

Radiation from a Microstrip Patch Antenna with an LHM Substrate

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1. Introduction

In recent years, an artificial material with simultaneously negative permittivity and permeability has received considerable attention from many workers in the electromagnetics community [1]-[5]. The material, called the left-handed material (LHM), is theoretically investigated by Veselago [6]. The LHM also has a negative refractive index, and a negative refraction is then occurred at the interface between an ordinary dielectric and the LHM. Furthermore, the direction of an energy flow is opposite to the wave vector of a plane electromagnetic wave. While the medium does not exist in nature, the LHM may be fabricated by periodic arrays of thin wires and split ring resonators [7].

The purpose of this paper is to investigate radiation characteristics of a microstrip patch antenna with 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. Since the LHM is dispersive, its permittivity and permeability are expressed by the lossy Drude equations [4]. We can derive differential equations for the polarization and the magnetization vectors in the LHM substrate by noting its constitutive relations. The electromagnetic radiation field from the microstrip patch antenna may be obtained based on the FDTD method [4]. Numerical results are presented to show the effectiveness of the LHM substrate in the design of a directional microstrip patch antenna.

2. Theory

Consider a microstrip patch antenna with an LHM substrate, as shown in Fig. 1. A rectangular radiation patch is located on the LHM substrate and the feed point of the antenna is at the edge of a microstrip line, which is connected to the patch. Assuming $\exp(j\omega t)$ time dependence, the constitutive relations for the LHM are expressed as

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

and

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

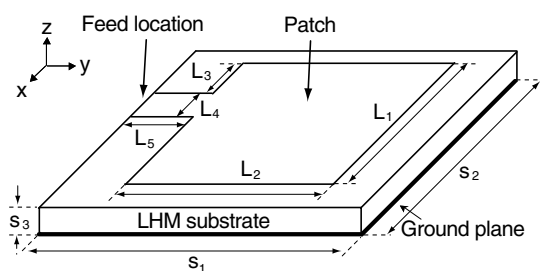


Figure 1: Geometry of the problem.

where \mathbf{E} , \mathbf{H} , \mathbf{D} , and \mathbf{B} are the vectors of the electric field, the magnetic field, the electric flux density, and the magnetic flux density, respectively. The parameters 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.

Furthermore we may write

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

and

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

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

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

and

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

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 by assuming $\omega_{pe} = \omega_{pm} = \omega_p$:

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

and

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

where \mathbf{J} and \mathbf{M} are the electric and the magnetic current density vectors, respectively. Other differential equations for \mathbf{E} and \mathbf{H} are derived from the Maxwell's equations in time-varying form.

Applying the auxiliary differential equation FDTD (ADE-FDTD) method [4] to these differential equations, one can obtain the FDTD update equations for the x , y , and z -components of \mathbf{J} ,

$$J_x^{n+\frac{1}{2}} \left(i + \frac{1}{2}, j, k + \frac{1}{2} \right) = A_{Jx1} \left(i + \frac{1}{2}, j, k + \frac{1}{2} \right) J_x^{n-\frac{1}{2}} \left(i + \frac{1}{2}, j, k + \frac{1}{2} \right) + A_{Jx2} \left(i + \frac{1}{2}, j, k + \frac{1}{2} \right) \cdot \left[E_x^n \left(i + \frac{1}{2}, j, k + 1 \right) + E_x^n \left(i + \frac{1}{2}, j, k \right) \right], \quad (9)$$

$$J_y^{n+\frac{1}{2}} \left(i + \frac{1}{2}, j + \frac{1}{2}, k \right) = A_{Jy1} \left(i + \frac{1}{2}, j + \frac{1}{2}, k \right) J_y^{n-\frac{1}{2}} \left(i + \frac{1}{2}, j + \frac{1}{2}, k \right) + A_{Jy2} \left(i + \frac{1}{2}, j + \frac{1}{2}, k \right) \cdot \left[E_y^n \left(i + 1, j + \frac{1}{2}, k \right) + E_y^n \left(i, j + \frac{1}{2}, k \right) \right], \quad (10)$$

and

$$J_z^{n+\frac{1}{2}} \left(i, j + \frac{1}{2}, k + \frac{1}{2} \right) = A_{Jz1} \left(i, j + \frac{1}{2}, k + \frac{1}{2} \right) J_z^{n-\frac{1}{2}} \left(i, j + \frac{1}{2}, k + \frac{1}{2} \right) + A_{Jz2} \left(i, j + \frac{1}{2}, k + \frac{1}{2} \right) \cdot \left[E_z^n \left(i, j + 1, k + \frac{1}{2} \right) + E_z^n \left(i, j, k + \frac{1}{2} \right) \right], \quad (11)$$

