

# A semi-log-periodic array of spheroidal nanoelements: broadbanding nanoantennas

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Received: 5 January 2014 / Accepted: 23 July 2014 / Published online: 6 August 2014  
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**Abstract** Nanoantenna arrays can offer unique possibilities for large local-field enhancement, high directivity, and also wavelength tunability over a wide spectral range. In this paper, a semi-log-periodic array of nanospheroidal elements has been studied, which exhibits a narrower beam and also a higher electric field enhancement in comparison with an equal size, equally distanced array of the same element. Through the numerical simulations, it has been presented that the suggested array is of a great potential for improvement of the directivity as well as the electric field enhancement over similar designs. Moreover, a considerable change has been observed in the electric field through gradual transformation of elements from sphere to very thin rod. Next, the effect of geometrical parameters on local-field enhancement has been investigated as a complementary job. Finally, it has been demonstrated that adjusting the number of elements can provide a narrower beam.

## 1 Introduction

Guiding light in nanostructures is an important challenge for current research and development in nanooptics. A solution to these kinds of nanoscale problems is to apply metallic and dielectric nanoantennas [1–4]. In recent years, optical antennas based on surface plasmons have triggered an explosion of interest and a variety of schemes taking advantage of localized optical near-fields generated by nanoparticles have been proposed to use them as optical

nanoantennas [5–12]. Research in the field of optical antennas is currently driven by the need for high field enhancement, strong field localization, and also realization of directional control of light over radiation [13, 14]. Thus, some researches focus on nanoantenna arrays because of their capability in tuning resonance specifications through the modification of both the geometry and/or the coupling between different array elements.

Most studies on directional optical antennas have focused on the classical Yagi-Uda design [15, 16], which provides directivity for a specific design frequency but a limited bandwidth. Since both bandwidth and directivity are important, some modifications on Yagi-Uda nanostructures have been proposed by Dregely and his colleagues [17]. As another solution to access bandwidth and directivity simultaneously, nanoantenna designs with self-similarity along a single dimension could be a promising approach. A good example of this category is log-periodic (LP) antenna consists a number of elements with decreasing length. As the elements are of different lengths, only one of them resonates at a given frequency. Therefore, the bandwidth of log-periodic antennas is relatively wide and is usually greater than that of conventional Yagi-Uda antennas. As a result, the log-periodic arrangement would be a proper offer for implementation in the optical frequencies. Thus, log-periodic nanoantennas could have applications in building broadband optical wireless communication systems, advanced nanosensor systems, high-performance solar cells as well as wavelength-tunable single-photon sources and detectors [18–21].

Our main purpose in this work is to achieve an optical antenna array with a major radiation beam as narrow as possible. Since plasmonic particles at/or near resonance can be used for the optical antenna array design and also based on our previous studies, we propose nanospheroids

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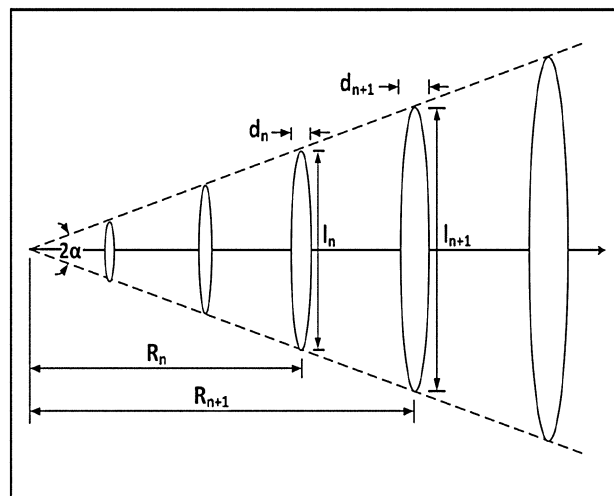
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as the best possible option for array elements. In addition to proper elements, a careful selection of the array geometry is essential for the achievement of the desired result. Since using a log-periodic geometry, one can transmit energy efficiently; we therefore suggest a log-periodic array of silver nanospheroidal elements [22–24]. In this work, the parameters influencing the behavior of antenna array including geometric parameters and also position of each particle are swept, and finally, the effects of these parameters on the performance of the nanoantenna array are discussed. Before ending this part, let us refer to the work by Lavasani and his colleagues [25]. In this well-done job, they more focus on unique color-switching property rather than directivity. Also, their suggested array of nanodisks has fixed element width and inter-element distance, and so it is not log-periodic.

