Transmission measurements in wedge-shaped absorbing samples: An experiment for observing negative refraction

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(Received 13 January 2003; published 10 June 2003)

We report on experiments of light transmissivity, at wavelengths of 532 nm and 400 nm, through an Au film with a wedge shape. Our results exhibit a resemblance with those reported for observing negative refraction in proposed left-handed materials. This resemblance is present even though the medium that we used is well known to be right handed with its refractive index, therefore, having a positive real part. Analogous results are obtained with a glass wedge at 320 nm where absorption dominates. The experiment is explained by the wave losses that dominate over propagation, as in the already reported observation of negative refraction in developed metamaterial wedges. We design and propose an experiment with metamaterials by using thicker wires and parallel face slabs, in correspondence with light measurements that we have carried out in positive refractive index samples. This experimental configuration should conclusively determine whether refraction is positive or negative.

DOI: 10.1103/PhysRevE.67.067601 PACS number(s): 42.30.−d, 78.20.Ci, 73.20.Mf, 78.66.Bz

I. INTRODUCTION

Recently, left-handed materials (LHM) [1] have received much attention in connection with electromagnetic wave propagation. Among other effects, these should exhibit refraction at negative angles. Nevertheless, the physics of metamaterials, developed so far to observe a negative refractive index [2], may have some analogies with that of metals. Namely, the proposed metamaterial has permittivity ϵ and permeability μ, with $\mathrm{Re}\,\epsilon<0$ and $\mathrm{Re}\,\mu<0$, which defines a refractive index n with $\mathrm{Re}\,n<0$, where Re denotes the real part. Such a statement of these optical parameters, however, is only meaningful when further specifications are introduced, because if $\mathrm{Re}\,\epsilon<0$ and $\mathrm{Re}\,\mu<0$, the condition of positive energy implies the existence of dispersion. Hence, both the permittivity and the permeability are frequency dependent and contain imaginary parts. As a consequence, the refractive index has an imaginary part $\mathrm{Im}\,n>0$. In these circumstances $\mathrm{Re}\,n$ alone plays no role, since the propagation conditions are determined by the choice of the sign of $\mathrm{Im}\,n$. This sign should be such that the wave dissipates its energy as it propagates [3], thus $\mathrm{Im}\,n>0$. Then, there are modes in the medium, which do not propagate; this is precisely the case for metals. Whether propagation or attenuation dominates in such a medium is determined by the transmissivity, which is, respectively, larger or smaller than $1/e$ when the wave has traversed a distance of several wavelengths. If propagation dominates in a slab, one observes the presence of Fabry-Perot-like oscillations (with a decay smaller than $1/e$), of either the transmissivity or the reflectance versus either the frequency or the slab thickness. This is the case of transparency in dielectrics. The opposite occurs, i.e., no oscillations, when attenuation is dominant.

The idea of negative refraction coming from LHM has attracted the interest of scientists because this may constitute a new area of science with technological applications. This is, however, a complicated territory although it deserves study, especially because new consequences may appear. The experiment done so far, aiming to observe negative refraction, [2] was done in the microwave range (around 1010 Hz), using a wedge-shaped sample of metamaterial. However, measurements were not done in the far zone, and the angles at which the distribution of transmitted intensity was maximum corresponded to the region of the thinnest part of the wedge. The point is that the metamaterial was made up of very thin copper wires (0.003 cm thick) and rings, embedded in a dielectric. In a recent paper, however [4], we have shown that the losses due to such thin wires are large enough to destroy propagation, whereupon only decaying waves exist in the medium (see also Ref. [5]). All these facts make the proof of a negative refractive index in Ref. [2] questionable, and hence necessitate further experiments in which absorption is clearly not dominant and does not act inhomogeneously across the sample, as with a wedge. In addition, to clearly characterize a propagation direction for the refracted beam, transmission measurements should be carried out in the far zone.

