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RADIATION CHARACTERISTICS OF A MICROSTRIP PATCH ANTENNA USING A LEFT-HANDED MATERIAL

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1. Introduction

In recent years, there has been a strong interest in a left-handed material (LHM) due to its applications in designing novel devices used in millimeter wave and microwave regions [1],[2]. The material with simultaneously negative permittivity and permeability was predicted by Veselago [3]. Smith et al. first fabricated an LHM consisting of periodic arrays of thin wires and split ring resonators [4]. An LHM was also constructed from a two-dimensional LC loaded transmission-line structure [5]. In the LHMs, the Poynting vector is antiparallel to the wave vector of a plane electromagnetic wave [3]. Furthermore, an LHM exhibits interesting properties of a reversed Doppler effect, inverse Snell's law, and the Cherenkov radiation [1],[2].

Microstrip patch antennas are widely used in a variety of wireless communication devices on account of its small size, light weight, and low profile. In the past decade, many workers have studied bandwidth widening techniques for microstrip patch antennas. To broaden the bandwidth of a resonant-type microstrip patch antenna, various shapes of patches have been proposed [6]. Since the radiation characteristics of a microstrip patch antenna also depend on the substrate, different kinds of materials have been used in its substrate [6].

The purpose of this paper is to investigate radiation characteristics of a microstrip patch antenna having an LHM substrate. A rectangular patch is located on the LHM substrate, and the microstrip line is connected to the patch to feed the antenna. The LHM is dispersive, and its permittivity and permeability are expressed by the lossy Drude equations. Noting the constitutive relations for the LHM, one can derive differential equations for the polarization and the magnetization vectors. The finite-difference time-domain (FDTD) update equations for the three-dimensional LHM may be obtained by using the auxiliary differential equation FDTD (ADE-FDTD) method [7]. Numerical results are presented to show the effectiveness of the use of the LHM substrate for a microstrip patch antenna.

2. Formulation of the problem

Consider a microstrip patch antenna having an LHM substrate. A rectangular patch is located on the LHM substrate backed by a ground plane and the antenna is fed at the edge of a microstrip line, which is connected to the patch. The geometrical configuration of the microstrip patch antenna situated in free space is illustrated in Fig. 1. The lossy Drude model is employed to represent the permittivity and the permeability of the LHM [7]. Assuming $\exp(j\omega t)$ time dependence, constitutive relations for the LHM are expressed as

$$\begin{aligned}\mathbf{D}(x,y,z,\omega) &= \varepsilon_0\,\varepsilon_r(x,y,z,\omega)\mathbf{E}(x,y,z,\omega)\\ &= \varepsilon_0\left\{1-\frac{\omega_{pe}^2(x,y,z)}{\omega[\omega-j\Gamma_e(x,y,z)]}\right\}\\ &\quad\cdot\mathbf{E}(x,y,z,\omega) \qquad (1)\end{aligned}$$

and

$$\mathbf{B}(x,y,z,\omega) = \mu_0\,\mu_r(x,y,z,\omega)\mathbf{H}(x,y,z,\omega)$$

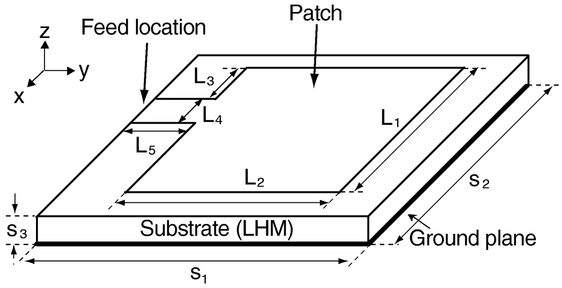

Fig. 1 Geometrical configuration of a microstrip patch antenna having an LHM substrate.

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$$= \mu_0 \left\{ 1 - \frac{\omega_{pm}^2(x,y,z)}{\omega[\omega - j\Gamma_m(x,y,z)]} \right\} \mathbf{H}(x,y,z,\omega), \tag{2}$$

where ω_{pe} and ω_{pm} are the plasma frequencies, Γ_e and Γ_m the collision frequencies, ε_0 and μ_0 the permittivity and the permeability of free space, and ε_r and μ_r denote the relative permittivity and the relative permeability.

The constitutive relations for the LHM are written as

$$\mathbf{D}(x,y,z,\omega) = \varepsilon_0 \mathbf{E}(x,y,z,\omega) + \mathbf{P}(x,y,z,\omega) \tag{3}$$

and

$$\mathbf{B}(x,y,z,\omega) = \mu_0 \mathbf{H}(x,y,z,\omega) + \mathbf{K}(x,y,z,\omega), \tag{4}$$

where $\mathbf{P}$ and $\mathbf{K}$ are the polarization and the magnetization vectors, respectively. Using Eqs. (1)-(4) and noting $\partial/\partial t = j\omega$, one obtains

$$\frac{\partial^2}{\partial t^2}\mathbf{P}(x,y,z,t) + \Gamma_e(x,y,z)\frac{\partial}{\partial t}\mathbf{P}(x,y,z,t) = \varepsilon_0 \omega_{pe}^2(x,y,z)\mathbf{E}(x,y,z,t) \tag{5}$$

and

$$\frac{\partial^2}{\partial t^2}\mathbf{K}(x,y,z,t) + \Gamma_m(x,y,z)\frac{\partial}{\partial t}\mathbf{K}(x,y,z,t) = \mu_0 \omega_{pm}^2(x,y,z)\mathbf{H}(x,y,z,t). \tag{6}$$

