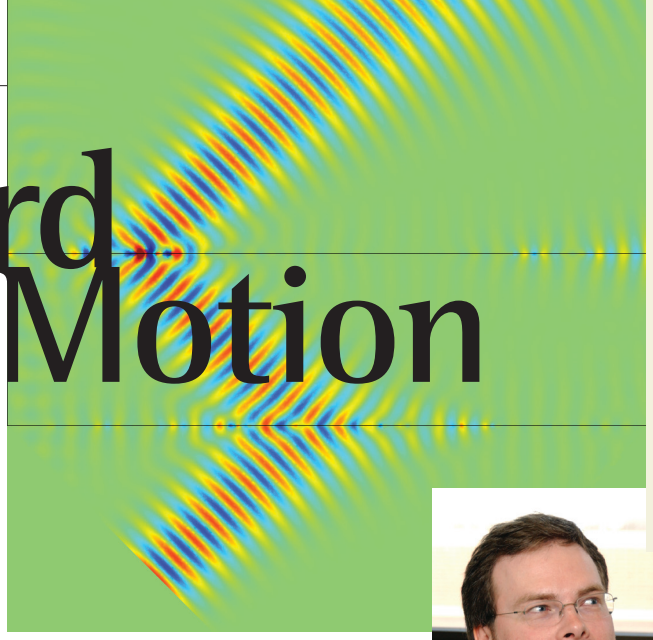
Fast Backward Motion

Metamaterials put a new slant on light – it's direction and speed

BY SAREN JOHNSTON



Negatively refracted light.

Thomas Koschny

LIGHT FLIES. IT ZIPS BY, MOVING EVER FORWARD at a mind-boggling 186,000 miles per second, the speed at which electromagnetic waves can move in a vacuum. That, folks, is "flying!" And Ames Laboratory senior physicist Costas Soukoulis and his research team are getting in on the action.

They're having the times of their lives reversing light's "flight pattern," making it travel backward at negative speeds that appear faster than the speed of light. The whole process is what Soukoulis, who is also an Iowa State University Distinguished Professor of physics and astronomy, says is "like rewriting electromagnetism." He predicts, "Snell's law on the refraction of light is going to be different; a number of other laws will be different."

Costas Soukoulis

Marvelous metamaterials

There's no stopping light as it zips along on the fast track to anywhere and everywhere it pleases. However, there is control. Researchers can manipulate light by using exotic, artificially created materials. Known as metamaterials, these substances can be created to respond to electromagnetic waves in ways that natural materials cannot. Natural materials refract light, or electromagnetic radiation, to the right of the incident beam at different angles and speeds. (An incident beam is one that strikes a surface.) However, metamaterials, also called left-handed materials, make it possible to refract light at a negative angle, so it emerges on the left side of the incident beam. This backward-bending characteristic of metamaterials allows enhanced resolution in optical lenses, which could potentially lead to the development of a flat superlens with the power to see inside a human cell and diagnose disease in a baby still in the womb.

Whittling down the wavelength

The challenge that Soukoulis and other scientists who work with metamaterials face is to fabricate them so that they refract light negatively at ever smaller wavelengths, with the ultimate goal of making a metamaterial that refracts light at visible wavelengths and achieving the much-sought-after superlens. Admittedly, that goal is a ways off. To date, existing metamaterials operate in the microwave or far infrared regions of the electromagnetic spectrum. The near infrared region of the spectrum still lies between the microwave and visible regions, and the wavelengths become ever shorter moving along the electromagnetic spectrum to visible light. Correspondingly, to negatively refract light at these shorter wavelengths requires fabricating metamaterials at extremely small length scales – a tricky feat.

However, recent research by Soukoulis and his co-workers from the University of Karlsruhe, Germany, published in the May 12, 2006, issue of *Science* demonstrates they have done just that. "We have fabricated for the first time a metamaterial that has a negative index of refraction at 1.5 micrometers," says Soukoulis. "This is the smallest wavelength obtained so far." Small, indeed; these wavelengths are microscopic and can be used in telecommunications. Soukoulis' success moves metamaterials into

