Efficiency of antenna solar collection

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EFFICIENCY OF ANTENNA SOLAR COLLECTION

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ABSTRACT

Antennas with rectifiers, "rectennas", have been proposed for high efficiency conversion of solar energy and high efficiencies have been demonstrated for quasi-monochromatic microwaves. Antennas receiving black body radiation may be modelled as a pair of resistors at the black body temperature, each supplying electrical noise power. Extraction of that power from a load as heat is feasible at the same limiting efficiencies as solar thermal converters. Rectennas, relying on rectification of the broadband electrical noise, appear to have lower efficiency limits due to the unavailability of a design for the Carnot conversion of the noise from a hot resistor.

1. INTRODUCTION

Solar cells are quantum devices, only able to be understood and designed by application of quantum physics. However, the wave nature of light is routinely exploited at longer wavelengths in radio and microwave frequency bands. In principle, there is no reason why the electromagnetic wave technologies which are so successfully used for radio cannot be scaled to optical frequencies but there are significant practical problems, especially the sub-µm size scales involved.

A rectenna, or rectifying antenna (Fig.1), is a device for the conversion of electromagnetic energy propagating through space to direct current in a circuit. It has one or more elements, each consisting of an antenna, filter circuits and a rectifying diode or bridge rectifier either for each antenna element or for the power from several elements combined (Fig. 1). The circuit in Fig. 1 is for a rectenna designed to convert a single microwave frequency. The first filter blocks re-radiation of harmonics and ensures continuity of power flow to the half-wave rectifier and the second filter smoothes the rectified power.

An antenna may be defined as a transducer for converting electromagnetic waves propagating through space to waves propagating along a transmission line or waveguide. Here, we further restrict ourselves to devices whose interaction with sunlight conceptually results in motion of free carriers in conductors. Hence, we exclude situations in which the power flow is simply concentrated into a waveguide or optical fibre in this case, and requires another stage for conversion of confined electromagnetic energy to electricity and exclude cases where the ultimate conversion to electrical output relies on quantum converters, as in antenna-coupled infrared detectors.

Rectennas have been proposed for a wide range of applications, particularly wireless electrical power transmission and various radio-powered devices [1]. They have been demonstrated to have achieved very highly efficient conversion, exceeding 80%, to DC electricity from monochromatic microwave radiation [2] and have been theoretically predicted to be "capable of nearly 100% absorption of a perpendicularly incident planar beam" at a single frequency [3].

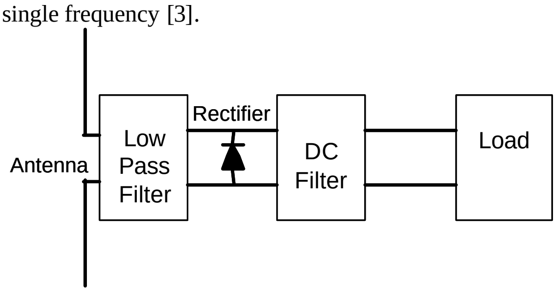

Fig. 1 Block diagram of rectenna and load (after [4]).

Bailey proposed the idea of collecting solar energy with devices based on the wave nature of light in 1972 [5]. He suggested artificial pyramid or cone structures analogous to those found in nature. Marks patented the use of arrays of submicron crossed dipoles on an insulating sheet with fast full-wave rectification, devices to collect and convert solar energy using oriented metal particles or molecules and antenna-like cylinders, each with an asymmetrical metal-insulator-metal diode for rectification (see [1] for references). Kraus [6] proposed two orthogonally-polarised arrays, one above the other with the front one supported by a transparent substrate and a reflector below them. Farber collected radio frequency energy with dielectric pyramids and light energy with SiC particles, although it was not conclusively shown that the effect was not photovoltaic [7]. The University of Florida has continued studies of antennas for solar energy collection and Goswami has given a review of the field [8]. Lin et al. [9] reported the first experimental evidence for light absorption in a fabricated resonant nanostructure and rectification at light frequency in a test structure. ITN Energy Systems Inc. (ITN) is investigating optical antennas coupled to fast tunnel diodes [10]. Another electromagnetic approach to the collection of solar energy is coupling light to surface plasmons [11].

