Antenna Applications of Superconductors

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Abstract —**The applicabilty of superconductors to antennas is examined. Potential implementations that are examined are superdirective arrays; electrically small antennas; tuning and matching of these two; high-gain millimeter-wavelength arrays; and kinetic inductance slow wave structures for array phasers and traveling wave array feeds. Superdirective arrays and small antennas will not benefit directly, but their tuning/matching networks will undergo major improvements. Miniaturization of antennas will not be aided, but much higher gain millimeter-wave arrays will be realizable. Finally, kinetic inductance slow wave lines appear advantageous for array phasers and time delay, as well as for traveling wave array feeds.**

I. Introduction

A brief examination of areas where high-T_c superconducting materials might improve antenna performance is given. These areas include superdirective arrays and matching, electrically small antennas and matching, large millimeter-wavelength arrays, and slow wave components such as phasers and traveling wave feeds. Each is discussed below, with additional details given in [1]. Active devices such as SQUID's are not included, except for a comment later.

The effects of conduction loss on an antenna can be clarified by considering the roles of external and internal fields. Currents flowing on the surface of a metallic antenna produce the radiated field and its associated radiation resistance, together with the stored energy in the near field and its associated reactance; these are external fields. Fields internal to the conductor are important only via the conduction loss, usually small; internal inductance is almost always negligible. Use of a superconductor will produce a negligible change in the external fields; hence antenna directivity, impedance, and pattern are unchanged in most cases. Efficiency will change, but in most antennas it is close to 100% with normal metals.

Whether superconductivity aids miniaturization is also of interest, and here again external fields clarify the situation. The size of most antennas is controlled by the requirement that certain dimensions be prescribed values of the free-space wavelength. Included in this category are dipoles, slots, patches, log-periodics, spirals, and Yagi-Uda's. Other antennas require a certain area in free-space square wavelengths to achieve specified directivity, for example, reflector antennas and planar arrays. These requirements all relate to external fields; thus superconductors should not facilitate miniaturization of antennas. A significant exception, where internal fields are critical, is the slow wave kinetic inductance discussed below.

As mentioned, SQUID's are outside the scope of this paper. However the idea of combining a SQUID and an antenna raises some interesting questions. The typical SQUID has energy coupled in through a winding on the loop frame. Since the superconducting loop can also act as an antenna, how does the flux quantization in the loop relate to the incident field? And how does the loop area in square wavelengths affect the *JJ* coupling? Can a multiturn loop SQUID be constructed? Perhaps there is a way to use one, or even a graded area set, of loop antenna SQUID's for direct digitization of RF.

II. Superdirective Arrays

Superdirectivity (supergain) exists when an antenna has directivity greater than normal; a broadside array with half-wavelength spacing and an end-fire array with quarter-wavelength spacing have normal directivity. Applications of these arrays have been limited by three factors: narrow bandwidth (high Q), small radiation resistance, and small allowable tolerances. Since small radiation resistance may produce low efficiency because of conductor loss, superconductors offer the possibility of high efficiency. An end-fire array is the best vehicle for examining the behavior quantitatively, as it offers the highest directivity for a fixed number of elements [2]. Both directivity and Q (bandwidth $\cong 2/Q$ for a matched antenna) can be calculated using quotients of sums of mutual resistances and excitation coefficients [3]. For a fixed number of elements and spacing, the maximum directivity excitation is found from a matrix equation where the drive vector contains the end-fire phases and the matrix is of mutual resistances. Arrays of isotropic elements may be evaluated using the virtual mutual resistance 120 $\mathrm{sinc}\,2\pi d/\lambda$.

