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United States Patent [19]

Koert et al.

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[45] **Date of Patent: Jun. 8, 1993**

[54] **POWER BEAMING SYSTEM WITH PRINTER CIRCUIT RADIATING ELEMENTS HAVING RESONATING CAVITIES**

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[73] Assignee: **APTI, Inc.**, Washington, D.C.

[21] Appl. No.: **419,144**

[22] Filed: **Oct. 10, 1989**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 239,289, Sep. 1, 1988, Pat. No. 5,068,669.

[51] **Int. Cl.**^{5} **H01Q 1/280**; H01Q 9/160; H01Q 13/080

[52] **U.S. Cl.** **343/789**; 343/795; 343/DIG. 2

[58] **Field of Search** .... 343/700 MS File, 769, 343/778, 789, 793, 795, 797, 846; 307/151; 361/395; 333/230, 250

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Primary Examiner—Rolf Hille
Assistant Examiner—Peter Toby Brown
Attorney, Agent, or Firm—Foley & Lardner

[57] **ABSTRACT**

A system and method for "power beaming" energy from a source at high frequencies and rectifying such energy to provide a source of DC energy is disclosed. The system operates at a frequency of at least 10 GHz and incorporates a rectenna array having a plurality of rectenna structures that utilize circuit elements formed with microstrip circuit techniques. Each rectenna element is associated with a resonating cavity structure.

16 Claims, 12 Drawing Sheets

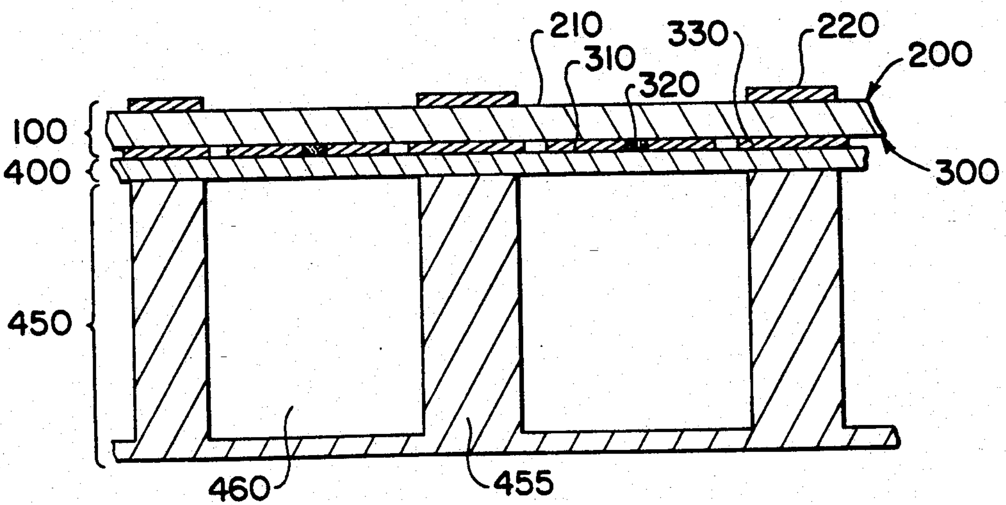


FIG. 1

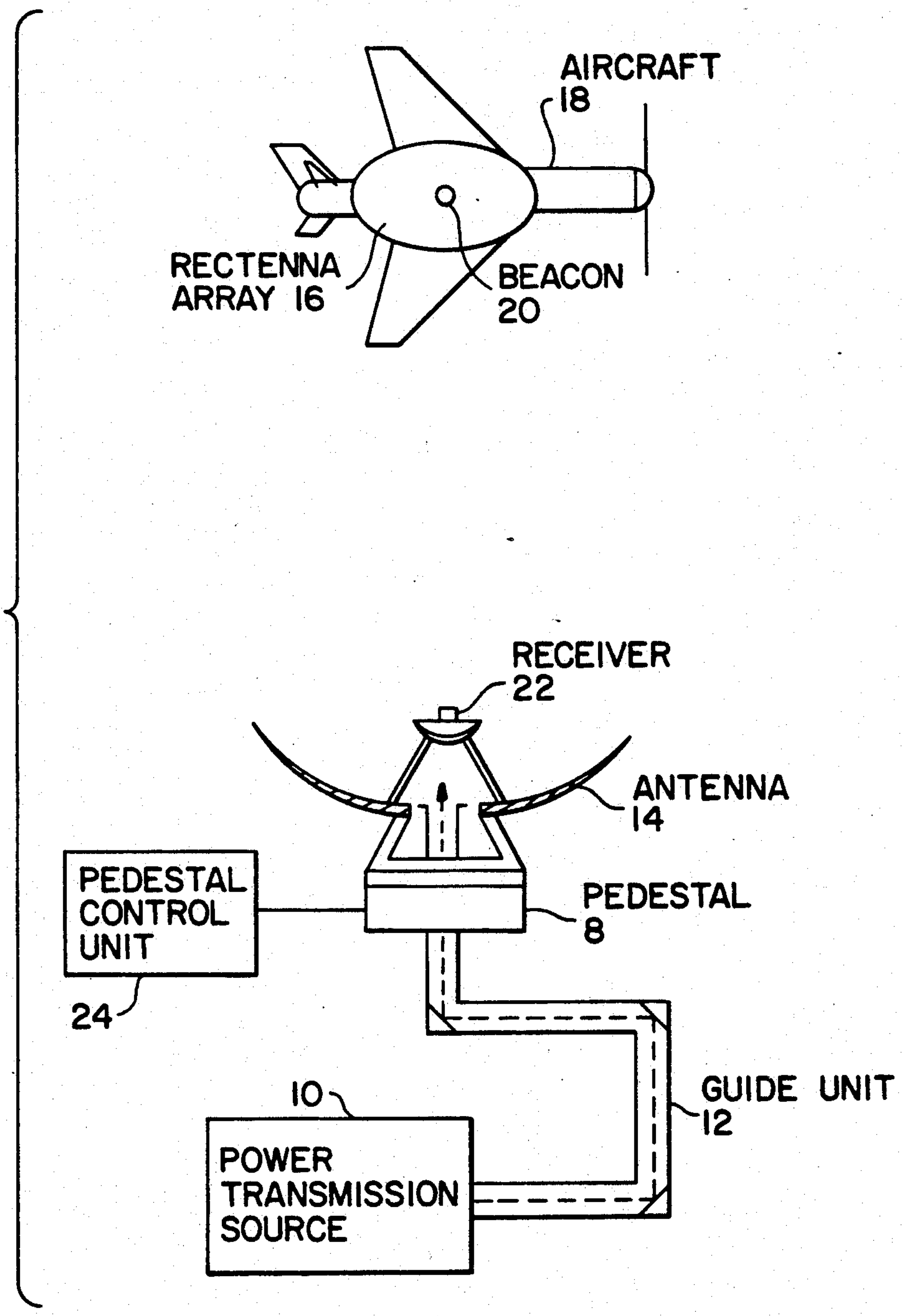
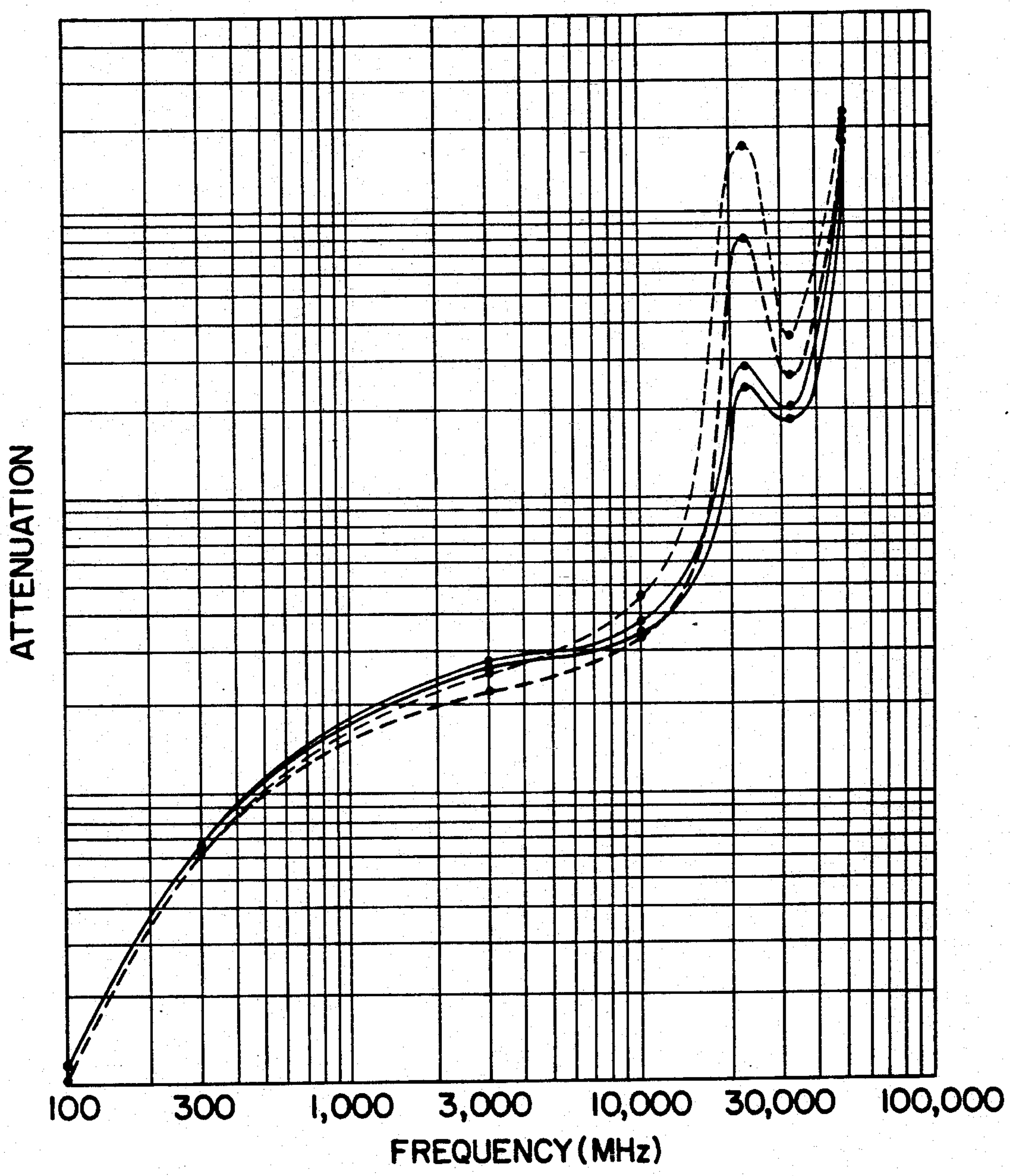

