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An ultra-small cavity resonator loaded with LHM and RHM layers

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ABSTRACT In this paper, an ultra-small cavity resonator (USCR) loaded with left-handed metamaterial (LHM) and right-handed material (RHM) layers is designed using a novel miniaturization approach. The resonant behavior is successfully observed, and the dimensions of the USCR are only 4.58 mm × 5.08 mm × 2.29 mm at the dominant resonance frequency of 10.3 GHz. Through the field distribution calculation, we confirmed that the miniaturization of the USCR arises from the left-handed property of the LHM. For a practical application, a miniaturized filter with overall length of 10.19 mm consisting of two USCRs is designed to confirm the frequency-selective characteristics. Results show that the filter has some narrow pass bands, which correspond to the resonant modes of the electromagnetic resonance in the USCR, and the insertion loss at the dominant resonance frequency of the USCR is as low as 0.65 dB. Moreover, the filtering characteristics of the filter can be controlled by changing its feeding loop positions in the USCR.

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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 [1]. The idea of LHM was originally initiated in 1968 by Veselago, who theoretically studied plane-wave propagation in a material whose permittivity and permeability were assumed to be simultaneously negative, and who stated that many electromagnetic characteristics of LHM are opposite to those of conventional material such as the Doppler effect, the Cherenkov effect and Snell's law [2]. Since the first LHM, which consists of metallic split ring resonators (SRRs) and wires, was reported [3], numerous rf devices such as patch antennas [4, 5], phase shifters [6, 7] and directional couplers [8, 9] with small sizes for design were reported. Particularly, the concept of the miniaturized cavity resonator (MCR) consisting of LHM and right-handed material (RHM) layers, as shown in Fig. 1a, was proposed in [10]. By assuming that both layers are lossless, the dispersion relation can be described by [10]

$$\frac{n_2}{\mu_2}\tan(n_1k_0d_1)+\frac{n_1}{\mu_1}\tan(n_2k_0d_2)=0\,, \tag{1}$$

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. Very recently, the idea of the MCR was realized in a rectangular waveguide cavity, which was filled partially with LHM consisting of Ω-like inclusions and partially with air [11], as shown in Fig. 1b, and its experimental results are in a good agreement with the theoretical ones. However, the y-direction length w of the MCR in [11] is still not small enough (it is 22 mm) although the z-direction length l is small (only 13 mm) at its resonance frequency of 9.6 GHz, due to the fact that w must be equivalent to integer multiples of half of the resonance wavelength according to the boundary condition of the electromagnetic (EM) field in the y direction. This condition needs to be satisfied in both regions filled with LHM and one filled with RHM in the cavity. In this case, the minimum limit of the miniaturization of the MCR is determined by w. In addition, the field distribution in the cavity is not given in [11], so it is difficult to confirm that the MCR, which is far more complicated in configuration than a normal cavity resonator, arises from the phase-compensation function of the LHM.

In this paper, a further miniaturization approach for the MCR shown in Fig. 1b is presented. Based on the concept mentioned above, an ultra-small cavity resonator (USCR) is designed by means of CST's MW STUDIO simulation tools. Compared with the dimensions of the MCR in [11], the dimensions of the newly designed USCR are as small as $w = 5.08$ mm and $l = 4.58$ mm. In this study, the LHM consisting of Ω-like inclusions with simultaneously negative permittivity and negative permeability in [11] is replaced with the LHM consisting of the rectangular cut-off waveguide (RCOW) with negative permittivity and the modified split ring resonators (MSRRs) with a single negative permeabil-

