“Slow” light in planar metamaterials

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Abstract: We demonstrate that propagation of microwave pulses can be significantly affected by the presence of a planar fish-scale metamaterial, which is at least 30 times thinner than the wavelength. In the resonant band of the fish-scale structure, a spectrally narrow pulse (18 ns) can be significantly delayed (by 5.6 ns) as if propagating through an 84 cm thick dielectric (ε=3.77), while a short pulse (220 ps) will split in two roughly equal pulses propagating with subluminal and superluminal velocity respectively. We also interpret the response of the metamaterial in terms of effective material parameters.

A light pulse propagating through bulk media may experience delay or acceleration depending on the type of the media. This is a well-known phenomenon resulting from light-matter interaction, which has been extensively studied in the past [1]. We show that a similar effect can be observed in a planar metamaterial - ultimately thin slab of material structured on a sub-wavelength scale. A typical example of such metamaterial is a planar “fish-scale” structure [2], which is a periodic array of continuous wavy metallic strips with translational cell of 15x15 mm placed on top of a 1.5 mm thin dielectric substrate (see inset to Fig. 1a). This type of metamaterial is known to exhibit a sharp resonant response in transmission with strong phase dispersion in the GHz range (see Fig. 1a).

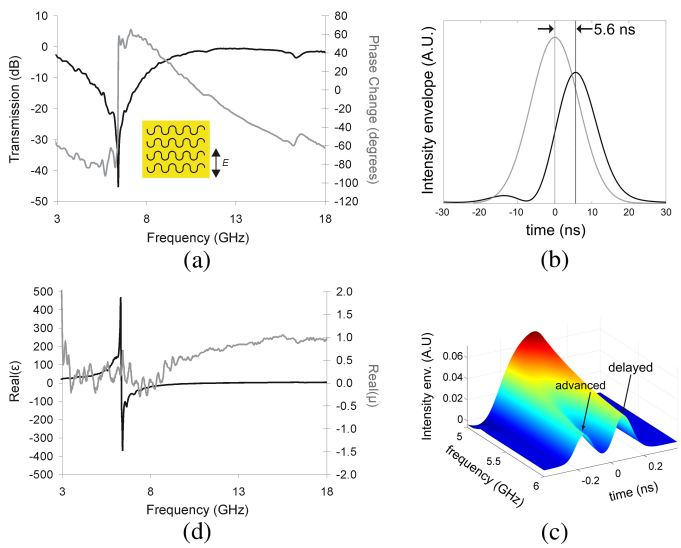

Fig. 1: (a) Amplitude (black) and phase (grey) transmission spectrum for the “fish scale” metamaterial shown in the inset. (c) Response (black, rescaled by 104) to a long Gaussian pulse (grey) at resonance. (d) Response (normalized to the incoming pulse maximum) to a short Gaussian pulse as a function of the pulse center frequency. (d) Effective permittivity (black) and permeability (grey).

Based on the experimentally obtained transmission spectrum, we have analyzed propagation of short (220 ps) and long (18 ns) Gaussian-shaped pulses through the structure using the inverse Fourier transformation technique. For the case of long incoming pulse with the center frequency located at the resonance, the propagation of the pulse through the metamaterial is delayed by 5.6 ns, while the shape of the transmitted pulse changes very little (see Fig. 1b). This would be equivalent to propagation through 84 cm (~18 wavelengths) of substrate (ε=3.77). More interestingly, a short pulse with the same central frequency will split in two approximately equal but shorter pulses traveling correspondingly slower and faster than the incoming pulse (see Fig. 1c).

In addition, we have been able to interpret the response of the metamaterial in terms of effective material parameters, such as permittivity ε and permeability μ. Fig. 1b shows the effective parameters calculated using reflection and transmission spectra of the fish-scale structure. Remarkably, near the resonance (~6.5 GHz) the metamaterial behaves as a very thin dielectric with exceptionally high permittivity (ε >450) and μ< 1, while at 8 GHz both ε and μ are very small with the latter approaching zero. As a result, the values of the effective refractive index will vary strongly near the resonance, ranging from about 13 to almost zero, which is consistent with the large group delay observed for long pulses.

[1] L. Brillouin, Wave Propagation and Group Velocity (Academic Press Inc., New York, 1960).
[2] V. A. Fedotov, P. L. Mladyonov, S. L. Prosvirnin, and N. I. Zheludev, Phys. Rev. **E** 72, 056613 (2005).