AIRCRAFT
18
RECTENNA
ARRAY 16
BEACON
20
RECEIVER
22
ANTENNA
14
PEDESTAL
CONTROL
UNIT
24
PEDESTAL
8
GUIDE UNIT
12
10
POWER
TRANSMISSION
SOURCE

FIG. 2



---- BISMARCK, AUGUST
---- WASHINGTON, AUGUST
—— BISMARCK, AUGUST
—— WASHINGTON, AUGUST
CALCULATED VALUES

FIG. 3a

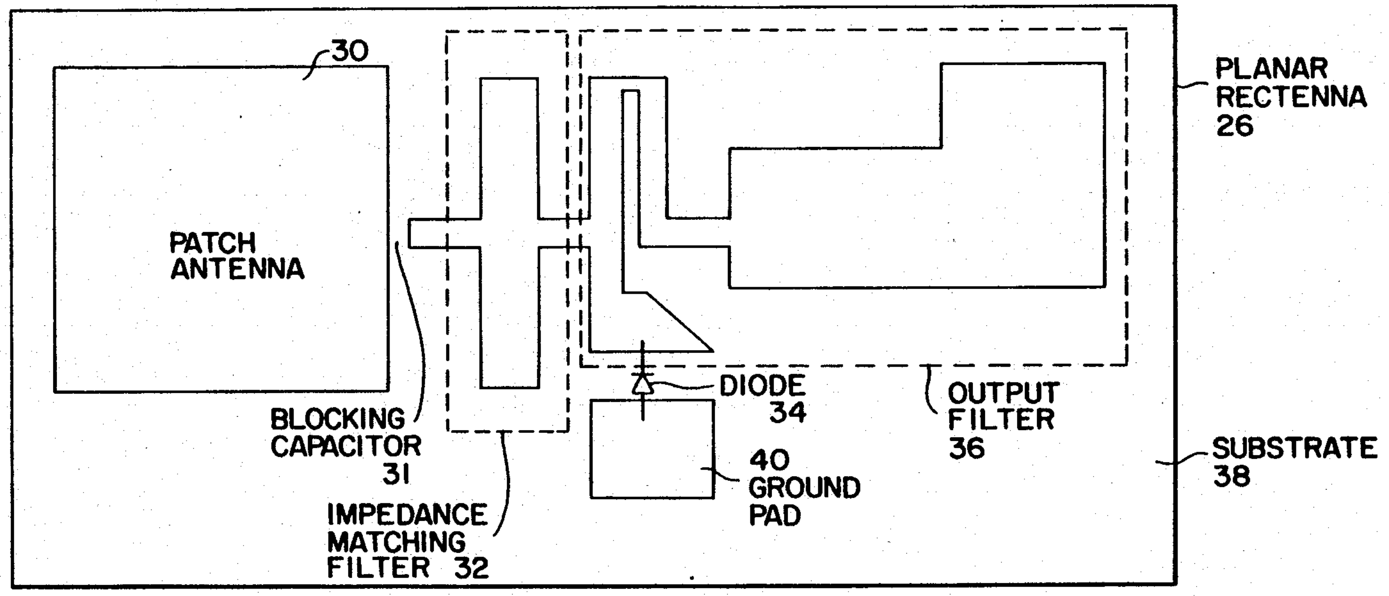

30
PATCH ANTENNA
BLOCKING CAPACITOR 31
IMPEDANCE MATCHING FILTER 32
DIODE 34
40 GROUND PAD
OUTPUT FILTER 36
PLANAR RECTENNA 26
SUBSTRATE 38

