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# Structural Design and Optimization of Optical Nano-Antenna Based on Bridge Structure

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**Abstract**—Optical nano-antenna offers a new scheme for solar energy collection by breaking through the band-gap limitation of semiconductor materials. However, complex structure, low efficiency, and narrow bandwidth remain major issues. To address these problems, we propose a novel helical optical nano-antenna based on the bridge structure. The antenna structure consists of two coplanar Archimedes spiral arms and a base layer. We analyze the influence mechanism of structural factors on its radiation efficiency and polarization characteristics. Our results show that the antenna structure achieves a total radiation efficiency of 83.13% in the wide wavelength range of 400 to 1600 nm, which is significantly higher than that of the previously proposed dipole nano-antenna. For different linearly polarized incident waves, the antenna structure obtains the same order electric field at the spiral gap, which indicates that the antenna structure can fully consider the polarization characteristics of sunlight. It fundamentally solves the problem that the linearly polarized antenna can only receive half of the solar energy, improving the absorption efficiency.

## 1. INTRODUCTION

The world is facing a significant energy crisis, and solar energy has emerged as one of the most abundant and least polluting renewable resources. To effectively utilize solar energy, efficient solar energy absorption devices are required [1]. Currently, solar cells based on the photovoltaic effect are the primary method for collecting solar energy. However, the absorption rate of semiconductor materials is limited by their band width, making it difficult to improve further. Alternatively, due to the wave-particle duality characteristics of sunlight, it can also be absorbed and radiated by nanoscale antennas [2–4].

The optical nano-antenna is composed of a nano-antenna and a rectifier diode, which can convert the incident sunlight into direct current for external loads. Theoretically, optical nano-antennas can achieve a light energy collection efficiency of over 85% or even 90% [5]. In 1972, Bailey first proposed the concept of a solar cell with a nano-rectifier antenna [6], and in 1984, Marks proposed a new structure using a submicron-cross dipole antenna array and a full wave rectifier [7]. However, due to the limitations of nanotechnology at the time, this structure could not be verified.

The efficiency of optical nano-antennas in converting sunlight includes several factors, such as light receiving efficiency, impedance matching efficiency between the antenna and diode, and rectification efficiency [8]. Vandenbosch and Ma conducted a study on 250 nm dipole antennas made of five different metal materials placed on a substrate [9]. Their results revealed that the total radiation efficiency of these materials in the 400–1400 nm wavelength range was the highest for silver at 61.6%, followed by aluminum at 50.3%, gold at 34.3%, copper at 29.5%, and chromium at 9.4%. Later, researchers

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proposed a flower-shaped dipole antenna that showed a 32.7% higher total radiation efficiency than the gold dipole antenna proposed by Vandenbosch and Ma [10].

The optical antennas discussed above are linearly polarized, whereas sunlight is a high-frequency electromagnetic wave with arbitrary polarization [11]. Therefore, if these antennas are used for solar energy collection, the absorbed power density will be reduced by half [12]. To address this limitation, spiral antennas have been proposed as a broadband solution that is independent of polarization direction [13, 14]. However, previous studies have mainly focused on the near-infrared frequency band [3, 5, 15–17] and have not covered the full solar spectral range. These studies have investigated the near-field characteristics of the antenna, such as surface plasma [18], electric field enhancement effects between multiple coupled spiral elements [17], and electric field enhancement effects of sunlight at the gap between single spiral elements [16], as well as radiation efficiency in infrared light energy collection. Although the near-field is an important parameter for antennas, little research has been done on the radiation efficiency of spiral nano-antennas for solar energy conversion.

This paper addresses the issues mentioned above by proposing an Archimedes spiral antenna that operates within a wavelength range of 400–1600 nm. Its working bandwidth covers 85% of the solar radiation energy, making it suitable for solar energy collection. For the first time, the FDTD method is used to analyze the antenna radiation efficiency and polarization characteristics, taking into account the influence of structural factors. The analysis results indicate that the total radiation efficiency of the antenna can reach 83.13%. The near-field electric field enhancement effect is also analyzed, proving that the antenna structure meets the requirements of arbitrary polarization of sunlight, overcoming the limitations of previous linearly polarized nano-antennas.

