Solar Energy Harvesting by Carbon Nanotube Optical Rectenna: A Review

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***Abstract*— Light has dual nature (particle and wave). Solar PV technology exploits particle nature of light and converts light to electricity by charge separation method. The lower efficiency of PV system is hindering their wide-spread commercial use. Optical rectenna exploits wave nature of light and not limited to the Shockley-Queisser efficiency limit. Carbon nanotubes are the quasi one-dimensional structure and possess exceptional thermo-mechanical and optical properties. They show antenna like properties and can be used in an optical rectenna due to their excellent properties. In this article, recent improvement in the design and efficiency of CNT optical rectenna is discussed.**

Keywords— CNT Optical Rectenna, CNT Antenna, Rectenna Solar Cell, Nano-antenna, Rectification

I. Introduction

A device in which an antenna is coupled with a diode and converts electromagnetic energy into DC electricity is called rectenna. Optical rectenna is a device which absorbs and rectifies optical frequencies. Optical rectenna is a combination of submicron antenna and the ultra-high speed diode [1]. Solar energy is harvested at industrial scale by using photovoltaic and solar thermal technology. Both of these technologies exploit only the particle nature of light. Optical rectenna exploit wave nature of light. A diode rectifies the AC current received by antenna and provides DC electrical power as described in Fig. 1.

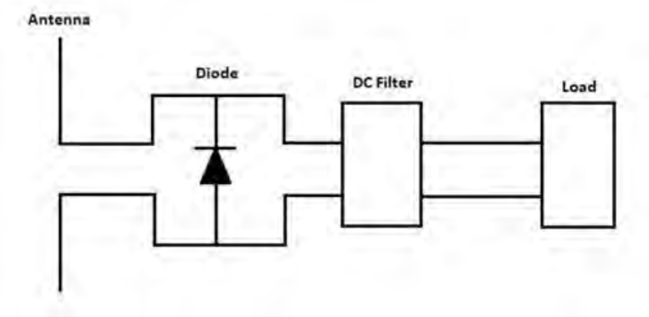

Figure 1 Schematic block diagram of a rectenna device.

Conventional semiconductor's solar cells are limited to the Shockley-Queisser efficiency limit [2]. According to this limit, the maximum conversion efficiency for a semiconductor band gap of 1.34 eV (928 nm) is 33.16% and requires AM 1.5G illumination. This theoretical limit of the photovoltaic solar cell results because: - (a) The incident light with energy less than the bandgap cannot be absorbed; and (b) For all the incident light with energy equal to or larger than the bandgap, only the energy equal to the bandgap can be efficiently converted into a useful DC current[3]. Multi-junctions solar cell provides a solution to overcome this efficiency limit, but they are expensive to produce because they use rare materials and require more manufacturing steps. On the other hand, the record conversion efficiency for a rectenna is 90.6% for 2.45 GHz[4]. Additionally, their cost can be very less compared to silicon PV cell because they use thin layers of metals and insulators. [1]. Carbon nanotubes are considered as the perfect material for optical rectenna because of their excellent electro-mechanical properties.[5]. The first carbon nanotube optical rectenna was demonstrated by Sharma et al. [6] in 2015 as a proof of the concept. Some evolving concepts like nanoparticles patch antennas and self-assembly of molecular diodes are in close competition with CNT thus worthwhile for separate analysis.

