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Design and Application of a Novel LHM with Small Unit Cell

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1. Introduction

Left-handed metamaterial (LHM) in which both permittivity and permeability possess negative values at some frequencies has recently gained considerable attention. In 1968, Russian physics scientist Veselago proposed the basic theories about LHM characteristics, and pointed out that many electromagnetic properties of LHM are opposite compared with conventional material including Doppler Effect, Cherenkov Effect and Snell's law. Based on Pendry's results, in 2000, Smith firstly designed and fabricated a LHM by reasonably arranging the array with rods and SRRs (Split Ring Resonators) [1]. However, the performance of the initial LHM is not so good that it cannot be used due to the drawback of high loss, narrow band and large dimension. From this point, many types of LHM such as ones consisting of a periodic arrangement of the capacitively loaded strips (CLSs) and the SRRs [2], the double S-shaped resonators [3], and also transmission line [4] are designed and fabricated to broaden the bandwidth and lower the loss of LHM recently.

However, only broad bandwidth and low loss are not sufficient for practical applications of LHM, what's more, the compact structural unit cell is needed, because the parasitic diffraction effects are necessarily present with increasing importance when the unit cell electrical size, which is defined as ratio of unit cell size in the propagation direction of electromagnetic wave to the operating wavelength, approaches 0.25. These effects include poor refraction, characterized by diffuse focal spots comparable to those caused by optical aberrations, diffraction losses due to the scattering occurring at each cell and restriction of the operation bandwidth.

In view of this consideration, a compact LHM unit cell, which smallest electrical size is only 0.1, is designed and optimised by us using CST's Microwave Studio (MWS) simulation tools. Compared with other LHM unit cells, which have already been reported, ours is reduced by 41%. The effective constitutive parameters of the LHM are extracted, and it is shown that the LHM can exhibit double negative parameters in 9.2 GHz ~ 11.8 GHz. Moreover, a miniaturized rectangular waveguide cavity resonator (MRWCR) depending on the backward wave property of the LHM is designed and simulated, and results show that the electrical length of the MRWCR is only a third of that of a conventional cavity resonator's. Particularly, the electrical length of the MRWCR is reduced to 50% of that of the MRWCR reported in [5], because the LHM here is constructed from smaller unit cells. The field distribution in the MCR is shown for the first time, and it is in agreement with the theoretical analysis. Moreover, the filtering characteristic of the MRWCR is simulated after the MRWCR is fed by two current loops, and a passband at the resonance frequency of the MRWCR is found.

2. Compact LHM unit cell

A LHM unit cell is shown in Fig. 1. It comprises the MSRR (Modified Split Ring Resonator) and strip embedded in the dielectric host medium with permittivity of ε_r=2.2, and the strip and the front ring (in dark grey colour) of the MSRR are on one plane. The MSRR includes two split square rings parallel to each other, and every ring has two gaps at opposite sides. The two rings have same physical size, and the back ring (in light grey colour) is obtained through rotating the front ring (in dark grey colour) 90 degrees. This is a 1-D LHM, and its negative permeability

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and negative permittivity is excited by the magnetic field penetrating though the MSRR plane and the electric field parallel with the strip, respectively.

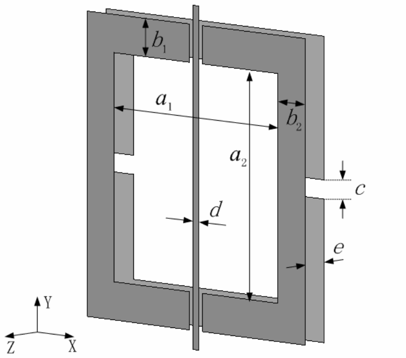


Figure 1: Geometry for the LHM unit cell

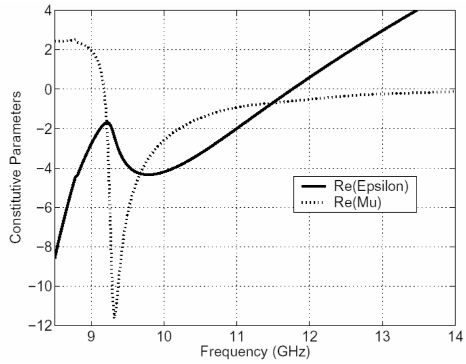


Figure 2: Constitutive parameters of the LHM

The dimensions in Fig. 1 are: $a_1 = a_2 = 1.78$ mm, $b_1 = b_2 = 0.254$ mm, $c = e$=0.17 mm, and d = 0.048 mm. The length of the strip is 2.286 mm. The size of the unit cell is 2.286 mm × 2.286 mm × 0.51 mm. The metal used is copper.

