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Metamaterials and the new rules of refraction

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Detail

Bio

Simone Zanotto is a researcher at the CNR – Istituto di Nanoscienze in Pisa, Italy. His research interests span from nanophotonics for photovoltaics, to quantum light–matter interaction, through tuneable photonics based on transition metal oxides and responsive polymers. Recently his main interest is the study of symmetries in functional nanostructured metamaterial.

Alessandro Pitanti is a researcher at CNR – Istituto di Nanoscienze and an Alexander von Humboldt fellow at Paul-Drude Institut for solid state electronics. His research interests span THz and NIR photonics, micromechanical systems, and optomechanical devices.

Collaborators

- Giorgio Biasiol, CNR-Istituto Officina dei Materiali (Trieste, Italy)
- Paulo V Santos, Paul-Drude Institut für Festkörperelektronik (Berlin, Germany)

Research Objectives

Zanotto and Pitanti are developing metamaterials, a new type of material for the manipulation of optical and mechanical waves.

Personal Response

What are the big challenges to overcome in making metamaterials more widely available?

" Metamaterial fabrication processes are quite varied, reflecting the fact that the wave the metamaterial is intended to manipulate can be either electromagnetic or mechanical, which means using very different base materials (glasses, metals, semiconductors, concrete, polymers, etc). Moreover, the wavelength can span several orders of magnitude, meaning that the feature size can span from micrometre to metre lengths – thus requiring techniques as different as nanolithography or concrete casting. What they have in common is that the metamaterial properties are always dictated by the accuracy employed to machine those base materials. Nowadays, in most cases there is a tight compromise between the tolerance of the metamaterial's element sizes and the overall dimension of the metamaterial. This somehow limits the applications to restricted cases such as high-end radar systems. We nonetheless envisage that in the near future, new fabrication techniques such as 3D printing (now available also at the micrometre scale) will pave the way for a much wider diffusion of metamaterials, including in everyday applications. "

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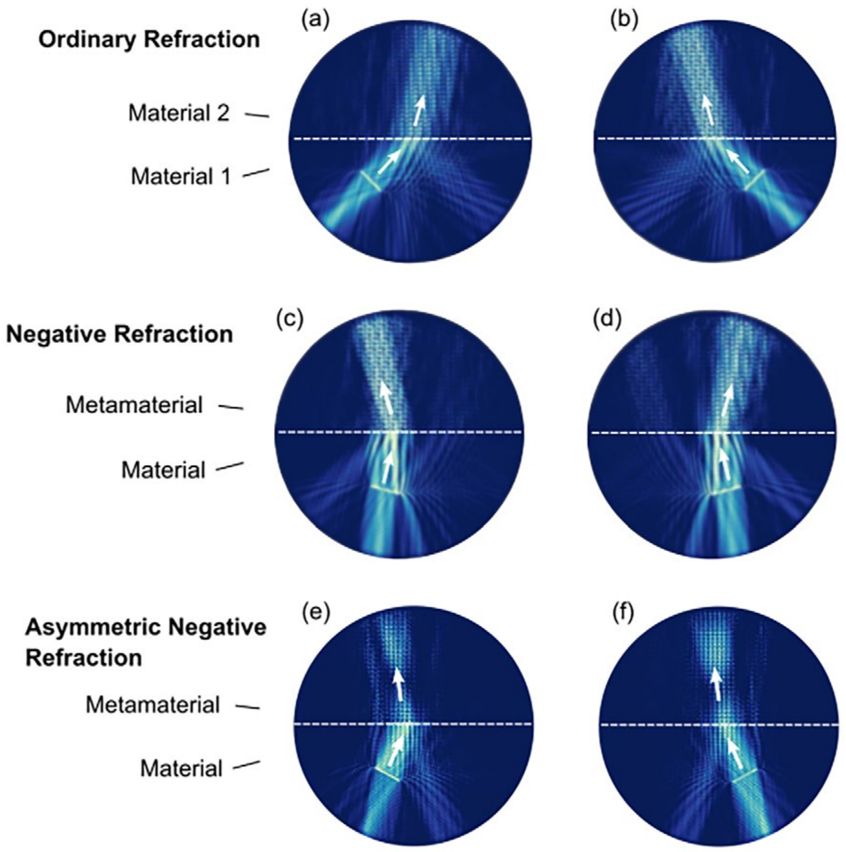
Physical Sciences | Simone Zanotto & Alessandro Pitanti

