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Log-periodic optical antennas with broadband directivity

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ABSTRACT

Optical antennas offer unique possibilities for light manipulation on a sub-wavelength scale. Here, we study log-periodic antennas that exhibit broadband directivity as a result of the self-similar relation between the lengths, separations and widths of the elements. We show through numerical simulations that the log-periodic designs have a considerable potential for improvement of both directivity and operation bandwidth over classical Yagi–Uda designs. Moreover, the directivity is more robust against changes in the location of the source or detector at different antenna elements. We systematically study the influence of geometrical parameters on angular performance and local field enhancement to arrive at optimum values. Next, we demonstrate that introducing a gap in the dipole array architecture can provide at least a ten-fold enhancement of the emitted power. Finally we present an optical zigzag antenna capable of both broader spectral response and even higher directivity.

1. Introduction

Optical antennas are a promising class of nano-devices that open up alternative routes for developing nano-sized light sources and detectors with tailored spectral and angular characteristics [1–4]. The analogy with radio-frequency (RF) antennas is a useful approach to the design and interpretation of the characteristics of optical antennas. In this communication, we extend the parallelism with RF antennas to self-similar designs.

Fractal antennas are important representatives of this category, providing a remarkable combination of compactness, broadband (or multiband) behavior and highly isotropic angular patterns. Fractal designs have been found to be especially suitable for compact microwave communication devices, such as mobile phones [5,6]. Their omnidirectional response can be a desirable property for certain applications of optical antennas, such as light-harvesting. However, for others such as single-photon sources and biochemical sensors, directivity is essential for efficient excitation and detection.

Most theoretical studies on directional optical antennas have focused on the classical Yagi–Uda design [7–9], which is one of the few that have been realized experimentally at optical frequencies [10–12]. It provides directivity for a specific design frequency with a limited bandwidth [6]. Both bandwidth and directivity could be improved by adopting a more general geometry, opening new degrees of freedom for further optimization. Antenna designs with self-similarity along a single dimension are a promising approach to combine directivity and broadband behavior. Indeed, a number of such designs have been extensively studied and used in the RF regime, and they have generally received the name of log-periodic (LP) antennas since they exhibit a series of resonance frequencies which are equally spaced when plotted in logarithmic scale [7,8]. These designs are characterized by the quality that the size of their elements and the mutual separation scale in a geometric-progression fashion.

Chains of metallic particles have been proposed for sub-wavelength light localization and guiding. For example, nanofocusing with self-similar chains of metal nanoparticles [13] or ultrafast, controlled changes in localization [14] were proposed. Graded-size particle chains were predicted to show localization at different positions for different excitation wavelengths [15], an effect that had also been observed experimentally for arrays of identical particles [16]. More recent simulations [17,18] for antenna designs based on tapered dipole arrays reveal directional and multiband characteristics. However, these designs are only partially log-periodic since the lengths of their elements were scaled while the inter-element distance and the element width were kept constant throughout the antenna. In the present study, we report on the performance of strictly self-similar LP antennas, accounting for the effects of the different parameters.

The geometrical parameters defining a dipole-array LP antenna are illustrated in Fig. 1a. The scaling factor r (or its reciprocal value τ) is the ratio between the lengths (a_n and a_{n+1}) of two consecutive elements, as well as between two consecutive widths (b_n and b_{n+1}) and between inter-element distances (d_n and d_{n+1}): $r = 1/\tau = a_n/a_{n+1} = b_n/b_{n+1} = d_n/d_{n+1}$. Hence, only one of the element lengths a_n suffices

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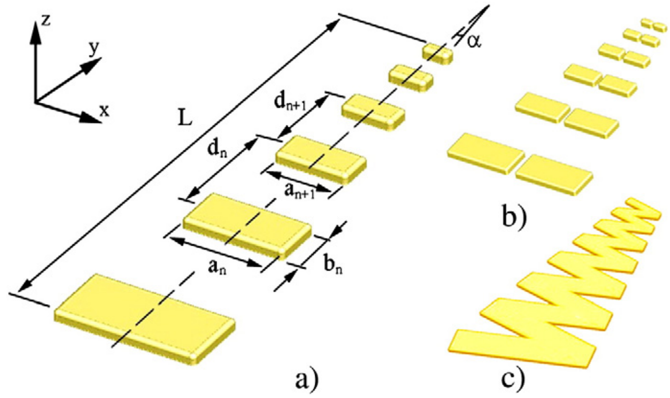

Fig. 1. Geometrical configuration of log-periodic antennas (a) dipole array, (b) gap-dipole array and (c) zigzag antenna.

to define all the lengths, once the scaling factor r is fixed. The distance d_n between adjacent elements with numbers n and $n+1$ is independent from the scaling factor and it will be expressed normalized to the element length [6], thus defining an inter-element distance factor: $\sigma = d_n/2a_n$. The parameters τ and σ are also related to the antenna apex half angle by $\alpha = \tan^{-1}(1-\tau)/4\sigma$. The geometrical description of the antenna is completed with the definition of the aspect ratio $AR = a_n/b_n$, the element thickness and the edge rounding.

All these parameters, except for the thickness of the elements and their edge rounding, were systematically varied in order to investigate their effect on the directivity, local field enhancement and radiated power of the dipole-array antennas.

