doi: 10.15407/ujpe62.10.0903

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PACS 41.20.Jb, 42.70.Qs,
73.20.-r, 84.40.Dc,
84.40.-x

LEFT-HANDED METAMATERIAL BASED ON THE COMPLEMENTARY SPLIT-RING RESONATORS TUNED WITH VARACTOR DIODES

The tuning of a left-handed metamaterial based on complementary split-ring resonators loaded with varactor diodes is experimentally studied. The experimental data for this metamaterial are compared with numerical ones. The possibility of the resonant tuning of the metamaterial in the microwave frequency range is experimentally proved. The constitutive parameters of the medium are obtained. The influence of the number of unit cells on the constitutive parameters and the spectral properties of the medium is demonstrated. It is shown that, as the bias voltage increases, the transmittance region shifts to higher frequencies.

Keywords: complementary split-ring resonator, left-handed metamaterial, microwave filter, transmission line.

1. Introduction

In recent years, the artificial planar materials (metamaterials) having simultaneously negative permittivity and permeability, [i.e., left-handed metamaterials (LHM)] are the subject of intense researches. Due to the negative permittivity and permeability, LHM has a negative refractive index with antiparallel phase and group velocities [1–3].

Today, the planar metamaterials attract the interest of researchers [4]. The usage of microstrip transmission lines as a basis for the design of planar LHM makes it possible to use these structures as effective narrow-band or wideband frequency filters. In this case, the microstrip LHM can be formed by combining a periodic array of gaps on the signal conductor microstrip line and arrays of non-magnetic complementary split-ring resonators (CSRR). Complementary split-ring resonators possess the negative effective permittivity in a vicinity of the resonance frequency [5], whereas the gaps provide the effective negative permeability [6].

Such LHM structure was considered in [5], but that work did not study the experimental tuning of the left-handed (LH) region of a metamaterial. This can be done by implementation of a varactor diode, whose capacity depends on the reverse bias voltage [8], into the structure aimed at the experimental tuning of a μ-negative metamaterial.

Thus, the goal of the given work is the experimental study of the tuning of a left-handed metamaterial based on the complementary split-ring resonators loaded with varactor diodes.

2. Experimental Details

The studied structure is fabricated on the basis of a microstrip line and consists of 5 unit cells (Fig. 1). The unit cell sizes are chosen so that its length is by 3–5 times less than the incident wavelength in the frequency range 1–5 GHz. In this frequency range, the varactor diode used for the tuning of the spectral properties works well. Parameters of the structure are the following: the width of a strip equals 1.23 mm, the dielectric constant of the substrate $\varepsilon_r = 3$ (brand Taconic TLC-30), and the height of the substrate is 0.5 mm. On the signal strip, the periodically arranged gaps 0.3 mm in width were made. Onto the ground electrode, the complementary split-rings resonators located under the gaps were made (Fig. 1). The CSRR parameters are: the outer radius $r_1 = 4$ mm, inner radius $r_2 = 3$ mm, the separation of rings $d = 0.3$ mm, and the width of a ring $c = 0.5$ mm (Fig. 1). Varactor diodes (Infineon

