Vietnam Journal of Science and Technology ***58*** *(2) (2020) 237-245*

doi:10.15625/2525-2518/58/2/14093

CHARACTERIZATION OF A SYMMETRIC FISHNET METAMATERIAL IN THE M-BAND

Tran Van Huynh[1, 2, 3], Bui Son Tung[1], Bui Xuan Khuyen[1], Vu Dinh Lam[1, 2], Nguyen Thanh Tung[1, 2, *]

[1]*Institute of Materials Science, VAST, 18 Hoang Quoc Viet, Ha Noi, Viet Nam*

[2]*Graduate University of Science and Technology, VAST, 18 Hoang Quoc Viet, Ha Noi, Viet Nam*

[3]*Department of Basic Sciences, University of Fire 243 Khuat Duy Tien, Ha Noi, Viet Nam*

[*]Email: *tungnt@ims.vast.ac.vn*

Received: 2 August 2019; Accepted for publication: 5 February 2020

Abstract. We study a symmetric fishnet metamaterial working in the M-band (60 - 100 GHz). Significant effects of the dielectric spacer and the metal pattern on the electromagnetic response are investigated. It is found that the left-handed peak was shifted, enhanced or even destroyed by changing the thickness and the permittivity of the dielectric spacer. In addition, we also present the effect of metal pattern properties on the left-handed transmission spectra. The effective medium parameters are calculated using the standard retrieval method. It is expected that this work will allow us to optimize the appropriate characteristic parameters even without avoiding the trial and error fabrications.

Keyword: metamaterials, fishnet, left-handed materials.

Classification number: 2.1.2, 3.4.1.

1. INTRODUCTION

Double negative metamaterials which exhibit a negative permeability (μ) and negative permittivity (ε) over a simultaneous frequency range were initially discussed by Veselago in 1968 [1]. Later studies showed that the negative permeability is the result of a resonance response to an external magnetic field while the negative permittivity comes from a plasmonic or a resonance response to an external electric field. These features of metamaterials bring forth the novel properties such as a negative index of refraction (n), and left-handed rule of **k**, **E** and **H**; hence, they are named “negative index materials” or “left-handed materials (LHMs)” [2]. The existence of LHMs was first demonstrated using a periodic array of split-ring resonators and continuous wires [3] based on Pendry's suggestion [4]. Afterwards, the negative *n*, the most challenging property of LHMs, was shown in Shelby's experiment [5] and was reaffirmed in subsequent ones [6-8]. Till now, many LHM structures, made of nonmagnetic materials such as metallic and dielectric components [9-13] or purely dielectric components [14-16], have been proposed to obtain the negative *n*. Others focus on how to make metamaterials with controllable LH properties using both internal and external parameters [17-21]. Among them, the symmetric fishnet structure, which consists of broadened cut-wire pairs (CWPs) and continuous wires, gets a lot of attention since its highly applicable properties and unpolarized capability [22 - 25]. The electromagnetic responses, the structural characteristics and the promising properties of this structure are still being studied [26 - 29].

Recently, the LH behavior of a planar metamaterial structure working at 100 GHz was experimentally and numerically demonstrated [23]. Then, the characterization of symmetric fishnet structure was examined by the standard retrieval method [30]. It was shown that the effective medium theory was a well-developed method to explain successfully the double negative behavior. Since the changes in the structural parameters were accounted for the different responses of the effective medium, the LH behavior of fishnet structure was proved to be sensitive to the shape and the content of the unit cell. In order to provide more rigorous features of such a structure, the important influences of metal pattern and dielectric spacer are studied and presented in this paper.

2. COMPUTATIONAL METHOD

The transmission simulations were done using a commercial code, CST Microwave Studio (Computer Simulation Technology GmbH, Darmstadt, Germany), based on the finite integration technique. The lossy metal model of copper with a conductivity of $\delta = 5.96 \times 10^{7}$ S.m^{-1} was used and the dielectric constant of the spacer was denoted as ε. The boundary conditions at top and bottom walls were assumed to be a perfect electric and magnetic conductor at the left and the right walls. In addition, the standard retrieval method was performed to extract the effective permittivity and permeability of the fishnet structure from complex scattering parameters [30]. This is a well-fashioned method to prove whether a metamaterial structure exhibits the LH behavior. The effective index of refraction was determined using formula $n = \sqrt{\mu\varepsilon}$.

