In Re Electric Switching Sense of Microwave Magnetic Field Rotation near Varactor-loaded Dipole Excited by a Plane Wave

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Abstract— A movement of a microwave magnetic field near a dipole, which is excited by a plane electromagnetic wave, is investigated theoretically. The total microwave magnetic field $\vec{H}$ being a superposition of fields of incident and scattered waves is under consideration. A varactor-loaded dipole is simulated by equivalent oscillator. It has been shown that projections of the field $\vec{H}$ of electromagnetic wave near the dipole satisfy the canonical ellipse equation (in the general case). This ellipse' orientation and magnitudes of half-axles depend on electric parameters of the equivalent oscillator as well on the dipole length and distance from it The total magnetic field $\vec{H}$ rotates in one direction at frequencies above the frequency ω_0 of the dipole resonance (DR) and in the counter direction below ω_0. Viz, left-handed $\vec{H}$-field takes place at frequencies $\omega > \omega_0$ while right-handed $\vec{H}$-field corresponds to $\omega < \omega_0$. When the dipole break is loaded with a varactor one can change the capacity C of the equivalent oscillator by application of bias voltage to the varactor. It results in tuning the DR. Electrically tunable DR can switch sense of rotating of the magnetic field. This effect in aggregate with the phenomenon of ferromagnetic resonance (FMR) in ferrite can provide electrically controlled nonreciprocity of transmission of microwaves. It can be useful in information technologies (IT) for development of fast-switched nonreciprocal devices.

1. INTRODUCTION

Dipoles are often used as elements of antennas and delay lines. At the last years there has been increasing interest in studies of metastructures based on resonant dipoles or other conductive elements (e.g., see [1, 2]). Usually, polarization of the electric field of these structures was subjecting to more detailed analysis. Now interesting effects have been observed in metastructures containing ferrite and chains or gratings of conducting elements [3–10]. These metastructures possess microwave nonreciprocity and are of interest for development of microwave devices such as nonreciprocal isolators and circulators. In these cases microwave nonreciprocity is due to different absorption of the wave whose sense of rotation of magnetic field $\vec{H}$ coincides with sense of precession of the ferrite spins, and of the wave possessing the opposite sense of magnetic field rotation [11]. That is why it is important to study properties of microwave magnetic field on a neighborhood of dipoles. Such searches were undertaken in papers [6–8, 10, 12].

Traditional experimental techniques can only provide data about the electric field. In [12] method of measurements of properties of magnetic field of surface wave was proposed using the resonance excited in a single planar double split ring. It has been shown experimentally that near planar grating of parallel dipoles irradiated by a plane wave with electric field parallel to dipoles, the microwave magnetic field lies in the plane orthogonal to dipoles and has both transverse and longitudinal components.

apers [6–8, 10] are devoted to theoretical investigations of gratings of conducting resonant elements (dipoles, double split rings, spirals, etc.) which were simulated by bianisotropic (in the general case) layers. In accounts [7, 10] it was used effective parameters (effective permeability and refractive index) of bianisotropic media [13–15]. It has been shown that near a bianisotropic layer the microwave magnetic field is rotating, the rotation senses being opposite at the right and at the left of the layer. The connection between microwave nonreciprocity and the magnetic field rotation has been noted. It was also found that there is reversal sense of the wave magnetic field rotation under transposition of the bianisotropic layer and ferrite as well under re-tuning between ranges of forward and backward waves (if the metamaterial is "left-hande" in some frequency diapasons).

Recently, it has been found experimentally that using a single varactor-loaded dipole one can control the nonreciprocity via voltage change [16–19]. Because the time constants of electrical control devices is in orders less than the time of ferrites magnetization reversal which takes place under traditional magnetic handling (e.g., see [20–22]), such metastructure can be a basis of fast-switched nonreciprocal devices and therefore causes peculiar interest.

In the paper under presentation it is theoretically researched behavior of a microwave magnetic field near a single dipole which is excited by a plane electromagnetic wave.

Theoretical methods based o effective parameters are inapplicable to this case. Therefore we carry out direct computations.

2. ELLIPTIC POLARIZATION OF TOTAL MICROWAVE MAGNETIC FIELD

The task configuration is depicted in Figure 1.

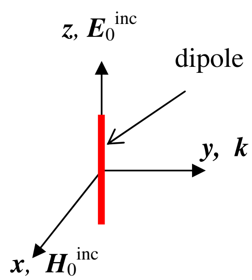

Figure 1: Disposition of dipole with respect to incident wave. $\mathbf{k}$, $\mathbf{E}_0^{\mathrm{inc}}$, $\mathbf{H}_0^{\mathrm{inc}}$ are wave, electric and magnetic vectors of incident wave.

