PROCEEDINGS OF ISAP '92, SAPPORO, JAPAN

Collinear supergain antennas with shaped radiation pattern

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INTRODUCTION

In order to use a collinear array antenna as the base-station antenna in a mobile radio system, its radiation patterns must be carefully shaped to obtain a sufficient D/U ratio[1]. Furthermore, antenna size must be significantly decreased to ease installation on a roof of a building. Supergain antennas, which have been a theoretical subject for half a century[2], seem to be attractive candidates for realizing small and high-gain antennas. However, collinear supergain antennas with shaped radiation patterns have hardly been investigated.

Supergain antennas are reported to be best constructed with superconductors[3,4], because the normal metal supergain antennas have extremely low radiation efficiency due to the large ohmic loss. Since oxide high Tc superconductors (HTSC) were discovered in 1987, electrically small antennas have been extensively studied as one possible application[5,6]. Supergain antennas are also known to have high Q values which requires extremely low structural tolerances to realize the exact excitation coefficients. However, sintered HTSC bulks are too brittle to be shaped into complicated antenna parts. From the structural requirements, HTSC can only be used to construct supergain antenna parts (elements, impedance transformers and so on) that have simple shapes; the antenna must have a simple feeding network configuration to fulfill the tight requirements for exact excitation coefficients.

This paper first proposes a simple supergain antenna structure that does not need any impedance tuning mechanism. Next, two actual collinear supergain antennas are presented and their shaped radiation patterns are examined. The advantage of using HTSC for the antenna element is also investigated.

SUPERGAIN ANTENNA DESIGN AND STRUCTURE

Figure 1 illustrates the block diagram of the antenna. The antenna consists of a feeding network, matching circuits and antenna elements. Desired excitation coefficients (amplitudes and phases) are obtained by designing the microstripline circuits of the feeding network. The input impedance (Z_i, $i=1,2,\cdots,n$, n: the number of elements) is expressed by the following equation.

$$Z_i=V_i/I_i, \qquad (1)$$

where

$$[V_i]=[Z_{ij}][I_i] \qquad i,j=1,2,\cdots,n$$

and

$$Z_i=R_i+jX_i=Z_{i1}I_1/I_i+Z_{i2}I_2/I_i+\cdots+Z_{ii}+\cdots+Z_{in}I_n/I_i \quad .$$

V_i and I_i are respectively the voltage and current at the i-th element and Z_{ij} $i,j=1,2,3\cdots n$, is the active impedance. The Z_i is matched to the characteristic impedance of the feeding network (Z_o) through the matching circuits. For previously reported supergain antennas, the input impedance Z_i $i=1,2,3\cdots,n$ consisted of a significantly large reactance, X_i, and an extremely small resistance, R_i[4]. The large reactance makes it difficult to exactly match the impedances of element and feeding network by using a conventional impedance tuner such as a stub. However Z_{ij} depends on the element size and element spacing, X_i may be made almost zero by adjusting the element size.

To clarify the advantages of superconductors as array antenna components, three-element collinear array antennas designed with the above principle were investigated. Figure 2 shows the relations between element spacing (d) and the main beam width for the normal- and supergain-antennas. The symmetrical radiation patterns with arbitrary beam width were synthesized with the least-mean-square method[7]. The solid line shows uniform phase and uniform amplitude excitation coefficients. The region between the solid line and the dotted line corresponds to the uniform phase and nonuniform amplitude excitation coefficients. In the shaded region, the excitation amplitude is higher at center element and the neighboring elements are excited in antiphase. This characteristic is peculiar to supergain antennas. The target of this study is indicated as the open square and its main beam width is much narrower than in-phase excited antennas. The radiation pattern of the target (open square in Fig.2, $d=0.25\ \lambda$) is depicted in Fig.3 together with the list of excitation coefficients.

