Delta University Scientific Journal Vol.07 – Special Issue (2024) 58-66

Delta University Scientific Journal
Journal home page: https://dusj.journals.ekb.eg

# A Study on the Performance of a Hybrid Solar-RF Energy Harvesting System Using a Transparent Antenna

**Ahmed A. Kabeel [1], Marwa E. Mousa[2], Amr H. Hussien[3], Amany A. Megahed[2], and Rania H. Elabd[2].**

*[1] Electronics and Communications Engineering Dept., Faculty of Engineering, Delta University Egypt, Gamasa, Egypt*
*[2]Electronic and Communication Dept., Higher Institute of Engineering and Technology in New Damietta, Damietta 34517, Egypt*
*[3]Electronics and Electrical Communications Engineering Dept., Faculty of Engineering, Tanta University, Tanta 31527, Egypt.*

Correspondence: Ahmed Abd Elnaby Kabeel Email: ahmed.kabeel@deltauniv.edu.eg

**ABSTRACT**

Energy harvesting technology has emerged as a significant area of research in light of the increasing demand for wireless devices. This field has garnered substantial scholarly attention on a global scale, largely due to its crucial role in providing convenient and cost-effective energy solutions for applications that are otherwise difficult to access. The core principle of energy harvesting involves the capture of energy from a wide variety of sources, including solar radiation, ambient light, thermal gradients, wind currents, and kinetic movements. Such technology plays a vital role in supporting applications that require compliance with specific quality-of-service standards. This paper aims to outline a multi-source energy system that proficiently harnesses both radio frequency and solar energy for computational uses. The methodology for radio frequency capture relies on the implementation of a transparent antenna, which can be easily integrated atop solar cells; this arrangement allows light to pass through the antenna, thus reaching the photovoltaic cell located underneath. The proposed energy harvesting framework is positioned to provide a dependable and sustainable source of electrical power, which can be utilized across various applications, thereby improving the feasibility and efficiency of contemporary energy systems.

***Keywords:*** *Energy Harvesting, Microstrip Patch antenna, solar Panel, transparent Antenna, Nano material.*

## I. INTRODUCTION

Energy harvesting is an emerging field that aims to harness and convert ambient energy sources into usable electrical power (Chen, 2018), This technology has gained significant attention in recent years due to the growing demand for sustainable and renewable energy solutions. One of the promising approaches in energy harvesting is the use of optical transparent antennas integrated with solar cells (Li, 2019). Solar cells have long been recognized as a reliable and efficient means of converting sunlight into electricity. However, their integration into various applications has often been limited by their bulky and opaque nature. This limitation has hindered their use in scenarios where transparency is required, such as windows, displays, and smart surfaces (Yang, 2020), To overcome this challenge, researchers have developed optical transparent antennas that can be seamlessly integrated with solar cells. These antennas are designed to transmit and receive electromagnetic waves in a specific frequency range while maintaining high transparency to visible light (Kim, 2017). By combining these antennas with solar cells, it becomes possible to harvest energy from sunlight without compromising transparency (Wu, 2019).The integration of optical transparent antennas with solar cells offers numerous advantages. Firstly, it allows for the creation of aesthetically pleasing and visually appealing energy (Zhang, 2020)harvesting systems that can be seamlessly incorporated into various surfaces without obstructing the view or compromising the overall design.

Secondly, these systems can potentially enable self-powered smart windows or displays that not only provide transparency but also generate electricity (Liu, 2018) Furthermore, the use of optical transparent antennas opens up new possibilities for energy harvesting beyond traditional solar panels (Wang J, 2019). These antennas can harvest energy from other ambient sources such as radio waves or Wi-Fi signals, thereby expanding the range of potential applications (Lin, 2017)In this paper, we will explore the concept of integrating optical transparent antennas with solar cells for energy harvesting purposes. We will discuss the design considerations, fabrication techniques, and performance evaluation of such systems. Additionally, we will highlight potential applications in areas such as architecture, automotive industry, wearable electronics, and Internet-of-Things (IoT) devices. Overall, this research aims to contribute to the advancement of energy harvesting technologies by exploring the potential of optical transparent antennas integrated with solar cells. By harnessing ambient energy sources in a transparent and efficient manner, these systems have the potential to revolutionize the way we generate and utilize electrical power in various everyday applications.