## 2. THEORY AND STRUCTURE

According to the principles of quantum mechanics, when an atom undergoes a dipole transition in a non-uniform medium, it can only experience attenuation through radiation. This fundamental concept can be linked to the radiation effect of a classical dipole in a uniform environment [19]:

$$\frac{\Gamma_r}{\Gamma_r^0} = \frac{P_r}{P_0} \tag{1}$$

In this equation, the symbols $\Gamma_r$ and $P_r$ represent the attenuation rate and radiation power in a nonuniform environment (where a nano-antenna is located near the dipole source), while $\Gamma_r^0$ and $P_0$ are the attenuation rate and radiation power in a uniform environment (without an antenna). The left-hand side of Equation (1) represents the phenomenon of spontaneous emission in quantum mechanics, while the right-hand side represents the classical form of dipole radiation.

To characterize the radiation efficiency of the nano-antenna at a specific operating wavelength, the finite-difference time-domain (FDTD) method is used to obtain the frequency response of a time-domain pulse excited by a point dipole placed at the gap of the spiral nano-antenna, which is then Fourier transformed. The ratio of the power radiated to the far field to the total power emitted by the dipole source can be used to determine the radiation efficiency of the nano-antenna.

$$\eta^r = \frac{\Gamma_r}{\Gamma_t} = \frac{P_r}{P_t} \tag{2}$$

The computation of $P_r$ involves the integration of the Poynting vector over the closed surface of the nano-antenna and dipole excitation source, whereas $P_t$ represents the integration of the Poynting vector over the closed surface of the dipole source alone [20, 21]. The radiation attenuation rate is represented by $\Gamma_r$. $\Gamma_t$ is the non-radiation attenuation rate [22], caused by the power absorbed by the metal nano-antenna itself due to the imaginary part of the dielectric coefficient of the optical frequency metal [23]. In line with the findings of [9], metallic silver is chosen as the antenna material in this study, and its dielectric coefficient is obtained through fitting the experimental values reported by Johnson and Christy [24]. To prevent stray reflection, a perfect absorbing boundary is implemented to truncate the computational domain, and the grid is set at 1 nm.

The total radiation efficiency of the antenna in a certain frequency range is defined as [9],

$$\eta^{\text{tot}} = \frac{\displaystyle\int_{\lambda_L}^{\lambda_U} P(\lambda, T) \times \eta^r(\lambda) \mathrm{d}\lambda}{\displaystyle\int_{\lambda_L}^{\lambda_U} P(\lambda, T) \mathrm{d}\lambda} \tag{3}$$

where $\lambda$ is the wavelength; $\lambda_L$ and $\lambda_U$ represent the upper and lower limits of the wavelength; and $P$ is the Planck's law of blackbody radiation.

$$P(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \times \frac{1}{e^{hc/\lambda kT} - 1} \tag{4}$$

where $T$, $h$, $c$, and $k$ are the absolute temperature ($K$), Planck constant ($6.626 \times 10^{-34}$ Js), the speed of light ($3 \times 10^8$ m/s), and Boltzmann constant ($1.38 \times 10^{-23}$ J/K) of blackbody, respectively.

## 3. RESULTS AND DISCUSSION

The optical nano-antenna proposed in this study is a bridge-type structure based on an Archimedes spiral antenna, as illustrated in Figure 1. The antenna comprises two coplanar Archimedes spiral arms,