Since $\mathbf{J}(x,y,z,t) = \partial \mathbf{P}(x,y,z,t)/\partial t$ and $\mathbf{M}(x,y,z,t) = \partial \mathbf{K}(x,y,z,t)/\partial t$, we have the following differential equations for the ADE-FDTD method [7] by assuming $\omega_{pe} = \omega_{pm} = \omega_p$:

$$\frac{\partial}{\partial t}\mathbf{J}(x,y,z,t) + \Gamma_e(x,y,z)\mathbf{J}(x,y,z,t) = \varepsilon_0 \omega_p^2(x,y,z)\mathbf{E}(x,y,z,t) \tag{7}$$

and

$$\frac{\partial}{\partial t}\mathbf{M}(x,y,z,t) + \Gamma_m(x,y,z)\mathbf{M}(x,y,z,t) = \mu_0 \omega_p^2(x,y,z)\mathbf{H}(x,y,z,t), \tag{8}$$

where $\mathbf{J}$ and $\mathbf{M}$ are the electric and the magnetic current density vectors, respectively. From Eq. (7), one can derive the FDTD update equation for the x-component of $\mathbf{J}$ at $x = (i+\frac{1}{2})\triangle x$, $y = j\triangle y$, $z = (k+\frac{1}{2})\triangle z$, and $t = (n+\frac{3}{2})\triangle t$,

$$\begin{aligned} J_x^{n+\frac{3}{2}}(i+\frac{1}{2},j,k+\frac{1}{2}) = & \frac{1 - 0.5\Gamma_e(i+\frac{1}{2},j,k+\frac{1}{2})\Delta t}{1 + 0.5\Gamma_e(i+\frac{1}{2},j,k+\frac{1}{2})\Delta t} J_x^{n+\frac{1}{2}}(i+\frac{1}{2},j,k+\frac{1}{2}) \\ & + \frac{\varepsilon_0 \omega_p^2(i+\frac{1}{2},j,k+\frac{1}{2})\Delta t}{2\left[1 + 0.5\Gamma_e(i+\frac{1}{2},j,k+\frac{1}{2})\Delta t\right]} \\ & \cdot \left[E_x^{n+1}(i+\frac{1}{2},j,k+1) + E_x^{n+1}(i+\frac{1}{2},j,k)\right], \end{aligned} \tag{9}$$

where $\triangle x$, $\triangle y$, and $\triangle z$ are the cell sizes in the x-, y-, and z-directions, and $\triangle t$ indicates the time-step size. Similarly, other five FDTD update equations relating $\mathbf{J}$ with $\mathbf{E}$ and $\mathbf{M}$ with $\mathbf{H}$ may be obtained from Eqs. (7) and (8). Furthermore, six FDTD update equations for the components of $\mathbf{E}$, $\mathbf{H}$, $\mathbf{J}$, and $\mathbf{M}$ can be derived from the Maxwell's equations in time-varying form. Applying the leap-frog scheme [7] to the twelve FDTD update equations valid in the

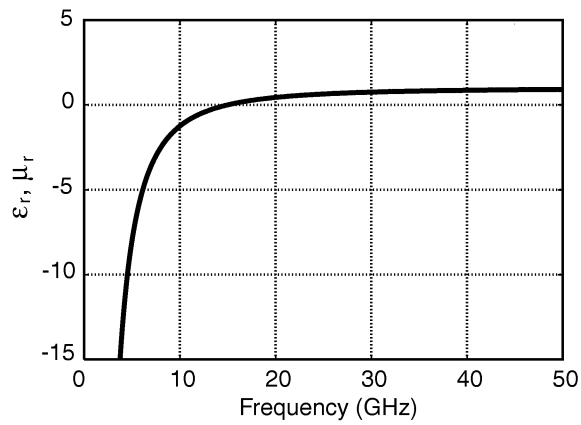

Fig. 2 Relative permittivity and permeability of the LHM substrate with $\omega_p = 9.4248 \times 10^{10}$rad/s.

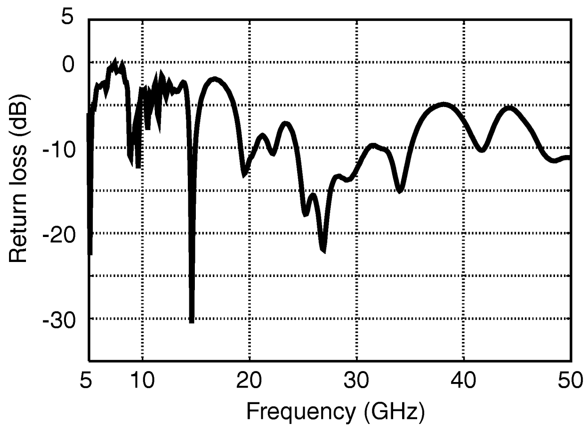

Fig. 3 Return loss of the microstrip patch antenna having the LHM substrate with $\omega_p = 9.4248 \times 10^{10}$rad/s.

