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Electromagnetic Analysis of Antenna Used for Optical Rectenna

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Abstract. Nowadays, energy consumption is rapidly increasing and more and more renewable energy is demanded to reduce the emission of CO_2 since global warming has become a very serious problem for us. Solar cells are popular and widely used worldwide because almost no CO_2 is emitted during energy generation. However, their power conversion efficiencies are not high enough and costly. In order to solve these problems, optical rectenna was proposed and researched in recent years. In this work, we focused on the antenna, an important part of optical rectenna. We proposed and simulated three types of possible antennas for optical rectenna by electromagnetic analysis. Patch antenna, one of these antennas exhibited very good directivity, implying that it is suitable for the optical rectenna.

1. Introduction

More and more energy is consumed with the development of our society. Therefore, we have to find some new ways to meet this need. In recent years, renewable energy is increasing fast because we have to reduce the emission of CO_2 as much as possible due to the critical global warming. Currently, solar cell is one of most important renewable energy sources [1-5]. However, its power conversion efficiency (PCE) is limited by the bandgaps of the materials used in the solar cell although some efforts have been taken in recent years. Quantum dot solar cell is expected to increase PCE up to 60% in photovoltaic operation because of the enhancement of photoexcitation in theory. But in fact most of report novel solar cells showed only low PCEs less than 10% [6-8]. Tandem solar cells can greatly improve the performance by adopting several materials with different bandgaps to increase absorption of light with different wavelengths. Han *et al* and L. Kranz *et al* reported a high-performance hybrid perovskite and $Cu(In,Ga)Se_2$ (CIGS) tandem solar cells [9-10]. They achieved a high efficiency of 22.43% by using nanoscale interface engineering of the CIGS surface. Except their current low PCEs, all of these so-called next generation solar cells require very complicated fabrication processes such as formation of quantum dots with a size of only several nanometers or many nano-layers. As a result, we should develop some new methods with simple fabrication processes and a potential of very high PCE. Optical rectenna is possible to meet these requirements and attracts much attention in recent years [11-16]. The configuration theoretically can provide 100% conversion efficiency as a classical rectifier [12]. The comparison of advanced technologies of various solar cells and optical rectenna based on the above description and the literature [17] is shown in Fig. 1. An optical rectenna couples an ultra-high-speed diode to a submicron antenna so that the incoming radiation received by the antenna is rectified by the diode to produce a DC power output. The antenna is a very important part to obtain a high efficiency. In this study, we proposed three types of antennas and compared them by electromagnetic field analysis.

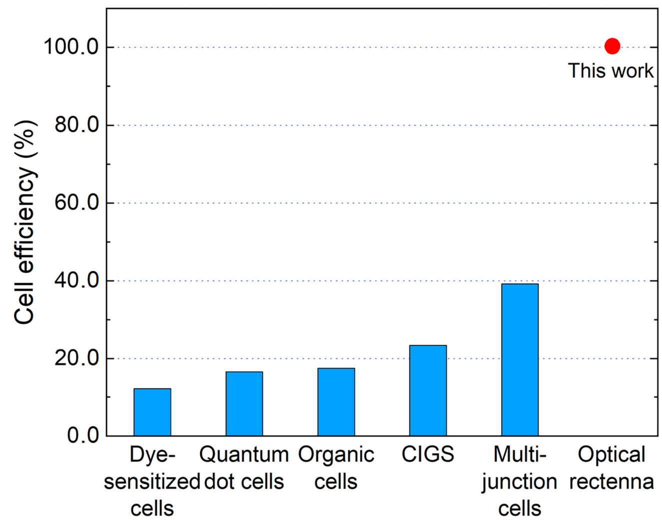


Fig. 1. Comparison of advanced technologies of solar cells and optical rectenna.

2. Principle of optical rectenna

Figure 2 shows the optical rectenna circuit which consists of an antenna and a diode. For operation at optical frequencies, an ultrafast diode rectifies the optical frequency signal absorbed by the antenna, producing a DC voltage [12].

