Analysis and Design of the Dielectric Yagi-Uda Nanoantenna with a Double Driven Element

Thanatcha Satitchantrakul and Rardchawadee Silapunt
Department of Electronic and Telecommunication
King Mongkut's University of Technology Thonburi, Bangkok, Thailand

Abstract— The Yagi-Uda silicon nanoantenna with the double driven element and 4 directors is proposed here. The simulation of single Si nanoparticles with a diameter between 40 and 53 nm shows an increasing of the directivities for all emitter locations. The trend of the directivity appears to be random as the nanoparticle dimension and emitter distance increase. For the double driven element, the directivity profiles as a function of the radius appears to be wave-like forms. The directivity is clearly determined by two competing factors that are particle coupling and dimension. The directivity of the Yagi-Uda Si nanoantenna can be improved with more number of directors. The maximum directivity of the proposed structure with optimized geometric parameters is 11.42. The preliminary numerical model for predicting the directivity of this antenna is determined. The directivity can be further improved to 12.52 by reducing the gap between the double driven element and the first director.

1. INTRODUCTION

The diffraction limit issue has significantly impeded the development of silicon photonic waveguides for nanoscale interconnect integration in integrated circuits. Currently, many researchers propose a variety of subwavelength scale methods to overcome this problem [1–3]. However, most of them still suffer from high absorption loss during guided-transmission when compared to the silicon (Si) photonic waveguide. Optical wireless nano interconnects using metallic antennas have later been explored. It is found that the plasmonic scheme can potentially reduce such loss [4–8]. However, the absorption loss can be further reduced by the introduction of Si nanoparticles antennas [8, 9]. This dielectric material possesses promising optical and radiation properties at the optical frequency. As the interconnect, the Si nanoparticles antenna can remarkably enhance the transfer data rate in an intrachip link. With a proper design, its performance can certainly be improved.

In this paper, we propose a design and simulation of the Si Yagi-Uda nanoantenna array with a double driven element, for optical transmission. We will determine radiation properties including directivity and radiation patterns for different antenna structures, using computer-aided simulation. Section 2 presents the design approach and simulation parameters and Section 3 presents results and discussion. The conclusion is described in Section 4.

2. DESIGN APPROACH AND SIMULATION PARAMETERS

All model structures consist of Si nanoparticles embedded in SiO_2 to minimize the loss associated with signal refraction. A dipole source is used as an emitter to excite the antenna and placed at the left end of a structure. The process of designing the Yagi-Uda nanoantenna array is as follows. First, the antenna directivity and radiation pattern of single Si nanoparticles with the radius between 40–80 nm are investigated [10]. The exciting wavelength of 660 nm (455 THz) is selected. Note that, this wavelength is simply chosen to demonstrate radiation properties of Si nanoparticles in the visible region. Next, the directivity, radiation pattern, and return loss of the double driven element are studied for different gap sizes at the same exciting wavelength. The Yagi-Uda structures with the double driven element with 1 and 4 directors respectively, are then investigated. The Lorentzian 4 parameters are applied to determine the correlation of geometric

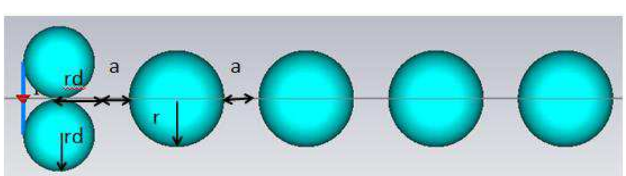


Figure 1: The Yagi-Uda silicon nanoantenna with the double driven element and 4 directors.

parameters. The Finite Integrated Method (FIT) has been used in all simulations. The proposed antenna with 4 directors is shown in Figure 1. The radii of the driven element and director are denoted at rd and r respectively, the side-to-side gap is denoted as d, the emitter distance is denoted as a, and the vertical gap between driven elements is denoted as g.

