SUPERCONDUCTIVE SMALL ANTENNAS WITH THIN-FILM MATCHING CIRCUITS

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ABSTRACT

We describe the superconductive antennas with thin-film matching circuits. These circuits make it possible to realize small antennas, 38 mm x 20 mm x 16 mm, which is one quarter the length of our previously reported antennas with sintered superconductive ceramics matching circuits. The actual gain of this antenna was -4.5 dBi at 470 MHz. This value was 5.5 dB higher than that of Cu antennas with entirely the same structure, but 3 dB lower than that of previously reported antennas. This slightly lower gain was mainly caused by additional loss at the joint.

INTRODUCTION

As radiation resistance becomes low as the antenna size is reduced, the radiation efficiency consequently becomes very low in a normal conductor antenna. However, with superconductive antennas, high radiation efficiency can be maintained[1-4], even when the antenna is small. We have previously demonstrated highly efficient small antennas[5] which we fabricated using sintered superconductive ceramics. In these antennas, a quarter-wave impedance matching circuits were very long compared with the size of the radiators because sintered superconductive ceramics are difficult to form into complex structures. As a result, although the radiators were small, the superconductive antenna was large. Thus, we employed superconductive matching circuits composed of high-T_c superconducting film to reduce the antenna size. The structure and properties of this antenna are described in this paper.

ANTENNA STRUCTURE

Figure 1 shows a photograph of the antenna. The parallel transmission lines on MgO substrates were used as a quarter-wave impedance matching circuit. Figure 2 shows a cross-sectional schematic diagram of the matching circuit. The line width and length were numerically analyzed with the finite-element method[6], in order to realize the impedance matching condition with the parallel transmission lines and designed as 700 μm and 10 cm, respectively. By bending the lines into meander patterns, the matching circuit could be formed in an area of 25.4 mm x 12.7 mm. This is one quarter the length of our previous matching circuit.

Helical coils made of sintered BiSrCaCuO ceramics were used as radiators[5]. The physical dimensions of the coil were designed to realize zero reactance at 500 MHz. By using thin-film matching circuits and helical radiators, the total size of the antenna can be reduced to 38 mm x 20 mm x 16 mm, which is one fifth the width and one fourth the length of our previously reported antennas.

EXPERIMENTS

EuBaCuO superconducting film, 0.6 μm thick, with a T_c of 85 K, was prepared on a 2.54 cm x 2.54 cm MgO (100) substrate by in-situ magnetron sputtering[7]. The film was patterned into meander lines by conventional photolithography and argon ion milling. The helical radiators were joined to the thin-film matching circuit with silver paste. A Cu antenna with the same geometry was also prepared for comparison.

Two glass vessels were used for cooling antennas. The small antenna was put into the inner glass vessel with a balun (quarter-wavelength sleeve). The outer vessel was partly filled with liquid nitrogen and the gas above its surface was evacuated to lower the temperature. In this way the antenna was cooled to 70K. Antenna gain was measured by using a standard dipole antenna and a network analyzer(HP8753A). The distance between the antennas was 1.7 m, and they were surrounded by radio-wave absorbers. The actual gain of the antenna was calibrated by using a pair of half-wavelength standard dipole antennas.

RESULTS AND DISCUSSION

Figure 3 shows the reflection coefficients (S_{11}) of the antennas as a function of frequency. The reflection coefficient of the superconductive antenna was -12 dB at 70 K, 470 MHz. The reflection coefficients of the Cu antenna were -10 dB and -33 dB, respectively, at room temperature and 70 K, 490 MHz. Although the resonant frequency of the antennas shifted slightly from 500 MHz, the reflection coefficient values were sufficiently low for both antennas. These results indicate that exact impedance matching was achieved for both antennas. However, the superconductive antenna exhibited no resonance at room temperature , due to higher surface resistance.

