APPLIED PHYSICS LETTERS VOLUME 81, NUMBER 23 2 DECEMBER 2002

Losses for microwave transmission in metamaterials for producing left-handed materials: The strip wires

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(Received 25 June 2002; accepted 14 October 2002)

This letter shows that the effective permittivity ϵ for those metamaterials so far used to obtain a left-handed medium, consisting of 0.003 cm thick Cu strip wires, is dominated by the imaginary part of ϵ at 10.6–11.5 GHz frequencies. This is the region of a bandpass filter for microwaves, and therefore there is no propagation since the wave is inhomogeneous inside the medium. We compare with results of Shelby *et al.* [Appl. Phys. Lett. **78**, 489 (2001)], and find that those are in error by ten orders of magnitude of the transmitted power. Also, from finite-difference time-domain calculations using the actual permittivity value of the Cu wires, we demonstrate that when the structure contains thicker wires, the losses are then reduced and the negative part of the permittivity dominates. Since the thickness of the wires is critical for the realization of a good transparent left-handed material, we propose that the strip wires should have thickness of 0.07–0.1 cm and the split ring resonators should be 0.030–0.06 cm thick. © *2002 American Institute of Physics.*
[DOI: 10.1063/1.1527982]

The subject of left-handed materials (LHM) is at present a prominent subject matter of optics and physics, due to the intriguing possibility of performing negative refraction.[1] Both claims using metamaterials[2] and disclaims[3] of observation of a negative refraction index have been reported. The disclaims were based on the fact that losses are high in those structures so far built, and preclude to observe negative refraction. Namely, the electromagnetic waves are inhomogeneous in those metamaterials. Hence, in experiments with a wedge-shaped geometry as performed in Ref. 2, there is a problem of correctly interpreting the transmission measurements due to the nonuniform absorption is such a sample.

This letter is organized as follows: first, we point out an error of ten orders of magnitude in calculations by Shelby *et al.*[4] of the microwave transmitted power in the structure employed in the aforementioned experiment of Ref. 2. As shown next, due to losses this power is much smaller than reported in Ref. 4 and actually below the detection threshold, hence this error questions the significance and validity of the interpretation of negatively refracted signal detection, claimed in the experiment of Ref. 2. Second, we show that the losses in the transmission of waves in metamaterials, critically depend both on the thickness of the metallic wires used and on their permittivity. This is done by performing finite-difference time-domain (FDTD) simulations. We thus observe that by using strip wires thicker (0.07–0.1 cm) than those of the structure employed in Ref. 2 which were 0.003 cm thick, one obtains a negative effective refractive index of the structure. But its losses are much smaller than in the experiment of Ref. 2, hence obtaining a low loss transparent LHM.

Figure 1(a) is taken from Ref. 4 (cf. Fig. 5 in that reference), and shows the microwave transmitted power as a function of frequency for the structure of the experiment of Ref. 2. On the other hand, our calculation for the same structure is shown in Fig. 1(b). A comparison of Figs. 1(a) and 1(b) shows that the result of Ref. 4 is ten orders of magnitude larger than it should be, as we have checked. The calculation of Fig. 1(b) is performed in the effective homogeneous medium appoximation, that the authors of Ref. 4 point out to be valid, (and we agree with this remark). This is done by using Eq. (4) of our previous work.[3] It is seen that the correct result using the permabilities, permittivities, damping constant γ and parameters of Ref. 4, is that of Fig. 1(b). This corrects Fig. 5 of Ref. 4. We also conclude that the value of γ for the permability and the permittivity that sets the attenuation of wave propagation, is not 1 GHz at the bandpass frequencies: 10.6–11.5 GHz of the experiments of Ref. 4 as stated in that reference, where the authors argue:[4] "To match the measured attenuation of the propagation band we set γ=1 GHz, suggesting that this structure has relatively large losses." Figure 1(b) also proves that the correctly calculated transmitted intensities are extremely small, and below the experimental detection threshold (−55 dB). Therefore, this disagreement with the experiments of Ref. 4 forces γ to be much smaller than 1 GHz, reported there.