3. RESULTS AND DISCUSSION

3.1. Single Si Nanoparticles

In this study, the emitter is placed at the distance a, from the Si nanoparticle as shown in Figure 2(a). Figure 2(b) shows the directivity as a function of the emitter location, for different sizes of Si nanoparticles. It can be seen that directivities increase monotonically with the radius only from 40 to 53 nm and start to oscillate after that. The trend of the directivity as a function of the emitter location is also random. The maximum directivity of 4.4 is obtained from the $r = 80$ nm particle and $a = 5.3$ nm. It is believed that the directivity can be further increased with larger particle sizes. However, they may be out of range for magnetic resonance support [10]. The inset shows the radiation pattern associated with the specified particle. We found that the return loss

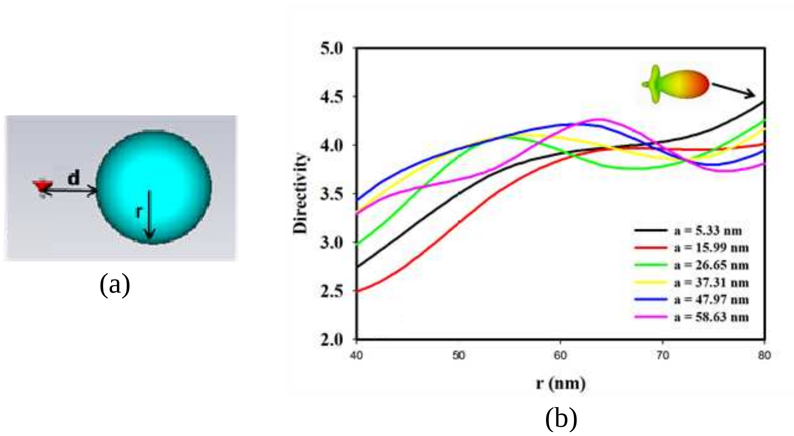


Figure 2: (a) A silicon nanoparticle and (b) directivity as a function of the emitter location.

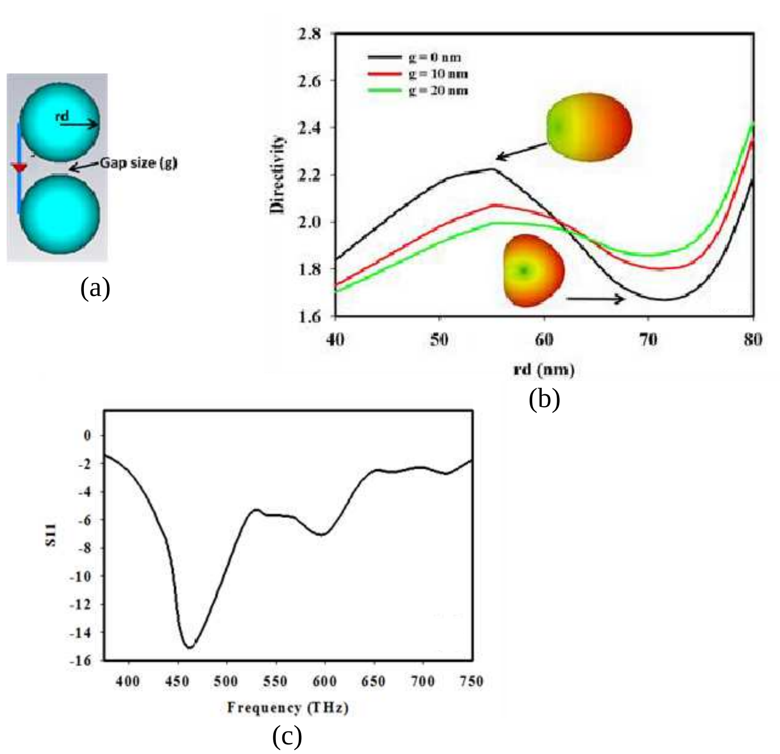


Figure 3: (a) Two silicon nanoparticles aligned vertically, (b) forward directivity as a function of rd for different gap sizes, and (c) insertion loss of the $rd = 54.5$ nm and $g = 0$ structure.

of the single Si nanoparticle, regardless of its dimension, is extremely high (the result is not shown here), suggesting very poor antenna efficiency.