## II. RADIO FREQUENCY AND SOLAR- ENERGY HARVESTING

RF energy harvesting is the conversion of RF signal energy into DC power. It is also known as power harvesting or energy scavenging for wireless devices. The ambient energy can come from various sources such as electronic devices, magnetic fields, radio waves from nearby electrical equipment, light, thermal energy, kinetic energy like vibration or motion (Khan, 2020). RF energy is widely available in everyday technologies like cell phones, radio towers, Wi-Fi routers, and laptops at different frequencies. Even a small amount of energy can be harvested through RF energy harvesting. This method is particularly useful for low-power applications like Wi-Fi routers that transmit 50-100mw and can be harvested up to 1.5 miles (Ibrahim, 2022). On the other hand, solar energy harvesting involves capturing and utilizing the sun's energy to generate electricity or heat. This is done through the use of solar panels, which contain photovoltaic cells that convert sunlight into electrical energy Figure 1 shows a general architecture of proposed energy harvesting system (Benkalfate, 2022).

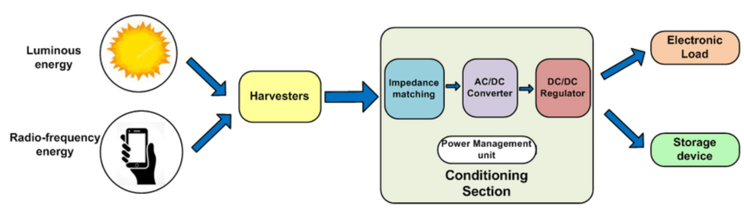


Figure 1: general architecture of proposed energy harvesting system

Recent developments in ultra-low power wireless communication and energy harvesting technologies have rendered the creation of self-sustaining devices a viable possibility (Assogba, 2020). The primary issue associated with these devices pertains to battery longevity and the necessity for replacement. The incorporation of energy harvesting techniques can substantially prolong battery life and, in certain circumstances, entirely eliminate the need for batteries. Ambient energy is accessible in various forms, such as minute vibrations, light, temperature gradients, and electromagnetic waves, among others. Figure 2 illustrates a solar panel integrated with a transparent antenna (M. J. Roo Ons, 2017).

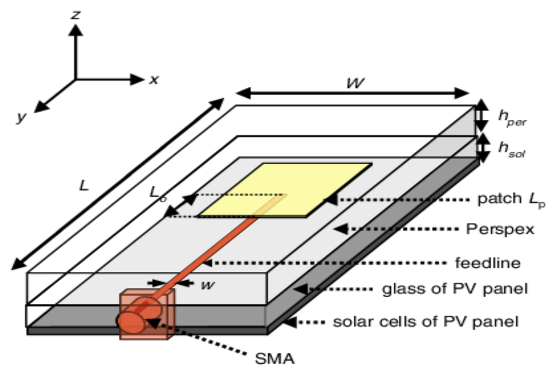


Figure 2: Solar panel combined with Transparent Antenna

The main part of energy harvesting is the antenna that is used to collect radio frequency, the next section is discussing overview about transparent antenna

## III. TRANSPARENT ANTENNA

The optical transparent antenna for radio frequency energy harvesting is a remarkable technology that revolutionizes the way we harness and utilize radio frequency energy. This innovative device combines the benefits of optical transparency and efficient energy harvesting, making it a game-changer in various industries. One of the most notable features of this antenna is its optical transparency. Unlike traditional antennas, which are often bulky and obstructive, the optical transparent antenna seamlessly integrates into transparent surfaces such as windows or screens without compromising their visual aesthetics. This characteristic opens up endless possibilities for incorporating energy harvesting capabilities into everyday objects and infrastructure. The efficiency of radio frequency energy harvesting is another impressive aspect of this technology. The optical transparent antenna efficiently captures and converts radio frequency signals into usable electrical energy. Furthermore, the optical transparent antenna has a wide operating bandwidth, allowing it to capture signals across various frequencies, this antenna can adapt to different scenarios without compromising its performance. Additionally, the durability and longevity of the optical transparent antenna are worth mentioning. With further advancements and improvements, this technology has the potential to revolutionize our energy consumption and contribute to a more sustainable future.