FIG. 3b

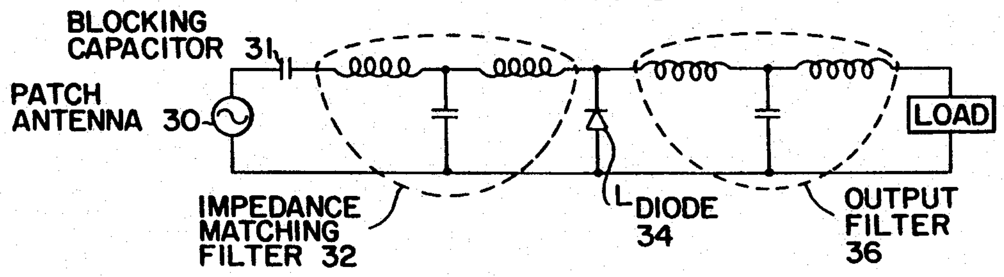

BLOCKING CAPACITOR 31
PATCH ANTENNA 30
IMPEDANCE MATCHING FILTER 32
DIODE 34
OUTPUT FILTER 36
LOAD

FIG. 4a

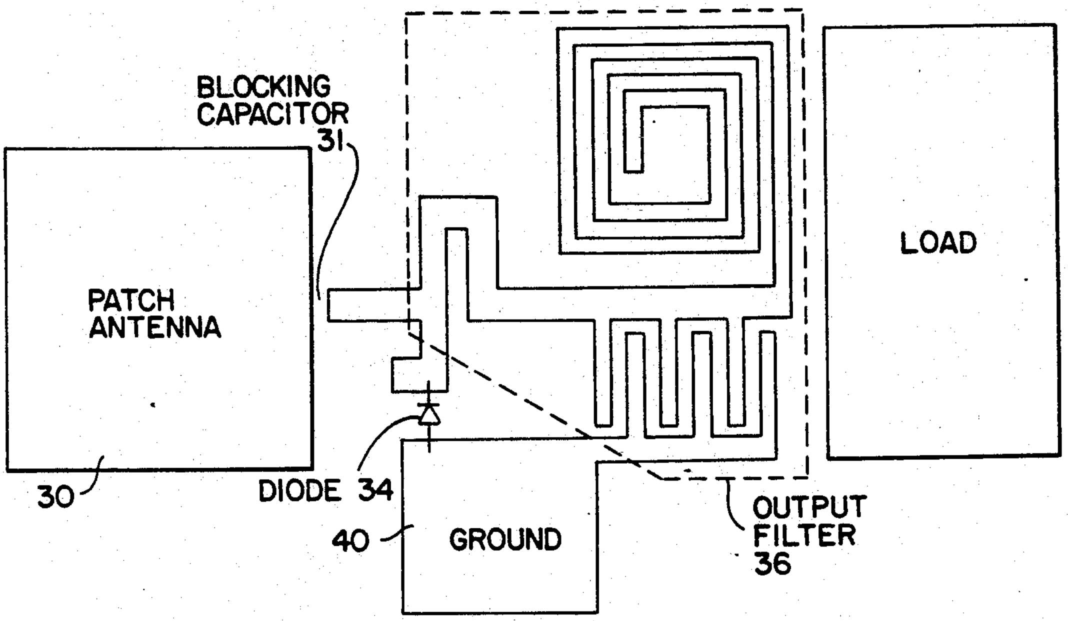

BLOCKING
CAPACITOR
31
PATCH
ANTENNA
30
DIODE 34
40
GROUND
LOAD
OUTPUT
FILTER
36

FIG. 4b

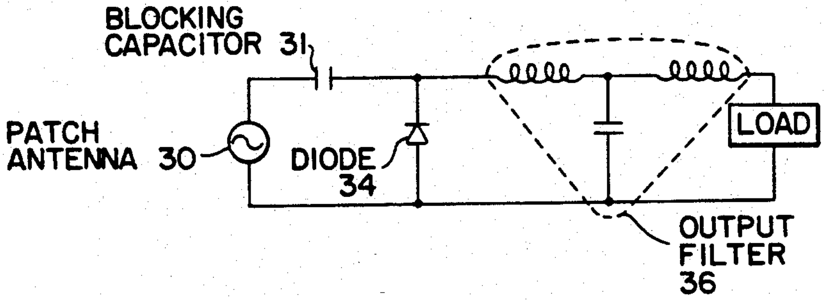

BLOCKING
CAPACITOR 31
PATCH
ANTENNA 30
DIODE
34
LOAD
OUTPUT
FILTER
36

FIG. 5a

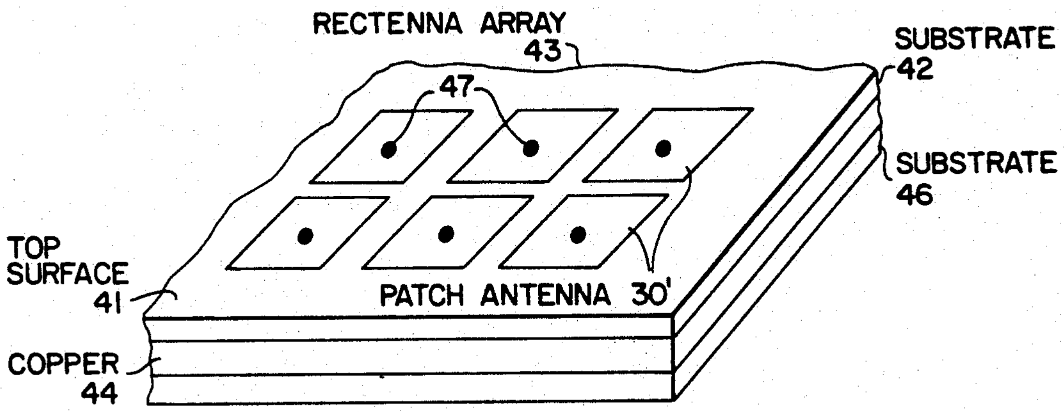

RECTENNA ARRAY
43
SUBSTRATE
42
47
SUBSTRATE
46
TOP
SURFACE
41
PATCH ANTENNA 30'
COPPER
44

FIG. 5b

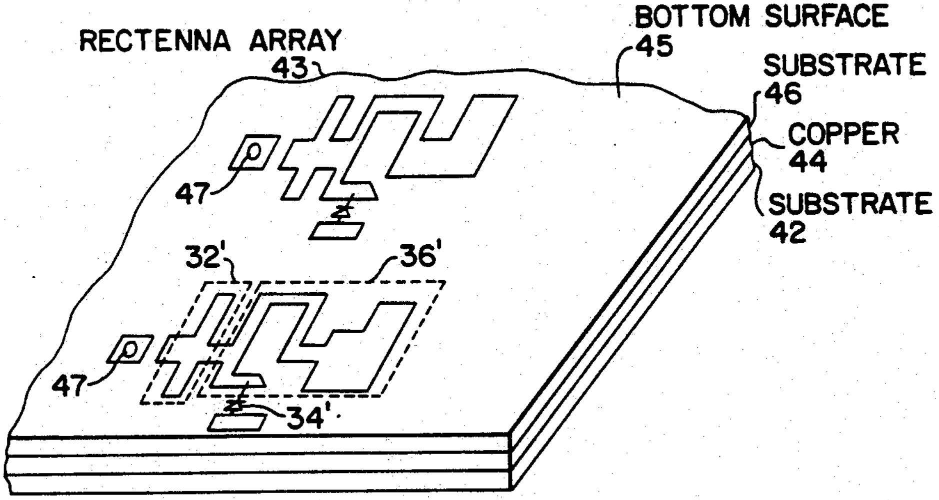

RECTENNA ARRAY
43
BOTTOM SURFACE
45
SUBSTRATE
46
COPPER
44
SUBSTRATE
42
47
32'
36'
47
34'

FIG. 6

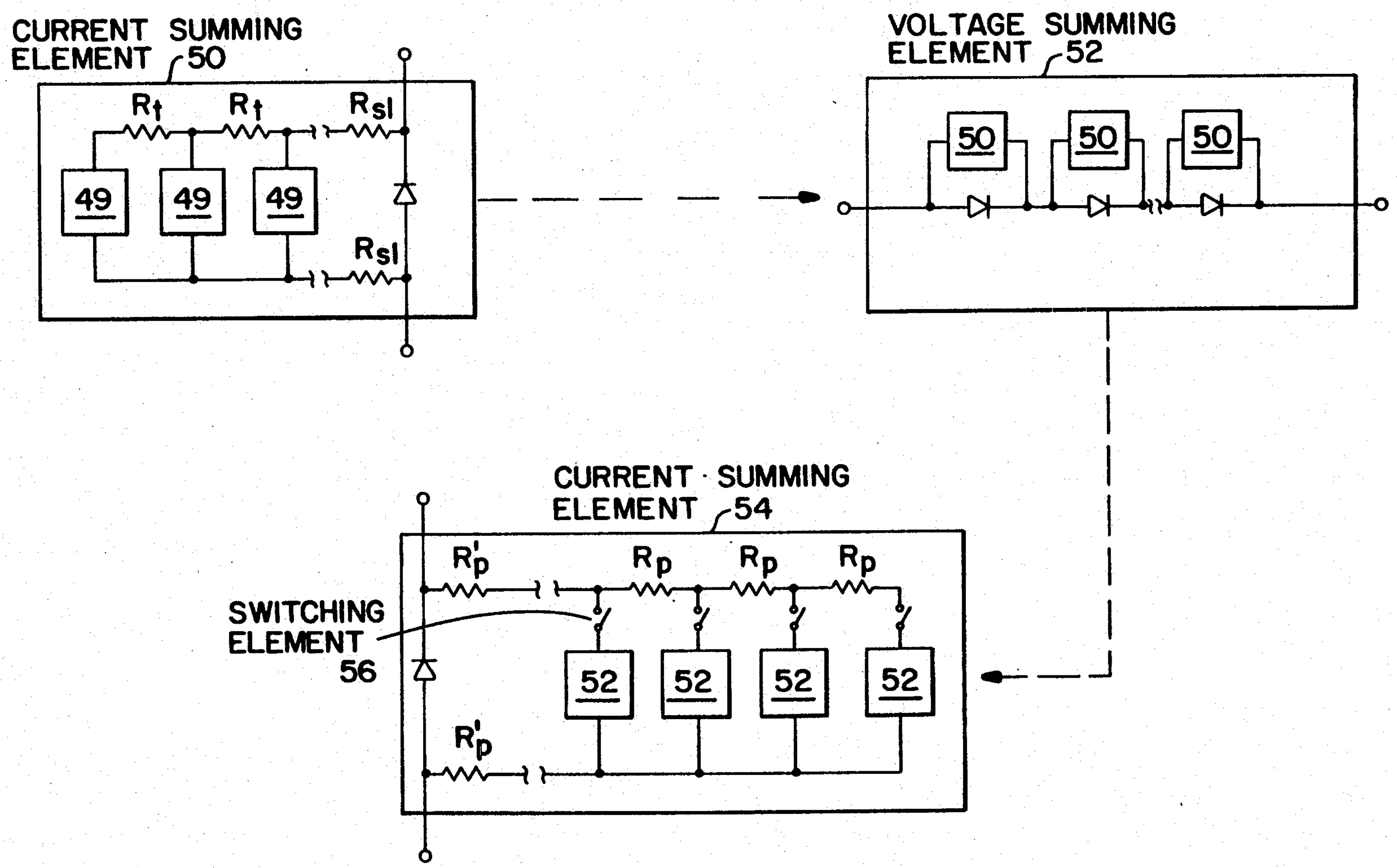

CURRENT SUMMING ELEMENT 50
R_t
R_t
R_{sl}
49
49
49
R_{sl}
VOLTAGE SUMMING ELEMENT 52
50
50
50
CURRENT · SUMMING ELEMENT 54
R'_p
R_p
R_p
R_p
SWITCHING ELEMENT 56
52
52
52
52
R'_p

