A Role for High Frequency Superconducting Devices in Free Space Power Transmission Systems

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NASA

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ABSTRACT

Major advances in space power technology are being made in photovoltaic, solar thermal (Brayton, Rankine, and Stirling Engine cycles), and nuclear systems. Despite these advances, the power systems required by the energy and power intensive missions of the future will be massive due to the large collecting surfaces (solar), large thermal management systems (heat engines), and heavy shielding (nuclear). Reducing this mass on board the space vehicle can result in significant benefits because of the high cost of transporting and moving mass about in space. An approach to this problem is beaming the power from a point where the massiveness of the power plant is not such a major concern.

The viability of such an approach has already been investigated. Efficient microwave beam power transmission at 2.45 GHz has been demonstrated over short range (1 - 2 km.) at JPL and in a recent Canadian aircraft experiment. Higher (millimeter) frequencies are desired for efficient transmission over several hundred or thousand kilometers in space.

Superconducting DC-RF (Josephson effect) conversion as well as RF-DC (reverse Josephson effect) conversion offers exciting possibilities. Multivoltage power conditioning for multicavity high power RF tubes could be eliminated since only low voltages are required for Josephson junctions. Small, high efficiency receivers may be possible using the reverse Josephson effect. The discovery of granular superconductivity in Y-Ba-Cu-O at 240 K, could lead to systems whereby the space environment at 3 K could be used to maintain the operating temperature of these systems with reduced mass and power requirements.

This paper assesses a conceptual receiving antenna design using superconducting devices to determine possible system operating efficiency. If realizable, these preliminary assessments indicate a role for superconducting devices in millimeter and submillimeter free space power transmission systems.

NOMENCLATURE

A_{ef} antenna effective area (m^2)

A_{phy} antenna physical area (m^2)

C Euler's constant 0.5772

c speed of light 3×10^8 m/sec

c_o speed of light in bounded media (m/sec)

d effective thickness of SIS junction (m)

e natural number (2.718...)

f RF frequency (Hz)

h distance between transmitter and receiver (m)

k	wave number (m^{-1})
ℓ	dipole's electric length (m)
ℓ'	dipole's physical length (m)
P_j	power at the junction (w)
P_{ohmic}	power dissipated at the junction (w).
$P_{out(DC)}$	Rectified RF power at the output of the rectenna. (w)
$P_{rad(RF)}$	Incident RF power at the rectenna (w).
R_N	Normal junction resistance (Ω)
r_R	radius of receiver antenna (m)
r_T	radius of transmitter antenna (m)
t	thickness of oxide substrate. (μm)
w	junction width (μm)
Z_a	Antenna input impedance (Ω).
Z_j	Junction impedance (Ω).
ϵ_r	dielectric constant
λ	RF radiation wavelength (m)
λ_L	London's penetration depth (μm).
η	free space intrinsic impedance $(120\pi\ \Omega)$.
η_G	Gaubau interception efficiency
π	3.14159...
Γ	reflection coefficient
ρ_N	normal resistivity $(\Omega \cdot \mu m)$.

INTRODUCTION

Electricity makes our homes run, our factories hum, our cities shine, and our lives better. In space it powers our spacecraft and sends messages from the far reaches of the solar system. To perform its miracles, electrical energy is traditionally generated by a source and transmitted by wires to its use in the form of direct current or low frequency (eg. 60, 400, or 20,000 Hz) alternating current. If this transmission frequency is raised to microwave bands (ie. 1 GHz or higher), the wires can be eliminated. Appropriate transmitting and receiving systems at the source and user ends would transfer the desired electrical energy through free space directly. The result could be a "wireless utility distribution system". Efficient, light weight, high frequency superconducting devices could help make such systems possible.

BACKGROUND

Free space power transmission offers an attractive alternative in many situations. Because of power transmission considerations, space power sources are located close to their loads. Power sources such as photovoltaics, solar thermal (Brayton, Rankine, Stirling Engine Cycles), and nuclear systems are being considered for the energy and power intensive missions of the future. Even with major advances in these technologies though, these power systems can be massive due to large collecting surfaces (solar), large thermal management systems (heat engines), and/or heavy shielding (nuclear). This attached mass and bulk can severely constrain the

mission. Therefore beaming the power from a remote location could enable desirable mission operations.