## IV. ANTENNA GEOMETRY

Usually, in order to maintain at least 80% optical transparency, the thickness of the sheet $t$ is kept within 30 nm. On the other hand, in order to have a resistivity no more than 30 times that of copper, the sheet resistance is maintained within 20 Ω. This means the thickness of the conductive sheet is less than 1 microwave skin depth within microwave spectrum. Means, high loss, less efficient antenna. As given in next equation

$$T(t) = e^{-t/m} \qquad \textit{Eq (1)}$$

Where T(t): Optical transparency and m is related to the material properties such as electron density, plasma frequency. It is limited by the material development, for the Sheet resistance has the same unit as resistance, hence we use “square” to specify.

$$R = \rho \frac{l}{Wt} (\Omega) \qquad \textit{Eq (2)}$$

$$R = \frac{\rho}{t} \frac{l}{W} (\Omega) \qquad \textit{Eq (3)}$$

$$R_s = \frac{\rho}{t} (\Omega \, \square) \qquad \textit{Eq (4)}$$

For a fix sheet resistance, a narrow strip is highly resistive. Sheet resistance is determined by the material properties such as electron mobility that is governed by the state of material development.

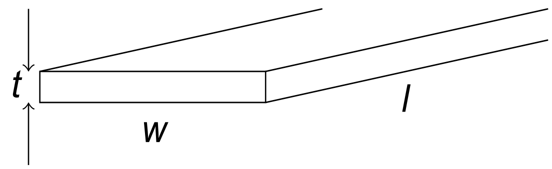


Figure 3: transparent antenna geometry

Only when $t$ is several times greater than δ, it is an effective conductor, i.e., reflector. If $t$ is smaller than δ, then it is a lossy layer. In another words, a not-effective conductor as shown in equation 2

$$\delta = \sqrt{\frac{R_S t}{\pi f \mu}} \quad \text{Eq (5)}$$

Transparency in the antenna depends on geometry as shown in figure 4, the transparent area is given by the equation number 6.

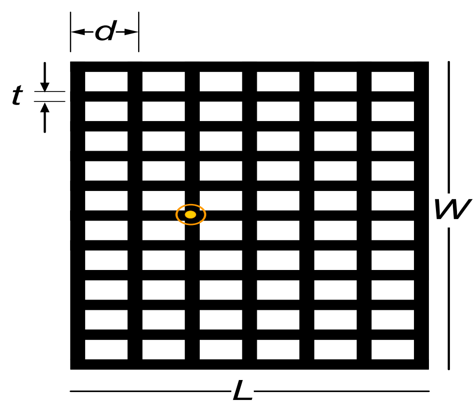


Figure 4: shape of transparent antenna array patched on solar cell

$$P_{tran} = \frac{A_{Antenna} - A_{metal}}{A_{Antenna}} = \frac{A_{trans}}{A_{antenna}} \quad \text{Eq (6)}$$

