# Dual-band metamaterial with a windmill-like structure*

Xiong Han(熊 汉)†, Hong Jing-Song(洪劲松), and Jin Da-Lin(金大琳)

*Institute of Applied Physics, University of Electronic Science and Technology of China, Chengdu* 610054, *China*

(Received 8 May 2012; revised manuscript received 21 June 2012)

A broadband negative refractive index metamaterial based on a windmill-like structure is proposed, and investigated numerically and experimentally at the microwave frequency range. From the numerical and experimental results, effect media parameters are retrieved, which clearly show that two broad frequency bands exist in which the permittivity and permeability are negative. The two negative bands are from 9.1 GHz to 10.5 GHz and from 12.05 GHz to 14.65 GHz respectively, and the negative bandwidth is 4 GHz. Due to the good bandwidth performance, the metallic cell with double negative property obtained in this paper is suitable for use in the design of multiband or broadband microwave devices.

**Keywords:** metamaterial, negative refractive index, broadband

**PACS:** 41.20.Jb, 42.25.Bs **DOI:** 10.1088/1674-1056/22/1/014101

## 1. Introduction

The first realization of metamaterial exhibiting an effective negative refractive index (NRI) was based on a combination of split-ring resonators (SRRs) and continuous wires,[1–3] which provided negative effective magnetic permeability and electric permittivity in the common frequency range. Since then, various negative refractive index metamaterials have been proposed, designed, and experimentally validated, such as S-shaped resonators,[4–7] Jerusalem cross conductor pairs,[8,9] chirality-shaped resonators,[10] and cut-wire pair (CWP) resonators.[11] However, the narrow DNG frequency is one of the important restricting factors in practical applications. In most SRR-based metamaterials, the negative refraction bands are around their magnetic resonance frequencies, which are often narrow, whereas the negative permittivity frequency bands are often wide due to the wire resonance behavior. So far, there has been no significant advance in the design of metamaterials that can be used for broadband practical applications, such as cloaking devices, bandstop filtering, and broadband absorption. Researchers have tried to realize broadband metamaterials utilizing a multiple stacked layer configuration.[12] Compared to a planar structure which can have a broad fundamental mode resonance, the multiple stacked layer configuration has its own complexities in fabrication.

In this paper, a novel metamaterial with a windmill-like structure is proposed, in which the metallic patterns are printed on the two sides of a substrate with reversed orientations to cancel the chiral effects.[13] The resonant structure exhibits left-handed properties in one frequency band due to the difference of current distributions. The DNG passband obtained by overlapping the wide negative permittivity with the wide magnetic response is very wide. In addition, the magnetic and electric resonances can be easily tuned by structural parameters such as the width and length of the metal lines and the thickness of the substrate. A sample of the structure is fabricated and tested in a waveguide measurement setup. Using the scattering parameters obtained by Ansoft's HFSS finite-element-method software package and experiment, we retrieve the complex constitutive effective parameters of this metamaterial.

## 2. Unit-cell design and simulation

The proposed unit cell is a combination of a cross and four L-shapes, which is shown in Fig. 1. The metallic patterns are printed on two sides of an FR4 substrate with relative permittivity $\varepsilon_r = 4.4$ and $\tan\delta = 0.02$. The metal used is copper with a thickness of $t = 17$ μm . The other geometrical dimensions shown in Fig. 1 are $W = 0.5$ mm, $L_{sub} = 5$ mm, $W_p = 0.4$ mm, $L_1 = 2.5$ mm, and $L_2 = 1.5$ mm. These parameters are important for controlling the paralleled impedance $Z$ to obtain a better match to the free space. The propagation direction of the incident electromagnetic wave is parallel with the metallic layer surface. The numerical simulations are performed with HFSS. A theoretical model based on an artificial waveguide with transverse boundaries of two ideal magnetic conductors and two ideal electric conductor planes is employed. Then, the model describes an infinite layer medium illuminated by an incident plane wave. To be specific, input/out ports are imposed in the $x$ direction, and perfectly electric conducting (PEC) and perfectly magnetic conducting (PMC) boundary conditions are imposed in the $z$ and the $y$ directions,

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61172115 and 60872029), the National High-Technology Research and Development Program of China (Grant No. 2008AA01Z206), the Aeronautics Foundation of China (Grant No. 20100180003), and the Fundamental Research Funds for the Central Universities, China (Grant No. ZYGX 2009J037).

