May 20, 1969 C. B. CRUMLY 3,445,748

MICROWAVE POWER RECTIFIERS

Filed March 16, 1967

FIG. 1

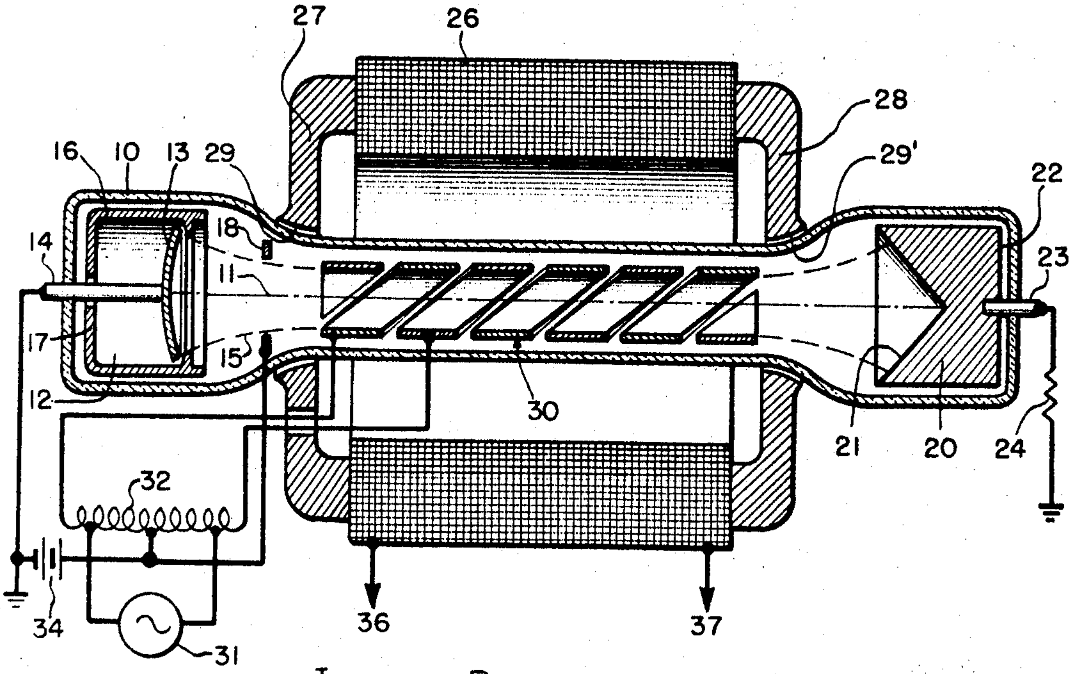


FIG. 2

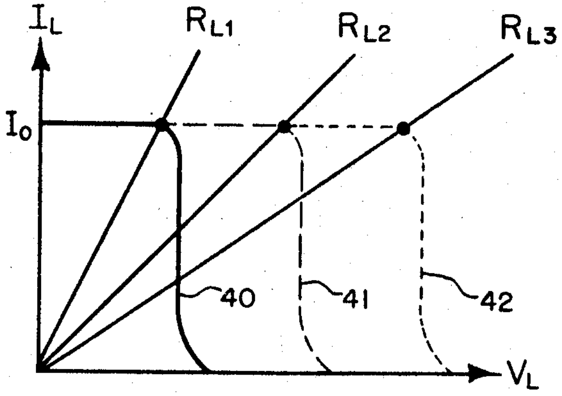
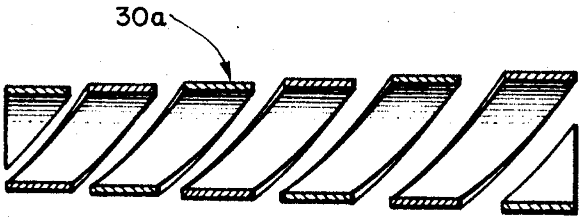


FIG. 3



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MICROWAVE POWER RECTIFIERS

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U.S. Cl. 321—8 12 Claims

ABSTRACT OF THE DISCLOSURE

Microwave energy fed to a bi-filar helix coupler is transferred thereby to an electron beam in the form of a positive synchronous wave. The modulated beam is then received by a depressed collector to which a load is connected. The apparatus functions as a rectifier of microwave power.