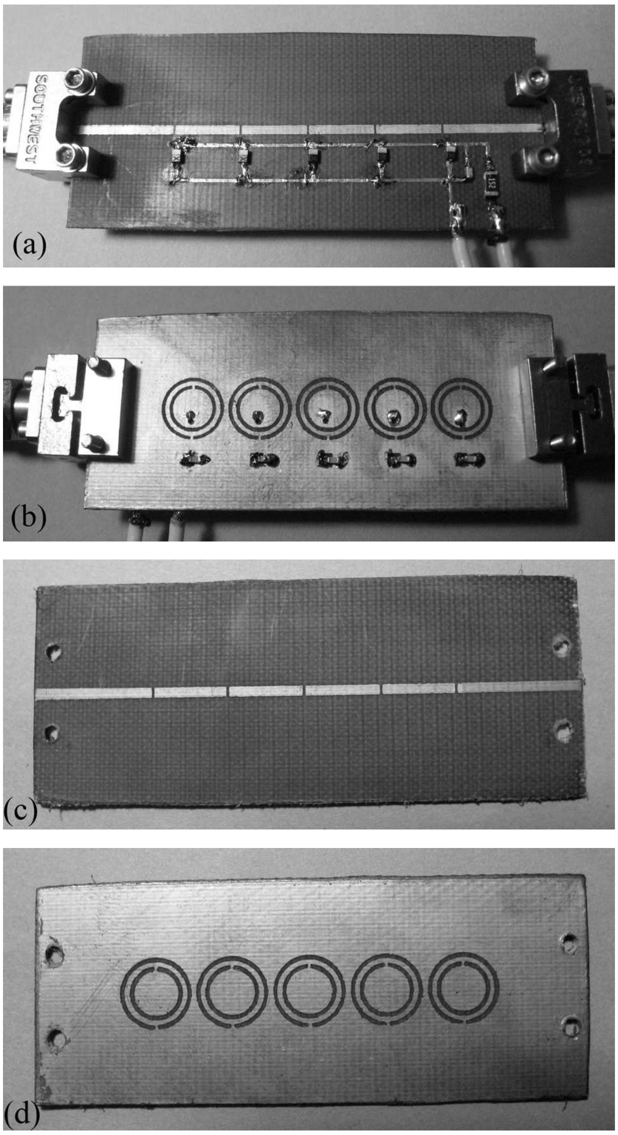

Fig. 1. Photograph of the investigated structures: the top view (*a*, *c*), the bottom view (*b*, *d*)

BB857) are connected with the innermost circle of the CSRR and with the outermost ground plane via an SMD-capacitor (Fig. 1, *a*, *b*).

In addition, another structure was fabricated with the same parameters, but with unloaded varactor diodes (Fig. 1, *c*, *d*).

The detailed description of the experimental technique is presented in [11].

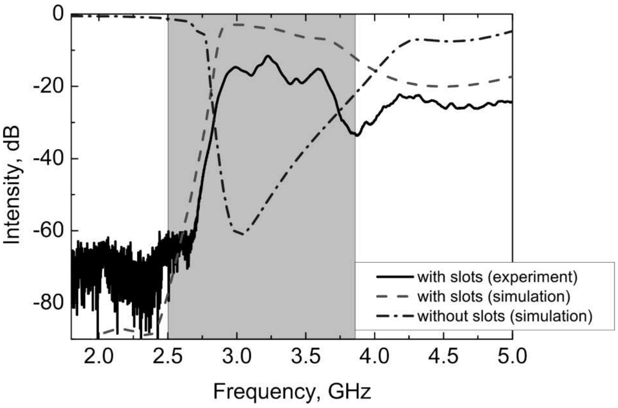

Fig. 2. Dependence of the transmittance for LHM and CSRR cases (experiment and simulation)

Figure 2 shows the transmittance versus the frequency in the absence of varactors on the structure (Fig. 1, *c, d*) for the cases of the structures with and without slots on the signal strip (simulation is shown by the blue dash-dotted and red dashed lines, respectively). It can be seen that, in the frequency range 2.5–3.7 GHz (the gray area in Fig. 2), the structure with slots exhibits the resonant transmission. The simulation is confirmed by experiment (the black solid line). This effect is presumably a consequence of the presence of left-handed properties in the structure. Now, let us prove this assumption.

We use the algorithm for symmetric structures described in [9]. The constitutive parameters of the medium (ϵ, μ, n) for the numerical calculation and the experiment (see Fig. 3) were obtained from the relations [9]

$$n = \frac{1}{kd}\cos^{-1}\left(\frac{1}{2S_{21}}\left(1 - S_{11}^2 + S_{21}^2\right)\right), \tag{1}$$

$$z = \pm\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}}, \tag{2}$$

$$\varepsilon = n/z, \mu = nz, \tag{3}$$

where z is the wave impedance of the medium, n is the refractive index, k is the wave number, S_{11} is the reflection coefficient, S_{21} is the transmission coefficient, and d is the metamaterial layer thickness. The signs in these expressions are selected from conditions $\mathrm{Re}(z) > 0$ and $\mathrm{Im}(n) > 0$.