A plane electromagnetic wave

$$\vec{E}^{\mathrm{inc}} = \vec{e}_z \frac{1}{2}\left\{E_{0z}^{\mathrm{inc}} \exp\left[\mathrm{i}\left(\omega t - ky\right)\right] + \mathrm{c.c.}\right\}, \quad \vec{H}^{\mathrm{inc}} = \vec{e}_x \frac{1}{2}\left\{H_{0x}^{\mathrm{inc}} \exp\left[\mathrm{i}\left(\omega t - ky\right)\right] + \mathrm{c.c.}\right\} \tag{1}$$

falls onto a dipole that is placed as it is pictured in Figure 1. Here $\vec{e}_j$are the coordinate orts, wave number $k = 2\pi/\lambda$, the dipole length $l << \lambda$. The ratio of electric and magnetic amplitudes is equal to the vacuum wave impedance $Z_0 = E_{0z}^{\mathrm{inc}}/H_{0x}^{\mathrm{inc}}$.

The scattered wave is characterized by complex amplitudes of projections of its magnetic field which in spherical coordinates are [23]

$$H_\varphi^{\mathrm{scat}} = \frac{I_z l}{4\pi} \sin\theta \left(\frac{\exp\left(-\mathrm{i}kr\right)}{r^2} + \mathrm{i}k\frac{\exp\left(-\mathrm{i}kr\right)}{r}\right), \quad H_\theta^{\mathrm{scat}} = H_r^{\mathrm{scat}} = 0. \tag{2}$$

Here θ, φ are zenith and azimuth angles, r is radial coordinate. I_z is complex amplitude of z-projection of the current that induced in dipole by electric field of the incident wave (1). To determine it let us simulate the dipole by equivalent oscillator possessing a capacity C, an inductance L and a resistance R. Introducing the oscillator impedance Z, current phase α and resonance frequency ω_0

$$Z = \sqrt{R^2 + \left(\omega L - 1/\omega C\right)^2}, \quad \alpha = \tan^{-1}\left[\left(1 - \omega^2/\omega_0^2\right)/\omega RC\right], \quad \omega_0 = \left(LC\right)^{-1/2}, \tag{3}$$

one can easily find that

$$I_z = H_{x0}^{\mathrm{inc}} l\left(Z_0/Z\right)\exp\left(\mathrm{i}\alpha\right). \tag{4}$$

Complex amplitudes of nonzero Cartesian projections of the scattered wave magnetic field are

$$H_x^{\mathrm{scat}} = -H_{x0}^{\mathrm{inc}} g \sin\theta \sin\varphi \exp\left(\mathrm{i}\beta\right)), \quad H_y^{\mathrm{scat}} = H_{x0}^{\mathrm{inc}} g \sin\theta \cos\varphi \exp\left(\mathrm{i}\beta\right). \tag{5}$$

Here the notations are

$$g = \frac{Z_0 l^2}{4\pi Z r^2}\sqrt{1 + k^2 r^2}, \quad \beta = \alpha - kr + \tan^{-1} kr. \tag{6}$$

Figure 2 shows vectors of magnetic fields of incident and scattered waves and their projections. Magnetic fields of both incident and scattered waves are plane-polarized. Let us consider their superposition at points $\mathscr{M}_0$ $(r, \theta = \pi/2, \varphi = 0)$ and $\mathscr{M}_\pi$ $(r, \theta = \pi/2,\ \varphi = \pi)$ that are placed in the entry plane $(y = 0)$ symmetrically with respect to the dipole. Normalized total magnetic field in this points is equal to $\vec{h}\left(t\right) = \vec{H}/H_{x0}^{\mathrm{inc}} = \vec{e}_x h_x(t) + \vec{e}_y h_y(t) = \vec{e}_x \cos\omega t + \vec{e}_y G\cos\left(\omega t + \beta\right)$. Magnitude $G = \pm g$, "+" and "−" refer correspondingly to points $\mathscr{M}_0$ and $\mathscr{M}_\pi$. Turning the coordinate system

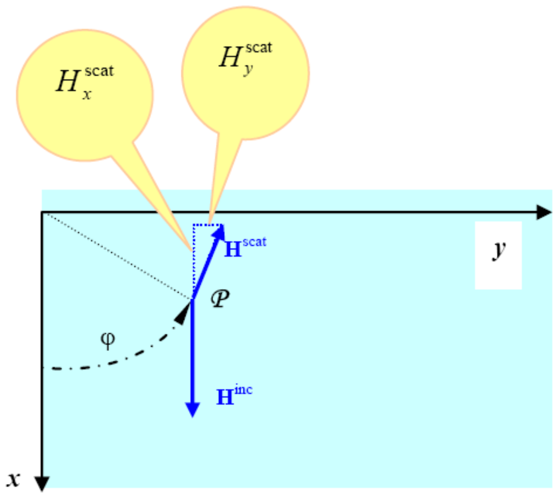

Figure 2: Magnetic fields of incident and scattered waves at an arbitrary point $\mathscr{P}$.

