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Storage and retrieval of electromagnetic waves using electromagnetically induced transparency in a nonlinear metamaterial

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We investigate the storage and retrieval of electromagnetic waves using a nonlinear metamaterial, analogous to the electromagnetically induced transparency (EIT) observed in atomic systems. We experimentally demonstrate the storage of the electromagnetic wave by reducing an auxiliary "control" wave; the stored wave is then released by recovering the control wave. We also confirm that the metamaterial can store and reproduce the phase distribution of the original input wave. These effects confirm a remarkable analogy between the metamaterial and an atomic EIT medium. *Published by AIP Publishing.* https://doi.org/10.1063/1.5035442

Electromagnetically induced transparency (EIT) is a nonlinear optical phenomenon whereby an opaque medium is made transparent for a probe light by the incidence of an auxiliary "control" light in an extremely narrow bandwidth.[1,2] In the frequency regions with high transparency, the group velocity of the probe light is dramatically reduced. Characteristic features of EIT, including a narrow-band transparency and slow propagation, have been extensively investigated in quantum systems that are composed of three-level atoms. Slow-light propagation in an EIT medium can be exploited for "optical memory" applications, or for storing and retrieving light by dynamically modulating the control light, whose intensity is proportional to the group velocity of the probe light.[3–6]

Narrow-band transparency and slow propagation can also be realized in other systems such as an optical waveguide coupled with optical cavities[7–9] and optomechanical systems,[10–12] to name but a few.[13,14] Metamaterials composed of artificially designed structures can also mimic the EIT effects observed in atomic systems. Since the experimental demonstration of the EIT-like effect in the microwave frequency regime,[15,16] various types of the EIT-like metamaterials have been reported to operate in different frequency ranges.[17–20] The EIT-like metamaterials can serve various applications, including high-accuracy sensing,[21,22] nonreciprocal propagation,[23,24] and nonlinearity enhancement.[25] For more practical applications, property-tunable metamaterials have been realized using nonlinear diodes,[26] superconductors,[27,28] air-discharge plasma,[29] photocarrier excitation in semiconductors,[30,31] and microelectromechanical systems.[32]

The storage of electromagnetic waves in a metamaterial requires the rapid control of the group velocity. The first demonstration of electromagnetic-wave storage was realized using an EIT-like metamaterial with variable capacitors.[33] The metamaterial had similar functionality to the original EIT medium with three-level atoms, but the transparency or the group velocity was controlled by a bias voltage applied to the variable capacitors, rather than by the electromagnetic waves. In this sense, the effect can be regarded as displaying "static-electric-field-induced transparency." The bias voltage on each constituent, or "meta-atom," should be applied via a bias circuit because a static field cannot propagate in free space. This constitutes a critical obstacle in increasing the number of meta-atoms or extending the frequency range.

Here, we focus on a metamaterial showing the genuine EIT effect, whereby transparency results from the incidence of an auxiliary electromagnetic wave (the control wave). We previously reported the static control of the EIT effect by using control waves via three-wave mixing in varactor diodes included within the meta-atoms.[34] In this paper, we demonstrate the storage and retrieval of electromagnetic waves in the true EIT metamaterial by dynamically modulating the control waves in the same way as in the original atomic EIT systems.

First, we review a conventional method used to mimic the EIT-related phenomena, namely, a narrow-band transparency and slow propagation. EIT-like metamaterials are well described using a coupled-resonator model.[14] It is intriguing that Fano resonances[35,36] can also be explained by this classical model[37,38] because the EIT effect can be regarded as a special case of Fano resonances, where the spectral lineshape becomes symmetric. One of the resonant modes, called a radiative mode, is responsible for directly interacting with propagating electromagnetic waves. The other resonant mode, called a trapped mode, is uncoupled from the external field and is excited only via coupling with the radiative mode. If the resonant frequencies of the radiative and trapped modes are close to the frequency of the incident waves and there is some degree of coupling between them, the waves received through the radiative mode are effectively transferred to the trapped mode. The electromagnetic waves are temporarily stored in the trapped mode and are subsequently re-emitted through the radiative mode. Owing to the high quality factor of the trapped mode, dissipation and scattering are substantially suppressed. In addition, the temporary storage in the trapped mode causes a propagation delay. Consequently, transparency and slow propagation in the metamaterial are realized. If the coupling between two resonant modes depends on a controllable parameter, the energy flow between the radiative and trapped mode can be dynamically controlled. By removing the coupling during