Here, S-parameters are taken from the simulation and the experiment to calculate n, ε, and μ. All parameters from formulas (1)–(3) are frequency-dependent, except for *d*. *S*-parameters also dependent on the number of unit cells. In the simulation, the losses were not taken into account.

In order to estimate the influence of the number of unit cells (N) on the spectral properties of the metamaterial, the numerical calculation was performed (see Figs. 3 and 4).

Both the *S*-parameters and the retrieved material parameters are presented in Fig. 5. It is seen that, both in calculations and the experiment, the regions with the negative refractive index are presented in the spectrum of the structure. These areas are marked in Fig. 3, *a* and Fig. 3, *c* by a solid hatch ($N = 1$), right hatch ($N = 3$), and left hatch ($N = 5$). This indicates that the structure shows the left-handed behavior in these regions. The regions with the refractive index $n' = 0$ correspond to the case where the electromagnetic wave is damped in the structure.

It is seen that the number of areas with $n' < 0$ increases from one to three with the number of unit cells (Fig. 3, *c*, Fig. 4). Figure 4 shows the dependence of the frequency position of these regions on the number of unit cells in the structure. Figure 4 demonstrates that the widths of the left-handed regions decrease, as the number of elementary cells increases. These areas are marked by dashed lines in Fig. 4.

The comparison of the results of the numerical simulation and the experiment is shown in Fig. 5. The frequency regions, where $n' < 0$, are marked with right hatch (simulation, Fig. 3, *c*) and left hatch (experiment, Fig. 5, *b*). It is seen that there are areas of 2.76–2.80 GHz, 2.94–3.14 GHz, and 3.49–3.73 GHz, in which the experimental data coincide with the results of the numerical simulation. It is also seen that, in the experimental plots (Fig. 5, *a, b*), these areas are considerably narrower than in the numerical simulation. Moreover, the additional area appears in the experiment. This may be due to the fact that the losses in the experiment were significantly higher than in the numerical simulation.

From Fig. 3, *c*, it is seen that, for $N = 3$ and 5, there are the frequency ranges with a continuous transition between the left- and right-handed parts of the spectrum. In these areas, the refractive index changes its sign.

In order to illustrate that structure has left-handed properties, we carried out a numerical calculation of the electric field distribution in the investigated struc-

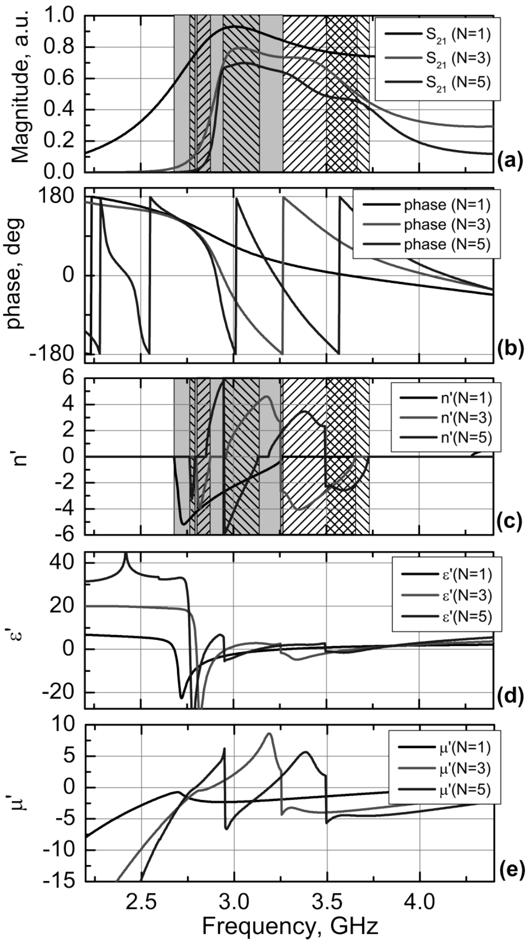

Fig. 3. Magnitude (*a*) and phase (*b*) of the simulated *S*-parameters for the one, three, and five unit cell structures. Retrieved refractive index (*c*), permittivity (*d*), and permeability (*e*) are shown as well

