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Preface

The International Conferences “Days on Diffraction” are annually held by the Faculty of Physics of St.Petersburg University, St.Petersburg Branch of V.A. Steklov Mathematical Institute and Euler International Mathematical Institute of the Russian Academy of Sciences.

Approximately 140 scientists from all over the world took part in the "Days on Diffraction - 2007" Conference. The Organizing Committee is thankful to all the participants. We appreciate their presentations which have been made during plenary, parallel and poster sessions. Our special gratitude is to the authors of 31 papers selected for publication in the Proceedings for preparation of their manuscripts in accordance with the required rules.

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Pulsed radiation produced by a travelling exponentially decaying bipolar current pulse with high-frequency filling

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Electromagnetic waves accompanying high-frequency modulated current pulses, exponentially decaying with time and travelling without losses along a line segment of a finite length, are investigated for both subluminal and luminal velocities of the pulse propagation.

1 Introduction

Investigation of electromagnetic radiation accompanying propagation of pulses with high-frequency filling moving along a line segment is stimulated by the problem of launching of directional waves and the results of experimental investigation of super-radiation waveforms [1]. In this work we consider the specific envelope function, an exponentially decaying pulse. This model and its simple derivative — the bipolar pulse, a sum of two exponentially decaying pulses of opposite polarity — are one of the simplest but feasible approximations of many real source currents.

Wave generation is described by solving the inhomogeneous Maxwell equations directly in the space-time domain $\rho, \varphi, z$ and $\tau$, where $\rho, \varphi, z$ are the cylindrical coordinates with the origin coincided with the point of current generation. The $z$ axis is directed along the radiator, which occupies the segment $\{\rho = 0, z \in [0, l]\}$, where $l$ is the radiator length, see Fig. 1, and $\tau = ct$ ($c$ is the velocity of light and $t$ the time reckoned from the start of the pulse generation) is the time variable. In this notation, the exponentially decaying source-current pulse $I$ is described by the equation

$$I(\pm) (z, \tau) = h(\tau) h(\beta\tau - z) I_0 \times M(\pm) (z, \tau) U (z, \tau).$$

Here $h(*)$ is the Heaviside step function, $\beta = v/c$ the dimensionless pulse propagation velocity and $I_0 = I(z = 0, \tau = 0)$ the initial pulse amplitude. The high-frequency modulation with the spatial period $2\pi/k$ and the phase velocity $v_{phase}$ (dimensionless form $\Omega = v_{phase}/c$) is represented by the factor

$$M(\pm) (z, \tau) = \exp (ik(\Omega\tau \pm z)).$$

From here on the symbols $(+)$ and $(-)$ in the variable subscripts denote propagation of the modulation waveform in the directions $-e_z$ (counterpropagation) and $e_z$ (copropagation) respectively. The factor

$$U(z, \tau) = \exp (-\alpha(\tau - z/\beta))$$

represents the envelope, a pulse whose exponential decay is characterized by the constant extinction coefficient $\alpha$.

The cylindrical symmetry of the current density

$$j^{(\pm)} (z, \tau) = j^{(\pm)} (z, \tau) e_z,$$

enables the electromagnetic field vectors to be represented using TM polarization and the Whittaker-Bromwich potential $u$,

$$D_\rho = \partial_\rho u + \delta_\rho^2 u, \quad D_z = -\partial_\tau^2 u + \delta_\tau^2 u, \quad H = -c\partial_\rho \partial_\tau u,$$
and the electromagnetic problem reduces to the scalar one,

\[
\left[ \frac{\partial^2}{\partial \tau^2} - \frac{1}{\rho} \frac{\partial}{\partial \rho} (\rho \partial_{\rho}) - \partial_z^2 \right] \Psi^{(\pm)} = \frac{1}{c^2} J^{(\pm)},
\]

\[
\Psi^{(\pm)} = 0 \quad \text{for} \quad \tau < 0,
\]

with respect to the function \( \Psi = \partial_\tau u \).