Figure 4 shows the actual gain of the antennas as a function of frequency. The actual gain of the superconductive antenna was -4.5 dBi at 70 K. The values were 5.5 dB and 9.5 dB higher than those of the Cu antenna at 70 K and room temperature, respectively. This demonstrates that the superconductive small antenna with the thin-film matching circuit is more effective in realizing high-gain than Cu small antennas. This antenna is also much smaller than our previously reported antennas with long ceramic matching circuits, however, its actual gain was 3 dB lower[5]. As the radiator was the same in the present and previous antennas, the slightly lower gain can probably be attributed to losses in the thin-film matching circuits and/or at the joints between the radiators and the matching circuits. The loss in the matching circuit is inverse proportion to line width, and the line width of thin-film matching circuits is about one fifth of previous sintered matching circuits.

In order to estimate the loss in the matching circuits, we measured the total loss of various combinations, such as a superconductive radiator and Cu matching circuit. The measured total loss is derived from the difference between the directive gain (calculated at 0.2 dBi for the radiator) and the actual gain based on the mismatching loss. Furthermore, we estimated the losses in the matching circuits using a T-matrix. The loss (ζ) in the matching circuit is given by the following equations;

$$\zeta=\{(R_{in}+Z_0)^2\exp(2\alpha L)-(R_{in}-Z_0)^2\exp(-2\alpha L)\}/4Z_0R_{in}$$

$$\alpha=R_S / wZ_0$$

where R_{in}, Z_0, and α are the input resistance of the radiator, the characteristic impedance and the attenuation constant of the matching circuit, respectively. L, w and R_S are the total length, line width and surface resistance of the matching circuit, respectively. Total losses can be estimated by adding the value of the loss at the radiator. Comparison of the total losses makes it possible to estimate the surface resistance and/or the losses at the joint. The measured and calculated total losses for various combinations are summarized in Table 1.

In the antennas with Cu-film matching circuits, the difference between the measured and the calculated total loss can probably be explained by loss at the joints, and the losses at joints are thought to be approximately 0.7 ~ 1.3 dB. In the small antenna consisting of a superconductive matching circuit and a Cu radiator, the measured total loss was 6.7 dB. Considering the joint loss of about 0.7 ~ 1.3 dB, the surface resistance of the superconductive lines in the matching circuits is less than 0.6 mΩ at 70 K and 500 MHz. In the antenna consisting of a superconductive matching circuit and a superconductive radiator, the measured total loss was 4.5 dB. On the assumption of a surface resistance of less than 0.6 mΩ, the calculated total loss is estimated to be less than 2.0 dB. Therefore, the joint loss is estimated to be more than 2.5 dB in this antenna. In contrast, the joint loss in previously reported antennas was less than 1 dB. The increase in loss by reduction of line width is estimated to be less than 1 dB. Accordingly, we conclude that the slightly higher loss observed in the superconductive small antennas with thin-film matching circuits is mainly caused by the additional loss at the joints. Furthermore, if the loss at the joint is vanished, it is expected that this small antenna showes the almost same efficiency as previously reported ones. Thus, the joint between the superconductive ceramic radiator and the thin-film matching circuit should be improved in this antenna.

CONCLUSIONS

Superconductive small antennas were fabricated with thin-film matching circuits and helical radiators. The antenna size was 38 mm x 20 mm x 16 mm, which was one quarter the length and one fifth the width of our previously reported antennas with long sintered ceramic matching circuits. The actual gain of this antenna was -4.5 dBi at 470 MHz, and the value was 5.5 dB higher than that of a Cu antenna with the same geometry. In contrast, the actual gain was 3 dB lower than the previous antennas because of a slightly higher loss at the joint between the radiator and the matching circuit.