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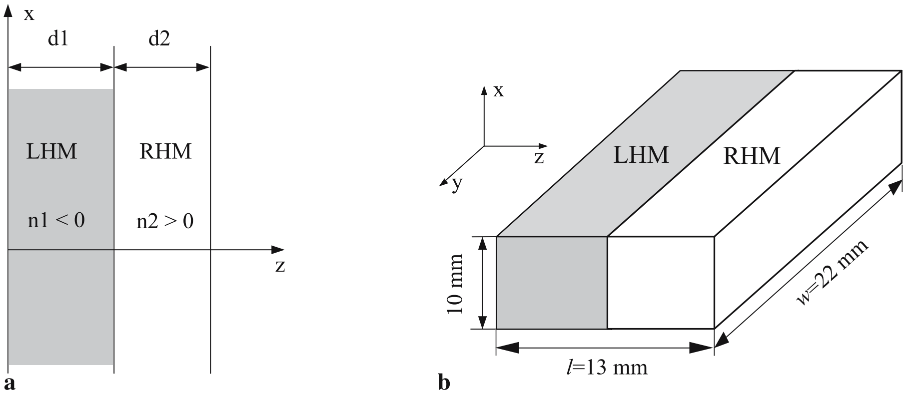

FIGURE 1 Illustration of the MCR. (**a**) Proposed in [10], (**b**) realized in [11]

ity covering a broad frequency range of 9.4–15.0 GHz. In this case, the y-directional boundary condition of the EM field in the USCR is satisfied because of the LH transmission of the EM wave in the LHM consisting of the RCOW and MSRRs according to [12, 13], and the boundary condition is much less dependent on the length w. Therefore, the length w can be much smaller than half of the resonance wavelength. The distributions of the magnetic field vectors in the USCR are simulated to confirm our prediction for the operating principle of the USCR, because the negative-permeability effects of the MSRRs, which are excited only when there is a magnetic field penetrating through the MSRRs' plane, are the essential condition for the existence of the LHM consisting of RCOW and MSRRs. Results show that there are four resonance modes including the dominant mode (at 10.3 GHz) and higher-order modes in the USCR, and there are strong magnetic fields penetrating through the MSRRs' plane for all these modes, so the negative permeability of the MSRRs is completely excited. A miniaturized filter based on a coplanar waveguide and the ultra-small cavity, which is excited by the electric current loop, is designed, and its transmission characteristic is simulated. Results show that the filter has some narrow pass bands, whose center frequencies are in a good agreement with the resonance frequencies of the USCR. Moreover, it is found that the filtering characteristics of the filter can be controlled to a certain extent by changing its feeding loop positions in the USCR, because the higher-order resonance modes in the USCR can be suppressed by changing the feeding positions according to the field distribution.

2 Modified split ring resonators (MSRRs)

The proposed MSRR cell is shown in Fig. 2 (inset). The MSRRs designed consist of two split square rings embedded in a dielectric host medium with a relative permittivity of 2.2. The two rings are parallel to each other, and each ring has two gaps at opposite sides. The two rings have the same physical size, and the back ring (in light-gray color) is obtained through rotating the front ring (in dark-gray color) by 90 degrees. The designed dimensions are: $a = b = 2.03$ mm, $c = d = 0.25$ mm and $e = f = 0.17$ mm. The dimensions of the unit cell are 2.29 mm × 2.29 mm × 0.51 mm. The metal material used in the paper is copper. The negative permeability of the MSRRs is excited by the time-harmonic magnetic field polarized in the y direction (penetrating through the MSRRs' plane).

The effective permeability and permittivity of the MSRRs are extracted from the transmission and reflection data based on the improved NRW (Nicolson–Ross–Weir) approach [14], as shown in Fig. 2. It can be seen that the real part of the effective permeability is negative in the range of 9.4–15.0 GHz, while the real part of the effective permittivity is positive.