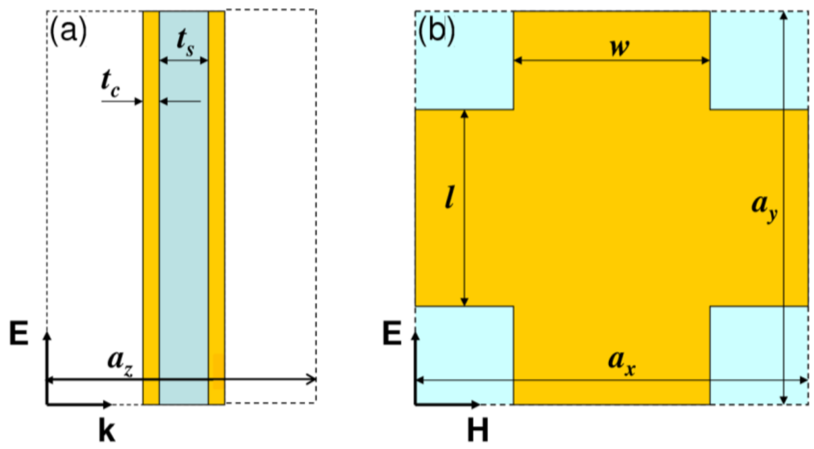

Figure 1. The unit cell and geometric parameters of a fishnet structure (a) viewed from H direction and (b) in E-H plane.

For all calculations, the incident wave is normal to the plane of fishnet structure, and the electric and the magnetic fields are parallel to **y-** and **x-**axis, respectively. The length of the slab and the width of wire are l = 1 mm and w = 1 mm, while the periodicities in **x-** and **y-**axis are a_x = a_y = 2 mm. The size of the unit cell along **k-**direction, a_z, is assigned to a value of 1 mm, because it is closest to the most experimental value. The thicknesses of metal pattern and spacer are defined to be t_c and t_s, respectively. A single unit cell of the symmetric fishnet structure with geometric parameters is shown in Fig. 1.