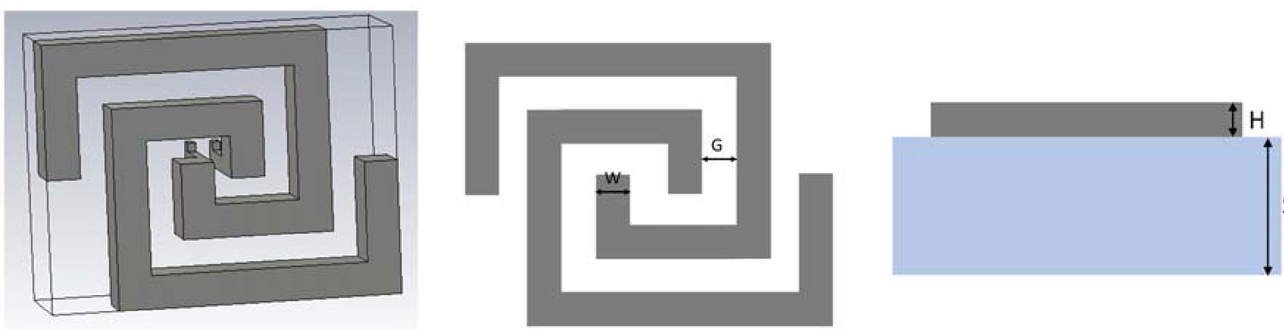


**Figure 1.** Structure model of bridge type nano-antenna.

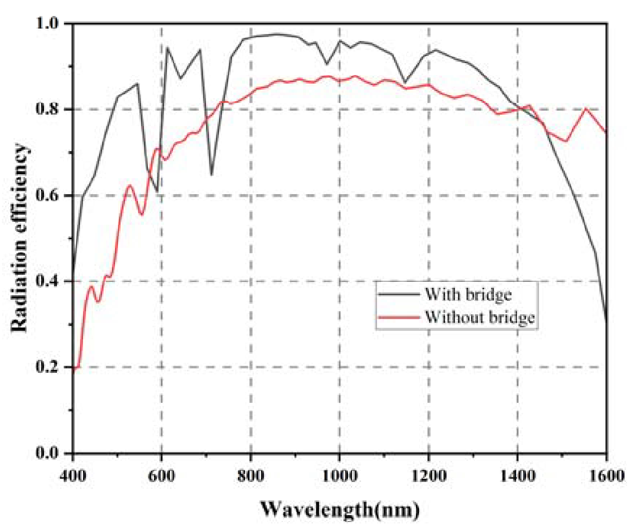


**Figure 2.** The effect of bridge structure on radiation efficiency.

each forming a ring. To ensure optimal performance, the initial arm height ($H$) and width ($W$) were selected based on prior research [9], with $H = 40\,\mathrm{nm}$ and $W = 40\,\mathrm{nm}$. The gap between the two arms ($G$) was set to $W$, forming a self-compensation structure. As the amplitude of the electric field generated by the dipole excitation source is proportional to the distance ($1/R^3$) from the source, a larger gap would result in weaker coupling between the excitation source and the antenna [25]. Thus, a gap distance of 20 nm was selected for the spiral feed.

The bridge structure of the nano-antenna serves the purpose of enhancing its radiation efficiency by increasing the radiation area. As depicted in Figure 2, this structure facilitates feeding, enabling the antenna to emit more electromagnetic waves. Moreover, the reciprocity theorem indicates that the nano-antenna can also receive solar energy, which excites surface plasmons under light. The bridge structure enables more electromagnetic waves to be confined between the two arms, leading to a stronger electric field enhancement.

### 3.1. Polarization

In order to maximize the amount of solar radiation energy that can be harvested, it is important to design nanoantennas that are polarization insensitive. Since sunlight is randomly polarized, a polarization-sensitive nanoantenna would only be able to capture a fraction of the available energy. Figure 3 demonstrates how a properly designed nanoantenna can generate an induced electric field that is insensitive to the polarization direction of incident plane waves. It means that the antenna is equally effective at capturing light with any polarization direction, resulting in a more efficient energy harvesting system.