A. Brief History of rectenna

The genesis of the rectenna concept lies in the dream of wireless power transmission beginning with Tesla in 1899[7]. Tesla promoted an intense research effort in WPT by his giant tesla coil experiment in Colorado Springs. The first rectenna is developed by Professor William Brown in 1963. In 1964, Brown demonstrated a flying helicopter with help of the assembly of 28 rectifying antennas powered by microwave source [8]. The driving force behind that research was to submit a surveillance device to the US Army which could power a hovering platform [9]. In 1968-William Brown and Peter Glaser patented a geo-stationary orbit satellite system equipped with PV panels that could transmit the received solar energy to the ground station by using microwave and then reconverted into electricity[10]. As the microwave rectification gave the promising results, Professor Bailey, from the University of Florida, pointed out in 1972 to scale down the rectifying antenna concept towards the visible frequencies[11]. He Suggested to use conical antenna with rectifying element fast enough to rectify visible frequency radiation. That conceptualization qualified as a *Solar Rectenna*. The ultimate efficiency of the device is still under debate[12] with several publications of ultimate power conversion efficiency derivations reported to this date [13][14][15][16]. Figure 2 represents the most important theoretical and experimental efficiency value of past four decades[17][18][19][4][20][21][22][23][24][25][26][27][16][6][28][13][15]. The nanofabrication technology has improved drastically over the past few decades, which leads to the fabrication of the rectenna with 40 to 50 % efficiency. But these rectennas operates only in the tens of GHz[24][25][26]and near THz[29] range. Lin et al. [30] fabricated the rectenna for the first time in 1996 that absorbs and rectifies the visible light frequency. In 2015, Qing-Yuan Lin et al. [31] have shown the technique of self-assembly of nanoparticles on metallic substrates with the help of complementarity of two DNA strands, which can be used as optical antenna. In the same year, Sharma et al. [6] developed first carbon nanotube optical rectenna with 10^{-5} % overall conversion efficiency. In 2018 Anderson et al. [32] reported the first air-stable CNT optical rectenna along with efficiency improvements. Despite these improvements, there has been no report of an optical rectenna with an efficiency above 1%.

