CHARACTERIZATION OF A SQUARE SPIRAL ALUMINIUM NANTENNA FOR SOLAR ENERGY HARVESTING

[1]APICHARD SAEAUNG, [2]RARDCHAWADEE SILAPUNT

[1,2]Electronic and Telecommunication Engineering Department KMUTT Thailand
E-mail: [1]apichard.saeaung@mail.kmutt.ac.th, [2]rardchawadee.sil@kmutt.ac.th

Abstract- In this paper, the aluminium square spiral nano-antenna is proposed for solar energy collection. The characterization of these nantennas based on their geometrical parameters is carried out using simulation. The geometrical parameters include inner radius, arm width, turn width, and gap width. The simulation is performed in the ultraviolet to near infrared region. It is found that geometrical parameters significantly affect the electric field enhancement capability and also resonant wavelengths. The results demonstrate 10^3-10^4 electric field enhancement at the feeding point of nantennas. The maximum field enhancement is achieved with smallest gap and arm widths, but largest radius and turn width structure. The resonant wavelength shifts up as the overall nantenna dimension increases. The simple linear mathematical prediction models for electric field enhancement and resonant wavelengths are generated for specific set of inputs. Both aluminium and gold nantennas produce comparable field enhancement over the range of interest, which suggests the aluminium nantenna as a potential candidate for nantenna applications.

Keywords- Aluminium nantenna, Finite Element Method, Solar Energy Collection, Spiral antennas

I. INTRODUCTION

During the last few decades, a demand for energy consumption in the world has been rapidly increased. Although the hydrocarbon-based energy is the most common energy source for current civilizations, this type of energy also causes various environmental problems. In order to solve these problems and sustain the demand, searching for clean and renewable energy resources is necessary [1]. One of the most powerful energy sources is the solar power. Solar cells or photovoltaic (PV) cells are developed to collect sunlight and convert it to usable electricity. However, the main disadvantage of PV cells is its low conversion efficiency. Therefore, many researches have been focused on searching and developing high efficiency solar energy collectors to replace PV.

The idea to use the nantenna (nano-antenna) for solar collecting was introduced by Bailey in 1972 [2]. It is known that 85% of solar radiation spectrum lies in visible and near-infrared wavelengths of around 0.4-1.6 μm, as shown as Fig.1. Therefore, nantennas are mostly designed to operate in the THz band [3]. Moreover, some of the nantennas could be used in the far-infrared region (around 8-14 μm) to capture reradiated energy from earth surface [1]-[4]. It was reported that nantennas can provide more efficiency than conventional solar cells [4]. The key mechanism of solar nantennas is a significant local field enhancement at a feeding point or a gap, based on the localized surface plasmonic resonance (LSPR) effect. Surface Plasmons (SPs) are electron oscillations occurred at the interface between metal and dielectric of sub-wavelength size. During the excitation, SPs will be coupled with photons, resulting in collective electron charge oscillations in the visible and near infrared regions. These electron oscillations will in turn, generate alternating currents with different phases and amplitudes. The current waves will eventually create a standing wave by interference at resonance and results in near field enhancement. For a nantenna, the near field that arises from LSPR phenomena will be affected by the nantenna configuration such as size, shape, material, and arrangement [5], [6]. In order to obtain a DC power for further use, a rectifier is required.

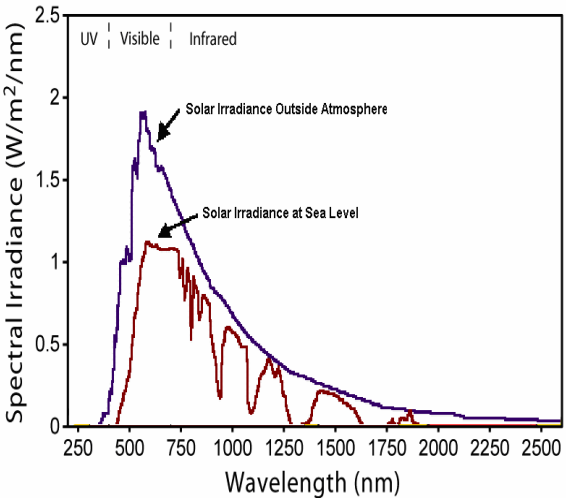


Fig.1. The solar radiation spectrum [3]

