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Epsilon-Near-Zero Nanoantennas

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ABSTRACT

In this paper the design of Epsilon Near Zero (ENZ) antennas, working in the infrared and optical regime, is presented. Two different structures are considered: the classical PEC antenna and the dielectric dipole covered by ENZ material antenna. The main crucial aspect concerning this paper is the possibility to reproduce the same behavior of a classical half-wavelength dipole also for shorter dimensions. The electromagnetic behavior of the structure (in terms of radiation efficiency, gain and bandwidth) becomes independent from its geometry. The proposed structure offers great potential in a wide variety of practical application fields such as detection and sensing, communications applications.

Keywords

Epsilon-Near-Zero, Antennas, Sensing, Telecommunications.

1. INTRODUCTION

Although antennas are a key enabling technology for everyday use devices in the radio-wave or microwave regime, their optical version is essentially not so common in today's technology. However, recent researches in nano-optics and plasmonics generated a huge interest in optical antennas, and new studies are at the moment focused on how to transfer the well-established radio wave and microwave concepts into the optical frequency regime. Recently the field of optics has significantly grown and researchers proved that nanostructures can represent the bridge between optical signals and near/far-field optical radiation, analogous to what a conventional metallic antenna represents for RF and microwave frequencies. While metallic wires were well-developed as solutions for communications and sensing problems in the radio and microwave frequency regime, first optical antennas were developed for imaging purposes [1].

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The development of dark-field microscopy, the scanning tunneling microscopy and the discovery of surface enhanced Raman scattering (SERS) gave rise to many theoretical studies aimed at predicting the electromagnetic field enhancement near electromagnetic wave-irradiated metal particles [2].

Irradiated metal tips, such as rods, bowties, and so on, were proposed as optical antenna probes for near-field microscopy and optical trapping [3]. Infrared structures fabrication has incredibly expanded in the past few decades, in order to fabricate many types of detectors, bolometers, and nanophotonic devices [4]. Recent progress in nanotechnology has allowed us to theoretically and experimentally study several optical nanoparticles configurations [5], paving the way to the new field of optical devices for telecommunications and sensing [6].

The lack of optical antenna devices in technological applications is associated with their small scale and the possibility to find materials that can behave as antennas at such frequencies. Typically such structures have characteristic dimensions of the order of the operative wavelength, this constrain leads for demanding fabrication accuracies of the order of nanometers. The advent of nanotechnology and the new kind of materials, the so-called metamaterials, provides access to these new technologies. Metamaterial structures are an emerging opportunity for novel optical tools. Typically, metamaterial-based antennas have been designed by using double-negative (DNG) [7], negative permittivity (ENG) [8], negative permeability (MNG) [9, 10] materials, and nanostructures [11, 12].

Recently, several studies focused their attention on a particular kind of metamaterials entitled epsilon-near-zero (ENZ) and on their particular electromagnetic properties [13]. In this regard several theoretical and numerical works on ENZ-based antennas can be found in literature, in order to improve its input impedance, bandwidth, directivity and gain [14]. Despite this, no one to the best of our knowledge has studied how to use ENZ materials to replicate the electromagnetic behavior of an antenna in the infrared and optical regime. Therefore, the aim of this work is to design new kind of optical antenna. We revisit the radio frequency (RF) and microwave antenna concepts and bring them to the higher frequency (infrared and optics), by exploiting the extraordinary ENZ material properties. Our results pave the way for new interesting and relevant applications in a variety of fields of optics, sensing, communications and nano-devices.

This article is organized as follows: first of all the classical antenna concepts are revisited and brought to the higher frequency (infrared and optics). Secondly, a brief overview of the general operation pattern of the ENZ+DIELECTRIC antenna is shown. Then, relevant differences between optical and conventional antenna operation are pointed out. A comparison with the traditional structures PEC structures is reported, in terms of radiation efficiency, gain and bandwidth. Finally, conclusions and possible applications are drawn in the final paragraph.