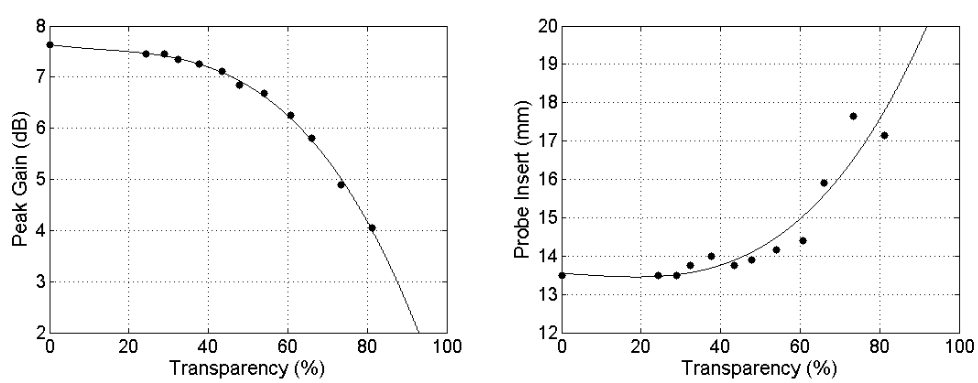


Figure 5: (a) Antenna Gain vs Transparency, (b) Probe Insert Diameter vs Transparency

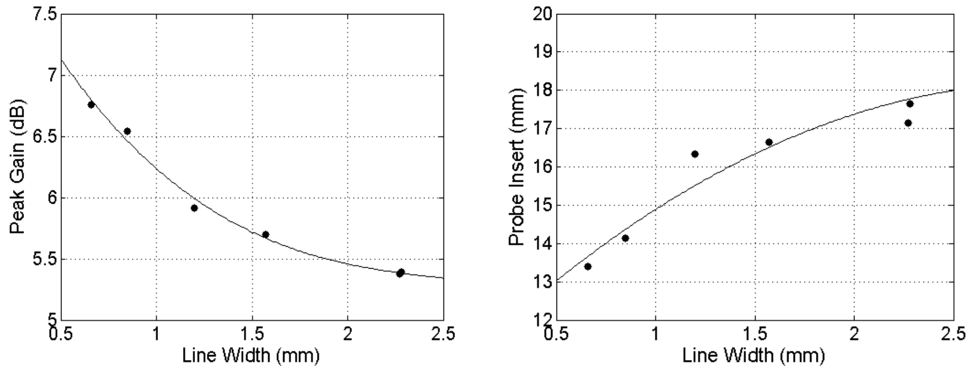


Figure 6: (a) Antenna Gain vs Mesh Line Width, (b) Probe Insert Diameter vs Line Width

As shown in Figure 5.a, For a fixed line width, higher transparency results in lower gain and vice versa. On the other hand, for a fixed transparency and varying the line width, the thinner the line the higher the antenna gain will be. From the previous observations it is noticeable that the transparency is inversely proportional to antenna gain, while with fixed transparency in Figure 6.a, the thinner the line the higher the gain thus the relation between the antenna gain and line width is also inversely proportional. According to this, the antenna design can be customized to obtain a specific gain and specific transparency

TABLE 1. Comparison of integrated solar antenna energy harvesting system designs

| Ref. No. | Frequency band (GHz) | Solar cell area ($mm^2$) | Antenna area ($mm^2$) | Type of antenna | Harvested RF power | Harvested solar power |
|---|---|---|---|---|---|---|
| (S. Gnanamurugan, 2017) | 2.38-2.5 | 150x150 | 150x150 | Microstrip | 0.34mW @ 2.45GHz | 1.68mW @ 360 lux |
| (Y. Ahmed, 2020) | 2.3-2.45 | N.A. | N.A. | Microstrip | 0.02mW @ 2.45GHz | 0.75mW @ 100 lux |
| (S. Ahmed, 2018) | 1.8-2, 2.1-2.4 | 80x150 | 180x150 | Microstrip | 0.08mW @ 2.29GHz | N.A. |
| (E. M. Ali, 2017) | 0.95-2.45 | 98x144 | 19.6x28.8 | Microstrip | 0.5µW @2.45GHz | 27.4mW @ 1450 lux |
| (T. Sanislav, 2018) | 2.2-12.1 | 17x33.5 | 38.86 | Microstrip | 6µW @ 2.51GHz | N.A. |
| (F. Z. Khoutar, 2018) | 2.28-2.55 | 22.8x24 | 45x45 | Microstrip | 35µW @ 2.45GHz | 0.07mW @ 334 lux |

## V. EFFECT OF SOLAR CELLS ON ANTENNA

Solar cells have a significant effect on antennas due to their ability to convert sunlight into electricity. When solar cells are placed near an antenna, they can cause interference and affect the performance of the antenna. This interference can result in a decrease in signal strength, increased noise, and reduced overall efficiency of the antenna system. The presence of solar cells can also lead to changes in the radiation pattern and polarization of the antenna, affecting its ability to transmit and receive signals effectively. Therefore, careful consideration must be given to the placement and orientation of solar cells in relation to antennas to minimize any adverse effects on their performance.