Many researches on design and optimization of energy harvesting nantennas have been proposed. Various types of nantennas have been studied including dipole [4], [7], bow-tie [4], [8], archimedean spiral [9], square spiral [10], [11], and logarithm spiral [10].

Noble metals have certain properties to efficiently induce the LSPR effect and the field enhancement efficiency depends to a large extent, on their permittivity [7]. It is found that energy harvesting nantennas are usually made of gold, not only because of its permittivity but also because of its low

oxidation rate compared to other materials [7]. The down side of gold is definitely the cost.
This research aims to design and characterize square spiral aluminium nantennas in the ultraviolet (UV) to near infrared (NIR) region. Aluminium is explored here since it is a good metal that is inexpensive and abundant [12].

It may be able to use as a gold replacement. Spiral antennas are proposed in this application due to their broad bandwidth. In particular, the square spiral antenna is chosen over the circular one to reduce the overall dimension comparatively with comparable gain.
This paper is organized as follows. Section 2 proposes nantenna design and simulation setup. Results and discussion of the performance of square spiral aluminium nantennas are presented in section 3. Finally, the conclusions are presented in section 4.

II. DESIGN AND SIMULATION SETUP

The design and simulation of the aluminium square spiral nantenna for solar energy collection is presented in this section. All simulations are carried out using the Finite Element Method (FEM) by COMSOL Multiphysics simulator. The nantenna structure consists of the aluminium antenna deposited in the silica glass substrate with frequency dependent dielectric constant (ε_r) [13]. The square spiral nantenna is illustrated in Fig. 2.
The complex dielectric constant of aluminium is also frequency dependent and adopted from [13], [14]. The aluminium dielectric constant profiles are shown in Fig. 3.
A plane wave is launched into the antenna at normal incident with a magnitude of electric field 1 V/m and polarized along the x-axis of the antenna. The antenna is surrounded with an assumed perfectly matched layer (PML) to eliminate reflected waves. Geometrical parameters including inner radius (R_{in}), arm width (AW), turn width (TW), and gap width (GW) are studied. Parameter values are shown in

Table. 1. The performance of the proposed nantenna is measured by electric field enhancement and resonant wavelengths associated with nantenna geometry variations. The studied wavelength is varied between 250-2,250 nm, which lies in the ultraviolet to near infrared region.
The electric field enhancement is defined as the ratio of electric field at the gap and input electric field

III. RESULTS AND DISCUSSION

The electric field enhancement profiles of aluminium square spiral nantennas as a function of exciting wavelength are illustrated in Figs. 4-7, respectively. From all profiles, the electric field enhancements increase steadily with the wavelength. The aluminium

