The left hand of brightness: past, present and future of negative index materials

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Recent advances have brought negative index materials and their fascinating properties from their theoretical origins into the domain of experimental physics and device engineering.

The resolving power of conventional optical systems is generally limited by the wavelength of light, which prevents imaging of subwavelength structures. However, in 2000 John Pendry proposed[1] that systems having a negative refractive index can produce sharper images, with a potential to resolve subwavelength features. Although such materials (originally named 'left-handed', but are now more often referred to as 'negative index materials', or NIMs) were first considered by Victor Veselago in 1967 (ref. 2), their recently added potential for subwavelength imaging led to an enormous interest in their properties — which for the last eight years followed an effective 'Moore's Law', where the number of papers in this area doubled every ten months (Fig. 1a).

Pendry's proposal for the 'superlens' generated some initial controversy that was soon resolved by David Smith and colleagues[3] with the first fabrication of a material with a negative refractive index and the demonstration of negative refraction. The race for the optical NIMs was on, and virtually every year saw a decrease of the operating wavelength where a negative index was observed — from centimetres in 2000 to infrared wavelengths in 2005 (refs 4–6). At longer wavelengths, NIMs have already found applications in reflectors and radio-antennas[7] as well as in magnetic resonance imaging (MRI)[8].

WHAT MAKES A NEGATIVE INDEX OF REFRACTION?

The negative sign of the refractive index naturally arises in the theoretical description of the electromagnetic properties of materials with simultaneously negative values of dielectric permittivity ε and magnetic permeability μ. A negative refractive index means that the phase velocity v_{ph} of a propagating wave, which describes the propagation of individual wave fronts in a wave group, is opposite to the movement of the energy flux of the wave, represented by the Poynting vector. The somewhat counterintuitive antiparallel propagation is essentially the definition of a negative index material[2], and leads to a variety of intriguing effects.

As the velocity of a wave group v_{gr} is typically (although not always) the same as the direction of the Poynting vector, in a NIM the group and phase velocities are antiparallel. This criterion should however be applied with caution, as strong dispersion and losses in a material can lead to a perceived negative group velocity in a positive index material[9] and to group and phase velocities in a negative refractive index system that are both negative[6].

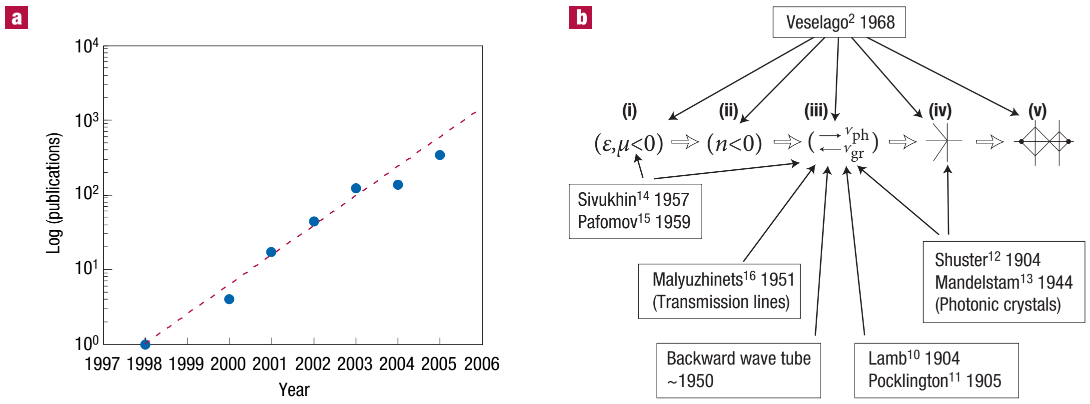

Figure 1 **The history of negative refraction.** a, **The number of research articles on negative index materials and negative refraction (in logarithmic scale).** b, **The 'logical diagram' connecting the different attributes of the concept of a negative index of refraction. The icons in the middle row represent from left to right (i) the concept of materials with simultaneously negative values of dielectric permittivity and magnetic permeability; (ii) the concept of negative index of refraction; (iii) the concept of 'backwards wave'; (iv) the phenomenon of negative refraction, and (v) the planar quasi-lens.**

A wave with the phase velocity opposite to the direction of energy flow is also sometimes referred to as a 'backwards wave'. In our view, the term 'negative phase velocity' is more appropriate in this case (assuming that the energy flux away from the source of radiation determines the 'positive' direction).