We are motivated to explore rectennas for solar energy conversion by claims of very high potential efficiencies, the high efficiencies demonstrated for microwave rectennas and by the prospect of another method, in addition to the photovoltaic effect, of direct conversion of light to electricity. Of particular interest is whether antenna-based converters could theoretically reach the Landsberg conversion efficiency limit.

2. EFFICIENCY LIMITS

It is not immediately obvious that such efficiencies as have been demonstrated for single microwave frequencies could also be expected for solar energy conversion. Sunlight is very different from monochromatic microwave radiation in that it is unpolarised, incoherent and distributed over a wide band of very small wavelengths.

2.1 Antenna Modelled as Resistors

Radio astronomers routinely represent the electrical noise power received in a narrow frequency band, df, through an antenna from a celestial source as being equivalent to that available from a resistor at a temperature, T_r, whose resistance is fixed equal to the radiation resistance of the antenna [12]. Our initial task is to determine the correct temperature for such a resistor to represent an antenna observing the sun (assumed to be a T_s = 6000 K black body).

This noise is "white", ie. independent of frequency, up to near infrared frequencies. It is common to describe it with the application, often unstated, of the Rayleigh-Jeans approximation, applicable for $hf/(kT) << 1$, to the Planck radiation spectrum [13]. The full expression is necessary at optical frequencies. The available noise power from a resistor is a one-dimensional analogue of the Planck law for the spectral distribution of radiation from a black body [13]. Hence, the resistor noise power in a spectral interval is, in Watts,

$$P(f) = \frac{hf}{\exp[(hf)/(kT_r)] - 1} df \tag{1}$$

that, in the Rayleigh-Jeans approximation, simplifies to $P(f) \approx kT_r\, df$ .The brightness of the solar disk is given, in, W. m^{-2}. Hz^{-1}. rad^{-2}, by [12]

$$B(T_s, f) = \frac{2hf^3}{c^2}\{\exp[(hf)/(k_B T_s)] - 1\}^{-1} \tag{2}$$

where k_B and h are Boltzmann's and Planck's constants. That approximately describes the brightness in W.m^{-2}.Hz^{-1}.rad^{-2} within the cone of half-angle $q_0 \approx 0.25°$ for the solar disk. Under the assumption that the antenna's acceptance cone, Ω_A, is restricted to the solar disk [12], the power spectral density, (W Hz^{-1}), intercepted by a singly polarised[1] antenna is

$$W = \frac{hf^3 \Omega_A A}{\{\exp[(hf)/(kT_s)] - 1\}c^2} \tag{3}$$

where A is the antenna's effective area, related to the acceptance cone by [12, eq. 6-15] $A = l^2 / \Omega_A$. Hence,

$$W = \frac{hf}{\exp[(hf)/(kT_s)] - 1}, \tag{4}$$

the same as for a resistor with T_r = T_s (see Eq. 1). Therefore, under the optimal conditions described, a singly polarised antenna observing the sun can be modelled by a resistor at the same temperature as the sun's black body temperature. An equivalent power collected from the same area could also be delivered to a second, orthogonally polarised port, modelled by a second resistor at T_s.

A detailed balance exists between a matched load connected to an antenna and the noise source(s) it is observing [14], according to the second law of thermodynamics and the principle of detailed balance. Under equilibrium conditions an antenna receiving power from a source and transferring it to a load must transmit the same amount of power back to the source in order to maintain equilibrium . The origin of the transmitted power is the voltage generated by thermal agitation of the charge carriers from the resistive load at the same effective temperature as the source.