Beaming electrical energy by microwaves from a geosynchronous satellite was proposed and studied for the Solar Power Satellite (1970's). It was found to be technically feasible, but not cost effective at the time versus other energy sources on the earth. Efficient microwave beam power transmission at 2.45 GHz has been demonstrated over a short range (1 - 2 Km)[6] at the Jet Propulsion Laboratory (1975), and in a recent (1987) Canadian experiment where a small aircraft was powered by microwaves as proof of concept for a long duration flight vehicle.[17] The light weight thin film rectifying antenna (rectenna) use by the Canadians was a modified version of the rectenna developed by Raytheon for Lewis Research Center that had a RF to DC conversion efficiency of 85% with a specific power of about 1 Kg/Kw.[7]

A particularly attractive space application would be beaming power to a rover on the surface of the Moon or Mars from a satellite in stationary orbit above the surface. The power would be beamed over distances of approximately 52,000 Km and 17,000 Km respectively. A recent study shows that such a system could significantly improve (1 -2 orders of magnitude) Mars rover performance (range) compared to rover based photovoltaic, nuclear reactor or RTG options.[10] The overall power system efficiency depends on the individual component efficiencies and the Gaubau (or transmitting) intercept efficiency expressed as follows:

$$\eta_G = 1 - \exp(-\tau^2) \qquad (1)$$

$$\text{where} \quad \tau = \pi r_R r_T f^2 / (ch)^2 \qquad (2)$$

As can be seen, the intercept efficiency is a function of transmit-

ting and receiving antenna sizes, frequency, and beaming distance. For the several hundred to thousands of kilometers beaming distances of many space applications, large antennas (100's of meters) and/or higher frequency (millimeter and submillimeter) operation is desired. Light weight, high efficiency, high frequency components will be the required building blocks for such systems.

Superconducting DC-RF (Josephson effect) conversion as well as RF-DC (reverse Josephson effect) conversion offers exciting possibilities. Multivoltage power conditioning for multicavity high power RF tubes could be eliminated since only low voltages are required for Josephson junctions. Small, high efficiency receivers may be possible using the reverse Josephson effect.[13]

The discovery of granular superconductivity in Y-Ba-Cu-O at 240 K, [20,9] could lead to systems whereby the space environment at 3 K could be used to maintain the operating temperature of these systems resulting in reduced mass and power requirements.

In recent years, new high T_c superconducting materials have been developed as well as techniques for manufacturing thin films of these materials with reproducible characteristics on substrates such as Si, SiO_2, Si_3N_4 and possibly GaAs [1,2] rather than conventional sapphire substrates. These developments could make superconducting materials compatible with microelectronic fabrication technology. Such fabrication technology could lead to the large arrays of superconducting devices desired for free space power transmission systems.

DISCUSSION

Josephson junctions have been very attractive in the area of high frequency/high resolution radar and

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radio astronomy because their high cut off frequency (up to 8 THz) [14] and low noise (10^{-14} W/(hz)$^{\frac{1}{2}}$)[19]. In some cases tunneling has been observed at quasioptical and optical frequencies.[16] Despite these obvious advantages over conventional GaAS technology, the low RF impedance of these junctions make the task of coupling the RF power in and out of the junction cumbersome and inefficient. [15] Some geometries have been designed in order to couple the RF power of several Josephson junction sources in a phase locked manner, although, no reference is made to the efficiency of such structures. [13]

A very simple radiator configuration could be a small dipole consisting of two strips overlapping in the center. As shown in figure 1, the overlapping area would form the junction . This configuration eliminates the need of coupling RF thru a transmission line to the junction. A whole array of these elements could be built in a three layer configuration (conductor - insulator - conductor) (fig. 1c). The conducting strip could be all superconducting, or metallic with superconducting materials in the area of the junction. In either case, the thickness of the superconducting strip should be several times larger than the London penetration depth (λ_L).

