Abstract—Electromagnetics has an important role in power and energy industry. In this paper, the concept of rectenna is introduced firstly. The history of rectenna for wireless energy harvesting and transmission is then reviewed. Finally examples are employed to illustrate some rectenna design and measurement issues such as rectenna impedance matching and its conversion efficiency. It is also shown that rectennas can harvest wireless energy efficiently under certain conditions and have the potential to become a power supplier for some special applications.

Key words: Rectennas, wireless power transmission, wireless energy harvesting, rectenna conversion efficiency

I. INTRODUCTION

Over the past two decades, many wireless systems have been developed and widely used around the world. The most important examples are cellular mobile radio and Wi-Fi systems. Just like radio and television broadcasting systems, they radiate electromagnetic waves/energy into the air but a large amount of the energy is actually wasted, thus how to harvest and recycle the ambient wireless electromagnetic energy has become an increasingly interesting topic.

One of the most promising methods to harvest the wireless energy is to use a rectenna which is a combination of a rectifier and an antenna. A typical block diagram is shown in Fig. 1. The wireless energy can be collected by the antenna attached to rectifying diodes through filters and matching circuit. The rectifying diodes convert the received wireless energy into DC power. The low-pass filter will match the load with the rectifier and block the high order harmonics generated by the diode in order to achieve high energy conversion efficiency which is the most important parameter of such a device.

There are at least two advantages for rectennas: (1) the lifetime of the rectenna is almost unlimited and it does not need replacement (unlike batteries). (2) It is "green" for the environment (unlike batteries, no deposition to pollute the environment).

II. BACKGROUND OF WIRELESS POWER TRANSMISSION AND ENERGY HARVESTING

Over 100 years ago, the concept of wireless power transmission was introduced and demonstrated by Tesla [1, 2], he described a method of "utilizing effects transmitted through natural media". This method has been brought particularly into prominence in recent years. In fact, Tesla was unsuccessful to implement his wireless power transmission systems for commercial use but he transmitted power from his oscillators which operated at 150 kHz to light two light bulbs. The reason for his unsuccessful attempt was that the transmitted power was radiated to all directions at 150 kHz radio wave whose wave length was 20 km and the efficiency was too low.

Based on the development of the microwave tubes during the World War II, rectification of microwave signals for supplying DC power through wireless transmission was proposed and researched in the context of high power beaming since 1950s. B. C. Brown started the modern era of wireless power transmission with the advancement of high-power microwave tube at Raytheon Company [3]. By 1958, a 15 kW average power-band cross-field amplifying tube was developed that had a measured overall DC to RF conversion efficiency of 81%. The first receiving device for efficient reception and rectification of microwave power emerged in the early 1960's. A rectifying antenna or rectenna was developed by Raytheon. The structure consisted of a half-wave dipole antenna with a balanced bridge or single semiconductor diode placed above a reflecting plane. The output of the rectenna element is then connected to a resistive load. 2.45 GHz is widely used as the transmitting frequency because of its advanced and efficient technology base, location at the center of an industrial, scientific, and medical (ISM) band and its minimal attenuation through the atmosphere even in heavy rainstorms. From the 1960's to the 1970's the conversion efficiency of the rectenna was increased at this frequency [4].

Conversion efficiency is closely linked to the microwave power that is converted into DC power by a rectenna element, the greatest conversion efficiency ever recorded by a rectenna element occurred in 1977 by Brown in Raytheon Company using a GaAsPt Schottky barrier diode, a 90.6% conversion efficiency was recorded with an input microwave-power level of 8 W. This rectenna element used aluminum bars to construct the dipole and transmission line [5]. Later, a printed
rectenna design was developed at 2.45 GHz with efficiencies around 85% [6]. More recently, McSpadden and Chang used the rectenna as a receiving antenna attached to a rectifying circuit that efficiently converts microwave energy into DC power [7].

As an essential element of the rectenna, the antenna of rectenna can be any type such as a dipole [3, 9], Yagi-Uda antenna [10, 11], microstrip antenna [12, 7, 13], monopole [14], coplanar patch [15], spiral antenna [16], or even parabolic antenna [17]. The rectenna can also take any type of rectifying circuit such as single shunt full-wave rectifier [7, 13, 14], full-wave bridge rectifier [3, 10], or other hybrid rectifiers [11]. The circuit, especially the diode, mainly determines the RF to DC conversion efficiency, rectennas with FET [14] or HEMT [15] appeared in recent years. The world record of the RF-DC conversion efficiency among developed rectennas is approximately 90% at 8 W input of 2.45 GHz [3]. As shown in Fig. 2, the RF-DC conversion efficiency of the rectenna with a diode depends on the microwave power input intensity and the optimum connected load. When the power is small or the load is not matched, the efficiency becomes quite low. The efficiency is also determined by the characteristic of the diode which has its own junction voltage and breakdown voltage, if the input voltage to the diode is lower than the junction voltage or is higher than the breakdown voltage the diode does not show a rectifying characteristic. As a result, the RF-DC conversion efficiency drops with a lower or higher input than the optimum.