The effective permeability and permittivity are extracted to confirm the presence from scattering parameters by the approach presented in [6] based on the effective medium theory. The variations of the effective permittivity and permeability are demonstrated in Fig. 2. In Fig. 2, the solid line marked with circles illustrates the real part of the effective permittivity while the dot line illustrates the real part of the effective permeability. It has been shown that the effective permittivity is negative from below 11.8 GHz, and the effective permeability is negative in 9.2 GHz ~ 15 GHz. Hence, the slab combined with both MSRRs and strips can exhibit double-negative property (DNG) over 9.2 GHz ~ 11.8 GHz according to the retrieve approach.

The smallest electrical size of the LHM unit cell shown in Fig. 1 can be calculated as the ratio of the absolute size to the wavelength at its lowest operating frequency. Table I gives the comparison between our LHM and others reported previously. It can be seen that the electrical size of LHM unit cell shown in Fig. 1 appears to be smallest.

Table 1: Comparison between different LHM unit cells

Structures	Smallest electrical size
CLS/SRR [2]	0.18
Double S [3]	0.17
SRR/Rod [7]	0.19
MSRR/Strip	0.10

3. Miniaturized cavity resonator

In 2002, the concept of the miniaturized cavity resonator (MCR) consisting of LHM and RHM layers, as shown in Fig. 3, was proposed in [8]. By assuming that both layers are lossless, the dispersion relation can be described [8] by

$$\frac{n_2}{\mu_2}\tan(n_1 k_0 d_1) + \frac{n_1}{\mu_1}\tan(n_2 k_0 d_2) = 0\,, \tag{1}$$

where k_0 represents the wave vector in free space. In conventional [right-handed (RH) only] materials, the dispersion relation in (1) can only be satisfied under some very specific conditions for d_1 and d_2. If one of the media is left-handed (LH), where the effective permeability and index of refraction are negative, the solution to (1) becomes, however, much less dependent on the two thicknesses d_1 and d_2, thus this MCR can be realized with a thickness far less than half of the wavelength. In this case, the LHM plays a role of phase compensator because of the backward wave property. Very recently, the idea of the MCR was used in a rectangular waveguide cavity, which was filled partially with LHM consisting of Ω-alike inclusions and partially with air [5], and a MRWCR has been designed. Therefore, we can construct a MRWCR using the LHM consisting of MSRRs and strips by the same way as that in [5] to confirm the backward wave property of the

LHM. Particularly, a smaller length of the MRWCR can be expected because of the smaller LHM unit cell compared with that in [5].

The MRWCR is shown in Fig. 4. It is composed of a 5.08 mm (200 mil) long rectangular cavity with a cross section of 14.70 mm×2.29 mm. The left half of the cavity is filled with the LHM consisting of MSRRs and strips while the right half is air. The MRWCR is simulated using the Eigenmode Solver in CST's MWS, and the results show that the EM wave in the MRWCR is resonant at 9.8 GHz. If we calculate the electrical length of the MRWCR in Z direction as the ratio of the absolute length to the resonance wavelength, it can be seen that it is only sixth of the resonance wavelength, so it is only a third of that of a conventional cavity resonator's. Particularly, the electrical length of the MRWCR is reduced to 50% of that of the MRWCR in [5], and the reason is just the LHM unit cell consisting of MSRR and strip is smaller than the Ω-alike inclusion. In addition, the magnetic field distribution in the MRWCR at 9.71 GHz is shown in Fig. 5. It can be seen that there are strong magnetic fields penetrating through the MSRRs plane, and the negative permeability of the MSRRs is excited.