Metamaterials and the new rules of refraction

Waves are amazing things. We use light waves for telecommunications applications and make use of mechanical waves for everything from musical instruments to sensing. Being able to control and use waves, though, relies on components to manipulate their properties. Drs Simone Zanotto and Alessandro Pitanti at the CNR – Istituto di Nanoscienze in Pisa, Italy, are now developing a new type of material for wave manipulation, called metamaterials. These materials have remarkable and unique properties such as negative refraction that may bring in a revolution in wave control.

Even though we might not realise it, we make use of the unusual physical properties of waves in our everyday life. Probably the most obvious example is how we use lenses to manipulate light in glasses for eyesight corrections. We also make use of wave manipulation in many telecommunications applications to help improve signal quality and avoid data loss.

One technique frequently used by the telecommunications industry to improve the quality of data transfer is the manipulation of waves using components called shields or frequency filters. Materials can be specially designed to block only certain frequencies of waves or to control which frequencies can pass to act as a filter for transmitted information. Such filters are commonly used in 5G transmission for communications, to improve the quality of acoustics or to shield highly sensitive equipment from sound or vibrational waves.



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THE CONCEPT OF REFRACTION

One property of all kinds of waves, including sound, light, seismic, and other kinds of mechanical waves, is the property of refraction. Refraction is the change in the velocity of a wave as it passes from one material to another – a property that is quantified by the refractive index of the material. When the velocity of the wave changes on entering the material, this changes the direction of the light path. Refraction is why objects underwater sometimes appear to be further or closer than they actually are.

A traditional lens uses some kind of curved surface to converge the light to a target area by controlling the amount of refraction with the thickness of the region the light passes through. Snell's Law, one of the most important optical laws, describes the relationship between the angles of incidence and refraction when a wave passes through a boundary of two different media. In short, the Law allows us to estimate and calculate how much a light beam will be deflected when passing through different material types.

We exploit refraction in fibre optics every day. By designing special fibres that can be used to bounce the light multiple times within the fibre without escaping, it is possible to transmit light pulses over kilometre distances, even as far as transmitting signals between continents with minimal data losses.

Exploiting refraction means designing special materials with the right refractive indices to control the light path as desired. Optics is undergoing something of a technological revolution with the development of new kinds of lenses and materials, known as metamaterials. Drs Simone Zanotto and Alessandro Pitanti at the CNR – Istituto di Nanoscienze in Pisa, Italy, have been looking at ways to create new kinds of lenses using novel metamaterials with an interesting property of a negative refractive index for the manipulation of mechanical waves.

NEGATIVE REFRACTION

Most materials have a positive index of refraction, which means that the wave is essentially slowed down in the material relative to how quickly it would travel in a vacuum. What Zanotto and Pitanti have been exploring, on the other hand, is materials with a negative index of refraction.

Negative refractive index materials would do the opposite to a positive refractive index. There are no naturally occurring materials with negative refractive indices, but the researchers have found ways of engineering very special nanomaterials that exhibit negative refractive indices, known as a type of metamaterial.

