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Novel concepts of negative-*n* optics in master's level educational courses

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Abstract. The novel ideas of negative refraction index (*n*) optics suitable for teaching special courses in universities at master's level are systematized and analyzed. The most important innovative ideas in this field are recounted in the logical order necessary for achieving the best understanding of the material. They are: the opposite signs of phase and group velocities of light; the change of the ordered right-hand triad of vectors **E**, **B** and **V** from the right-handed to the left-handed one; the change of the sign of the Doppler effect; the bent of the incident light, when entering the negative n material, in the "wrong" direction; the emergence of new class of materials – artificial metamaterials that have negative n; current state of the search for possibilities to achieve invisibility.

Keywords: negative refraction index, metamaterial, invisibility..

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1. Introduction

Nano-physics and nanomaterials are a rapidly developing area of knowledge. With the emergence of this vast field many conventional concepts are revised and new approaches in various fields of physics appear. Opening new fascinating horizons in physics leads to the necessity of changing the tuition programs, and, especially, the special courses at graduate students level. Among the impressive new effects that have already gained recognition of public, the most spectacular are the phenomena observed in the newly-constructed class of metamaterials. These materials were purposely developed to achieve the naturally non-existing property of refractive media – negative refraction index. After the first reports on fabrication of the materials with negative refraction index, predictions of the theory of negative-*n* media (which was seemingly far from reality) were verified. The coincidence of the experimental results obtained with the predictions of the theory that at the time of its appearance looked like a game of mind proves the power of purely mathematical approaches and is favorable for the development of student's thinking flexibility.

The development of new revolutionary concepts in optics goes back to 1967 when Viktor Veselago published the paper [1] with the detailed analysis of electrodynamics of light propagation in hypothetic media that are characterized by negative *n*. At that time, this paper sounded as a mere theoretical curiosity. In the assumption of the existence of negative-*n* materials Veselago predicted that light would behave in ways not found in nature and many of generally assumed and convenient properties of optical systems would be altered. In the 70-s of the previous century, there were no ways for experimental verification of this theory, because none of known natural materials has the required properties. Moreover, at that time physicists were not sure whether the existence of materials with both negative ε and μ is forbidden because of first principles or not.

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This obstacle has been overcome almost 30 years later when a group of scientists reported on the fabrication of a hybrid system, a metamaterial, that met the demands [2].

Thus, the new field of optics had proven its viability and got being known far beyond the society of physicists, therefore, at present there is an urgent need to develop new instructional approaches that would prepare the students for perception of altered physical concepts. In what follows, we propose the sketch of graduate–level instruction in introducing novel concepts based on negative index of refraction.

2. Basic concepts of wave optics in negative-*n* media

Originally the source for the revision of basic concepts in optics lies in the relation between the refractive index of a medium and its fundamental properties – electrical permittivity and magnetic permeability. As this relation is $n^2 = \varepsilon\mu$ or $n = (\varepsilon\mu)^{1/2}$, the value of refractive index must not change after reverse of signs for both ε and μ. Veselago started to explore possible changes of electrodynamical consequences with the analysis of Maxwell equations. In these equations, the values ε and μ are present not as a product but separately, thus their sign is of importance. In the assumption that $\varepsilon < 0$ and $\mu < 0$, Veselago got the following conclusions.

For propagation of a monochromatic plane wave, he found that, on the contrary to the conventional case of positive *n* when the triad of vectors **k**, **E** and **H** is right-handed, the corresponding triad in the negative-*n* media has to be a left-handed one. However, the direction of the Pointing vector $\mathbf{S} = c/4\pi\,[\mathbf{E}, \mathbf{H}]$ turned out to be independent of the sign of *n*. Physically, it means that the phase and group velocities of light have opposite signs. In other words, the wave fronts of a wave travel in one direction, while the energy of this wave propagates in the opposite direction.

This consequence immediately leads to another exotic conclusion: the sign of Doppler shift depends on sign of refractive index. In negative-*n* materials, the waves of a source that moves away from the observer are registered as the ones having shorter wavelengths, while in the materials with $n > 0$ the wavelengths become longer. Similarly, in the materials with $n > 0$ the Vavilov–Cherenkov effect will also be inversed.

3. Basic concepts of ray optics in negative-*n* media

One of the most difficult tasks that has to be addressed while preparing a modern ray optics course narrative is to achieve understanding of rays propagation in the negative-*n* materials. This concept in particular leads to a cognitive dissonance in light of unexpected visualization of Snell's law as compared to that known by students since high school. Detailed explanation of each effect caused by newly learned concept of negative index of refraction necessitates thorough re-analysis of many well-known effects and devices.