†Corresponding author. E-mail: xiong1226han@126.com

© 2013 Chinese Physical Society and IOP Publishing Ltd 

respectively. There are many methods to retrieve constitutive parameters of metamaterials.[14–16] Most of them use scattering parameters to obtain impedance $Z$ and effective refractive index $n$ and then calculate $\mu = nz$ and $\varepsilon = n/z$. In this paper, the constitutive parameters of metamaterials are extracted by using the standard algorithm.[16]

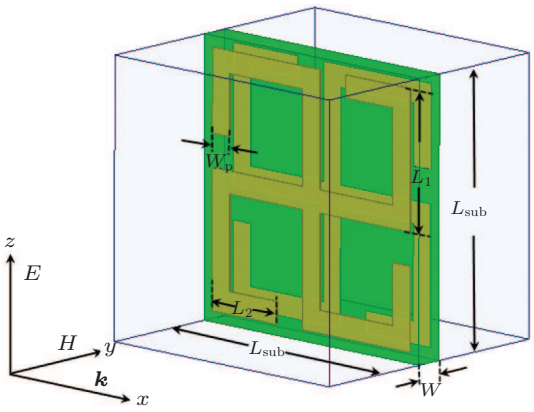



**Fig. 1.** (color online) Unit cell of the proposed structure.

Figure 2 gives the simulated magnitudes of parameters $S_{11}$ and $S_{21}$, as well as the retrieved real (solid curves) and imaginary (dashed curves) parts of effective permeability and effective permittivity. Figure 2(a) shows that there are three transmission peaks at 9.4 GHz, 13 GHz, and 14.5 GHz respectively. It indicates that there are two passbands.[17] As clearly shown in Figs. 2(b) and 2(c), there is obviously one electric resonance and two magnetic resonances. The first magnetic response laps the negative permittivity of the strips, enabling a narrow left-handed passband, while the wide part of the second magnetic response and the electric response overlap with each other. The effective permittivity is negative in the frequency range of 9.1–14.65 GHz, while the frequency ranges of negative effective permeability are 9.1–10.5 GHz and 12.05–15 GHz, much narrower than the negative permittivity range. From Fig. 2(d), we can find that the negative refractive bandwidth is very wide, from 9.1 GHz to 15 GHz. However, the DNG bands are 9.1–10.5 GHz and 12.05–14.65 GHz (shaded areas). So the DNG bandwidth is 4 GHz. The second DNG band is much wider than that of the other conventional left-handed materials (LHMs)[1–6,10,18] for the parallel incidence case.

Note there is a right-handed (RH) passband between the two left-handed (LH) passbands. The reason is that the permeability is negative only in the negative magnetic response frequency range, while the permittivity is negative in the frequency range from 9.1 GHz to 14.65 GHz. Thus, outside the LH passbands, the permeability is positive while the permittivity is negative, so there is a stopband between the two LH passbands. Generally, the negative response bandwidths of the magnetic and electric responses are usually not equal. So there is usually a RH passband between two LH passbands.[11]

