Metamaterials Cavity Resonator with Simultaneously Shorten Length and Width

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1. Introduction

There has been much interest recently in the area of engineered materials with unusual electromagnetic properties known as metamaterials. Since the first DNG metamaterial, which consists of metallic split ring resonators (SRRs) and wires, was reported [1], numerous investigations have been conducted both theoretically as well as experimentally in order to make use of the metamaterial to improve the performance of the RF devices, and reduce their size [2, 3]. Particularly, an one-dimensional (1D) miniaturized cavity resonator (MCR) consisting of DNG and DPS bilayer was proposed in [4]. Very recently, the idea of the 1D MCR in [4] was realized in a rectangular cavity, which was filled partially with DNG consisting of Ω-alike inclusions and partially with air [5]. However, the width of the MCR in [5] is still not small enough (it is 22 mm) although the length is small (only 13 mm) at its resonance frequency of 9.6 GHz, due to the fact that the width must be equivalent to the integer multiples of the half of the resonance wavelength.

In this presentation, we propose a further miniaturization approach for the MCR through extending the analysis to a three-dimensional (3D) case. We explore the resonance equation solutions of the general case of a 3D rectangular cavity resonator filled with anisotropic metamaterials bilayer. It is shown that both the resonant modes in such a resonant cavity and the transmission characteristics of its corresponding waveguide are closely dependent on the spatial dispersion relation of the filling anisotropic metamaterials. Based on the concept mentioned above, a novel miniaturized rectangular cavity resonator (MRCR) is designed by means of CST's MW STUDIO simulation tools. Compared with the MCR in [5], the MRCR's width and length normalized to the resonance wavelength are shorten simultaneously.

2. Theory Description

As shown in Fig. 1, a rectangular cavity is filled partially with anisotropic metamaterial I with constitutive parameters tensor $(\overline{\varepsilon}_1, \overline{\mu}_1)$, and partially with anisotropic metamaterial II with constitutive parameters tensor $(\overline{\varepsilon}_2, \overline{\mu}_2)$. The dimensions of the cavity along the x, y, and z-axes are denoted by *a*, *b,* and *d*, which satisfy the assumption of $a > b$. The region of the metamaterial I has a thickness of d_1 along the z-axis, and the region of the metamaterial II has a thickness of d_2. According to Ref.[6], the field components of TEm0 modes in region I and II are written as follows:

$$
\begin{aligned}
E_{y1} &= \frac{j\omega\mu_0\mu_x}{\gamma^2 + k_0^2\mu_x\varepsilon_y}\frac{m\pi}{a}H_{01}\sin(\frac{m\pi}{a}x)\sin[k_{z1}(z+d_1)] \\
H_{x1} &= \frac{\gamma}{\gamma^2 + k_0^2\mu_x\varepsilon_y}\frac{m\pi}{a}H_{01}\sin(\frac{m\pi}{a}x)\cos[k_{z1}(z+d_1)] \qquad (1) \\
H_{z1} &= -H_{01}\cos(\frac{m\pi}{a}x)\sin[k_{z1}(z+d_1)]
\end{aligned}
$$

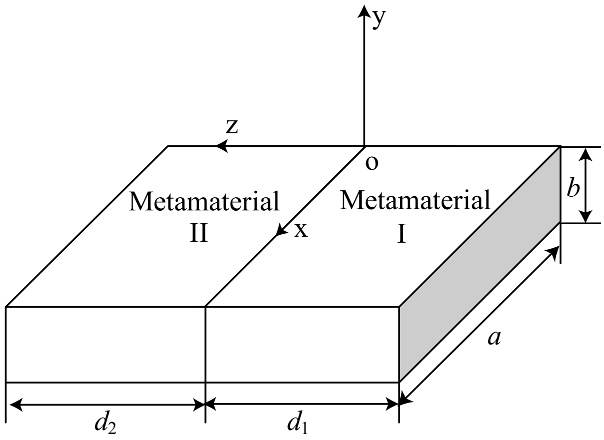

Fig.1 Configuration of the rectangular cavity resonator filled with metamaterials bilayer

$$
\begin{aligned}
E_{y2} &= \frac{j\omega\mu_0\mu_x}{\gamma^2 + k_0^2\mu_x\varepsilon_y}\frac{m\pi}{a}H_{02}\sin(\frac{m\pi}{a}x)\sin[k_{z2}(d_2 - z)] \\
H_{x2} &= \frac{-\gamma}{\gamma^2 + k_0^2\mu_x\varepsilon_y}\frac{m\pi}{a}H_{02}\sin(\frac{m\pi}{a}x)\cos[k_{z2}(d_2 - z)] \\
H_{z2} &= H_{02}\cos(\frac{m\pi}{a}x)\sin[k_{z2}(d_2 - z)]
\end{aligned} \tag{2}
$$

