The 21st Iranian Conference on Optics & Photonics &
7th Iranian Conference On Photonics Engineering
13-15 January 2015, Shahid Beheshti University

بهبود جهت گیری تشعشع نانو آنتن های نوری بر اساس طراحی زیرلایه های متامواد و آرایه نانوذرات فلزی

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چکیده – *در این پژوهش، با استفاده از زیرلایه‌های متامواد هیپربولیک جهت گیری نانو آنتن های نوری را در طیف مرئی بهبود داده‌ایم. حضور یک یا دو لایه از زیرلایه جهت‌گیری نانوآنتن نوری را تغییر می‌دهد. از الگوی تابش میدان تشعشع ساختار طراحی شده، با استفاده از روش المان محدود (FEM) توسط نرم افزار کامسول، برای بدست آوردن مشخصات جهت گیری استفاده شده است. نشان می‌دهیم که، با استفاده از یک ساختار زیرلایه‌ای از HMTM، دامنه میدان تابشی از ۸۲ به ۹۴V/m افزایش می‌یابد. ثابت شد که با طراحی ساختاری شامل نانوذرات با آرایش منظم و زیر لایه‌های متامواد می‌توان الگوی تابش و زاویه پرتو را مهندسی کرد.*

کلید واژه - نانو ذرات فلزی، نانو آنتن، زیر لایه های متا مواد هیپربولیکی.

Radiation Directivity Enhancement of Optical Nano-antennas based on Metamaterial Substrate and Metal Nanoparticles Array Design

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Abstract- *Based on designed hyperbolic metamaterial (HMTM) substrate, we report enhancement of radiation directivity of the metallic optical nano-antenna in the visible spectrum. Placing monolayer and sub-layers as substrate for the optical nanoantenna results in radiation directivity changing. The far-field radiation patterns of the designed structures have been calculated using FEM (finite element method). The COMSOL package has been used for obtaining the directivity characteristics. It has been shown that a HMTM substrate enhances the radiation field amplitude from 82 to 94 V/m. It is established that by novel arraying of nano-particles and tailoring their metamaterial substrates, one can successfully engineer the radiation patterns and beam angles.*

Keywords: Metallic nanoparticle, Nanoantenna, Hyperbolic metamaterial substrate.

1. Introduction:

Optical nano antennas are an enabling technology for manipulating and controlling optical radiation at subwavelength scales [1]. Optical antennas have been shown to focus optical fields to sub diffraction limited volumes, enhance the excitation and emission of quantum emitters, and modify their spectra exploiting the unique properties of metal nanostructures, which behave as strongly coupled plasmas at optical frequencies [2]. Yagi-Uda nano-antennas, which borrow their name and operation principle from well-known radio-frequency counterparts, can radiate light preferably along a certain direction, and could find applications in bi-stable devices, nano-focusing of light, particle manipulation, optical interconnects and coupling light from free-space into a waveguide [3].

Nanoantennas have promising applications in near-field spectroscopy, high-density data storage, and optical imaging [4]. The exciting properties of optical nanoantennas have also been explored in connections with energy applications. Large field enhancements are usually associated with more efficient energy harvesting, suggesting a route to apply optical nanoantennas to solar cells and photomixers [5].

Engineered substrates are investigated to manipulate the radiation performance of nanoantennas [6]. Hyperbolic metamaterials can support unique bulk modes, tunable surface plasmon polaritons, and surface hyperbolic states (Dyakonov plasmons) that can be used for a variety of applications [7]. Nanoscale slot waveguides of hyperbolic metamaterials are proposed and demonstrated for achieving large optical field enhancement. Optical intensity in the metamaterial slot waveguide can be higher than that in a conventional silicon slot waveguide [8].

In this work, we have initially show effect of size and distance between nanoantennas array, and then we explicitly show that the strong enhancement of free-space radiative emission and efficiency when placed On HMTM substrates. It has been shown that a placing monolayer and bilayers of substrate under the optical nanoantenna change in the directivity, it is established that HMTM substrate enhances the radiation field.

2. Design Theory:

Nanoantenna consists of single or multiple nanometer scale metallic particles. When excited by light, these particles can exhibit strong surface plasmon resonance, thus generating efficient concentration of luminance, i.e., confined optical fields nearby.

In the field of antenna design, it is commonly required to design an antenna system with a prescribed far-field radiation pattern.

Configuration of the introduced structure involves an array of gold nanospheres excited by a plane wave. The far-field characteristics of nanoantenna are studied using the COMSOL which is developed based on the finite element method (FEM), highest mesh accuracy was selected to give the most accurate results.

The detailed scheme of such an antenna has been depicted in Fig. 1(a). A plane wave with frequency of 650THz with an electric vector of 1V/m is radiated as the excitation source to the array of spheres. In this condition, particles work as induced dipoles which can couple to each other without any additional source. By carefully designing their dimension, they may play the roles of antenna elements like those in a conventional RF antenna.