2. METAL AND ENZ ANTENNAS

2.1 Metal Antennas at optical frequencies

Light and radio waves are governed by the same equations, and therefore similar phenomena are expected. Unfortunately, a direct translation of conventional design rules to optical frequencies is not possible, due to the fact that material properties, physical operation and wave-matter interaction change significantly when the operating frequency is higher (near-infrared and visible spectrum) than the radio/microwave regime. In addition to this, the corresponding antenna dimensions become comparable to the components of materials. Conventional metal structures are usually realized with very good conductors characterized by negligible skin depth, in which conduction phenomena largely dominate. At optical frequencies, however, conductivity is generally lower and polarization and displacement effects play the crucial role. In this way, it modifies the physics of the antenna, and the definition of currents and radiation properties of the metallic structure needs to consider displacement effects, in addition to the conduction ones. Plasmonic effects and field penetration in the metal are typically manifested under these conditions. In other words, at higher frequencies (for example in the infrared frequency range) the metal thickness can no longer be neglected. New capacitive and inductive effects, considering the effect of the metal thickness have to be added to the traditional model [15]. In addition, at such frequencies, as reported before, metals cannot be considered ideal conductors anymore. Therefore, in the antenna model additional effects (considering the electric and magnetic energy stored within the metal, respectively) must be considered [16].

Moreover, the total resistance is given by two contributions, the ohmic one and the radiated one, related to the metal losses caused by radiation effects. Losses (high at such considered frequencies) reduce the quality factor of the system and this phenomenon must be taken into account, in particular for telecommunications applications. In the optical region, the losses depend not only on the material used but also on the particle shape [16].

For such reasons metallic antennas generally exhibit some properties which are not very suitable for most of the practical applications, in terms of gain, radiation efficiency and bandwidth .

2.2 ENZ Antennas

The aim of this paragraph, by exploiting the extraordinary properties of the ENZ materials, is to design a new kind of ENZ antenna in order to overcome all the issues listed above. Figure 1 shows the structure under study: the ENZ+DIELECTRIC antenna is characterized by a cylindrical air dipole with radius $a=\alpha\lambda_p$, length $l=\beta\lambda_p$, embedded in a concentric ENZ material cylinder as cover, whose thickness is $s=\gamma\lambda_p$, where λ_p is the plasma wavelength of the ENZ material. The ENZ permittivity is described by the complex electric permittivity $\varepsilon_{ENZ}(\omega)=\varepsilon_0(\varepsilon_r(\omega)-j\varepsilon_i(\omega))$ and magnetic permeability $\mu_{ENZ}=\mu_0\mu_r$ (being $\mu_r=1$ the relative magnetic permeability of the free space and $\omega=2\pi f$ is the angular frequency in rad/s). The system is excited by a discrete port placed between two circular metallic plates. They are filled by the ENZ material too, whose thickness is $d=\delta\lambda_p$. Let's assume the surrounding region as free space with electric permittivity ε_0 and magnetic permeability μ_0. In order to compare the traditional metal antenna electromagnetic behavior with the proposed ENZ structure, the following relevant major differences/aspects must be pointed out.

First of all the different electromagnetic behavior of such structures: it's well known that at RF and microwave antennas are realized with very conductors elements, in which skin depth can be neglected and the conduction phenomena largely dominate [17]. Metallic wires function as conduits for the flow of electronic charges and the relative conduction currents. Metals due to their high conductivity σ, when surrounded by insulators (having zero or low conductivity) as free space, play the role of a medium with high contrast in electric conductivity, leading to the confinement of the conduction currents σ**E** [18].

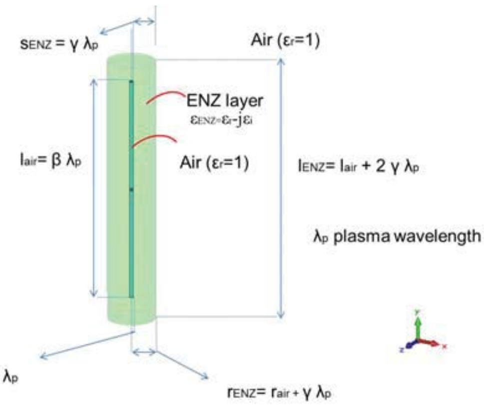


Figure 1. The ENZ+DIELECTRIC ring operation pattern.