around z-axis on the angle $\Phi = 0.5 \tan^{-1}\left(2G\cos\beta/(1-G^2)\right)$ one can obtain that the magnetic field projections on new axes x', y' satisfy the canonical ellipse equation

$$h_{x'}^2 b_{x'}^{-2} + h_{y'}^2 b_{y'}^{-2} = 1. \tag{7}$$

It confirms and extends the derived for $kr << 1$ proposition of [19] about elliptical polarization of microwave magnetic field near a dipole. Figure 3 shows rotating microwave magnetic field.

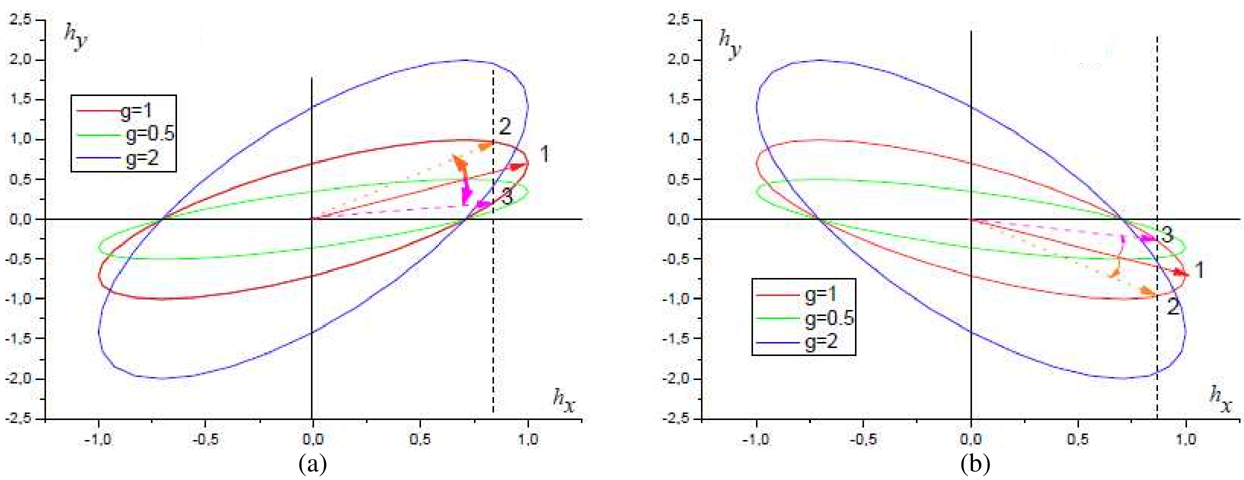

Figure 3: Movement of normalized total microwave magnetic field **h** in points $\mathscr{M}_0$ (a) and $\mathscr{M}_\pi$ (b) for various values of g. Straight arrows depicts field **h** in instants of time t =0 (No. 1, red) and $t = \tau < \pi/2\omega$ (color) for $g = 1$. Bent arrows point sense of rotation of **h**. Brown lines (No. 2) correspond to $\omega_0 < \omega$, magenta lines (No. 3) correspond to $\omega_0 > \omega$.

In (7) inverse squares of half-axles of the ellipse, along which the end of the vector $\vec{h}(t)$ moves, are equal to

$$b_{x',y'}^{-2} = \frac{1+g^2}{2g^2\sin^2\beta}\left[1 \mp \text{sign}\left(\cos 2\Phi\right)\sqrt{1-\left(\frac{2g\sin\beta}{1+g^2}\right)^2}\right]. \tag{8}$$

Elliptical polarisation degrades into the plane one when $g \to 0$ or $\sin\beta \to 0$ as well under $g \to \infty$.

First condition takes place by sizeable moving from resonant frequency ω_0, second one can be fulfilled near exact resonance under small kr. Curves of Fig. 3 have been calculated under the last condition for frequency detuning from the resonance on half-width of resonance curve for which $\alpha = \pm\pi/4$.

As follows from Fig. 3, re-tuning between these frequencies changes sense rotating of total magnetic field. Obviously, the same effect can be gotten by re-tuning of resonance frequency ω_0. The last can be provided with varactor-loaded dipole by application of bias voltage to the varactor that changes the capacity C of the equivalent oscillator.

3. CONCLUSION

It has been developed unique features of microwave magnetic field $\vec{H}$ near a dipole due to incident and scattered fields' superposition. Particularly, rotating of total microwave magnetic field nearby a dipole and possibility of change of this rotating sense have been revealed. Thereby the way to explanation of effect of the nonreciprocity electric control [17–19] has been found.

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