Introduction

The present application relates to power rectifiers. More particularly, it pertains to apparatus for receiving and rectifying high-power microwave energy.

Various proposals have been advanced for delivering large quantities of power from a source to a load by means of microwave transmission. For example, where it is necessary to deliver power to a moving element of a machine or the like it may be difficult or impossible to use fixed connectors and the nature of the apparatus may be such as to preclude the use of such conventional expedients as slip rings or commutators together with brushes.

In a more exotic example, it has been proposed to transmit power to satellites, space vehicles and aircraft such as helicopters in the form of a concentrated beam of microwave energy. While numerous devices are known for generating, radiating and receiving high-power microwaves, great difficulty is encountered at the receiving end in converting the received energy to a form convenient for use in energizing the ultimately driven equipment. Typically, the received microwave energy must be converted to direct current. In communication systems where the received power level need be only of the order of microwatts, or at most milliwatts, little difficulty is encountered with systems for rectifying intelligence signal information. However, when the microwave power levels involved are in terms of kilowatts, for example, conventional rectification techniques often become unwieldly or completely unusable because of their comparatively poor efficiencies and consequent power dissipation in the form of heat.

It is, therefore, a general object of the present invention to provide a microwave power rectifier overcoming the aforenoted disadvantages of prior rectifier apparatus.

Another object of the present invention is to provide a microwave power rectifier characterized by simplicity of operation while capable of obtaining a high level of efficiency.

A further object of the present invention is to provide a microwave power rectifier of a kind enabling substantial freedom of design and consequent flexibility of application.

A microwave power rectifier constructed in accordance with the present invention includes means for developing and projecting a beam of electrons along a predetermined path together with means for creating a magnetic field directed along that path and having a strength establishing a condition of cyclotron resonance for the electrons at a predetermined frequency. An electron coupler is disposed along the path and is responsive to signals from a

source of microwave energy for selectively interacting only with the positive synchronous wave on the beam. Disposed across the beam path downstream of the coupler are means for collecting the electrons. Finally, a load is coupled to the collecting means.

The features of the present invention which are believed to be novel are set forth with particularity in the appended claims. The organization and manner of operation of the invention, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawing, in the several figures of which like reference numerals identify like elements and in which:

FIGURE 1 is a diagramatic cross-sectional view of one embodiment of a microwave power rectifier;

FIGURE 2 is a plot of load current against load voltage and is useful in explaining the characteristics of the device of FIGURE 1; and

FIGURE 3 is a diagrammatic cross-sectional view of a modification of an element included in the device of FIGURE 1.

The device illustrated in FIGURE 1 includes an elongated evacuated envelope **10** having an axis of symmetry **11**. For developing and projecting a beam of electrons along a path generally coincident with axis **11**, an electron gun **12** is disposed in one large end portion of envelope **10**. Electron gun **12** includes as its primary element a cathode **13** connected by a terminal post **14**, projecting through the end wall of envelope **10**, to a plane of reference potential here shown as ground. The electron gun also includes a heating element for the cathode but, being strictly conventional, it has been omitted from the drawing.

The developed stream of electrons preferably is caused to converge toward axis **11** in the downstream direction. While numerous beam-converging electron guns are known to the art, as here illustrated such convergence is initiated by forming cathode **13** in the shape of a partial section of a sphere so that in operation the electron stream **15** tends naturally to converge as it departs from cathode **13**. Cathode **13** preferably is disposed inside the open end of a cylindrical heat shield **16** closed across its end behind the cathode by a wall **17** having an aperture through which terminal post **14** projects. Completing the electron gun assembly is an annular anode or accelerating electrode **18** disposed downstream from cathode **13**.

Disposed across the electron path in the opposite enlarged end portion of envelope **10** is a depressed collector **20** for collecting the electrons at the end of their travel. As shown herein, collector **20** is in the form of a generally cylindrical anode having its surface facing the oncoming electrons shaped in the form of an inverted cone **21**. Projecting from the opposite surface **22** of cone **20** and through envelope **10** is a terminal post **23** connected to ground through a load resistor **24** so that the load is coupled to the collector.