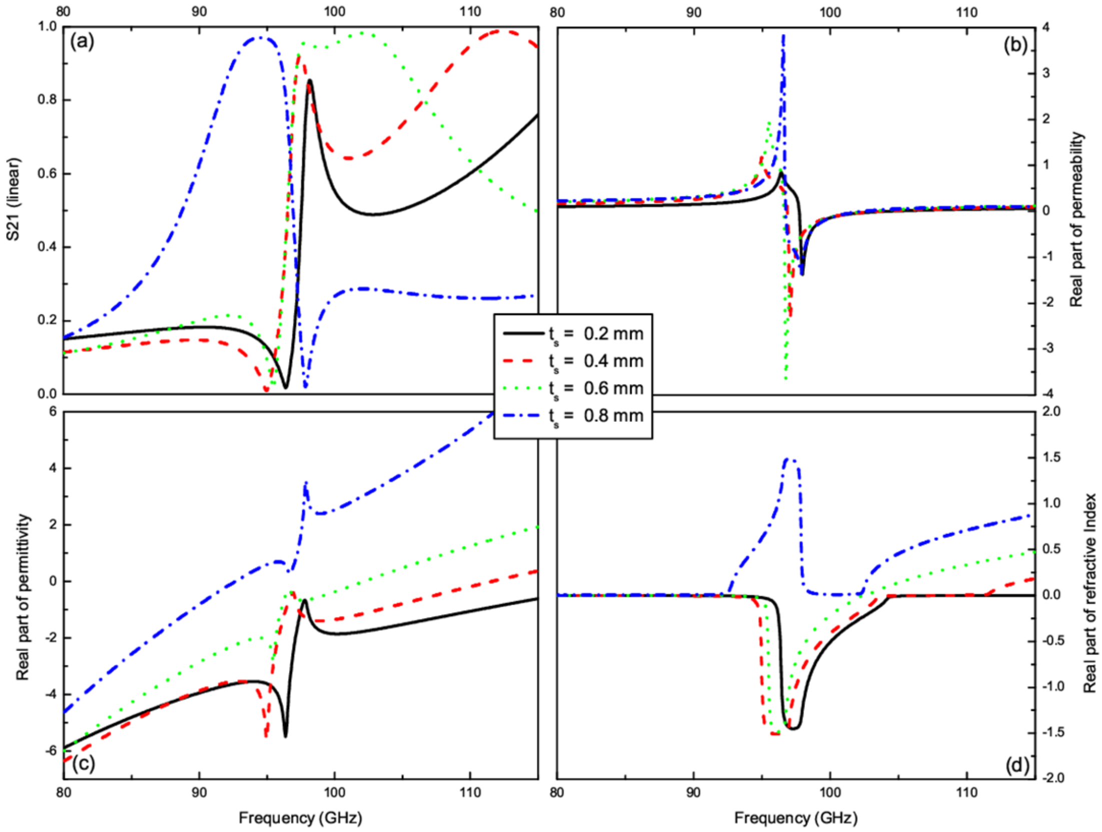

Figure 2. (a) S_{21} spectra, (b) extracted real part of the permeability, (c) that of the permittivity and (d) refractive index for a fishnet structure with different spacer thicknesses t_s.

3. RESULTS AND DISCUSSION

3.1. Influence of spacer properties on LH behavior

The LH behavior of the fishnet structure has been demonstrated elsewhere [22, 23, 26]. In which, still most of the commonly used spacer for constructing this kind of metamaterials are dielectric with unit permeability. But so far, studying the effects of constituent materials on LH properties of fishnet structure remains to be explored further. The substrate and metal properties dependence of the electromagnetic response of one other metamaterial structure, the split-ring resonator, was examined both theoretically and experimentally as a strongly contributed parameter [31, 32]. For fishnet structure, the spacer does not only play a part of substrate but also to be a valuable constituent in forming magnetic resonance as well as LH behavior. Therefore, howsoever the spacer properties act upon constructing the LH behavior, it is still important parameter in handling effective responses of fishnet structure. In fact, the electromagnetic properties of the fishnet structure are significantly affected by both the thickness and the dielectric constant of spacer, which is further discussed in this paper. The simulated S_{21}

spectra of one-layer fishnet structure with 0.2, 0.4, 0.6 and 0.8 mm-thick spacer are presented in Fig. 2(a). In this study, the dielectric constant of spacer, ε_s, is fixed to be 2.2 + *i*0.0009 and the thickness of metal pattern, t_c, is 9 µm. The real parts of corresponding effective permeability, permittivity and refractive index, extracted from the complex scattering parameters, are also displayed in Figs. 2(b), 2(c) and 2(d), respectively.

In case of 0.2 mm-thick spacer, it is observed that the negative refractive index is around 98.1 GHz, which is in a good agreement with previous work [23]. Interestingly, the real part of the effective refractive index goes from negative to positive value when the thickness of spacer increases from 0.2 to 0.8 mm [see Fig. 2(d)]. The LH transmission peak is strengthened with the spacer thickness but suddenly disappears at t_s = 0.8 mm. Notice that the right-handed S_{21} peak is getting closer to the LH one. The reason can be seen in Figs. 2(c) and 2(d). At larger values of the spacer thickness, there is a significant movement of the total plasma frequency towards the lower-frequency regime while the magnetic resonance frequency nearly remains unchanged. Essentially, a decreased plasma frequency of continuous wires leads to a reduction of the total one. Meanwhile, an increase in t_s can be considered as stretching of the distance *a* between continuous wires of fishnet structure. The dependence of the effective plasma frequency ω_p of continuous wires on distance *a* is given by $\omega_p \sim 2\pi c_0^2/\varepsilon_s a^2$ in which c_0 is light velocity in vacuum and ε_s is the permittivity of medium between continuous wires. This prediction was proposed by Pendry *et al.* [33]. Clearly, the plasma frequency ω_p is reduced when distance *a* gets longer. At t_s = 0.8 mm where the total plasma frequency becomes lower than the magnetic resonance, we do not have an overlap of the negative regions of ε and μ. Hence, the LH behavior has entirely vanished.