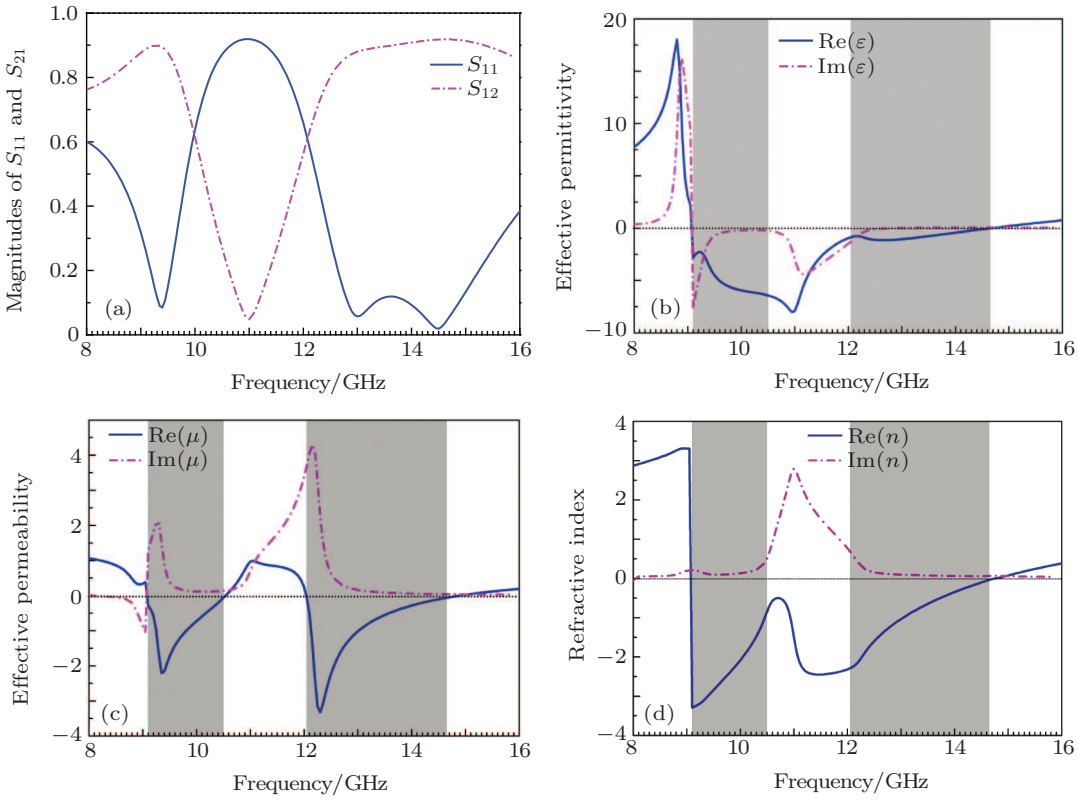



**Fig. 2.** (color online) (a) Simulated magnitudes of parameters $S_{11}$ and $S_{21}$, and real and imaginary parts of the effective (b) relative permittivity, (c) relative permeability, (d) index of refraction.

To understand the magnetic response behavior, the surface current distributions in the metallic wires at the two magnetic resonance frequencies are shown in Fig. 3. The results show that the two resonant frequencies are caused by different effective inductance–capacitance (LC) resonances. As shown in Fig. 3(a), the surface current mainly concentrates on the two C-shaped branches near the first resonant frequency 9.4 GHz. The electromagnetic behavior at the frequency of 12.3 GHz is shown in Fig. 3(b). The surface current mainly concentrates on the cross wire, possessing a very wide negative permeability response.

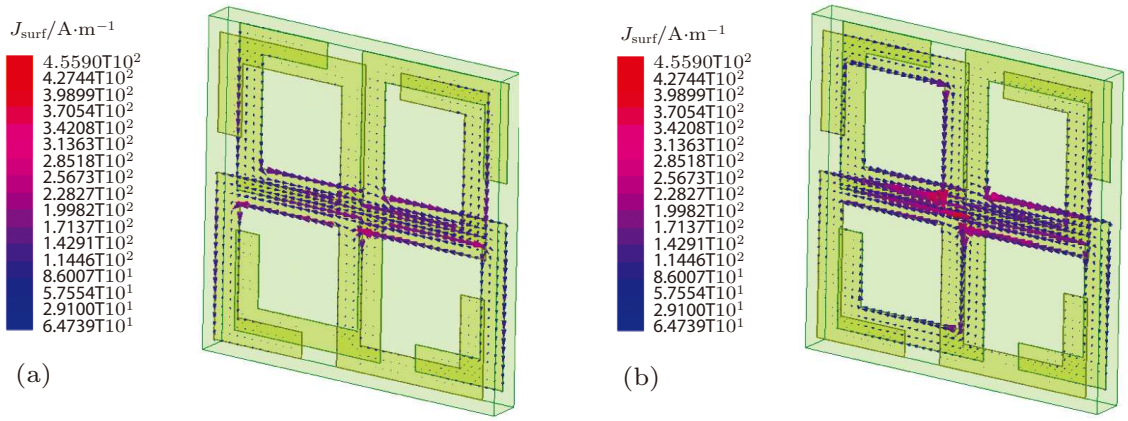



**Fig. 3.** (color online) Current distributions just above (a) the first and (b) the second magnetic resonances.

## 3. Experimental results

The proposed wideband and two-frequency-band metamaterial was also fabricated and investigated experimentally. The geometric dimensions of the fabricated sample are the same as those in the simulation. A photograph of the fabricated wideband and two–frequency-band metamaterial is shown in Fig. 4.