2.2 Efficiency of Conversion

How may the energy from such a pair of virtual resistors be converted to a usable form, preferably DC electricity? One path is to simply dissipate that from each into a matched resistive load, thereby heating them. By directing the electrical noise energy into a resistive load, we could take advantage of several theoretically demonstrated methods for high efficiency conversion to work. Using a hot load resistor as a source for a Carnot cycle heat engine would reduce its temperature to 2544 K and allow work to be produced at an efficiency of 85.4%, as for a concentrating solar thermal converter [15]. Splitting the light spectrum to an infinite series of antennas, each accepting an infinitesimal bandwidth, offers a limiting efficiency of 86.8%, as for multi-colour thermal and photovoltaic converters [15]. Alternatively, we could employ an infinite set of optical circulators to redirect light along an infinite series of antennas, each delivering noise power to a pair of load resistors with Carnot heat engines (Fig. 2) to achieve overall conversion at the Landsberg efficiency of 93.3% [16]. However, all of these methods are mediated by heated loads and heat engines. They are, in effect, very complicated and expensive solar thermal energy converters. They are not rectennas, since they are not rectifying the received electrical noise.

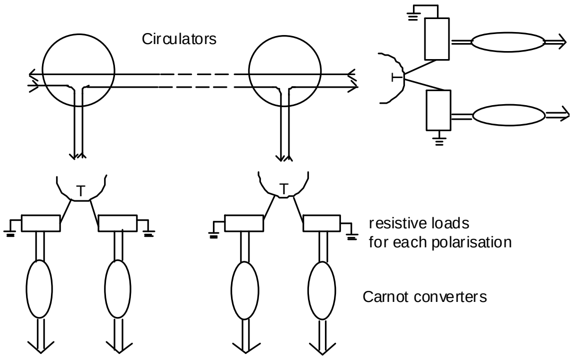

Fig. 2 Conceptual high efficiency conversion via series of optical circulators and dual-polarised antennas supplying heat to Carnot converters.

2.3 Noise Rectification

Of more interest are potential means to immediately rectify to DC electricity the noise produced at the antenna terminals. The rectification of noise is a topic of wide interest and has been addressed in many ways [17]. The rectification of electrical noise, in particular, has been of interest at least since Brillouin's paradox, which proves the inability of a diode to rectify its own noise or the noise from a resistor at the same temperature [18]. Sokolov has investigated the rectification by a diode at one temperature of the noise from a resistor held at a higher temperature [19]. This "thermal Brownian motor" is of considerable interest due to the above-demonstrated possibility of representing the sun-antenna combination as a pair of resistors at the sun's black body temperature. Unfortunately, on the basis of Sokolov's analysis, the conversion is shown to be irreversible, ie. efficiency less than that of a Carnot heat engine working between the

[1] An antenna can deliver power only from a single polarisation to any output port.

same pair of temperatures. The indicated maximum conversion efficiency for temperatures of 6000 and 300 K is around 48%. We are unaware of any proposals for the reversible rectification of the noise generated by a hot resistor [20].

Another alternative is to use a series of "electronic" quasi-circulators [21, 22], assuming for the sake of this discussion that they could be operated at optical frequencies, to channel noise power between a series of noise rectifiers (Fig. 3). Then, the resistor and the diodes in the rectifiers far along the series of rectifiers would be at small temperature differences. Sokolov [19] predicts that the ratio of the efficiency of the noise rectifier to the Carnot efficiency becomes small for small temperature differences, so that this scheme cannot help achieve reversible operation.

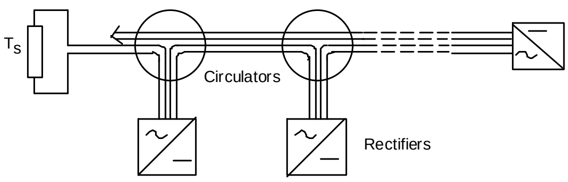

Fig. 3 Electronic isolators and circulators to extract electronic noise power from heated resistor.

3. PRACTICAL ISSUES FOR SOLAR RECTENNAS

3.1 Bandwidth

One challenging issue for rectenna collection of solar energy is the very wide frequency bandwidth, much wider than for most conventional antenna applications. However, so-called frequency-independent antennas have been developed that are able, in practice, to achieve suitable bandwidths [23]. These avoid the variation of performance with wavelength by using structures defined by angles rather than distances. Planar designs are bidirectional but two unidirectional designs are conical spiral antennas and arrays of log-periodic antennas. An alternative approach to approach a unidirectional radiation pattern is to attach a planar antenna, such as a planar log periodic design, to a transparent dielectric substrate or lens. Then, radiation is better received through the substrate side [24]. Planar frequency independent antennas have already been applied with lenses in the THz range [24]. Conical structures at light frequency will be a significant technological challenge although a 3D optical bow-tie antenna formed by deposition of aluminium on two opposite sides of a hollow SiO_2 pyramid has been demonstrated [25].