Figure3 shows an example of our proposed structure. It consists of a metal-insulator-metal (MIM) diode and a patch antenna.

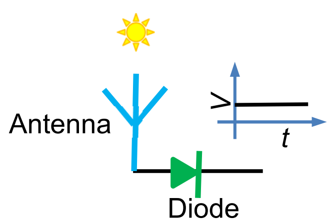


Fig. 2. Principle of the optical rectenna.

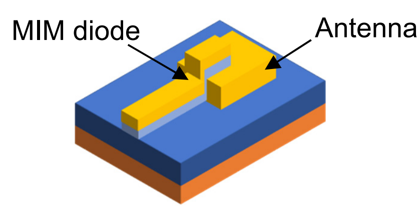


Fig. 3. Diagram of an optical rectenna.

3. Electromagnetic analysis of antenna for optical rectenna

3.1 Patch antenna

A patch antenna is a typical example of a flat antenna. It can be fabricated by using a printed circuit board with a copper foil and etching technology. It can behave as a radiator. The element size of a patch antenna is usually less than half a wavelength. The radiation pattern has unidirectional directivity with a maximum value in the vertical direction (+ z direction) from the antenna regardless of whether it is a circular or square patch antenna.

As an example, the resonance frequency f of a square patch antenna is expressed by the following equation, where c is the speed of light, L is the side length of the element, and ε is the relative permittivity of the dielectric (printed circuit board).

$$f = \frac{c}{2L\sqrt{\varepsilon}} \tag{1}$$

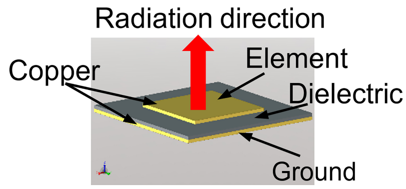
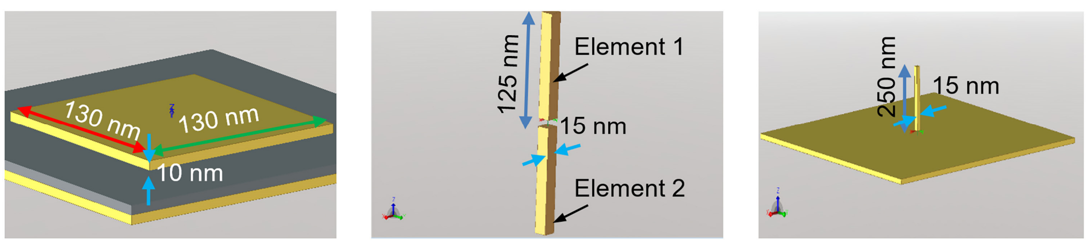


Fig. 4. An example of a square patch antenna.

As shown in Fig. 4, the structure of this type of antenna is simple. Copper foil is on a thin dielectric, and the copper foil can be processed to change the element part into a circle or square by using printing technology. Moreover, even if the antenna becomes small, it is possible to keep the minimum element size by making the element part square. As a result, it is easy to manufacture and suitable for arraying.