Arrays of dipoles are of more practical interest, and for these the mutual resistance is well known to be expressible in terms of sine and cosine integrals. With superdirectivity, the sums used in calculating R_{rad} and Q involve subtracting large numbers, so that a double-precision Si and Ci subroutine is needed. A Chebyshev economized series was developed by Luke [4], and was coded by the author. Through use of codes that calculate R_{rad}, Q, and G, many interesting things were learned about superdirective arrays [5], [6], but of critical importance here is the behavior of radiation resistance with Q [1]. Fig. 1 shows

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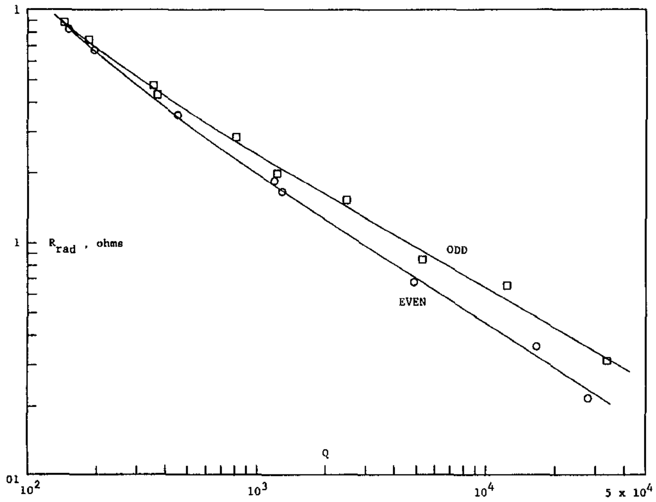

Fig. 1. Q versus center element resistance for end-fire arrays.

data for many maximum directivity arrays, ranging from three to ten elements, with spacings from 0.1 to 0.45 λ; R_{rad} for the center element is given. Arrays with odd and even numbers of elements fit slightly different envelopes, owing to the different degrees of freedom. The significance of these data is that for $Q \approx 1000$ (bandwidth $\approx 0.2\%$) the radiation resistances are greater than 0.2 Ω. Typical normal dipole loss resistances are 0.0001 to 0.01 Ω, so that the efficiency is greater than 95%. Thus even for such extremely narrow band antennas, which are almost impractical owing to environmental detuning, the efficiency is close to 100%. The important conclusion then is that superdirective arrays will not benefit directly from superconductors. However the matching of low radiation resistance and high reactance will benefit, as discussed in Section IV.

III. Electrically Small Antennas

As observed by Wheeler [7], [8], antennas whose dimensions are small in free-space wavelengths are either dipoles or loops or are combinations of these two. Formulas for radiation resistance and reactance of dipoles are available in many texts; short dipoles are capacitative and an inductive tuning coil is usually used. When the radiation resistance is as low as 0.2 Ω, the Q is of the order of 10^4. So again, for all practical dipoles the intrinsic efficiency is always high. When the tuning coil is included the results change dramatically, as practical coils have Q's from 20 to 200. Fig. 2 gives dipole plus tuning coil efficiency versus dipole half length h; the transformer loss to match to 50 Ω has not been included [1]. Clearly the superconductor is needed in the tuning coil (and matching network). There is a drawback, as the tuning (and matching) losses reduce the overall Q; with zero or very small losses the dipole bandwidth is again small, as shown in Fig. 3. Thus the practical range of short dipoles with superconducting tuning and matching is roughly $h = 0.07$ to 0.15 λ. Dielectric losses must also be kept low [9], [10].

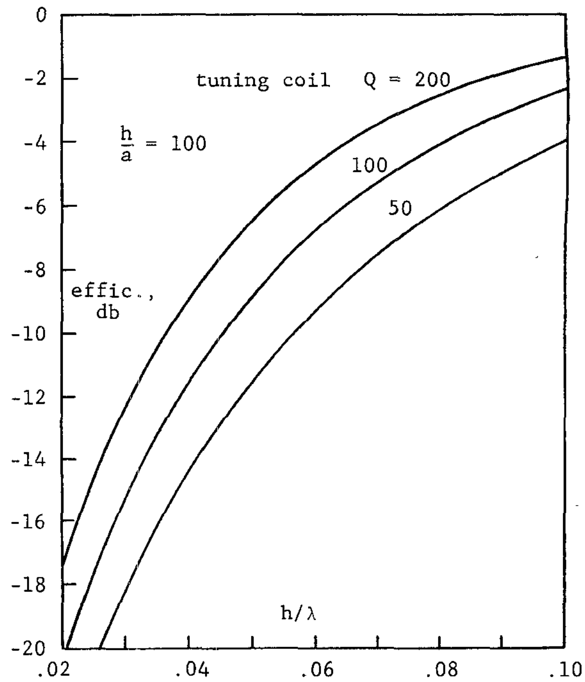

Fig. 2. Efficiency of dipole with tuning coil.

