High Directive Cavity Antenna Based on 1D LHM-RHM Resonator

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Abstract—We propose a novel high directive antenna based on 1-D cavity resonator which is composed of a layer of air and a layer of anisotropic left-handed material. Resonance conditions for such a cavity resonator are analyzed, and in the cavity, the resonant frequency is independent of the lateral thickness. A cavity antenna can be made ultra-thin based on the aforementioned property.

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1. INTRODUCTION

In 1968, Veselago predicted and investigated a medium (also named left-handed material, LHM) with simultaneously negative permittivity and permeability [1]. After the experiment verifying the characteristic of LHM is carried out in 2000 [2], much attention has been focused on fabrication and application of this kind of new medium. In 2002, Engheta theoretically analyzed the possibility of constructing a thin one-dimensional cavity resonators which combines both conventional material and metamaterial possessing negative permittivity and permeability [3], and this idea was experimentally verified [4, 5]. Later several kinds of subwavelength cavity antennas were put forward, whose ground plane reflective phase are negative [6–8]. In this paper, we propose an ultra-thin high-directive cavity antenna based on the 1-D resonator which is made of air and the anisotropic LHM.

2. THEORY ANALYSIS

Engheta [3] theoretically analyzed a thin one-dimentional (1-D) cavity resonator in which a slab of left handed material (LHM) act as a phase compensator, combined with another slab of conventional dielectric material. When the thicknesses of the LHM and the conventional material are small enough, the resonant frequency is only dependent on the ratio of thickness of the two slabs, therefore, the resonator can be very thin. Engheta's theory is based on the isotropic assumption, in this letter we consider a 1-D cavity resonator made of anisotropic LHM.

The cavity structure is schematically shown in the Figure 1. Between the perfectly electrical conducting (PEC) plates, there are two layers of media: a layer of air and a layer of anisotropic medium with the constitutive parameters \( \epsilon = [\epsilon_x, \epsilon_y, \epsilon_z] \) and \( \mu = [\mu_x, \mu_y, \mu_z] \). Their thicknesses are \( d_1 \) and \( d_2 \), respectively, and for the 1-D LHM, \( \epsilon_x < 0, \mu_y < 0 \).

We first consider the case that the electric field is along the \( x \) direction and the magnetic field is on the \( y-z \) plane, thus the wave vector is in the \( y-z \) plane. By utilizing the boundary conditions, the resonance condition is given as

\[
k_{1z}\mu_y \tan k_{2z} d_2 + k_{2z} \mu_0 \tan k_{1z} d_1 = 0
\]

where \( k_{1z}, k_{2z} \) are the \( z \) components of the wave vectors \( \vec{k}_1 \) (the wave vector in the air) and \( \vec{k}_2 \) (the wave vector in the medium). For the oblique incidence, \( k_{1z} = \sqrt{k_{0z}^2 - k_y^2} \) and \( k_{2z} = -\sqrt{\omega^2 \epsilon_x \mu_y - \frac{\mu_z}{\mu_x} k_y^2} \), where \( k_y \) is the tangential component of the wave vectors.

Similarly for the case that the magnetic field is along the \( y \) direction and the electrical field is in the \( x-z \) plane, the corresponding wave vector is in the \( x-z \) plane, the resonant condition is

\[
k_{1z} \epsilon_x \tan k_{1z} d_1 + k_{2z} \epsilon_0 \tan k_{2z} d_2 = 0
\]
for oblique incidence, \( k_{1z} = \sqrt{k_0^2 - k_x^2} \) and \( k_{2z} = -\sqrt{\frac{\omega^2 \varepsilon_x \mu_y - \varepsilon_x \mu_y k_x^2}{\mu_y}} \), where \( k_x \) is the tangential component of the wave vectors.

Given a certain \( \omega \), for the normal incidence, i.e., \( k_x = k_y = 0 \) for both cases, when \( d_1 \) and \( d_2 \) are very small, make use of small argument approximation, from Equations (1) and (2) we get the resonance condition

\[
\frac{d_1}{d_2} \approx -\frac{\mu_y}{\mu_0} \quad (3)
\]

Thus the resonant frequency is only dependent on the ratio of \( d_1 \) and \( d_2 \), which implies that resonance is independent of the total thickness \( d = d_1 + d_2 \). Therefore, resonance can occur in ultra-thin cavity.

If a finite-sized monopole antenna oriented in the \( x \) direction is put inside the cavity, and a partially reflective plate instead of the PEC is placed on one side of the cavity, we can get the high directive emission.

3. SIMULATION RESULTS

The 1-D LHM- RHM cavity antenna is illustrated in Figure 2. As is shown, inside the cavity a monopole antenna is used as a source. On the left side of the cavity, a partially reflective plate (the reflectivity is about 0.97) is used so that the EM waves can transmit through it at the resonant frequency. The constitutive parameters of the LHM are as follows: \( \varepsilon_y = \varepsilon_z = 4 \), \( \mu_x = \mu_z = 1 \), \( \varepsilon_x \) and \( \mu_y \) are described by the Drude model \( \varepsilon_x = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma_e)} \) \( \mu_y = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma_m)} \), where \( \omega_p = 2\pi \times 2.45 \times 10^9 \text{ rad/s} \), \( \omega_m = 2\pi \times 1.96 \times 10^9 \text{ rad/s} \), \( \gamma_e = \gamma_m = 2\pi \times 1.59 \times 10^6 \text{ rad/s} \).

The thicknesses of the air and the LHM (along the \( z \) direction) are \( d_1 = 1 \text{ mm} \) and \( d_2 = 3 \text{ mm} \) respectively, while the lateral size of the cavity (along the \( x \) and \( y \) directions) is 80 mm \( \times \) 80 mm. The calculated resonant frequency is 10.655 GHz, according to the theoretical analysis.
We performed FDTD simulations and calculated far-field radiation patterns. Figures 3(a) and (b) give the far-field radiation patterns in the $H$-plane and $E$-plane, respectively at the frequency 10.46 GHz, which is very close to the resonant frequency according to theoretical prediction. The half power beamwidth (HPBW) in the $E$-plane is 23.2 degree and in the $H$-plane is 21.9 degree. A high directivity is obtained for the cavity antenna, and the directivity will be further improved if larger lateral size of the structure is used.

![Figure 3](image.png)

Figure 3: (a) Radiation pattern in $E$-plane, (b) Radiation pattern in $H$-plane.

4. CONCLUSIONS

In this paper, we proposed a novel cavity antenna based on 1-D LHM-RHM cavity resonator. The resonance condition for such cavity resonator is given analytically, and the FDTD simulation results for a 4 mm-thick cavity antenna agree with the theoretical prediction. This indicates that a high-directive cavity antenna with any thickness can be realized.

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REFERENCES