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Radiation of electromagnetic waves by a time-harmonic surface charge density

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ABSTRACT

The radiation process of waves by a time-harmonic electric charge density, located on the surface of a conducting sphere, is investigated. The current density is evaluated using the continuity equation. The scalar and vector potential are obtained by using the integral solution of the inhomogeneous Helmholtz equation. The radiated electric and magnetic fields are derived. The effect of the ground is put forth. The behaviors of the waves are studied numerically.

1. Introduction

The radiation of waves by antennas is based on two sources. The first one is the electric current density and the second source is the electric charge density. These current and charge densities are dependent on each other by the continuity equation. The electric scalar (ϕ) and magnetic vector $\left(\vec{A}\right)$ potentials are evaluated by the integrations of charge and current densities respectively [1]. Although it is supposed by the electromagnetism community that the potentials does not have any physical reality, the studies of Aharonov and Bohm showed that the magnetic vector potential was interacting with charged particles in a region where the magnetic field was zero [2]. An experiment on the Aharonov-Bohm effect, which was performed in the microwave frequencies, led to interesting results related with the radiated electromagnetic waves [3]. The electric field, in the direction of propagation, was excited in a circular waveguide by a monopole antenna. Zimmerman interpreted his results as a proof for the existence of the magnetic vector potential, which was propagating the longitudinal direction. In another experiment, the same author excited electric waves by a monopole antenna, located on a circular ground plane, in free space [4]. The propagating fields were only received by using a plasma antenna. Thus Zimmerman offered this behavior as a proof of the vector potential. However, the structure and location of the transmitter antenna hints the radiation of the longitudinal electric waves as was shown by us for discontinuous antennas [5]. In the literature, there is a general tendency against the existence of electric fields that are polarized in the direction of propagation because of the arguments of Heaviside [6], but it is well known in the antenna theory that the longitudinally polarized fields exist in the near field of the radiating system [1]. Their influence on radiation is neglected in the far field, because their dependence on distance is proportional to $1/r^2$ where r is the distance between the antenna and observation point. But there are experiments in the literature that supports the existence of the electric waves, polarized in the direction of propagation, in the far field region. The first set of experiments belongs to Zimmerman, as mentioned above [3,4]. Another realization of longitudinally polarized electric and magnetic fields was performed by Giakos and Ishii in 1992 [7]. They observed the radiated fields

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by a rectangular waveguide. The final experiment on longitudinal electric waves was carried out by Monstein and Wesley [8]. The radiated wave was excited by a center fed ball antenna and they used a polarizer in order to prove the existence of the longitudinally polarized electric wave. Although this work was criticized in the literature, the arguments were not refuting the reality of the observed fields [9–12]. The main problem of Monstein and Wesley's paper is their theoretical basis. Another support for the longitudinal waves came from the area of optics. In 2008, Niziev and Nesterov showed theoretically that longitudinally polarized electromagnetic waves could be constructed by a suitable superposition of plane waves [13]. Miyaji et al [14] generated electric fields that were polarized in the direction of propagation by using laser pulses. Driscoll et al [15] put forth the existence of longitudinal waves in nanowire waveguides by numerical computation. Also quantum electrodynamics foresees the longitudinally polarized fields in quantum vacuum [16,17]. In 2014, Onoochin [18] derived the longitudinal components of the electric field, radiated by a coil, with the aid of Jefimenko equations.

The aim of this paper is to investigate the radiated electric and magnetic waves by a time-harmonic charge density, which is distributed homogeneously on the surface of a spherical conductor. The problem is similar to the construction that was realized by Monstein and Wesley [8]. We will analyze the conditions that will lead to a longitudinal electric field, which has a distance variation of $1/r$. First of all the electric charge and current densities will be constructed. Then the electric scalar and magnetic vector potentials will be evaluated by using the integral solutions of the inhomogeneous Helmholtz equations. The electric and magnetic fields will be obtained from the potentials. The effect of perfectly electric and magnetic conducting grounds on the radiated waves will be studied. The behaviors of the radiation fields will be studied numerically.

A time factor of $\exp(j\omega t)$ is suppressed throughout the paper. ω is the angular frequency.

2. Equations of electromagnetic radiation

In this section, we will review the equations that are related with the radiation process of electromagnetic waves by current and charge densities. The magnetic vector and electric scalar potentials satisfy the inhomogeneous Helmholtz equations of

$$\nabla^2\vec{A} + k^2\vec{A} = -\mu_0\vec{J}_e \tag{1}$$

and

$$\nabla^2\varphi + k^2\varphi = -\frac{\rho_e}{\varepsilon_0} \tag{2}$$

provided that the Lorenz condition of

$$\nabla\cdot\vec{A} = -j\omega\mu_0\varepsilon_0\varphi \tag{3}$$

holds. μ_0 and ε_0 are the permeability and permittivity of free space respectively. k shows the wave-number. $\vec{J}_e$ and ρ_e are the electric current and charge densities, which satisfy the continuity equation of

$$\nabla\cdot\vec{J}_e = -j\omega\rho_e. \tag{4}$$

The integral solutions of the inhomogeneous Helmholtz equations, given by Eqs. (1) and (2), can be expressed as

$$\vec{A} = \frac{\mu_0}{4\pi}\iiint\limits_V \vec{J}_e\frac{e^{-jkR}}{R}dV' \tag{5}$$

and

$$\varphi = \frac{1}{4\pi\varepsilon_0}\iiint\limits_V \rho_e\frac{e^{-jkR}}{R}dV' \tag{6}$$

respectively [1]. R is the distance between the integration and observation points. The electric and magnetic fields can be found by the equations

$$\vec{E} = -j\omega\vec{A} - \nabla\varphi \tag{7}$$

and

$$\vec{H} = \frac{1}{\mu_0}\nabla\times\vec{A} \tag{8}$$

in terms of the vector and scalar functions.

3. Electric charge and current densities

A perfectly conducting sphere is taken into account as shown in Fig. 1. A discontinuous current element, like open-ended coaxial cable, feeds a conducting hollow sphere at its center. The radius of the sphere is a. The current can be excluded from