Figure 4 is a photograph of the designed array antenna. Its center frequency is 900 MHz. The antenna consists of helical radiators, $\lambda/4$ parallel line matching circuits and a feeding network. The length of the helical coils was around 0.1λ i.e., less than the element spacing (0.25λ). Cu and Pb-doped $Bi_2Sr_2Ca_2Cu_3O_{8+x}$, BSCCO, ceramic was used to construct the helical coils. The BSCCO coils were fabricated by sintering and the Tc of BSCCO is about 103 K. The $\lambda/4$ parallel line matching circuits were composed of two square Cu rods separated by a Teflon spacer. The dimensions of the circuit were computed using the finite element method which is effective for simulating thick circuits. The feeding network was laid out on a conventional printed circuit board (a 1.6 mm thick BT resin substrate both sides of which were covered with 35μm thick Cu film). The superconductor antenna was put into a glass vessel and cooled down to 80 K with liquid nitrogen. The surface resistances of Cu at 300K and 80 K and BSCCO at 80 K were speculated to be 8 mΩ, 3 mΩ and 1.5 mΩ, respectively.

When $X_i=0\ \Omega$ array antennas need no impedance tuner. To determine which helical coil configuration achieved this condition, the input impedances were computed by substituting the designed excitation coefficients, I_i, and the active impedances, Z_{ij}, of the elements into equation (1). The active impedances were calculated with the moment method. Figure 5 shows the input impedances (R_i and X_i) against the number of helical coil turns. The reactance falls to 0 Ω at about 4.35 coil turns. On the other hand, the radiation resistances are almost constant (~0.3Ω at center element and 0.8Ω at edge elements), which are both much lower than that of the single coil (~4Ω) because of large mutual impedance. The zero reactance and constant resistance are significant advantages in achieving exact impedance matching. Only $\lambda/4$ matching circuits were adopted to match the R_i to the characteristic impedance of the feeding network (Z_o) and no other impedance tuner was needed.

EXPERIMENTAL RESULTS

Figure 6 shows the measured reflection coefficients, S_{11}, of the equivalent Cu antenna at 300 K and the BSCCO antenna at 80 K. The -3dB bandwidth of the Cu and BSCCO antennas are respectively 0.38 and 0.95%. By arraying the elements, the bandwidth was significantly reduced comparing with that of a single element (~1.3%). Since the bandwidth due to the array factor is calculated to be about 10 %, it was proved that the bandwidth of this antenna was mainly restricted by the bandwidth of the elements used. Accordingly, it is speculated that the number of elements can be increased or the element spacing decreased without reducing the bandwidth.

Figure 7 shows the radiation patterns of the Cu antenna at 300 K and at 910 MHz and the BSCCO antenna at 80 K and at 905 MHz. The -3 dB beam width of the Cu antenna at 300 K and the BSCCO antenna at 80 K are respectively 28 and 32 deg, which shows the deviations in excitation phase and amplitude are both within 6%. The increase in gain with the BSCCO antenna was about 3.2 dB. This can be attributed to decreased ohmic loss of the elements (~3dB) and that of the matching circuit (~0.4 dB) . The ohmic loss of the elements was calculated by the moment method by loading the resistances on the diagonal elements of the impedance matrix. The ohmic loss in the matching circuit was evaluated as the transmission loss of the parallel transmission lines. The gain of the BSCCO antenna was however about 6 dB lower than the calculated value for a ideal conductor. This discrepancy could be attributed to the power radiated from the feeding network and the ohmic losses of the other antenna parts. Since the surface resistance of BSCCO, ~1.5 mΩ, is several orders higher than the theoretical value, further increase in antenna gain is possible with improved BSCCO quality.

CONCLUSION

The design principle of supergain antennas with arbitrary excitation coefficients has been presented. Based on the design concept, a three-element collinear array with element spacing of 0.25λ, was developed by combining self-resonating helical elements, quarter wavelength matching circuits and a feeding network. The antenna so designed realized the desired excitation coefficients within an accuracy of 6% without any impedance tuners. This concept is applicable for any arbitrary excitation coefficients and for any short array antenna. A prototype BSCCO antenna at 80 K showed 3.2 dB higher available gain than an equivalent Cu antenna at 300 K. This is consistent with the calculated decreases in ohmic losses in elements and matching circuits and confirm the potential of HTSC for antenna use.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Kouzou Morita and Dr. Etsuji Sugita of NTT laboratories for their encouragements in the course of this study. The authors would also like to thank Dr. Osamu Michikami, Dr Yasuhiro Nagai and Mr. Makoto Kijima of NTT laboratories and Prof. Kunio Sawaya of Tohoku University for their helpful discussions. The authors thank Mr. Yuichi Ito and Dr. Shuji Yoshizawa of Dowa Mining Co., Ltd. for assistance in fabricating the BSCCO coils.