However, at higher frequencies (infrared and optical) the conductivity is lower and the polarization/displacement effects grow, becoming more relevant especially when the wavelength is reduced. In this case, electric displacement currents play a more dominant role than the conduction ones. It means that at such frequencies the conduction current has to be substituted by the displacement one: -jωε**E**, where **E** is the electric field and ε is the local material permittivity [19]. Unlike the conduction current, in this case the displacement one can flow in the surrounding background material. Therefore in order to confine the displacement current, in the same way as metallic wires confine the conduction one, we have to replicate the contrast in conductivity existing between the metallic wire and the surrounding space. In other words the role of material conductivity is replaced by the material permittivity. The equivalent of a poor conductive material is represented by the ENZ material in which, due to its low (nearly zero, $\varepsilon \ll 1$) permittivity values, the displacement current is close to zero. In this way ENZ plays as an insulator for the displacement current, exactly the same role that air (very poorly conducting material $\sigma \approx 0$) plays for the conduction current. Analogously, the role of the metallic wire in classical antennas (good conductor $\sigma \gg 1$) may be taken here by a dielectric with high permittivity values ($\varepsilon \geq 1$). In this way the large contrast in the permittivity values is reached and the displacement current can flow in the dielectric medium as the conduction current flows on metals.

Secondly, in traditional metallic structures no fields penetrate into the metal due to the large wavelength (comparable in terms of order of magnitude to that of free space) leading to a small penetration depth effect. On the other hand, at optical frequencies the wavelength is dramatically reduced, as a consequence the skin depth cannot be neglected anymore. Such differences lead to crucial consequences:

- The definition of voltage and current (and consequently the impendence concept) change. In particular we have to refer to the integral quantities of the local field distribution and the related displacement field around and inside the structure, as reported in [20]
- If in traditional radio-frequency the physical and resonant length of a wire structure are comparable (half-wavelength of operation), at higher frequencies the guided wavelength on the arms of the optical antenna becomes significantly smaller than in free space [21]. On the other hand, conduction currents are forced to be zero at the end of the antenna arms, at the optical regime the displacement current is not necessarily zero at the edge of the antenna. So the effective antenna length results longer compared to its physical one, and the related resonant frequency is shifted to higher wavelengths compared to the traditional case.
- Due to the larger penetration of the field, losses and absorption become more important in optical antennas, affecting their radiation efficiency and gain.

We simulated the electromagnetic field distribution of the considered structures by using the commercial electromagnetic software CST Microwave Studio [22]. The results are shown in Figure 2, where the vector plot of the displacement electric field distribution for the ENZ+DIELECTRIC dipole, is depicted.

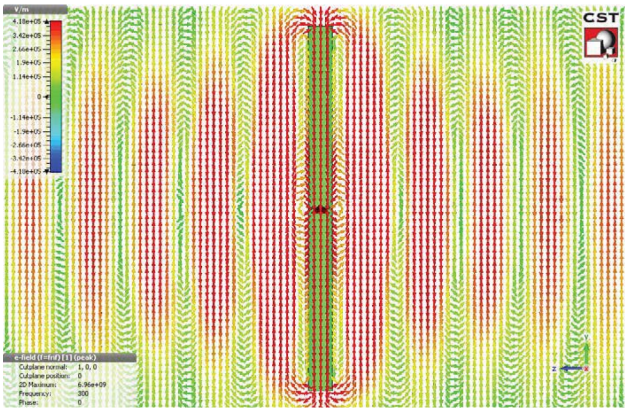


Figure 2. Vector field plot of displacement current for the ENZ+DIELECTRIC dipole.

Starting from that point, for the ENZ antenna what we have obtained is that:

- The phase has little changes from the source to the edges, without leaking into the air region. Whereas is transversally directed in the ENZ shell.
- The displacement current is predominantly longitudinal, strongest at the center of the cross section, flowing forward along the air structure, strictly confined in the dielectric path.

From the uniform phase over along all the cross section of the dipole derives that:

- The electric and magnetic field distribution around the structure, remind those of a regular metallic wire at radiofrequencies;
- Negligible amplitude decay and radiation losses, due to the fact that the ENZ shell acts as a perfect magnetic conductor reducing the field to zero outside the dielectric path. Therefore, the thickness of the ENZ shell is not crucial in ensuring the guidance properties of the structure. Instead it plays a crucial role in the amplitude of the guided and irradiated electric field and on the phase variation along the dipole and on the radiation losses.

In the same manner as classical metallic conducting antenna at RF and microwave frequencies allows the flow of conduction currents without current leakage and negligible voltage drop, here the ENZ antenna is able to permit the displacement current to flow in the dielectric dipole with no phase delay and without leaking it along its path and to sustain the current flow with no electric field discontinuity across its top/bottom edge. In absence of electric field drops we obtain that, at the end of the dipole as in a traditional antenna, the displacement current close itself on the other side of the structure. As a consequence it radiates.