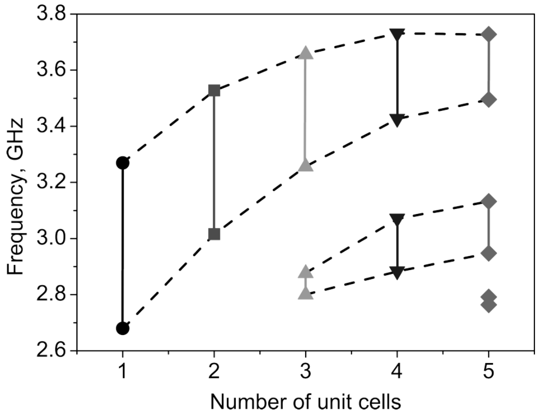

Fig. 4. Dependence of the frequency position of areas, where $n' < 0$, on the number of unit cells

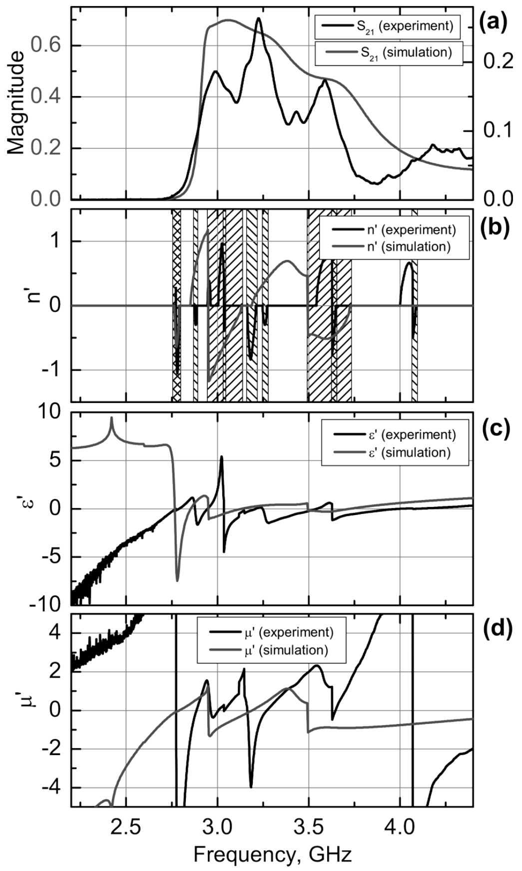

Fig. 5. Magnitude (*a*) of the simulated and measured *S*-parameters for the five unit cell structure. Retrieved refractive index (*b*), permittivity (*c*), and permeability (*d*) are also shown

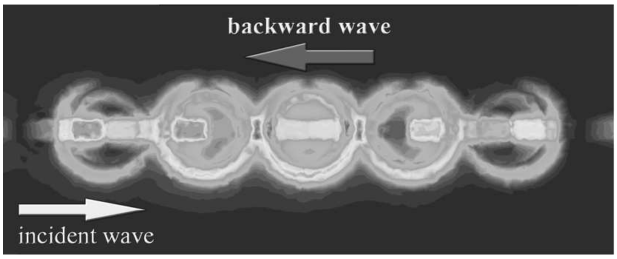

Fig. 6. Electric field distribution $f = 3.6$ GHz (simulation)

ture (5 unit cells) at a frequency of 3.6 GHz. The plane of the cross-section, in which we observe the distribution of the electric field, passes through the center of the structure. Figure 6 shows the presence of the backward wave propagating in the structure.