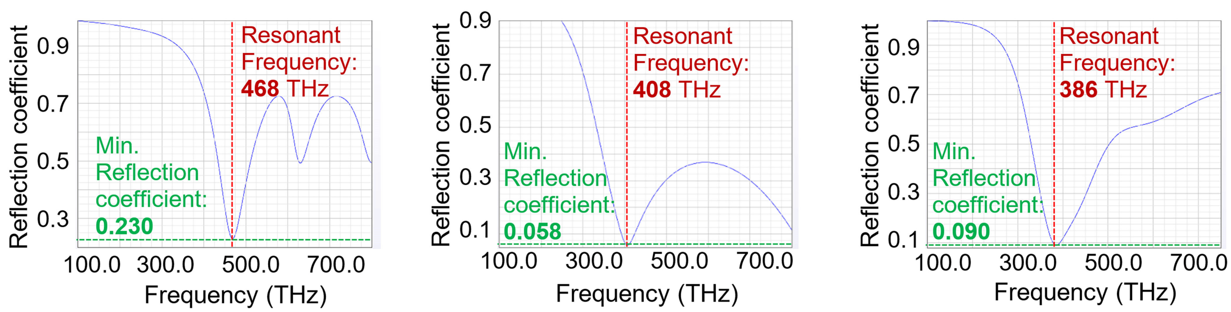
3.2 Analysis of antennas

Electric fields in the antennas were analyzed by using electromagnetic simulation software (EMpro, Keysight).
Here, we proposed and analyzed three types of antennas: patch antenna, dipole antenna and monopole antenna. The models of these antennas are shown in Fig. 5. For the patch antenna, the length and the height of the square element are 130 nm and 10 nm, respectively. The dipole antenna has two elements with a length of 15 nm of a square and a height of 125 nm. The monopole antenna has a structure similar to the dipole one as shown in Fig. 5(c).



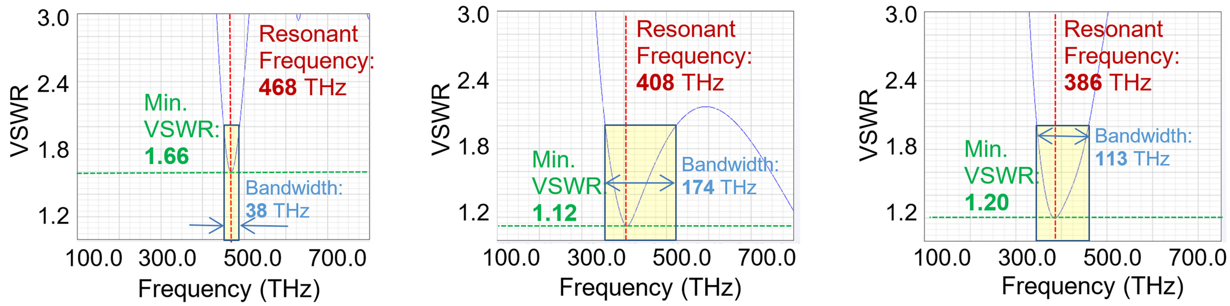
(a) Patch antenna (b) Dipole antenna (c) Monopole antenna

Fig. 5. Structures of antennas.



(a) Patch antenna (b) Dipole antenna (c) Monopole antenna

Fig. 6. Reflection coefficient as a function of frequency.



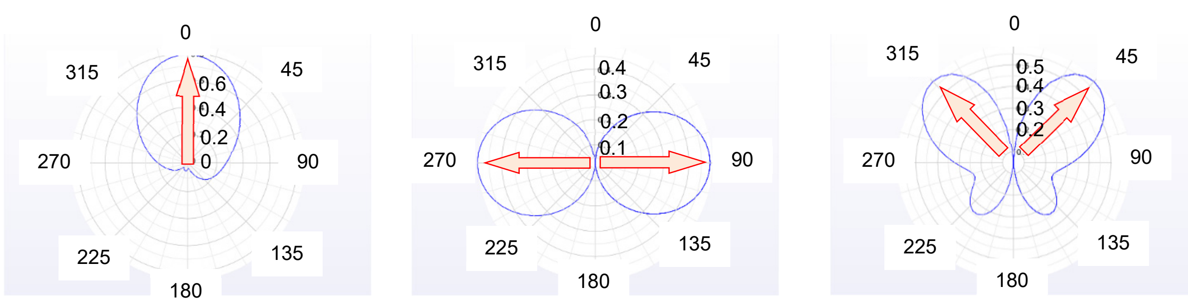
(a) Patch antenna (b) Dipole antenna (c) Monopole antenna

Fig. 7. VSWR as a function of frequency.