It is worth noticing that all the recorded high conversion efficiencies were generated from high power incident level due to the reason we mentioned above. For low power incident level, a measured conversion efficiency of 21% was achieved at a power incident of 250 μW/cm² [18], of course, in principle a high efficiency should be achievable.

There are basically two approaches to increase the efficiency at the low microwave power density. The one is to increase the antenna aperture as shown in [17]. There are two problems for this approach. It produces a high directivity and this is only applied for exclusive applications as SPS satellite experiment and not for low power applications like RFID or microwave energy recycling. The other approach is to develop a new rectifying circuit to increase the efficiency at a weak microwave input.

### III. RECTENNA DESIGNS

#### A. Bandwidth of rectenna

The rectenna can be divided into narrow-band rectennas and wide-band rectennas. Many narrow-band rectennas have been developed. For example, a dual-polarized patch rectenna at 2.4 GHz and a high conversion efficiency rectenna at 5.8 GHz were designed by McSpadden in 1994 and 1998 respectively [8, 20]. However, very few broad-band rectennas have been developed which are the most desirable rectennas for wireless energy harvesting. They may collect energy from systems operating at different frequencies to maximize the output power at a given location.

#### B. Rectenna impedance matching

In order to optimize the rectenna for maximum power transfer, the antenna impedance must be matched to the impedance of rectifier diode. For example in [20], Alpha SMS7630-079 Schottky diodes were used for rectification, and a source-pull simulation was used to obtain the diode input impedance. For a variable input power, the resulting DC voltage is quantified for each source impedance as shown on Fig. 3 (a) [20]. The results shown on the Smith Chart indicate that the optimum source impedance has to be presented to each diode moving counter-clockwise with an increase in frequency, and closer to the centre of the Smith Chart with an increase in input power. The region of optimal source impedance is used to optimize the antenna design which needs to match the diode impedance.

![Fig. 3 (a) Simulated range of optimal source impedance for schottky diode from 1 to 16 GHz and with a input power from -30 dBm to 10 dBm](image1)

![Fig. 3 (b) Simulated input impedance for spiral antenna](image2)
The simulated input impedance for a spiral antenna is plotted on Fig 3(b). In this rectenna structure the antenna is directly connected to a shortcircuit diode, not a transmission line. Therefore, the spiral antenna should match to the diode input impedance. Form Fig. 3(a) and (b), a good impedance matching between the antenna elements and their respective diodes occurs in the region around 2.7 GHz for low-input powers and around 5.8-8 GHz for high-input powers.

C. Rectenna testing

A typical experimental setup adopted to perform rectenna measurements is illustrated in Fig. 4. In order to produce a variable power density, a signal generator and an amplifier are used. Measurements can be performed by varying the distance \( R \) from the transmitter antenna to the rectenna or the output power. For both cases, the far field conditions should be met for both antennas. The output voltage is measured from the load resistor connected to the rectenna by a voltage meter.

![Image of experimental setup](image)

**Fig. 4** Experimental Set-up for rectenna characteristic

D. Rectenna efficiency.

The efficiency of the rectenna system is basically equivalent to its transfer function. The general definition of any efficiency (\( \eta \)) used hereafter is the ratio of the output power \( P_{out} \) over the input power \( P_{in} \),

\[
\eta = \frac{P_{out}}{P_{in}}.
\]

The conversion efficiency (\( \eta \)) of the whole system is the DC power at the receiver end over the AC input power captured by the system (antenna). This efficiency is strongly dependent on the power density (\( P_d \)) distributed across the receiver aperture. The maximum incident power density can be expressed as

\[
P_d = \frac{P \cdot G_t}{4\pi R^2}
\]

(2)

Where \( P \) is transmitted power, \( G_t \) and \( G_r \) are the gains of the transmitter and receiver antennas, and \( R \) is the distance. The effective area \( A_{eff} \) for the antenna is given as

\[
A_{eff} = \frac{\lambda^2 G_t}{4\pi}
\]

(3)

Therefore, use equations (2) and (3) to obtain the power received by the antenna as

\[
P_{in} = P_d \cdot A_{eff}
\]

(4)

Because the rectenna output is DC power, thus the output power we can obtain from the output voltage generated on the load resistance by

\[
P_{out} = \frac{V_{out, DC}^2}{R_{load}}
\]

(5)

Therefore, from equation (1), (4) and (5) the conversion efficiency can be obtained by

\[
\eta = \left( \frac{V_{out, DC}^2}{R_{load}} \right) \frac{1}{P_d A_{eff}}
\]

(4)

It should be pointed out that this definition is slightly different from the one used in the photovoltaic community and it will give higher efficiency due to the use of the effective aperture rather than the physical antenna aperture.

IV. CONCLUSIONS

In this paper, we have introduced the concept of rectennas and reviewed its history briefly. Some important design issues of rectennas have also been addressed. Moreover, a detailed discussion on the rectenna efficiency has been conducted. It is clear that to achieve high energy conversion efficiency, many parameters have to be taken into account. For low power density cases, high energy conversion efficiency may not be possible.

REFERENCES