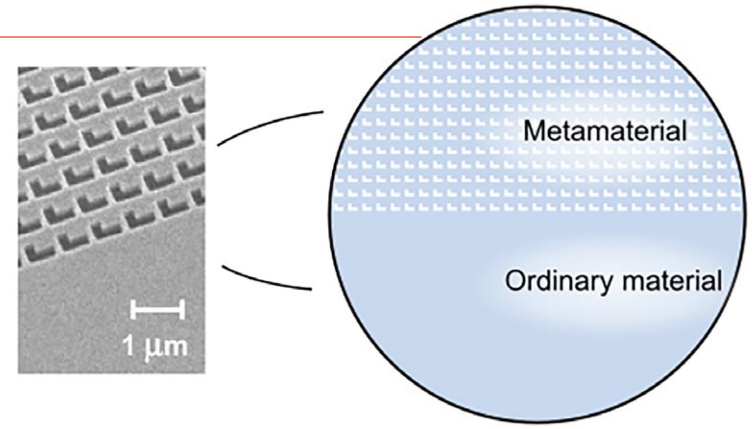
The motivation for making such materials is not just a technical curiosity to look at the unusual physics that occur in these types of light-matter interactions. Negative refractive index materials offer an opportunity to steer waves at will – something that is incredibly challenging with more conventional positive refractive index materials.

SYMMETRY

Zanotto and Pitanti have gone one step further than just creating a metamaterial with a negative refractive index though. Together with their collaborators at CNR – Istituto Officina dei Materiali (Trieste, Italy) and the Paul-Drude Institut für Festkörperelektronik (Berlin, Germany), they have been working to model and create metamaterials that don't just show symmetric behaviour – that essentially bend the direction of the light in the opposite direction to what would be expected for positive refractive index materials – but asymmetric behaviour.

The asymmetric negative refraction is an interesting phenomenon as this allows for even more complex manipulation and control over waves; for example, it enables controlled negative refraction but only for waves that arrive from a particular direction.

The metamaterial Zanotto and Pitanti designed is made of L-shape holes arranged in a square lattice.



To achieve this unusual level of wave control, the team fabricated a metamaterial in close vicinity to an ordinary material. Finding a metamaterial that would exhibit this asymmetric negative refraction was somewhat serendipitous for the research team, who happened to be developing some highly sophisticated materials for another application on superchiral photonic metasurfaces.

The metamaterials were thin membranes perforated with asymmetric, L-shaped holes smaller than 1 micrometre – many times thinner than a human hair. When mechanical vibrations propagate through the lattice of the material and light passes through, the asymmetric negative refractive behaviour is observed.

Asymmetric negative refraction allows for even more complex manipulation and control over waves.

THE FUTURE

Making such metamaterials is still very challenging as we need fabrication techniques that are capable of performing precise machining on smaller than microscopic levels. However, despite this challenge, Zanotto and Pitanti were able to prove that their new metamaterials showed the desired optical properties under experimental conditions.

How could such materials be used? Zanotto and Pitanti demonstrated their material could allow for a variety of negative refractive indices for GHz waves – a frequency that could be used to create new on-chip hybrid optomechanical and electromechanical devices.

While the development and manufacture of such materials and exploiting asymmetric negative refractive are still in their infancy, the possibilities opened by the creation of these devices are numerous. Optomechanical and electromechanical devices interconvert between mechanical and electrical/optical signals and are a very powerful way of creating highly sensitive sensors.

One future outlook Zanotto and Pitanti envision is in 5G wireless communications. At present, there are filters within the smartphone to select a particular radiofrequency that filters out all other frequencies to ensure there is no contamination of the desired signal. These new asymmetric negative index materials could also be used for filtering and selecting signals in a more effective way.

The fabrication methods for these metamaterials could also be applied to other types of metamaterials and be used for large-scale manufacture. This is an important development for the large-scale rollout of such metamaterials, which have been largely limited to laboratory settings to date.

The new generation of asymmetric negative refractive index materials is an exciting step, not just in new realms of physics but in realising the potential benefits for related technologies. The work of Zanotto and Pitanti may just be a critical step towards a future filled with metamaterial sensors and lasers.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