Here,

$$k_{zi}^2 = \omega^2\varepsilon_{yi}\mu_{xi} - \left(\frac{m\pi}{ak_0}\right)^2, i = 1,2 \tag{3}$$

In addition, the field of the TE modes is defined by the simple set of constraints

$$
\begin{aligned}
E_{y1}|_{z=0} &= E_{y2}|_{z=0} \\
H_{x1}|_{z=0} &= H_{x2}|_{z=0}
\end{aligned} \tag{4}
$$

Substituting (1) and (2) into (4) leads to

$$
\begin{aligned}
& H_{01}\sin(k_{z1}d_1) - H_{02}\sin(k_{z2}d_2) = 0 \\
& \frac{k_{z1}H_{01}}{\mu_{x1}}\cos(k_{z1}d_1) + \frac{k_{z2}H_{02}}{\mu_{x2}}\cos(k_{z2}d_2) = 0
\end{aligned} \tag{5}
$$

In order to have a nontrivial solution, i.e., $H_{01} \neq 0$ and $H_{02} \neq 0$, the determinant in (2) must vanish. Therefore, the following resonance equation of the rectangular resonant cavity is obtained

$$-\frac{k_{z1}}{\mu_{x1}}\cot(k_{z1}d_1) = \frac{k_{z2}}{\mu_{x2}}\cot(k_{z2}d_2) \tag{6}$$

Because k_{zi} is finite quantity, as the total thickness d=d_1+d_2 approaches zero, the resonance equation (6) is approximately simplified as

$$-\mu_{x1}d_1 = \mu_{x2}d_2 \tag{7}$$

One can see immediately that it is very easy to satisfy the approximate resonance equation (7) if μ_{x1} and μ_{x2} has opposite sign, which is independent on both the cavity width a and the cavity length d. Therefore, when μ_{x1} and μ_{x2} has opposite sign it is possible that there is a group of parameters satisfying the resonance equation (6), which is much less dependent on both the cavity width a and the cavity length d. Particularly, when $\varepsilon_{y1} = 1$, $\varepsilon_{y2} = 1$, $\mu_{z1} = \mu_{z2} = 1$, $\mu_{x1} = -\mu_{x2} = 1$, $a = b =$ 0.1 λ, $d_1 = 2d_2 = 0.41\lambda$ and m=1, the resonance equation (6) is satisfied.

3. Simulation Results

From above analysis, one can see that the MRCR with simultaneously shorten width and length is quite possible when the metamaterial I in Fig. 1 has negative permeability component in x-direction and metamaterial II has positive permeability component in x-direction.

The negative permeability metamaterial is based on the inclusions in the form of the double-ring [7], which is a special case of the widely used split-ring resonator [8, 9]. It comprises two conductive rings placed back to back on the thin dielectric substrate ($\varepsilon_r = 2.6$) with the slits oriented in the opposite directions. Substrate thickness is 0.7 mm, and ring thickness is 0.02 mm. The rings have outer diameter of 4 mm with track width of 1 mm and slit width of 0.5 mm.

The simulation model is composed of a 10-mm-long rectangular cavity with width of 9 mm and height of 5 mm, as shown in Fig.2. The left half of the cavity is filled with the double-ring inclusions while the right half is filled with a DPS with the relative permittivity of 2.6. Simulation results show that the cavity is resonant at 7.7 GHz. Calculating the electrical dimensions of the MRCR as the ratio of the absolute dimensions to the resonance wavelength with respect to the permittivity of 2.6, one finds that the electrical length and width of the MRCR are only 0.16 and 0.15, respectively. Thus, the length and width are simultaneously shortened by 70 %, compared with a conventional cavity resonator. The magnetic field distribution at the resonance frequency of 7.7 GHz is shown in Fig.3. One can see that there is strong magnetic field component penetrating through the double-ring plane, and the negative permeability of the double-ring is excited.