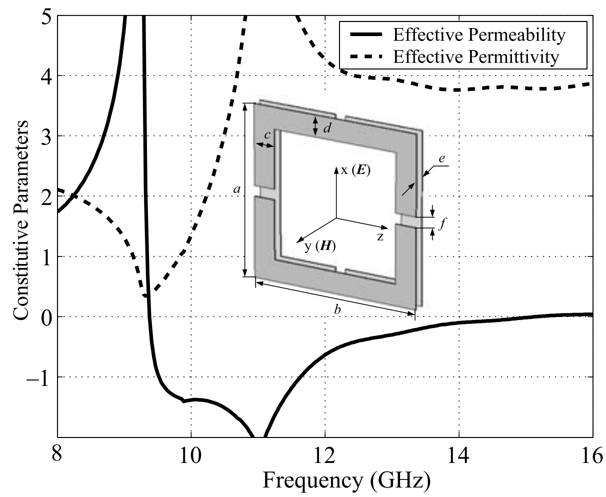

FIGURE 2 Constitutive parameters of the MSRRs

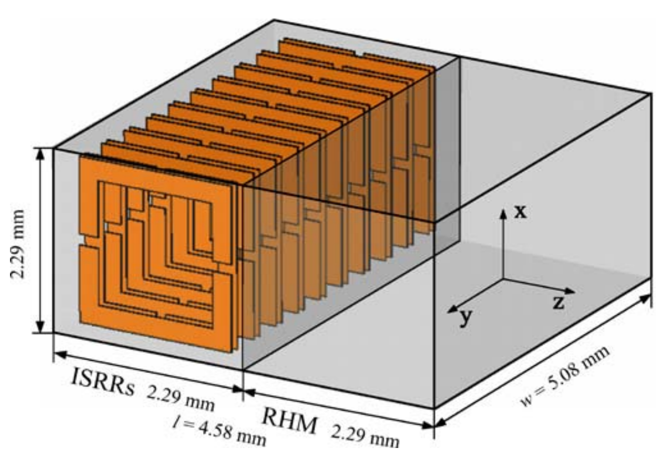

FIGURE 3 Illustration of the USCR

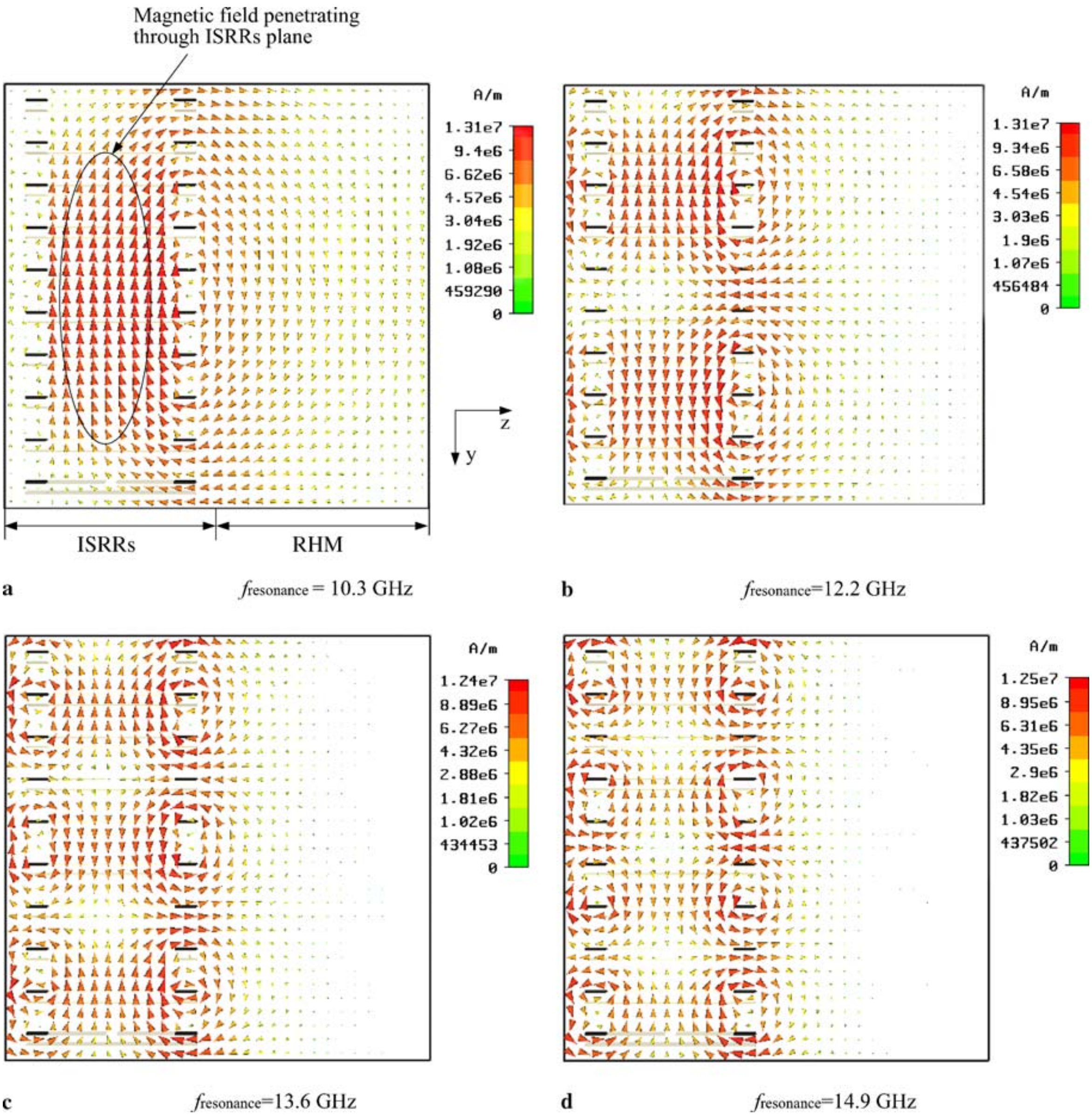

FIGURE 4 Distributions of the magnetic field vectors in the USCR at the resonance frequencies. (**a**) 10.3 GHz, (**b**) 12.2 GHz, (**c**) 13.6 GHz and (**d**) 14.9 GHz

3 Ultra-small cavity resonator partly filled with the MSRRs

The resonance characteristics of the USCR are simulated using the eigenmode solver of CST's MW STUDIO simulation tools. The simulation model is composed of a 4.58-mm-long rectangular cavity, which is surrounded by six perfect electric conductor (PEC) walls, with a cross section of 5.08 mm × 2.29 mm, as shown in Fig. 3. The left half of the cavity is filled with the MSRRs while the right half is filled with the RHM with relative permittivity of 2.2. In this case, the LHM is realized by the MSRRs and the cavity itself.

Simulation results show that the cavity is resonant at four frequencies in 9.4–15.0 GHz, i.e. 10.3 GHz, 12.2 GHz, 13.6 GHz and 14.9 GHz. The distributions of the magnetic field vectors at 10.3 GHz, 12.2 GHz, 13.6 GHz and 14.9 GHz are shown in Fig. 4a–d, respectively. It can be seen that there are strong magnetic fields penetrating through the MSRRs' plane, and the negative permeability of the MSRRs is excited at all of these frequencies. In fact, the field distribution in Fig. 4a exhibits the dominant resonance mode of the cavity while the field distributions in the other figures exhibit the higher-order resonance modes. In addition, it is found that the electric field in the cavity is mostly gathered around the metal strips of the MSRRs while the electric field is disorderly distributed in the USCR, although its distribution plot is presented here. In such a case, a magnetic dipole (small electric current loop) is more efficient than an electric dipole for feeding the USCR.