In a NIM, the negative phase velocity has direct implications on the refraction of a light beam at the boundary of two media. Whereas in the ordinary case, the refracted ray follows the regular path and propagates on the other side of the normal perpendicular to the surface (Fig. 2a), in the case where one of the media is a NIM, the refracted ray undergoes 'negative refraction' and both beams stay on the same side of the normal (Fig. 2b).

Note that regardless of the signs of ε and μ, the fundamental Maxwell's equations, and their corresponding boundary conditions for refraction of light, can be formally satisfied by both positive and negative refraction solutions. The appropriate solution is only selected by the additional requirement that in the refracted beam the energy flows away from the interface. In the regular material, this corresponds to the normal refraction, whereas for the negative index media the solution of Maxwell's equations must be chosen such that it leads to negative refraction.

The physical picture described above was introduced by Victor Veselago[2] in his 1967 work, along with the concept of 'left-handed materials' and related phenomena. However, some of its elements find their origins in the beginning of the twentieth century.

THE ROOTS OF NEGATIVE INDEX MATERIALS

Perhaps the first step towards the concept of negative index materials was taken by Horace Lamb[10] in 1904, and then Henry Pocklington[11] in 1905, when they pointed out that mechanical systems (such as certain suspended loaded chains) can have the phase and the group velocities in the opposite direction. Arthur Schuster showed that this behaviour could also be realized in optical systems[12]. It seems that he also understood the resulting negative refraction in such cases. However, it took 40 more years until Leonid Mandelshtam described negative refraction in reasonable detail[13], and concluded that "as unfamiliar as this construction may be, there is, of course, nothing surprising about it".

The fact that simultaneously negative values of ε and μ lead to an antiparallel propagation of energy flux and phase velocity was first noticed by Dmitriy Sivukhin[14] in 1957 (who also pointed out that "media with $\varepsilon < 0$ and $\mu < 0$ are not known; whether they exist is not clear"), and studied in more detail by Pafomov[15] who considered the Cherenkov effect in materials with negative permeabilities.

Note that the one-dimensional analogue of a negative index system where the phase velocity is opposite to the direction of energy flow has not only been well known since the 1950s, but also widely used in vacuum electronics under the name of 'backwards wave tube'. A similar phenomenon can also be observed in radio-frequency transmission lines, as pointed out by Georgiy Malyuzhinets in 1951 (ref. 16).

NATURAL MATERIALS, PHOTONIC CRYSTALS AND METAMATERIALS

For a uniform and isotropic material, the only way to achieve a negative index of refraction is to have simultaneously negative values of dielectric permittivity and magnetic permeability. However, negative refraction encompasses a much broader range of phenomena, and can be achieved in a variety of physical settings.

In particular, it is well known that a simple dielectric anisotropy in birefringent crystals is sufficient to experience negative refraction at some angles of incidence[17]. When such behaviour is desired for all incidence angles, a strong anisotropy of the material — where the electrical permittivity transverse to the surface is negative, while the in-plane component remains positive — is sufficient (Fig. 2c,d)[18]. Note, however, that the phase velocity here remains positive, that is, in the direction of the energy flow. Nevertheless, in systems of reduced dimensionality (such as in a waveguide geometry) a dielectric anisotropy is sufficient to develop the full analogue of a negative index material — with both negative refraction for all angles and the phase velocity opposite to the energy flow[19].