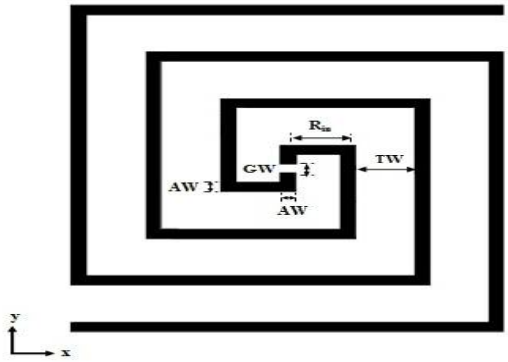


Fig.2. Aluminium Square Spiral Nano-antenna with Geometrical Parameters

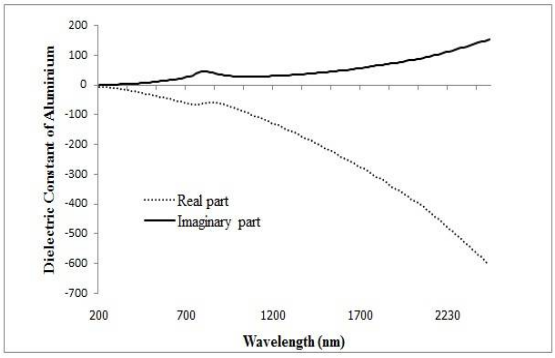


Fig.3. Dielectric constant of aluminium versus wavelength

Table 1: Spiral Nano-antenna Geometrical Parameters

No.	Parameters	Range (nm)
1	Inner radius (R_{in})	80-140
2	Arm width (AW)	20-50
3	Turn width (TW)	80-140
4	Gap width (GW)	20-50

nantennas can offer the electric field enhancement around 10^3 - 10^4 times. The captured electric field is obviously increased when the inner radius and turn width increase, except for the first resonance of the inner radius variation in Fig. 4 at around 790 – 990 nm. On the other hand, increasing arm width and gap width results in decreasing field enhancement.
It is also seen that the resonant wavelengths are shifted to longer wavelengths when parameter values increase except for the gap width that the resonant wavelengths remain relatively the same. These results suggest that the resonant wavelength actually increases with the overall size of the nantenna. In case of gap width variation, the third resonant wavelength is observed at around 1,990 nm, as shown in Fig. 7.
By comparing these results, it is found that the maximum electric field enhancement is produced by the structure with 80-nm inner radius, 20-nm arm width, 140-nm turn width, and 20-nm gap width. The enhancement values are 1.24×10^4 at the first resonance (990 nm) and 2.22×10^4 at the second resonance (2,030 nm). The electric field distribution at the second resonance is shown in Fig. 8. Simple

mathematical prediction models of electric field enhancements and resonant wavelengths as a function of geometrical parameters are shown below. Note that, these models are valid only in the specified ranges of parameters and with the input electric field magnitude of 1 V/m polarized along the x-axis.

$E_1 = 19805 - 87.9R_{in} - 72.5AW + 45.6TW - 220GW$

$E_2 = 2649 + 112R_{in} - 135AW + 137TW - 297GW$

$\lambda_1 = 134 + 3.40R_{in} + 5.94AW + 3.25TW + 0.364GW$

$\lambda_2 = 23.9 + 4.66R_{in} + 13.2AW + 9.66TW + 0.757GW,$

where E_1 represents the electric field enhancement at the first resonance, E_2 is the electric field enhancement at the second resonance, λ_1 is the resonant wavelength (nm) at the first resonance, and λ_2 is the resonant wavelength (nm) at the second resonance.