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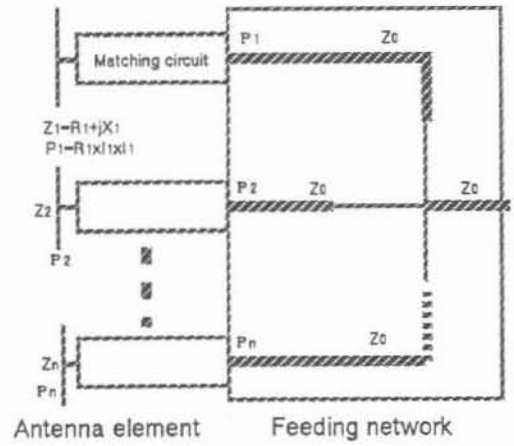

Fig.1 Block diagram of an array antenna.

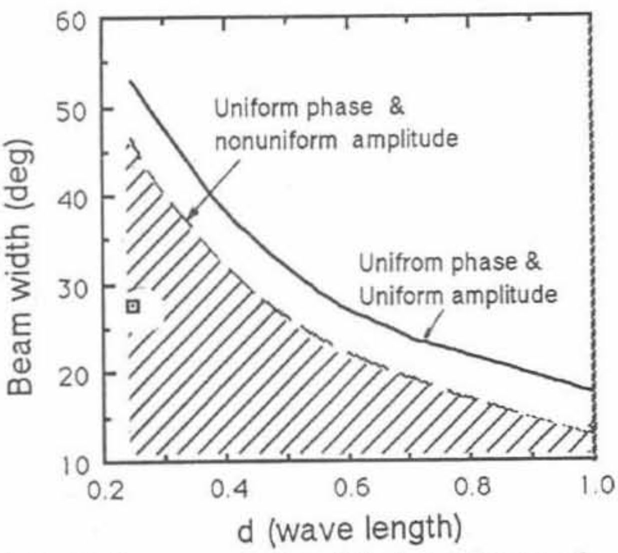

Fig.2 Element spacing (d) dependence of the main beam width.

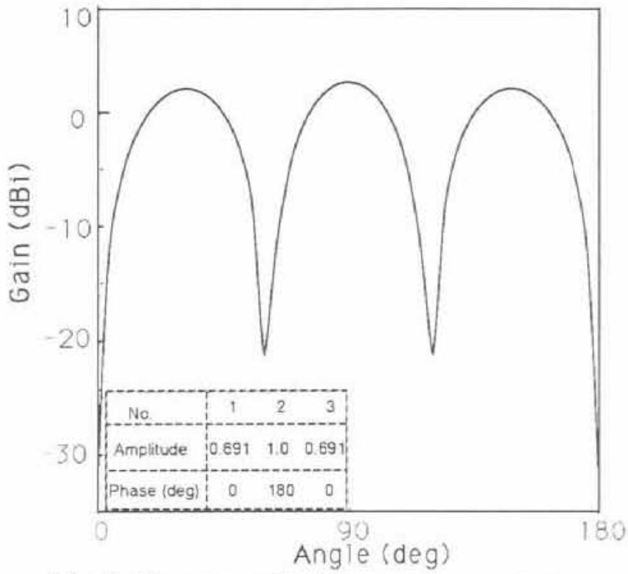

Fig.3 Target radiation pattern and the excitation coefficients.

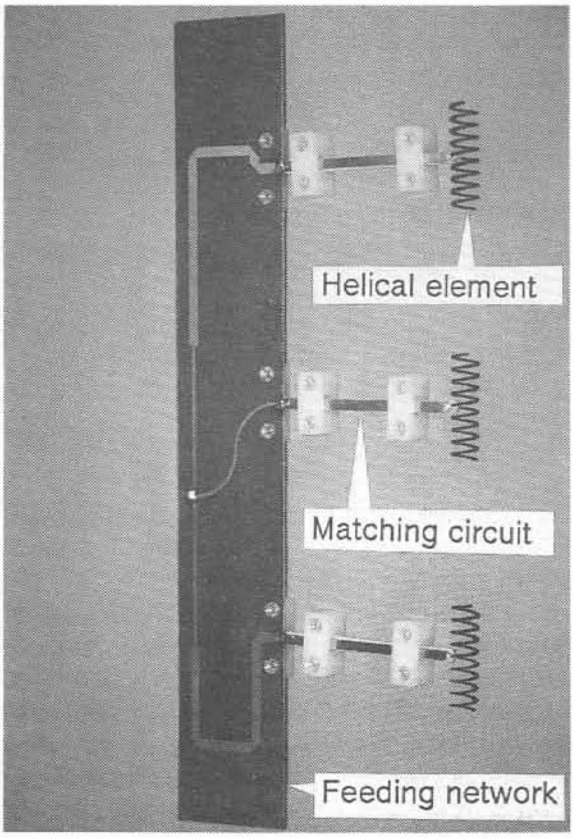

Fig.4 Photograph of the HTSC three-element colinear supergain antenna.