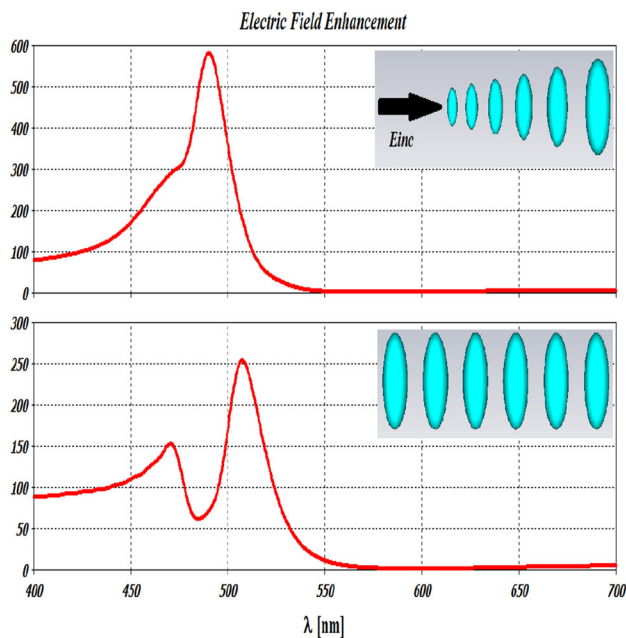
## 2 Simulations and results

Here, design parameters are selected in such a way that the resulting resonances occur in the optical part of the spectrum. As simulation tool, the CST Microwave Studio (commercial full-wave 3D software) is used. We start first with version 2011 and then continue with CST 2013. Also, it is important to note that the simulations were performed in receiving mode, and antennas were illuminated with a plane wave directed along the array axis. The electric fields around the antenna elements as a function of wavelength, the near electric field enhancement, and radiation pattern were considered as outputs. Moreover, since metals behave very differently in the optical domain [26, 27], the decision to use certain metals for optical antenna design is an important one. Noble metals such as gold and silver are candidates for optical antenna design, mainly due to their specific optical property. Thus, the ideal choice for metal is silver, which covers a broader region of frequency spectrum. Since the parameters of modeled materials have to be applicable over broad frequency bands, choosing a proper method for modeling the dielectric response of silver is of great importance [28, 29]. Fortunately, our model is nearly identical to the one presented in the latest version of CST (2013) for modeling dispersive behavior of silver at optical frequencies.

The log-periodic antenna is a truly broadband device and can be built to operate over essentially any desired frequency band. This antenna was developed by D. E. Isbell at the University of Illinois and was part of an extensive research program on frequency-independent antennas. The underlying concept in log-periodic antenna design is that of building a structure that scale into itself periodically as the frequency, and hence wavelength changes [30]. In fact, a log-periodic antenna is defined as a