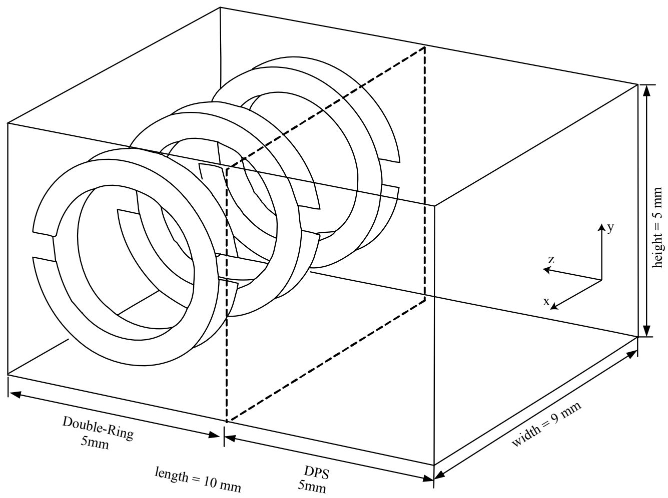

Fig.2 Illustration of the MRCR

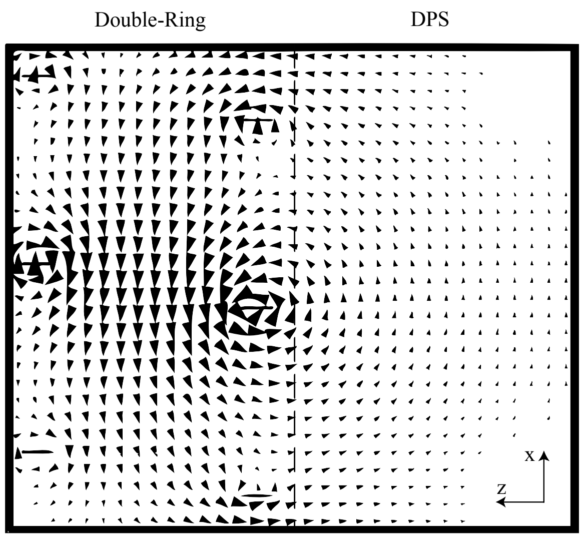

Fig. 3 Magnetic field distribution at the resonance frequency in the MRCR

4. Conclusions

In this paper, a further miniaturization approach for the existing MCR design reported recently in the literature is proposed. It is shown that the subwavelength resonance occurs when x-direction permeability components (μ_{x1} and μ_{x2}) have opposite signs. Based on these results, a miniaturized rectangular cavity resonator (MRCR) filled partially with double-ring inclusions and partially with a conventional material is designed and simulated. It is shown that the electrical length and width of the MRCR are only 0.16 and 0.15, respectively. Therefore, the length and width are simultaneously shortened by 70 %, compared with a conventional cavity resonator.

References

[1] R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of negative index of refraction," *Science,* vol. 292, pp. 77-79, March 2001.

[2] J. B. Pendry, "A chiral route to negative refraction," *Science,* vol. 306, pp. 1353-1355, 2004.

[3] R. W. Ziolkowski and C. Y. Cheng, "Existence and design of trans-vacuum-speed metamaterials," *Physical Review E,* vol. 68, pp. 026612:1~18, May 2003.

[4] N. Engheta, "An idea for thin subwavelength cavity resonators using metamaterials with negative permittivity and permeability," *IEEE Antennas and Wireless Propagation Lett.,* vol. 1, pp. 10-13, Aug. 2002.

[5] Y. Li, L. Ran, H. Chen, J. Huangfu, X. Zhang, K. Chen, T. M. Grzegorczyk, and J. A. Kong, "Experimental realization of a one-dimensional LHM-RHM resonator," *IEEE Trans. Microwave Theory Tech.,* vol. 53, p. 1521, July 2005.

[6] F. Y. Meng, Q. Wu, and L. W. Li, "Transmission characteristics of wave modes in a rectangular waveguide filled with anisotropic metamaterial," *Applied Physics A: Materials Science and Processing,* vol. 94, pp. 747-753, Aug. 2009.

[7] R. Marques, F. Medina, and R. Rafii-El-Idrissi, "Role of bianisotropy in negative permeability and left-handed metamaterials," *Physical Review B,* vol. 65, pp. 144440-1~144440-6, May 2002.

[8] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," *Physical Review Lett.,* vol. 84, pp. 4184-4187, May 2000.

[9] R. Marques, J. Martel, F. Mesa, and F. Medina, "Left-handed-media simulation and transmission of EM waves in subwavelength split-ring-resonator-loaded metallic waveguides," *Physical Review Lett.,* vol. 89, pp. 183901/1~4, June 2002.