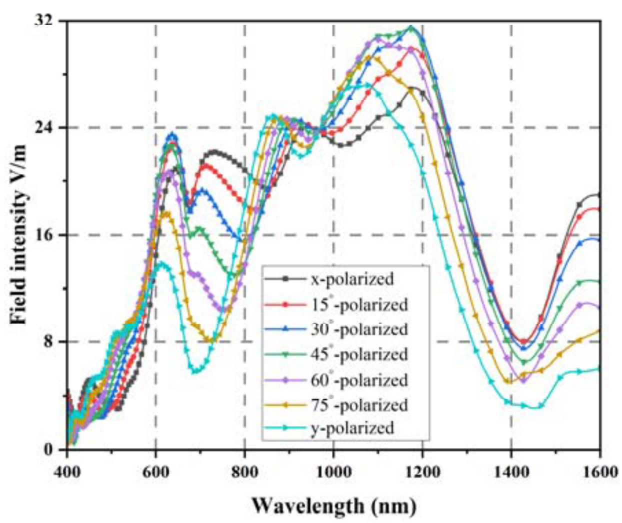


**Figure 3.** Response of the designed spiral nanoantenna to three different polarizations.

Figure 4 depicts the spatial distribution of electric field intensity within the nanoantenna when it is illuminated by polarized plane waves from different directions. It is noteworthy that the electric field experiences a pronounced enhancement at the gap between the antenna arms, where incident light is concentrated and efficiently converted into electrical energy. An intriguing aspect is the precise alignment of the field enhancement with the polarization direction of the incident wave, enabling the antenna to effectively capture light with a specific polarization state. Furthermore, the central region of the antenna helix exhibits the highest electric field intensity, coinciding with the intersection point of the two arms. This concentrated field amplification at the center further augments the antenna's energy harvesting capabilities, facilitating the efficient conversion of light energy into usable electrical power.

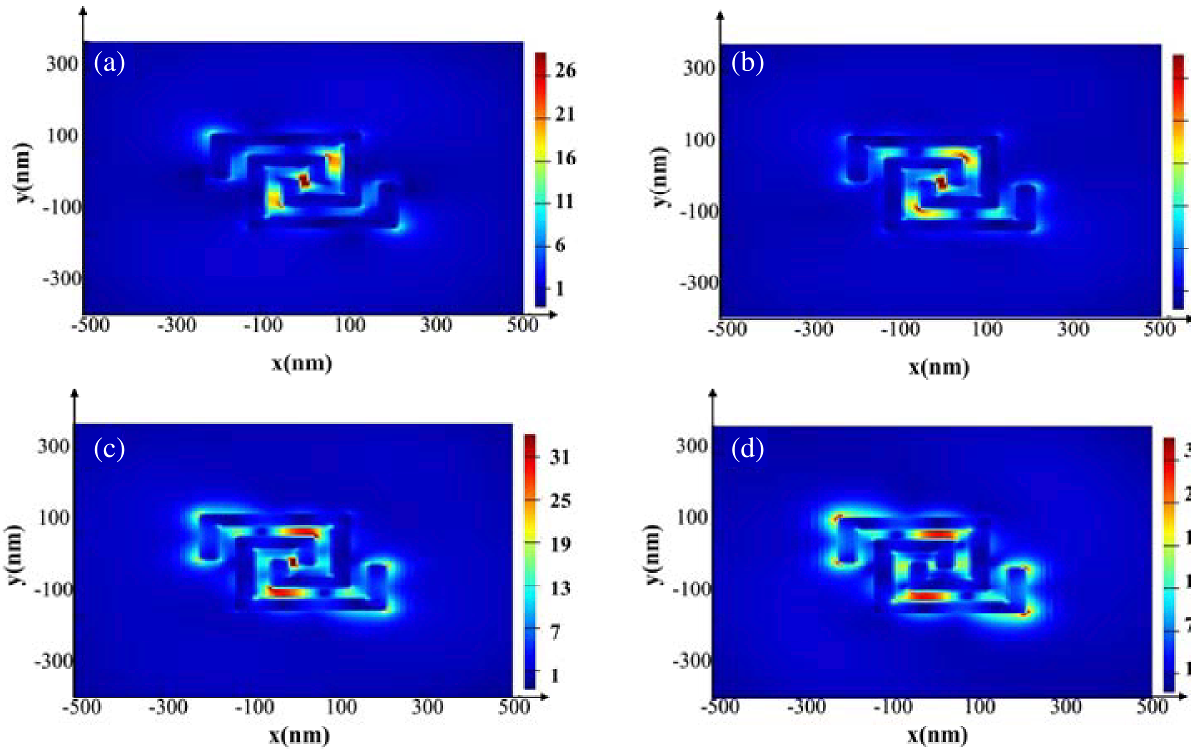


**Figure 4.** Electric field under different polarization. (a) $x$-polarized, (b) 30°-polarized, (c) 60°-polarized, (d) $y$-polarized.

