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Pulsed EM radiation from a traveling-current plasmonic nanowire

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ABSTRACT

Pulsed electromagnetic (EM) radiation from a traveling-current plasmonic-wire segment is studied analytically using the unilateral Laplace-transform technique. This approach yields closed-form expressions that can be readily evaluated for given configurational and excitation parameters, thereby revealing physical insight into the time-domain (TD) EM radiation behavior of a plasmonic nanowire. Illustrative numerical examples concerning pulsed EM fields radiated from a gold nanowire are given and discussed.

1. Introduction

Antennas capable of efficiently operating with optical wave fields show a lot of promise because of their applications in THz and photonic devices [1,2] and plasmonic biosensors [3], for example.

Notwithstanding the applicability of some general-purpose numerical EM solvers (see e.g. [4]), the still increasing complexity of plasmonic structures has necessitated the development of dedicated (and more efficient) numerical methodologies [5–7]. As to the corresponding TD (i.e. space–time) modeling, this category is (almost) exclusively limited to the finite-difference time-domain (FDTD) technique (see [8] and [9, Ch. 4], for example). Although the FDTD technique is a well-established tool for engineering practice, its purely numerical outcomes can hardly be sufficient to fully grasp all peculiarities of plasmonic phenomena. The latter can be best addressed by solving canonical problems such as the excitation of surface plasmon polaritons at planar interfaces [10, Ch. 2]. Despite the fact that all physical phenomena manifest themselves in space–time, only a few initial attempts to describe plasmonic effects analytically in TD do exist so far (see [11–14], for example).

Except for the observation that the skin depth cannot be neglected anymore [15], analytical models characterizing frequency-domain (FD) EM scattering from optical plasmonic nanowires (see [16], for example) rely largely on the classic FD theory of straight-wire antennas [17]. To the best of our knowledge, there is presently no study available that analyzes the pulsed EM radiation from a plasmonic nanowire analytically. Filling this void is hence the main purpose of this work.

This paper follows in part the methodology based on the unilateral Laplace transformation that has been successfully applied to analyzing a relaxation-free traveling-current straight-wire segment in TD [18]. Here it is demonstrated that such a methodology is also applicable to describing the pulsed EM radiation from a current pulse traveling along a plasmonic nanowire. Indeed, it is shown that the pulsed EM radiation characteristics of such a radiating segment can be expressed as the superposition of the EM radiation characteristics pertaining to the corresponding electrically perfectly-conducting (PEC) wire and the (Boltzmann-type) relaxation part describing its plasmonic behavior.

For an earlier work on pulsed EM radiation from a traveling-wave PEC antenna we refer the reader to [19]. Finally, a somewhat more general TD approach accounting for the complete space–time electric-current distribution along a thin PEC wire can be found in [20].

2. Problem definition

The plasmonic nanowire under consideration is shown in Fig. 1. The wire is placed in the unbounded, homogeneous and isotropic embedding of permittivity ϵ_0 and permeability μ_0. The corresponding EM wave speed is $c_0 = (\epsilon_0\mu_0)^{-1/2} > 0$ and $\eta_0 = (\mu_0/\epsilon_0)^{1/2} > 0$ is the free-space impedance. The EM properties of the wire itself are described by the radial plasma frequency

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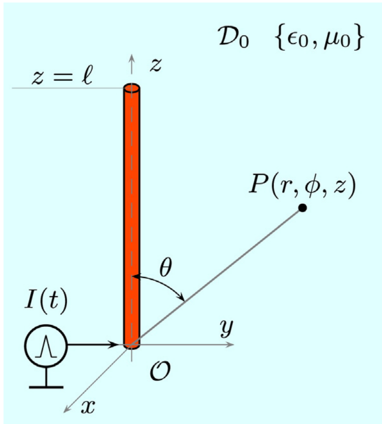

Fig. 1. Problem configuration.

ω_p and the collision frequency ν_c via the conduction relaxation function (see [21, Section 19.5] and [11])

$$\sigma(t) = \epsilon_0 \omega_p^2 \exp(-\nu_c t)\mathrm{H}(t) \tag{1}$$

in which $\mathrm{H}(t)$ is the Heaviside unit-step function. Finally, the wire length is denoted by ℓ.

The wire segment is at $z = 0$ and $t = 0$ excited by an electric-current pulse $I(t)$ that travels along the segment's axis. We assume that $I(t) = 0$ for $t < 0$ along with the zero initial conditions for all EM fields throughout the problem configuration. Similarly to [19], we shall primarily limit ourselves to describing pulsed EM radiation of the electric-current pulse as it traverses the plasmonic segment from $z = 0$ to $z = \ell$. Beyond this limitation, reflections at the antenna end points have to be properly accounted for. This fact is demonstrated on a numerical example given in Section 5. The spatial point where the pulsed EM radiation is observed is specified by the radial, azimuthal and axial coordinates $\{r, \phi, z\}$, respectively, with respect to the Cartesian reference frame with the origin $\mathcal{O}$. The time coordinate is t. Partial differentiations are denoted by ∂ with the corresponding subscript. The time-integration and time-convolution operators are denoted by ∂_t^{-1} and $*$, respectively.