Interestingly, the same authors state in the letter report-

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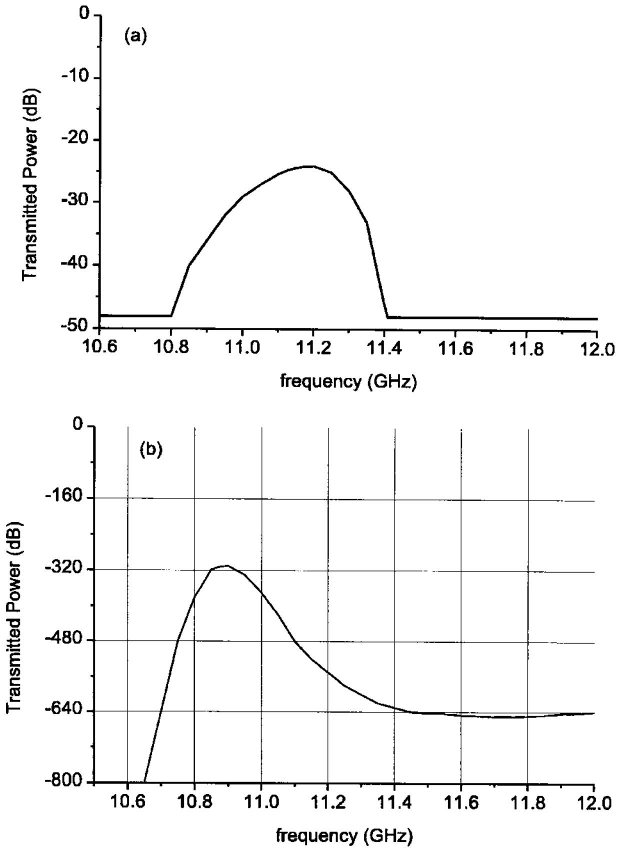

FIG. 1. (a) Calculation of Ref. 4, Fig. 5, using a value of $\gamma=1$ GHz and the homogeneous medium approximation. This result is off by ten orders of magnitude. The correct calculation is presented in Fig. 1(b).

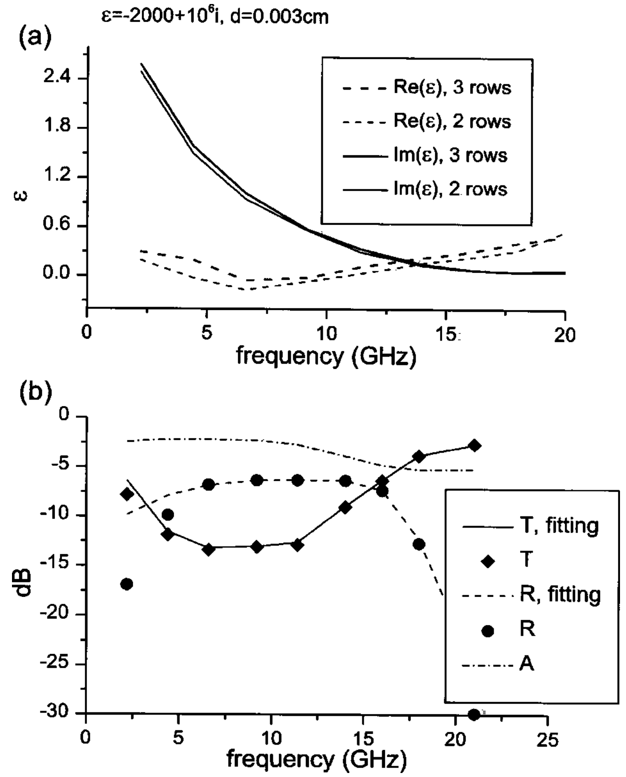

FIG. 2. (a) Real and imaginary parts of the effective permittivity of a squared array of $d=0.003$ cm thick strip wires of Cu as used in the metamaterials of Refs. 2 and 4. The results are practically the same for either two or three rows of wires. The calculation is for *s*-polarization, i.e., the electric field is parallel to the wires. The imaginary part dominates and the real part is practically zero at 11.2 GHz where the experiment shows the bandpass. (b) Shows the FDTD calculations (dots and rhombus) for the reflectivity and transmittivity of the strip wires structure. The lines correspond to the fitting that gives the values of ϵ in Fig. 2(a) using the homogeneous medium approximation.

