath.

To our knowledge this is the first demonstration of this kind using thin epitaxial superconducting films. A similar demonstration using superconducting YBCO wire was recently reported in the literature [1].

It has been shown that there is no advantage in making a short monopole out of superconducting material. A discussion of the way in which the radiation and resistive losses and their reactance vary as a function of dipole length and the benefits of using superconductors is available in [2]. In a short monopole ($\leq 0.15\lambda$), the radiation resistance is small and the (capacitive) reactance large. The resistive losses are, in turn, small compared to the radiation resistance. Losses in the matching network may also be large compared to the radiation resistance and could affect the antenna efficiency. The significant improvements in efficiency obtained when using thin film superconductors for a small half-loop antenna and its matching network have been demonstrated [3,4]. The use of HTS matching networks will expand the applications of electrically short antennas in the future.

Extending HTS circuits to superdirective arrays has been discussed in the literature [5]. The same arguments for using electrically short antennas on small platforms apply to superdirective arrays. Whenever uniformly illuminated arrays cannot be used because of space constraints, superdirectivity, which requires closely spaced radiators and special excitations, can provide a solution. Again, the higher efficiency provided by the use of HTS matching networks can be applied to superdirective antenna arrays.

HTS FILM GROWTH

The HTS films used in this project were exclusively $YBa_2Cu_3O_7$ (YBCO), deposited on (100) $LaAlO_3$ substrates by off-axis sputtering. Details of the deposition technique have been published elsewhere [6]. Briefly, a single, stoichiometric YBCO target was sputtered in a reactive gas mixture of 50 mtorr O_2, 100 mtorr Ar, and 5 mtorr H_2O. Both dc and rf magnetron sputtering were used without apparent differences in film properties. The substrate was positioned with its normal parallel to the plane of the target. The substrate was heated to approximately 720°C during deposition. After deposition, the O_2 pressure was raised to 20 torr, the sample was cooled to 400°C for a 20 minute soak, and then cooled to room temperature.

YBCO films were deposited on both sides of two-inch diameter $LaAlO_3$ wafers which were heated directly by radiation while resting on a transparent $LaAlO_3$ holder. Westinghouse was the first to develop a heater of this type for large-area substrates [7].

Some uncertainty was found in the value of the RF surface resistance, R_s, of YBCO deposited on 2-inch diameter $LaAlO_3$ wafers heated solely by radiation. Measurements of R_s performed on small chips cut from these wafers indicate that the typical R_s was 0.7 mΩ at 77K and 10 GHz on either side of the wafer. Since R_s is proportional to the square of frequency for superconductors, 0.7 mΩ at 10 GHz extrapolates to a factor of 750 improvement over Cu at 800 MHz and 77K. Although R_s was uniform across a wafer to within ±30%, the average R_s from one wafer to another ranged from 250 to 1500 times lower than copper at 800 MHz and 77K.

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SINGLE RADIATOR

Gain measurements were first performed on single radiators in order to determine the improvement that could be obtained by using a microstrip HTS matching network compared to one made with gold on a $LaAlO_3$ substrate.

The radiator was a 3.2-cm-long monopole with a 0.091-cm diameter operating near 800 MHz (0.088λ) on a 50-cm-by-50-cm ground plane. Its radiation impedance was calculated to be $Z_r = 3.1 - j327\ \Omega$ using a method of moments surface patch technique [8]. The matching network was, for simplicity, a single, shunt, open-circuit stub. Figure 1 is a photograph of the gold matching network, shown here without its cover. The HTS matching network is similar.

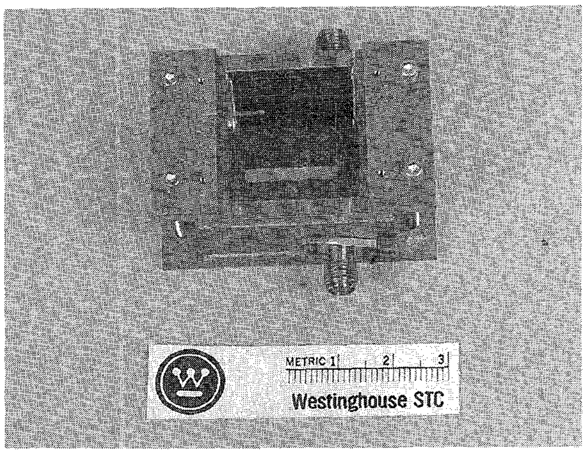

Figure 1 — Photograph of the single-stub microstrip gold matching network. The substrate is 0.05-cm-thick, single crystal $LaAlO_3$ ($\epsilon_r \approx 23.5$, $\tan\delta \approx 3x10^{-5}$ at 77K). This is the same substrate used for HTS thin film growth. A similar device was made in HTS $YBa_2Cu_3O_7$.