FIG. 7a

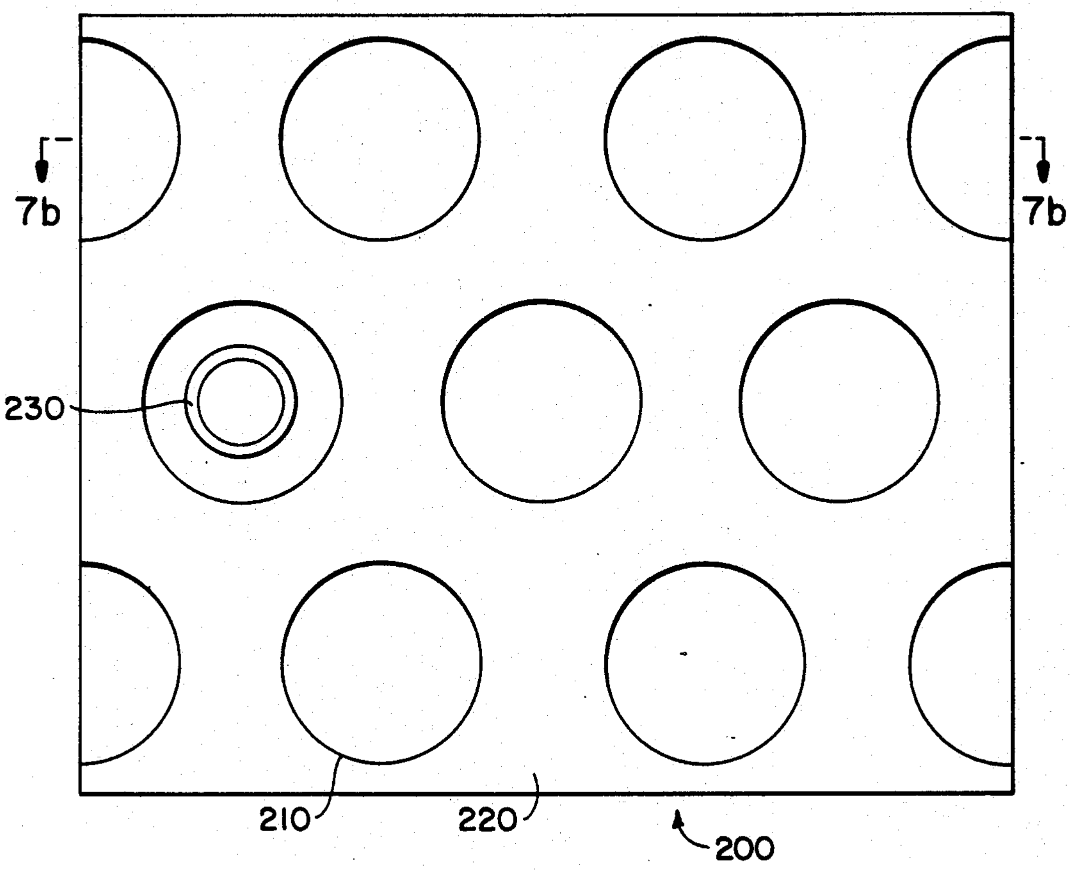

7b
7b
230
210
220
200

FIG. 7b

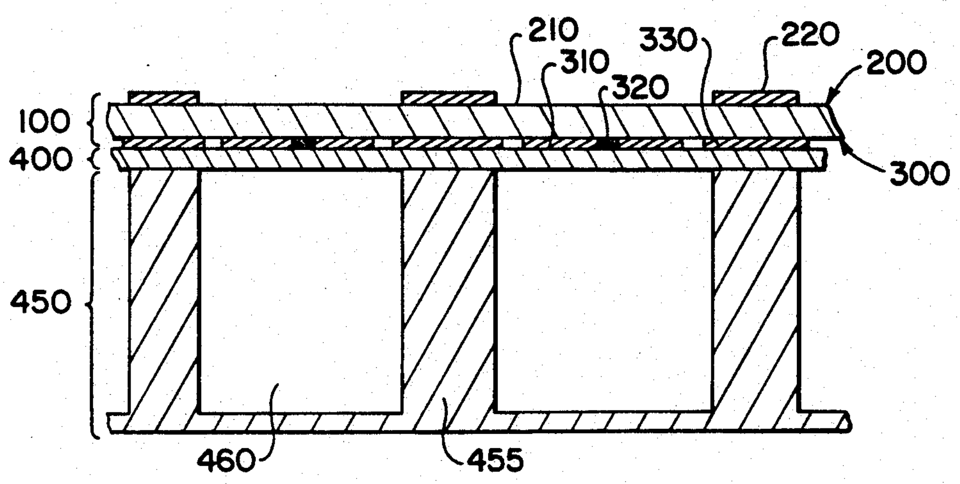

210
310
330
320
220
200
100
400
300
450
460
455

FIG. 7c

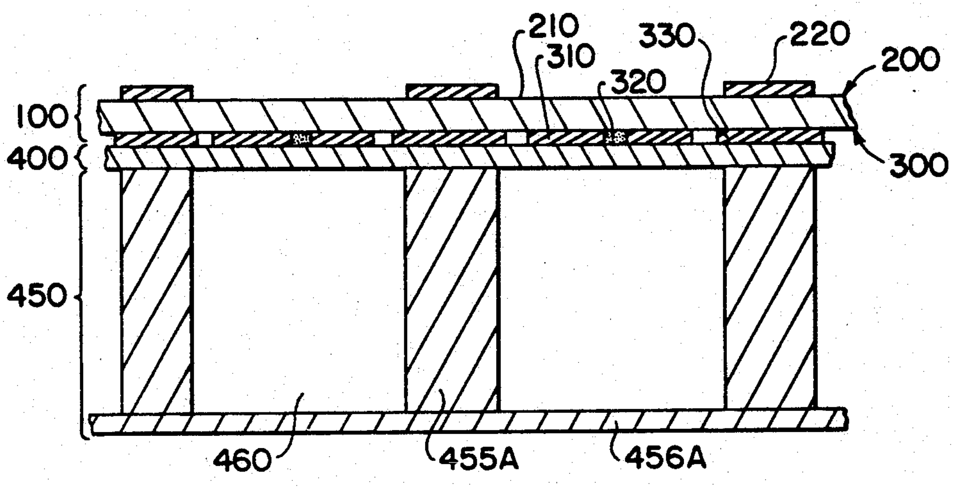


FIG. 7d

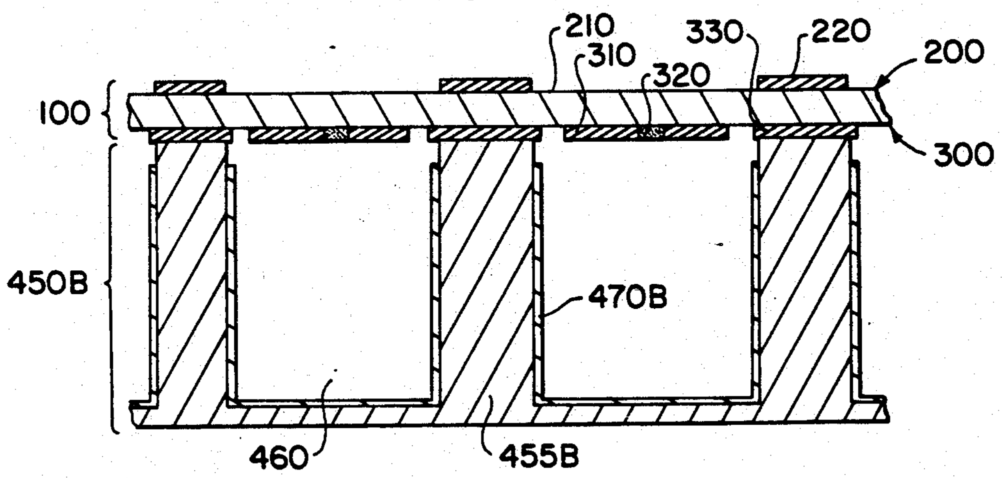


FIG. 7e

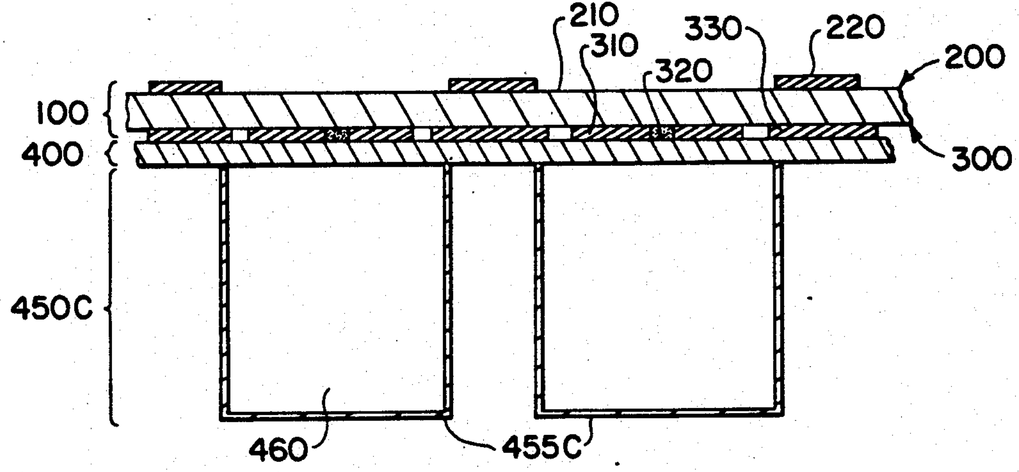


FIG. 8A

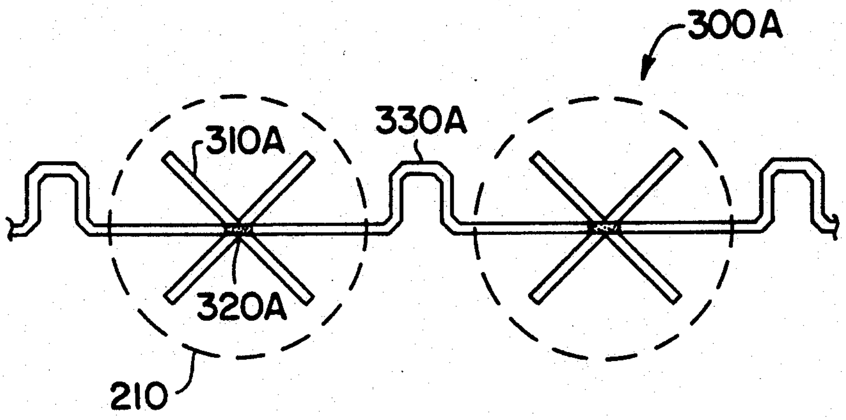


FIG. 8B

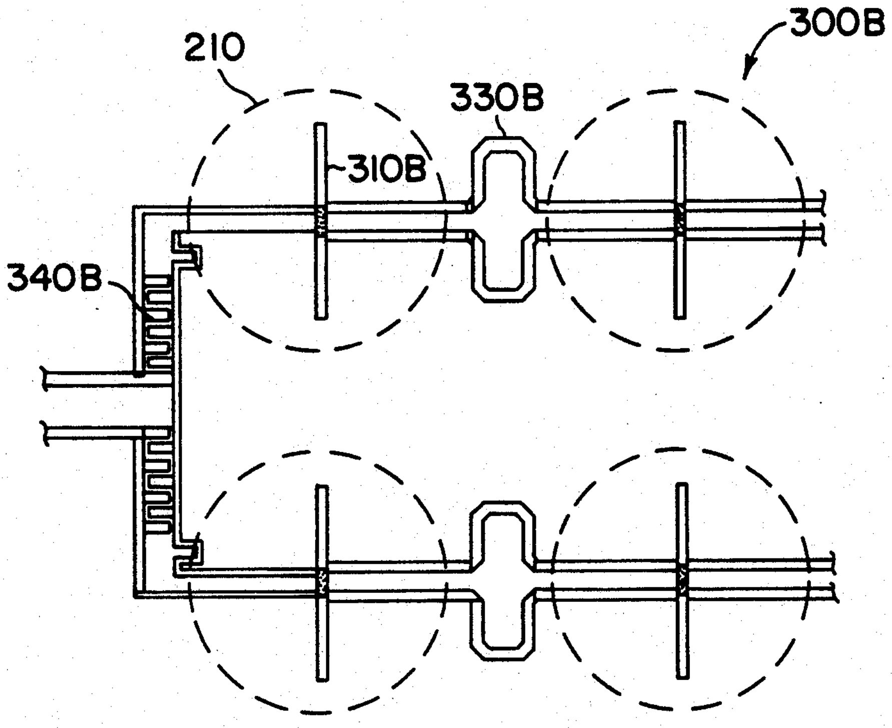


FIG. 9A

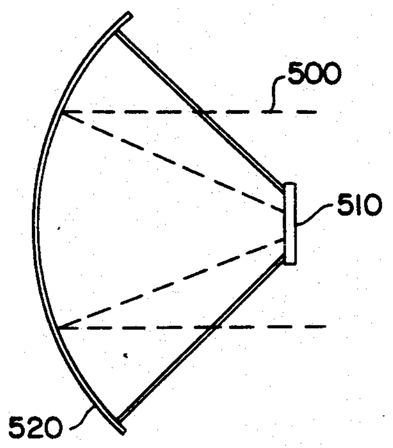


FIG. 9B

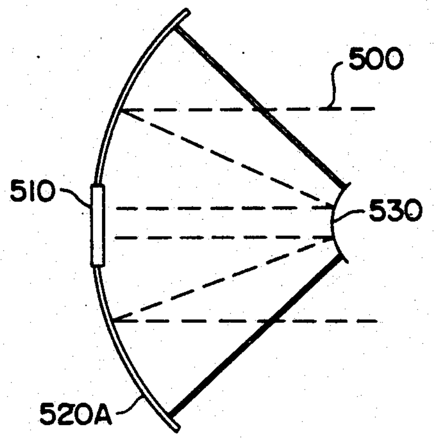


FIG. 9C

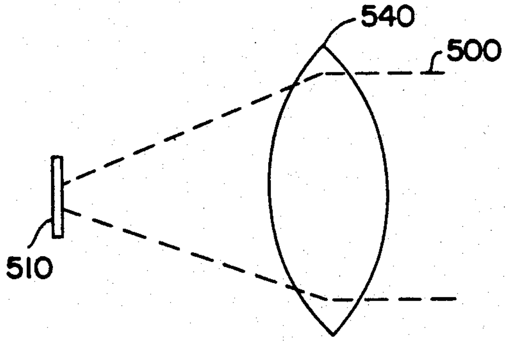


FIG. 9D

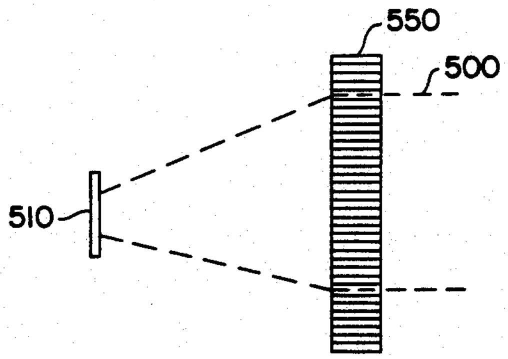


FIG. 10

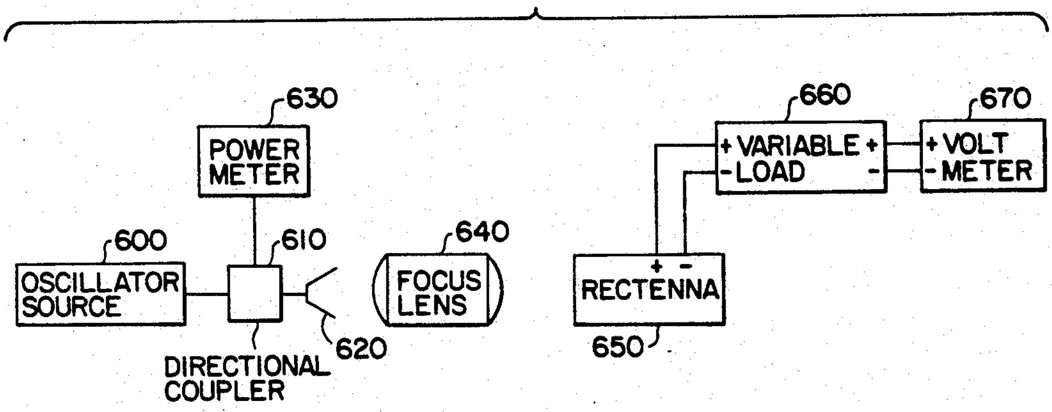