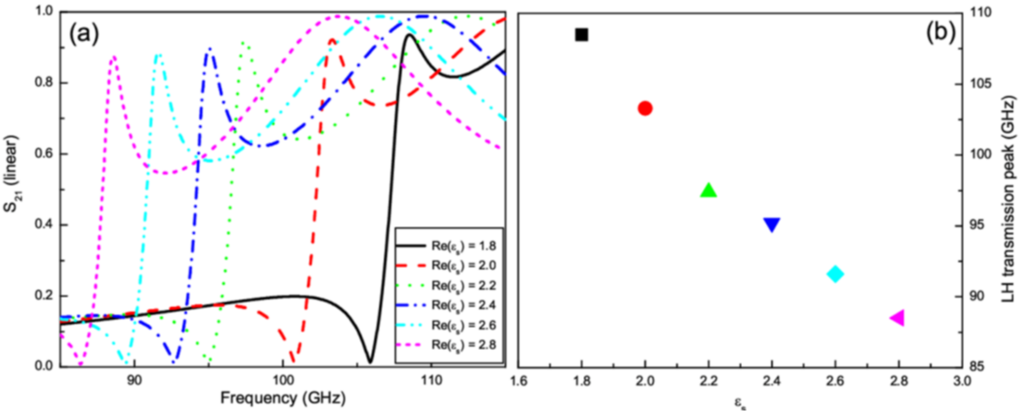

Figure 3. (a) LH transmission spectra and (b) LH peak with according to ε_s.

In Fig. 3(a), we plot the LH transmission spectra according to spacer dielectric constant ε_s. The thickness and the loss tangent of the dielectric spacer are kept constant at 0.4 mm and 0.0009, respectively. The real part of dielectric constant of spacer was increased from 1.8 to 2.8 with step of 0.2. We found that the intensities of LH transmission spectra are nearly unchanged [see Fig. 3(a)], but it is obvious that the LH transmission frequency can be tuned by changing the dielectric constant of spacer. As we can see, the LH peak drops linearly from 108.5 to 88.5 GHz when ε_s varies from 1.8 to 2.8. The extracted effective permittivity and permeability from the complex scattering parameters are depicted in Fig. 4 to get a profound view of the electromagnetic responses. At first glance, the plasma frequency also understandably decreases with dielectric constant ε_s [33] as well as with the thickness of spacer. On the other hand, it is clearly seen that the magnetic resonance frequency also strongly drops towards lower frequency and thereby, the LH behavior has still remained. The reasonable explanation for this effect can be expressed using LC equivalent model proposed by Zhou *et al.* [34]. Under the excitation of incident wave, the magnetic resonance frequency ω_m is given by $\omega_m = \frac{1}{\sqrt{LC}}$, in which L is inductance and C is capacitance. The capacitance here is formed in proportion to ε_s by the charge coupling at the ends of CWP along the **E**-direction. Consequently, the dependence of the magnetic resonance frequency and also the LH transmission peak on the dielectric constant of spacer can be considered as a linear function in interested frequency domain. By tuning this parameter, we can obtain a fishnet structure which exhibits the LH behavior at an expected frequency, in other words, as a tunable metamaterial.

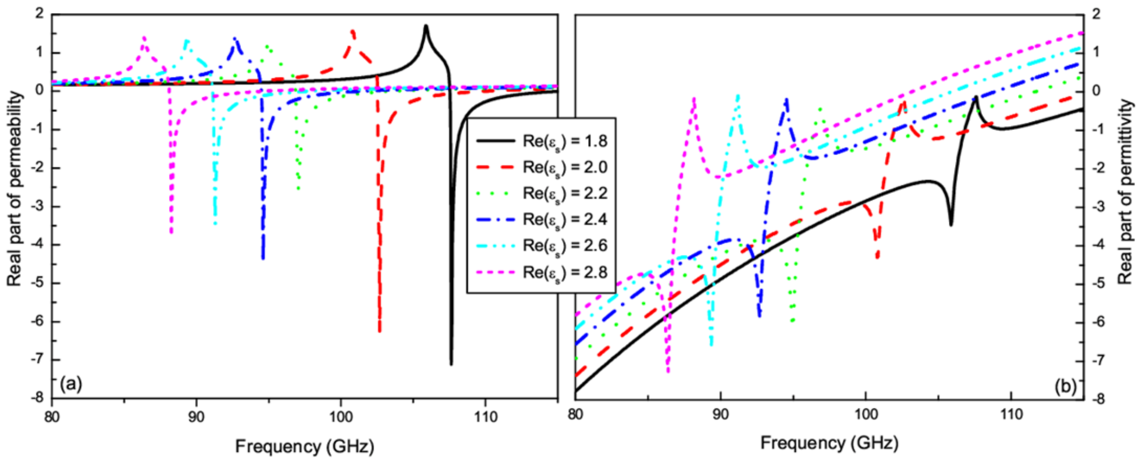

Figure 4. Retrieved effective (a) permeability and (b) permittivity from the simulated complex scattering data with different values of ε_s.