### 3.2. Influence of Geometric Parameters on Radiation Efficiency

The effect of the spiral arm height, $H$, on the antenna radiation efficiency was investigated. The other parameters were kept constant while $H$ was varied from 40 nm to 80 nm, and the resulting curves of antenna radiation efficiency and total radiation efficiency are shown in Figure 5. It was observed that increasing $H$ led to a significant increase in radiation efficiency in the 500–1000 nm wavelength range,

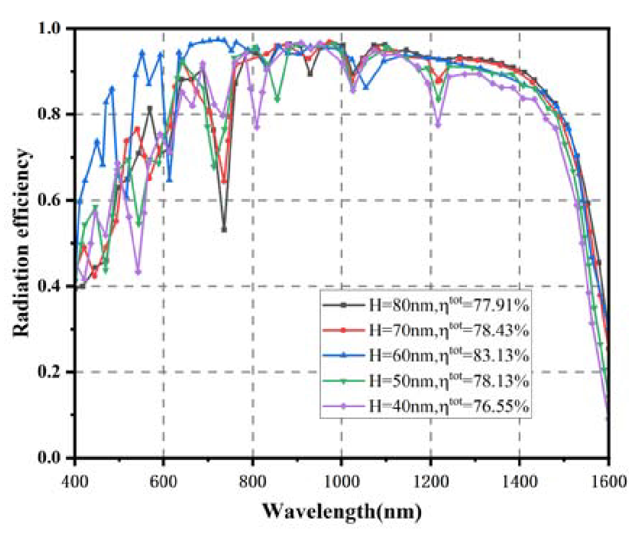


**Figure 5.** Radiation efficiency and total efficiency with different arm height.

with little change in the 1000–1600 nm range. The increase in $H$ favored resonance of the antenna at shorter wavelengths due to the greater transmission depth of metallic silver in the short wavelength range. The total radiation efficiency first increased and then decreased with increasing $H$, with a maximum at $H = 60$ nm.

The width of the spiral arm is an important structural parameter that affects the performance of the antenna. To investigate this parameter, we kept all other parameters constant and increased the width $W$ of the spiral arm from 20 nm to 80 nm in increments of 20 nm. To maintain the self-compensation structure, we also adjusted the spacing $G$ between the two arms accordingly. The variation curve of the antenna radiation efficiency is shown in Figure 6. Based on Planck's law of blackbody radiation, we found that the peak solar radiation power was at a wavelength of $\lambda = 500$ nm. As we widened the nano spiral antenna arm, we observed an increase in radiation efficiency. This suggests that widening the spiral arm is beneficial for antenna resonance, allowing it to radiate more energy to the far field. When $W$ is greater than 60 nm, the radiation efficiency of the antenna within the wavelength range of 600–1400 nm reaches more than 90%. However, we found that the arm width of the spiral arm was not linearly related to the total radiation efficiency. When $W = 80$ nm, the total radiation efficiency of the nanoantenna is the highest.