3.2. Double Driven Element

Next, we consider two particles aligned vertically as shown in Figure 3(a). This study is performed in order to measure radiation properties of the double driven element. The emitter is placed on the left end of the elements. The exciting wavelength is 660 nm. Figure 3(b) shows the directivity as a function of the radius for $g = 0$, 10, and 20 nm. All directivity profiles exhibit wave-like forms. The directivity increases as the gap decreases up to $r = 62$ nm. The relation of the two parameters is clearly inversed after that. The insets show associated radiation patterns at $g = 0$, and $rd = 54.5$ and 72 nm, respectively. The result suggests that the directivity is likely product of two competing factors, i.e., rd and g. Note again that, the directivity can be further increased with larger particle sizes; however, they will be out of the magnetic resonance support range. Therefore, we instead consider the double driven element with $rd = 54.5$ nm that generates the maximum directivity of around 2.24 at $g = 0$. The insertion loss vs. the frequency of the mentioned structure is shown in Figure 3(c). The reflection coefficient $|\Gamma|$ at the wavelength of interest is calculated. We find that approximately, 96.9% of power can be transmitted through the double driven element.

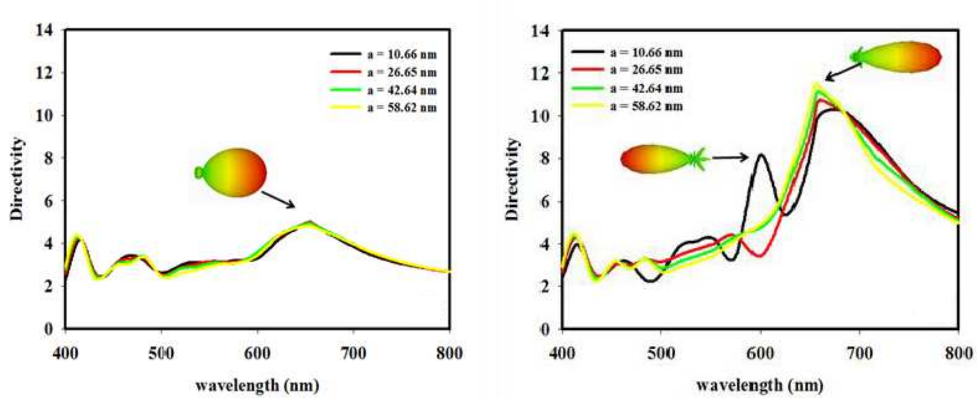
3.3. Yagi-Uda Silicon Nanoantenna

The Yagi-Uda nanoantenna structure with the double driven element is created. The antenna with the double driven element and 1 director is first investigated followed by the proposed structure with 4 directors. The relationships of geometric parameters from both cases are considered for optimization of the antenna directivity. The optimized director and driven element parameters include $r = 74.6$ nm, $rd = 54.5$ nm, and $g = 0$, respectively. Figure 4 illustrates the directivities as a function of the wavelength for 1- and 4-director structures for different side-to-side gap distances. For the 1-director structure, the directivity profiles are fairly similar for all gap distances. The maximum directivity is around 5 and achieved at $\lambda = 650$ nm. The improvement of the directivity can be realized using the 4-director structure, as shown in Figure 5(b). We obtain the maximum directivity of around 11.42. The wavelength at maximum directivity slightly shifts up to 665 nm. Profiles are more similar as a increases. The result suggests the number of directors as one of the important design factors to improve the antenna performance.

From the result of the Yagi-Uda nanoantenna with the double driven element and 4 directors, we can derive the correlation among geometric parameters and directivity by Lorentzian 4 parameters. The preliminary numerical model of the directivity is shown in Equation (1). Note that, this equation can be used in the 400–800 nm range.

$$D = \left(2.549 + \frac{8.546}{1 + \left(\frac{\frac{rd}{r} - 0.805}{0.173}\right)^2}\right) - a, \tag{1}$$

where D is the nanoantenna directivity.



(a) (b)

Figure 4: Directivity profile comparison between Yagi-Uda nanoantenna with (a) 1 director and (b) 4 directors.