Snell's law for negative-n materials [1, 4]. The very first concepts of optics that are studied in the school are the concepts of geometrical optics or ray optics, which describe propagation of light in terms of rays. The simplicity and obviousness of the ray optics laws, such as law of reflection and law of refraction (Snell's law) makes them easy for understanding and memorizing. While studying the latter law, the value named the refractive index (or index of refraction), *n*, has been introduced. It determines how much the light beam is bent, or refracted, when crossing an interface between two different materials. The mathematical formulation of Snell's law is $n_1 \sin\theta_1 = n_2 \sin\theta_2$, where θ_1 and θ_2 are the angles of incidence and refraction, respectively, of a ray crossing the interface between two materials with refractive indices n_1 and n_2. The refractive index is used to represent the factor by which the velocity of light is reduced when traveling through a refractive medium with respect to its value in vacuum: the velocity of light in a medium is $V = c/n$, where *c* is the speed of light in vacuum. The traditional illustration of Snell's law known from school is shown in Fig. 1a. Note that at school level, the students are taught to use only the positive value *n* which is, as it was shown by Veselago, not obvious *a priori*.

More strict approach to refraction index interpretation that implies to the hypothetic possibility of negative sign of the refraction index (in accordance with the possibility of the negative sign of square root $(\varepsilon\mu)^{1/2}$) leads to refracting light in a way that light *is not* normally refracted in nature. A beam incident on a material with negative *n* from a material with positive *n* refracts to the same side of the normal as the incident ray. This situation is illustrated by Fig. 1b. It shows that the light beam in the medium with negative *n* is deflected in the "wrong" direction (from the conventional point of view). Thus, the unshakable conviction of students about the direction of light that was gained during previous studies must be revised. However, it should be stressed that Snell's law is not violated. Indeed, the change of the sign of refraction index leads merely to the change of sign of the angle of refraction.

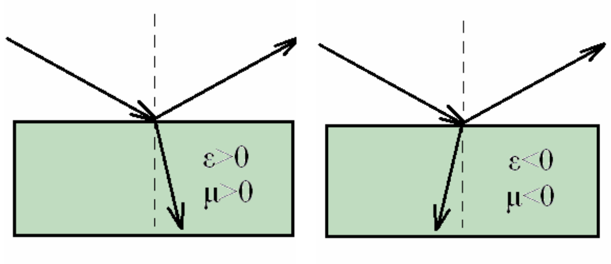

Fig. 1. The beam path at the refraction on the boundary of vacuum and medium with the refractive index *n*. a) The refractive index of the medium is positive. b) The refractive index of the medium is negative. *1* – incident beam; *2* – reflected beam, *3* – refracted beam at $n > 0$; *4* – refracted beam at $n < 0$.

Changes in lenses properties. One more conviction of students has to be ruined when teaching negative-*n* optics. While the biconvex lens (or plano-convex) made of positive-*n* material is positive or converging lens, the same type of lens made of negative-*n* material is negative or diverging. The collimated parallel beam passing through this lens will be diverged (spread). And *vice versa*, the light passing through the biconcave or plano-concave lens made of negative-*n* material converges to a spot (a *focus*). Thus, the lens is a positive or converging lens.

Flat quasi-lens [5]. Due to different refraction, a flat parallel slab of the material with negative *n* can exhibit "focusing" properties, which also contradicts to everyday experience of students. It can be shown that the rays from a point source impinging on a flat, parallel slab of negative-*n* material would be refocused to a point on the opposite side of the material. The condition of this refocusing is that the width of the slab is larger than the distance between the source and the slab. Fig. 2 illustrates the beams passing the parallel slabs of positive-*n* (a) and negative-*n* (b) materials. Despite certain similarity with action of the lens (the possibility to focus light from a point source) the slab of negative n material is not able to focus parallel beam of light into point, thus it is named quasi-lens. Another name of this device is a super-lens or perfect lens, because it transforms 3D object into 3D image without distortions and overcomes the diffraction limit (i.e. there are no losses of evanescent waves).

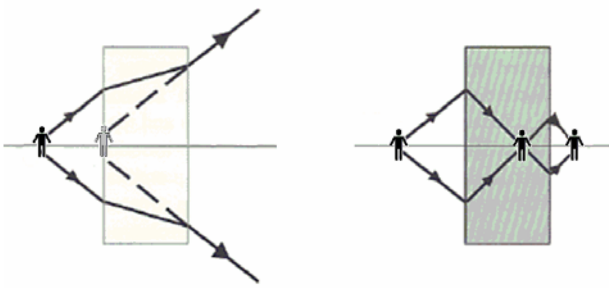

Fig. 2. The beams passing through the parallel slabs of positive-*n* (a) and negative-*n* (b) materials.

