

# Left-handed material based on ferroelectric medium

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**Abstract:** Left-handed metamaterials always gain the electromagnetic properties from the structure rather than inherit them directly from the materials they are composed of. In this article, a metamaterial was made using split-ring resonators and slabs of ferroelectric materials, where negative permittivity was realized by intrinsic properties of ferroelectric materials. Using a waveguide-based retrieval method, the permittivity and permeability of the metamaterials were experimentally retrieved, showing successfully the left-handed behaviors of the metamaterial over certain frequency band.

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## References and Links

1. V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of permittivity and permeability," *Sov. Phys. Usp.* **10**, 509 (1968).
2. D. R. Smith, W. J. Padilla, and D. C. Vier, "Composite medium with simultaneously negative permeability and permittivity," *Phys. Rev. Lett.* **84**, 4184 (2000).
3. R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *Science* **292**, 77 (2001).
4. R. Marques, F. Medina, and R. Rafii-El-Idrissi, "Role of bianisotropy in negative permeability and left-handed metamaterials," *Phys. Rev. B.* **65**, 144440 (2002).
5. P. Gay-Balmaz, and O. J. F. Martin, "Efficient isotropic magnetic resonators," *Appl. Phys. Lett.* **81**, 939 (2002).
6. H. Chen, L. Ran, J. Huangfu, X. M. Zhang, K. Chen, T. M. Grzegorzczak, and J. A. Kong, "Magnetic properties of s-shaped split-ring resonators," *Progress In Electromagnetics Research, PIER* **51**, 231 (2005).
7. L. Ran, J. Huangfu, H. Chen, X. M. Zhang, K. Chen, T. M. Grzegorzczak, and J. A. Kong, "Experimental study on several left-handed metamaterials," *Progress In Electromagnetics Research, PIER* **51**, 249 (2005).
8. J. D. Baena, R. Marques, and F. Medina, "Artificial magnetic metamaterial design by using spiral resonators," *Phys. Rev. B.* **69**, 014402 (2004).
9. H. Chen, L. Ran, J. Huangfu, X. M. Zhang, K. Chen, T. M. Grzegorzczak, and J. A. Kong, "Metamaterial exhibiting left-handed properties over multiple frequency bands," *J. Appl. Phys.* **96**, 5338 (2004).
10. Y. Yuan, L. Ran, J. Huangfu, H. Chen, L. Shen, and J. A. Kong, "Experimental verification of zero order bandgap in a layered stack of left-handed and right-handed materials," *Opt. Express* **14**, 2220 (2006).
11. J. B. Pendry, A. J. Holden, W. J. Stewart, and S. Youngs, "Extremely low frequency plasmons in metallic mesostructures," *Phys. Rev. Lett.* **76**, 4773 (1996).
12. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microw. Theory Tech.* **47**, 2075 (1999).
13. A. Pimenov, A. Loidl, P. Przyslupski, and B. Dabrowski, "Negative refraction in ferromagnet-superconductor superlattices," *Phys. Rev. Lett.* **95**, 247009 (2005).
14. J. Pacheco, "Theory and application of left-handed metamaterials," Ph. D. thesis, Massachusetts Institute of Technology, (2004).
15. A. L. Pokrovsky, and A. L. Efros, "Electrodynamics of metallic photonic crystals and the problem of left-handed materials," *Phys. Rev. Lett.* **89**, 093901 (2002).
16. R. Marques, and D. R. Smith, "Comment on electrodynamics of metallic photonic crystals and the problem of left-handed materials," *Phys. Rev. Lett.* **92**, 059401 (2004).