When performing the gain measurements for both the gold and HTS cases, only the matching networks were cooled by immersion in liquid nitrogen contained in a dewar. Figure 2 shows schematically the experimental arrangement. Using a network analyzer, independent transmission measurements were made between the short monopoles connected to the HTS and gold matching networks, respectively, and a 7.6-cm-long monopole which was used as the reference. This reference antenna was positioned at the edge of the test antenna ground plane and parallel to the test monopole. The S-parameters for this arrangement were measured repeatably even after the test fixture was repositioned. The following data were obtained for the HTS and gold matched monopoles, respectively:

HTS at 769 MHz
$S_{12} = 29$ dB, $S_{11} = -4.5$ dB, $S_{22} = -4.8$ dB
Gold at 769 MHz
$S_{12} = 31$ dB, $S_{11} = -5$ dB, $S_{22} = -4.6$ dB

Therefore, the HTS matched monopole had about 2 dB more gain than the gold matched monopole. Since the return losses (S_{11}) for both matching networks were about equal, the difference in gain is due to the lower loss in the HTS device. The theoretically predicted gain improvement was 5.5 dB at 800 MHz for a monopole length of 3.2 cm. The discrepancy between theory and experiment is attributed to inaccuracy in the calculation of the radiation impedance of the monopole antenna used to design the matching network.

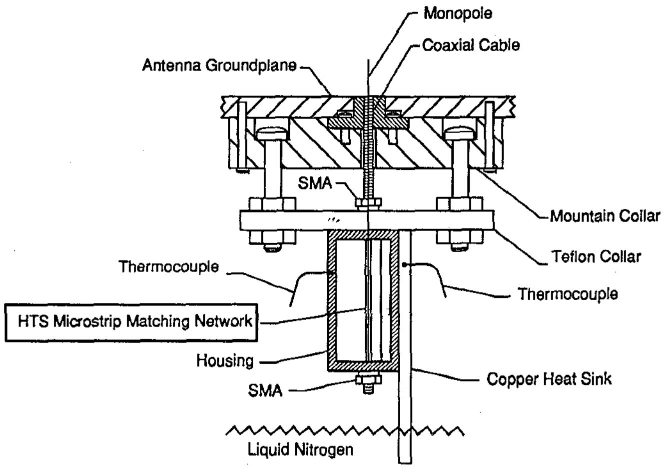

Figure 2 — Schematic drawing of experimental arrangement for testing the monopole-matching network antenna assembly.

SUPERDIRECTIVE ARRAY

A two-element superdirective array was designed using the Hansen-Woodyard excitation [9] as the starting point. The array was designed at 800 MHz with monopoles 4-cm long (0.1λ) and 0.091 cm in diameter. The spacing between the radiators was 8 cm (0.2λ) on a 50-cm-by-50-cm ground plane. The phase difference between the two elements was chosen to be 140° for a moderate amount of superdirectivity as well as stability with respect to the geometrical parameters. Figure 3(a) is a plot of the calculated far-field radiation pattern for the two-element monopole array with lossless matching networks for both a superdirective and a uniform excitation. Azimuth angle $\phi = 0$ corresponds to the end-fire direction. Lossless feed network and phase shifters were assumed in the calculation.

Figure 3(b) is a plot of the measured far-field radiation pattern. The position of the nulls and the overall shape of the pattern are as expected for a superdirective array. The plot shows actual power level normalized to an isotropic radiator but uncorrected for feed network losses (power splitter, phase shifters, feed lines, etc.). From a separate measurement of these losses, the correction factor for Figure 3(b) was estimated to be +14 dB. That is, the corrected maximum radiated power level would be about -3 dBi.

Figure 3(b) was taken at zero elevation angle. We were not able to make radiation pattern measurements at other elevations in order to confirm the superdirective pattern.

This result was achieved with an unoptimized matching network for one of the radiators. In order to compensate for defects which arose during fabrication the monopole lengths were altered from design to 2.11 cm and 4.37 cm, respectively, and an additional 4 dB attenuation was introduced for the longer monopole. These lengths and attenuation were determined experimentally. Operation was at 781 MHz.

Figures 4(a), 4(b) and 4(c) are photographs of the array experimental set-up. Figure 4(c) shows the portion of the arrangement which holds the matching networks and is immersed in liquid nitrogen, as also depicted in Figure 2.

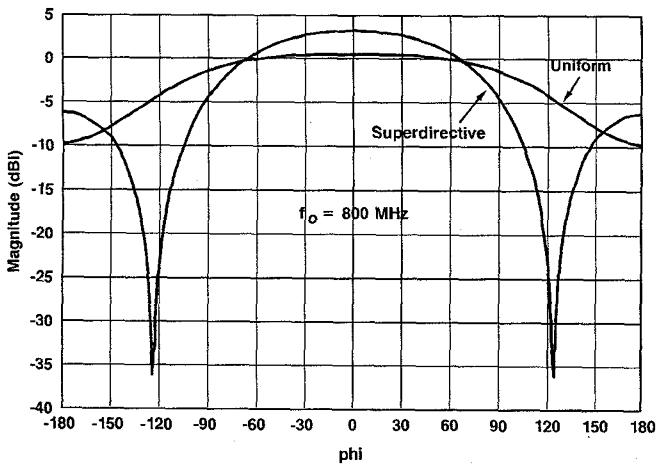

Figure 3(a) — Calculated far-field radiation patterns for the two-element monopole array with lossless matching networks for uniform and superdirective excitations.