In order to confine the electron beam during its passage from the cathode to the collector and also to establish for the electrons a condition of cyclotron resonance, a magnetic field is created and directed along the beam path. While this magnetic field may be created by a single, properly-shaped or contoured electromagnetic solenoid encircling envelope **10** along its intermediate region or by a suitably shaped permanent-magnet structure, as shown in FIGURE 1 it takes the form of a cylindrical solenoid supported between pole-defining flux-conducting end caps **27** and **28**. End caps **27, 28** are annular in form, having peripheral portions abutting the respective end faces of solenoid **26** and defining respective inner surfaces **29** and **29'** serving as pole faces and shaped to lie closely adjacent to the external surface of envelope **10**.

One of the circular pole faces thus is disposed just downstream from cathode **13** and the other is just upstream from collector **20**. In practice, end caps **27** and **28** are each split along a diameter to enable mounting.

Disposed along beam path or axis **11** between cathode **13** and collector **20** is an electron coupler **30** which responds to microwave signals from a source **31** and selectively interacts only with the positive synchronous wave on the electron beam. Source **31** typically is a receiving antenna. To the end of very efficiently delivering energy only to positive synchronous wave motion of the electrons, coupler **30** is typically in the form of a bifilar helix wound coaxially around beam path **11** and occupying the intermediate region between the electron gun and the collector regions. As such, couple **30** is described and claimed in Robert Adler Patent No. 3,296,543, issued Jan. 3, 1967 and assigned to the same assignee as the present application. The two helical windings of the bifilar coupler are in this case coupled across a coil **32** with source **31** being in turn coupled across balanced points on coil **32** selected to match the impedance of coupler **30** to source **31**.

In order to cause the electrons to travel from cathode **13** to collector **20**, both windings of coupler **30** are biased at a positive potential relative to ground. To maintain a more uniform positive potential along substantially the entire beam path, envelope **10** may be formed of or coated with a conductive material biased to a positive potential. As illustrated, a positive potential source **34** is connected between ground and anode **18** and also is electrically connected to a center tap on coil **32**.

The positive potential established throughout the intermediate region of the device causes the electrons to flow from cathode **13** to collector **20**. The longitudinal magnetic field created by solenoid **26** tends to confine the electrons into a narrow beam throughout their travel. Moreover, pole face **29** adjacent to cathode **13** tapers inwardly in the downstream direction so as to create a magnetic field pattern which supplements the cylindrical shape of the cathode in causing the electrons to be converged from the large surface area of the cathode into the more narrow beam entering coupler **30**. Similarly at the other end of the device, pole face **29′** tapers outwardly in the downstream direction so as to create a magnetic flux distribution in that region which permits the electron beam to expand or diverge prior to impinging upon collector **20**.

Of course, the strength of the magnetic field created by solenoid **26** is adjusted by selecting the value of direct current conducted through the windings of the solenoid; for this purpose, a direct current source (not shown) is coupled across solenoid terminals **36**, **37**. As indicated earlier, the strength of the magnetic field establishes a condition of cyclotron resonance for the electrons in the beam. The application of signal energy in the form of a transverse electric field causes the electrons to arrange themselves on helical loci or orbits having a periodicity determined by the strength of the magnetic field developed by solenoid **26** in accordance with the well understood cyclotron relationship; the cyclotron frequency f_c in megacycles is equal to 2.8 H, where H is the strength of the field in gauss. The number n_c of cyclotron orbits per unit length is expressed by the relationship

$$n_c = f_c/u \qquad (1)$$

where u is the average electron velocity in the axial direction.

An electron beam so formed and traveling through the longitudinal magnetic field is capable of several different modes of electron motion, one of which is termed the positive synchronous wave. Such a beam sometimes is described as exhibiting the positive synchronous wave and signal-energy created fields on an appropriate electron coupler are said to interact with or couple to that positive synchronous wave. Stated another way and applied specifically, coupler **30** serves as an input element and the signals from source **31** applied to coupler **30** create electric fields transverse to the beam path. These fields in this case initiate the development of a positive syncronous wave and cause its amplitude to grow along the length of the coupler. As so modulated, the beam assumes a helical shape and there is no overall rotation of the beam. The signal fields developed by the coupler, in this positive-synchronous-wave mode, cause pure transverse motion of the beam; all electrons in the beam move axially at the same velocity.