17. X. Cai, X. Zhou, and G. Hu, "Numerical study on left-handed materials made of ferrite and metallic wires," *Chinese Phys. Lett.* **23**, 348 (2006).
18. G. Dewar, "A thin wire array and magnetic host structure with  $n < 0$ ," *J. Appl. Phys.* **97**, 10Q101 (2005).
19. J. S. Guerra, and J. A. Eiras, "Dielectric anomalies in La modified PbTiO<sub>3</sub> ferroelectric ceramics in the microwave frequency region," *Ferroelectrics* **294**, 25 (2003).
20. M. P. McNeal, S. Jang, and R. E. Newnham, "The effect of grain and particle size on the microwave properties of barium titanate BaTiO<sub>3</sub>," *J. Appl. Phys.* **83**, 3288 (1998).
21. H. Chen, J. Zhang, Y. Bai, Y. Luo, L. Ran, Q. Jiang, and Jin Au Kong, "Experimental retrieval of the effective parameters of metamaterials based on a waveguide method," *Opt. Express* **14**, 12944 (2006).
22. J. A. Kong, *Electromagnetic Wave Theory* (Wiley and Sons, 1986, 1990, EMW Publishing, 2000, 2005).
23. J. A. Kong, "Electromagnetic wave interaction with stratified negative isotropic media," *Prog. Electromagn. Res.* **35**, 1 (2002).
24. W. B. Weir, "Automatic measurement of complex dielectric constant and permeability at microwave frequencies," *Proceeding of IEEE* **62**, 1 (1974).
25. D. R. Smith, S. Schultz, P. Markos, and C. M. Soukoulis, "Determination of effective permittivity and permeability of metamaterials from reflection and transmission coefficients," *Phys. Rev. B.* **65**, 195104 (2002).
26. X. Chen, T. M. Grzegorzczuk, B.-I. Wu, J. Pacheco, and J. A. Kong, "Robust method to retrieve the constitutive effective parameters of metamaterials," *Phys. Rev. E.* **70**, 016608 (2004).
27. T. C. Choy, *Effective medium theory: principles and applications*, (Oxford science publications 1999).

## 1. Introduction

Since the left-handed material (LHM) [1] was experimentally realized in 2000 [2], much attention has been paid on designing various LHMs and fabricating innovation microwave devices [3-10]. Currently, most of the LHMs were realized by artificial metallic structures with metallic plasma resonance, such as using wires to produce effective negative permittivity and using split-ring resonators (SRR) to produce effective negative permeability [11,12]. Their unusual electromagnetic properties originate from the structure rather than inherit directly from the materials. Hence, it becomes interesting and significant to realize LHM by homogenous medium using their intrinsic material properties [13,14]. The first step toward homogenous left-handed material might be replacing one of the two composite structures by a homogenous material, i.e. the wire array by a homogenous negative permittivity medium, or the SRRs array by a homogenous negative permeability medium. However, theoretical result showed that LHM can not be realized by simply placing parallel wires in a homogeneous medium with negative permittivity because the effective permittivity of the metallic wires will be modified by strong coupling between the host medium and the wires [15]. Further investigations indicated that strong coupling can be alleviated and the LHM properties can be observed if some right-handed material (RHM) was introduced between the homogeneous host medium and the metallic wires [14,16-18]. This is also true for the composite material realized by SRRs and homogeneous negative permittivity medium. However, as the best of our knowledge, all of these works reported so far are based on simulations or theoretical calculations, and no experimental results have been reported so far. In this paper, we experimentally realized such kind of metamaterial by embedding SRRs in a homogenous ferroelectric (FE) material buffered by a RHM layer. The ferroelectric materials have already been shown to exhibit negative permittivity that originates from its dielectric resonance [19,20]. The constitutive parameters of the metamaterial are experimentally retrieved based on a waveguide retrieval method [21]. The result shows that simultaneously negative constitutive parameters can be obtained, confirming the left-handed behaviors of the metamaterial in the microwave frequency range.

## 2. Experiment and retrieve technology

In the experiment, a typical ferroelectric ceramic  $0.8\text{Pb}(\text{Ni}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-}0.2\text{PbTiO}_3$  (PNNT) is fabricated using standard ceramics method. X-ray diffraction results show a pure perovskite structure of PNNT. After dry-pressed and sintered, the slabs of PNNT are grinded precisely to the wanted dimensions. Figure 1 shows the metamaterial laminated structure with alternate ferroelectric layers and SRR layers. The FE layer has a thickness of 5 mm. The SRR is printed

on both sides of a 2 mm thick FR4 substrate (dielectric constant  $\epsilon_r=4$ ) and the parameters are:  $w=7$  mm,  $c=1$  mm,  $g=2$  mm, and  $d=2$  mm. As suggested in [14, 16-18], a 2 mm thick empty FR4 resin layer is sandwiched between every SRR layer and FE layer to alleviate the coupling between them. The composite material has a periodicity of 11 mm along the  $e_1$  direction, 10 mm along the  $e_2$  direction and 11.3 mm along the  $e_3$  direction. The three coordinate axes  $e_1$ ,  $e_2$ , and  $e_3$  are the principal axes.