3.2. Effect of metal pattern properties

Generally, most of the metamaterials use metallic resonator to enact a desired response. Under incident excitation wave, the fishnet structure can be treated as a LC equivalent model [23, 34], in which the nature of inductive capacitance comes from the circular currents in metallic components. Hence, it is easily understood that the conductivity and the thickness of metal pattern should play an important role in forming of metamaterial behavior, especially for high-frequency regime.

In this section, we examine the effect on the electromagnetic response of changing the thickness of the metal pattern. Figure 5(a) presents the S_{21} spectra of one-layer fishnet structure with a fixed t_s and the thickness of metal pattern is varied to be 3, 6, 9, 18 and 36 μm, which is much larger than the skin depth of copper (δ = 0.21 μm) at 100 GHz [35]. All other parameters are defined in Fig. 5. The results show that the LH transmission peak is enhanced for smaller t_c. The LH transmission peak and the negative refractive index regime are slightly shifted to a lower frequency when t_c increases from 3 to 9 μm, and gets saturated at t_c > 9 μm [see Figs. 5(a) and 5(b)].

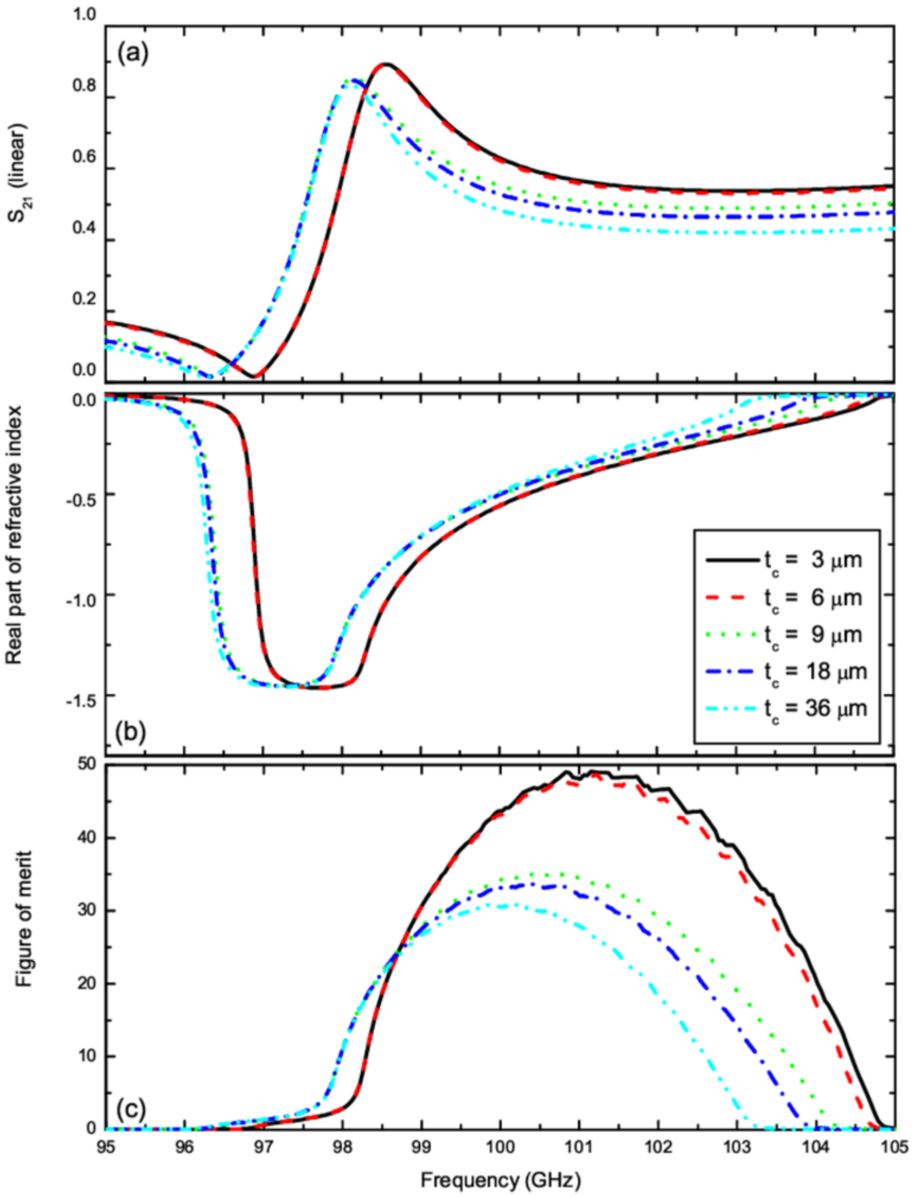

Figure 5. (a) Transmission spectra; (b) the retrieved real part of refractive index according to thickness of metal pattern (t_c) in which t_s = 0.2 mm and $\varepsilon_s = 2.2 + i0.0009$. The LH maximum transmission is 0.90 at t_c = 3 µm and 0.77 at t_c = 36 µm; (c) Figure of merit [-Re(n)/Im(n)] as a function of frequency for different t_c.

