insulin resistance and neurodegenerative disorders. ■

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APPLIED PHYSICS

Extreme light-bending power

Metamaterials are best known for their ability to bend light in the opposite direction to that of all materials found in nature. A hidden ability of these man-made materials has now been discovered. **SEE LETTER P.369**

XIANG ZHANG

You've probably noticed that, if you look at it from the side, a straw in a glass of water seems to bend. This is because light bends and slows down when it travels from air into water or other substances. How much the light bends depends on the type of material through which it travels or, more specifically, on the material's refractive index. Ideally, with a view to applications, we would want unlimited power to control the refractive index. A computer-chip maker, for example, would be thrilled to have a lens of huge refractive index in their lithographic machine, because such a lens would allow chips to be made that are much smaller and perform better than those currently available. But nature cannot always supply our ideals: naturally occurring materials have only a limited range of optical refractive indices, typically between 1 and 3. However, on page 369 of this issue, Choi and colleagues[1] bring us good news: they have found a way to create metamaterials with an unnaturally high refractive index.

During the past decade, metamaterials[2] have generated great enthusiasm among scientists and engineers. These artificially engineered composite materials gain their unique properties, which are not attainable with naturally occurring materials, from their physical structure rather than their chemical composition. The very ability of metamaterials to reach beyond nature's limitations is not only scientifically exciting, but also technologically important: scientists have achieved intriguing physical phenomena and properties in these composite materials that their parent materials do not possess. For example, strong magnetic responses in the terahertz frequency regime have been engineered[3] with a composite material containing split-ring structures made of copper. Such strong magnetic responses do not occur in natural materials.

Metamaterials research has made it possible to create the negative-refractive-index materials first envisioned[4] by the Russian scientist Victor Veselago in 1968. The negative electrical and magnetic responses of these materials cause them to bend light in the 'wrong' direction[5,6]. Consider a fish in a tank of water. If water had a negative refractive index — which it doesn't — the fish would seem to an observer to be swimming upside down above the water. Naturally occurring materials have an index with a small positive value, which fundamentally limits the resolution of optical-imaging lens systems to about half the wavelength of the incident light, and so prevents the tiny details of an object from being imaged. Negative-index materials can overcome this limitation. The 'perfect imaging' capability of metamaterials would open the door to many exciting applications, including ultra-high-resolution medical imaging and data storage, and revolutionary miniaturization of computer chips[7].

At the other end of the metamaterials spectrum would be materials with a very large positive index — beyond that of naturally occurring materials. A lens with such an index would allow more details to pass through an imaging system. Recently, an ultra-high-index metamaterial has been proposed theoretically[8] that uses metallic (conducting) structures embedded in a dielectric (insulating) host. However, its experimental implementation has been impeded by its complicated three-dimensional geometry. Inspired by this idea, Choi *et al.*[1] stacked centimetre-

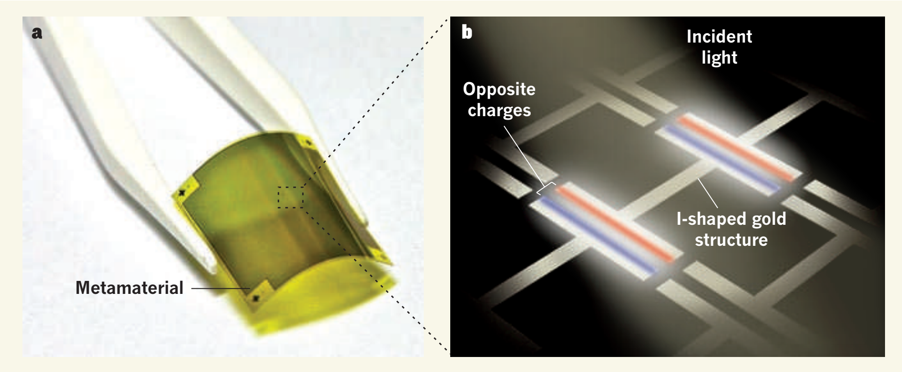

Figure 1 | Choi and colleagues' high-refractive-index metamaterial[1]. **a**, Photograph of the centimetre-sized, free-standing and flexible metamaterial. **b,** The internal structure of the metamaterial consists of a lattice of I-shaped gold unit cells, each 60 micrometres in size. When light of terahertz frequency is shone onto the material, the small gap between the bars of two adjacent I cells produces an extremely strong electric dipole of equal but opposite oscillating charges, which confers a high refractive index on the material. (Modified from ref. 1.)