Parameters such as the refractive index represent the response of the medium averaged on a scale

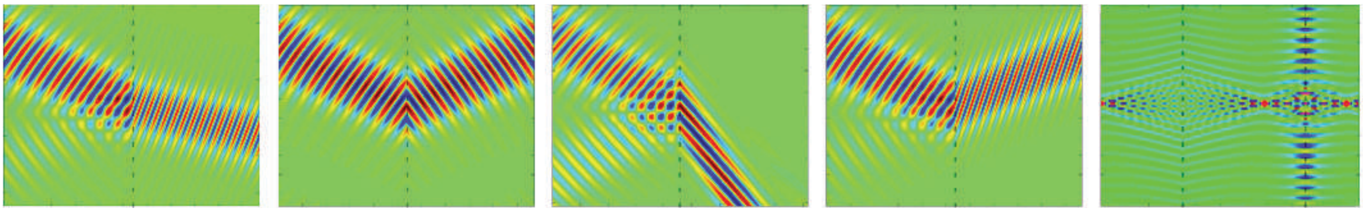

Figure 2 **Different forms of negative refraction. The electric field is shown in false colour, where red corresponds to positive values, blue to negative values and green to zero.** a,b, **As opposed to the standard 'positive' refraction at the boundary of a dielectric** (a), **a beam of light incident on the surface of a material with simultaneously negative dielectric permittivity ε and magnetic permeability μ undergoes negative refraction** (b). c,d, **Negative refraction can be also observed at the surface of a non-magnetic ($\mu \equiv 1$) material with strong dielectric anisotropy — but with a quirk. As opposed to isotropic negative index materials where both the 'beam' and the 'wavefronts' simultaneously show negative refraction** (b), **here negative refraction of the wavefronts is accompanied by the positive refraction of the beam** (c) **— whereas negative refraction of the beam is accompanied by the positive refraction of the wavefronts** (d). **Case** c **corresponds to $\varepsilon_{\perp} > 0$, $\varepsilon_{||} < 0$, whereas** d **corresponds to $\varepsilon_{\perp} > 0$, $\varepsilon_{||} < 0$ — where $\varepsilon_{\perp}$ and $\varepsilon_{||}$ are the values of the dielectric permittivity in the directions orthogonal and parallel to the boundary respectively. Only the transverse magnetic (TM) polarization is considered, although a similar behaviour for transverse electric (TE) polarization is observed in the case of magnetic anisotropy[26].** e, **Repeated negative refraction at the surfaces of a parallel slab with simultaneously negative ε and μ lead to the focusing of light emitted by a subwavelength source — both inside and outside of such a 'quasi-lens'.**

much smaller than the wavelength λ (but much larger than the material scale δ). As such, the medium can always be characterized by global parameters as long as $\delta << \lambda$, regardless of whether it is a natural material or an artificial structure patterned on a subwavelength scale. Owing to this essential similarity with the response of 'natural' materials, these artificial structures are often referred to as 'metamaterials'.

In contrast to metamaterials, photonic crystals that are periodic on a scale comparable to the wavelength, $\delta \sim \lambda$, cannot be characterized by a single value of the refractive index. Although negative refraction can be observed in a photonic crystal near the band edge, this effect has a very different origin — arising from Bragg scattering rather than refraction. As a result, NIMs and photonic crystals with negative refraction often show very different behaviour — particularly regarding image formation.

REALIZING NEGATIVE REFRACTIVE INDEX MATERIALS

After Veselago predicted the existence of negative index materials and analysed their properties[2], he and his collaborators endeavoured on an extensive search for such system. The magnetic semiconductor $CdCr_2Se_4$ and other members of its family, showing both dielectric and magnetic resonances, seemed particularly promising. However, the task of adjusting the corresponding resonance frequencies to close proximity of each other proved impossible.

It was only in 2001 when the first negative index metamaterial was developed, and negative refraction demonstrated in microwave frequencies[3]. Extending this approach to the optical domain, however, is a very challenging problem, as this would require scaling the meta-atoms down to the nanometre size.

Nevertheless only two years later, the measurements of terahertz reflectivity from a single layer of nanometre-sized resonators demonstrated that a three-dimensional (3D) metamaterial formed by such meta-atoms would have negative magnetic susceptibility[20]. Finally, meta-atoms for negative index materials in the infrared regime were developed in 2005 — first by the Purdue group[4] and within several weeks by the New Mexico–Columbia collaboration[5], followed by optimized structures from the Karlsruhe group[6]. The problem of negative index materials for optical frequencies is, however, far from being solved, as existing structures are made of only single layers of meta-atoms, rather than being fully 3D metamaterials (Fig. 3).