We analyzed these antennas. Figure 6 shows the reflection coefficient as a function of frequency of these three types of antennas. The resonant frequencies of patch, dipole and monopole antennas are 468, 408, 386 THz, respectively. The minimum reflection coefficients of these three types of antennas are 0.230, 0.058 and 0.090, respectively. Figure 7 shows the voltage standing wave ratio (VSWR) as a function of frequency of these three types of antennas. The values of VSWR at their resonant frequencies of patch, doplar and monoplar antennas are 1.66, 1.12 and 1.20, respectively. The bandwidth of the patch antenna, where VSWR is 2.0, is 38 THz, while those of dipole and monopole are 174 and 113 THz, respectively. The wider bandwidth means that both dipole antenna and monopole antenna are possible to absorb more sunlights. Figures 8 and 9 illustrate the radiation patterns of these antennas. The radiation of patch antenna has a direction along *z* axis, which is perpendicular to the patch pattern. The radiation direction of the dipole antenna is parallel to the substrate while the monopole has a radiation direction, which has an angle of 45 degrees to the substrate. The radiation directions are along large red arrows shown in Fig. 7. The summery of our simulation results is shown in Table 1.

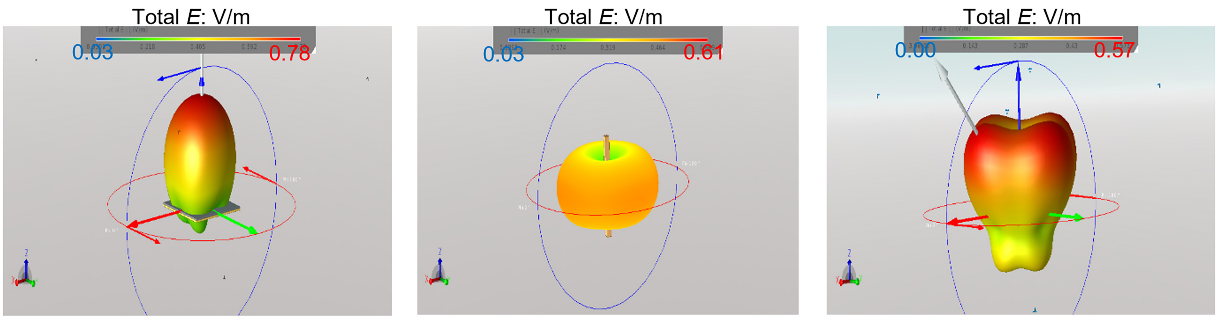
Table 1 Comparison of three types of antennas

Antenna type	Minimum reflection coefficient	Bandwidth (THz)	Radiation direction (Directivity)	Element size (nm)
Patch	0.230	38	90° (Good)	130
Dipole	0.058	174	0° (Bad)	15
Monopole	0.090	113	45° (Fair)	15



(a) Patch antenna (b) Dipole antenna (c) Monopole antenna

Fig. 8. Radiation pattern.



(a) Patch antenna (b) Dipole antenna (c) Monopole antenna

Fig. 9. Radiation pattern (3D).

The patch antenna has strong directivity in the vertical direction and a large element size. As a result, it is easy to manufacture and suitable as an antenna for an optical rectenna. Since minimum reflection coefficient of the patch antenna is a large value compared to those of the other two antennas, it is necessary to reduce it for practical use. In the future, some improvements for the patch antenna will be done to obtain both a good directivity and a wide bandwidth based on our current research results.

4. Conclusion

Based on our electromagnetic analysis of three types of antennas for optical rectenna, we can draw conclusions as follows.

(1) The patch antenna exhibited very good directivity. It should be suitable for optical rectenna if we also consider its fabrication process.

(2) There exists some problem for the narrow bandwidth of the patch antenna.

(3) We will improve the structure of the patch antenna to obtain both a good directivity and wide bandwidth in the future.

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