To illustrate the problem with a highly absorbing wedged sample as used in Ref. [2], we first present in this paper measurements of the transmissivity of light at wavelengths $\lambda=532$ nm and $\lambda=400$ nm through an Au wedge. We, subsequently, employ a glass wedge at $\lambda=320$ nm. The thickness of the wedge is scaled to the wavelength in the same way as in the LH metamaterial wedge [2]. Our experiment shows that when measurements are recorded at a finite dis-

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tance from the sample, the measured transmitted intensity apparently peaks at negative refraction angles, namely, towards the thinner region of the wedge as in the experiment of Ref. [2], even if the angle of the Au wedge is only 10^{-4} rad. The material is, of course, more transparent in the thinner region. Motivated by these observations, we illustrate an experiment with a parallel face glass sample at $\lambda = 320$ nm, and consequently, propose an equivalent experiment with a metamaterial slab that should determine the sign of the refraction angle, and hence of n.

II. TRANSMISSION MEASUREMENTS WITH A METAL WEDGE

An Au wedge on glass was prepared at NIST. It is 5 mm long, and the thickness varies from 25 nm to 4400 nm, which produces a wedge angle of 10^{-3} rad. Notice that, except for absorption effects, this sample has for all intensive purposes practically parallel faces. It has been built in such a way that it maintains a difference in distance of approximately one wavelength λ between the thicker and the thinner widths. This scales with the experiment of Ref. [2]. The light measurements were performed, in the Laboratorio de Física de Sistemas Pequeños y Nanotecnologia (CSIC), with a streak camera having a slit aperture of 6 mm, which is very convenient in order to pick up the transmitted signal at once through a bunch of optical fibers. The camera is operated in focus mode just as a detector, i.e., without using its time resolution function. The laser beam, whose profile is depicted in Fig. 1(a), and is measured as shown in the upper frame of Fig. 2, has its peak at the center of the wedge faces (shaded central and extreme upper and lower portions represent maximum and minimum intensities, respectively). When light impinges on the wedged sample, it has a maximum intensity at the incident beam center [cf. Fig. 1(a)]. The transmitted beam, however, peaks at $x = 1$ mm [see Fig. 1(b)], as expected from the larger transparency of the Au wedge in its thinner region. Here, absorption is smaller, as is the associated exponential decaying behavior of the wave intensity in the metal. This is confirmed in Fig. 1(c)—where the value of the measured transmissivity T is plotted versus the transversal ordinate X—which shows the typical exponential decay. Experimental agreement with the theory is excellent, while the permittivity e for Au is used [6] at two values of λ (532 nm and 400 nm), thus proving that the sample surface is smooth compared to λ and no scattering effects exist. The sample was checked with a scanning tunnel microscope (STM), which revealed a grain size and corrugation of 40 nm and 10 nm, respectively. Figure 1(b) (left side) shows a sketch of the region where the intensity appears located in X (lower shaded area). The angle θ of the transmitted intensity peak is plotted [cf. right-hand side of Fig. 1(b)] as a function of the distance d between the detector (array of optical fibers) and the sample, and also as a function of the apparent angular width θ_{op} of the detected beam. These two angles are plotted versus d in the right-hand side of Fig. 1(b), utilizing the data of Fig. 2 as shown by the streak camera. In this figure, the panels represent the detected transmitted beam under the following conditions:

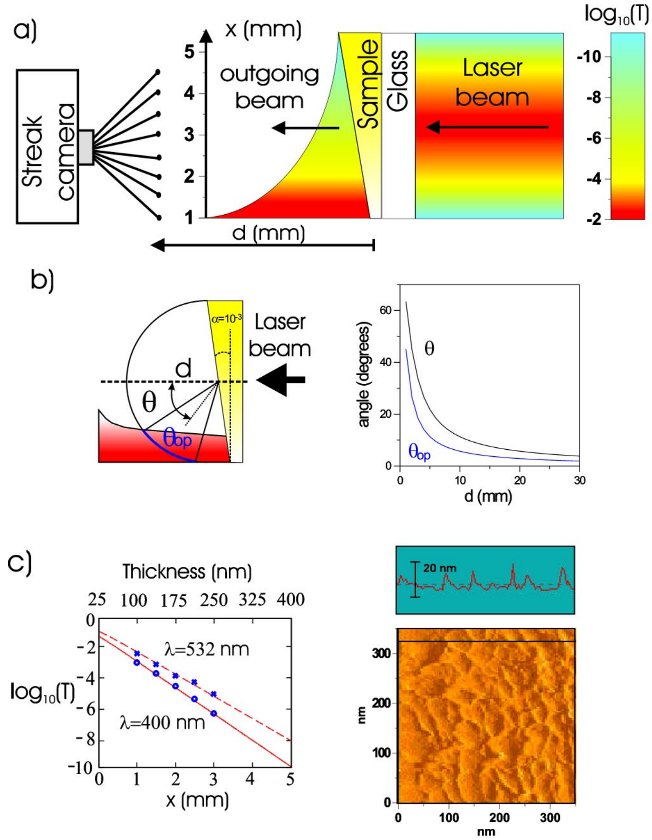

FIG. 1. (a) A sketch of the experimental setup. Due to absorption, an incident beam normal to the wedge sample with maximum intensity at the center of the plate emerges from this sample with an intensity distribution, which is maximum in the thinner region of the wedge. The entire intensity is measured by a bunch of optical fibers focused to the streak camera. The scale bar is for the transmitted intensity, while for the incident intensity the center portion (at the arrow), corresponds to unity. (b) Left side: representation of the configuration with the angles θ and θ_{op}. Note that these angles change with the distance d between detector and sample. Right side: variation with distance d of the angles as measured from the recorded intensity (see Fig. 2). (c) Left: variation of the transmissivity T vs lateral coordinate X (lower abscissa) [cf. (a)], and vs the sample thickness (upper abscissa), showing an exponential decay vs these parameters. Circles and crosses correspond to the experiment, whereas lines represent the theory by using the measured dielectric constants of Ref. [6], showing excellent agreement. There is no scattering in the sample, which indicates the flatness of the Au surface. This is supported by the STM image [(c), right], which shows a grain size of 40 nm and a roughness of 10 nm, both much smaller than λ. Note that the z coordinate of the surface roughness is magnified as indicated by the bar.

without the sample (top panel), and with the sample at the following corresponding distances d from the detector: 0.5, 2.5, 10, 15, and 25 mm. The left panels are a plot of the spatial distribution of intensity detected by the camera along the X-direction, whereas the right panels are the digitized peak data of the left panels along the X direction. As seen, the intensity is very localized at short distances d and slightly spreads as d increases. Figure 1(c) shows $\log_{10} T$ versus X and the corresponding thickness of the Au film traversed by