3.2 Polarisation and Directionality

These designs are responsive to only a single circular or a single linear polarisation, respectively, and are therefore immediately limited to half the available solar power. Their form militates against use of a second such feed intercepting the same solar flux. However, the "sinuous" antenna is an improvement. It has a unidirectional conical four-arm form that is effectively two intertwined antennas for both polarisations (Fig. 2). They can produce outputs for either the two linear or the two circular polarisations. None of the frequency-independent antenna designs are very directive (ie. they are restricted to low solar concentration ratios) but it would be feasible to use them as "feed" antennas for concentrating reflectors or lenses. The sinuous antenna has been used as a feed element in either a dual linear or dual circularly polarized mode [23]. The upper frequency limit is determined by the feed point at the vertex, where the spacing should be smaller than quarter of the upper frequency. The cone outer radius determines the lower frequency limit. A 10:1 bandwidth has been demonstrated.

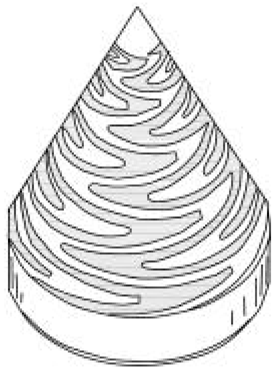

Fig. 2 Conical sinuous antenna. (After Ref. [23])

3.3 Matching

A further concern is the need to have all system components impedance-matched across the full spectrum of interest. Mismatches lead to reflection, rather than absorption of power. Matching will be particularly challenging for fundamentally non-linear components such as rectifiers. Rectifier non-linearity generates re-radiation of harmonic frequency energy that cannot be easily retained and converted to DC [2, 26]. An input filter can help to improve power flow continuity and matching, even with single-diode rectification [27] but may not be practical for broadband reception.

3.4 Physical Scale

Conduction electrons interacting with the electric field of a coherent light beam simultaneously undergo two motions stimulated by the optical field [28]. We are interested, here, in estimating the magnitude of the transverse oscillation at the frequency of the coherent light. Semchuk et al. [28] obtain an expression, valid for non-relativistic motion, for the amplitude of the transverse oscillation of $x_{\max} = qE_0/(4p^2 f^2 m)$,where E_0 is the peak field amplitude. This means a corresponding maximum velocity of $v_{\max} = eE_0/(2pfm) << c$ and leads to a restriction on the maximum excursion of the electron from its equilibrium position of $x_{\max} << c/(2pf) \equiv l/2p$. For light of wavelength 500nm this results in an amplitude of several nanometres and places a restriction on the dimensions of the structures that could be used as rectifying elements. Although not impossible, it appears the task will be extremely technologically demanding.

4. CONCLUSION

It appears that thermodynamically reversible operation of rectenna conversion of solar insolation is not possible. We have modelled the output of an ideal antenna observing the sun as a pair of hot resistors, one per polarisation. Each resistor produces a spectrum of electrical noise which must be rectified but the relevant literature indicates that this cannot be done reversibly, or even with a limiting efficiency higher than approximately 48%. Reversible operation is, in principle, possible if optical circulators are used to redirect light between a series of antennas connected to resistive loads and ideal heat engines but Ries' scheme, using optical circulators, is simpler. Circulators break the normal reciprocity between absorption and emission of light. Without such a break, solar thermal converters have limits of 85.4% and 86.8% for broadband and multicolour conversion respectively. Antenna-based converters should have the same upper limits but the limits for those rectifying electrical noise, without a thermal stage, are lower, due to the relative inefficiency of the noise rectification process.

Significant challenges exist to the possible realisation of antenna collection of solar energy, particularly relating to the fabrication of antennas and circuitry on such small physical scales and for such high frequencies, the impedance matching of sections, the necessary separation of orthogonally polarised components of power, the bandwidth requirements and the physical scale.

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