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Stopping light in metamaterials: the trapped rainbow

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Storing light inside solid-state materials may speed up communication networks and information processing.

A global web of optical fibers forms the backbone of the Internet. This network relies on routers that switch the transmitted pulses from one fiber to another, so that information ends up at the desired destination. Currently, data traffic at major interconnections requires routers to first convert the travelling optical pulse into an electrical one, perform a switching operation, and then convert the electrical pulse back to its original form. This process can slow-down systems by a factor of 1000.

Until now, the prime difficulty in designing an all-optical network router was finding a means to temporarily store or buffer the packets of information. Researchers have recently proposed a variety of methods for completely stopping light. Unfortunately, inherent limitations prevent their deployment. For instance, previous approaches employed ultra cold or hot gases[1] and did not use solid-state materials. Other methods stored the data pulses as acoustical disturbances, which still travelled slowly down the fiber[2].

We have proposed[3] a light-guiding structure that does not require cryogenic temperatures and can efficiently bring an optical pulse to a complete halt. In this approach, light travels inside an engineered solid-state meta-material (MM), that has a negative refractive index. This material was developed[4] in 2001 and the scheme is conceptually simple.

The device we envisioned is a three-layer waveguiding heterostructure, in which the middle MM layer is surrounded by two regular dielectrics. The center portion tapers from wide to narrow. Because the power-flow direction inside the MM layer is opposite to the one in the dielectric regions, the guided electromagnetic waves are markedly slowed.

Figure 1 shows the propagation of a monochromatic ($f = 1$THz) p-polarized magnetic-field component. The light enters the device from the wide end and stops at the prearranged critical thickness. Because of the MM's anomalous frequency dispersion, the longest (red) wavelength components stop at the thinnest portion of the middle-layer. The smallest (blue) wavelengths stop at larger thicknesses. Thus, the guided light field spectrum is decomposed into its color constituents, forming what we call a trapped rainbow.

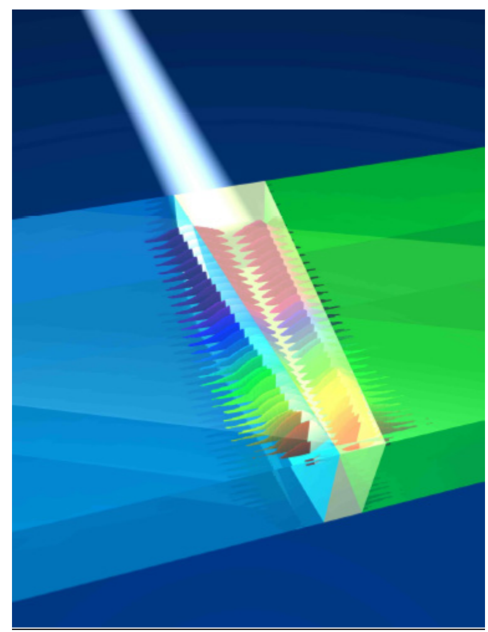

Figure 1. *A white light beam hits the tapered negative refractive index layer (shown in white), which is surrounded by two regular dielectric layers (shown in blue and green). Upon entering the structure, each frequency component, or color, of the beam stops at different thicknesses, forming a trapped rainbow.*

The top right inset of Figure 2 shows that at the broadest end, a zigzag guided light ray makes three steps forward and one step backwards in each half-period and is thus slowed down. At exactly the critical thickness, the ray always returns to its original point (shown in the bottom left inset of Figure 2). At this width, the pulse becomes permanently trapped, with a zero group velocity.

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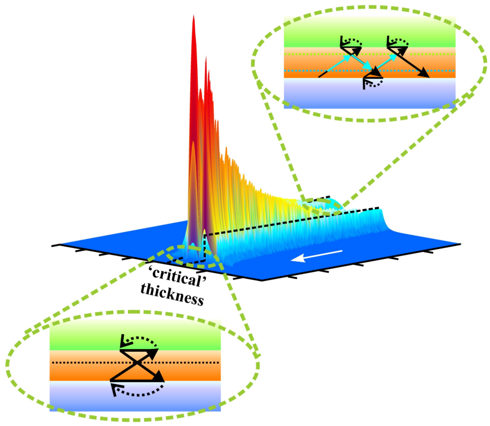

Figure 2. *Snapshot of the propagation of a monochromatic light signal along the negative-index heterostructure. The lightwave completely stops upon reaching the 'critical' thickness. The top right and bottom left insets associate the wave propagation with the corresponding zigzag ray analysis for the corresponding guide widths.*

The method we propose can, in theory, stop light in its tracks and store it, without radiation, over a range of frequencies. Furthermore, the design does not require atomic media or cryogenic temperatures. Currently, a number of groups worldwide are working to create a prototype. This effort may lead to a new generation of hybrid opto-electronic devices for information processing and communication networks.

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