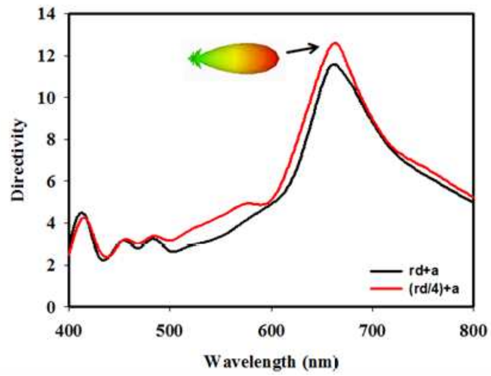


Figure 5: Directivity profiles for structures with distances $rd + a$ and $(rd/4) + a$.

We find that the directivity can be further improved by decreasing the distance between the double driven element and the first director. By simply reducing it from $rd + a$ to $(rd/4) + a$, the directivity can be slightly raised up to 12.52, found at $\lambda = 660\,\text{nm}$. Figure 5 compares the directivities for $rd+a$ and $(rd/4)+a$ structures. Inferred from this result, we believe that coupling between particles strongly affect the radiation properties of the antenna.

4. CONCLUSIONS

Overall, we have discussed the silicon optical nanoantenna as the transmitter for optical wireless link. Our proposed Yagi-Uda Si nanoantenna is made of Si particles and embedded in SiO_2. It is found that the directivity generated by the single Si particle only increases with the particle for $r = 40$–$53\,\text{nm}$, and the profiles become quite random after that. The directivity of two vertically-aligned particles used as the driven element increases as the gap decreases up to $rd = 62\,\text{nm}$. The relation of the two parameters is clearly inversed after that. The result suggests that the directivity is determined by competing effects between particle coupling and particle dimension. Geometric parameters are optimized for the Yagi-Uda with the double driven element structure to enhance directivity and antenna efficiency. The maximum directivity of 11.42 is achieved for the proposed 4-director structure. In addition, we derive the analytical expression for predicting the directivity of this nanoantenna in 400–800 nm range. We finally find that the directivity can be further improved by reducing the gap between the double driven element and the first director. The result suggests strong influence of coupling between particles.

REFERENCES

1. Bozhevolnyi, S. I., *Plasmonic Nanoguides and Circuits*, Pan Stanford Publishing Pte. Ltd., Singapore, 2009.
2. Dionne, J. A., E. Verhagen, A. Polman, and H. A. Atwater, "Are negative index materials achievable with surface plasmon waveguides? A case study of three plasmonic geometries," *Optical Society of America*, Vol. 16, No. 23, 2008.
3. Ctyroky, J., J. Homola, and M. Skalsky, "Modelling of surface plasmon resonance waveguide sensor by complex mode expansion an propagation method," *Optical and Quantum Electronics*, Vol. 29, No. 2, 301–311, Feb. 1997.
4. Alù, A and N. Engheta, "Wireless at the nanoscale: Optical interconnects using matched nanoantennas," *Physical Review Letters*, Vol. 104, 213902, 2010.
5. Novotny, L. and N. V. Hulst, "Antenna for light," *Natural Photonics*, Vol. 5, 83–90, 2011, Doi: 10.1038/nphoton.2010.237.
6. Taminiau, T. H., F. D. Stefani, and N. F. V. Hulst, "Enhanced directional excitation and emission of single emitters by a nano-optical Yagi-Uda antenna," *Optics Express*, Vol. 16, 10858–10866, 2008.
7. Solis, D. M., J. M. Taboada, F. Obelleiro, and L. Landesa, "Optimization of an optical wireless nanolink using directive nanoantennas," *Optics Express*, Vol. 21, No. 2, 2377, Jan. 28, 2013.
8. Maksymov, I. S., I. Staude, A. E. Miroshnichenko, and Y. S. Kivshar, "All-dielectric optical nanoantennas," *Physics Optics*, Jun. 25, 2012.

9. Krasnok, A. E., A. E. Miroshnichenko, P. A. Belov, and Y. S. Kivshar, "Optical Yagi-Uda nanoantennas," *Nanophotonic*, Vol. 1, No. 1, 65–81, Jun. 2012, Doi: 10.1515/nanoph-2012-0005.
10. Evlyukhin, A. B., C. Reinhardt, A. Seidel, B. S. Lukyanchuk, and B. N. Chichkov, "Optical response features of Si-nanoparticle arrays," *Phys. Rev. B*, Vol. 82, 045404, 2010.