To analyze the frequency tuning of the structure (Fig. 1, *a, b*), let us consider Fig. 7. Figure 7, *a* shows the dependence of the center frequency shift of the transmittance region (Fig. 7, *b*) on the magnitude of the bias voltage (experiment).

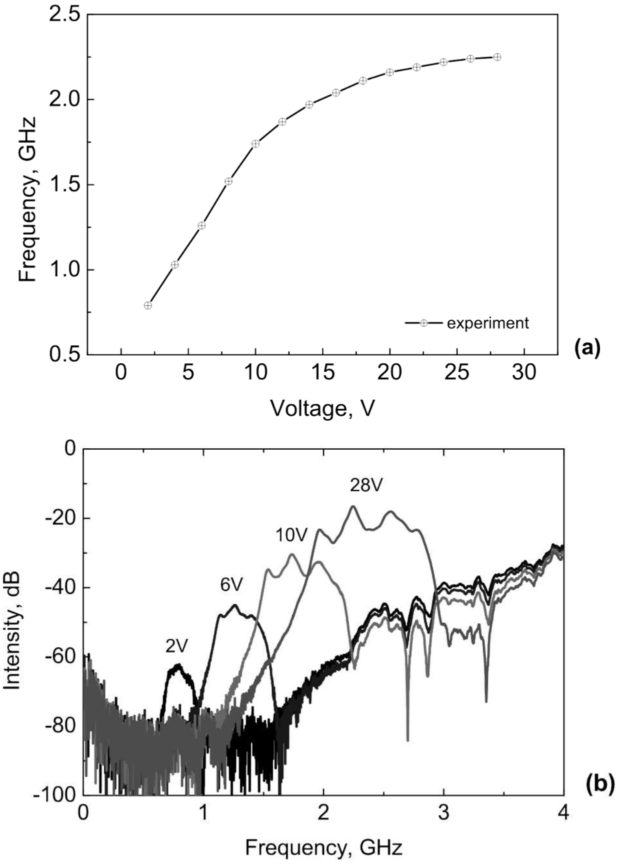

Fig. 7. Dependence of the center frequency of the transmittance region on the bias voltage (*a*), the transmittance versus the frequency on the bias voltage (*b*)

It is seen that, as the bias voltage increases in the interval 2–28 V, the central frequency of the transmittance region shifts to higher frequencies (Fig. 7).

Thus, we summarize:

- the possibility of the resonant tuning the left-handed metamaterial based on complementary splitting resonators loaded with varactor diodes is experimentally demonstrated;
- the qualitative coincidence of the results of numerical calculations and the experiment is obtained;
- as the number of unit cells increases, the number of areas with negative refraction increases as well, but their width decreases;
- it is shown that, as the bias voltage increases, the transmittance region shifts to higher frequencies.

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Received 22.09.16

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ЛІВОБІЧНИЙ МЕТАМАТЕРІАЛ, ПОБУДОВАНИЙ НА ОСНОВІ КОМПЛЕМЕНТАРНИХ КІЛЬЦЕВИХ РЕЗОНАТОРІВ ЗІ ЩІЛИНОЮ ТА КЕРОВАНИЙ ЗА ДОПОМОГОЮ ВАРАКТОРНИХ ДІОДІВ

Резюме

Робота присвячена експериментальному вивченню керування лівобічного метаматеріалу, побудованого на основі комплементарних кільцевих резонаторів зі щілиною та навантажених варакторними діодами. Виконано порівняння розрахункових і експериментальних даних для цього метаматеріалу. Експериментально продемонстровано можливість резонансного керування лівобічним метаматеріалом, побудованим на основі комплементарних кільцевих резонаторів зі щілиною та навантажених варакторними діодами в мікрохвильовому діапазоні частот. Були отримані матеріальні параметри середовища. Показано вплив кількості елементарних комірок на значення матеріальних параметрів та спектральні властивості середовища. Показано, що, коли напруга зсуву збільшується область пропускання зміщується в бік більш високих частот.