Slow group velocity in a metamaterial with field-gradient-induced transparency

Yasuhiro Tamayama*, Toshihiro Nakanishi, and Masao Kitano
Department of Electronic Science and Engineering, Kyoto University, Kyoto 615-8510 Japan
**E-mail: tama@giga.kuee.kyoto-u.ac.jp*

Electromagnetically-induced-transparency (EIT) has attracted considerable attention in recent years as a way to achieve extremely low group velocity propagation of electromagnetic waves.[1] EIT is a quantum phenomenon that arises in three-state Λ-type atoms interacting with electromagnetic fields and causes the suppression of the absorption of incident electromagnetic waves in a narrow frequency range. Based on the Kramers-Kronig relations, steep dispersion, or low group velocity, can be achieved in the frequency range.

Since a somewhat complicated arrangement is necessary in order to achieve EIT, a number of studies have focused on mimicking the effect in classical systems, such as optical resonators and metamaterials.[2] However, few studies have focused on the dynamic control of the group velocity in classical EIT-like systems. In the present study, we investigate an EIT-like metamaterial having properties that can be controlled dynamically.[3]

We consider the metamaterial shown in Fig. 1. We focus on two types of resonant modes. One (The other) is the electric dipole (magnetic quadrupole-like) resonance whose current flow is represented by solid (dashed) arrows. The latter resonant mode has a higher Q-value than the former mode because the magnetic quadrupole is less radiative than the electric dipole. These two types of resonant modes are magnetically coupled to each other.

Magnetic coupling occurs between the two types of resonant modes when the field gradient of the incident electromagnetic fields exists. When the x component of the electric field has a gradient in the y direction, the induced current of the low-Q mode becomes y dependent. The difference between adjacent currents creates a magnetic flux through the loop of the high-Q mode and induces anti-parallel currents via the electromotive force. When the plane electromagnetic wave is normally incident on the metamaterial, this coupling vanishes due to the uniformity in the y direction of the currents of the low-Q mode. Thus, only the low-Q mode can be excited. This system is similar to the classical model of EIT.[4] Since the transparency phenomenon is induced by the field gradient of electromagnetic waves, we refer to the metamaterial as a "field-gradient-induced-transparency metamaterial."

The group velocity in the metamaterial depends on the coupling strength between the two resonant modes, and therefore, we can tune the group velocity by controlling the field gradient in the y direction of the incident electromagnetic wave. That is, the group velocity can be changed, for example, by the incident angle of the electromagnetic wave.

We fabricated the metamaterial shown in Fig. 1 using printed circuit board. The thicknesses of the copper layer and the polyphenylene ether substrate (relative permittivity: 3.3) of the printed circuit board were 35 μm and 0.8 mm, respectively. The geometrical parameters were $l_a = 7.8$ mm, $l_b = 11.0$ mm, $l_c = 1.2$ mm, $w_a = 4.0$ mm, $w_b = 2.0$ mm, $w_c = 1.0$ mm, and $g = 0.4$ mm.

First, we measured the transmission spectrum of the fabricated metamaterial using a network analyzer. A layer

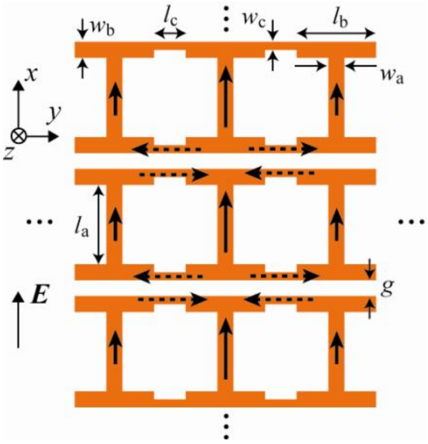

Fig. 1: Metal structure of field-gradient-induced-transparency metamaterial. The solid (dashed) arrows represent the current of low-Q (high-Q) resonant mode.

of the metamaterial, the cross-sectional dimensions in the *x* and *y* directions of which were, respectively, 207.4 mm and 549.0 mm, was placed in a free space. The electromagnetic wave was generated and detected by horn antennas connected to the network analyzer. Figure 2(a) shows the measured transmission spectra for four different incident angles. The transmission peak at 6.8 GHz grows as the incident angle θ increases. (We omit the description of the transmission windows around 3.9 GHz and 9.4 GHz for simplicity.)