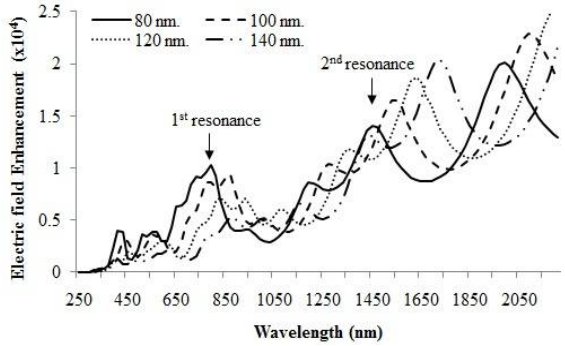


Fig.4. Electric field enhancement versus wavelength for different inner radii

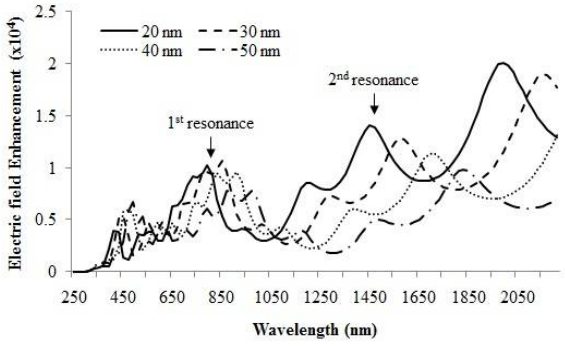


Fig.5. Electric field enhancement versus wavelength for different arm widths

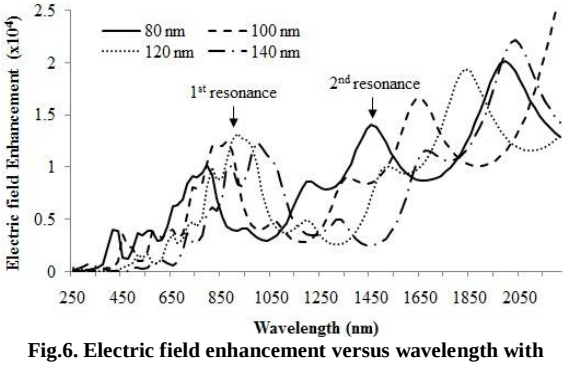


Fig.6. Electric field enhancement versus wavelength with different turn widths

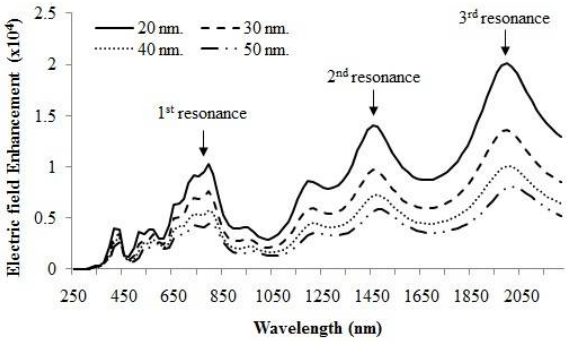


Fig.7. Electric field enhancement versus wavelength for different gap widths

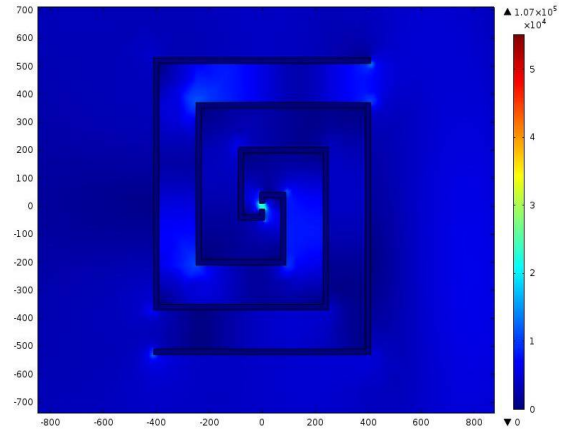


Fig.8. Electric field enhancement at 2,030 nm of optimized aluminium square spiral nantenna

Moreover, we also compare the field enhancement characteristics of square spiral aluminium and gold nantennas using the maximum field enhancement geometry as illustrated in Fig. 9. The result shows that both nantennas produce comparable field enhancement over the range of interest. In addition, the resonant wavelengths appear roughly at the same locations. The first resonant wavelength is found at 990 nm and the second one is found at 2,010 nm. The result suggests that the aluminium nantenna is a viable candidate for nantenna applications.

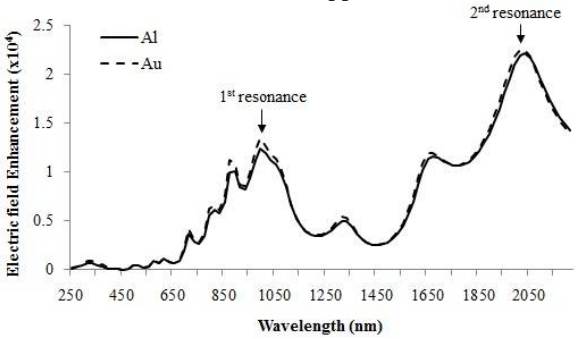


Fig.9. Electric field enhancement versus wavelength between aluminium and gold square spiral nantennas.