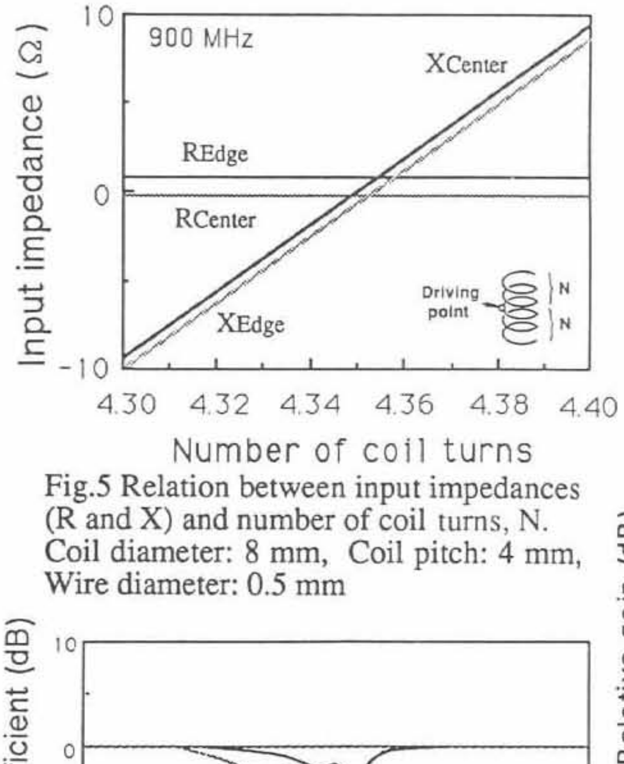

Fig.5 Relation between input impedances (R and X) and number of coil turns, N. Coil diameter: 8 mm, Coil pitch: 4 mm, Wire diameter: 0.5 mm

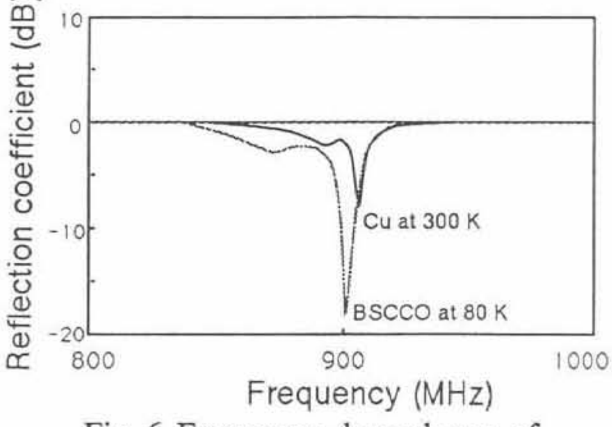

Fig 6 Frequency dependency of measured reflection coefficients.

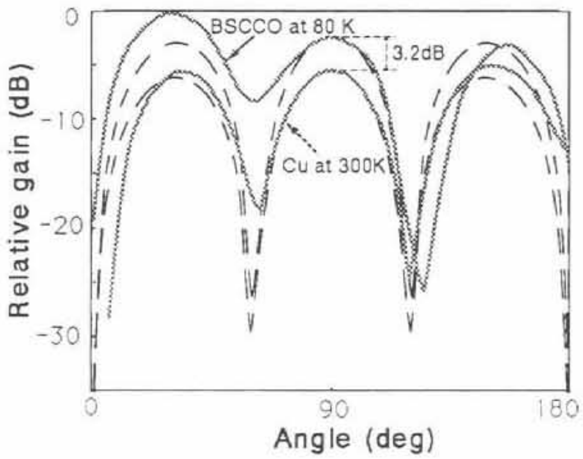

Fig.7 Measured radiation patterns. Dotted lines indicate target patterns.