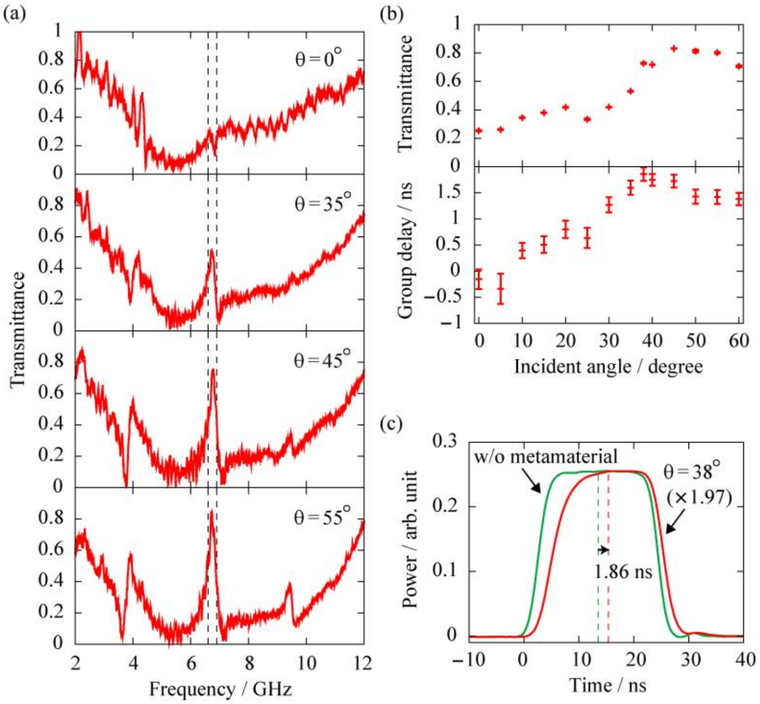

Fig. 2: Experimental results. (a) Transmission spectra for four different incident angles. (b) Dependences of transmittance and group delay on incident angle θ for 6.8 GHz. (c) Envelopes of transmitted pulses.

Then, we performed pulse measurements. We used a signal generator to generate the microwave pulse. The pulse period, pulse width, and carrier frequency were set to be 100 ns, 20 ns, and 6.8 GHz, respectively. The envelope of the transmitted pulse was measured by a microwave diode detector and its output signal was observed using an oscilloscope. Figure 2(b) shows the dependences of the transmittance and the group delay on θ. The group delay reaches a maximum value of 1.86 ns with the transmittance of 0.73 at $\theta = 38^\circ$. Assuming that the thickness of the metamaterial equals that of the substrate 0.8 mm, this group delay corresponds to the group index of 698. The comparison between the envelope of the transmitted pulse for the incident angle 38° and that in the absence of the metamaterial is shown in Fig. 2(c). It is confirmed that the distortion of the transmitted pulse for $\theta = 38^\circ$ is not so large.

We investigated a field-gradient-induced-transparency metamaterial that behaves as an EIT-like medium. The metamaterial consists of an electric dipole resonance and a magnetic quadrupole-like resonance coupled with each other. The coupling between these resonant modes is induced by the field gradient of the incident electromagnetic wave. We experimentally demonstrated that the transparency phenomenon was observed for obliquely incident electromagnetic waves. The slow group velocity of $c_0/698$ (where c_0 is the speed of light in a vacuum) with the transmittance of 0.73 was achieved in the transmission window. In addition, the group velocity was controlled dynamically by the incident angle of the electromagnetic wave.

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