Yet another recent development deals with negative index in 2D and 3D 'media' formed by electronic circuit elements. When properly designed, such electromagnetic transmission lines show all the phenomena associated with NIMs[21].

APPLICATIONS

Negative index materials show many interesting properties that could lead to practical applications, from subwavelength optical waveguides[22] and the enhancement of MRI[8] to low-weight antennas and reflectors[7]. The most important so far is the superlens.

Owing to the negative refraction of two surfaces, a parallel slab of negative index material will form an optical image without geometrical distortions (Fig. 2e). Note that even though this device represents an aberration-free optical instrument, strictly speaking it is not a lens, as it does not focus a parallel beam. Although this quasi-lens was originally introduced by Veselago[2], it was only recently that John Pendry discovered that this device could form a subwavelength image[1]. The key to this behaviour lies in the fact that the surface of negative index materials can support surface waves (generally referred to as plasmon polaritons) that can effectively couple to the exponentially decaying short-range evanescent fields that carry the information on the subwavelength details of an object. It is the resonant enhancement of

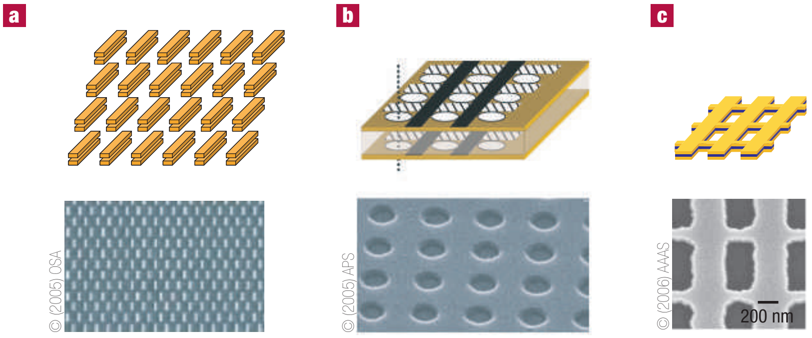

Figure 3 **Different designs of metamaterials at optical frequencies.** a–c, **as reported in refs 4 (**a**), 5 (**b**) and 6 (**c**). The top row shows the schematic representations of the different 'meta-atoms', with microscope images of the actual samples below.**

the evanescent fields by the surface waves that allows them to propagate for longer distances and reach the image plane of the 'superlens'.

As the resonant enhancement of the evanescent fields is limited by the material losses and the deviation from perfect resonance, the superlens only 'shines' when the distance to the object (as well as the thickness of the lens) is of the order of the wavelength. Here, the superlens has the role of a matching device that transfers light between the object and the image planes[27] as opposed to a classical optical instrument. In this regime, the superlens is a powerful imaging device that has already found applications in enhancing the resolution of MRI[8].

Finally, the concept of negative refractive index and its implications are now being extended from the world of electromagnetism to acoustic phenomena[23].

A LOOK INTO THE FUTURE

Although the field of negative index materials has seen enormous progress over the past few years, some critical issues remain unresolved.

Particularly important is the problem of high losses that originates from the design required to achieve a negative magnetic response. Since the demonstration of the first optical NIM the corresponding figure of merit (the ratio of the real to the imaginary part of the refractive index) was improved by more than an order of magnitude, however, the losses are still too high for the negative index superlens to become practical.

Yet another issue is the development of truly 3D optical NIMs. Although the task of placing the nanoscale meta-atoms into a uniform 3D arrangement of the desired topology can be thought of as a purely technological challenge, its complexity is mind-boggling. Perhaps some degree of self-organization will be needed for such fabrication.

It is not clear how and when these issues will be resolved, but the quest for optical NIMs and the superlens has already initiated the whole new field of metamaterials. These artificial structures, with electromagnetic response tailored to a particular objective (such as the 'magnetic mirror'[24] or an electromagnetic 'cloaking device'[25]) and their applications, may well eclipse the area of negative index materials that stimulated their development.

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