A similar geometry using a thin oxide film forming a metal-oxide-metal (MOM) junction (figure 2) was proposed for direct laser to DC conversion [21]. Structures such as Ni-NiO$_2$-Au and Al-Al$_2$O$_3$-Al have been studied for an infrared rectenna (10 μm radiation). [5,11] These junctions are still at early experimental stages.

Other structures utilizing superconducting materials have been tried for infrared radiation detection.[15] They consisted of a λ/4 dipole coupled to a microbridge structure.

The unsuccessful outcome of the attempt is felt to be attributable to impedance mismatch between the dipole and the microbridge. Microbridges have inheritable low input impedance (< 1Ω) and handle less power than a Josephson junction, but their planar geometry is very attractive for coplanar stripline microwave circuits.[15,20]
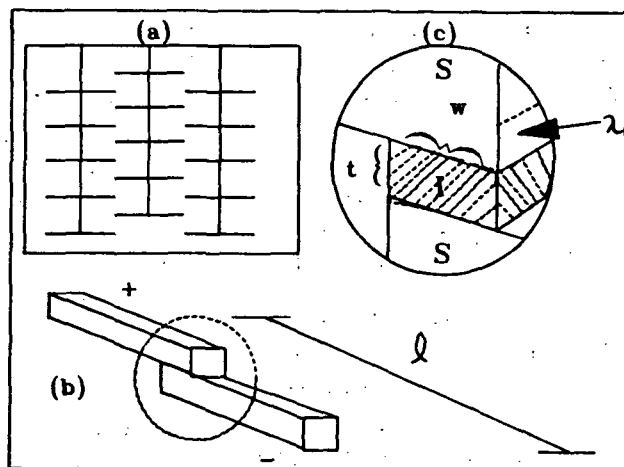

FIGURE 1. (a) Stripline rectenna array consisting of (b) dipole elements of length ℓ which its two overlaping conductors define a (c) superconductor/insulator/superconductor structure (SIS) or Josephson Junction.
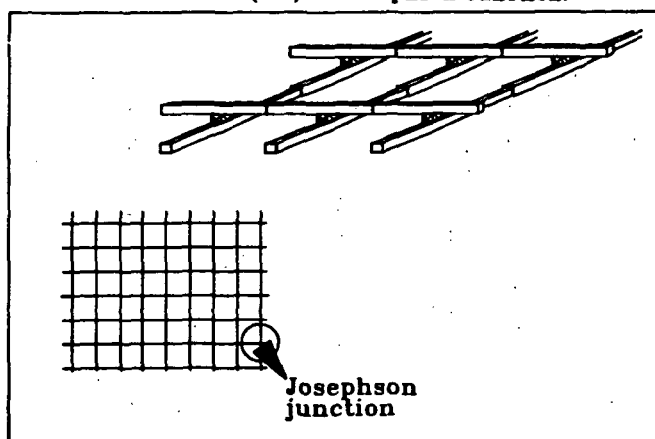

FIGURE 2. Stripline grid which defines set of crossed dipoles for circulary polarized radiation. Overlaping strips determine SIS junction as in figure 1(c).

ANALYSIS

Array:

The overall efficiency of an array is:

$$eff=(A_{ef}/A_{phy})\times(P_{out}/P_{rad}) \quad (3)$$

The effective area of the array (A_{ef}) can be assumed to be equal to the number of elements in the array times the effective area of a single element, taking into consideration that the maximum affective area of the array will be its physical area (A_{phy}).