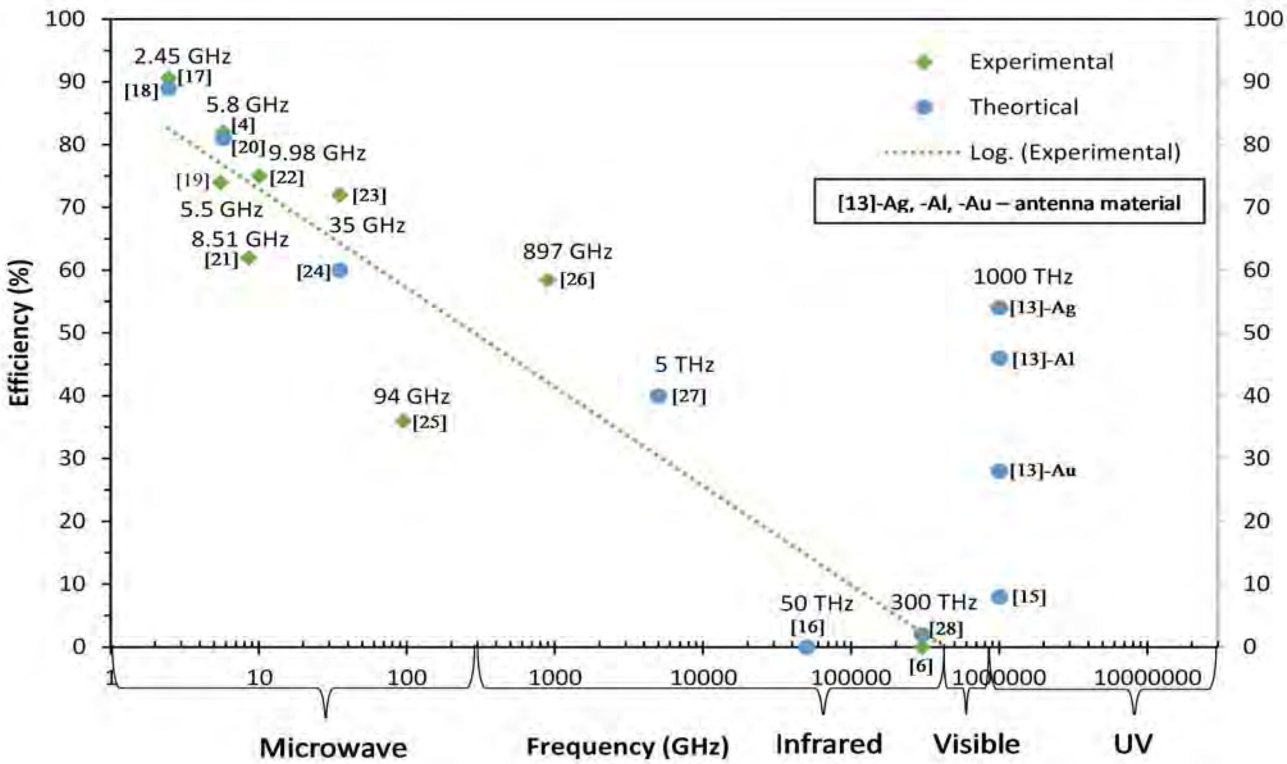

Figure 2 Logarithmic plot of theoretical and experimental efficiency as a function of operating frequency. The Green line shows the trend in experimental efficiency from microwave to UV.

But the seducing efficiency in microwave range, maximum efficiency not limited by Shockley-Queisser efficiency limit and the potential to solve the energy and environment problem still attracts researchers in this field. The only thing standing in its way is a cost-effective and efficient prototype.

II. The Optical Rectenna and CNT

A. *Carbon nanotube*

Carbon nanotubes are seamless cylinders made by rolling of graphene layers. On the basis of number of graphene layers being rolled, carbon nanotubes can be divided into three categories: - single walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes (DWCNTs) and multi walled carbon nanotubes (MWCNTs) [33]. Depending on their indices, CNTs can be metallic or semiconducting[34]. CNTs possess superlative mechanical, thermal and electronic properties. They are the strongest materials ever discovered by human beings[34]. The Thermal conductivity of SWCNTs is comparable to diamond[35]. The current densities of CNTs is as high as 10^9 A/cm^2. Because of their 1-D nature, scattering of the charge carrier is negligible which minimizes Joule heating effect and results in ballistic transport[36].

B. *CNT as optical antenna*

An Antenna is a device that transmits and/or receives electromagnetic waves. It can receive different wavelengths in accordance to their dimensions. All antennas possess two following major properties: (1) The polarization effect, and (2) the antenna-length effect. The Polarization effect suppresses the response of an antenna when the electric field of the incoming radiation is polarized perpendicular to the dipole antenna axis. The Antenna-length effect maximizes the antenna response when the antenna length is a multiple of the radiation half wavelength in the medium surrounding the antenna[37]. In 1993, synthesis of SWCNTs take place for the first time [38][39]. Soon after the discovery, both of the polarization and antenna-length effects of CNTs were found theoretically [40]. In 2004, Wang et al.[41] pointed out experimentally that an electromagnetic antenna could be made by an array of aligned carbon nanotubes. Goswami et al. (2004) [42] and Wijewardane et al. (2009)[43] have shown the suitability of carbon nanotubes as a potential material for manufacturing a practical solar optical rectenna device.

The development of carbon nanotube optical antennae can be divided into three stages. The first stage was ranging from 2004 to 2010. During this period, the analysis of antenna performance of different types of carbon nanotubes were carried out [44]. Researchers changed the finite length and diameter of carbon nanotubes ranging from armchair [45][46], zigzag[47], chiral[47]and metallic[48] carbon nanotubes [44]. Theoretical analysis and experimental measurement of the antenna efficiency were also carried out in that phase[44]. It was found that the performance of the arrays or bundles of carbon nanotubes is significantly better than isolated ones[49][50].

The second lustrum was from 2011 to 2016. At this stage, the main focus area of research was to combine carbon nanotubes with leading-edge technologies by integrating them with advanced materials such as metamaterials. The alignment of carbon nanotube was also improved by many methods in that phase[51] which result in the fabrication of CNT films on a macroscopic scale [52].

The research situation has changed in the past four years with the demonstration of first CNT optical rectenna[6]. Integration of CNT antenna with high-speed diodes (for example:- MIM diode) has been the main trend in recent years[53].