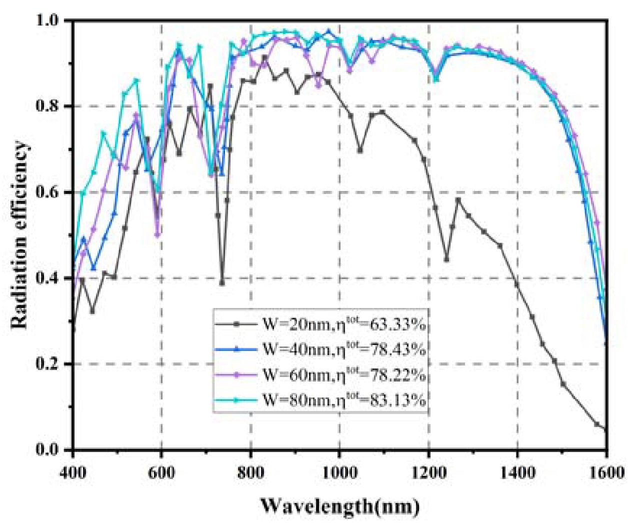


**Figure 6.** Radiation efficiency and total efficiency with different arm width.

The variation rule of antenna radiation efficiency with wavelength for different numbers of spiral arm rings $N$ is shown in Figure 7. The results demonstrate that the antenna structure has obvious broadband characteristics. Although the total radiation efficiency does not increase significantly with the increase of the number of rings $N$, it only changes near the wavelength of 800 nm, indicating that multiple rings are conducive to resonance here and can increase the radiation efficiency. As the number of rings increases, the radiation efficiency remains unchanged in the wavelength range of 400–600 nm. The reason for this is that the surface plasma mode experiences significant loss when propagating at the metal-air interface and can transmit for a limited distance. Therefore, the response wavelength of the antenna at the optical frequency is shorter than that at the radio frequency, which is known as the size reduction effect [26]. Basic theory suggests that, without considering impedance matching, the total efficiency of an antenna system can be improved by reducing the antenna size while maintaining a high radiation efficiency. To avoid wasting the antenna geometric aperture, we have chosen the case of $N = 1$.

Overall, the design of the antenna should take into account the supporting medium for convenience. In this study, silicon dioxide ($\varepsilon_d = 2.25$) is used as the supporting medium, and the Archimedes spiral nano-antenna is placed on it. Based on the analysis of previous parameters, the antenna parameters were set to $N = 1$, $W = 80$ nm, $G = 80$ nm, and $H = 60$ nm, and the total radiation efficiency in a

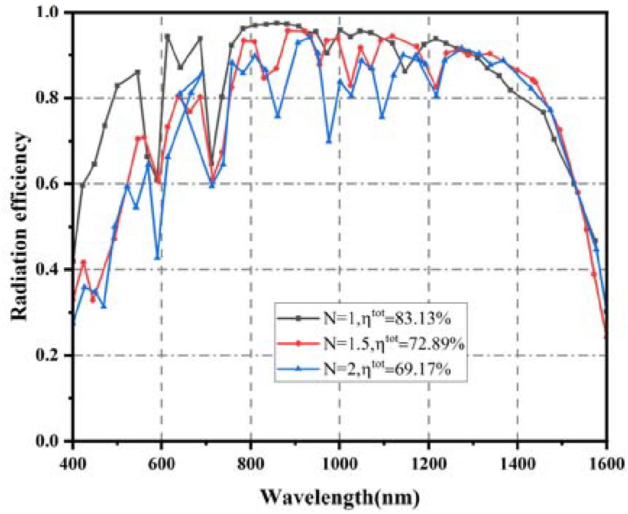


**Figure 7.** Radiation efficiency and total efficiency with different ring numbers.

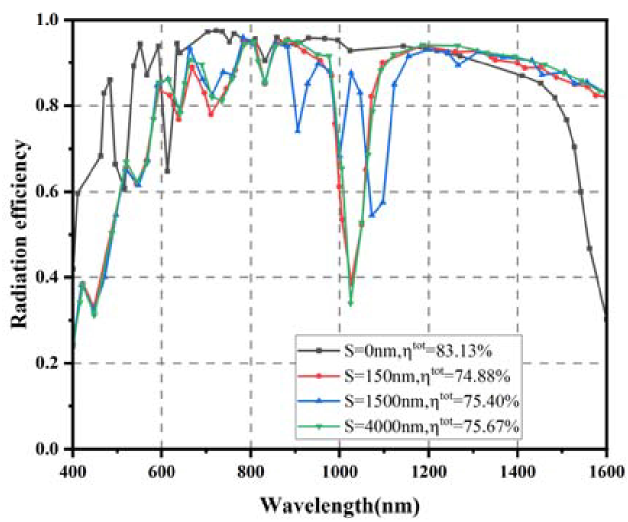


**Figure 8.** Radiation efficiency and total efficiency with different dielectric thicknesses.

vacuum was found to be 83.13%. Next, the thickness of the medium ($S$) was used as an influencing factor to study the change of radiation efficiency with wavelength and the total radiation efficiency within the entire working wavelength.