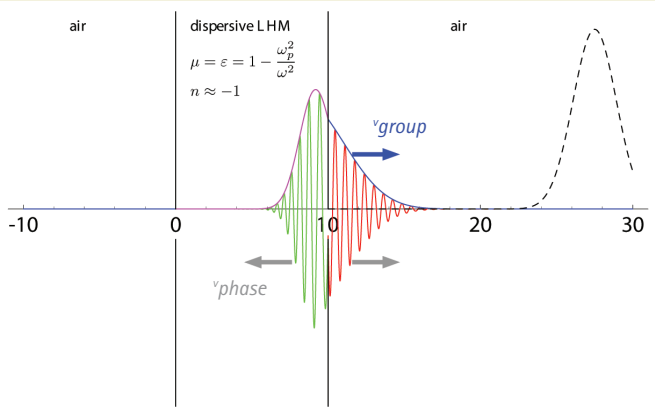


Fig. 1: *Realistic metamaterial with dispersion – A wave packet strikes a physical, dispersive metamaterial slab from the left and then travels to the second interface of the slab. The group velocity (that of the wave packet) is positive both inside and outside the slab. The phase velocity (that of the individual wavelengths) is negative inside the slab. There is no violation of Einstein's theory of relativity. The dashed line represents the predicted position of the wave packet if the metamaterial slab had not been there.*

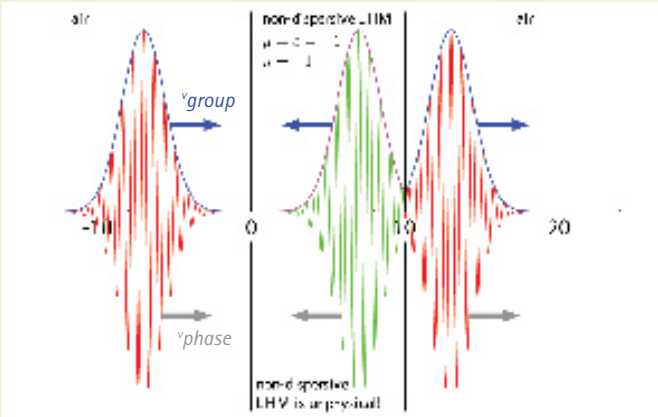


Fig. 2: *Fictitious (theoretical) metamaterial without dispersion — The same situation as in Fig. 1 is shown for an unphysical, dispersionless metamaterial. A wave packet strikes the first interface of a nondispersive metamaterial slab from the left. While the wave packet is still outside the slab, a response is already forming at the second interface of the metamaterial. A wave packet is generated and leaves the slab to the right while a second packet is sent backwards through the slab (with negative phase and group velocities) and will eventually annihilate the original wave packet at the first interface of the slab. This situation violates special relativity. Thus, the assumption of no dispersion in metamaterials is fictitious (unphysical).*

the near infrared region of the electromagnetic spectrum – very close to visible light, which would permit superior resolution and a wealth of potential applications.

Revealing experiments

Not only did Soukoulis and his University of Karlsruhe colleagues bring metamaterials closer to visible light, the work yielded something unexpected. The researchers transmitted a laser pulse through a fictitious (theoretical), nondispersive metamaterial (one that does not spread out the light pulse into individual wave components with different velocities). The experiment showed that the velocity of the individual wavelengths, called phase velocity, was negative inside the metamaterial. In addition, the experiment showed, contrary to popular thought, that the velocity of the wave packets, called group velocity, can also be negative simultaneously.

"We can have a wave packet hit a slab of negative index material, appear on the right-hand side of the material and begin to flow backward before the original pulse enters the negative index medium," says Soukoulis. "This is possible because the components of the wave packet can be reshaped and make a pulse inside the dispersion medium before the original pulse enters the negative index medium. In this way, one can argue that the wave packet travels backward with velocities much higher than the velocities of light, seemingly defying Einstein's theory of relativity," he says.

In experiments with a more realistic metamaterial with dispersion, the researchers found that the phase velocity can be either positive or negative, depending on the frequencies of the dispersed light being studied. "When we have a metamaterial with a negative index of refraction at 1.5 micrometers with dispersion, we can tune our lasers to play a lot of games with light," says Soukoulis. "This is due to the dispersion of the negative index of refraction; there is nothing wrong with Einstein's theory of relativity."

Making movies

The detailed interactions of electromagnetic radiation within metamaterials lead to phenomena that are counter-intuitive and difficult to explain in ordinary terms. To help clarify the out-of-the-ordinary nature of the experimental results obtained by Soukoulis and his University of Karlsruhe collaborators, postdoctoral fellow Thomas Koschny has taken on the additional role of metamaterial movie-maker for the research team. He has developed simulations that depict a pulse of light entering both a fictitious metamaterial without dispersion and a realistic metamaterial with dispersion. So if like most of us you find the relationship between electromagnetism and metamaterials a difficult one to understand, grab your popcorn and soda and go check out the movies at: *www.external.ameslab.gov/final/News/Lightmovies.htm.*

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Research funded by:
DOE Office of Basic Energy Sciences,
Materials Science and Engineering Division