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Analytical Approximations for the Analysis of Helical Nano-Antennas

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Abstract

In this work we introduce analytical expressions for the study and analysis of helical nano-antennas. Utilizing closed form expressions for the loop antenna, and by using array theory we are able to characterize for the first time nano-helices in the infrared and optical regimes. Based on our preliminary results, when the penetration of the radiation into the antennas' metals is taking into account, superior directivity compared to the impenetrable - perfectly electric conductive - microwave antenna case is obtained.

1 Introduction

6G communication systems are expected to play a key role in the next decade transforming our lives by connecting everyone and everything, everywhere, [1]. For this effort to be viable new high frequency devices are needed. Specifically, these devices will be designed to deliver multi-gigabit-per-second data speeds (i.e., 20 $Gbps$ for downlink and 10 $Gbps$ for uplink) and latencies in the order of 1 ms, e.g., [2], that can meet the needs of a broad range of bandwidth-hungry applications, e.g., [3]. To accommodate such communications, the design of nano-antennas is needed that will be integrated with these devices, targeting operation anywhere from the terahertz to the optical regimes [4].

Nano-antennas or optical antennas is a new concept introduced ten years ago, [5]. The design, though, of this type of antennas is extremely challenging. First their small size demands fabrication accuracy better than 10 nm, especially for optical frequencies. Second appropriate materials are needed and a thorough investigation of their behavior has to be performed. Designing nano-antennas is not just a "simple" scaling of traditional antennas from the RF or microwave regimes. For example, the penetration of radiation into metals can no longer be neglected since the electromagnetic response is dictated by collective electron oscillations, a characteristic of a strongly coupled plasma, [6]. So far, many attempts have been done on the design of nano-antennas at the THz regime, e.g., [7], but significantly fewer at the optical frequencies with the introduction of only some dipole-type, [8], and loop-type, [9] nano-antennas.

In this paper we are investigating the performance of a helical nano-antenna (see Fig. 1). To our knowledge only Wang et al., [10], have done some initial study on the radiation properties of helical nano-antennas utilizing the dispersion parameters of Au with the use of the method of moments. In this work we are taking a completely different route. Specifically, an analytical approach is developed for the analysis and design of helical nano-antennas. This is highly beneficial for the antenna designer as it allows for a quick and fairly accurate prototype design. Additionally, the existence of an analytical approach provides deeper understanding of the underlying physics with the possibility to reveal hidden electromagnetic phenomena that can lead to designs with enhanced performance. In the next section, a brief representation of our theoretical analysis is presented, while in the results section a helical gold nano-antenna is analyzed showing for the first time superior directivity compared to its counterpart microwave antenna, when both are operated in their axial mode.

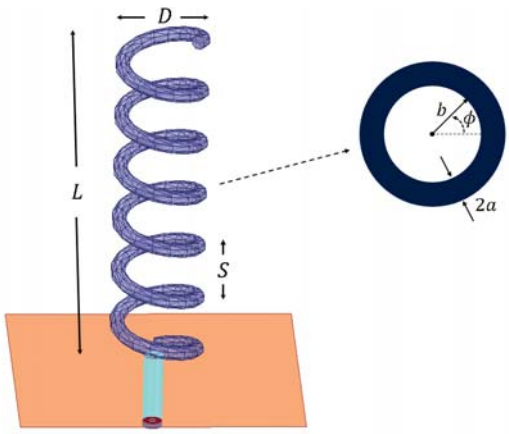

Figure 1. Demonstration of a helical gold nano-antenna with $N = 7$ turns. At the right, a detailed top view for one of the turns is shown.