ing observation of negative refraction,[2] the value: $\gamma=0.01$ GHz. Nonetheless, the metamaterial is the same as in Ref. 4. Then how can a difference exist with a factor of 100 in γ between both publications, the material being the same? Further, in another recent article[5] the same authors claim: $\gamma=2$ GHz from a fitting through transfer matrix method simulations. However, this value does not match the experiments of Ref. 4. Nevertheless, the simulations of Ref. 5 do not have much connection with the experiments of Refs. 2 and 4 because the proper value for the permittivity of copper wires: $-2000+10^6-10^7 i$ is not used in the metamaterial employed in Ref. 5. Neither the proper thickness of the strip wires and the split rings resonators (SRR) of the experiments of Refs. 2 and 4 (0.003 cm) is used in Ref. 5. In fact, due to computation limitations, the value employed in Ref. 5 for the thickness of the SSR is 0.025–0.033 cm (i.e., ten times larger than in Refs. 2 and 4), whereas that of the strip wires is 0.1 cm (30 times larger than in the experiments of Refs. 2 and 4). The same shortcoming mars other proposals of LHM structures (c.f. Ref. 7).

This confusion in the values of the damping constant γ is due to two facts: (i) the expression used for the permittivity in Ref. 4 has nothing to do with reality, and should be ruled out as brilliantly demonstrated in a recent comment by Walser *et al.*[6] and in agreement with our full FDTD calculations for the effective permittivity presented in Fig. 2 of this work, and (ii) estimations done from the wire thickness, indicate that $\gamma\approx 0.2-0.5$ GHz. Thus, for modeling metamaterial structures that behave like a LHM, one should:

(1) study the effective permittivity of the structure as a function of both the frequency and the strip wire thickness;
(2) carry out a similar study for the split ring resonators; and
(3) combine the study for the strip wires and the resonators together.

It should be stressed that the proper permittivity of the metallic elements is required, and not its approximations. We next show how the thickness of the wires is crucial to obtain either a good transparent left-handed material, or a lossy one. In order to calculate the permittivity of the wires we use the FDTD method[8] discretizing the Maxwell equations in time and space. We set periodic boundary conditions at the boundaries along the wave propagation. For the boundaries perpendicular to the propagation first order absorbing Mur's condition were used.[8,9]

Figure 2(a) shows the effective permittivity versus frequency ν of the incident microwave, for an array of copper strip wires ($\epsilon_{\mathrm{Cu}}=-2000+i10^6$) of square section with size 0.003 cm, (size of unit cell 0.5 cm), obtained through an FDTD calculation. This is the size of the strip wires of the experiments of Refs. 2 and 4. As seen, the imaginary part of the effective permittivity ϵ of the structure is positive and up to 1.5 for $v<5$ GHz, and it is about 0.5 near the microwave frequencies of interest around 11 GHz. On the other hand, the real part of ϵ is small and practically zero for ν around 11