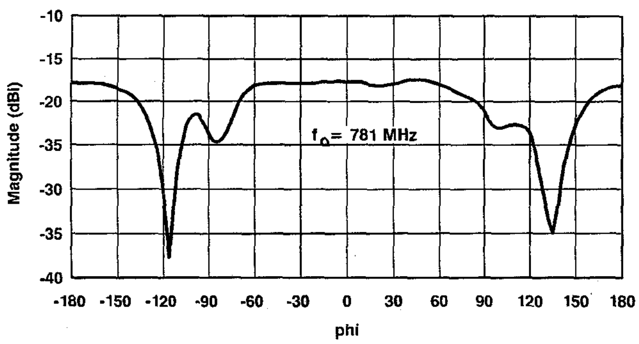

Figure 3(b) — Measured far-field radiation pattern for superdirective excitation.

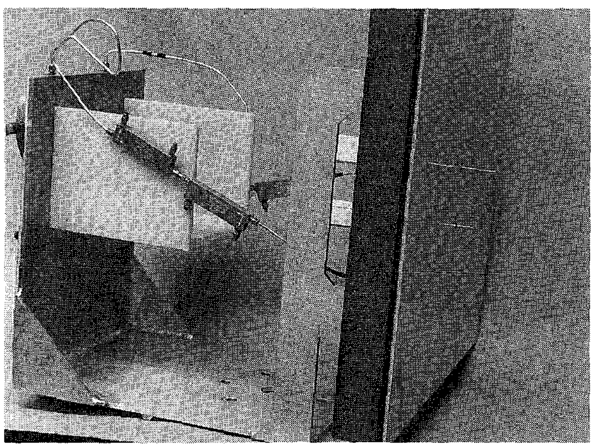

Figure 4(a) — Front view showing ground plane and monopoles.

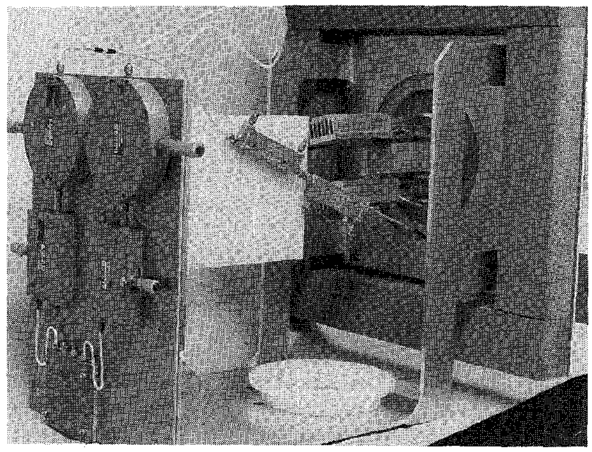

Figure 4(b) — Back view showing feed network comprising power splitter, attenuators and phase shifters. Also shown are the matching networks and their cooling arrangements.

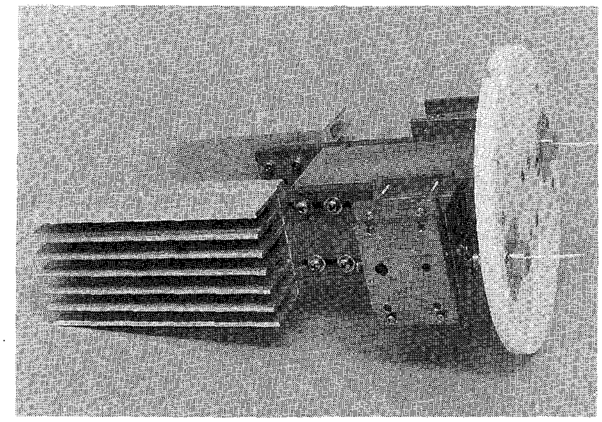

Figure 4(c) — Detail showing matching networks and monopoles.

DISCUSSION AND CONCLUSION

The benefits of using HTS compared to normal-metal matching networks are realized only in the case of sufficiently short monopoles. In principle, because HTS films have two to three orders of magnitude lower R_S than gold at UHF and L-band frequencies, a very dramatic demonstration of the improvement in efficiency could have been carried out at shorter monopole lengths than used here. However, the radiation impedance varies very rapidly as the monopole length becomes smaller than 0.15λ [2]. This makes the design of the matching network critically dependent on the length of the monopole and the experiment much more difficult to carry out. Hence a relatively conservative set of parameters was chosen for this first demonstration, such that a theoretical improvement in efficiency over gold of about 5 dB could be obtained both with a single monopole and a two-element superdirective array. This improvement could be quite significant for some system applications.

ACKNOWLEDGEMENT

The helpful discussions with R. J. Dinger, D. R. Bowling and A. M. Martin at the Naval Weapons Center; and D. C. Buck, L. E.

Dickens, and P. S. Hacker at Westinghouse ESG are greatly appreciated.

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This work is supported in part by the Navy under contract No. N00014-89-C-0810, and by DARPA under contract No. 972-88-C-0050.