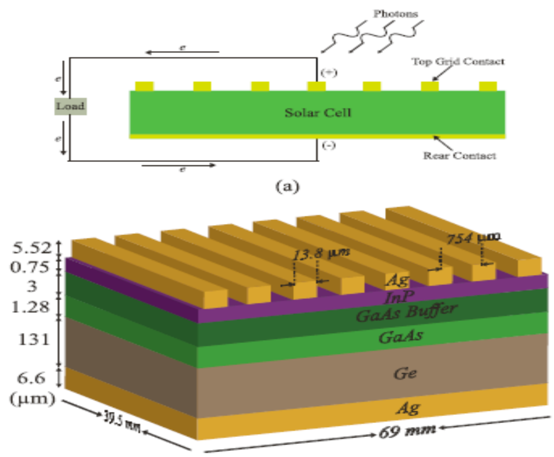


Figure 7: structure of solar panel with optically transparent antenna

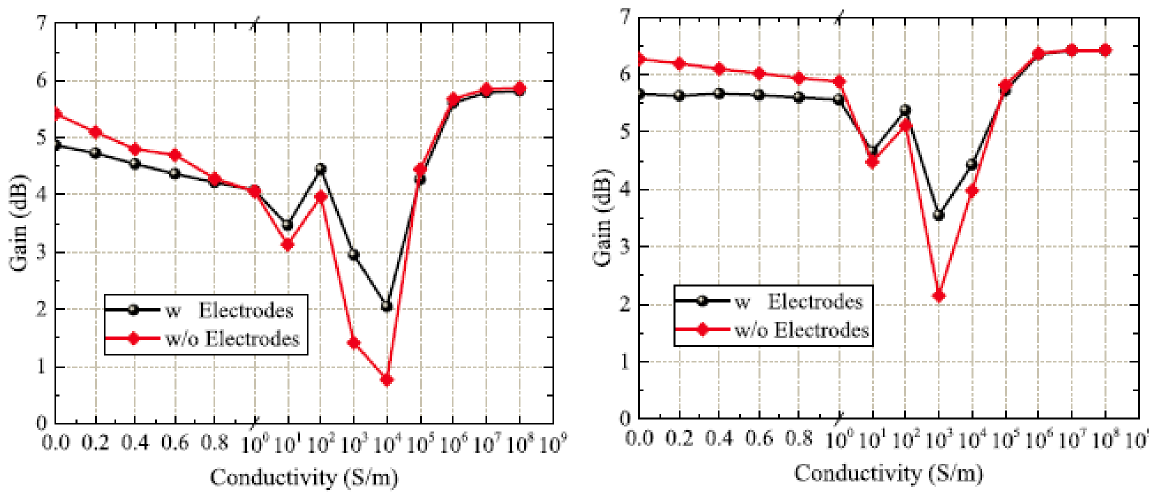


Figure 8: Gain Reduction vs Conductivity of Solar Cell

As shown in Figure 8, the nature of semiconductors in solar cells affects the antenna gain due to semiconductors does not behaving as dielectric due to their ability to conduct current in certain conditions thus being a lossy material, it shows the relation between conductivity and gain reduction in a bare solar cell without DC conductor lines, as it is noticeable from the figure, the maximum gain reduction occurs at $10^4\ S/m$ which is the conductivity of active solar cell.