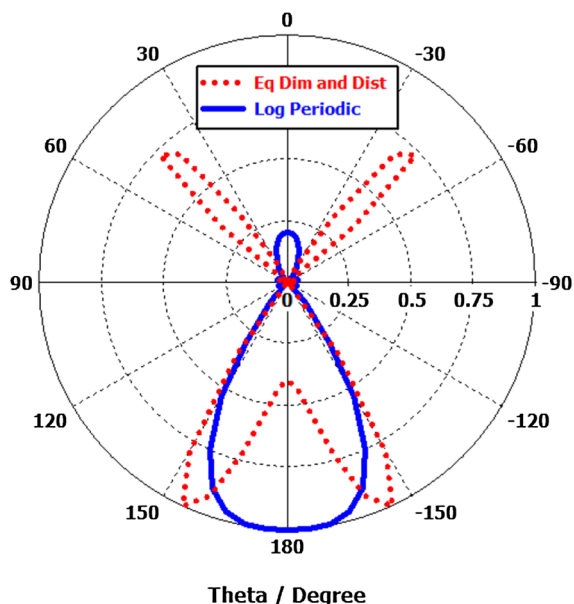
**Fig. 1** Geometrical configuration of a log-periodic nanoantenna with nanospheroidal elements



**Fig. 2** Spectrum of electric field enhancement: a log-periodic (LP) nanoantenna in comparison with an array of equal size-equally distanced nanospheroidal elements. Largest element of the log-periodic array and all elements of the non-LP one are in the same size

structure whose electrical properties vary periodically with the logarithm of frequency. If an antenna is realized such that within each period its performance changes within bandwidth-defined conditions, then multi-decade operation can be obtained. To produce the described performance, similar mathematical relationships must be applied to the antenna's structural parameters [31].

In this work, we focus on log-periodic structures at optical regime. General schematic diagram of a log-

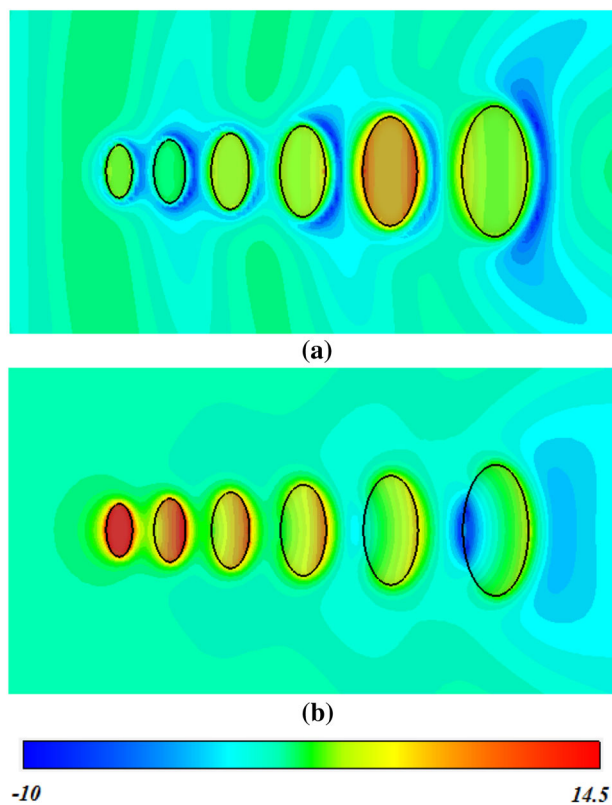


**Fig. 3** Comparing far-field pattern of a log-periodic nanoantenna (solid line) with an array of equal size-equally distanced nanospheroidal elements (dotted line)

periodic antenna array of spheroidal elements is illustrated in Fig. 1. While the geometrical dimensions of the Yagi-Uda array elements do not follow any pattern, the lengths ( $l_n$ 's), spacings ( $R_n$ 's), and diameters ( $d_n$ 's) of the log-periodic array increase logarithmically as defined by the inverse of the geometric ratio  $\tau$ . The scaling factor  $r$  (or its reciprocal value  $\tau$ ) is  $r = 1/\tau = l_{n+1}/l_n = R_{n+1}/R_n = d_{n+1}/d_n$ . Another important parameter is the inter-element distance factor ( $\sigma$ ) defining as  $\sigma = R_n/2l_n$ . Additionally, the geometrical description of the antenna is completed with the definition of antenna apex half angle  $\alpha = \tan^{-1}(1 - \tau)/4\sigma$  and aspect ratio  $AR = l_n/d_n$ .