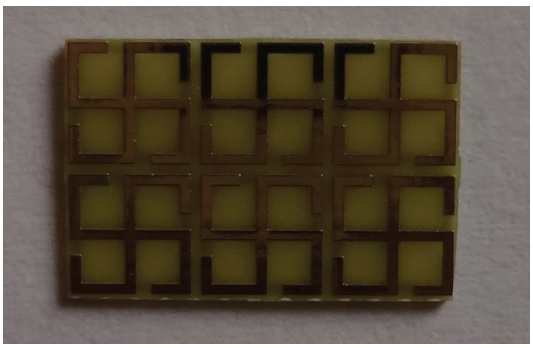


**Fig. 4.** (color online) Photomicrograph of a fabricated windmill-like structure.

The expected behavior was confirmed experimentally by measuring the transmission and reflection properties of the proposed metamaterial using the waveguide method. The sample was put into a standard waveguide BJ100 and a non-standard waveguide. Scattering parameters of the fabricated metamaterial were measured by the Agilent network analyzer E8361A. By using the recorded scattering parameters, the constitutive effective parameters were retrieved.

Figure 5(a) shows the simulated and the measured reflection and transmission coefficients for the investigated structure. The experimental and the simulation results agree with each other. As the residual differences are likely to result from some deviations in the experiment conditions from the idealized ones used in the simulations, a possible candidate is the dispersion of the dielectric constant of the substrate FR4. A second candidate is the fabrication tolerances of the design we used. The measured magnitudes of $S_{11}$ show clearly that there are also three resonance dips, at 9.4 GHz, 13 GHz and 14.5 GHz. For comparison, the retrieved constitutive effective parameters from the simulation and those obtained by measurement are shown in Figs. 5(b)–5(d). From Figs. 5(b)–5(d), we can see that the bandwidths obtained from the measurement are in excellent quantitative agreement with the simulated results and confirm the existence of the two bands of double negative. But the amplitudes from the measurement are about half of those in the simulation. This is because the measured amplitudes of $S_{11}$ and $S_{21}$ are lower than the simulated ones shown in Fig. 5(a). The two DNG bands are from 9.1 GHz to 10.5 GHz and from 12.05 GHz to 14.65 GHZ respectively. The DNG bandwidth is 4 GHz.