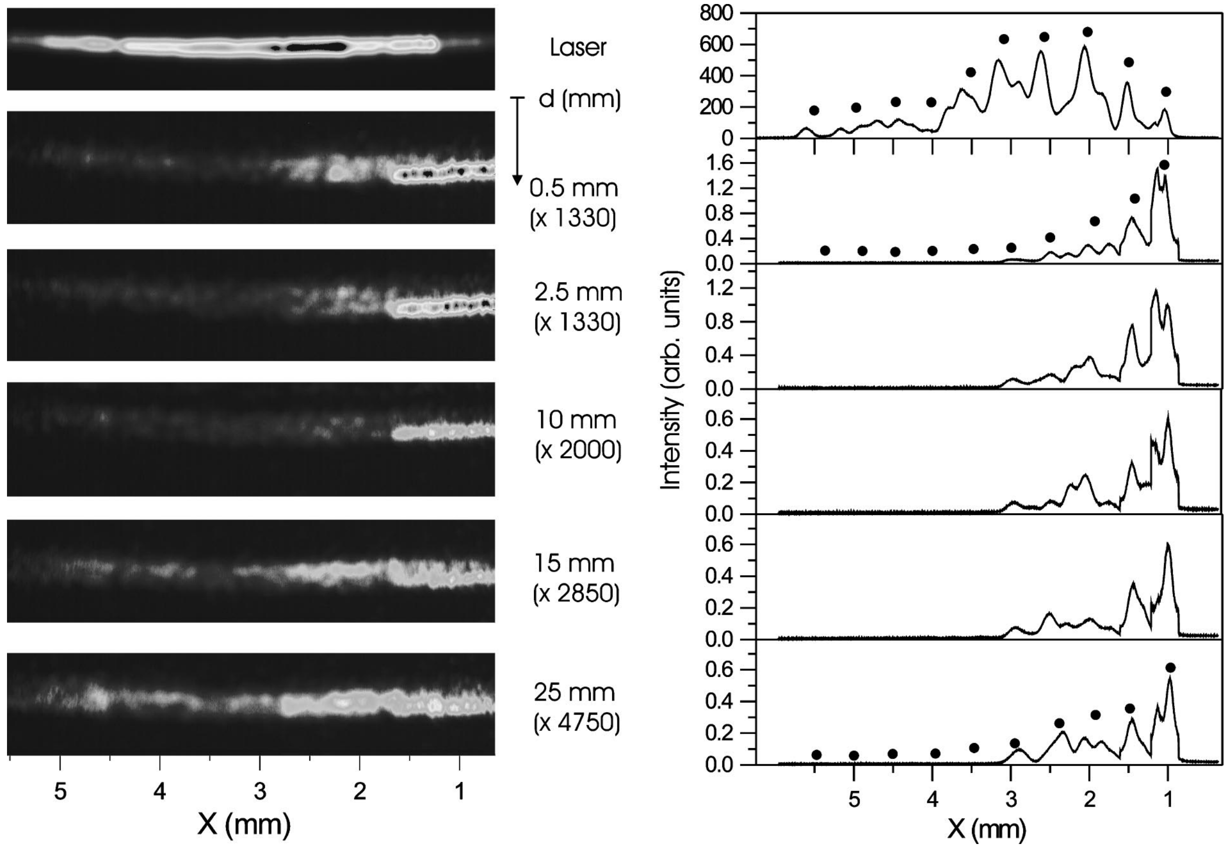

FIG. 2. Left: streak camera measurements as the optical fiber separates from the sample. The top panel is the beam picture without sample. Note that the intensity spreads slowly as d is increased. The numbers at the side scale the intensity. Right: digitized transversal cut of the intensity distributions displayed on the left. The intensities for the sample are normalized to the incident intensity (top panel) and the thick dots represent the position of each fiber [see Fig. 1(a)].

the light. It can be observed that the exponential spatial distribution of intensity, sketched in Fig. 1(a), very accurately corresponds to the measurements of Fig. 1(c).

This experiment with the Au wedge exhibits an analogy with the one performed in Ref. [2] to prove the negative refraction. The results of both experiments agree in scale according to their respective wavelengths: visible light for Au and microwaves for the metamaterial. In the case of Au apparent negative refraction appears at finite distances because the wedge angle is only 10^{-3} rad. We even measured the apparent angle of refraction at $-70°$ when the detector is near the sample, if this angle is taken at a finite distance d as in Ref. [1], and as illustrated in Fig. 1(b). Note that in the metamaterial experiment [2], the detector is located at 15 cm from the sample. This, however, is not a far-field condition for $\lambda = 3$ cm. It is evident, furthermore, that θ is not the appropriate angle of refraction. This should be considered between the surface normal and the axis of the emerging beam, and not between the surface normal and the position vector of the detection point as in Ref. [2] and as illustrated in Fig. 1(a). As stated, this effect is due to a combination of the wedge shape of the sample and the absorption represented by the imaginary part of ϵ in the case of gold, and of both μ and ϵ in the case of the metamaterial dealt with in Ref. 2. We, therefore, believe that due to this absorption effect, it is impossible to determine whether the sample is left handed or right handed, and thus whether refraction is negative or positive in a wedge-shaped geometry. In addition, we note that Au for the frequencies at hand is highly dispersive. Dispersion, however, does not play a role in explaining the experiments. The explanation comes from an absorbing effect, not from dispersion [3,7].