sized planar layers to create bulk-like metamaterials. They formed each layer by printing arrays of thin I-shaped gold building blocks, or 'meta-atoms', onto a polymer (polyimide) substrate using the conventional lithographic technique used for printing electronic circuits. The resulting metamaterials, which are free-standing and flexible (Fig. 1a), have a very high refractive index — more than 30 at the terahertz frequency regime.

The refractive index depends on the product of a material's electrical and magnetic responses to an electromagnetic field. The authors achieved a large electrical response by placing the I-shaped meta-atoms close to one another, leaving only a small gap. Upon irradiation with terahertz light, the small gap between the bars of two adjacent I meta-atoms produces an extremely strong electric dipole that significantly enhances the electrical response (Fig. 1b). However, at the same time, the incoming light has the detrimental effect of decreasing the material's magnetic response by inducing electric-current loops that prevent the light's magnetic field from penetrating the metallic structures. The authors came up with a creative approach to minimize this effect: they thinned the metallic structures such that the area subtended by the loop current was reduced, effectively minimizing the loss of the magnetic response. In this way, the overall refractive index, which arises primarily from huge electrical dipole moments, was kept at a high value.

To measure the refractive index, Choi *et al.*[1] used terahertz time-domain spectroscopy, in which terahertz pulses are sent through the sample and the time-dependent transmitted pulses are recorded and transformed into frequency-dependent values. The detailed features of these transmitted pulses are then used to deduce the sample's refractive index. The authors found that the metamaterial's observed high index occurs over a broad band of frequencies with low energy loss in the metal. This is caused by strong interactions between the meta-atoms.

Choi *et al.*[1] estimate that a much higher refractive index — of a few hundred — could be obtained by further shrinking the gaps and embedding the layers of metamaterial in a substrate that has a higher refractive index than polyimide, for example strontium titanate. Such an index would be a remarkable amplification of the refractive indices of nature's materials. However, this requires a precision of 10–50 nanometres for the manufacture of the metallic structures into a large (centimetre-scale) area of metamaterial, which can be challenging.

A shortcoming of Choi and colleagues' I-shaped metamaterials is the fact that they are sensitive to the polarization of incident light. Although the authors also designed isotropic two-dimensional metamaterials, which are insensitive to polarization, it will be a challenge to build truly isotropic three-dimensional metamaterials with a refractive index that is both high and does not depend on polarization. But for now, the unusually high index of Choi and colleagues' materials has demonstrated a hidden potential of metamaterials, which once again beats the limitations of naturally occurring materials and will greatly extend our ability to manipulate light. ■

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CLIMATE CHANGE

Human influence on rainfall

Rising concentrations of anthropogenic greenhouse gases in the atmosphere may already be influencing the intensity of rainfall and increasing the risk of substantial damage from the associated flooding. **SEE LETTERS P.378 & P.382**

RICHARD P. ALLAN

The varying distribution of fresh water across the globe, involving complex patterns of rainfall in space and time, crucially affects the ecosystems and infrastructure on which human societies depend. The recent severe floods in Australia, Sri Lanka and Brazil, which were partly associated with an episodic cooling in the equatorial Pacific Ocean (La Niña), highlight the effect of natural fluctuations in atmospheric circulation systems on rainfall distributions. However, global warming resulting from anthropogenic emissions of greenhouse gases may have compounded the effects of such fluctuations, a possibility that is considered in two papers in this issue[1,2].

Min *et al.* (page 378)[1] provide evidence that human-induced increases in greenhouse-gas concentrations led to the intensification of heavy precipitation events over large swathes of land in the Northern Hemisphere during the latter half of the twentieth century. They combined a rigorous 'detection and attribution' framework with extreme-value theory (a statistical technique designed for analysing rare events) to place daily rain-gauge data and climate-model simulations on a common scale. A tentative but intriguing finding by these authors is that climate models may underestimate the effects of anthropogenic global warming on rainfall intensification, a possibility that has implications for projections of future climate.