It can be seen more informatively in Fig. 5(c), where we present the figure of merit [FOM = -Re(n)/Im(n)] for various values of t_c. Obviously, the FOM decreases drastically as t_c getting thicker while the value of the real part of negative refractive index is nearly unchanged. It means that at the larger t_c, the larger Im(n) and hence, the lower transmission. With a carefully noticing, it is realized that the maximum values of FOM always exhibit at a higher frequency than LH peak. In other words, the Im(n) takes the larger value at LH transmission frequency and then, decreases as it goes away. For example, the maximum FOM for t_c = 9 µm is located at 100.5 GHz while the corresponding LH peak exhibits at 97.8 GHz.

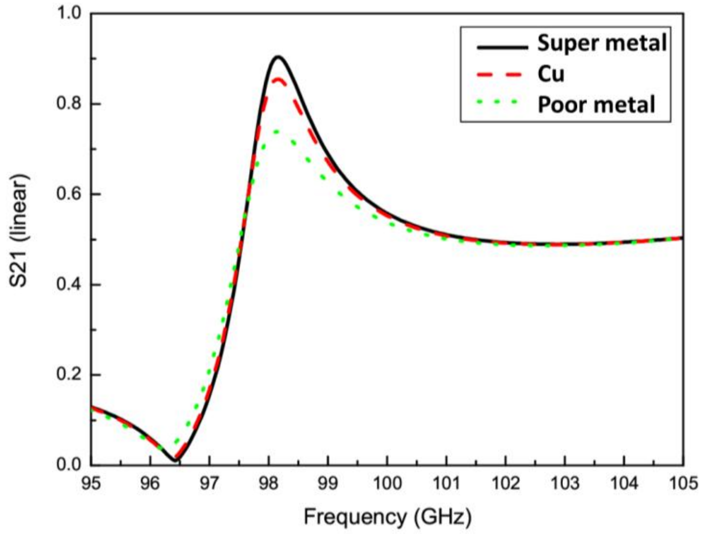

Figure 6. Transmission results of fishnet structure made of copper, poor and super metal pattern. The conductivity of copper is taken to be 5.96×10^7 Sm^{-1}, and 5.96×10^6 and 5.96×10^8 Sm^{-1} for poor and super metal cases, respectively. The thickness of spacer and metal pattern are kept to be 0.2 mm and 9 µm, while the dielectric constant of the spacer is 2.2 +i0.0009.

Furthermore, it is important to note that the real conductivity δ of metal decays as a function of life time. Evaluating the effect of metal conductivity on the electromagnetic response of metamaterial and the existence of LH behavior is useful in applications. For this reason, we will go further by presenting the simulated transmission for fishnet made from a poor metal and a super metal whose conductivities are ten times smaller and larger than the copper model. In Fig. 6, still a lower LH transmission peak can be observed for the structure made of poor metal and understandably the LH peak is strengthened in case of super metal.