The main stages for solving problem (1) are described in detail in [2] and will be discussed here only briefly. Following the Smirnov method of incomplete separation of variables, the spatial coordinate \( \rho \) is first separated via the Fourier-Bessel transform \( \rho \to s \)

\[
\left( \Psi_{j} \right) (\rho, z, \tau) = \int_{0}^{\infty} \left( \Psi \right) (s, z, \tau) J_{0}(s \rho) s \, ds
\]

(\( J_{0} \) is the Bessel function of the first kind of order zero). Solution of the problem with respect to the residual variables \( z, \tau \) is obtained by the Riemann method, the Riemann function being

\[
R(z, \tau; z', \tau') = J_{0} \left( s \sqrt{(\tau - \tau')^2 - (z - z')^2} \right).
\]

Transforming the solution back to the space-time domain \( (s, z, \tau) \to (\rho, z, \tau) \), rearranging the integrals, using the orthogonality property of the Bessel function (see, e.g., item 21.8-4 of [3]), expanding the result in terms of \((kl)^{-n}\) and neglecting the terms of order \((kl)^{-2}\) and higher reduces the solution for \( H^{(\pm)} = -\partial_\rho \Psi^{(\pm)} \) to

\[
H^{(\pm)} = \begin{cases} 
0 & \text{for} \quad -\infty < \tau < r_{0} \\
H^{(\pm)}_{0} - H^{(\pm)}_{l} & \text{for} \quad r_{0} < \tau < \tau_{1} \\
H^{(\pm)}_{0} - H^{(\pm)}_{l} & \text{for} \quad \tau_{1} < \tau < +\infty
\end{cases}
\]

Here \( r_{0} = \sqrt{\rho^2 + z'^2} \) is the distance from the coordinate origin to the observation point \( \rho, \varphi, z \), \( \tau_{1} = l/\beta + r_{1} \) denotes the moment of time in which the spherical wave, emanated by the source-current front at its absorption at the second radiator’s end (space-time coordinates of the event are \( \rho = 0, \ z = l, \ \tau = l/\beta \)), arrives, passing the distance \( r_{1} = \sqrt{\rho^2 + (z + l)^2} \), at the observation point, and the terms \( H^{(\pm)}_{0, l} \) have the form

\[
H^{(\pm)}_{\gamma} = \frac{I_{0}}{4\pi} K_{\gamma} U_{\gamma} \chi^{(\pm)}_{\gamma} R^{(\pm)}_{\gamma}, \quad \gamma = 0, \beta, l. \quad (2)
\]

2 Generalized solution

Explicit relations for the factors composing (2) in the case \( \beta < 1 \) are derived in [2]. With the approach developed in [4] for the case \( \beta = 1 \), one can extend this result for the case \( \beta \leq 1 \), getting the generalized formulas, conventionally separated into the following groups:

- “Divergence” factors of the dimensionality \([m^{-1}]\), responsible for the wave attenuation at long distances from the radiator

\[
K_{0} = 1 \quad r_{0}, \quad K_{\beta} = \frac{1}{\Lambda_{\beta}}, \quad K_{l} = \frac{1}{r_{l}}, \quad (3)
\]

\[
\Lambda_{\beta} = \sqrt{(1 - \beta^{2}) \rho^{2} + (z - \beta \tau)^{2}}, \quad (4)
\]

- “Extinction” factors (dimensionless), describing the wave decay due to the decaying nature of the source current

\[
U_{0} = U(0, \tau - r_{0}) = \exp (-\alpha (\tau - r_{0})), \quad (5)
\]

\[
U_{\beta} = U(\beta \rho, P) = 1, \quad P = \frac{\tau - r_{0}^{2}}{\tau - \beta z + \Lambda_{\beta}}, \quad (6)
\]

\[
U_{l} = U(l, \tau - r_{1}) = \exp (-\alpha (\tau - \tau_{1})). \quad (7)
\]

- “Phase” factors (dimensionless)

\[
\chi^{(\pm)}_{0} = \exp (ik\Omega (\tau - r_{0})), \quad (8)
\]

\[
\chi^{(\pm)}_{\beta} = \exp (ik\Omega \left( 1 + \frac{\beta}{\Omega} \right) P), \quad (9)
\]

\[
\chi^{(\pm)}_{l} = \exp (\pm ikl) \exp (ik\Omega (\tau - r_{1})). \quad (10)
\]