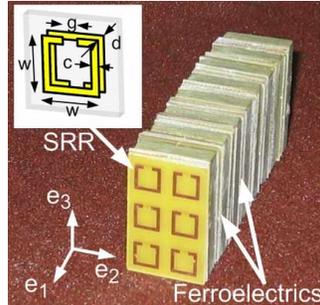


Fig. 1. Sample of the metamaterial with SRR embedded in ferroelectric medium. The inset shows the unit cell of the SRR structure.

A waveguide-based experimentally retrieval method was used to obtain the constitutive parameters of this composite material [21]. The experimental setup is shown in Fig. 2. It consists of two coaxial-to-waveguide adapters connected to a rectangular waveguide loaded with the slab of the material under test. A WR-284 rectangular waveguide ( $a=72.14$  mm and  $b=34.04$  mm) is used for measurement with the operation frequency range from 2.5 to 3.95 GHz (TE<sub>10</sub> mode). The distances between the adapters and the sample are large enough, so that the higher order evanescent modes due to the coaxial-to-waveguide adapters are significantly attenuated prior to reaching the sample under test. The  $S$  parameters are recorded by an Agilent 8722ES network analyzer and calibrated to the reference planes, which are the two interfaces between the material and the air. The constitutive relations for the material are [22]:  $\bar{D} = \bar{\epsilon} \bar{E}$  and  $\bar{B} = \bar{\mu} \bar{H}$ , where the parameter tensors have the following forms in the principal system ( $e_1, e_2, e_3$ ):  $\bar{\epsilon} = \epsilon_0 \text{diag}[\epsilon_1 \ \epsilon_2 \ \epsilon_3]$ ,  $\bar{\mu} = \mu_0 \text{diag}[\mu_1 \ \mu_2 \ \mu_3]$ . The material under test is both electrically and magnetically anisotropic. The retrieval algorithm [21] based on the reflection coefficients and transmission coefficients [23] is developed for these electrically and magnetically anisotropic materials, which is different from the retrieval methods for isotropic material in waveguide [24] or for anisotropic material in free space [25,26].



Fig. 2. Experimental setup for the scattering parameters measurement in rectangular waveguide

### 3. Results and discussion

After FR4 substrate with known parameters ( $\epsilon_r=4$ ;  $\mu_r=1$ ) is measured and retrieved as a guide sample, the results highly consistent with the known parameters well prove the accuracy of the experimental measurement technique (Fig. 3). Thereafter, the three kinds of materials: SRR only, FE material only, and the SRR/FE composite materials are measured. For the case of SRR/FE material, the electric field is always along the  $e_3$  direction when the sample is measured in the waveguide. It is required in the retrieval method [21] that the slab sample

should fully fill the cross section of the waveguide, therefore, along the  $e_3$  direction, three periodic unit cells with a total height of 33.9 mm are used, and along the other directions, the SRR layer, buffer layer, and FE layer are repeated until the cross section of the waveguide is fully filled. Since the axis of the SRR is along the  $e_1$  direction, which indicates SRR has a strong coupling with the magnetic field along the  $e_1$  direction, the  $\mu_1$  component shows most interest. From Ref [21] it can be seen that in order to obtain the two parameters  $\mu_1$  and  $\epsilon_3$ , two measurements are necessary. The retrieved real part of the effective  $\mu_1$  and  $\epsilon_3$  for the three kinds of materials are plotted in Fig. 4. Where we see that for the SRR,  $\mu_1$  has a resonance at 2.76 GHz, and  $\epsilon_3$  is around 8; for the FE material,  $\mu_1$  is close to 1, and  $\epsilon_3$  is around -30; while for the SRR/FE material,  $\mu_1$  is negative from 2.6 GHz to 2.95 GHz, and  $\epsilon_3$  is around -15. The results indicate that in the frequency range of 2.6-2.95 GHz, a wave with  $E_3$  polarization undergoes backward propagation when propagating along the  $e_2$  direction, confirming the left-handed behavior of the SRR/FE composite structure.