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Table 1 Measured loss and calculated loss at 70K

Radiator	Matching circuit	Measured Total loss [dB]	Calculated Circuit loss [dB]	Calculated Total loss [dB]
Cu	Cu	10.2	4.0	9.5
Superconductor	Cu	9.1	7.1	7.8
Cu	Superconductor	6.7	——	——
Superconductor	Superconductor	4.5	——	——

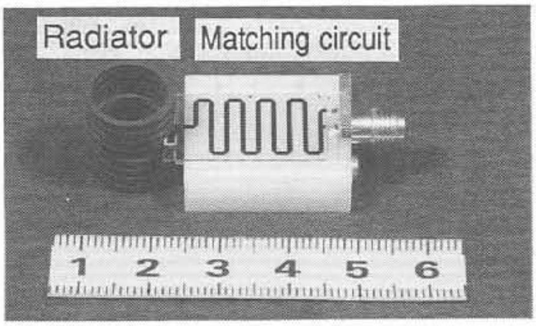

Fig.1 Photograph of the small antena

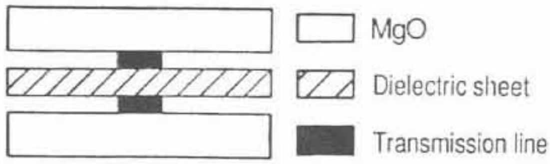

Fig.2 Cross-sectional diagram of the matching circuit

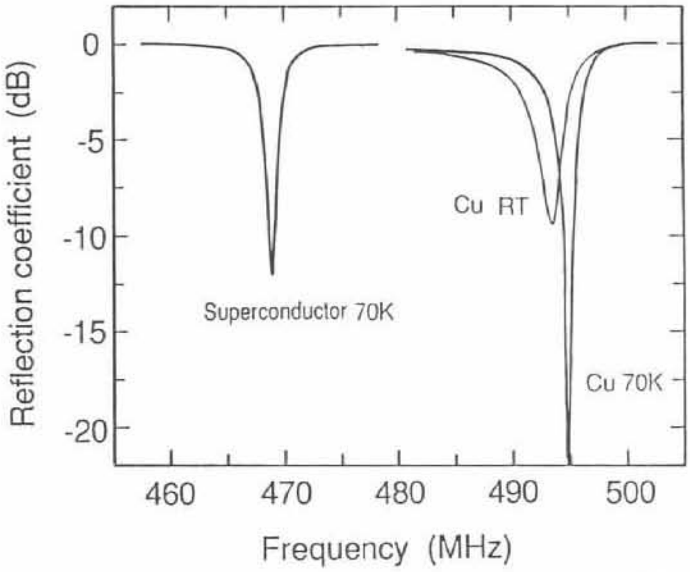

Fig.3 Reflection coefficient of antennas as a function of frequency

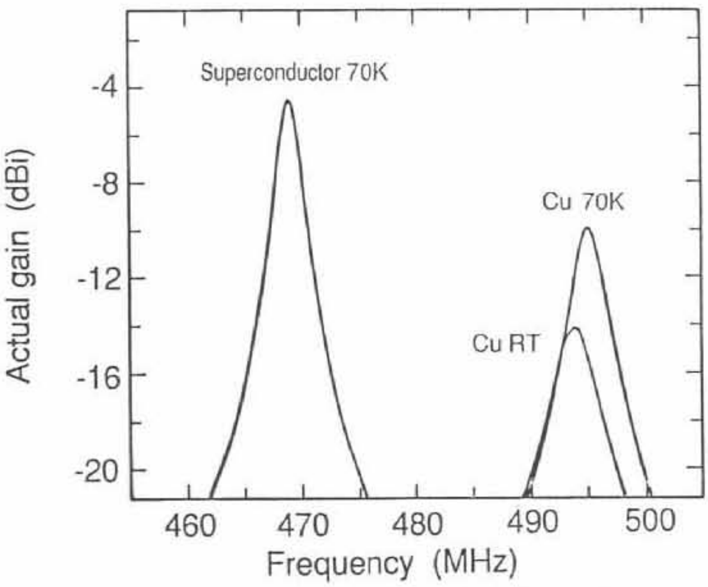

Fig.4 Actual gain of antennas as a function of frequency