CONCLUSIONS

In this paper, the aluminium square spiral nanoantenna for solar energy collection is designed and characterized. The performance of antennas is

measured using electric field enhancement and resonant wavelengths. The results show that the aluminium nantenna can provide 10^3-10^4 electric field enhancement. The geometrical parameters of square spiral nano-antennas such as inner radius, arm width, turn width, and gap width can be optimized to give the maximum electric field.

The electric field enhancement can be increased by increasing inner radius and turn width, and reducing arm width and gap width. The resonant wavelengths shift to longer wavelengths when inner radius, arm width, and turn width increase. The result implies that the resonant wavelength increases with the overall size of the nantenna. Both aluminium and gold nantennas produce comparable field enhancement over the range of interest, which suggests the aluminium nantenna as a potential candidate for nantenna applications. The power conversion and extraction for further use will be focused in future works.

REFERENCES

[1]. L. Mescia, and A. Massaro, "New Trends in Energy Harvesting from Earth Long-Wave Infrared Emission", Advances in Materials Science and Engineering, vol. 2014, Article ID 252879, 10 pages, 2014.

[2]. D. K. Kotter, S. D. Novack, W. D. Slafer, and P. J. Pinhero, "Solar Nantenna Electromagnetic Collectors", Proceedings of the 2nd International Conference on Energy Sustainability, Florida, USA, August 2008.

[3]. M. Bozzetti, G. de Candia, M. Gallo, O. Losito, L. Mescia, and F. Prudenzano, "Analysis and design of a solar rectenna", Industrial Electronics (ISIE), 2010 IEEE International Symposium, pp.2001-2004, 4-7 July 2010.

[4]. A.M.A. Sabaawi, C.C. Tsimenidis, and B.S. Sharif, "Infra-red nano-antennas for solar energy collection", Antennas and Propagation Conference (LAPC), pp.1-4, 14-15 November 2011.

[5]. W. Yu-Ming, "Analysis and Design of Nanoantennas", Ph.D. thesis, Electrical and Computer Engineering, National University of Singapore, pp.4-12, 2010.

[6]. M. C. KILINC, "Resonant Optical Nanoantennas and Applications", M.S. thesis, Material Science and Technology, The Institute of Engineering and Sciences of Bilkent University, pp.8-13, August 2010.

[7]. G.A.E. Vandenbosch, and Z. Ma, "Upper bounds for the solar energy harvesting efficiency of nano-antennas", Nano Energy, vol. 1,no. 3,pp. 494-502, May 2012.

[8]. A.M.A. Sabaawi, C.C. Tsimenidis, and B.S. Sharif, "Planar Bowtie Nanoarray for THz Energy Detection", Terahertz Science and Technology, IEEE Transactions, vol. 3, no. 5, pp.524-531, September 2013.

[9]. Y. Li, K. Sun, and Y. Jiang, "A Computation Model for Nanoantenna-based Solar Cell with High Conversion Efficiency", 2013

[10]. A.M.A. Sabaawi, C.C. Tsimenidis, and B.S. Sharif, "Infra-red spiral nano-antennas", Antennas and Propagation Conference (LAPC), pp.1-4, 12-13 November 2012.

[11]. M. Gallo, L. Mescia, O. Losito, M. Bozzetti, and F. Prudenzano, "Design of optical antenna for solar energy collection", Energy, vol. 39, no. 1, pp. 27–32, 2012.

[12]. M. W. Knight et al, "Aluminum Plasmonics Nanoantennas", Nano Lett., pp. 6000–6004, 2012.

[13]. Refractive index database (http://refractiveindex.info/)

[14]. A. D. Rakić, "Algorithm for the determination of intrinsic optical constants of metal films: application to aluminum", Applied Optics, vol. 34, no. 12, pp. 4755-4767, 1995.

★★★