Coupling:

To have an efficient RF to DC converter (rectenna) or a DC to RF converter (transmitter), the junction should be properly coupled to the radiator. A simple electrical model of a Josephson junction rectenna is shown in figure 3. This model consists of three shunt loads which are Z_a (antenna's input impedance), Z_j (RF junction impedance) and R_N (junction normal resistance). The amount of the power delivered to the junction (P_j) by the antenna is a function of the voltage reflection coefficient Γ, as shown in equation (4).

$$P_j = (1-|\Gamma|^2)\, P_{rad} \qquad (4)$$

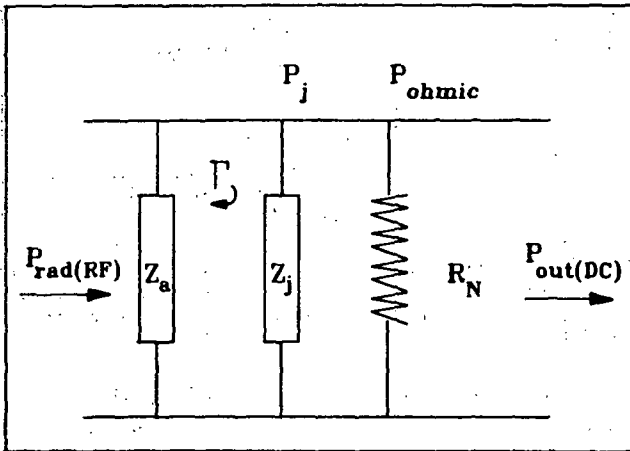$$\text{where } \Gamma = (Z_j-Z_a)/(Z_j+Z_a) \qquad (5)$$

FIGURE 3. Simple impedance model of a Josephson Junction coupled to the input of an antenna element.

P_{ohmic} will account for some ohmic losses due to R_N. Assuming that all the RF power arriving at Z_j is converted into DC, the ratio of the DC output power (P_{out}) to RF input power (P_{rad}) is given by the expression:

$$P_{out}/P_{rad} = (1-|\Gamma|^2)(1-Z_j/R_N) \qquad (6)$$

This expression shows the importance of good impedance matching in order to have maximum power transfer from the antenna to the junction. Likewise, a large normal resistance $(R_N > Z_j)$, contributes in maximizing the power coupled to the load. Coupling between the radiator and the junction and Z_j and R_N can be maximized by judiciously choosing material parameters as well as antenna and junction geometries.

Junction:

The RF impedance of the junction Z_j formed by the two overlapping conducting strips is given by:[4]

$$Z_j = \frac{c_o}{c\,(t/(\epsilon_r w))} \qquad (7)$$

where c_o is the speed of light in free space, t is the thickness of the insulating layer, w is the width of the junction (in this case assumed to be a square), ϵ_r is the relative dielectric constant of the insulating material and c is the speed of light in the junction:

$$c = c_o \sqrt{\frac{t}{\epsilon_r d}} \qquad (8)$$

$$d = 2\lambda_L + t \qquad (9)$$

The normal resistance (R_N) is given by an RF radiation passing through a junction with a crossectional area of $\lambda_L \times w$, and a length of w. Then:

$$R_N = 2\rho_N w/(\lambda_L w) = 2\rho_N/\lambda_L \qquad (10)$$

where ρ_N is the normal resistivity of the material.

Antenna:

From antenna theory, the radiation resistance of a dipole of infinitesimal width ($<\lambda/10$) is given by the expression:[3]

$$R_r = (\eta/2\pi)\{C + \ln(\kappa\ell) - C_i(\kappa\ell) + 1/2\sin(\kappa\ell)\times[S_i(2\kappa\ell) - 2S_i(\kappa\ell)] + 1/2\cos(\kappa\ell)\times[C + \ln(\kappa\ell/2) + C_i(2\kappa\ell) - 2C_i(\kappa\ell)]\} \qquad (11)$$

where ℓ is the electrical length of the dipole, η is the medium intrinsic impedance ($120\pi\ \Omega$ in this case), κ is the wave number ($2\pi/\lambda$), C is the Euler constant (0.5772), C_i and S_i are the cosine and sine integrals respectively, defined by the expressions:

$$C_i(\chi) = -\int_\chi^\infty \frac{\cos(\tau)}{\tau}\,\partial\tau \qquad (12)$$

$$S_i(\chi) = \int_0^\chi \frac{\cos(\tau)}{\tau}\,\partial\tau \qquad (13)$$

then, the input impedance of is then given by:[3]

$$Z_a = R_r/\sin^2(\kappa\ell)]/2) \qquad (14)$$

The input impedance of this infinitesimal thickness dipole is mostly resistive, but this assumption could not be true for thickness comparable to the wavelength of the incident radiation. For this case, a more complex analysis (induced emf method or the moment method) would have to be used. This was beyond the scope of this preliminary study.