FIG. 11a

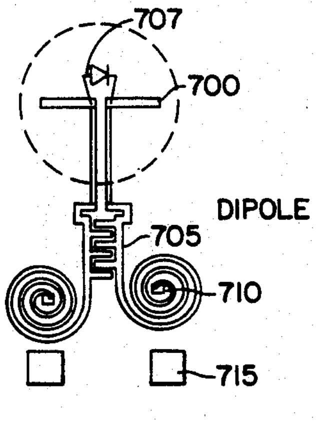


FIG. 11b

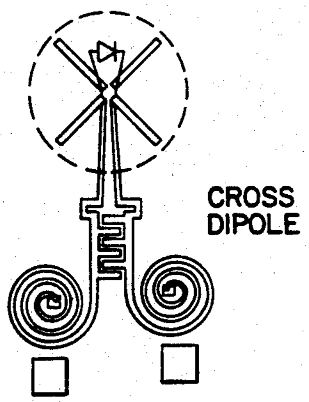


FIG. 11c

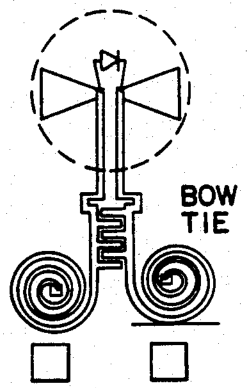


FIG. 11d

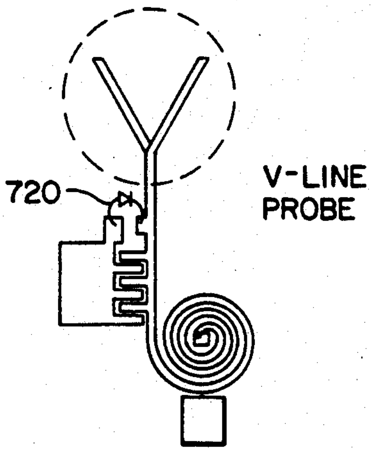


FIG. 11e

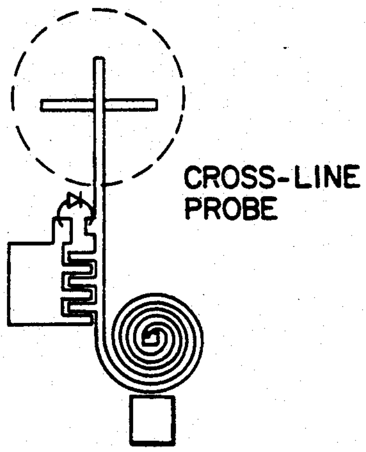


FIG. 11f

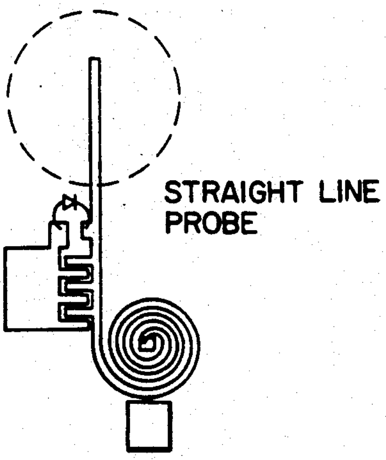
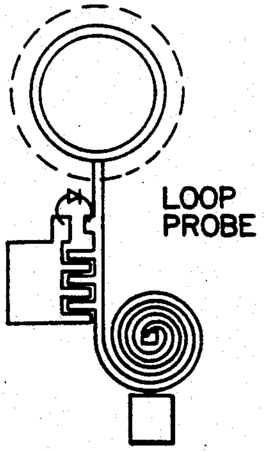


FIG. 11g



POWER BEAMING SYSTEM WITH PRINTER CIRCUIT RADIATING ELEMENTS HAVING RESONATING CAVITIES

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part of U.S. Ser. No. 07/239,284 now U.S. Pat. No. 5,068,669 entitled "Power Beaming System" by Koert et al., filed Sep. 1, 1988, and claims priority therefrom.