On the other hand, the solar cells with a DC conductor lines (Ag) adds a gap between the solar cell semiconductor material and the antenna patch which helps in reducing the gain loss introduced by the semiconductor material as shown in figure

## VI. EFFECT OF ANTENNA ON SOLAR CELL

Due to the antenna geometry being above the solar cells, and due to the nature of the conductor used to design the antenna geometry, the light reaching to the solar cell will be attenuated and/or blocked by the antenna geometry and the material protecting the solar cell itself such as the glass sheet above the solar cell. To study the effect of the antenna, the measurements of solar cell power using bare solar cells with bare cell and with glass protective cover as well as with glass cover with antenna geometry must be considered. Figure 9 shows that the solar cell output using bare cell outputs the most power and when adding the glass cover, the output power drops significantly. However, when comparing the output power of the cell with glass cover verses the glass cover with antenna geometry, it is noticeable that a small power loss compared to the loss between bare solar cell and solar cell with glass cover, this leads to the conclusion that the most of power loss is due to the glass cover not the antenna geometry.

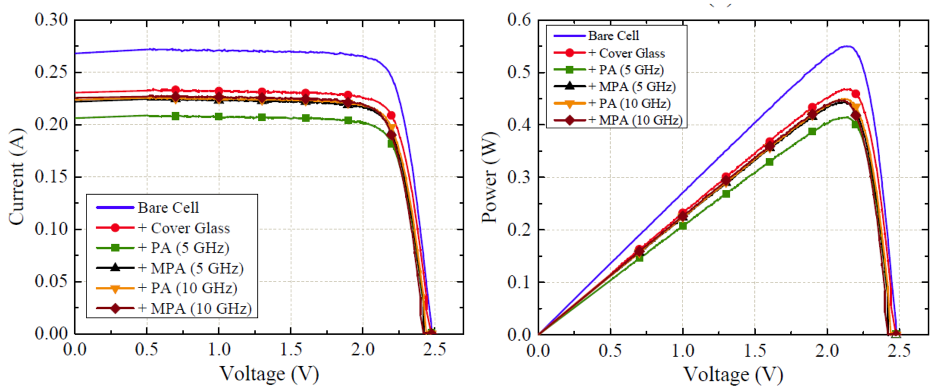


Figure 9: (a)voltage vs current (b) voltage vs power

Table 2. shows efficiency comparison between the bare, glass covered cell, glass with patch antenna (PA), and glass with meshed patch antenna (MPA).

| Name | Bare Cell | Bare Cell + Glass Cover | Bare Cell + Glass Cover + Patch Antenna (5 GHz) |
|---|---|---|---|
| Efficiency (%) | ٢١ | ١٨ | ١٦ |
| Name | Bare Cell + Glass Cover + Meshed Patch Antenna (5 GHz) | Bare Cell + Glass Cover + Patch Antenna (10 GHz) | Bare Cell + Glass Cover + Meshed Patch Antenna (10 GHz) |
| Efficiency (%) | 17.4 | 17.4 | 17.55 |

As shown in the table, efficiency of solar cells decreases by 3% compared to solar cell with glass cover, however, the decrease of solar cell with glass cover and the patch antenna is 2% more or less. Also, with the meshed patch antenna, the difference is around 0.6% which is a very small loss in efficiency considering the glass cover.

## VII. CONCLUSION

In conclusion, the use of a transparent antenna with a solar panel for energy harvesting offers several advantages and opportunities. Firstly, the transparency of the antenna allows for efficient sunlight penetration to reach the solar panel, maximizing the energy conversion process. This ensures that a significant amount of solar energy is harvested, leading to higher energy production. Additionally, the integration of an antenna with a solar panel eliminates the need for separate structures or installations, reducing costs and simplifying the overall system design. This streamlined approach not only saves resources but also enhances aesthetics by maintaining transparency and `minimizing visual obstructions. Furthermore, the combination of an antenna and a solar panel enables dual functionality. While the solar panel harnesses sunlight for electricity generation, the antenna can simultaneously receive and transmit wireless signals. This versatility opens up possibilities for applications such as wireless communication systems or Internet of Things (IoT) devices that require both power supply and connectivity

## VIII. REFERENCES


Assogba, O. M. (2020). Efficiency in RF energy harvesting systems: A comprehensive review. *IEEE International Conf on Natural and Engineering Sciences for Sahel's Sustainable Development-Impact of Big Data Application on Society and Environment (IBASE-BF)* , (pp. (pp. 1-10)). Ouagadougou, Burkina Faso.