So far we have discussed the experiments in metamaterials using strip radii 0.003 cm thick [8]. In this case the losses are important, although these may be reduced by increasing the radius size by a factor 10–20 because these losses are inversely proportional to the wire radius [9]. Our finite-difference time-domain simulations show that for a thin radius of 0.003 cm for the copper strip wires, using a permittivity between $\epsilon = -1000 + i106$ and $\epsilon = -2000 + i107$, as given by textbooks and experiments [3,6,7], loss of transmission at each metallic element dominates. If, on the other hand, the radius of the copper wires is approximately between 0.03 cm and 0.05 cm, the effective losses in the whole sample are much reduced because then reflection with very little loss at each metallic element is dominant. Therefore, experiments aiming to observe a negative refractive index should be carried out with thicker wire metamaterials and slab samples in the configuration that we propose next.

III. AN EXPERIMENT TO UNAMBIGUOUSLY OBSERVE NEGATIVE REFRACTION

There is a way to avoid the aforementioned inhomogeneous absorption problems produced by a wedge, and to check the sign of the refraction angle in a proposed metamaterial, as well as in any other composite material that can be produced with magnetic elements near the ferromagnetic resonance. For this case we have designed, and hereby propose the following experiment depicted in Fig. 3. It consists of measuring the beam displacement ΔX due to the refraction of the beam at both faces of a slab of parallel faces, as it traverses the medium, with the incident beam impinging at an angle θ_1.

We have performed this experiment for a glass plate at 320 nm using the streak camera, and have measured the displacement ΔX_{exp}, which is in excellent agreement with the theoretical displacement ΔX_{cal} (see Fig. 3, upper panel). We propose the same kind of experiment to verify a negative refractive index (see the lower panel of Fig. 3). The displacement provoked by negative refraction should be larger than the displacement by a factor $2b \tan \theta_2$, due to positive refraction. For example, for $b = \lambda = 3$ cm and $\mathrm{Re}\, n = -1$, the transmissivity decays to 10^{-2} of its incident value and we obtain that $\Delta X_{cal} = 10.30$ cm; which is a displacement clearly observable.

We believe that this constitutes a way to unambiguously assess LHM in the microwave region where losses will appear, as in metamaterials and other media that may have a negative permeability by means of metallic magnetic grains or wires, immersed in a dielectric matrix. The reason is that even if the losses are important, with such a configuration they will be uniform in all cross sections of the slab traversed by the wave, i.e., they will not vary along the x direction of the sample.

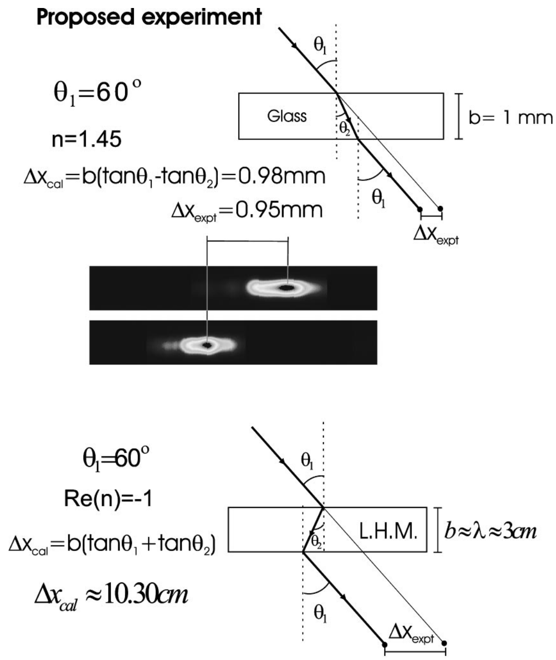

FIG. 3. Proposed experiment. Top panel: scheme for the experimental displacement measured in the streak camera with the parameters as indicated. Lower panel: the proposed experiment for a LHM in order to observe a negative refraction index. Note that the beam displacement is much larger for the LHM in the microwave region than for a glass slab in the visible region.

ACKNOWLEDGMENTS

We thank M. Muñoz, E. Ponizowskaya, and C. Guerrero for their valuable help. This work has been supported by the Spanish DGICyT.

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