BACKGROUND OF THE INVENTION

The present invention relates in general to the transfer of energy by means of electromagnetic waves to power a remote device. More specifically, the present invention relates to a system for "power beaming" energy from a source at high frequencies and rectifying such energy to provide a source of DC energy to a remote device.

Attempts have been made for many years to develop a system for beaming energy from a source to power a remote device with a high degree of efficiency (for a general discussion see "The History of Power Transmission by Radio Waves" by William C. Brown, IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-32, No. 9, September 1984). In particular, the concept of powering a satellite or free flying aircraft by power beaming has received a great deal of attention. The advantagès of such a system are readily apparent, for example, an aircraft could be maintained on station indefinitely to act as a low cost communications or reconnaissance platform. Early concepts included the conversion of microwave energy into thermal energy to power a helicopter type platform as illustrated in U.S. Pat. No. 4,542,316 issued to Hart. A more practical approach, however, has focused on converting the microwave energy into DC energy to directly power the platform.

The practical conversion of microwave energy to DC energy for power beaming purposes has been based on the use of rectennas to receive and rectify the microwave energy. Generally, rectennas are limited in their power-handling capabilities, but can be a highly efficient means of converting microwave energy into DC energy for power beaming purposes when employed in large numbers in an array structure. U.S. Pat. No. 3,434,678 issued to Brown et al. illustrates the use of a rectenna array to power a helicopter platform by power beaming.

More recently, a scale model of a long endurance high altitude platform powered by microwave energy known as SHARP (Stationary High Altitude Relay Platform) has been successfully demonstrated. See "A Microwave Powered High Altitude Platform" by Schlesak et al., 1988 IEEE MTT-S Digest, pp. 283-286. The SHARP concept calls for an array of ground antennas which must be focused on the aircraft. The underside of the aircraft would be coated with a thin-film array of thousands of half-wave dipole rectennas to convert the received microwave energy into DC energy which would be used to power the aircraft's electrical motor.

The scale model of the SHARP aircraft was powered by a microwave beam formed form the outputs of two 5 kW continuous-wave magnetrons, which were combined and supplied to a 4.5 meter diameter parabolic antenna to transmit 10 kilowatts of energy at a frequency of 2.45 GHz. Dual polarization rectennas formed of two orthogonal linearly-polarized rectenna arrays were provided on the model aircraft to convert the microwave energy to DC power.

Efforts at power beaming to date, like SHARP discussed above, have focused primarily on using S-band transmission sources due to their ready availability and to reduce power losses due to atmospheric attenuation. S-band power beaming, however, is limited in the amount of power that can be delivered in a practical system. In order to generate sufficient power densities, a large array of ground antennas must be employed which complicates the problem of concentrating the transmitted energy on the aircraft. One could reduce the number of ground antennas employed in the array, but the size of the antennas would increase significantly making them as difficult to track as the array while greatly increasing their expense. In addition, S-band power beaming requires a large amount of surface area for the rectenna array on the aircraft to generate significant power quantities. For example, the SHARP system discussed above would need an array of 100 m^2 of rectenna surface of generate only 35 kW of DC power, 25 kW of which is required to power the propulsion system, wile requiring a transmitter having a diameter of 85 meters with an output of 500 kW.

SUMMARY OF THE INVENTION

The present invention departs from the prior art by providing a power beaming system that operates at a much higher frequency, on the order of tens of GHz or greater, to thereby provide a system having a power density an order in magnitude greater than conventional power beaming systems while at the same time having the advantage of a smaller transmission source and rectenna array.

More specifically, the present invention provides a power beaming system including a power transmission source capable of generating electromagnetic radiation having a preferred frequency of at least 10 Gigahertz, a transmission antenna mounted on a movable pedestal, a guide unit that guides the electromagnetic radiation generated by the power transmission source to the transmission antenna and a rectenna array located at a position remote from the antenna structure.

BRIEF DESCRIPTION OF THE DRAWINGS

A preferred exemplary embodiment will hereinafter be described in conjunction with the appended drawings wherein like designations denote like elements, and wherein:

FIG. 1 is an overall system diagram of a power beaming system according to the present invention;

FIG. 2 is a graph illustrating atmospheric attenuation of electromagnetic waves at various frequencies;

FIG. 3*a* illustrates a planar rectenna structure that may be incorporated in the system illustrated in FIG. 1;

FIG. 3*b* is a circuit diagram of the planar rectenna array shown in FIG. 3*a;*

FIG. 4*a* illustrates a second planar rectenna structure that may be incorporated in the system illustrated, in FIG. 1;

FIG. 4*b* is a circuit diagram of the planar rectenna illustrated in FIG. 4*a;*

FIGS. 5*a* and 5*b* illustrate top and bottom surfaces, respectively, of a multi-layer rectenna structure that may be incorporated in the system illustrated in FIG. 1;

FIGS. **6** illustrates various components of a power combining network;

FIG. **7A** is a top view of third rectenna structure that can be incorporated in the system illustrated in FIG. **1**;

FIG. **7B** is a cut away view of the rectenna structure illustrated in FIG. 7A;

FIG. **7C** is an alternative configuration for FIG. **7B** with the cavity substrate divided into two parts for ease of fabrication;

FIG. **7D** is an alternative configuration for FIG. **7B** with the resonating cavity structure extended to eliminate the insulating layer;

FIG. **7E** is an alternative configuration for FIG. **7B** used for ease of manufacturing at low frequencies;

FIG. **8A** illustrates an antenna structure that can be employed in the rectenna illustrated in FIG. **7A** which uses cross dipole antennas to receive circularly polarized RF energy;

FIG. **8B** illustrates another antenna structure that can be employed in the rectenna illustrated in FIG. **7A** which uses single dipole antennas to receive linearly polarized RF energy;

FIG. **9A** shows use of a parabolic reflector to focus incident RF energy onto a rectenna;

FIG. **9B** shows a cassegrain combination of a parabolic reflector and a subreflector to focus incident RF energy onto a rectenna;

FIG. **9C** shows the use of a focusing lens to refract incident RF energy onto a rectenna;

FIG. **9D** shows a waveguide phasing array consisting of multiple waveguides with various phases set to focus incident RF energy onto a rectenna;

FIG. **10** shows a test set-up for testing individual rectenna structures illustrated in FIG. **8A**;

FIG. **11A** illustrates the test configuration for a dipole antenna;

FIG. **11B** illustrates the test configuration for a cross dipole antenna;

FIG. **11C** illustrates the test configuration for a bow tie antenna;

FIG. **11D** illustrates the test configuration for a V-line probe antenna;

FIG. **11E** illustrates the test configuration for a cross-line probe antenna;

FIG. **11F** illustrates the test configuration for a straight line probe antenna;

FIG. **11G** illustrates the test configuration for a loop probe antenna.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. **1**, a power beaming system according to the present invention is illustrated having a power transmission source **10** operating at a preferred frequency of at least 10 GHz, and more preferably of at least 18 Ghz, that feeds energy to an antenna **14** via a guide unit **12**. The antenna **14** is mounted to a movable precision pedestal **8** that is controlled by a pedestal control unit **24**. The energy generated by the power transmission source **10** is focused into a beam by the antenna **14** to illuminate a preferable circular rectenna array **16** affixed to the bottom of an electrically powered aircraft **18**. The rectenna array **16** converts the energy received from the antenna **14** to DC energy which is used to directly drive the electrical motor of the aircraft **18**. The aircraft **18** in a preferred embodiment operates at an altitude of 21 kilometers.

In order to aid in tracking the antenna **14** to the movements of the aircraft **18**, a directional beacon **20** is fixed to the center of the rectenna array **16**. The directional beacon **20**, preferably operating in the X-band frequency range, emits a tracking signal that is received by a receiver **22** located on the antenna **14**. The output signal from the receiver **22** is used by a pedestal control unit **24** to control the tracking movements of the antenna **14** and insure that the energy beam generated by the system is centered on the rectenna array **16**.