Figure 8 shows that the radiation efficiency of the antenna with the medium is lower than that without the medium. This is because the reflection of the electromagnetic wave at the interface of the medium causes more energy loss in the material, leading to a decrease in radiation efficiency when there is a medium. As the thickness of the medium increases, the total radiation efficiency first decreases, but for thicker dielectric layers, the total radiation efficiency gradually recovers and becomes larger, which is consistent with previous literature [9]. If the dielectric thickness tends to be infinite, the total radiation efficiency should be theoretically the same as the total efficiency of the skyline in a vacuum. However, due to the limitations of simulation conditions, this paper does not set the media as infinite thickness. In the manufacture of nano-antennas, the thickness of the dielectric layer is typically much greater than the wavelength of the optical frequency, so a thicker dielectric layer is also in line with practical considerations.

However, considering the practical limitations in achieving ideal dimensions during the fabrication of nanoantennas, it is often challenging to realize straight edges as designed. To address this issue, we introduce a rounding to the straight edges of the nanoantennas in our simulation software, aiming to achieve a closer representation of real-world conditions. As shown in Figure 9, the rounding radius varies from 0 nm to 20 nm. The simulation results indicate that the presence of rounded edges leads to a slight decrease in radiation efficiency. This phenomenon can be attributed to the bending and scattering of the electromagnetic field at the edges caused by the rounding. Nevertheless, the reduction in radiation efficiency due to the presence of rounded edges is generally acceptable since the size of nanoantennas is already extremely small, resulting in minimal energy losses from edge scattering. Furthermore, adopting rounded edges enhances the feasibility of fabricating nanoantennas, aligning them more closely with practical manufacturing considerations.

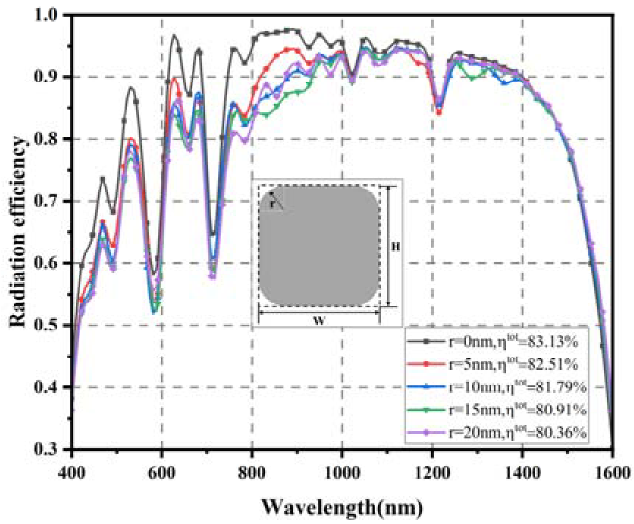


**Figure 9.** Radiation efficiency and total efficiency with different rounding radius.

## 4. CONCLUSION

Overall, the new bridge-type optical nano-antenna structure designed in this paper shows great potential in efficiently utilizing solar energy. The analysis results demonstrate that the antenna has a total radiation efficiency of 83.13% in the working wavelength range of 400–1600 nm, which covers most of the solar spectrum and matches the solar polarization characteristics. This efficiency is significantly higher than what has been reported in the existing literature. Although experimental verification was not feasible due to current limitations in nanoscale metal material processing, simulations were conducted by applying rounded corners to the nanoantenna to approximate real-world conditions. The results showed that the impact of rounded corners on the radiation efficiency was negligible. Future work can focus on exploring methods for the precise manufacturing of the antenna structure and further experimental verification to fully validate its potential for solar energy utilization.

## DISCLOSURES

The authors declare that there are no conflicts of interest related to this article.

## DATA AVAILABILITY

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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