2 Theoretical Formulation

Helical antennas have been known for a long time and their behavior in both RF and microwave frequencies has been thoroughly investigated, [11]. For instance the radiation

characteristics (e.g., the beam direction, the type of polarization, etc.) of a helical antenna are controlled by the size of its geometrical properties, as compared to the wavelength, and the input impedance value depends on the pitch size and the size of the conducting wire. Based on a vast number of measurements, empirical expressions have been derived and they are often used to determine the main properties of a helical antenna, such as its input impedance, its half-power beamwidth, its beamwidth between nulls, its directivity, and its axial ratio, [11]. Here, by taking advantage of these empirical expressions, and combining them with closed form expressions of the single loop, we are able to derive novel expressions capable of studying helical nano-antennas in the THz, infrared, and optical regimes.

Let us assume a helical antenna (see Fig. 1) consisting of N turns, diameter D, and spacing S between each turn. The total length of the helix is $L = NS$, and the total length of the wire is $L_n = N\sqrt{S^2+C^2}$. In addition, $C = \pi D$ is the circumference, and $\alpha = tan^{-1}S/C$ is its pitch angle. Aiming to an analytical formulation we follow Kraus' approach, [11], assuming that the helical antenna consists of an array of circular loops. Each loop as shown in Fig. 1 has inner radius b and metal thickness $2a$. Assuming that the loop is excited by an infinitesimal voltage V_0 at an arbitrary position ϕ, we express the resulting current distribution as a Fourier series, [12]:

$$I(\phi) = V_0\left[\frac{1}{i\pi\eta_0\alpha_0 + (b/a)Z_s} + \sum_{m=1}^{\infty}\frac{2cos(m\phi)}{i\pi\eta_0\alpha_m + (b/a)Z_s}\right] \tag{1}$$

where $\eta_0 = 120\pi$. The terms α_0 and α_m can be found in [12], and are omitted here for brevity. Note that in Eq. (1) the surface and characteristic wire impedance Z_s appears (see Eq. (13) in [12] for its detailed definition). As is shown later in our preliminary results the Z_s plays a significant role affecting drastically the electromagnetic behavior of the helical nano-antenna. After we define the current in the optical regime the far-zone electric field of the loop is expressed as, [14]:

$$E_\theta \approx -\frac{\eta_0 cot(\theta)}{2}\frac{e^{-jk_0r}}{r}\sum_{m=1}^{\infty} mj^m I_m sin(m\phi)J_m(k_b sin(\theta)) \tag{2}$$

$$E_\phi \approx -\frac{\eta_0 k_b}{2}\frac{e^{-jk_0r}}{r}\sum_{m=1}^{\infty} j^m I_m sin(m\phi)J_m^{'}(k_b sin(\theta)) \tag{3}$$

where J_m is the Bessel function, and $J_m^{'}$ is the derivative of the Bessel function of order m, respectively, while $k_b = 2\pi b/\lambda$. The far-zone electric field of the helical antenna is evaluated as, [11]:

$$E = sin(\frac{pi}{2N})E_0\frac{sin(N/2\psi)}{sin(\psi/2)} \tag{4}$$

where E_0 is the element pattern, computed based on Eq. (3) and $\psi = k_0 S cos(\theta) - \frac{\sqrt{S^2+C^2}}{p}$ with $p = \frac{L_0/\lambda_0}{S/\lambda_0+1}$, and $L_0 = \sqrt{S^2+C^2}$ for the case of ordinary end-fire radiation, [15].

3 Results

In order to validate our analytical approach, described in the previous section, we compare our results with the corresponding ones provided by HFSS and Antenna ToolBox^{TM}. First, we study the case of a perfectly electric conductive (PEC) helical nano-antenna. The circumference of the nano-antenna is chosen to be $C = 600\ nm$ with a thickness of $2a = 18\ nm$. In addition, the number of turns is chosen as $N = 12$ with the spacing between (center to center) them to be at $S = 80\ nm$. The results of this analysis, namely the directivity of the nano-helical antenna along a wide range of wavelengths, are summarized in Figure 2. Even though the coupling phenomena have not been taken into account in our analytical model, Figure 2 manifests a good agreement among the two commercial software and our analytical approach. It is for this reason that the forthcoming incorporation of coupling terms in Eq. 1 is expected to enhance further the accuracy of our results.