Note that \( \left| \chi^{(\pm)}_{\gamma} \right| = 1. \)

- “Directionality” factors (dimensionless) responsible for the anisotropy of the emanated-wave intensity with respect to the zenith angle reckoned from the radiator direction \( OZ \)

\[
R^{(\pm)}_{0} = \frac{\Omega \rho}{r_{0} \pm \Omega z} = \frac{\Omega \sin \theta_{0}}{1 \pm \Omega \cos \theta_{0}}, \quad (11)
\]

\[
\theta_{0} : \{ \rho = r_{0} \sin \theta_{0}, \ z = r_{0} \cos \theta_{0} \}
\]

\[
R^{(\pm)}_{l} = \frac{(1 - \beta^{2}) (\Omega \pm \beta) \rho}{(1 \pm \Omega \beta) \Lambda_{\beta} \pm (\Omega \pm \beta) (z - \beta \tau)}, \quad (12)
\]

\[
R^{(\pm)}_{l} = \frac{\Omega \rho}{r_{l} \pm \Omega z_{l}} = \frac{\Omega \sin \theta_{l}}{1 \pm \Omega \cos \theta_{l}}, \quad (13)
\]

\[
z_{l} = z - l, \quad \theta_{l} : \{ \rho = r_{l} \sin \theta_{l}, \ z_{l} = r_{l} \cos \theta_{l} \}.
\]

In the case of subluminal pulse propagation, \( \beta < 1 \), the factors \( K_{\beta} R^{(\pm)}_{\beta} \) may be represented in a form similar to that for \( K_{0} R^{(\pm)}_{0} \) and \( K_{l} R^{(\pm)}_{l} \)

\[
K_{\beta} R^{(\pm)}_{\beta} = \frac{1}{r_{\beta}} \frac{(\Omega \pm \beta) \sin \theta_{\beta}}{(1 \pm \Omega \beta) \pm (\Omega \pm \beta) \cos \theta_{\beta}}.
\]
\[ r_{\beta} = \sqrt{\rho^2 + z_{\beta}^2}, \quad z_{\beta} = \frac{z - \beta \tau}{\sqrt{1 - \beta^2}}. \]

\[ \theta_{\beta} : \{ \rho = r_{\beta} \sin \theta_{\beta}, \quad z_{\beta} = r_{\beta} \cos \theta_{\beta} \} \]

while in the vicinity of \( \beta = 1 \) Eqs. (3), (4) and (12) yield

\[ K_{\beta} = \frac{1}{\tau - z} + O(1 - \beta^2), \]

\[ R_{\beta}^{(\pm)} = \pm \frac{2 \rho (\tau - z)}{1 + \Omega (\tau - z)^2 + \rho^2} + O(1 - \beta^2). \]

3 Analysis of the field structure

Two factors of the second term \( H_{3,l}^{(\pm)} \), composing the solution \( H^{(\pm)} \), are continuous at \( \tau = \tau_l \)

\[ U_{\beta} \big|_{\tau = \tau_l} = U_{l} \big|_{\tau = \tau_l} = 1, \]

\[ \chi_{\beta}^{(\pm)} \big|_{\tau = \tau_l} = \chi_{l}^{(\pm)} \big|_{\tau = \tau_l} = \exp(\pm i l) \exp \left( \frac{\Omega l}{\beta} \right). \]

Nevertheless, the magnetic field amplitude \( |H^{(\pm)}| \) experiences a jump of the first kind as the other two factors behave differently:

\[ K_{\beta} R_{\beta}^{(\pm)} \big|_{\tau = \tau_l} = \frac{(\Omega \pm \beta) \rho}{(r_l - \beta z_l) (r_l \pm \Omega z_l)} \]

while

\[ K_{l} R_{l}^{(\pm)} \big|_{\tau = \tau_l} = \frac{\Omega \rho}{r_l (r_l \pm \Omega z_l)} \neq K_{\beta} R_{\beta}^{(\pm)} \big|_{\tau = \tau_l} \]

—a phenomenon predicted by the general formulas given in [4], resulted from the abrupt absorption of the travelling current pulse in the moment of time \( l/\beta \) at the radiator end \( \rho = 0, z = l \). Similar discontinuity was previously observed and discussed for the case of the exponentially decaying source-current pulse without modulation in [5].