Antennas can operate either in reception or in emission mode. In the case of optical Yagi–Uda antennas, operation in emission can be achieved by placing a small fluorescent molecule or a quantum dot at a position of maximum modal field [13], where coupling is most efficient. For a Yagi–Uda antenna to be directional, this source must best be positioned at the end of the resonant feed element, usually next to the largest element or reflector. This requirement can be relaxed by making use of a log-periodic design, where the roles of feed and directors are distributed over all the elements of the antenna.

As a result, in the case of optical LP antennas, the optimal position for the fluorescent particle is not known *a priori*, so that one of the aims of this study is to uncover the effect of the chosen source position on the directivity and radiated power of the antenna.

We also propose an improved variant of the dipole-array antenna design. It is well known that two nanorods placed close together, so that a narrow gap is left between them, present local field enhancement in the gap, considerably larger than the one at the ends of the individual rods [19]. We suggest the use of this gap effect for enhancing the emitted power and we investigate a gap-dipole array LP antenna (Fig. 1b), as opposed to the simple dipole array (Fig. 1a).

Finally, we will discuss a self-similar antenna with zigzag geometry, so far studied only in the RF range [5] (Fig. 1c). It can also be regarded as a descendant of the dipole-array antenna, derived by tilting its elements until their ends join together.

2. Methods

Although analytical methods can be applied for the study of relatively simple antenna architectures [7,9], for the present study we will employ the Finite-Difference Time-Domain (FDTD) method which constitutes a more powerful approach, since it allows one to solve numerically Maxwell equations for complex three-dimensional distributions of complex dielectric functions [20]. All FDTD simulations were carried out using commercially available software (FDTD Solutions by Lumerical Solutions, Inc.). The values of the antenna parameters were selected in such a way that the resulting dipolar resonances of their elements were in the visible and near infrared part of the spectrum.

The simulations were performed in two configurations: reception and emission. In the reception configuration the antennas were illuminated with a plane wave directed along the y-axis either in positive (forward) or in negative (backward) direction. The local electric fields around the antenna elements were studied as a function of time and wavelength. On the other hand, in emission configuration, the antennas were driven by placing an electric dipole source in the antenna near field and the resulting angular far field power distribution was analyzed.

In both configurations, the effect of changing the position of the dipoles or point field monitors was investigated as well as the effect of placing the antennas on the surface of a substrate or inside it. The directionality in both operation modes was assessed by calculating the forward-to-backward ratio, $F/B = 10\ \log(|E|^2{}_{fw}/|E|^2{}_{bw})$, and the full-width at half-maximum beam width, both of which are commonly used antenna parameters [6,17]. Additional simulation settings are presented as supplementary material.

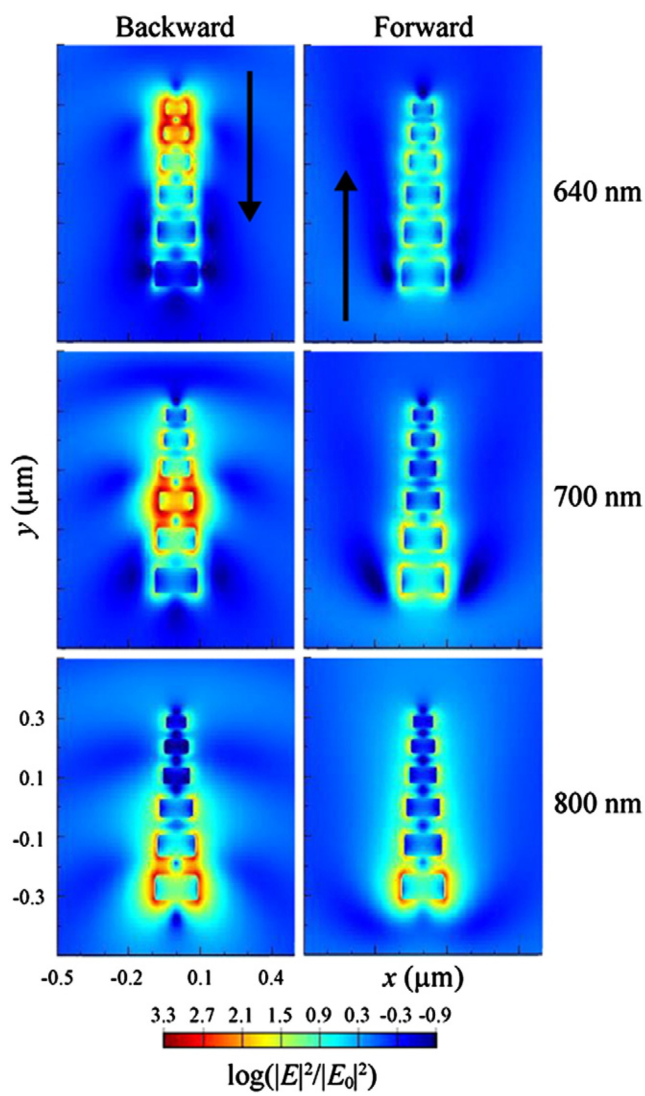

Fig. 2. Shift of the electric field enhancement within a dipole-array antenna (DA6) depending on the direction of incidence and the wavelength of the plane wave. The electric field is normalized to the incident plane wave. Antenna parameters are $N=6$, $r=1.14$, $\sigma=0.4$, $AR=2.1$, $a_3=120$ nm.