The basic element is a prolate spheroid with the dimension of  $a_n$  [major axis]  $\times b_n$  [minor axis]  $\times b_n$ , the fixed length ( $l_n$ ) of which is equal to  $2 \times a_n$ . First, an array of six equal elements with an equal distance of  $R_n$  has been compared by a log-periodic array with the same number of element while its largest element is equal to the element size of first array. As Fig. 2 shows, near electric field of the log-periodic arrangement is more than twofold stronger. Since position of observation point is also significant, it should be noted that probes are situated in the vicinity of the first element (smaller one in log-periodic model) and with the same distance from the element's center (in both cases).

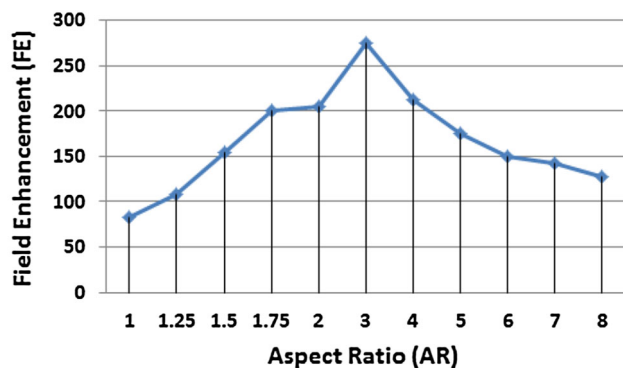
Figure 3 demonstrates a comparison among directivities while wavelength of the incident plane is fixed at 470 nm. Here, it can be seen that the radiation pattern of log-periodic model is more directive than non-log-periodic and as a result, the log-periodic configuration is more appropriate.



**Fig. 4** Near-field enhancement within a log-periodic array antenna experiences shift depending on the wavelength of the incident plane wave. Antenna parameters are  $N = 6$ ,  $r = 1.2$ ,  $\sigma = 0.6$ ,  $AR = 2$ ,  $a_6 = 100$  nm. **a**  $\lambda = 496$  nm, **b**  $\lambda = 470$  nm

We will hereafter focus on a 6-element log-periodic array (with  $r = 1.2$ ,  $\sigma = 0.6$ ,  $AR = 2$ ,  $a_6 = 100$  nm) made of silver under plane-wave illumination. The electric field enhancement in the vicinity of the antenna elements shifts from the shortest element ( $n_1$ ) to the longest one ( $n_6$ ) with increasing wavelength of the incident plane wave (Fig. 4). Here, we consider electric power density ( $\log|E|^2/|E_{inc}|^2$ ) to study field enhancement. In fact, we aim to show how field enhancement shifts in elements by changing the wavelength of the incident wave. Moreover, for sufficiently small inter-element distance ( $\sigma$ ) or scaling factor ( $r$ ), this field enhancement may occur simultaneously at several elements because adjacent resonances have overlapping bandwidths. This effect is observable in Fig. 4b.

The dependence of field enhancement on the element shape for a 6-element LP antenna has been considered (Fig. 5). In other words, a complete study on aspect ratio ( $AR = a_n/b_n$ ) has been presented in this part. As seen in Fig. 5, a gradual increase in AR (from 1 to 2 by steps of 0.25) and transformation from sphere to prolate spheroid will cause a stronger field enhancement. This variation will occur gradually as an increase in AR in a nearly linear manner. While array experiences its maximum field

