Optical Yagi-Uda antenna consisting of an array of nanospheres

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Abstract — In this paper, an array of gold nanospheres is especially designed to be proposed as the optical Yagi-Uda antenna. Its mechanism is the mutual coupling between the dipole resonances of the nanoparticle elements induced by the light. The finite integration technique calculation is developed especially in a wide frequency range to investigate this antenna's properties. It is shown that the antenna provide good directivity by shaping beam in the optical range. An in-depth study is conducted on this optical Yagi-Uda antenna's far-field radiation features by calculating its antenna parameters. The effects influencing its performance have been also considered. Compared with the exiting studies, it has improved flexibility and adjustability. So it can be further integrated with other optical devices for more useful applications.

I. INTRODUCTION

Antennas have been helpful and even indispensable in modern communications over the last several decades. Although there are extensive useful applications of kinds of antennas, most of them are mainly restricted to the radio frequency (RF) in the electromagnetic (EM) spectrum particularly for the wireless communications. The RF spectrum has been allocated so intensively that few resources remain for study. On the contrary, sufficient resources of infrared (IR) and optical range are left for further exploration. As a result, to design the optical antennas with higher performance applicable for optical communications is a recent demand of researchers.

The antenna's size is in the nanometer scale when the frequency grows higher to the optical range. Corresponding nanoantennas have drawn increasing research interest currently. These nanoantenna designs include the subwavelength nanoparticles in terms of diverse material constitutions, configurations, and arrangements [1, 2]. Usually it involves the coupling between the metallic particles and the light. In the optical range, the metals have a negative real part for their frequency-dependent dielectric constant, thus causing surface plasmon excitation. Based on this, the nanoantennas generate the strong concentrated and highly confined light in the subwavelength area, which relies on the detailed designs [3, 4]. In other words, by adjusting the particle's dimension, the focused light can be manipulated in the nanometer scale.

Yagi-Uda antenna, an antenna widely used in the RF frequencies, have attracts our attention to develop its nanometer scale counterpart, because it possesses both high directivity and simple structure. Conventional Yagi-Uda antenna consists of a number of linear dipole elements. The driven element is a λ/2 dipole to excite the other parasitic radiator elements. Since a single plasmonic nanoparticle can be considered as a dipole when excited by light, the idea of arranging some spheres with different dimensions to form the Yagi-Uda antenna arises. The optical Yagi-Uda antenna was firstly proposed as a chain of plasmonic core-shell nanoparticles driven by an optical dipole source in [5]. The shell elements are designed with different thickness to couple to each other to achieve the directivity. But this theoretical study is lack of practical considerations. Both the important parameter like the shell thickness and the ideal optical dipole source are difficult to control in the fabrication. Hence we propose a design as an improvement by only adopting the nanoparticle elements and plane wave excitation. Its fundamental is the resonance coupling between the nanospheres of different dimension upon excitation by plane wave. The resonant particles at a given frequency serve as the "driven element" and it can replace the optical dipole that is hard to implement in the previous studies.

II. OPTICAL YAGI-UDA ANTENNA CONSISTING OF AN ARRAY OF NANOSPHERES

A. Optical Resonant Properties of Nanosphere as the Antenna Array Element

In this section, the light enhancement dependent on the spheres' dimension is determined first. Fig. 1 shows the light intensity spectra of the nanosphere with different radii. The finite integration technique is adopted to calculate the field of the gold nanoparticles. The intensity $\left|E\right|^2$ is computed at the very edge along the excitation direction. Each curve exhibits a peak value, which can be considered as the resonance in this frequency range. For example, the spheres with radius of 30 nm are found to be resonant with maximum intensity at the incident wavelength of 535.7 nm.