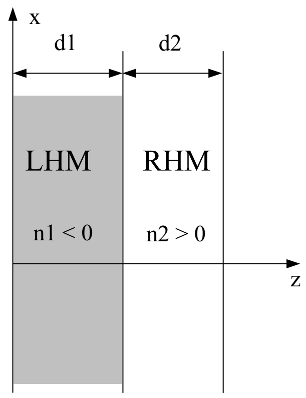


Figure 3: Illustration of the MCR

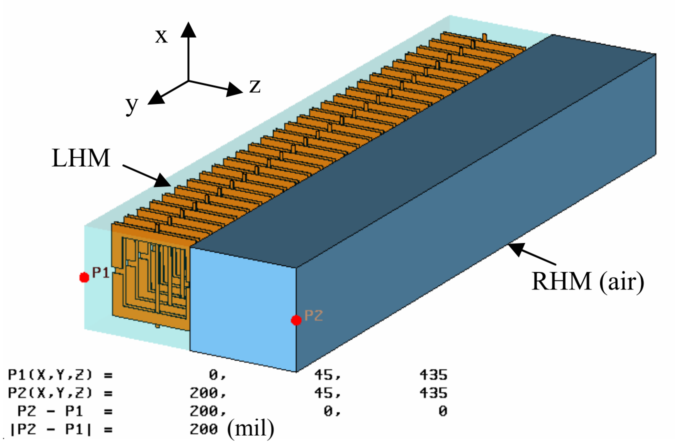


Figure 4: MRWCR consisting of LHM and RHM

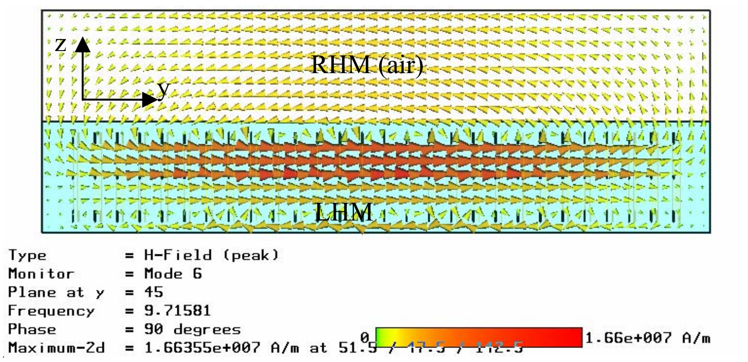
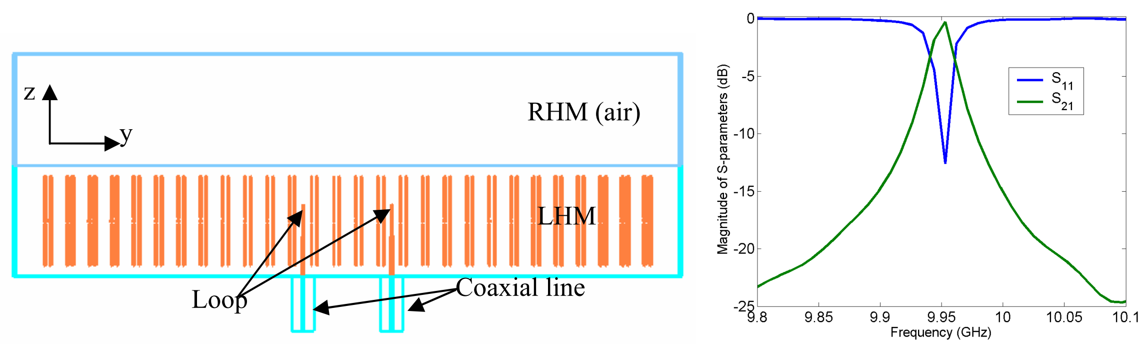


Figure 5: Magnetic field distribution in the MRWCR



(a) (b)

Figure 6: filtering characteristic of the MRWCR: (a) simulation model; (b) S-parameters

The filtering characteristics of the MRWCR is also simulated using Transient Solver in CST's MWS after it is fed by two current loops to confirm the MRWCR, as shown in Fig. 6 (a). In this case, two coaxial lines, which are connected with loops at their end, are inserted into the MRWCR as the feedings. The transmission and reflection curves are shown in Fig. 6 (b), it can be seen that there is a clear passband at 9.95 GHz, which is in a good agreement with the resonance frequency of the MRWCR.

5. Conclusions

In this paper, the concept and design of a novel composite LHM with small structural unit cell are presented, and it is applied to a miniaturized rectangular waveguide cavity resonator (MRWCR) depending on the backward property of the LHM. Its constitutive parameters are extracted, and results show that its effective permittivity and permeability are simultaneously negative in 9.2 GHz ~ 11.8 GHz. Moreover, a MRWCR partially filled with the LHM and partially filled with the RHM is designed and simulated to confirm the backward property of the LHM, results show that the EM resonance in the MRWCR can be observed clearly at 9.71 GHz while the length of the MRWCR is reduced to a sixth of the resonance wavelength. Worth noting is that the MRWCR is smaller compared with the one reported in [5], because the LHM consisting of smaller unit cell is used.

Acknowledgments

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