4 Miniaturized filter applications based on the ultra-small cavity resonator

The proposed configuration of the miniaturized filter is shown in Fig. 5a. The filter consists of two USCRs symmetrically placed on the ground planes of a coplanar waveguide. The overall length of the coplanar waveguide is

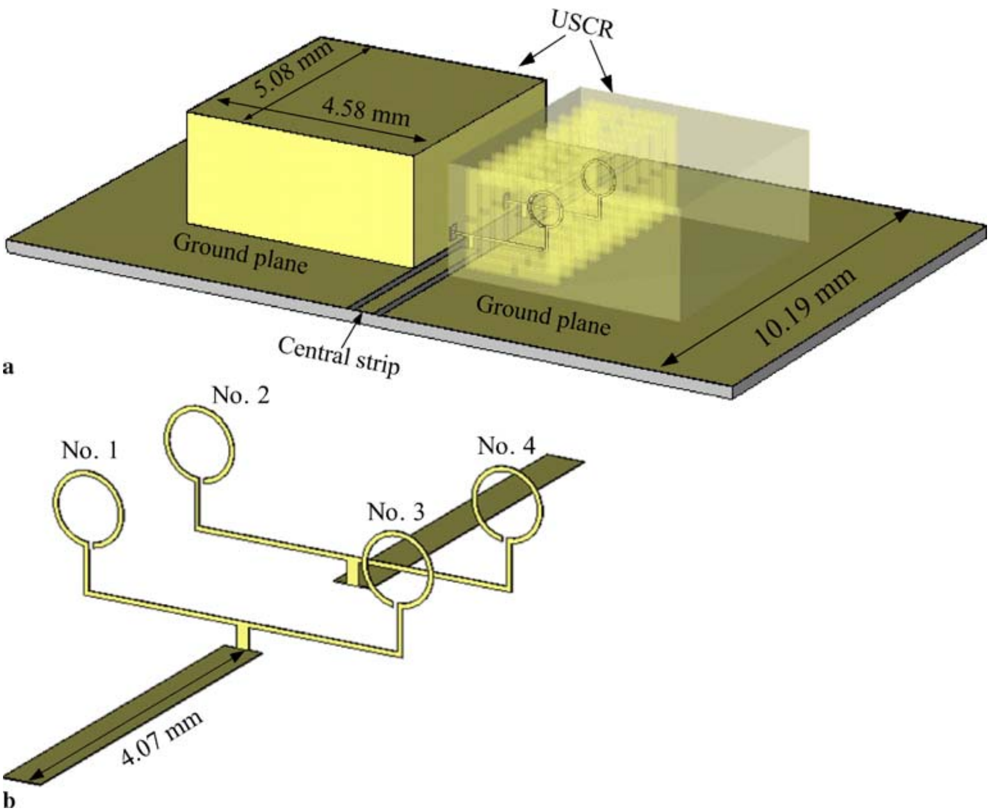

FIGURE 5 Configuration of the miniaturized filter. (**a**) Three-dimensional structure, (**b**) feeding mechanism

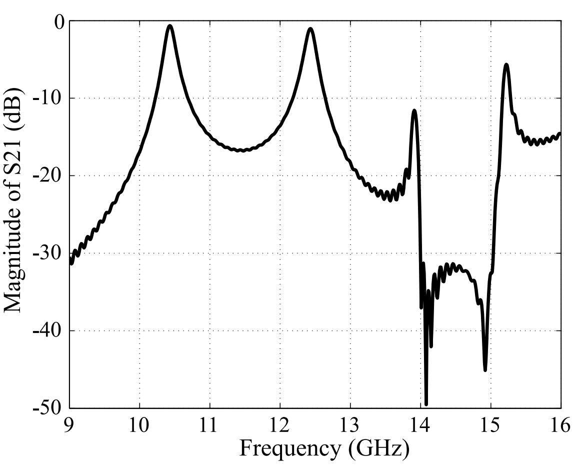

FIGURE 6 Magnitude of S21 simulated when the distance between loop No. 1 and the front edge of the coplanar waveguide is 4.07 mm