4. Metamaterials – artificial materials with negative *n*: basic ideas and realization

As it was mentioned above, none of the naturally existing materials has negative refraction index. In the Table, signs of the electrical permittivity and magnetic permeability of all natural materials are systematized (rows 1-3). The row 4 of this Table corresponds to the artificial materials that will be discussed below. All these materials can be distinguished in accordance with specific features of their reflectance and refraction. Fig. 3 demonstrates interaction of the incident light beam with the materials with varied signs of ε and μ.

In view of the absence of natural materials with negative *n* (in other words, with simultaneously negative electrical permittivity and magnetic permeability) and in order to bring to life the promising predictions of negative-*n* optics, the new class of materials has been developed. These materials have diverse notifications. Mostly, they are named metamaterials because they are not the convenient materials built of atoms and molecules, instead, they are constructed of tiny elements fabricated by modern nano-technologies. Another name of these materials is negative refraction index materials in accordance with the main property of interest. One can also find the name left-handed materials because of different orientation of **E**, **H** and **k** vectors in the triad. One more name is backward wave media, which is caused by the unusual direction of phase velocity – in the opposite direction to the energy propagation. Thus, all these new terms and concepts should be elucidated for students and deserve including to the special courses of master's level, keeping in mind that all these names are used in accordance with the focus of corresponding discussion. Hereafter, we will use the name metamaterials.

The fundamental idea of creating negative-*n* materials was the construction of such a hybrid system that would combine the elements responsible for negative electrical permittivity and negative magnetic permeability. The first success was achieved by the authors of [2], who have assembled arrays of tiny components.

Table.

Name of material	Electrical permittivity ε	Magnetic permeability μ	Naturally existing materials
Right-handed material (the name appeared after the introduction of the term left-handed materials)	$\varepsilon > 0$	$\mu > 0$,	Usual dielectrics, ferroelectrics
No special name	$\varepsilon < 0$	$\mu > 0$,	Plasmas: – electronic plasma in metals, – ionic plasma in ionosphere
No special name	$\varepsilon > 0$	$\mu < 0$	No isotropic material exist with μ<0 Anisotropic ferromagnets in magnetic field can exhibitμ<0
Left-handed material	$\varepsilon < 0$	$\mu < 0$	Only artificial metamaterials

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They were the metallic rods, which were responsible for $\varepsilon < 0$, and split-ring resonators, which provided $\mu < 0$. These components must be of subwavelength size, therefore, the first metamaterial worked at microwave frequencies. More modern metamaterials are the nanostructured artificial media with specific building blocks. Fabrication of these structures poses a big challenge because of rather high resolution demands: the shorter the wavelength, the higher spatial resolution [6]. High reproducibility of the building blocks geometry and composition is also of great importance.

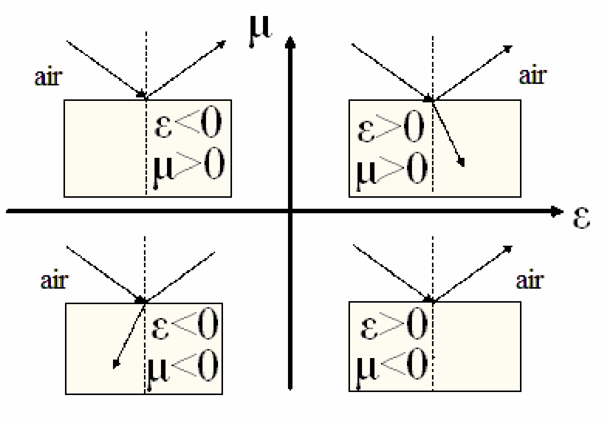

Fig. 3. Light reflection and refraction in the materials with notified ε and μ signs at the boundary with air.