As previously mentioned, one of the reasons conventional systems have been limited to S-band power beaming is to reduce power losses due to atmospheric attenuation of the transmitted beam. Generally, attenuation increases as operating frequency increases as illustrated by the chart shown in FIG. 2 (see "Radar Handbook" by M. I. Skolnik, McGraw-Hill Book Company, NY 1970, p. 24–26). At around 35 GHz., however, atmospheric attenuation drops off. Thus, a power beaming system operating in the range of about 28–44 GHz and preferably around 35 GHz, provides the advantages associated operating at higher transmission frequencies, such as the reduction in size of the ground antenna and the rectenna array while operating at higher power densities, with without experiencing an exponential growth in attenuation as frequency is increased.

In order to generate sufficient power densities at the desired frequency, one or more gyrotrons are preferably used for the power transmission source **10**. The term "gyrotron" will be used throughout this specification to generically describe microwave oscillators based on the interaction of electrons orbiting in a DC magnetic field under the conditions of cyclotron resonance where the magnitude of the DC magnetic field and the microwave frequency are specifically related. Typically gyrotrons include single-cavity oscillators wherein the entire interaction takes place in a single microwave cavity, but it will be understood that the same basic interaction can be used with varying devices, such as amplifiers using several resonant cavities, which may sometimes be referred to as gyroklystrons, gyro TWTs or even cyclotron resonance masers, and that the term gyrotron is intended to cover all such devices. A more detailed explanation of gyrotrons is provided in the paper "Introduction to Gyro Devices", VARIAN publication number 4762, 11/84, incorporated herein by reference. Gyrotrons producing power outputs between 200–300 kW at frequencies of 28 Ghz to 60 GHz are presently available, and the outputs of one or more gyrotrons can be combined to obtain desired power output levels for the power transmission source **10**. VARIAN has also demonstrated gyrotrons operating at 94 GHz, 110 GHz and 140 GHz with respective power outputs of 100 kW CW, 500 kW pulsed and 400 kW that could also be employed for the power transmission source **10**.

Gyrotrons generally produce TE_{On} modes which produce a hollow conical radiation pattern with zero power along the waveguide axis. When using a gyrotron for the power transmission source **10**, however, it is desirable to perform a mode conversion operation in order to generate a narrow beam with a well-defined polarization. Accordingly, the guide unit **12** is constructed to perform the desired mode conversion. Mode converter assemblies for use in the guide unit **12** may be constructed out of waveguide assemblies as illustrated in the paper entitled, "Very High Power mm-Wave Components in Oversized Waveguides" by Thumm et al., Microwave Journal, November 1986, incorporated herein by reference, to produce a beam having the desired characteristics. Alternatively, beam waveguides could be employed for the guide unit **12** as described in the article entitled "Some Aspects of Beam Waveguide Design" by Chan et al., IEEE Proceedings, Vol. 129, Pt H, No. 4, August 1982, incorporated herein by reference.

Referring now to FIG. 3*a*, a planar rectenna **26** that may be employed in the rectenna array of the present system is shown having a patch antenna **30** which acts as a ½ wave resonator, an impedance matching filter **32**, coupled to the patch antenna **30** by a blocking capacitance **31**, for matching the impedance of the patch antenna **30** to a diode **34** (for example, ALPHA DMK6606), and an output filter **36**.

The impedance matching filter **32** and output filter **36** of the planar rectenna **26** are formed using microstrip circuitry techniques on a dielectric substrate **38** (for example RT-DUROID manufactured by Rogers Corporation, dielectric constant 2.2) of the planar rectenna **26**. Microstrip circuitry provides a simple and economical method of providing the circuit elements of the impedance matching filter **32** and output filter **36** in a compact structure, and permits the diode **34** to be located as close as possible to the patch antenna thereby avoiding losses due to lengthy interconnect lines. For example, the components of the impedance matching circuit **32** and the output filter **36** are formed by conventional copper etching techniques on a top surface of the dielectric substrate **38**. A ground pad **40** is also provided to provide electrical connection via plated through holes to a ground plane (not shown) provided beneath the dielectric substrate **38**.

The patch antenna **30** provides the advantage of dual polarization in a very simple structure without necessitating the overlapping of two linearly-polarized antenna layers. Other antenna structures may be employed; however, an antenna which is independent of the polarization of the incoming electromagnetic radiation is preferred.

A circuit diagram of the planar rectenna **26** is provided in FIG. 3*b*. Configurations and circuit arrangements other than those illustrated in FIGS. 3*a* and 3*b* are of course possible. For example, a second planar rectenna structure is illustrated in FIG. 4*a* which does not utilize an impedance matching filter. The circuit diagram for this planar rectenna structure is shown in FIG. 4*b*. The impedance matching filter is desirable, however, to optimize the output of the rectenna.

While the above described rectenna structure has been demonstrated to operate effectively in the frequency range of interest, it has a disadvantage in that the impedance matching and output filters take up a large percentage of the surface area of the substrate which limits the power conversion efficiency of the rectenna array. In other words, the rectenna array provides maximum efficiency when the maximum number of antennas can be provided on the surface area of the array. This problem can be addressed by providing a multi-layer rectenna structure, as opposed to the planar rectenna illustrated in FIG. 3*a*, in which the antenna is located on the surface of the substrate and the circuit elements, i.e., the impedance matching and output filters and the diode, are located in a separate layer beneath the antenna to provide a compact structure.

Referring now to FIG. 5*a*, a top surface **41** of a rectenna array **43** incorporating multi-layer rectennas is shown having a first substrate **42** on which a patch antenna **30'** of each multi-layer rectenna is provided, a copper ground plane **44**, and a second substrate **46** on which the circuit elements, i.e., the impedance matching filter **32'**, diode **34'** and output filter **36'**, are provided as shown in FIG. 5*b*. The patch antennas **30'** are coupled to the impedance matching filter **32'** on the bottom surface **45** of the rectenna array **43** via plated-through holes **47**. Thus, the patch antennas **30'** may be readily spaced in the rectenna array (in this case ½ wavelength center to center) to provide maximum power conversion efficiency while maintaining a rectenna structure that may be easily fabricated using multi-layer circuit board fabrication techniques. It will be readily understood that in an array structure one output filter may be provided for a plurality of rectennas instead of providing each rectenna with its own output filter, and that the circuit elements may be provided on the inside surface of the substrate **46** if an insulating layer is positioned between the circuit elements and the ground plane **44**.

It is of course necessary to combine the outputs from each of the individual rectennas in the array **43** to provide useful voltage and current levels. FIG. 6 illustrates a power combining network which can be used to match the voltage and current output of the rectenna array to any desired load. In addition, the power combining network prevents the failure of one or more rectennas from seriously effecting the output of the entire array by providing a plurality of current and voltage summing elements.

As shown in FIG. 6, a current summing element **50** is formed by combining the output of several individual rectennas **49** in parallel. The resistance R_t represents the resistance associated with the interconnect lines between the individual rectennas. Discrete resistors R_{sl}, having a value much greater than R_t, couple the rectennas to a diode D_{dc}. The current summing elements may then be combined in series to form a voltage summing element **52**. Individual voltage summing elements **52** can then be combined to form additional current summing elements **54**. Switching elements **56** are also provided so that the various current and voltage summing elements can be combined in any desired pattern to match the voltage and current requirements of the load.

A third type of rectenna array is illustrated in FIGS. 7A–7B. This alternative rectenna array offers the advantages of lower conductor loss due to placement of the diode in close proximity to the antenna, reduced weight, and simplicity of eliminating feedthrough links between layers. The illustrated rectenna structure is readily adaptable from 1 GHz to 300 GHz or more depending on the dimensions of the components.

Referring to FIG. 7B, the rectenna array is composed of multiple rectenna elements which include a top layer **100** (for example RT/Duroid 5880), an insulating layer **400**, and a resonating cavity structure **450**. The top layer **100** contains a top surface **200** and a bottom surface **300** on which a conductive coating, such as a metal film is deposited. The conductive coating, or metal film **220** deposited on the top surface **200** has a hole **210** (preferably formed by etching) which permits radiation to pass to an antenna **310** formed from the conductive coating or metal film deposited on the bottom surface **300**. Deposited on the antenna **310** is a diode **320** that converts RF energy directly into DC energy. Connected to the antenna **310** is a feed line **300** which also forms a DC bus and low pass filters (also formed from the conductive coating deposited on the bottom surface **300**).

The resonating cavity structure **450** includes a substrate **455** containing holes, or resonator cavities **460** formed therein. The cavity substrate **455** can be formed either from a solid conductive material, such as aluminum, in which the resonator cavities **460** are drilled as shown in FIG. 7B, or from a light weight conductive coated material, such as a metal coated foam, in which the resonator cavities **460** are drilled or molded. The insulating layer **400** is provided between the resonating cavity structure **450** and the feed lines **330** to prevent grounding.

FIGS. 7C through 7E illustrate alternate configurations for the rectenna array shown in FIG. 7B. FIG. 7C shows the cavity substrate **455** of FIG. 7B separated into two layers, a cavity substrate top **455A** and a cavity substrate bottom **456A**. Using two layers makes fabrication simpler since drilling holes to precise depths and shapes is more difficult than drilling completely through the cavity substrate top **455A** and attaching a separate cavity substrate bottom **456A**. FIG. 7D shows a method of eliminating the insulating layer **400** from FIG. 7B. In FIG. 7D, the resonating cavity structure **450** of FIG. 7B. is replaced with an extended resonating cavity structure **450B**. The extended resonating cavity structure **450B** has an extended cavity substrate **455B** made of a lightweight material with a conductive coating **470B** deposited, but the conductive coating **470B** does not extend quite to the top of the resonator cavity **460**. Since the metal does not extend to the top of the resonator cavity **460**, circuitry on top layer **100** will not be grounded out. In FIG. 7E, the resonating cavity structure **450** of FIG. 7B is replaced with a low frequency resonating cavity structure **450C**. The low frequency resonating cavity structure **450C** includes individual canisters **455C** instead of a single cavity substrate **455** shown in FIG. 7B. The individual canisters make manufacturing easier at low frequencies since sizes are substantially increased.