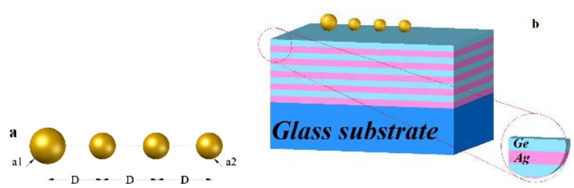

Fig. 1; Schematic view of the (a) nano-antenna consisting of metallic nano-spheres, where a_1, a_2, as the reflector and director radiuses respectively, and D represent the distance between nanoparticles, and (b) nanoantenna on HMTM substrate.

Figure 1 shows an example of Yagi-Uda nanoantenna consisting of three directors and one reflector. The whole structure is composed of a director and a reflector part. In the director part, metallic spheres are positioned on a direct line with same radius (a_2), while in the reflector part sphere has differ radius (a_1),an array of equally spaced (D) gold nano-spheres. The radius of the directors should be smaller than the radius of the reflector, so the director nanoparticles sustain 30nm, and the reflector nanoparticle sustains 43nm.

The dimensional properties of nanoantenna affect its radiation characteristics. By optimization of these parameters it is possible to find the best geometry to gain the optimum directivity characteristics as depicted in Fig. 2. It is observed that the ratio of the particle size to the wavelength of the incident light is a helpful parameter to classify nanostructures. Metal nanoparticles strongly absorb and scatter light at the plasmon resonance frequency. It is found that the ratio of scattering to absorption is highly sensitive to the changes in size. Large particles scatter light significantly, whereas the color of small particles is mainly caused by absorption. It is found that in metal particles with dimensions above 30 nm, scattering phenomena is of great importance. This work investigates the scattering properties of nanoparticles with sizes 30 nm, 50 nm and 100 nm.

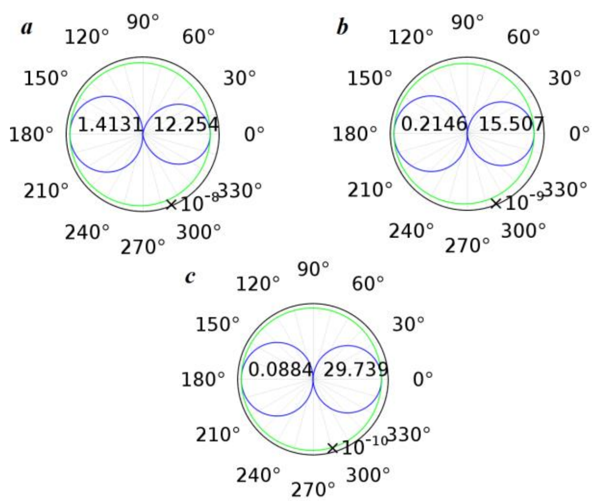

Fig. 2; (a)The far-field radiation pattern in the E-plane (blue) and H-plane (green) when wavelength is 400 nm, for Radius ۱۰0nm (b) 50nm (c) ۳0nm, gold sphere, Due to symmetry, only one-quarter of the sphere has to be modeled (3D).

The directivity of the nanoantenna will be improved by increasing the number of directors and tuning the distance between nanoparticles. This fact could be observed in Figs. 3 and 4, where the variations of main lobe magnitude, angular beam width and side lobe level of the nanoantenna have been obtained as functions of director numbers considering typical separation between the directors in the Yagi-Uda nanoantennas (0.3 to 0.4λ) [9]. The resulting radiation pattern show, with reduce of distance between antenna arrays, a narrow beam toward the direction of the directors and a minimum toward the reflector direction. In our simulations the separation distances between nanoparticles is 0.35λ to enhance the directivity properties of nanoantenna.

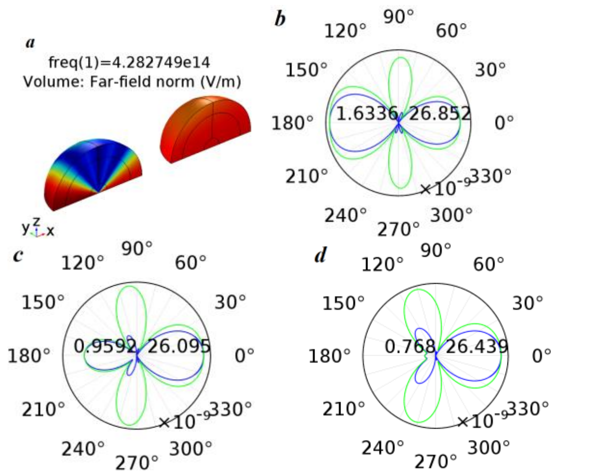

Fig. 3; (a) Far-field norm (b)The far-field radiation pattern in the E-plane (blue) and H-plane (green) when wavelength is 400 nm, Radius 50nm distance between particles is 700nm (c) 600nm (d) 520nm, gold spheres, Due to symmetry, only one-quarter of the sphere has to be modeled (3D).