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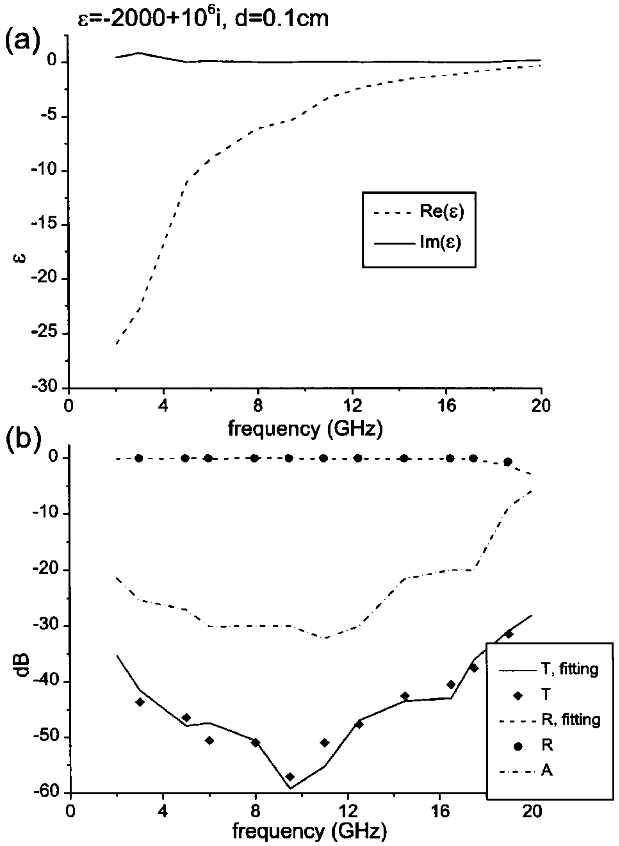

FIG. 3. (a) The same as in Fig. 2(a) for wires $d=0.1$ cm thick. Now the real part is negative and dominates over the imaginary part. Like in Fig. 2(b), the data in Fig. 3(b) are obtained from FDTD calculations by fitting the simulated data (dots and rhombus) to those using the homogeneous approximation.

GHz. So that clearly the imaginary part of the permittivity dominates at 11 GHz, the real part being negligible. So even at 11 GHz the real part of the permittivity is not clearly negative but if any a little positive and therefore the LHM character of the metamaterials is more than dubious even if the imaginary part of the permittivity is neglected.

For three rows of wires of size 0.003 cm, the absorption of the transmitted wave, shown in Fig. 2(b) is rather large for this structure: -5 dB near the frequency of the experiments, whereas at this frequency the transmittivity is -15 dB. As the number of rows increases, the transmittivity decreases. On the other hand, if the thickness of the wires becomes larger, for example 0.1 cm as shown in Fig. 3(a), the effective permittivity ϵ of the structure now has a practically zero imaginary part, whereas its real part is now negative and large. Recent calculations with frequency dependent dielectric constant stress more these points.[10] Accordingly, the corresponding absorption and transmittivity are now -20 and -60 dB, respectively [see Fig. 3(b)]. Note, however, that the important feature in these curves is the absorption distribution, which is large for the thin wires, and small for the thicker wires, as shown by Figs. 2(b) and 3(b). An analogous thing happens for μ which has a negative real part and zero imaginary part for the thicker SSRs. The product $\epsilon\mu$ now results positive and the structure becomes dielectric with low losses.

In other words, in a structure where the imaginary part of ϵ is large, like that with thin wires, the absorption will remain large when the SSR are added to it. The SSRs also being thin, produce an effective permability μ that now has a negative real part and a non-negligible imaginary part. Then the product $\epsilon\mu$ results a complex number with a negative real part and a rather large negative imaginary part. Therefore, the effective refractive index $n=(\epsilon\mu)^{1/2}$ of the whole structure has a large imaginary component. Whereas for the thicker strip wires and thicker SSRs μ has a negative real part and a negligible imaginary part, the resulting structure then having an effective product $\epsilon\mu$ that now is positive, so that the refractive index $n=(\epsilon\mu)^{1/2}$ is a negative real number, the material then behaving like a transparent dielectric.

From all these calculations we infer therefore that, in order to obtain a structure with low absorption and thus a transparent LHM with an effective refractive index that is practically real and negative, one should make an array of SSRs and strip wires whose thickness is between 0.03 and 0.06 cm, (namely, five times thicker than in Refs. 2 and 4 for the SSRs), and between 0.07 and 0.1 cm for the strip wires.

This work has been supported by the Spanish DGICyT.

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