The structure of the pulsed magnetic-field components \( H_{0}^{(\pm)}, \ H_{\beta}^{(\pm)} \) and \( H_{l}^{(\pm)} \) in relatively distant observation points, \( r_{0}/l = 10 \), is illustrated in Fig. 2. According to formulas (3)-(13), for the subluminal source current pulses (\( \beta < 1 \)) the emanated wave tends to zero in the vicinity of directions parallel and antiparallel to the \( OZ \) axis as \( \Omega (\theta_0) \) and \( \Omega (\pi - \theta_0) \) respectively. Great similarity between two sets of factors (3) for \( \gamma = 0 \) and \( \gamma = l \), the first describing the pulse generation at one radiator’s end and the second the pulse absorption at the opposite end, results in two pulses of similar shape: an abrupt splash, decaying as \( \frac{1}{r_{0}\gamma} \exp(-\alpha \gamma \tau^{*}) \), where \( \tau^{*} \) denotes time reckoned from the moment of pulse arrival at the observation point. More complicated nature of the factors \( K_{\beta} \) and \( R_{\beta}^{(\pm)} \) results in more complex behaviour of the \( H_{\beta}^{(\pm)} \) envelope, which admits both increasing and decreasing with time. In contrast to the case of unmodulated current pulse [5], the amplitude of the emanated wave cannot be represented as a sum of the functions depicted in Fig. 2 due to the interference of the phase factors \( \chi_{\beta}^{(\pm)} \). However, except in a few special cases of pronounced coherence, one can follow the classic optics approach and estimate the relative mean intensity \( \left| H^{(\pm)} \right|^{2} \) as

\[ \begin{align*}
0 & \text{ for } -\infty < \tau < r_{0} \\
\left| H_{0}^{(\pm)} \right|^{2} + \left| H_{\beta}^{(\pm)} \right|^{2} & \text{ for } r_{0} < \tau < \tau_{l} \\
\left| H_{0}^{(\pm)} \right|^{2} + \left| H_{l}^{(\pm)} \right|^{2} & \text{ for } \tau_{l} < \tau < +\infty
\end{align*} \]

The contour plots of \( \left| H^{(\pm)} \right|^{2} \) for \( \tau = 0.3 \) and \( 3 \) m are depicted in Fig. 3. The magnetic-field singularities in the source-current area at \( r_{0}/l = 0 \) and \( \Delta_{\beta} = 0 \) represent a natural specificity of the chosen model involving the Dirac distribution of the current density.

Another important characteristic of the solution, especially pertinent for detection and communication applications, is the front amplitude,

\[ \Delta H_{p}^{(+)} = \left| \lim_{\tau \rightarrow r_{0}} H_{0}^{(+)} \right| - \left| \lim_{\tau \rightarrow \tau_{l}} H_{\beta}^{(+)} \right| - \left| \lim_{\tau \rightarrow \tau_{l}} H_{\beta}^{(-)} \right| \]

Substitution of (3), (6), (9) and (12) into the above equation gives

\[ \Delta H_{p}^{(+)} = \frac{I_{0}}{4\pi r_{0}} \frac{\beta \sin \theta_{0}}{1 - \beta \sin \theta_{0}} \]

that coincides with the analogous characteristic obtained in [5] for the case of the unmodulated exponentially decaying source-current pulse (\( k = 0 \)). The maximum front amplitude,

\[ \Delta H_{p}^{(+)} = \frac{I_{0}}{4\pi r_{0}} \frac{\beta}{\sqrt{1 - \beta}}, \]

is radiated in the direction \( \theta_{0,\text{max}} = \arccos \beta \). As \( \beta \) approaches 1, the radiation pattern