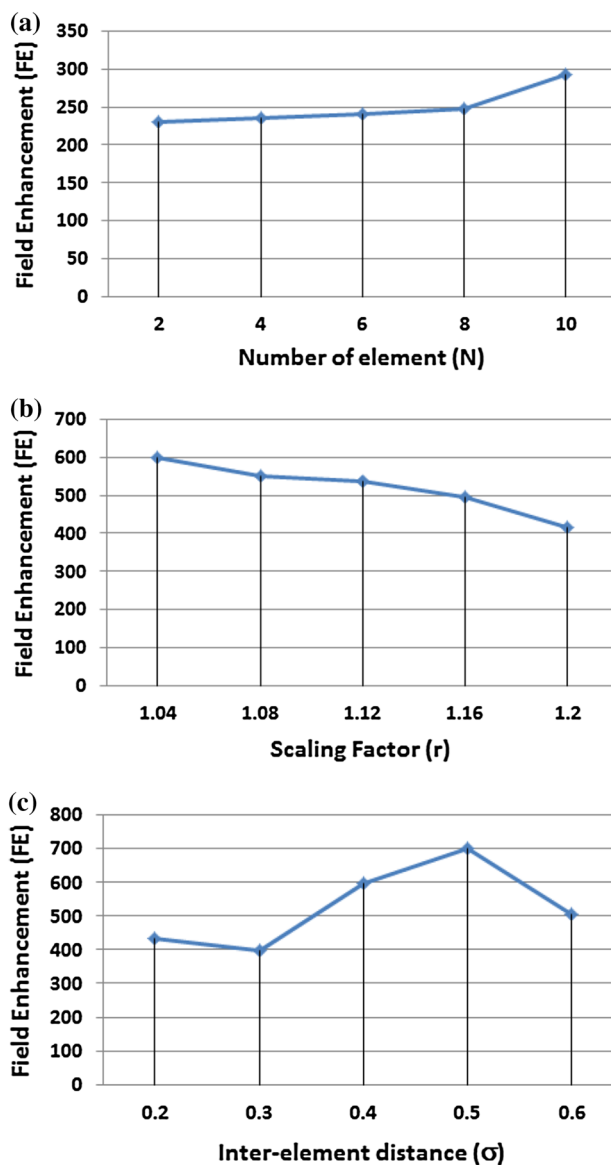


**Fig. 5** How near field enhances within a log-periodic array nanoantenna by increasing aspect ratio (AR). Antenna parameters are  $N = 6$ ,  $r = 1.2$ ,  $\sigma = 0.6$ ,  $a_6 = 100$  nm

enhancement at  $AR = 3$ , more drastic increases of AR (from 3 to 8 by a step of 1) and transformation from prolate spheroid to a semi-rod figure have an inverse effect and will cause a decrease in field enhancement. Since the spheroid causes higher field enhancement, it is more appropriate than either sphere or bar as an element for LP array.

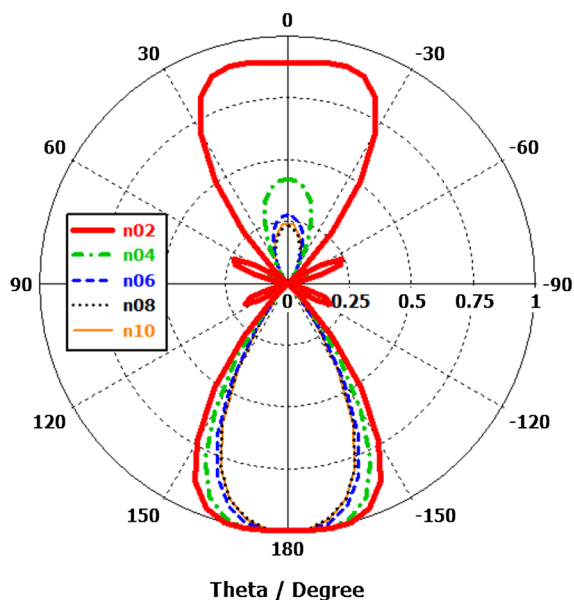
In addition to element shape, we investigate the variation in field enhancement as a function of the number of elements ( $n$ ) and also two important array geometry parameters: scaling factor ( $r$ ) and inter-element distance ( $\sigma$ ) (Fig. 6). As Fig. 6a shows, sweeping  $n$  from 2 to 10 by multiples of 2 causes a gradual increase in field enhancement. Therefore, it is obvious that adding to the number of elements improves LP array performance. However, larger  $n$  results in much smaller elements near the tip of the array, and this reduction in size which causes a limitation in fabrication limits the possibility of a larger  $n$ . Another parameter is the scaling factor ( $r$ ), the sweeping effect of which is demonstrated in Fig. 6b. By considering five different values for  $r$  ranging from 1.04 to 1.20, we observed a decrease in field enhancement. Final sweeping job dedicates to inter-element distance ( $\sigma$ ), which gradually grows from 0.2 to 0.6. As seen in Fig. 6c, the result curve is not purely ascendant or descendant, and so the best choice for the inter-element distance which results in the maximum field enhancement within our selected range is  $\sigma = 0.5$ .