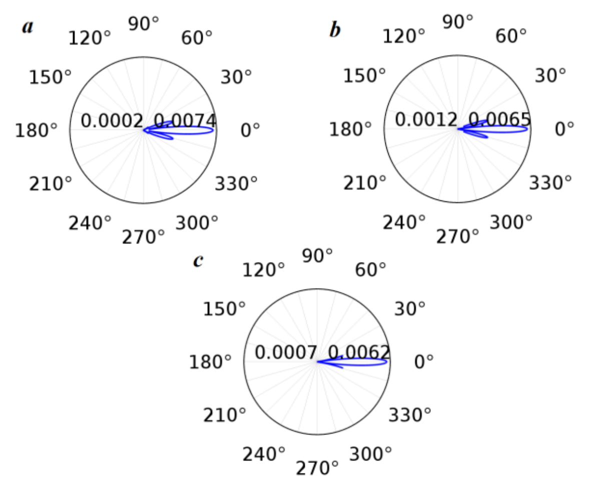

Fig. 4; Far-field norm & The far-field radiation pattern for (a) 1 Nano particle (b) 4 nanoparticles (c)10 nanoparticles, wavelength is 400 nm, Radius50nm distance between particles 0.35λ, gold spheres (2D).

The radiation patterns of a nano-antenna with 1, 4 and 10 nanoparticles are illustrated in Fig.4. Therefore, it could be deduced that increasing the number of directors increases the main lob magnitude and vanish side lobe leading to enhanced structure directivity.

A further enhancement of the directivity is found when the antenna is placed on a dielectric substrate. The reflected wave of the substrate may couple to the incident light and provide a positive effect on the radiation directivity enhancement. Table 1 shows the effect of adding different substrate with different thickness under the structure. The best result have been obtained with a substrate total thickness of 0.1 λ, the substrate is designed as block made of four pairs of alternating layers of germanium and silver (thicknesses of layers are equal).

Table.1: Main lobe magnitude (V/m) of far-field radiation

Types of substrate layer	Dimensions(*λ)	Number of nanoparticles	Main lobe magnitude
Without substrate;		1	83.3
		2	82
		3	118
With substrate; Ag	0.1	2	80.2
Ag	0.3	2	83.2
Si	0.1	2	80.4
Sio_2	0.1	2	80.2
$Sio_2^{(0.1)}$-$Ag^{(0.2)}$	0.3	2	83
Ge-Ag-Ge	0.1	2	83.2
Ge-Ag-Ge-Ag	0.1	2	135.8

Since simulating the real size structure requires considerable memory and takes a long time, we put a slice of HMTM in a parallel plate to approximate the radiation effect. The procedure of the nano-antenna has been outlined previously. The poroposed nano antenna has been put on the HMTM substrate.

In the following, the radiation enhancement for nanoantenna on HMTM substrate (comprising silver and germanium periodic multilayers) has been reported where have elaborated on the radiation enhancement produced by a 2 array of nanoantenna on HMTM substrate with 0.1 wavelength thickness. By substitution of 2 nanoparticles in space without any substrate, we obtained a 82 maximum amplitude. However, by placing hyperbolic metamaterial with germanium and silver with ten periodic sub-layers, an amplitude equal with 94 V/m is obtained (Fig. 5.)

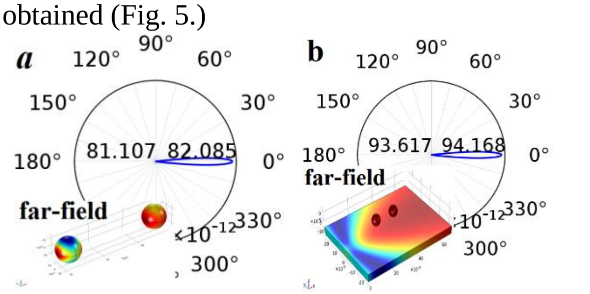

Fig. 5; (a) The far-field pattern of 2 nanoparticles in free space (b) On HMTM substrate with 10 layers.

3. Conclusion:

We utilized an array of metal nano particles to design a nano antenna, which can direct the incident radiation. In an improved nanoantenna designing, using appropriate type and size of nano particles and adjusting their relative distance and their multilayer substrate are the main parameters for radiation pattern directivity enhancement. Using periodic sub-layers of hyperbolic metamaterial with Ge and Ag types and embedding nano particle array on the sub-layer enhanced the radiation beam intensity. Furthermore, it is found that placing monolayer and bilayers as substrate for the optical nanoantenna resulted in radiation directivity change, then established that HMTM substrate enhances the radiation field.

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