\[ R_{\beta} \left( \theta_{0} \right) = \frac{\beta \sin \theta_{0}}{1 - \beta \cos \theta_{0}} \]
Figure 2: Envelopes of the magnetic field components $H_0^{(\pm)}$, $H_{\beta}^{(\pm)}$ and $H_l^{(\pm)}$ observed at the distance $r_0 = 10$ m from the pulse-generation point $\rho = 0$, $z = 0$ for $I_0 = 1$ A, $l = 1$ m, $\alpha = 1$ m$^{-1}$, $\beta = 0.8$ and $\Omega = 0.9$. 
Figure 3: Spatial distribution of $|H^{(\pm)}|^2$ for $\tau = 0.3$ and 3 m. The source-current parameters are the same as for Fig. 2.
exhibits more pronounced directionality and the emanated wave tends to a localized wave structure akin to Brittingham’s focus wave modes [6].

Being a special case of a more general solution considered in [2], \( H^{(\pm)} \) inherits all its common properties. In particular, for each direction of the wave propagation, \( \theta_0 = \text{const} \), the effective modulation frequency of the contribution \( H^{(\pm)}_\beta \) is transformed with respect to the initial modulation frequency \( \omega_0 = k \nu_{\text{phase}} = k \nu \Omega \). In the case of nearly luminal phase velocity, \( |\Omega - 1| \ll 1 \), expression (9) yields the following limits for the transformed frequency \( \omega^{(\pm)}_\beta (\theta_0) \):

\[
\omega_0 \left[ \frac{1 + \beta}{1 - \beta} + (\Omega - 1) \frac{\beta}{1 - \beta} \right] \leq \omega^{(-)}_\beta (\theta)
\]

\[
\leq \omega_0 \left[ 1 + (\Omega - 1) \frac{\beta}{1 - \beta} \right],
\]

\[
\omega_0 \left[ 1 - (\Omega - 1) \frac{\beta}{1 - \beta} \right] \leq \omega^{(+)}_\beta (\theta)
\]

\[
\leq \omega_0 \left[ \frac{1 + \beta}{1 - \beta} - (\Omega - 1) \frac{\beta}{1 - \beta} \right],
\]

corresponding to the red shift in the case of modulation copropagation and to the ultraviolet shift in the case of counterpropagation. In the case \( |\omega^{(\pm)}_\beta - \omega| \ll \omega_0 \) one can observe beatings between the field components \( H^{(\pm)}_0 \) and \( H^{(\pm)}_\beta \). In the case \( \Omega = \beta \) and modulation copropagation, the source current pulse and the modulating wave travel with the same speed in the same direction. The term \( H^{(-)}_\beta \) corresponds to the contribution of a current pulse of a constant shape moving with a constant velocity and the general principle of electromagnetics is satisfied due to zero value of the factor \( H^{(-)}_\beta \).

However, if \( \Omega \) and \( \beta \) are different but very close, so that \( k (\Omega - \beta) P \cong 1 \), the low-frequency oscillations are observed – due to propagation of the modulation and the pulsed current envelope in the same direction at slightly different speed – within the single component \( H^{(-)}_\beta \).

4 CONCLUSION

Electromagnetic waves accompanying high-frequency modulated current pulses, exponentially decaying with time and travelling without losses along a line segment of a finite length, are investigated for both subluminal and luminal velocities of the pulse propagation. Being an extension of a well-known description of the travelling-wave antenna, this model can explain peculiarities of some non-stationary electromagnetic waves produced by traditional artificial and natural line radiators, in particular, frequency transform, beatings, directionality and localization. The choice of the specific envelope function allows deriving observable and easy-to-analyse expressions related to the space time structure of the emanated waves, which may be used for characterizing natural phenomena and optimizing parameters of man-made radiators.

Despite the analytical relations obtained are derived as a first-order series approximation conditioned to the case \( kl \gg 1 \), in many practical situations they yield better results as a direct application of the general quadrature formulas as the latter deal with strongly oscillating integrands of complicated phase structure.

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