Extreme Light-Benders

Common materials have only limited light-bending power. A new, manmade material can bend light to the extreme thanks to the ultra-high value of its refractive index.

Homo faber suae quisque fortunae, literally: *every man is the artisan of his own destiny*; some 2,300 years ago, these very same words were used by Roman politician Appius Claudius Caecus to describe man's ability to control his fate and influence his surroundings. Two millennia later, these famous words aptly befit the attitude towards the natural world of some modern scientists who, unsatisfied with what nature has to offer, design artificial materials with properties which are non-existent in known natural materials. The refractive index is one such natural property that is difficult to modify at will. Researchers from the Korea Advanced Institute of Science and Technology (KAIST), headed by Bumki Min, have recently fabricated a material with a very high refractive index, thus showing an unprecedented power to bend light.

What makes light bend? Think, for example, of a spoon in a glass of water that appears to break at the air-water interface when observed from the side. The reason for this optical illusion is the change of refractive index between the two media; this same effect is at the core of the use we make, for example, of glass lenses to focus light or form images. The refractive index is a measure of the reduction of the vacuum speed of light in a material due to the interaction between light and its atoms [1]. When light passes from one material to another with different refractive indices, its direction of propagation also bends proportionally to the ratio of the indices of the two materials. Air, for example, has a refractive index of around 1, while water has a refractive index of around 1.33. This difference, small as it may seem, can bend light enough to appear to break a spoon. The refractive index of known materials typically varies approximately between 1 and 3, thus limiting how much we can bend light for practical applications. Can we bend light even further? Yes, we can! Thanks to *metamaterials*.

A metamaterial is a material of human creation, designed *ad hoc*, in order to show properties non-existent in known natural materials [2]. "I was curious about the limit of positive refractive index that is achievable with metamaterials," Min explains. "Researchers have been investigating negative refraction for the past years, but I believe that a high positive refractive index will also be useful for various applications, such as high-resolution imaging — preferably at the subwavelength scale — and very compact photonic devices." This motivation is what pushed Min and colleagues to fabricate a metamaterial whose refractive index is greater than 30 — one order of magnitude above known materials —, thus demonstrating a light bending power that greatly overcomes present limitations.

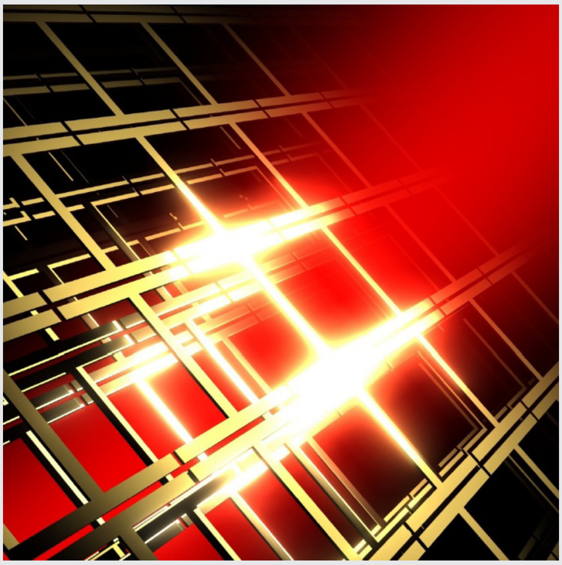

Figure 1: The extreme light-bender. The metamaterial, which shows a refractive index of more than 30, was fabricated by placing many metallic I shapes very close to each other onto a hosting medium with a refractive index of only 1.8. Figure courtesy: Bumki Min.

In order to achieve a very high refractive index, Min and colleagues had to fabricate a material with both large electric permittivity and magnetic permeability. In fact, the refractive index is related to the product of these two physical properties, which respectively measure how an electric field and a magnetic field *affect* and *are affected* by a material. It is relatively easy to achieve high electric permittivity by embedding tiny metallic inclusions inside the hosting medium that forms the metamaterial. However, the presence of metals typically backfires resulting in small magnetic permeability, because electric currents are induced on the metal surface to oppose the applied magnetic field. Fortunately, this effect can be reduced by shaping the metallic inclusions: in particular, metallic structures containing gaps or slits are preferable.

Min and colleagues' experiment is the first to achieve an ultra-high refractive index material, despite the fact that a metamaterial with a high refractive index had already been theoretically proposed [1]. In particular, the material was fabricated by placing many metallic particles shaped into the form of an "I" very close to each other onto a polymer. Only a very small gap separated one "I" from the next. The full 3D metamaterial was built by stacking one layer on top of another. In the terahertz regime, the polymer itself had a refractive index of around 1.8, but with the metal inclusions

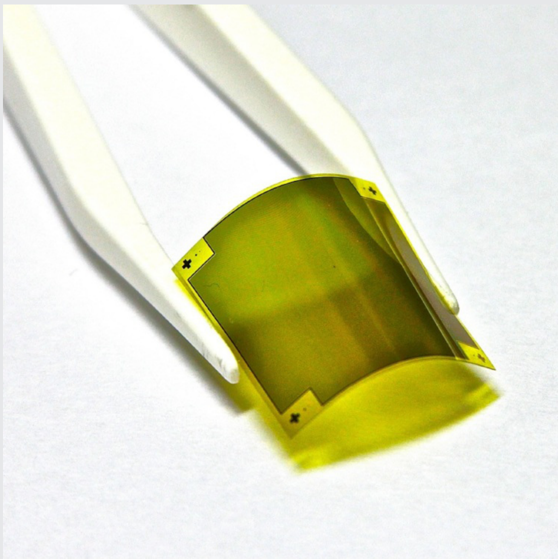

Figure 2: A flexible metamaterial. The metallic I shapes, which give the metamaterial its high refractive index, are placed onto a polymer that also makes the material very flexible. Figure courtesy: Bumki Min.

the metamaterials reached a value of more than 33.2. "We expect that a higher refractive index could be achieved with the use of higher index natural materials as a substrate," envisions Min. "At least, we think that a peak refractive index of around 100 should be possible experimentally. However, the real limit is difficult to estimate at present, as other considerations, such as the tunneling of electrons, should be taken into account."

One drawback of this design is that it works well only in the terahertz frequency range. "Scaling to lower frequencies, such as to microwaves, will be quite easy as the tools for fabrication are readily available," Min adds. "However, it will be a more challenging task to scale down to the near-infrared or visible frequencies, as the fabrication of metamaterials in these regimes requires the most advanced nanofabrication technology. With further advances in top-down or bottom-up fabrication technology, it could be possible to scale down to infrared or visible frequencies. Other concerns are related to the loss of metal in visible/near-infrared frequencies, as the loss will deteriorate the performance of metamaterials." With scientific advances in new nanofabrication techniques, it is clear that these metamaterials will emerge in different forms and designs, with an extreme potential for bending light.

[1] G. Volpe, *Refractive Index: To the Limits and beyond*, Opt. Photon. Focus **6**, 2 (2009) http://www.opfocus.org/index.php?topic=story&v=6&s=2

[2] G. Volpe, *Magical Metamaterials*, Opt. Photon. Focus **6**, 6 (2009) http://www.opfocus.org/index.php?topic=story&v=6&s=6

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Muhan Choi, Seung Hoon Lee, Yushin Kim, Seung Beom Kang, Jonghwa Shin, Min Hwan Kwak, Kwang-Young Kang, Yong-Hee Lee, Namkyoo Park & Bumki Min, **A terahertz metamaterial with unnaturally high refractive index**, Nature (2011) **470**, 369–373.