be reduced by optimizing the charge and volume of the bunches of electrons produced from the source[8], a prediction confirmed by initial results at SLAC (P. Emma and D. Dowell, personal communication). Combining this approach with a high-gradient accelerator such as that used by Shintake *et al.*[1] would reduce the size and cost of FELs still further.

Because any reduction in cost and size also implies a reduction in the average number of photons produced, some experiments will always require large facilities such as the LCLS or XFEL. The new smaller systems would nevertheless add significantly to our experimental capabilities. There is a new world to explore at atomic and molecular scales of time and distance, and a multiplicity of approaches, such as that described by Shintake *et al.*, together with other FEL systems, would speed up the exploration of this uncharted territory. ■

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OPTICS

Farewell to Flatland

Ortwin Hess

Metamaterials are the key to perfect lenses, 'invisibility' cloaks and slow and stored broadband light. A three-dimensional optical metamaterial with a negative refractive index has now been created.

Picture a straw in a glass of water. Looking at the glass from the side, the straw seems to break at the water surface and continue inside the liquid slightly shifted to one side and slightly wider than in the air. The difference between the 'optical density' of water and air, which is responsible for this phenomenon, is usually expressed in terms of the materials' refractive indices — that of water is higher than that of air. All naturally occurring materials, such as water, have a positive refractive index. However, if water had a negative refractive index, the straw would seem to be slightly shifted at the interface but would continue inside the water as if it had been shifted 'the wrong way' (Fig. 1, overleaf).

This unusual light-bending property is a feature of metamaterials — artificially engineered structures — with a negative refractive index. Part of the excitement surrounding these materials is that they could be engineered to 'cloak' objects from electromagnetic radiation such as light — that is, make them seem invisible[1]. On page 376 of this issue, Valentine *et al.*[2] report a three-dimensional 'fishnet' metamaterial consisting of alternating layers of silver and magnesium fluoride. This exceptional material exhibits a negative refractive index across a broad region of the electromagnetic spectrum.

For some time, Victor Veselago's 1960s Gedankenexperiment of a negative refractive index[3] seemed little more than just that, a 'thought experiment'. It was not until 2000, when John Pendry proposed that a material with a negative refractive index would make a 'perfect' lens[4], that negative refraction began to attract increasing attention[5]. But optical negative-index metamaterials have so far effectively been two-dimensional surfaces, very much at home in the two-dimensional Flatland world of Edwin Abbott's classic novella[6].

Recently, materials such as semiconductor metamaterials[7] and composite nanowire materials[8], which display negative refraction but do not have a bulk negative refractive index, have been manufactured. So how can we tell that the remarkable chunk of nano-structured material reported by Valentine and colleagues[2] really does exhibit a bulk three-dimensional negative refractive index? To confirm this, we will need to be sure of two features of the material.

First, are the unit cells, the 'atoms' of the metamaterial, sufficiently small relative to the wavelength (colour) of light for the material viewed with such light to appear homogeneous, and for the individual unit cells not to be apparent? The dimensions of the material's unit cell (80 nm × 860 nm × 265 nm) mean that it is not yet quite isotropic. However, particularly in the case of light travelling close to perpendicularly to the fishnet-structure layers, the periodicity (separation) of the layers is clearly much smaller than the light's wavelength. Moreover, the metamaterial's dispersion relation, which describes the way wave propagation varies with wavelength, reveals that in the negative-index regime there is a single propagating mode (with approximately fixed frequency) that can

50 & 100 YEARS AGO

NATURE

50 YEARS AGO

The Committee for Biological Acoustics organized a demonstration meeting to illustrate the wide range of research in this comparatively new and expanding field … The progress made in the United States in underwater recording was emphasized by a demonstration of the acoustic emission of whales by Dr. W. E. Schevill … Mr E. F. Woods, of the B.B.C., demonstrated his work on the sounds of colonies of honey bees, while developing an electronic device, the 'Apidictor', which can assist apiarists in detecting the onset of swarming in hives.
From *Nature* 20 September 1958.

100 YEARS AGO

Coast Erosion and Foreshore Protection. By John S. Owens and Gerald O. Case — The authors very properly point out that there is no one method of protection that can be applied to all coasts, but that each shore much be considered on its merits, and that it is only after due consideration has been given to the special circumstances which may influence the effect of the sea upon any particular shore that the proper remedy can be designed … The chapter on ferro-concrete groynes contains much useful informal information on the application of this material to sea defence work, and gives illustrations and cost of works carried out for the protection of the coast of Sussex. The cost of these groynes is given as twenty shillings a foot run, which compares favourably with timber.

ALSO:
An appliance for working the keyboard of a typewriter on a type-setting machine from a distance by means of wireless telegraphy has been devised by Mr. Hans Knudsen, and a demonstration of the experimental apparatus was given at the Hotel Cecil on Thursday last.
From *Nature* 24 September 1908.