To the end of achieving such interaction only with the positive synchronous wave, couple **30** is circularly polarized by cause it to have a twist in the same direction as the direction of twist of the helical electron arrangement caused by the magnetic field. The pitch of coupler **30** is assigned a value the same as that of the synchronous-wave electron-helix pitch or pattern. This relationship is expressed as

$$n = f/u \qquad (2)$$

where n is the number of coupler helix turns per unit length and f is the signal-interaction frequency (frequency of the signal from source **31**). From Equation 1, the relationship of Equation 2 may be expressed in terms of the cyclotron frequency as follows:

$$n = n_c\, f/f \qquad (3)$$

In coupler **30** as thus constructed, the electron velocity is such that a given electron passes one complete turn of the helical windings of coupler **30** for each signal cycle. The single electron effectively is under the influence of a D.C. field which causes the electron to drift at right angles to that field as well as to the axial magnetic field. Because of the circular symmetry of bifilar helix **30**, corresponding forces are exerted on all electrons and the direction in which any given electron moves depends on its phase at entry into the coupler section. Consequently, the incoming narrow beam is spread into a corkscrew of growing diameter. The corkscrew pattern has the same direction of twist as the bifilar windings of coupler **30**, and in passing through the coupler structure the electron pattern induces current in the coupler at the signal frequency. The phase of this induced current is such as to constitute a positive conductance load on the coupler. As a result, the device of FIGURE 1 constitutes a unidirectional signal energy translator in which the energy is carried on and stored by the electron beam in the form of the positive synchronous wave.

By utilizing the coupler to achieve pure monoenergetic positive synchronous wave development, the beam electrons are accelerated uniformly with a minimum of velocity spread. Axial velocity modulation at the second harmonic of the input signal is avoided by virtue of the circular polarization. Since the twist of the coupler renders it inherently circularly polarized, it discriminates against and prevents the development of the negative synchronous wave. The latter is a wave having a twist in the opposite sense and would result in a deceleration of the beam electrons with an increase in the power carried on the coupler. With the positive synchronous wave, however, interaction between the external circuit composed of the coupler structure and the synchronous wave on the beam is passive so that a complete transfer of coupler power to the synchronous wave may be accomplished with sufficient length of the coupler.

It is to be noted that the coupler operates as a so-called lumped device as opposed to the operation of a traveling-wave coupler. That is, in coupler **30** the instantaneous signal potential along either of the bifilar windings is essentially the same throughout the length of the coupler. Where in a particular tube the coupler is of sufficient length that there is significant delay between the signals at the upstream and downstream ends, lumped operation preferably is enforced by electrically shorting together opposite ends of each of the bifilar windings.

The apparatus of FIGURE 1 permits wide flexibility of design. Since the signal from source **31** may be confined to a single carrier frequency of extremely small bandwidth, coil **32** is selected to tune the inherent capacitance of the coupler to resonance at the signal frequency with the circuit exhibiting a high Q corresponding to the narrow bandwidth. Similarly, the transformation properties of coil **32** enable source **31** to be accurately impedance matched to the electron beam through coupler **30**. The magnetic field strength also is an uncritical parameter in the design of the device and thus can be somewhat freely chosen. A high magnetic field strength is desirable from the standpoint of efficiency and power handling capability for given transverse dimensions; on the other hand, low values of magnetic field are, of course, desirable from the standpoint of magnet design, magnet materials, size and weight. As indicated by Equation 3, the magnetic field strength, and hence the cyclotron frequency, may be chosen to have any of a variety of values relative to the signal frequency.

The length of coupler **30** is not determined by bandwidth consideration as is usual in the typical low-level signal amplifier utilizing such couplers, although in a given system a requisite bandwidth might be specified in order to achieve a desired transient response. In general, however, there is no criticality on the coupler length. Nevertheless, if made very short there is the possibility of interaction with cyclotron and negative-synchronous waves; these are to be avoided because of their deteriorating effect on performance. At the same time, the coupler should be sufficiently long that any transient conditions excited on the beam at its entrance into the coupler are negligible compared to the desired positive synchronous-wave amplitude at the output end of the coupler. Where undesirable transients are encountered, their amplitude may be reduced by appropriately shaping the entrance region of the coupler; that is, the first few turns may slightly decrease in diameter in the downstream direction to define an outwardly flared entryway so that the signal field from the coupler is applied to the beam with gradually increasing strength in the downstream direction.