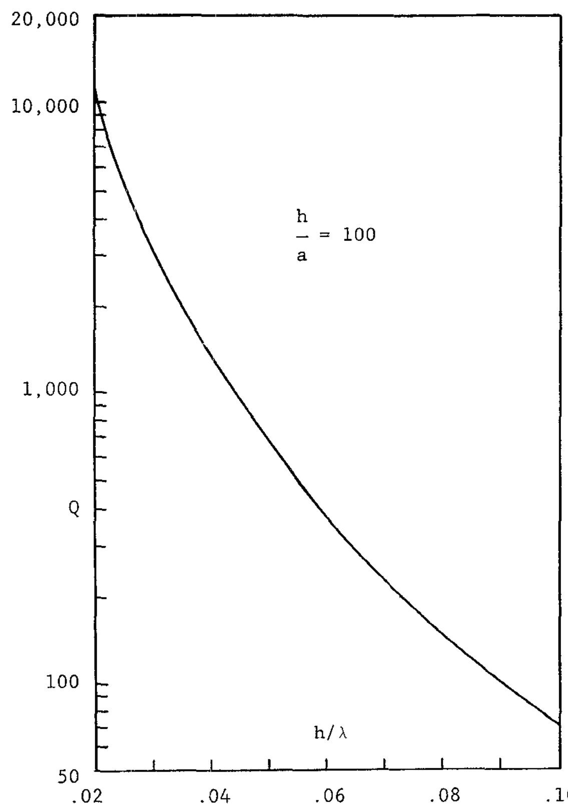

Fig. 3. Q of dipole with lossless tuning coil.

Small loops are magnetic dipoles and are typically tuned with a capacitor, and these can have very high Q's. Tuning losses are very low, but radiation resistance varies with loop diameter/wavelength to the fourth power, so small loop efficiencies tend to be low. Use of a superconductor in the loop can, in principle, increase efficiency to

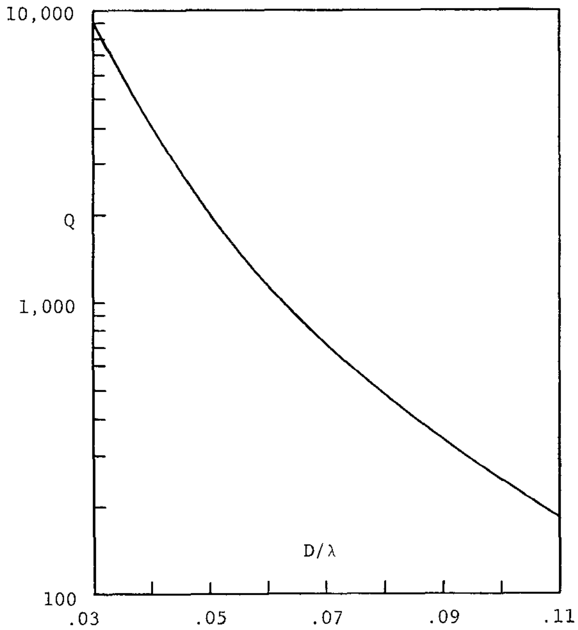

Fig. 4. Q of loop without loss.