4. CONCLUSIONS

In summary, the effect of metal pattern and dielectric spacer on the fishnet structure has been studied. The retrieval effective parameters were calculated along with the simulated transmission spectra to interpret the essence of these influences. It can be concluded that not only the effective permeability but also the permittivity, in other words, the LH behavior of fishnet structure are very sensitive to the properties of spacer and metal pattern. The role of the dielectric constant of the spacer in tuning the LH behavior of the fishnet structure was investigated for a tunable metamaterial. In addition, a considerably high pass of LH peak can be observed or even suddenly destroyed when increasing the thickness of spacer. Moreover, the significant dependence of scattering and effective parameters on the metal thickness is also presented. The existence of LH behavior with low metallic conductivity is taken into account. Above all others, the results can be served as supplementary important information to adjust precisely the effective properties of fishnet structure while avoiding other unexpected impacts.

Acknowledgements. This work is supported by Vietnam Academy of Science and Technology under grant number KHCBVL.01/18-19 and Institute of Physics under grant number ICP.2019.10.

REFERENCES

1. Veselago V. G. - The electrodynamics of substances with simultaneously negative values of ε and μ, Sov. Phys. Usp. **10** (1968) 509.
2. Pendry J. B. - Light runs backwards in time, Phys. World **13** (2000) 27.
3. Smith D. R., Padilla W. J., Vier D. C., Nema-Naser S. C., and Shultz S. - Composite Medium with Simultaneously Negative Permeability and Permittivity, Phys. Rev. Lett. **84** (2000) 4184.
4. Pendry J. B., Holden A. J., Robbin D. J., and Stewart W. J. - Magnetism from Conductors and Enhanced Nonlinear Phenomena, IEEE Trans. Microwave Theory Tech. **47** (1999) 2075.
5. Shelby R. A., Smith D. R., and Shultz S. - Experimental Verification of a Negative Index of Refraction, Science **292** (2001) 77.
6. Drachev V. P., Cai W., Chettiar U., Yuan H.-K., Sarychev A. K., Kildishev A.V., Klimeck G., and Shalaev V. M. - Experimental verification of an optical negative-index material, Laser Phys. Lett. **3** (2006) 49.
7. Dolling G., Wegener M., Soukoulis C. M., and Linden S. - Negative-index metamaterial at 780 nm780 nm wavelength, Opt. Lett. **32** (2007) 53.
8. Guven K., Caliskan M. D., and Ozbay E. - Experimental observation of left-handed transmission in a bilayer metamaterial under normal-to-plane propagation, Opt. Express **14** (2006) 8686.
9. Chen H., Ran L., Huangfu J., Zhang X., Chen K., Grzegorczyk T. M., and Kong J. A. - Left-handed materials composed of only S-shaped resonators, Phys. Rev. E **70** (2004) 057605.
10. Podlovsk V. A., Sarychev A. K., and Ahalaev V. M. - Plasmon modes and negative refraction in metal nanowire composites, Opt. Express **11** (2003) 735.
11. Zhou J., Koschny T., Zhang L., Tuttle G., and Soukoulis C. M. - Experimental demonstration of negative index of refraction, Appl. Phys. Lett. **88** (2006) 221103.
12. Dong Z. G., Lei S. Y., Li Q., Xu M. X., Liu H., Li T., Wang F. M., and Zhu S. N. - Non-left-handed transmission and bianisotropic effect in a π-shaped metallic metamaterial, Phys. Rev. B 75 (2007) 075117.
13. Liu N., Guo H., Fu L., Kaiser S., Scheizer H., and Ceissen H. - Plasmon Hybridization in Stacked Cut-Wire Metamaterials, Adv. Mater. **19** (2007) 3628.
14. Jylha L., Kolmakov I., Maslovski S., and Tretyakov S. - Modeling of isotropic backward-wave materials composed of resonant spheres, J. Appl. Phys. **99** (2006) 043102.
15. Holloway C. L., Keuster E. F., Baker-Jarvis J., and Kabos P. - A double negative (DNG) composite medium composed of magnetodielectric spherical particles embedded in a matrix, IEEE Antennas Propag. Mag. **51** (2003) 2596.
16. Kim J. and Gopinath A. - Simulation of a metamaterial containing cubic high dielectric resonators, Phys. Rev. B 76 (2007) 115126.
17. Xhao H., Zhou J., Zhao Q., Li B., Kang L., and Bai Y. - Magnetotunable left-handed material consisting of yttrium iron garnet slab and metallic wires, Appl. Phys. Lett. 91 (2007) 131107.
18. Chen H. T., Padilla W. J., Zide J. M. O., Bank S. R., Gossard A. C., Taylor A. J., and Avertt R. D. - Ultrafast optical switching of terahertz metamaterials fabricated on ErAs⁄GaAsErAs⁄GaAs nanoisland superlattices, Opt. Lett. **32** (2007) 1620.