In order to investigate the behavior of directivity as a function of number of elements ( $n$ ), let us have a look at far-field angular radiation patterns. Based on Fig. 7, increasing  $n$  causes a considerable improvement in radiation pattern, so that main lobe directivity increases and back lobe becomes smaller. Therefore, more number of elements results in both stronger field enhancement and better directivity.



**Fig. 6** Effect of geometric design parameters of log-periodic antenna array on electric field enhancement by sweeping **a** number of elements [ $n = 2:2:10$ ]; **b** scaling factor [ $r = 1.04:0.04:1.20$ ], and **c** inter-element distance [ $\sigma = 0.2:0.1:0.6$ ]

Before ending this paper, it is important to note that nanoantennas will generally be supported by a substrate in many practical applications. This added substrate refractive index acts as parasitic impedance and causes a shift in the resonance frequency. Furthermore, the larger refractive index of the substrate compared to air strongly influences the emission pattern of the nanoantenna. Therefore, the real directivity diagram of the nanoantenna strongly depends on the environment. From other aspect, antenna's emission is redirected into the substrate in directions very close to the critical angle. Also, substrate can cause nonlinearity in nanoantenna performance. For example, the conditions of



**Fig. 7** Number of element's effect on the far-field radiation pattern in the log-periodic nanoantenna array by nanospheroidal element

nanoantenna operation may vary in time, as a result of heating the underlying substrate.

Although, substrate effect is strongly regarded as a complementary job for future, but let us look at some of its influences here. According to analytical studies [32, 33] and presimulations, we can estimate how a dielectric substrate affects the behavior of a log-periodic nanoantenna array. To determine substrate effect, we first assume a log-periodic array of nanospheroidal elements in the close proximity to the interface of free space ( $\epsilon_1 = \epsilon_0$ ) and a dielectric with permittivity  $\epsilon$  ( $\epsilon_2 = \epsilon$ ). As next step, we replace free space with another dielectric medium ( $\epsilon_1 > \epsilon_0$  and  $\epsilon_1 \leq \epsilon_2$ ) in our model. Based on standard directivity parameter [34], radiation pattern can be highly directional with a narrow main lobe and a set of much weaker side lobes in both case. Either array situated above a substrate or immersed in that, its dielectric constant brings about an additional degree of freedom allowing focus a plan wave into a narrow beam of light with adjustable characteristics. Also, it has potential of controlling the radiation pattern and the direction of main beam especially in light sources. As a result, this interesting phenomenon opens new possibilities in precisely addressing and exciting nanostructures.

### 3 Conclusion

In conclusion, we have proposed a log-periodic array made of silver nanospheroidal elements. Based our simulations, use of this array can cause to enhancement in electric field

and also directivity. Moreover, control of the structure geometry would be effective in improving its performance. As a matter of fact, by adjusting number of element ( $n$ ), inter-element distance ( $\sigma$ ), scaling factor ( $r$ ), and aspect ratio (AR), one can handle the resonant frequency, field enhancement, and directivity. Finally, the narrow beam generated by this log-periodic array has great applications in different areas such as quantum information technology, emission devices, and optical sensors. As an open future road, we should refer to considering substrate effect for the array proposed here.

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