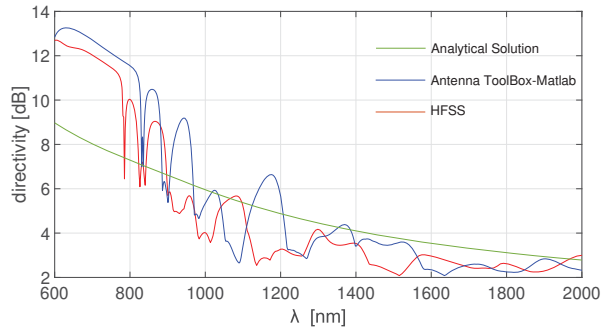

Figure 2. Comparison of the peak directivity of a PEC helical nano-antenna versus λ evaluated with three different simulation techniques.

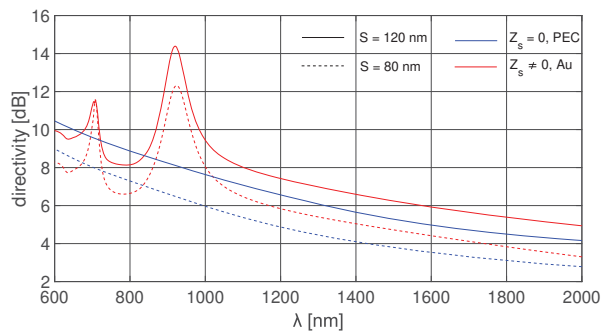

Figure 3. Peak directivity versus λ for the case of two different materials PEC and Au in the case of two different turn spacing, S.

Based on the satisfactory performance of our analytical method, we investigate the peak directivity of a gold and PEC helical nano-antenna. As shown in Figure 3, interesting physics are revealed for the case of a gold helical antenna. The abrupt increase of directivity appeared in certain bandwidths, is a phenomenon that does not occur in the PEC case. This is expected due to the optical properties

of gold. Such type of phenomena might suggest the super directivity concept which is left to be proven.

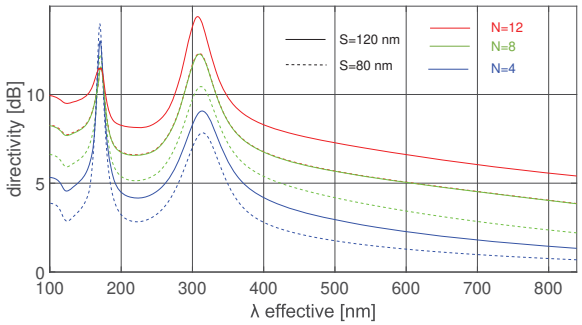

Figure 4. Peak directivity versus λ effective for three different values of N and S. It is clearly shown that the increase of N enhances the Array Factor leading to the increase of directivity. Large values of spacing between the turns of the helix also lead to directivity enhancement.

In order to investigate further the design parameters of the helical nano-antenna, we focus on parameters S and N. Note, here, that we have considered the effective wavelength concept, [5] as it describes the plasmonic mode propagation. Figure 4 shows that directivity is strongly dependent on the number of turns of helix and the spacing among them. The number of turns is expected to play a crucial role to the directivity due to its straight relation with the array factor of Eq. 4.

One should note here that the values of S should lie within specific range since the increase of S starts to deform the circular shape of each turn of the helical antenna. This leads to inaccurate results as our model utilizes closed form expressions for loop antennas placed parallel to each other.

4 Conclusions

In this work, for the first time analytical expressions for the study and analysis of helical nano-antennas were introduced. Using closed form expressions for the loop antenna, and array theory we were able to characterize nano-helices in the infrared and optical regimes showing superior directivity compared to the counterpart microwave helical antennas. In the conference a thorough analysis of our analytical formulation will be presented along with a complete characterization of helical nano-antennas.

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