Slow Light in "Zero Thickness" Metamaterials

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Abstract: We show for the first time that a classical analogue of EIT can be realized in "zero thickness" planar metamaterials (meta-surfaces) resulting in substantial delay of propagating electromagnetic pulses.

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Here we demonstrate that a classical analogue of EIT can be implemented by appropriately patterning of a thin metal film (planar metamaterial) and significant pulse delays can be observed. The phenomenon arises as a result of engaging high-quality "trapped-mode" resonances [1] of currents in the plane of the material.

Two examples of planar metamaterials that can display such resonances are presented Figs. 1a and 1b. The metamaterials are periodically patterned on a subwavelength scale with a unit cell of 15 x 15 mm size and are supported by 1.5 mm thick dielectric substrates. The first structure is a single-layered array of split ring resonators with asymmetric arc lengths (see Fig. 1a), while the second is a bi-layered "fish-scale" consisting of an array of continuous wavy metallic strips residing on both faces of the substrate (see Fig. 1b). The corresponding experimental transmission spectra are presented in Figs 1c and 1d, respectively. The planar metamaterials exhibit strong normal dispersion in a transmission window (~5.5 GHz) with a 500 MHz bandwidth, as a result of "trapped-mode" excitation. The maximum transmission level is controlled mainly by dissipative losses on the dielectric substrate.

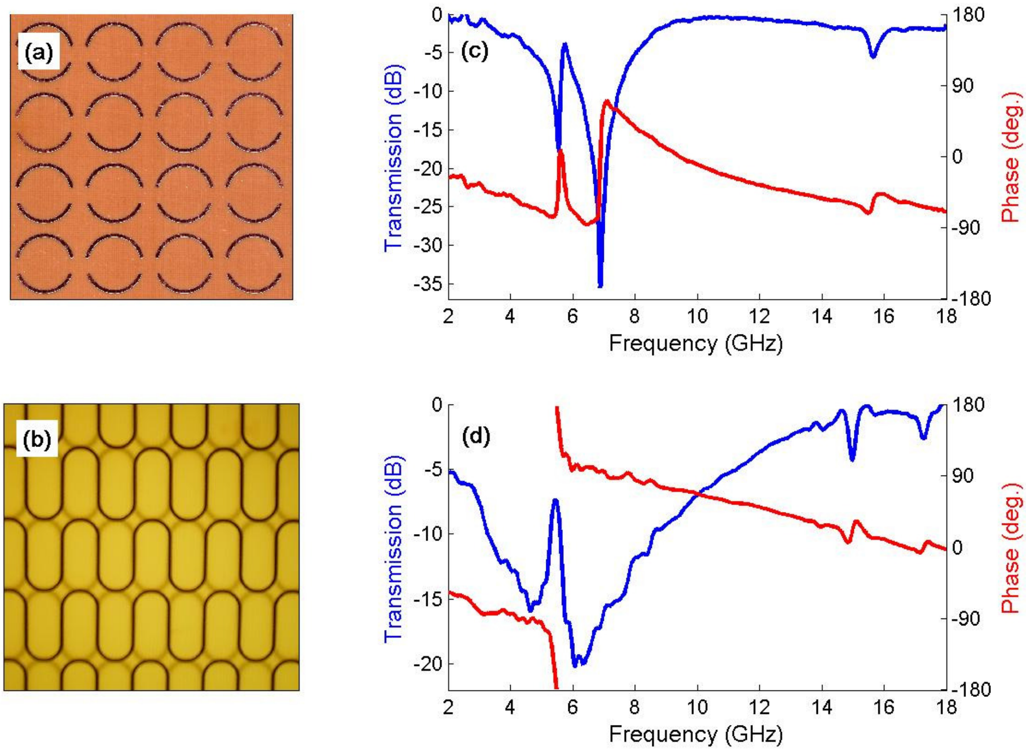

Fig. 1: (a) Transmitted intensity (blue) and phase change for the asymmetrically-split ring array (a) and the bi-layered "fish-scale" (b). The metamaterials are shown in the corresponding insets

The origin of these transmission bands lies in the patterning of the metal surface, which splits the main reflection resonance and leads to a pair of closely-spaced interacting states coupled to the same continuum (free-space radiation). In the split ring array, this is achieved by the different arc length, while in the bilayered fish scale, by the physical displacement of the two metamaterial layers. The spacing of the two states is controlled by the difference in arc length and the separation distance, respectively. The emerging Fano-type interference leads to an out-of-phase current configuration which minimizes the radiation losses of the metamaterials and results in a situation analogous to the dressed state picture of EIT. Contrary to the metamaterial approach, in the latter scheme, the closely-spaced states are not a result of the structure of the medium, but they are created by a pump electromagnetic field, whereas their spacing depends on the pump field intensity. Furthemore, in EIT, absorption is eliminated through quantum interference of probability transition amplitudes, while in the metamaterial case, losses are minimized by classical field interference of counter-propagating currents. Nevertheless, the resulting dispersive profiles share the same origin and lead to similar delay effects.

The dispersive behavior of the metamaterials is further illustrated in Fig. 2, where the response of the bilayered fish scale to a 2.5 ns long Gaussian microwave pulse is presented. The incident pulse is centered at the maximum of the transmission window, whereas its spectral width is limited by group velocity dispersion to about 500 MHz. When the incoming pulse propagates through single slab of planar metamaterial, it experiences a time delay of about 0.7-1 ns, which corresponds roughly to ~0.3-0.4 of the pulse width, with reasonable transmission levels. This is remarkable in view of the vanishing thickness of the metamaterials (35 times thinner than the wavelength), which enables the successive stacking of metamaterial slabs and can lead to significant increase of both transmission and bandwidth. In fact, we observed that when the fish-scale design is cascaded, then each additional layer results in a 500 MHz bandwidth enhancement.

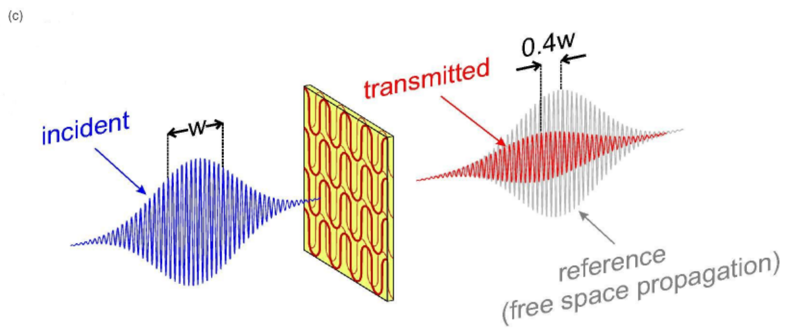

Fig. 2: Example of pulse delay by propagation through a planar metamaterial. Pulse delays of up to 40% of the pulse width can be achieved with a single layer of $\lambda/35$ thickness.

In conclusion, we have shown that the propagation velocity of microwave pulses can be controlled by realizing a classical analog of EIT on a planar metamaterial, which has vanishing thickness along the propagation direction. The use of geometrical resonances enables wide scalability and allows the structure to operate at prescribed frequencies. Such properties render planar metamaterials of this type, potentially useful as ultra-compact optical components.

[1] V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis, and N. I. Zheludev, "Sharp Trapped-Mode Resonances in Planar Metamaterials with a Broken Structural Symmetry," Phys. Rev. Lett. **99**, 147401 (2007).