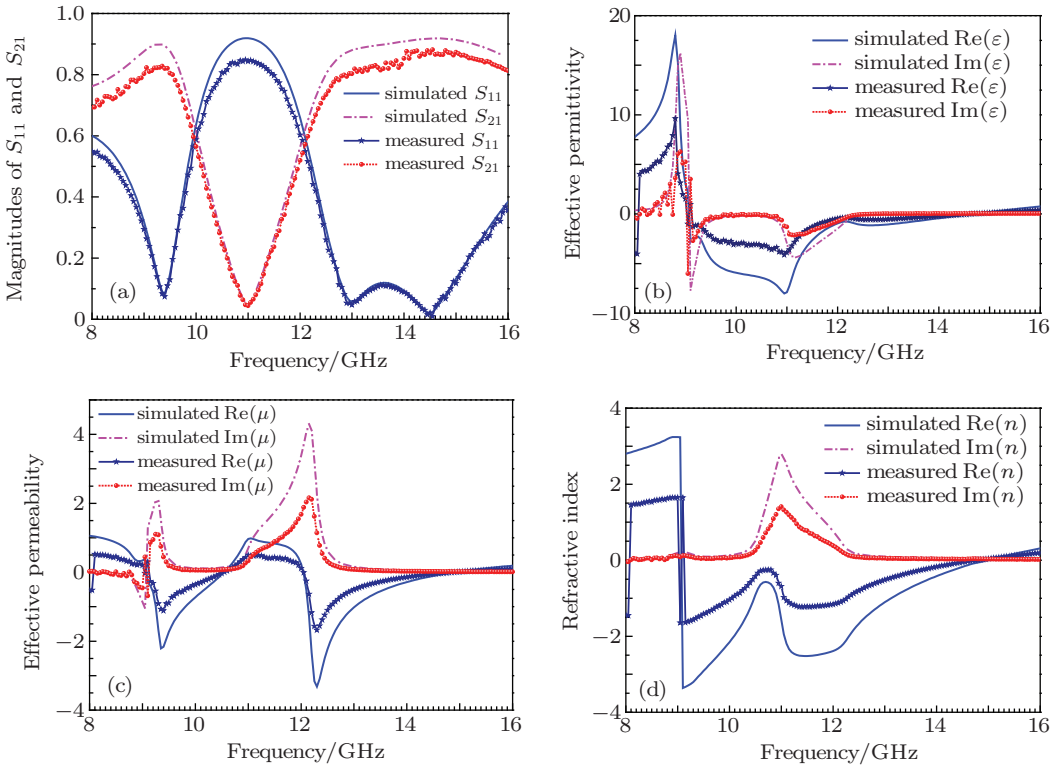



**Fig. 5.** (color online) Computed and measured (a) reflection and transmission coefficients, (b) permittivity, (c) permeability, and (d) index of refraction.

## 4. Conclusion

A windmill-like resonator has been proposed, which is a novel double-sided metamaterial with two DNG passbands. Its relative DNG bandwidth is very wide (about 4 GHz), which can be considered a very wideband LHM among the conventional inclusions. A sample of this metamaterial has been fabricated and tested to verify the simulation results. Due to good bandwidth performance, this metamaterial may be very useful in the design of multiband or broadband microwave devices.

## References

[1] Pendry J B, Holden A J, Robbins D J and Stewart W J 1999 *IEEE Trans. Microw. Theory Tech.* **47** 2075
[2] Smith D R, Padilla W J, Vier D C, Nemat-Nasser S C and Schultz S 2000 *Phys. Rev. Lett.* **84** 4184
[3] Lu W B and Ji Z F 2011 *Chin. Phys.* B **20** 054101
[4] Chen H, Ran L, Huangfu J, Zhang X, Chen K, Grzegorczyk T M and Kong J A 2004 *Phys. Rev.* E **70** 057605
[5] Chen H, Ran L, Huangfu J, Zhang X, Chen K, Grzegorczyk T M and Kong J A 2005 *Appl. Phys. Lett.* **86** 151909
[6] Wang D, Ran L, Chen H, Mu M, Kong J A and Wu B I 2007 *Appl. Phys. Lett.* **90** 254103
[7] Wang J, Qu S, Xu Z, Zhang J, Ma H, Yang Y and Gu C 2009 *Photonics and Nanostructures-Fundamentals and Applications* **7** 108
[8] Vallecchi A, Capolino F and Schuchinsky A G 2009 *IEEE Microw. Wirel. Co.* **19** 269
[9] He X J, Wang Y, Mei J S, Gui T L and Yin J H 2012 *Chin. Phys.* B **21** 044101
[10] Han N R, Chen Z C, Lim C S, Ng B and Hong M H 2011 *Opt. Express* **19** 6990
[11] Amiri N, Forooraghi K and Atlasbaf Z 2011 *IEEE Antennas Wireless Propag. Lett.* **10** 524
[12] Chowdhury D R, Singh R, Reiten M, Chen H T, Taylor A J, O'Hara J F and Azad A K 2011 *Opt. Express* **19** 15817
[13] Simovski C R and He S 2003 *Phys. Lett.* A **311** 254
[14] Chen X, Grzegorczyk T M, Wu B I, Pacheco Jr J and Kong J A 2004 *Phys. Rev.* E **70** 016608
[15] Houck A A, Brock J B and Chuang I L 2003 *Phys. Rev. Lett.* **90** 137401
[16] Smith D R, Vier D C, Koschny T and Soukoulis C M 2005 *Phys. Rev.* E **71** 036617
[17] Wang J, Qu S, Yang Y, Ma H, Wu X and Xu Z 2009 *Appl. Phys. Lett.* **95** 014105
[18] Ran L, Huangfu J, Chen H, Li Y, Zhang X, Chen K and Kong J A 2004 *Phys. Rev.* B **70** 073102