At the operating frequency, coupler **30** presents a matched termination to the signal source which is independent of power level. As a result, substantially all incident power is absorbed into the beam where it is manifested in an increased kinetic energy of the electrons. That is, the input microwave energy is stored in the electron beam, the altered electron positions represent a source of potential energy, and it is the function of collector **20** and load **24** to derive the stored energy in the form of direct current.

The electrons accepted by depressed collector **20** flow through load **24**, rendering the end of load **24** connected to terminal **23** negative in relation to ground and also negative relative to the potential of the beam as it enters the collector region. It is this negative potential that effects depressed collector operation and causes the electrons to be decelerated and yield up power to the collector circuit. Terminal **23** represents to load **24** a source of constant current (essentially equal to the beam current) which is independent of load resistance up to a critical point where maximum D.C. power is extracted. Beyond that point, the current rapidly drops to zero because the collector begins to reflect the beam back toward the coupler interaction area. This critical point is a direct function of the microwave power input.

Such behavior is depicted in FIGURE 2 where load current I_L is plotted as the ordinate and load voltage V_L as the abscissa. The point I_0 represents the condition of zero input signal power so that the load current equals the D.C. beam current and, because of the depressed mode of collector operation, the load voltage is zero corresponding to a load resistance of zero. Curve **40** represents the load current characteristic for a first signal power input. Consequently, for maximum power output load **24** is selected to present a D.C. resistance defining a load line R_{L1} which crosses curve **40** just before the point where the curve begins to drop in value. Similarly, curve **41** represents the operating characteristic with a higher signal power input; in that case, load **24** is selected to have a load resistance defined by load line R_{L2}. For a still higher microwave input the operating characteristic is defined by curve **42** for which the load resistance is selected to define load line R_{L3}.

In any case, when the load resistance is too low for the power being fed into the coupler, so that the load line falls to the left of the knee in the curve in FIGURE 2, excess power is undesirably dissipated in collector **20**. On the other hand, if the load resistance is too high, the beam is at least partially reflected with the result that power is undesirably dissipated in one or more of the high-potential electrodes upstream from collector **20**. In an exemplary application of the device, a system of storage batteries are connected to serve as load **24** with the operating voltage of the battery system being chosen just below the knee of the curve appropriate to the microwave power level applied to the input of coupler **30**; alternatively, the input power to the device is selected relative to the desired load system voltage.

The interesting applications of the disclosed device are in so-called large-signal operation, as compared to the typical small-signal operation encountered in intelligence communications systems. With coupler **30** of uniform pitch and diameter as shown in FIGURE 1, the power handling capability of the device is limited by interception of the beam with the output end of the coupler and by loss of synchronism due to increased axial electron velocity near the output end of the coupler. These limitations may be extended by substituting in the device of FIGURE 1 the modified coupler **30***a* shown in FIGURE 3. Specifically, both the pitch and the diameter of the bifilar windings are caused to gradually increase throughout the length of the coupler in the downstream direction.

To illustrate one particular form of the device of FIGURE 1, it may be assumed that the cyclotron frequency f_c is chosen to be equal to the signal frequency f with both frequencies being 3000 megahertz. The D.C. beam power is assigned a value of 10 kilowatts and its perveance is 2 micropervs. This results in a beam current of 1.32 amperes at a beam voltage of 7,580 volts. Coupler **30** at that voltage has a pitch of 1.48 turns per inch. The Brillouin beam density at the strength of magnetic field (1,071 gauss) necessary for a cyclotron frequency of 3000 megahertz, and at the designed beam voltage is 46.2 amperes/centimeter^2. For typical operation at 70 percent of theoretical Brillouin current, the actual density is 32.3 amperes/centimeter^2. To achieve this density, the amount of beam convergence from cathode **13** is only about 6.5 to 1, utilizing a dispenser cathode operating at 5.0 amperes/centimeter^2.

Based on the above operating current density and total beam current, the calculated beam diameter is 0.090 inch. By assigning an inner diameter to coupler **30** of 0.180 inch (twice the beam diameter), it can be shown that the maximum power capable of being carried by the positive synchronous wave is 6940 watts.