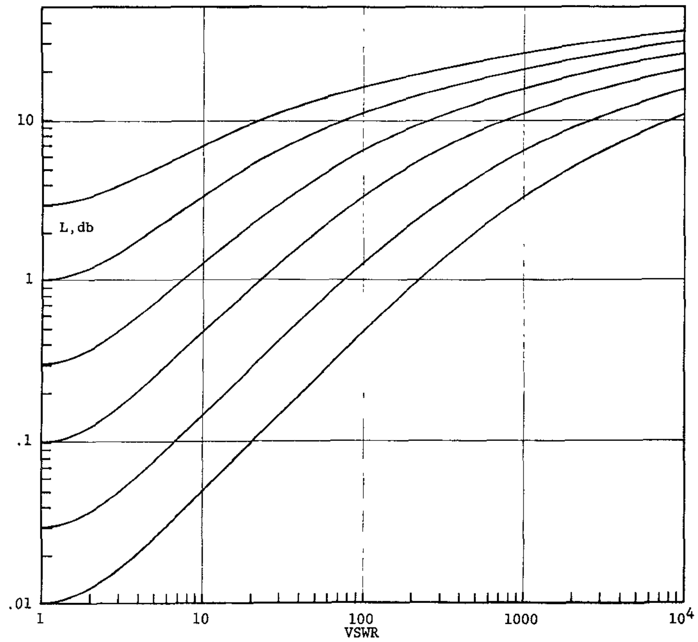

Fig. 5. Increase of loss from standing wave.

near 100%, but again high Q is the result. Fig. 4 shows loop Q versus diameter/wavelength, assuming radiation resistance to be the sole loss [1]. The practical range of small superconducting loops is roughly $D = 0.1$ to $0.2\ \lambda$.

IV. Impedance Matching

Both superdirective arrays and electrically small antennas, as mentioned, tend to have small radiation resistance and large reactance. Whether the reactance is tuned out first, followed by an impedance transformer, or the tuning is combined in the latter, a small intrinsic loss can be magnified to a large loss. A transmission line transformer is typical. Let the matched loss be L, and the antenna VSWR be V. Then the apparent loss L_a is [11]

$$L_a = \frac{(V+1)^2 L^2 - (V-1)^2}{4VL}.$$

A radiation resistance of 0.2 Ω and a reactance of 100 Ω give $V = 1250$! From Fig. 5 for this VSWR, a circuit loss of only 0.05 dB becomes a 9.1 dB loss. For example, Khamas *et al.* [12], [13] measured a short dipole, tuned by a shorted two-wire stub, with the output line tapped at the 50 Ω point. Both superconducting and copper models were built; radiation resistance was approximately 0.27 Ω, and reactance was roughly 2000 Ω. Since the copper dipole loss was at least an order of magnitude lower than the radiation resistance, the dipole efficiency was essentially 100%. But a matching stub loss of only 0.002 dB could easily account for the 12 dB improvement from the superconducting antenna. Superconductor matching will also be important for physically large but electrically small antennas, such as those for VLF submarine communications and Omega navigation.

V. Millimeter-Wavelength Arrays

At millimeter (and shorter) wavelengths, transmission line loss, whether waveguide, stripline, or microstrip, is critical in determining the practicality of a large array. To illustrate this point, a planar waveguide slot array is evaluated. It consists of side-by-side waveguide linear slot arrays, with a feed waveguide at right angles, using cross-guide couplers. Frequently such arrays are divided into quadrants for monopulse operation. The linear arrays are resonant and produce a broadside beam. A square array of width L has a feed path length of $2L$. For small to moderate loss, the efficiency is simply $1 - 4\alpha L$. Formulas for the attenuation coefficient, α, are readily available. For an example, the lower part of a waveguide band is chosen, $\beta / k = 0.5$, and the guide aspect ratio is 2. Using the theoretical conductivity of copper, array efficiency has been calculated and is given in Fig. 6 for array directivities of 40, 50, and 60 dB [1]. In practice, copper waveguide conductivity is about half of the theoretical value used here, so the actual gain limit is worse than indicated in the figure. Gain is just directivity times efficiency. Higher frequencies often require higher gains to offset increased path loss and atmospheric attenuation, but these data show that gains are severely limited by conduction loss. Superconducting waveguide will allow higher gains to be realized, and thus will significantly extend array applicability.