C. Rectification

Rectification is a process in which an alternating physical quantity (current or voltage) is converted into continuous physical quantity. Light rectification has always been a main challenge in optical rectenna concept[42]. This is due to the high frequency of solar radiation which requires ultra-high-speed diode for rectification. MIM diode is a promising candidate due its ultra-fast photon assisted tunneling mechanism. The contact area of the MIM diode should be very small for successful operations in the optical range [43]. CNT can be used as one electrode in MIM diode due to its very small contact area. This leads to the concept of Metal-Insulator-CNT (MIC) diode. The electrical asymmetric characteristic was improved in the MIC diode due to asymmetric structure effect [53]. The resistance of MIC diode arrays can be reduced significantly by opening the tips of the multiwalled carbon nanotubes by, for example, plasma etching[32]. This is because of the opening of extra channels for electronic transport as the inner walls of multiwalled carbon nanotubes also form contacts with the electrodes. A recent study of Golibjon et. al [54] suggested that fluorination at the tip area of carbon nanotubes increases quantum transport through the Metal-carbon nanotubes junction.

III. INTEGRATION OF CNT ANTENNA AND MIM DIODE

The cutoff frequency for a rectenna is defined as: -

$$F_C = 1/(2\pi R_A C_D) \qquad (1)$$

where C_D represents diode capacitance of the rectenna and R_A represents resistance of the antenna [6]. The diode capacitance is defined as: -

$$C_D = \varepsilon_0 \varepsilon A/t \qquad (2)$$

where t is the insulator thickness, ε_0 is the permittivity of vacuum, ε is the relative permittivity of the insulator and A is the area of the diode. An optical rectenna can be obtained by increasing the cut-off frequency. The cut-off frequency can simply increase by reducing the diode area[55]. That can be done by using one electrode in a metal–insulator–metal (M-I-M) diode as the antenna in order to obtain an efficient antenna–diode coupling. Sharma et. al [6] demonstrated the first CNT optical rectenna in 2015 using the above approach. The metal–insulator–metal junction was created by depositing successive layers of insulator and conductor. Al_2O_3 and calcium is used as insulator and conductor respectively. This approach dramatically reduces the contact area of MIM junction which leads to increment in cut-off frequency of the device. The contact area became equal to the diameter of the nanotube (8-10nm). Rectification of two experimentally used lasers with a wavelength of 532 and 1064 nm is reported using the above diode structure. The conversion efficiency of $\sim 10^{-5}$% was reported under 1,064 nm laser illumination[6]. The design was further improved in 2018 by introducing multiple insulating layers, CNT tip opening and the air stable top electrode (Al)[32]. Table 1. represents the inventory of optical rectification experiments of past 25 years.

TABLE I. EXPERIMENTAL MEASUREMENTS OF OPTICAL RECTIFICATION

Wavelength	Irradiance (W/m^2)	Junction	Efficiency (%)	Reference
632 / 1400 / 1500 nm				Lin1996[30]
785 nm	2.2×10^8	MVM[a]		Ward2010[56]
685 nm	6.5×10^9			Arielly2011[57]
810 nm	8.3×10^8 / 2.9×10^9			Stolz2014[58]
7 μm	300		10^{-2}	Davids2015[59]
532 / 1064 nm	260/ 920/ 1000	MIM[b]	10^{-5}	Sharma2015[6]
785 nm	6 - 91		8.7×10^{-5}	Piltan2017[60]
10.6 μm	3×10^4		1.75×10^{-12}	Jayaswal2018[61]
785 nm	3.5×10^9			Dasgupta2018[62]
638 nm	200	MIIM	2.5×10^{-5}	Anderson2018[32]
638 nm	50	MI^4M	3×10^{-6}	Anderson2019[63]

[a]MVM stands for Metal-Vacuum-Metal junction & [b]MIM stands for Metal-Insulator-Metal Junction

IV. SUMMARY

Great progress has been made in the development of optical rectenna in the past two decades. CNT played an important role in demonstrating the proof of concept of technology. However, the reported efficiencies are still below 1%. The theoretical maximum efficiency limit is still under debate which further increases the uncertainty of future events. The growth process of CNTs must be further improved in order to improve the efficiency of the optical rectenna and to obtain a practical device. Interdisciplinary research including molecular electronics, nano-photonics, DNA nanotechnology is needed for further understanding and improvement of these devices.

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