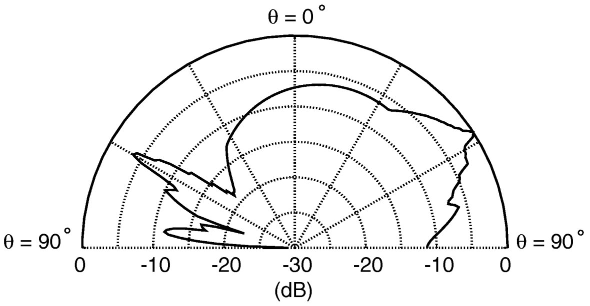

Fig. 4 Radiation pattern of the microstrip patch antenna in x-z plane at the resonant frequency of $f = 5.1$GHz.

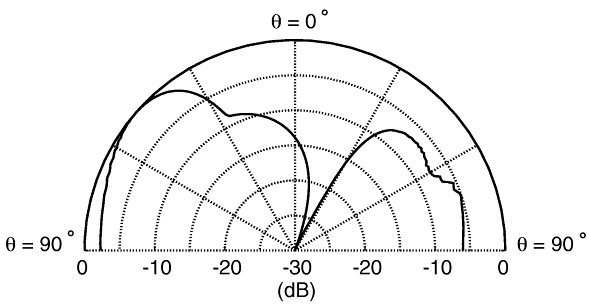

Fig. 5 Radiation pattern of the microstrip patch antenna in y-z plane at the resonant frequency of $f = 5.1$GHz.

regions inside and outside the LHM, we finally obtain all the electromagnetic field components in the investigation domain.

3. Numerical results

Computer simulations are performed for a microstrip patch antenna having a lossless and homogeneous LHM substrate with $\Gamma_e = \Gamma_m = 0$. The intrinsic impedance of the LHM substrate is matched to that of free space since $\varepsilon_r = \mu_r$ at any frequency. The dimensions of the microstrip patch antenna are $L_1 = 12.45$mm, $L_2 = 16.00$mm, $L_3 = 2.09$mm, $L_4 = 2.46$mm, $L_5 = 4.00$mm, $s_1 = 24.00$mm, $s_2 = 23.34$mm, and $s_3 = 0.795$mm. Note from Eqs. (1) and (2) that ε_r and μ_r of the LHM tend to $-\infty$ at dc. Then the antenna is excited by a delta-gap source expressed by a first-order derivative of a Gaussian-pulse function with the voltage of unit-amplitude. Now the investigation domain containing the microstrip patch antenna and the background free space is divided into $100 \times 120 \times 18$ cells in the x-, y-, and z-directions. The perfectly matched layer (PML) is implemented as an absorbing boundary condition for the electromagnetic wave. The cell sizes of $\triangle x$, $\triangle y$, and $\triangle z$ are 0.389mm, 0.400mm, and 0.265mm, and the time-step size is $\Delta t = 0.6407$ps.

Let us consider a microstrip patch antenna having the LHM substrate with $\omega_p = 9.4248 \times 10^{10}$rad/s. Figure 2 shows ε_r and μ_r of the LHM substrate. It is seen from Fig. 2 that the values of ε_r and μ_r are zero at $f = 15.0$GHz. Figure 3 presents the return loss of the microstrip patch antenna. One can see from Fig. 3 that the return loss changes as that of a conventional microstrip patch antenna with a dielectric substrate in the frequency band where the refractive index of the LHM is positive. It is also seen that extra resonances occur at the frequencies less than

$f = 15.0$GHz. At these frequencies, refractive index of the LHM is negative. Since the refractive index of the LHM is zero at the resonant frequency of $f = 15.0$GHz, the electromagnetic wave is not transmitted through the LHM substrate [8],[9].

Figures 4 and 5 illustrate the radiation patterns of the microstrip patch antenna in the x-z and the y-z planes at the resonant frequency of $f = 5.1$GHz. These radiation patterns may be obtained from the near-to-far field transformation. We can see from Figs. 4 and 5 that the radiation is biased to the positive x-direction, and two major lobes are tilted toward and against the feed location.

It is confirmed from Figs. 2-5 that the use of the LHM substrate is effective in the design of wideband microstrip patch antennas due to the occurrence of extra resonances.

4. Conclusion

Radiation characteristics of a microstrip patch antenna using an LHM have been investigated. The frequency-dependent permittivity and permeability of the LHM are described by the lossy Drude equations. The ADE-FDTD method for dispersive media are extended to the FDTD analysis of the three-dimensional LHM. Numerical results demonstrate that an LHM can be used as an efficient substrate of a microstrip patch antenna with wideband performance. Furthermore, the microstrip patch antenna shows interesting radiation patterns.

Consideration of the effects of a patch shape on radiation characteristics of a microstrip patch antenna remains a topic for future work.

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