5. Invisibility or electromagnetic cloaking

One of the most thrilling perspectives of negative-*n* optics is the possibility to achieve invisibility, thus it deserves a separate paragraph. Invisibility that for centuries and centuries has been a subject of fairy tales comes to the scene due to the emergence of nanotechnologies that make it possible to produce the materials with negative *n*. Up to now, real invisibility was associated either with absolute transparency or with mimicry (like that observed for chameleon or certain species of bottom-dwelling fishes that are champions of camouflage). The fictitious artifacts, like Harry Potter's cloak, were supposed just to provide visual disappearance of an object. Regardless fairy tales, what would be the demands to a possible device that could ensure invisibility of a macroscopic object? This device must have the following characteristics: it must neither reflect nor scatter the incident light, it must not produce a shadow, and, naturally, it must not absorb the light. That is, this device must not perturb the electromagnetic field around the object. Obviously, all these demands can be fulfilled only in a limited spectral range. And, naturally, the most appealing is the visible range. The devices for gaining invisibility are built of novel metamaterials. In them, an object is hidden inside a hollow surrounded by a metamaterial (a metamaterial cloak). This coverage works by bending the light around an object in the way shown in Fig. 4b. Scattering of light by the same object without coverage is shown for comparison in Fig. 4a. It is obvious that this type of invisibility differs from that used in Stealth technology, because its aim is not to prevent reflection of electromagnetic waves. Review of current experimental state-of-the-art of simple core–shell invisibility cloaking can be found in [7]. It should be noted that modern technologies provide the possibility to construct artificial materials with regulated values of ε and μ (positive as well as negative). However, the metamaterials are not ideal media, they absorb light thus the presence of an object can cast weak shadows; thus, the cloaking performance degrades with increasing optical losses.

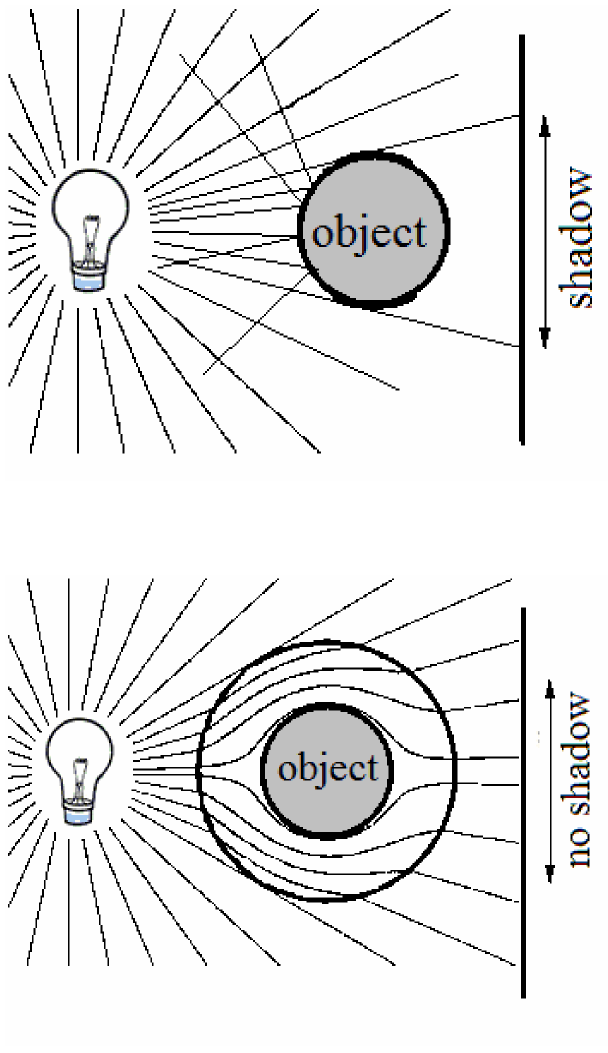

Fig. 4. Light scattering by an object (a) and invisibility (b) gained due to propagation of light inside the coverage made of metamaterial.

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6. Conclusions

In summary, the present paper is a brief overview of new fundamental concepts and ideas that appeared in physics with the emergence of the new vast field – the optics of negative-*n* materials. The most important innovative ideas in this field are intuitively controversial to the well-established concepts of conventional physics. By mastering these new non-trivial phenomena, the students get deeper insight into the nature of light and its interaction with refracting media. New tuition material has to be communicated in a such way that it increases elucidation and is built on simple concepts, steadily increasing the degree of difficulty when letting new concepts settle in students memory. Students need to grasp that the group velocity direction is opposite to phase velocity direction, that **E**, **H** and **k**-vectors follow left-hand screw rule instead of right-hand, that Doppler effect acquires negative sign, *etc*. The special appeal of the course is achieving of understanding of invisibility (or electromagnetic cloaking) that causes acute interest and promises attractive applications. This interest stimulates learning the basics of nanotechnologies that are the only known interest to produce the materials with negative *n* (metamaterials). The revolutionary ideas of building the materials that never existed before facilitate broadening of the horizons of comprehension of physics and optics, in particular.

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