where

$$A_{Jx1} \left(i + \frac{1}{2}, j, k + \frac{1}{2} \right) = \frac{1 - 0.5 \Gamma_e \left(i + \frac{1}{2}, j, k + \frac{1}{2} \right) \Delta t}{1 + 0.5 \Gamma_e \left(i + \frac{1}{2}, j, k + \frac{1}{2} \right) \Delta t}, \quad (12)$$

$$A_{Jx2} \left(i + \frac{1}{2}, j, k + \frac{1}{2} \right) = \frac{\varepsilon_0 \omega_{pe}^2 \left(i + \frac{1}{2}, j, k + \frac{1}{2} \right) \Delta t}{2 \left[1 + 0.5 \Gamma_e \left(i + \frac{1}{2}, j, k + \frac{1}{2} \right) \Delta t \right]}, \quad (13)$$

$$A_{Jy1}\left(i + \frac{1}{2}, j + \frac{1}{2}, k\right) = \frac{1 - 0.5\Gamma_e\left(i + \frac{1}{2}, j + \frac{1}{2}, k\right)\Delta t}{1 + 0.5\Gamma_e\left(i + \frac{1}{2}, j + \frac{1}{2}, k\right)\Delta t}, \quad (14)$$

$$A_{Jy2}\left(i + \frac{1}{2}, j + \frac{1}{2}, k\right) = \frac{\varepsilon_0\omega_{pe}^2\left(i + \frac{1}{2}, j + \frac{1}{2}, k\right)\Delta t}{2\left[1 + 0.5\Gamma_e\left(i + \frac{1}{2}, j + \frac{1}{2}, k\right)\Delta t\right]}, \quad (15)$$

$$A_{Jz1}\left(i, j + \frac{1}{2}, k + \frac{1}{2}\right) = \frac{1 - 0.5\Gamma_e\left(i, j + \frac{1}{2}, k + \frac{1}{2}\right)\Delta t}{1 + 0.5\Gamma_e\left(i, j + \frac{1}{2}, k + \frac{1}{2}\right)\Delta t}, \quad (16)$$

and

$$A_{Jz2}\left(i, j + \frac{1}{2}, k + \frac{1}{2}\right) = \frac{\varepsilon_0\omega_{pe}^2\left(i, j + \frac{1}{2}, k + \frac{1}{2}\right)\Delta t}{2\left[1 + 0.5\Gamma_e\left(i, j + \frac{1}{2}, k + \frac{1}{2}\right)\Delta t\right]}. \quad (17)$$

The parameter Δt in Eqs. (12)-(17) denotes the time-step size.

Similarly, the FDTD update equations for \mathbf{M} are derived from Eq. (8). Furthermore, electromagnetic fields outside the LHM can be obtained from the ordinary FDTD update equations.

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 $L_1 = 12.45\text{mm}$, $L_2 = 16.00\text{mm}$, $L_3 = 2.09\text{mm}$, $L_4 = 2.46\text{mm}$, $L_5 = 4.00\text{mm}$, $s_1 = 24.00\text{mm}$, $s_2 = 23.34\text{mm}$, and $s_3 = 0.795\text{mm}$. Note from Eqs. (1) and (2) that ε_r and μ_r of the LHM tend to $-\infty$ at dc. Then the antenna excitation is modeled by a delta-gap voltage source, which is defined by a first-order derivative of a Gaussian-pulse function with unit-amplitude. Now the investigation domain $27.2307\text{mm} \times 30.6659\text{mm} \times 4.76982\text{mm}$ containing the microstrip patch antenna and the background free space is divided into $210 \times 230 \times 54$ cells in the x -, y -, and z -directions. The perfectly matched layer (PML) is implemented as an absorbing boundary condition to truncate the computational domain. The cell sizes of Δx , Δy , and Δz are 0.12967mm , 0.13333mm , and 0.08833mm , and $\Delta t = 0.2029\text{ps}$.