Constructing the elements of twisted bifilar coupler **30** of flat, tape-like windings which together fill one-half of the axial space parallel to the beam, the required width of each winding in the axial direction is 0.169 inch. This construction results in a space harmonic reduction factor of 0.90. Assigning a length to the coupler of 3.0 inches, the beam loading resistance becomes 149 ohms; it may be noted that the beam loading resistance is inversely proportional to the square of the coupler length.

Of course, with the power levels involved it is very important to keep the coupler circuit losses to a minimum, since each 0.1 db loss of microwave power represents a loss of about 2 percent in efficiency. By virtue of the fact that the couplers need not exhibit a broad bandwidth, the coupler circuit losses may be held to less than 0.2 db, representing only a 4.7 percent power loss.

In practical operation, the amount of power dissipated in depressed collector 20 is of the order of 5 percent of the original beam power. Thus, with a power output of 6940 watts, approximately 500 watts are dissipated in the collector and 326 watts in coupler **30**.

In terms of overall efficiency, then, the power output plus the collector dissipation and circuit losses total, in this example, 8096 watts. That represents a maximum efficiency of a very respectable 85.6 percent. In the overall sense, a small further reduction in that efficiency results from the power delivered to the heater for cathode **13**. Additional efficiency reduction may result in given applications from unavoidable stray electron interception by the different electrodes in the device. Of course, interception on coupler **30** is to be avoided since an interception of only 1 percent of the beam current at full voltage in this example would result in a dissipation on the coupler of 100 watts or more and this would result in a corresponding reduction in the overall efficiency of about 1 percent.

As can be seen from this illustrative example, a device utilizing a coupler only 3 inches long is capable of delivering rectified power to a load in a magnitude measured in kilowatts. At the same time, high efficiencies of the order of 80 percent are obtainable. Consequently, the disclosed devices are particularly suitable for microwave power transmission and rectification. At the same time, the devices are simple in structural design and feature the use of individual parts or components of a straightforward nature.

While particular embodiments of the invention have shown and described, it will be obvious to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects.

I claim:

1. A microwave power rectifier comprising:

means for developing and projecting a beam of electrons along a predetermined path;

means for creating a magnetic field directed along said path and having a strength establishing cyclotron resonance of said electrons at a predetermined frequency;

an electron coupler disposed along said path and responsive to microwave signals for selectively interacting only with a positive synchronous wave on said beam;

means comprising a collector having a potential depressed substantially relative to the potential of said coupler and disposed across said path downstream of said coupler for collecting said electron;

and a load coupled to said collecting means.

2. A rectifier as defined in claim **1** in which said developing means creates a stream of electrons which converge toward said coupler.

3. A rectifier as defined in claim **1** in which said coupler is circularly symmetrical about an axis defined by said beam path and has a diameter increasing in the downstream direction in an amount generally corresponding to increasing growth of said synchronous wave.

4. A rectifier as defined in claim **1** in which said coupler is a bifilar helix encircling said beam path.

5. A rectifier as defined in claim **4** in which said helix has a pitch which increases in the downstream direction generally in correspondence with an increase along the helix of the energy in said synchronous wave.

6. A rectifier as defined in claim **4** in which said electrons follow helical orbits in consequence of said condition of cyclotron resonance and in which said bifilar helix has a twist of the same sense as that of said orbits and a pitch such that

$$n = n_c f / f_c$$

where n is the number of helix turns per unit length, n_c is the number of electron helical orbits per unit length, f is the nominal frequency of said microwave signals, and f_c is the cyclotron resonance frequency.

7. A rectifier as defined in claim **1** in which said developing means is coupled to a plane of reference potential and said load is coupled between said collecting means and said plane of reference potential.

8. A rectifier as defined in claim **1** in which the developing means is coupled to a plane of reference potential and said coupler is biased to a potential substantially positive relative to said plane.

9. A rectifier as defined in claim **1** in which said creating means includes pole-defining elements disposed adjacent to said path at opposite ends of said electron coupler.

10. A rectifier as defined in claim **1** in which said coupler is biased to a predetermined positive potential and said load is coupled between said collecting means and a potential plane substantially negative relative to said predetermined positive potential.

11. A rectifier as defined in claim **1** which further includes means matching the impedance of said source to the impedance of said coupler.

12. A rectifier as defined in claim **1** in which the impedance of said load is of a value selected to extract substantially a maximum level of power from said collecting means.

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U.S. Cl. X.R.

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