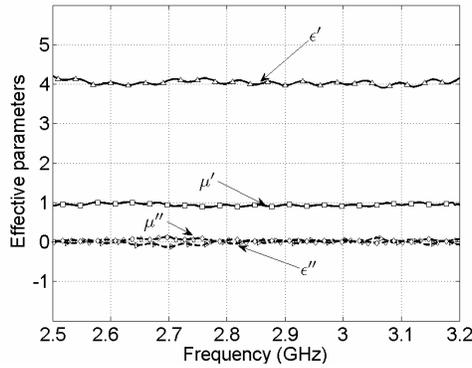


Fig. 3. Measured  $\epsilon_r$  and  $\mu_r$  for the FR4 substrate. (') and (") denote the real part and the imaginary part of the parameters, respectively.

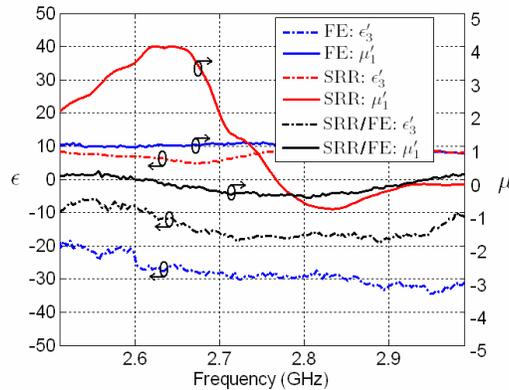


Fig. 4. Real part of the measured effective  $\epsilon_3$  [dashed line, left-hand scale] and  $\mu_1$  [solid line, right-hand scale] for the three kinds of materials: SRR only, FE only and SRR/FE. In the legend, (') denote the real part of the parameters.

It is worth mention that in the composite SRR/FE material, the negative permeability of SRR is derived from the effective magnetic plasma like behavior [14], while the negative permittivity of FE originates directly from its intrinsic dielectric resonance [19,20]. FE ceramics have complex domain structure where some cations in special areas (such as in micro domains or on the domain walls) can be driven by the electronic field to vibrate around their equilibrium position. When the electromagnetic wave's frequency equals to the nature oscillation frequency of these cations, a dielectric resonance occurs. Above the dielectric resonance frequency, the motion of the cations cannot keep up with the variation of electric field. The phase lag of polarization to electric field results in the negative permittivity. Figure

4 shows that the permittivity of the FE material is negative over the whole measured spectrum (from 2.5 GHz to 3.0 GHz), indicating that the dielectric resonance is smaller than 2.5 GHz. Further experimental result shows that the dielectric resonant peak of the FE material locates at 2.39 GHz (see Fig. 5), the imaginary part is also very high around the resonant frequency, and as the frequency goes up to 2.7 GHz, the imaginary part of the permittivity decreases to be around 40.

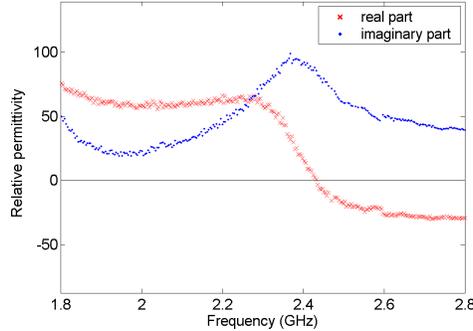


Fig. 5. The measured permittivity of the FE material around the dielectric resonance.

Furthermore, the measured effective permittivity and permeability for the three kinds of materials shown in Fig. 4 can be explained by the effective medium theory [27]. For example, due to the positive permittivity of the SRR structure, the permittivity of the SRR/FE composite material goes up (positively shifted) compared with that of the FE only material. Meanwhile, due to the positive permeability of the FE material, the permeability resonant behavior of the SRR/FE composite material becomes less obvious compared with that of the SRR only structure. Although the additional FE material can affect the magnetic resonant frequency of the SRR, we can still see that the effective permittivity (or permeability) of the SRR/FE structure is approximately between that of the SRR only and FE only material. Obviously, it will be easier to observe left-handed properties of the metamaterial if the permittivity of FE materials and the permeability of SRR structures become more negative.

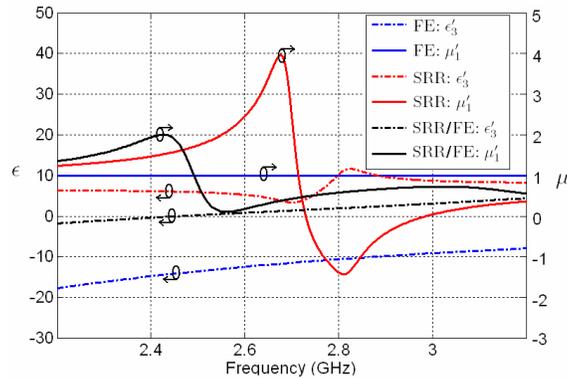


Fig. 6. Retrieved  $\epsilon_3$  and  $\mu_1$  for the three materials where the permittivity of FE only material is around -10 at 2.8 GHz. In the legend (') denote the real part of the parameters.