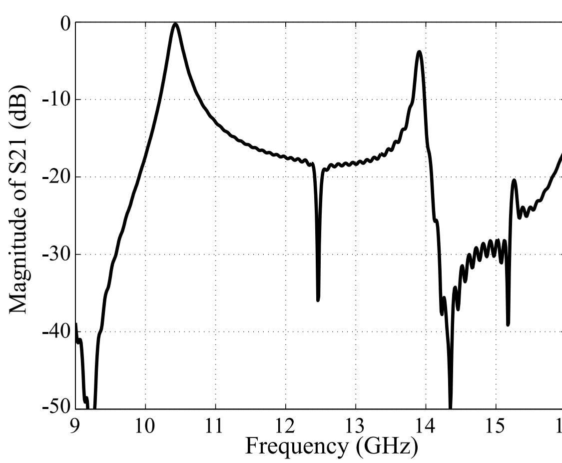

FIGURE 7 Magnitude of S21 simulated when the distance between loop No. 1 and the front edge of the coplanar waveguide is 5.09 mm

10.19 mm, the slot width is 0.19 mm, the central strip width is 0.41 mm and the thickness of the substrate is 0.25 mm, while its relative permittivity is 2.2, and the thicknesses of both the central strip and the ground strip are 0.017 mm. In such a case, the characteristic impedance of the coplanar waveguide is 82.5 Ω. The distance between the front edge of the coplanar waveguide and the USCRs is 2.67 mm.

The feeding mechanism of the filter consists of four bilaterally symmetrical loops, which are connected with the central strip of the coplanar waveguide using connection strips, as shown in Fig. 5b. These loops are inserted between the MSRRs of the two cavities, and the left two loops (labeled as No. 1 and No. 2) are used to feed the left USCR while the right two loops (labeled as No. 3 and No. 4) are used to feed the right USCR. The inner radius of the loop is 0.58 mm while the outer radius is 0.63 mm, and the width of the connection strip is 0.05 mm. The distance between the loop No. 1 and the front edge of the coplanar waveguide is 4.07 mm, and the distance between the loop No. 2 and the loop No. 1 is 2.04 mm.

The transmission curve of the simulated filter is shown in Fig. 6. It can be seen that there are three pass bands with the center frequencies respectively at 10.4 GHz, 12.4 GHz and 15.2 GHz, which are in a good agreement with the resonant frequencies of the USCR, and the insertion loss at 10.4 GHz is as low as 0.65 dB only. Note that the third resonance of the USCR at a frequency of 13.6 GHz is not clearly exhibited in Fig. 6 because this resonance mode is weakly excited. In fact, the higher-order resonance modes in the USCR can be suppressed by changing the positions of the loops in the cavity, according to the distributions of the magnetic field vectors shown in Fig. 4. For example, the transmission data of the filter are shown in Fig. 7 when the loops No. 1 and No. 3 are moved to the middle position (i.e. 5.09 mm away from the front sides of the left and right cavities, respectively), where the magnetic field is very weak at the second resonance frequency of 12.4 GHz. From Fig. 7, it can be seen that the pass band at 12.4 GHz shown in Fig. 6 disappears while other pass bands still exist.

5 Conclusions

In this paper, the USCR loaded with the LHM and RHM layers and the miniaturized filter constructed from the USCRs and a coplanar waveguide are presented and numerically simulated. It is demonstrated that the size of the USCR is small as compared with the existing MCR design reported recently in the literature. It has been shown that the length and width of the USCR can be simultaneously much smaller than half of the resonance wavelength. It is found that the center frequencies of the pass bands of the miniaturized filter, which is constructed from the USCRs placed on the ground plane of the coplanar waveguide, are in a good agreement with the resonance frequencies of the USCR. It has been demonstrated that the frequency-selective characteristics of the filter can be controlled to a certain extent by changing its feeding loop positions in the USCR, because the higher-order modes of the EM field in the USCR can be suppressed by moving the feeding loops to the positions where the field intensity is weak. Those results indicate that the miniaturized cavity resonator can be realized with only MSRRs or other structures with single negative permeability instead of a double-negative LHM, and the volume of the cavity resonator is limited only by the size of the unit cell of the MSRRs. In fact, the structure with a single negative permeability is much simpler than a double-negative LHM in design and fabrication.

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