E. SCHREMPP/SPL

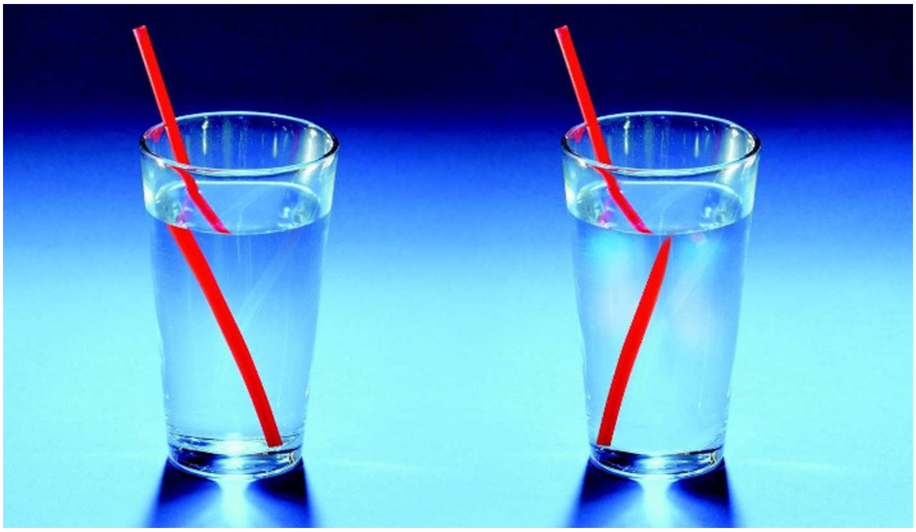

Figure 1 | Negative refraction. The difference in the optical density of air and 'normal' water (left) causes a straw in a glass of water to seem to be shifted at the interface and slightly enlarged inside the liquid. In 'negative-index water' (right), the straw would seem to continue in 'the wrong direction'. This is the principle that applies to negative-index metamaterials, such as that created by Valentine *et al.*[2].

be associated with a propagation constant and, in turn, with an effective refractive index.

Second, does the material exhibit a negative phase velocity? In other words, how can we tell that the phase of a forward-moving wave is moving backwards inside the material? This might be possible if, to measure a beam deflected in the 'wrong' direction, we apply Snell's law[9], which relates the angles of incidence and refraction of a wave. However, even everyday optical materials, such as a bathroom mirror, may at least partially display the effects of negative refraction yet have a positive refractive index[10]. Indeed, it is now established that negative refraction can occur in materials displaying anisotropy, such as calcite, and in two- or three-dimensionally structured materials such as photonic crystals[11].

To identify the signatures of negative refraction from a negative refractive index, Valentine *et al.*[2] combined experimental results with theoretical modelling. Experimentally, the authors did turn to Snell's law to determine the refractive index, but crucially they retrieved its value from the far-field transmission pattern of a prism configuration representing a signature of the (backward) phase evolution inside the metamaterial. Together with supporting theoretical simulations that show a backward-moving phase inside the prism, this strongly indicates that Valentine and colleagues' fishnet structure is indeed a three-dimensional material with a negative refractive index.

Another point in considering Valentine and colleagues' material is whether, when light is shone onto it, the light lost passing through it is low. To be useful, materials should certainly not absorb all light. However, because the constituent elements of a metamaterial, particularly metals, always exhibit a loss in some part of the frequency spectrum, the engineering of losses is an important task. A promising solution is to use nano-structuring (tightly coupled nano-plasmonic resonators) to simultaneously increase the bandwidth and effectively shift the losses to a frequency range where the optics is not impaired. In this respect, the metamaterial described by Valentine *et al.*[2] scores very well, with a record-breaking 'figure of merit' of 3.5, indicating low loss. In addition, this metamaterial displays a negative refractive index over a remarkably wide window of the spectrum, ranging from around 1,800 nm to less than 1,500 nm.

Finally, what uses might there be for a broadband, low-loss, three-dimensional optical material with a negative refractive index? First, it would be a way of constructing Pendry's perfect lens[4], and thus imaging a three-dimensional object the size of a molecule. Second, it would be beneficial for electromagnetic cloaking[1] and its applications, in that a cloaking material that absorbs less radiation will ideally prevent the cloaked object from appearing as a dark silhouette. Third, the ability to slow down and store broadband light using the 'trapped rainbow' principle[12] has clearly come closer to reality.

Saying goodbye to Flatland and entering Spaceland was not only a great achievement for A. Square, the protagonist in Abbott's novella. It is also a promising step towards producing optical negative-index metamaterials. The prospects that this step offers for research involving the control and manipulation of light could hardly be more exciting. ■

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BIOCHEMISTRY

Divergence from the superfamily

Lawrence J. Marnett

The unique structure of an enzyme that synthesizes lipid mediators in plants defines its function and serves as a characteristic footprint in genomes of plants and some animals.

In plants and animals, molecular signalling pathways that are mediated by metabolites of polyunsaturated fatty acids are essential for communication at cellular and organismal levels. For example, the plant metabolites known as jasmonates and green-leaf volatiles control not only growth but also responses to wounding and infection[1,2], and contribute to the characteristic taste and smell of certain plants. Jasmonates and green-leaf volatiles are formed from fatty-acid hydroperoxides through the action of the allene oxide synthase (AOS) and hydroperoxide lyase (HPL) enzymes, respectively[3,4]. Exactly how these enzymes react with their hydroperoxide substrates has remained unclear. The crystal structures of AOS — as free enzyme and in complex with substrate and intermediate analogues — are presented by Lee *et al.*[5] on page 363 of this issue, and provide fascinating clues.

Both AOSs and HPLs are members of the CYP74 family, which belongs to the cytochrome P450 (CYP) superfamily. CYP proteins contain a haem group, and are defined by the characteristic absorption of their ferrous carbon monoxide complex at a wavelength of 450 nanometres. These enzymes catalyse oxidation reactions that are central to many metabolic pathways in a wide range of organisms — for example, they mediate steroid biosynthesis in humans and nutrient breakdown in bacteria[6]. To do this, they take two electrons from a reduct-