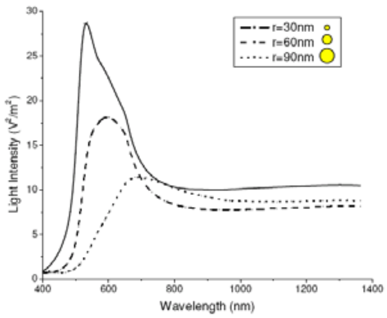


Fig. 1. Light intensity as a function of dimension of nanospheres

B. Optical Yagi-Uda Antenna by Plane Wave Excitation

Fig. 2 provides the configuration of our proposed Yagi-Uda antenna composed of an array of gold nanospheres incident by a plane wave. The particles of different dimension are elaborately arranged required by optical Yagi-Uda antenna. They can work as light induced dipoles coupling with each other. The "driven element" is denoted by a pair of spheres with diameter of 65nm at resonance ~550 THz. The other spheres of different size are placed on both sides of the driven element to form the parasitic elements. The directors here are a chain of spheres instead of two rows to avoid the performance like the waveguide [6]. The excitation source is a plane wave with frequency of 547.8 THz, polarized in the *x*-direction with an electric vector of 1 V/m and propagating in the *z*-direction.

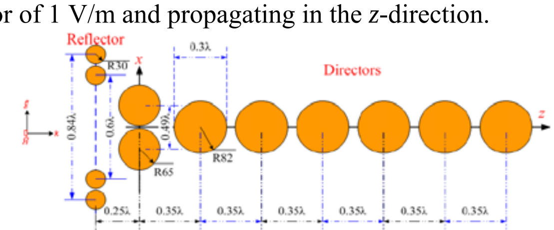
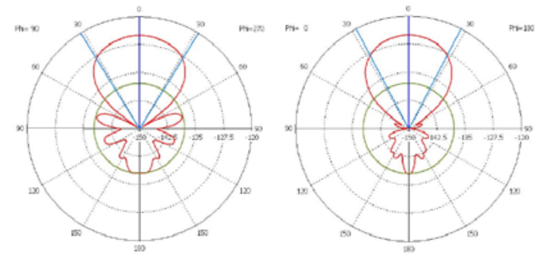


Fig. 2. Scheme of Yagi-Uda antenna consisting of an array of nanospheres

Fig. 3 draws the far-field pattern of the optical Yagi-Uda antenna with four directors. The half-power beamwidths Θ_{1d} and Θ_{2d} in two vertical planes are marked. By using the empirical equations $D = 41253/(\Theta_{1d}\Theta_{2d})$ for the directivity and $G = 30000/(\Theta_{1d}\Theta_{2d})$ for the gain, these two parameters can be calculated as 10.72 dB and 9.34 dB.

By changing the number of the directors in the array, we can further explore its effects on the antenna performance. The results of the peak E-field, power flow, gain and directivity under the influence by the number of directors are given in Table I. It is clearly seen that these parameters are all improved as the number of directors increases. Thus the director has a positive role in enhancing the optical Yagi-Uda nanoantenna performance, which is the same as the RF Yagi-Uda antenna.



(a) E_θ in $\phi = 90°$ plane (b) E_θ in $\phi = 0°$ plane

Fig. 3. Radiation patterns of the array with four directors.

TABLE I
PARAMETERS FOR THE ARRAYS WITH DIFFERENT NUMBER OF DIRECTORS

Number	4	5	6
E-filed (V/m)	30.81	31.52	37.24
Power flow (VA/m^2)	0.64	0.058	0.061
gain (dB)	9.34	10.33	10.96
Directivity(dB)	10.72	11.72	12.34

III. CONCLUSION

Due to the effective coupling between the spheres as the antenna elements, our designed array does not rely on an additional source like the optical dipole for feeding in the traditional studies. Instead, the problem of driven element is solved and the plane wave is adequate for the excitation. Thus our designed Optical Yagi-Uda antenna has higher compatibility with other optical device. It may be combined with an optical fiber to gain high transmission in the optical circuit.

Broadband calculation covering visible and infrared frequencies based on the finite integration technique is developed to explore such antenna's both near-field optical resonances and far-field radiation performance. Antenna performance dependent on the number of the directors has been determined as a systematic study.

IV. REFERENCES

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