Similar calculations have been made for a planar array of patch elements fed by microstrip lines. Results are similar to those for the waveguide array except that the losses are higher [1]. With superconducting microstrip at millimeter wavelengths, the dielectric substrate will probably control the loss and, hence, the array efficiency. Such

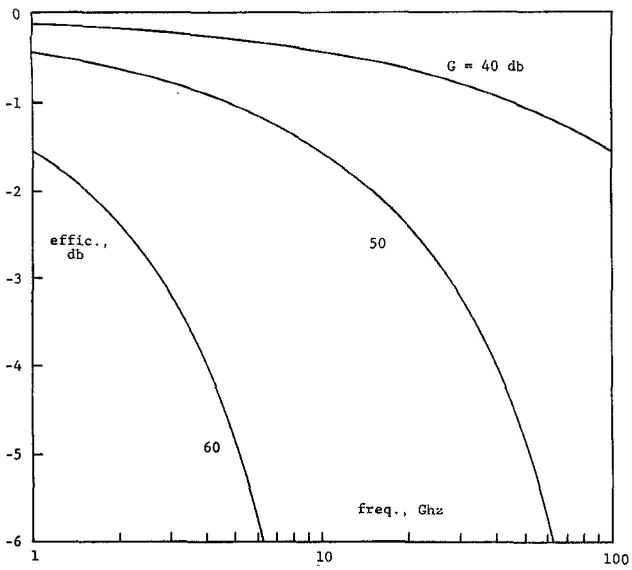

Fig. 6. Waveguide slot flat plane array efficiency.

techniques as inverted stripline and suspended stripline may reduce this loss.

Practical realization of low transmission line loss is important not only for arrays, but also for matching/tuning networks and slow wave lines. Loss and dispersion calculations in microstrip are given in [14] and [15], while coplanar lines are treated in [16] and [17].

VI. Applications of Kinetic Inductance

When the thickness of a thin-film superconductor is small compared with the London penetration depth, λ, the Cooper electron pairs show a slow wave type velocity, as shown by Pippard in 1957. Note that here λ is not the wavelength. The thin-film effective penetration depth, λ_e, is

$$\lambda_e = \lambda \coth t/\lambda$$

where t is the film thickness [18], [19]. The Cooper pair velocity is equivalent to an inductance, with velocity ratio [20]

$$\frac{v}{c} = \frac{1}{\sqrt{\epsilon}\sqrt{1+\lambda_e/t}}.$$

Because the thin film presents a surface resistance and reactance, moment method techniques can be applied using a complex resistive boundary condition [21]. However to produce very slow waves, most of the magnetic energy storage must be in the film, not in the interconductor space. Thus very thin dielectrics are indicated. Since the thin films are diaphanous, they need to be used in such a way that the fields are contained. How a practical thin-film slow waveguide can be made is an interesting problem.

One application of this phenomenon is in phasers for electronic scanning of phased arrays. Phasers, which produce the phase shift, are typically either ferrite–waveguide combinations or lengths of transmission line switched by diodes. Below roughly 1 GHz the line lengths of the latter become cumbersome, while above about 10 GHz line losses become important. A superconducting thin-film line utilizing the kinetic inductance slow wave would eliminate both these problems. The frequency range for switched line phasers would be extended to both lower and higher frequencies.

Another phaser option would use variable temperature and a single fixed line length per element to produce variable delay. Changing temperature would then produce beam scanning in one plane. The line lengths would provide true time delay for broad-band electronic scanning.

Another application is to traveling wave feeds. For example, a frequency scanning planar array uses a serpentine (snake) feed to provide the requisite phase between constituent linear arrays. This bulky and lossy component could be replaced by a superconducting slow wave structure, which would be compact and undergo low loss. Frequency scan within a single linear slot array is also possible, where the waveguide provides the slow wave via kinetic inductance. As with all new technology many problems must be solved, but the advantages are sufficient to warrant vigorous development.

VII. Conclusions

Superdirective arrays and electrically small antennas will not benefit directly from superconductors, but their tuning/matching networks will. The useful range of these antennas will thereby be significantly extended. Miniaturization of antennas will not occur. Superconductors will allow millimeter-wavelength arrays with much higher gain to be utilized, both in waveguide and in microstrip. Kinetic inductance slow wave lines will allow switched line phasers to be designed over a much wider frequency range, and will reduce size and loss of traveling wave array feeds. Much work is needed on how to fabricate and use both normal and slow velocity waveguides and transmission lines.

