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# Ultraslow and Stopped Light in Metamaterials

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## Introduction

- ***Metamaterials*** – Man-made materials, containing sub-wavelength features and showing novel EM properties.
- ***Negative refractive index*** – The interaction between the electric and magnetic fields of an electromagnetic wave with these sub-wavelength features can lead to the production of negative permeability and permittivity. The values of these quantities define how the material affects the light passing through it. Negative permittivity and permeability lead to the material having a ***negative refractive index***. This means that the ***phase velocity (k)*** travels in the opposite direction to the ***energy flow (S)/group velocity***.

*Figure* 1. Relative directions of the phase velocity and energy flow/group velocity. For a conventional material the **E**, **H** and **k** vectors form a **right handed (RH)** triad, while for a material with a negative refractive index they form a **left handed (LH)** triad.

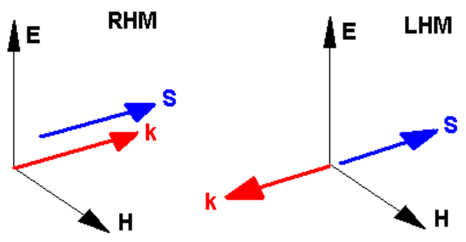

*Figure 1*

## The 'trapped rainbow'

Our recent work has revealed that different frequency components of a guided wave packet can be *completely stopped without being reflected* at different thicknesses inside a tapered left-handed (LH) waveguide (***Figure* 3(a)**). In ***Figure* 3(b)** we show a snapshot from the propagation of a monochromatic ($f$ = 1 THz) p-polarized lightwave, which enters the LH waveguide from the right, wide-thickness, end and stops at the 'critical' thickness.

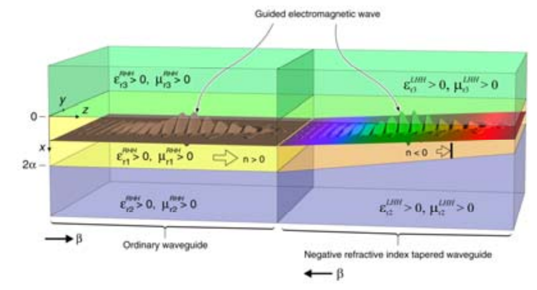

*Figure* 3(a)

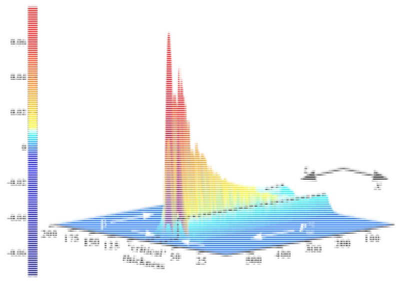

*Figure* 3(b)

[K. L. Tsakmakidis, *et al*., *Nature* (London) **450**, pp. 397-401 (2007)]

## Ray propagation in metamaterials

The Goos-Hänchen effect occurs when a light beam experiences total internal reflection: The reflected waves of different frequencies are phase shifted by different amounts, which manifests itself as a lateral displacement of the whole pulse at the dielectric interface.

- Between two conventional materials (positive refractive index) the Goos-Hänchen shift is positive (in the direction of energy flow, ***Figure* 2(a)**).
- However in a waveguide containing a conventional material in the cladding and a material with negative refractive index material in the core, the shift is negative (***Figure* 2(b)**), thus reducing the propagation speed of the energy/group velocity, even down to a *complete halt* (***Figure* 2(c)**) !

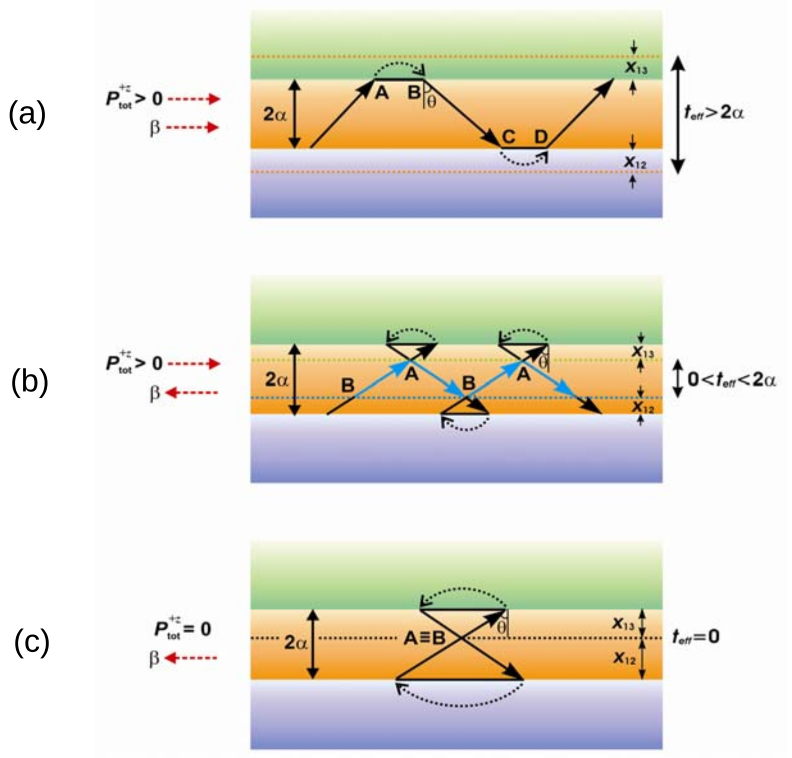

*Figure* 2

## Conclusion

We have shown how guided electromagnetic fields can be brought efficiently to a complete standstill whilst travelling inside axially varying left-handed heterostructures. The scheme involves solid-state materials and, as such, is not subject to low-temperature or atomic coherence limitations.

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