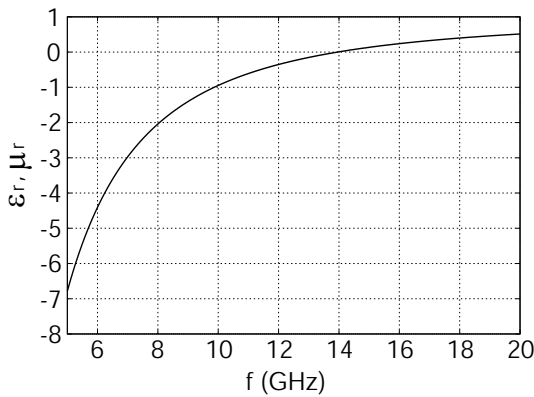


Figure 2: Relative permittivity and permeability of the LHM substrate with $\omega_p = 2\pi \times 13.95 \times 10^9$ rad/sec.

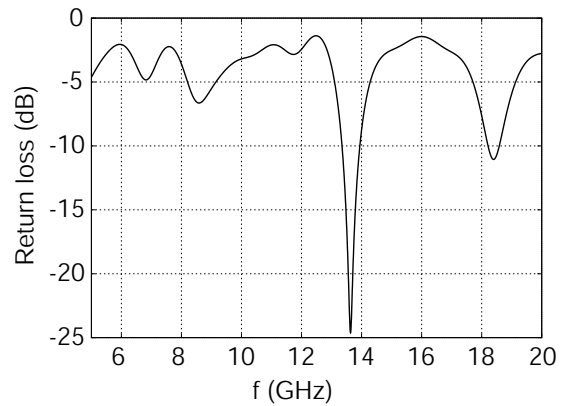


Figure 3: Return loss of the microstrip patch antenna having the LHM substrate with $\omega_p = 2\pi \times 13.95 \times 10^9$ rad/sec.

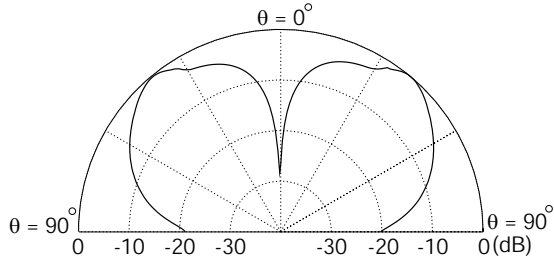


Figure 4: Radiation pattern of the microstrip patch antenna having the LHM substrate with $\omega_p = 2\pi \times 13.95 \times 10^9$ rad/sec in the x - z plane at $f = 13.630$ GHz.

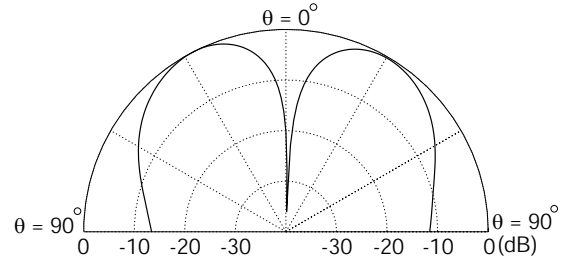


Figure 5: Radiation pattern of the microstrip patch antenna having the LHM substrate with $\omega_p = 2\pi \times 13.95 \times 10^9$ rad/sec in the y - z plane at $f = 13.630$ GHz.

We consider the microstrip patch antenna having the LHM substrate with $\omega_p = 2\pi \times 13.95 \times 10^9$ rad/s. Figure 2 shows ϵ_r and μ_r of the LHM substrate versus the frequency, f . It is seen from Fig. 2 that ϵ_r and μ_r become zero at the frequency, $f = 13.95$ GHz. Figure 3 presents the return loss of the microstrip patch antenna. One can see from Fig. 3 that some resonant frequencies are obtained for $f < 13.95$ GHz where refractive index of the LHM is negative and that the return loss is minimum at the frequency of $f = 13.630$ GHz. 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 $f = 13.630$ GHz. These radiation patterns may be obtained from the near-to-far field transformation. It is observed from Figs. 4 and 5 that the microstrip patch antenna with the LHM substrate exhibits minimum radiation in the zenith direction.

We can confirm from Figs. 2-5 that the use of the LHM substrate is effective in the design of a directional microstrip patch antenna with low return loss.

4. Conclusion

Radiation characteristics of a microstrip patch antenna with an LHM substrate have been investigated. The LHM is dispersive and its permittivity and permeability are modeled by the lossy Drude equations. The ADE-FDTD method is employed to obtain the electromagnetic field radiated from the microstrip patch antenna. Numerical results confirm the effectiveness of the use of the LHM in the substrate of a microstrip patch antenna, which shows interesting radiation characteristics.

Study on the effects of a patch shape and a feeding method on radiation characteristics of a microstrip patch antenna remains a topic for future work.

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