2.3 Radiation efficiency, gain and bandwidth

The antenna *efficiency* takes into account the reflection, conduction, and dielectric losses [23]:

$$e = \frac{R_r}{R_r + R_L} \tag{1}$$

Where R_r is the radiation resistance and R_L represents the conduction-dielectric losses.

The conduction and dielectric losses of an antenna are very difficult to evaluate and in most cases they are measured. If the skin depth of the metal is very small compared to the smallest diagonal of the cross section of the antenna, the current is confined to a thin layer near the conductor surface. Therefore the high-frequency resistance can be written, based on a uniform current distribution, as [23]

$$R_{L\_PEC} = \frac{l}{2\pi r}\sqrt{\frac{\omega\mu_0}{2\sigma}} \tag{2}$$

In our case, instead by substituting the conduction current with the displacement one, the formula assumes exactly the same form with the imaginary part of the structure permittivity (taking into account the losses at high frequencies) instead of the conductivity (representing the losses in RF and microwave ranges):

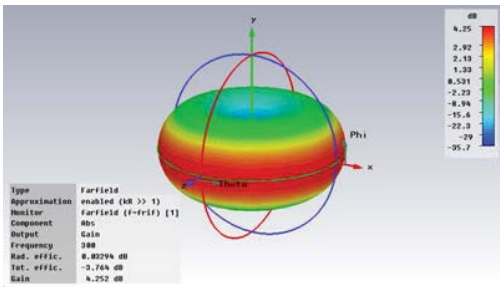
$$R_{L\_ENZ} = \frac{l}{2\pi r}\sqrt{\frac{\omega\mu_0}{2\varepsilon_i}} \quad (3)$$

Being *l* the dipole length, *r* the radius, $\omega=2\pi f$ the angular frequency, μ_0 the magnetic permeability of the free space and ε_i the imaginary part of the ENZ cover permittivity.

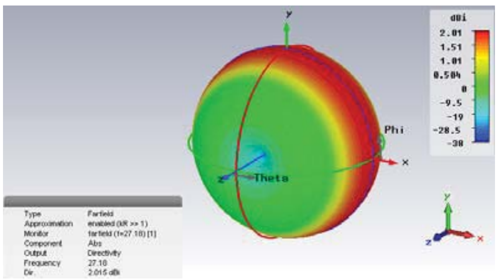
It's worth noting that in the ENZ antenna case, the radiation efficiency exclusively depends on the ENZ cover losses, being the dielectric dipole (air) lossless.

More complex is the determination of the radiation resistance R_r of the antenna. In the classical antenna system the possibility to calculate the radiation resistance is well-established, as reported in [23]. In our case, the behavior is slightly different and numerical techniques are needed to properly evaluate its value.

The *directivity* of an isotropic source is unity since its power is radiated equally well in all directions. For all other sources, the maximum directivity will always be greater than unity. In this case the uniform displacement current distribution in the antenna system leads to an isotropic radiation pattern (Figure 3a), therefore the directivity of the ENZ antenna (independently from the length) is similar (in value) to the classical half-wavelength metallic dipole (Figura 3b).



(a)



(b)

Figure 3. Far-field radiation properties for the (a) ENZ+DIELECTRIC dipole and (b) PEC dipole.

The *bandwidth* of a classical antenna depends on several characteristics such as input impedance, radiation pattern, gain, polarization, etc. In addition it does not necessarily vary in the same manner or is even critically affected by the frequency. In the ENZ case, instead, the antenna bandwidth is a function exclusively of the frequency, due to the fact the cover material behaves as epsilon near-zero only in a small frequency bandwidth.

3. CONCLUSIONS

The aim of the paper is to design a new kind of ENZ antenna. We revisit the RF and microwave antenna concepts and bring them to the higher frequency (infrared and optics), by exploiting the extraordinary ENZ material properties. The main crucial aspects concerning this study can be summarized as follows:

• the possibility to reproduce the same behavior of a classical half-wavelength dipole also for shorter dimensions.

• let the antenna electromagnetic properties independent from the geometry of the structure and a function exclusively of the frequency at which the cover material acts as ENZ.

It means that it is possible to find similarities to transfer the classical metallic wire concepts at the higher frequencies (infrared and visible), obtaining similar electromagnetic behavior. Our results pave the way for new interesting and relevant applications in a variety of fields of optics, sensing, communications and nano-devices.

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