References

[1] R. C. Hansen, "Superconducting antennas", *IEEE Trans. Aerosp. Electron. Syst.*, vol. 26, pp. 345–355, Mar. 1990.
[2] Y. T. Lo, S. W. Lee and Q. H. Lee, "Optimization of directivity and signal-to-noise ratio of an arbitrary antenna array," *Proc. IEEE*, vol. 54, pp. 1033–1045, Aug. 1966; correction, p. 292, 1967.
[3] A. Bloch, R. C. Medhurst, and S. D. Pool, "A new approach to the design of super-directive aerial arrays," *Proc. Inst. Elec. Eng.*, vol. 100, pp. 303–314, Sept. 1953.
[4] Y. L. Luke, *Mathematical Functions and Their Approximations*. New York: Academic Press, 1975.
[5] R. C. Hansen, "Fundamental limitations in antennas," *Proc. IEEE*, vol. 69, pp. 170–182, Feb. 1981.
[6] R. C. Hansen, "Some new calculations on antenna superdirectivity," *Proc. IEEE*, vol. 69, pp. 1365–1366, Oct. 1981.
[7] H. A. Wheeler, "Fundamental limitations of small antennas," *Proc. IEEE*, vol. 35, pp. 1479–1484, Dec. 1947.
[8] H. A. Wheeler, "Small antennas," *IEEE Trans. Antennas Propagat.*, vol. AP-23, pp. 462–469, July 1975.
[9] R. J. Dinger and D. J. White, "Theoretical increase in radiation efficiency of a small dipole antenna made with a high temperature

superconductor," *IEEE Trans. Antennas Propagat.*, vol. 38, pp. 1313–1316, Aug. 1990.
[10] F. A. Miranda *et al.*, "Measurements of complex permittivity of microwave substrates in the 20 to 300 K temperature range from 26.5 to 40 GHz," in *Advances in Cryogenic Engineering*, R. W. Fast, Ed. New York: Plenum, 1990.
[11] T. Moreno, *Microwave Transmission Design Data*. New York: Dover, 1948, ch. 2.
[12] S. K. Khamas *et al.*, "A high-T_c superconducting short dipole antenna," *Electron. Lett.*, vol. 24, pp. 460–461, 14 Apr. 1988.
[13] S. K. Khamas *et al.*, "Significance of matching networks in enhanced performance of small antennas when supercooled," *Electron. Lett.*, vol. 26, no. 10, pp. 654–655, 1990.
[14] H-Y Lee and T. Itoh, "Phenomenological loss equivalence method for planar quasi-TEM transmission lines with a thin normal conductor or superconductor," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1904–1909, Dec. 1989.
[15] E. B. Ekholm and S. W. McKnight, "Attenuation and dispersion for high-T_c superconducting microstrip lines," *IEEE Trans.* vol. 38, pp. 387–395, Apr. 1990.
[16] J. F. Whitaker *et al.*, "Propagation model for ultrafast signals on superconducting dispersive striplines," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 277–285, Feb. 1988.
[17] D. P. McGinnis and J. B. Beyer, "A broad-band microwave superconducting thin-film transformer," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1521–1525, Nov. 1988.
[18] J. C. Swihart, "Field solution for a thin-film superconducting strip transmission line." *J. Appl. Phys.*, vol. 32, pp. 461–469, Mar. 1961.
[19] W. H. Henkels and C. J. Kircher, "Penetration depth measurements on type II superconducting films," *IEEE Trans. Magn.*, vol. MAG-13, pp. 63–66, Jan. 1977.
[20] J. M. Pond, W. L. Claassen, and W. L. Cater, "Measurements and modeling of kinetic inductance microstrip delay lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 1256–1262, Dec. 1987.
[21] J. M. Pond, C. M. Krowne, and W. L. Carter, "On the application of complex resistive boundary conditions to model transmission lines consisting of very thin superconductors," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 181–190, Jan. 1989.

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