Numerical simulations are carried out to explore under what condition this kind of SRR/FE composite material can still exhibit left-handed behavior. In the simulations, the arrangement of the SRR and FE material is kept consistent with the former arrangement, and only the permittivity of the FE material ( $\epsilon_{FE}$ ) is changed. First we consider the influence of the real part of  $\epsilon_{FE}$  on the LHM properties. The value of  $\epsilon'_{FE}$  is changed from -30 to -5 at the center frequency of 2.8 GHz. Fig. 6 shows the retrieved parameters based on the simulated

scattering data for the case of  $\epsilon'_{\text{FE}} = -10$ . Since at 2.8 GHz the permittivity of the SRR is around 10, the estimated permittivity for the composite SRR/FE medium using the effective medium theory is around zero, showing agreement with the simulation result (Fig. 6). Similar phenomenon can be observed for the effective permeability of the three kinds of the material. From the simulation result, we can conclude that if  $\epsilon'_{\text{FE}}$  becomes larger than  $-10$  the LH pass band for the SRR/FE medium disappears, while if  $\epsilon'_{\text{FE}}$  is smaller than  $-10$ , the permittivity and permeability of the SRR/FE composite material can still be kept simultaneously negative in certain frequency range.

Second, we consider how the imaginary part of the permittivity of the FE material ( $\epsilon''_{\text{FE}}$ ) affects the LHM properties. We keep the real part of the permittivity fixed ( $\epsilon'_{\text{FE}} = -30$ ) at 2.8 GHz, and changed its imaginary part ( $\epsilon''_{\text{FE}}$ ). Our simulation results show that an increase of loss in FE material lowers the transmission level of the composite SRR/FE material, but the left-handed properties still exist. Even when  $\epsilon''_{\text{FE}}$  increases to be 50, left-handed pass band still can be identified. For the case of FE with  $\epsilon_{\text{FE}} = 30(-1 + i 0.9)$  at 2.8 GHz, we plot in Fig. 7 the electric-field distribution within one period in a 6-cell metamaterial slab (Region 2) under plane wave incident from the left (Region 1). The field in region 2 contains both the transmitting field through the first interface and the reflected field from the second interface. Due to the loss of the metamaterial, the amplitude of the reflected wave is much smaller than that of the transmitting field, and the field inside the metamaterial sample is very close to a propagating wave. From the results we see the wave fronts propagate toward the source, indicating a backward wave. However, because of the high loss of the material, the transmitted electric field is  $-35\text{dB}$  lower than the incident field.

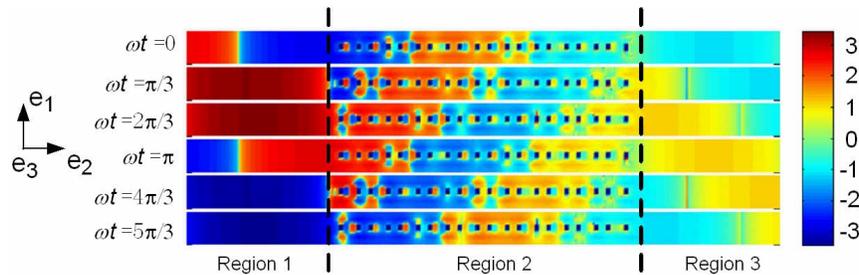


Fig. 7. Electric field  $E_3$  in the mid-plane when the structure has reached steady state. The wave is incident onto the slab from the left. The magnitude of field is in log scale.

#### 4. Conclusion

In conclusion, a left-handed metamaterial composed of SRRs and ferroelectric materials is experimentally realized. The permittivity and permeability tensors of this metamaterial are experimentally retrieved using a waveguide-based retrieval method, and the left-handed properties are successfully verified. It is shown that the increase of negative permittivity (less negative) of ferroelectric goes against the realization of LHM, while an increase of mere permittivity loss has less effect on the existence of left-handed pass band. Besides, our work also provides a new way to understand the physics insight in the left-handed materials from a microscopic point of view.

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