19. Landy N. I., Sajuyigbe S., Mock J. J., Smith D. R., and Padilla W. J. - Perfect Metamaterial Absorber, Phys. Rev. Lett. **100** (2008) 207402.
20. Huynh T. V., Tung B. S., Khuyen B. X, Tung. N. S., Lam V. D., and Tung N. T - Controlling the absorption strength in bidirectional terahertz metamaterialabsorbers with patterned graphene, Computational Materials Science **166** (2019) 276.
21. Hien N. T., Le L.N., Trang P. T., Tung B. S., Viet N. D., Duyen P. T., Thang N. M., Viet D. T., Lee Y. P., Lam V. D., And Tung N. T. - Characterizations Of A Thermal Tunable Fishnet Metamaterial At Thz Frequencies, Comp. Mat. Sci. **103** (2015) 189.
22. Kafesaki M., Tsiapa I., Katsarakis N., Koschny T., Soukoulis C. M., and Economou E. N. - Left-handed metamaterials: The fishnet structure and its variations, Phys. Rev. B **75** (2007) 235114.
23. Alici K. B., and Ozbay E. - Characterization and tilted response of a fishnet metamaterial operating at 100 GHz, J. Phys. D: Appl. Phys. **41** (2008) 135011.
24. Hien N. T, Tung B. S., Sen Y., Guy A. E. V, Peter L., Lam V. D., And Ewald J. - Broadband negative refractive index obtained by plasmonic hybridization in metamaterials, Appl. Phys. Lett. **109** (2016) 221902.
25. Tung N. T., Tung B. S., Ewald J., Peter L., And Lam V. D. - Broadband negative permeability using hybridized metamaterials: Characterization, multiple hybridization, and terahertz response, J. Appl. Phys. **116** (2014) 083104.
26. Lam V. D., Kim J. B., Lee S. J., and Lee Y. P. - Left-handed behavior of combined and fishnet structures, J. Appl. Phys. **103** (2008) 033107.
27. Aydin K., Li Z., Sahin L., and Ozbay E. - Negative phase advance in polarization independent, multi-layer negative-index metamaterials, Opt. Express **16** (2008) 8835.
28. Zhou J., Koschny T., Kafesaki M., and Soukoulis C. M. - Size dependence and convergence of the retrieval parameters of metamaterials, Photonics Nanostruct.: Fundam. Appl. **6** (2008) 96.
29. Trang P.T., Nguyen B.H., Tiep D.H., Thuy L.M., Lam V.D., and Tung N. T. - Symmetry-Breaking Metamaterials Enabling Broadband Negative Permeability, Journal Of Electronic Materials **45** (2016) 2547.
30. Chen X., Grzegorczyk T. M., Wu B. I., Pacheco J., Jr., and A. Kong J. - Robust method to retrieve the constitutive effective parameters of metamaterials, Phys. Rev. E **70** (2004) 016608.
31. Sheng Z., and Varadan V. V. - Tuning the effective properties of metamaterials by changing the substrate properties, J. Appl. Phys. **101** (2007) 014909.
32. Singh R., Azad A. K., O’Hara J. F., Taylor A. J., and Zhang W. - Effect of metal permittivity on resonant properties of terahertz metamaterials, Opt. Lett. **33** (2008) 1506.
33. Pendry J. B., Holden A. J., Stewart W. J., and Youngs I. - Extremely Low Frequency Plasmons in Metallic Mesostructures, Phys. Rev. Lett. **76** (1996) 4773.
34. Zhou J., Economon E. N., Koschny T., and Soukoulis C. M. - A unifying approach to left handed material design, Opt. Lett. **31** (2006) 3620.
35. https://chemandy.com/calculators/skin-effect-calculator.htm, 2019.