RESULTS

A modified algorithm from ref. 3 was used to calculate the input impedance and the effective area (A_{ef}) for a dipole of physical length ℓ for different frequencies ($\ell/10 < \lambda < 10\ell$).

Ohmic losses in the radiator were not included in the analysis for the sake of simplicity.

A number of design parameters were tried but no attempt was made for a fully optimized design. Figure 4, shows the theoretical efficiency of a rectenna using a Josephson junction for the following typical parameters:

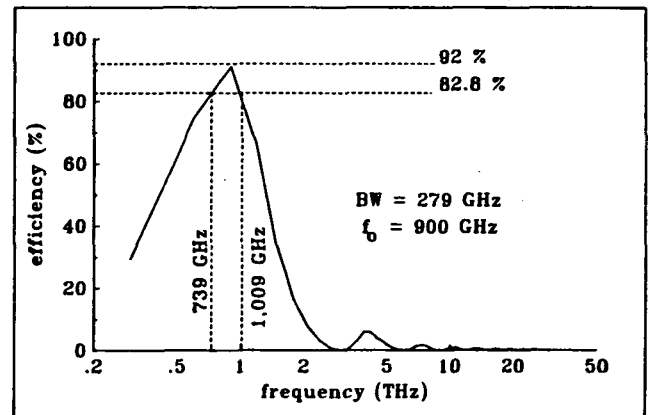| length	$\ell' =$	100 μm
width	w =	10 μm
thickness	t =	1 μm
normal resistivity	$\rho_N =$	48 $\Omega\cdot\mu$m
London penetration depth	$\lambda_L =$	.1 μm
dielectric constant	$\epsilon_r =$	4

FIGURE 4. Theoretical efficiency as a function of frequency of rectenna array, consisting of dipole elements of 100 μm dipole elements and Josephson junctions diodes for RF rectification at the imput of the radiator.

In this particular case, the junction's normal resistance was 240 Ω, the RF resistance 206.49 Ω and the junction capacitance 4 μf.

If the bandwidth is taken as the points where the efficiency is not less than 10% of the peak efficiency (92% @ 900 GHz), then the lower and the maximum operational points are located at 739 GHz and 1009 GHz respectively (for a bandwidth of 270 GHz).

Authors did not consider in this model the temperature dependence of λ_L, nor attempted to determine the maximum power that these junctions could handle. If 10 μW per junction is the maximum power that could be obtained with these junctions, then for our study case a maximum of 1 Kw/m^2 for an array of 10^8 elements (100 μm dipole length), 92% efficiency and up to 1.2 THz operating frequency may be expected.

More in-depth studies should follow this preliminary theoretical assessment. They should consider other properties of high temperature superconducting materials as well as other kinds of radiators that may be more suitable for this application.

CONCLUSIONS

Beaming power at frequencies around 1 THz is very desirable when distance between transmitter and receiver is several thousand kilometers.

Preliminary theoretical assessment indicate Josephson junctions to be potential candidates for the construction of such submillimeter rectennas. More in depth analysis and construction of prototypes will be necessary to confirm their possible role in free space power transmission systems.

REFERENCES

1)- Aslam, M., et al., Technology of Superconducting Films on Si, SiO$_2$ and Si$_3$O$_4$ Substrates, presented at the 1st International Vacuum Microelectronics Conference, sponsored by the IEEE-EDS, Williamsburg, Virginia, June 13-15, 1988

2)- Aslam, M., et al., Rapid Thermal Annealing of Y-Ba-CuO Films on Si and SiO$_2$ Substrates, Applied Physics Letters, July 1988

3)- Balanis, C.A., "Linear Wire Antennas" in Antenna Theory and Design, Harper & Row Publishers INC., New York, 1982, p. 100-162

4)- Barone, A. and G. Paterno, Physics and Applications of the Josephson Junction Effect, John Wiley & Sons, New York, 1982.