The holes **210** in the conductive coating **220** are illustrated in FIG. 7A. A tuning or resonate element **230** can be formed within the hole **210** if desired, in order to more efficiently couple the incoming RF energy into the antenna **310** located beneath the hole **210** to increase the gain of the rectenna element. The tuning or resonate element **230** can be formed as a ring as shown in FIG. 7A or it may take the shape of a bar or series of dots. The tuning or resonate element **230** is a metal film and is formed by etching the top surface **200** with holes as described on page 13.

FIGS. 8A and 8B show various configurations of the antennas **310** formed on the bottom surface **300** of the top layer **100**. In FIG. 8A, the antenna **310** is composed of a cross dipole antenna **310A** which is used to receive incident circularly polarized RF energy. A diode **320A** (for example Alpha DMK 2606 Schottky diode) is deposited on the dipoles **310A** to directly convert RF to DC energy. Line **330A** is a varying impedance line to form both a feed line serving as a DC bus and low pass filter. FIG. 8B illustrates a second configuration that uses a single dipole antenna **310B** to receive incident linearly polarized RF energy. In this embodiment, feed lines **330B** serve only as a DC bus which channels RF energy to a central low pass filter unit **340B**.

FIGS. 9A through 9D show methods to distribute incident RF energy **500** to the rectenna array **510**. These methods offer the advantage of keeping the incident power level at the antenna constant and optimize performance of the rectenna array at various power levels.

FIG. 9A shows use of a parabolic reflector **520** to focus incident RF energy **500** onto rectenna array **510**. FIG. 9B shows a cassegrain combination with a parabolic reflector **520A** and subreflector **530** to focus incident RF energy **500** onto rectenna array **510**. FIG. 9C shows use of a focusing lens **540** to refract incident RF energy **500** onto rectenna array **510**. Finally, FIG. 9D shows a waveguide phasing array **550** consisting of multiple waveguides with various phases set to focus incident RF energy **500** onto rectenna array **510**.

Single rectenna elements of type illustrated in FIGS. 8A and 8B have been tested using a test set-up illustrated in FIG. 10. The test set-up includes an RF source **600** (Millitech GDM Dual Gun Oscillator) operating at a frequency of 35 GHz at 500 mW, that is coupled to a horn **620** via a directional coupler **610**. The directional coupler **610** is also connected to a power meter **630** in order to monitor the power output of the source **600**. The horn **620** directs the generated RF energy to a spot focusing lens **640** (Millitech GOA 6-inch) which in turn focuses the RF energy on the rectenna array **650** to be tested. The rectenna array **650** is located from the spot focusing lens antenna at a distance equal to the diameter of the spot focusing lens **640**. A variable load box **660** is connected to the output of the rectenna array **650** in order to optimize the rectenna array efficiency. A voltage meter **670** is coupled to the output of the variable load box.

Rectenna array elements of the type illustrated in FIG. 8B have been tested in various configurations. FIGS. 11A–11G show the different antenna elements tested, and the test configuration used. Referring to FIG. 11A the test configuration of a dipole antenna also described in FIG. 8B is shown. The dipole **700** is connected to a low pass filter and DC bus configuration **705**. Diode **707** is connected to the antenna. A spiral center contact **710** on the low pass filter **705** is used to wire bond to DC contact **715** so that electrical testing can be performed. A cross dipole test configuration is shown in FIG. 11B, and a Bow Tie in FIG. 11C. FIG. 11D shows a V-line probe, FIG. 11E a cross-line probe, FIG. 11F a straight line probe, and FIG. 11G a loop probe. Note the diode in the structures 11D through 11G as illustrated are connected ½ wavelength from the antenna center.

Rectenna elements shown in FIGS. 11A–11G were tested using various loads, cavity diameters, and cavity heights. Table 1 shows the test results of the various test configurations. The illustrated results are not indicative of relative efficiencies as the test configurations have not been optimized.

It will be readily understood that variations and modifications may be made within the spirit and scope of the invention as expressed in the appended claims, and that the invention is not limited to the specific forms illustrated above. For example, monolithic microwave integrated circuit (MMIC) technology can be used to fabricate top layer **100** and insulating layer **100**. The top layer **400** could consist of gallium arsenide with conductive coating **220** deposited on one side, and the diodes, **320**, antennas **310**, and feed lines **330** deposited on the other. Insulating layer **400** would be the final deposited material. The resonating cavity structure **450** could be included using either monolithic technology, or bonded to the surface of the insulating layer **400** to create a hybrid microwave integrated circuit (HMIC).

TABLE 1

RECTENNA TYPE	LOAD (OHMS)	CAVITY DIAMETER (IN)	CAVITY HEIGHT (IN)	P_{out} (mW)
DIPOLE	50	1/6	¼	28.0
DIPOLE WITH FOCUS ELEMENT	50	¼	⅛	13.0
DIPOLE	185	¼	⅛	17.5
DIPOLE	150	3/16	⅛	16.2
DIPOLE	150	7/32	⅛	14.0
DIPOLE	150	¼	⅛	12.7
DIPOLE	150	½	⅛	1.7
CROSS DIPOLE	100	¼	¼	40.0
BOW TIE	50	¼	⅛	24.0
V-LINE PROBE	50	¼	¼	3.5
CROSS-LINE PROBE	50	¼	¼	0.3
STRAIGHT-LINE PROBE	50	¼	¼	3.0
LOOP PROBE	50	¼	¼	28.8
LOOP PROBE	50	7/32	¼	20.0

What is claimed is:

1. A rectenna array including at least one rectenna structure, comprising:

a.) a top layer containing a top and bottom surface on which conductive coating is deposited, said bottom surface conductive coating being deposited to form an antenna, and said top surface conductive coating being formed to include a hole to allow RF energy to pass to said antenna;

b.) a diode connected to said antenna; and

c.) a resonating cavity structure containing at least one resonating cavity, wherein said resonating cavity structure is located adjacent said bottom surface and said resonating cavity is aligned with said hole in said top surface.

2. A rectenna array as claimed in claim **1**, wherein said resonating cavity structure comprises a cavity substrate made of a conductive material.

3. A rectenna array as claimed in claim **1**, wherein said resonating cavity structure comprises a cavity substrate having said resonating cavity formed therein, and a conductive coating applied over substantially the entire surface of said resonating cavity.

4. A rectenna array as claimed in claim **1**, wherein said resonating cavity structure comprises a cavity substrate top connected to a cavity substrate bottom.

5. A rectenna array as claimed in claim **1**, wherein an insulating layer is provided between said top layer and said resonating cavity structure.

6. A rectenna array as claimed in claim **1**, wherein said resonating cavity structure comprises a resonating canister attached to said top layer.

7. A rectenna array as claimed in claim **1**, wherein said antenna comprises a single dipole to receive linearly polarized RF energy.

8. A rectenna array as claimed in claim **1**, wherein said antenna comprises a cross dipole to receive circularly polarized RF energy.

9. A rectenna array as claimed in claim **1**, wherein said antenna comprises a bow tie antenna.

10. A rectenna array as claimed in claim **1**, wherein said antenna comprises a V-line probe.

11. A rectenna array as claimed in claim **1**, wherein said antenna comprises a cross-line probe.

12. A rectenna array as claimed in claim **1**, wherein said antenna comprises a straight line probe.

13. A rectenna array as claimed in claim **1**, wherein said antenna comprises a loop probe.

14. A rectenna array including at least one rectenna structure, comprising:

a) a top layer containing a top and bottom surface on which conductive coating is deposited, said bottom surface conductive coating being deposited to form an antenna, and said top surface conductive coating being formed to include a hole to allow RF energy to pass to said antenna;

b) a diode connected to said antenna; and

c) a resonating cavity structure containing at least one resonating cavity, wherein said resonating cavity structure is located adjacent said bottom surface and said resonating cavity is aligned with said hole in said top surface, and

wherein said top layer includes a focus element formed within said hole.

15. A rectenna array as claimed in claim **14**, wherein a feed line connected to the antenna forms a low pass filter and DC bus.

16. A rectenna array including at least one rectenna structure, comprising:

a) a top layer containing a top and bottom surface on which conductive coating is deposited, said bottom surface conductive coating being deposited to form an antenna, and said top surface conductive coating being formed to include a hole to allow RF energy to pass to said antenna;

b) a diode connected to said antenna; and

c) a resonating cavity structure containing at least one resonating cavity, wherein said resonating cavity structure is located adjacent said bottom surface and said resonating cavity is aligned with said hole in said top surface, and wherein said resonating cavity structure further comprises a resonating canister attached to said top layer, said canister having no surrounding lower substrate.

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