Benkalfate, C. O. (2022). A new RF energy harvesting system based on two architectures to enhance the DC output voltage for WSN feeding. *Sensors*, 22, 3576.

Chen, Y. &. (2018). Transparent antenna for energy harvesting applications. . *IEEE Transactions on Antennas and Propagation*, 1009-1016.

E. M. Ali, N. Z. (2017). Design of microstrip patch antenna at 900 MHz for charging mobile applications,. *J. Eng. Appl. Sci.*, vol. 12, no. 4, pp. 988–993,.

F. Z. Khoutar, M. A. (2018). Gain and directivity enhancement of a rectangular microstrip patch antenna using a single layer metamaterial superstrate. *6th International Conference on Multimedia Computing and Systems, ICMCS* , (pp. pp. 1–4.). Rabat, Morocco.

Ibrahim, H. H.-B. (2022). Radio frequency energy harvesting technologies: A comprehensive review on designing, methodologies, and potential applications. *Sensors, .* , 22(11), 4144.

Khan, D. O. (2020). An efficient reconfigurable RF-DC converter with wide input power range for RF energy harvesting. *IEEE Access*, 8, 79310-79318.

Kim, H. K. (2017). Transparent antenna for energy harvesting in wearable electronics using flexible solar cells. *IEEE Transactions on Components, Packaging and*, 7(5), 749-756.

Li, L. &. (2019). Transparent solar cell integrated with transparent antenna for energy. *IEEE Transactions on Antennas and Propagation*, 1964-1970.

Lin, C. &. (2017). A transparent antenna design for energy harvesting from ambient RF signals . *IEEE Transactions on Antennas and Propagation Letters,* , 16(5), 1432-1435.

Liu, Y. W. (2018). Design and optimization of a transparent antenna for energy harvesting from ambient RF signals at Wi-Fi frequency band. Progress In Electromagnetics Research C:. *Journal of Electromagnetic Waves and Applications*, 87 , pp .17–27.

M. J. Roo Ons, S. V. (2017). Transparent Patch Antenna on a-Si Thin Film Glass Solar Module. *ELECTRONICS LETTERS*, Vol. 47, issue 2, pp. 85-86, 01/2011.

S. Ahmed, Z. Z. (2018). A novel design of circularly polarized aperture-coupled antenna with harmonic rejection for rectenna application. *nt. J. Commun. Antenna Propag*, vol. 8, no. 4, pp. 288–293,.

S. Gnanamurugan, B. N. (2017). Gain and directivity enhancement of rectangular microstrip patch antenna using HFSS,'. *Asian J. Appl. Sci. Technol.*, vol. 1, pp.1-6.

T. Sanislav, S. Z. (2018). Wireless energy harvesting: Empirical results and practical considerations for Internet of Things,. *J. Netw. Comput. Appl*, Vol 121 pp. 149–158.

Wang J, Z. L. (2019). Dual-Band Transparent Antenna With High Efficiency for Energy Harvesting Applications. *IEEE Transactions on Antennas and Propagation*, 67(2):1184-1190.

Wu, Z. C. (2019). Design of a transparent antenna with high efficiency for energy harvesting applications in smart windows. *IEEE Transactions on Antennas and*, 18(5), 911-915.

Y. Ahmed, S. M. (2020). A planar inverted-F antenna (PIFA) loaded with slot for RF energy harvesting application. *Int. J. Commun. Antenna Propag.,* , vol. 10, no.1pp 51–57,.

Yang, Y. (2020). transparent antenna design for energy harvesting from ambient electromagnetic waves. *Journal of Applied Physics,*, 127(20), 204501.

Zhang, H. Y. (2020). Transparent solar cell integrated with transparent antenna for energy harvesting in Internet of Things applications. *Electronics Letters,*, 56(2), 69-71.