5)- Boyd, J.T., Metal-Insulator-Metal Rectifying Devices with Integrated Antennas for Energy Conversion, Dept. of Electrical and Computer University of Cincinnati for NASA Lewis grant NAG3-532, Cleveland, Ohio, January 1985

6)- Brown, W.C., The History of the Development of the Rectenna, presented at the Rectenna Session of the SPS Microwave System Workshop, Lyndon B. Johnson Space Center, Houston, Texas, January 15-18, 1980

7)- Brown, W.C., Rectenna Technology Program: Ultra Light 2.45 GHz Rectenna and 20 GHz Rectenna, Raytheon Co. for NASA Lewis contract NAS3-22764 (CR179558), March 11, 1987

8)- Brown, W.C., Can an Airplane Fly Forever?, IEEE-MTTS Newsletter, Winter 1988, p. 20-21

9)- Chen, J.T., et al., Observation of the Reverse AC Josephson Effect in Y-Ba-Cu-O at 240 K, Physical Review Letters, vol. 58, pp 1972-1975, May 11, 1987

10)- Christian, J.L. Jr., R.C. Cull and I.T. Myers, Electromagnetic Powered Vehicles for Mars Exploration, presented at the 5th Symposium on Space Nuclear Power Systems at Albuquerque, New Mexico, January 13-16, 1988

11)- Kumar, S., Infrared Detection in Schottky Barrier Devices Using the Inelastic Electron Tunneling Effect, Master Thesis, Department of Electrical and Computer Engineering, University of Cincinnati, Cincinnati, Ohio, 1985

12)- Kwok, W.K., et al., Supercon-
ductivity in La$_{1.85-x}$Nd$_x$
Sr$_{.15}$CuO$_4$, Material Science and
Chemistry Divisions, Argonne National
Laboratory, Argonne, Illinois, June
1987

13)- Lukens, J.E., A.K. Jain, P.M.
Mankiewich, Transmission Line Biased
Coherent Array of Josephson Oscil-
lators, U.S. Patent # 4,468,635,
August 28, 1984

14)- McDonald, D.G., et al., High
Frequency Limit of the Josephson Ef-
fect, Journal of Applied Physics, vol
42, no. 1, January 1971, p.179-181

15)- Octavio, M., Nonequilibrium
Properties of Variable Thickness Su-
perconducting Microbridges, Harvard
University for Office of Naval
Research contract # N0014-77-C-0085,
Arlington, Virginia, January 1978

16)- Richard, P.L., The Josephson
Junction as a Detector of Microwave
and Far Infrared Radiation, Califor-
nia University for Office of Naval
Research, contract N00014-69-A-0200-
1056, Arlington, Virginia, December
1974

17)- Rogers, M., K. Springgen, Can
an Airplane Fly Forever?: An aviation
First Powered Flight without Fuel,
Newsweek Magazine, September 28, 1987

18)- So, C.K. and W.O. Hamilton, Un-
tuned Josephson Detector of Microwave
and Millimeter Wave Radiation, Jour-
nal of Applied Physics, vol. 48, no.
5, May 1977, p. 2037-2042

19)- Warman, J., M.T. Jahn and Y.H.
Kao, Josephson Effect in Bulk
Granular Superconductor, Journal of
Applied Physics, vol. 24, November
1971, p. 5194-5196

20)- Wenger, L.E., et al., Reverse
AC Josephson Experiments in Y-Ba-Cu-O
at 240 K, MRS High T$_c$ Superconduc-
tivity Symposium, April 23-24, 1987

21)- De Young, R.J., et al., A NASA
High-Power Space Based Laser Research
and Application Program, NASA SP-464,
Washington, DC, 1983

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