3. Radiated-field source-type representations

Owing to the rotational symmetry of the plasmonic-wire configuration, the non-zero EM-field components are ϕ-independent and can be expressed through (cf. [21, Section 26.4])

$$E_r(r, z, t) = \epsilon_0^{-1} \partial_t^{-1} \partial_r \partial_z A_z(r, z, t) \tag{2}$$

$$E_z(r, z, t) = -\mu_0 \partial_t A_z(r, z, t) + \epsilon_0^{-1} \partial_t^{-1} \partial_z^2 A_z(r, z, t) \tag{3}$$

$$H_\phi(r, z, t) = -\partial_r A_z(r, z, t) \tag{4}$$

in which A_z can be, symbolically, cast into the following form (cf. [18, Eq. (3)])

$$A_z(r, z, t) = I(t) * \Gamma(r, z, t) \tag{5}$$

where we have assumed the thin-wire approximation and (the complex-frequency-domain counterpart of) $\Gamma(r, z, t)$ will be specified below. Under a unilateral Laplace transformation

$$\hat{A}_z(r, z, s) = \int_{t=0}^{\infty} \exp(-st) A_z(r, z, t) \mathrm{d}t \tag{6}$$

with the complex-frequency parameter $\{s \in \mathbb{C}; \mathrm{Re}(s) > 0\}$, Eq. (5) can be transformed as follows:

$$\begin{aligned} \hat{A}_z(r, z, s) &= \hat{I}(s)\hat{\Gamma}(r, z, s) \\ &= \hat{I}(s) \int_{\xi=0}^{\ell} \exp\left[-sR(\xi)/c_0\right]/4\pi R(\xi) \\ &\quad \exp\left\{-\left[s^2 + \left[s/(s+\nu_c)\right]\omega_p^2\right]^{1/2} \xi/c_0\right\} \mathrm{d}\xi \end{aligned} \tag{7}$$

with $R(\xi) = [r^2 + (z - \xi)^2]^{1/2}$. In Eq. (7) we may distinguish between the propagation factors $\exp(-sR/c_0)$ and $\exp(-\hat{\gamma}\xi)$ with $\xi \in (0, \ell)$ pertaining to the wave propagation in the embedding and along the wire segment itself, respectively. In accordance with Eq. (1), the propagation coefficient corresponding to the plasmonic wire can be found as $\hat{\gamma} = \{s^2 + [s/(s+\nu_c)]\omega_p^2\}^{1/2}/c_0$ (see [21, Eqs. (24.4-13), (24.4-14) and (26.2-3)]). Upon expanding $R(\xi)$ about $R(0) = (r^2 + z^2)^{1/2} \to \infty$ we arrive at the following far-field approximation

$$\hat{A}_z(r, z, s) = \hat{A}_z^{\infty}(\theta, s) \exp\left[-sR(0)/c_0\right]/4\pi R(0)\left\{1 + O[R^{-1}(0)]\right\} \tag{8}$$

in which

$$\begin{aligned} \hat{A}_z^{\infty}(\theta, s) &= \hat{I}(s) \int_{\xi=0}^{\ell} \exp\left[s\xi\cos(\theta)/c_0\right] \\ &\quad \exp\left\{-[s^2 + [s/(s+\nu_c)]\omega_p^2]^{1/2}\xi/c_0\right\} \mathrm{d}\xi \end{aligned} \tag{9}$$

Along these lines, the transient EM radiation characteristics can be then expressed using the TD counterpart of (9) with (2)–(4) as follows:

$$E_r^{\infty}(\theta, t) = \mu_0 \partial_t A_z^{\infty}(\theta, t) \sin(\theta)\cos(\theta) \tag{10}$$

$$E_z^{\infty}(\theta, t) = -\mu_0 \partial_t A_z^{\infty}(\theta, t) \sin^2(\theta) \tag{11}$$

$$H_\phi^{\infty}(\theta, t) = c_0^{-1} \partial_t A_z^{\infty}(\theta, t) \sin(\theta) \tag{12}$$

with (cf. Eq. (8))

$$E_r(r, z, t) = E_r^{\infty}\left[\theta, t - R(0)/c_0\right]/4\pi R(0)\{1 + O[R^{-1}(0)]\} \tag{13}$$

$R(0) \to \infty$, for example. Finally note that the θ-component of the electric-type radiation characteristic directly follows as

$$E_\theta^{\infty}(\theta, t) = \mu_0 \partial_t A_z^{\infty}(\theta, t) \sin(\theta) \tag{14}$$

which gives $E_\theta^{\infty}/H_\phi^{\infty} = \eta_0$ for all $t > 0$ and $\{0 < \theta \le \pi\}$. From Eqs. (10)–(12) and (14) it is clear that the transient radiation characteristics of the analyzed plasmonic wire are proportional to $\partial_t A_z^{\infty}(\theta, t)$. Accordingly, the main subject of the following section is to find (the time-derivative of) the TD counterpart of Eq. (9).

4. Pulsed EM radiation characteristics

Owing to the availability of low-loss plasmonic materials such as gold or silver (see e.g. [22]), we will, in the first approximation, limit ourselves to the collision-free case by taking the limit $\nu_c \downarrow 0$. In this case, the solution is attainable in terms of standard functions. After some straightforward steps we end up with

$$\begin{aligned} A_z^{\infty}(\theta, t) &= A_z^{\infty;\mathrm{PEC}}(\theta, t) - \frac{c_0\omega_p}{[1-\cos(\theta)]^2} I(t) \\ &\quad * \int_{\tau=0}^{\min[t, T(\theta)]} \frac{\mathrm{J}_1\left\{\omega_p[t-\tau]^{1/2}[t+q(\theta)\tau]^{1/2}\right\}\tau\mathrm{d}\tau}{[t-\tau]^{1/2}[t+q(\theta)\tau]^{1/2}} \end{aligned} \tag{15}$$

where $T(\theta) = (\ell/c_0)[1 - \cos(\theta)]$, $q(\theta) = [1 + \cos(\theta)]/[1 - \cos(\theta)]$, $\mathrm{J}_1(x)$ is the Bessel function of the first kind and of the first order and $A_z^{\infty;\mathrm{PEC}}$