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the interaction with the external waves, the energy in the trapped mode is completely captured in the metamaterial, and thus, storage of electromagnetic waves can be achieved.[33]

Next, we introduce a metamaterial showing genuine EIT, as realized in atomic EIT systems. The metamaterial design, shown in Fig. 1(a), is the same as in our previous work.[34] The directions of the electric field E and magnetic field B of the incident waves are also displayed. The dimension of the unit structure is $120\,\text{mm} \times 25\,\text{mm}$. The structure, made of copper, is fabricated on a dielectric material of thickness $0.8\,\text{mm}$ and permittivity of 3.3. Two nonlinear capacitors, called varactor diodes, whose capacitances are functions of the voltage across the diode, are inserted with opposite directions on the two lateral circuit paths. The metamaterial has three resonant modes: a radiative mode, a trapped mode, and an additional mode called the control mode. The current flow for these modes is illustrated using the dashed lines with arrows in Figs. 1(b)–1(d). The functions of the radiative and trapped modes are the same as those in the conventional EIT-like metamaterials discussed above, but the resonant frequencies, f_r for the radiative mode and f_t for the trapped mode, are notably different. The probe wave (with frequency ν_p) and the control wave (with frequency ν_c) can directly excite the radiative mode [Fig. 1(b)] and the control mode [Fig. 1(c)], respectively. On the other hand, the trapped mode cannot be excited by an incident wave with one frequency only. The transmission of the control wave can be made relatively strong by adjusting ν_c to be located in the tail of the control-mode resonance at f_c.

In the absence of the control wave, the transmission of the probe wave (with $\nu_p = f_r$) is low because of the high radiation loss of the radiative mode. On the other hand, in the presence of an intense control wave, the probe wave becomes mixed with the control wave to produce other components with the frequencies $|\nu_p \pm \nu_c|$ via three-wave mixing in the nonlinear capacitors. If the resonant frequency of the

trapped mode f_t satisfies the condition $f_t = \nu_p + \nu_c$ or $f_t = \nu_p - \nu_c$, the energy received in the radiative mode becomes effectively transferred into the trapped mode owing to the resonance of the generated components. (The proposed metamaterial is designed to satisfy $f_t = \nu_p - \nu_c$.) The reverse process also occurs, and the radiative and trapped modes become coupled via three-wave mixing with the control wave. As a result, the metamaterial becomes transparent for the probe wave.

Figure 2(a) shows a schematic diagram of the experimental setup for performing the transmission measurements and for demonstrating the storage of electromagnetic waves. The resonant frequencies of the radiative, trapped, and control modes are $f_r = 1.05\,\text{GHz}$, $f_t = 0.65\,\text{GHz}$, and $f_c = 0.4\,\text{GHz}$, respectively.[34] The probe and control waves are combined and sent to an open-type waveguide, in which the meta-atoms are placed. The waveguide, designed as a stripline with a height of $25\,\text{mm}$ and a width of $122\,\text{mm}$, supports the propagation of a quasi-TEM mode.[39] A unit comprising a directional coupler and a $5\,\text{dB}$ attenuator is inserted at each port of the waveguide. The attenuators serve to suppress undesired multiple reflections. We utilize the directional couplers followed by frequency filters, which transmit the probe wave, in order to monitor the transmitted and reflected signals for the probe wave.

First, we observed transmission spectra for the probe wave in the presence or absence of the control wave for a single-layer metamaterial. A network analyzer was introduced to acquire spectra for the transmission between points N_1 and N_2 in Fig. 2(a), as the probe waves were swept from 0.8 to $1.4\,\text{GHz}$. The transmission spectra were normalized by a signal transmitted through the empty waveguide. The transmission spectrum without the control wave is shown by a dashed line in Fig. 2(b). A broad transmission dip is observed around the resonant frequency of the radiative mode. The solid line in Fig. 2(b) represents the transmission
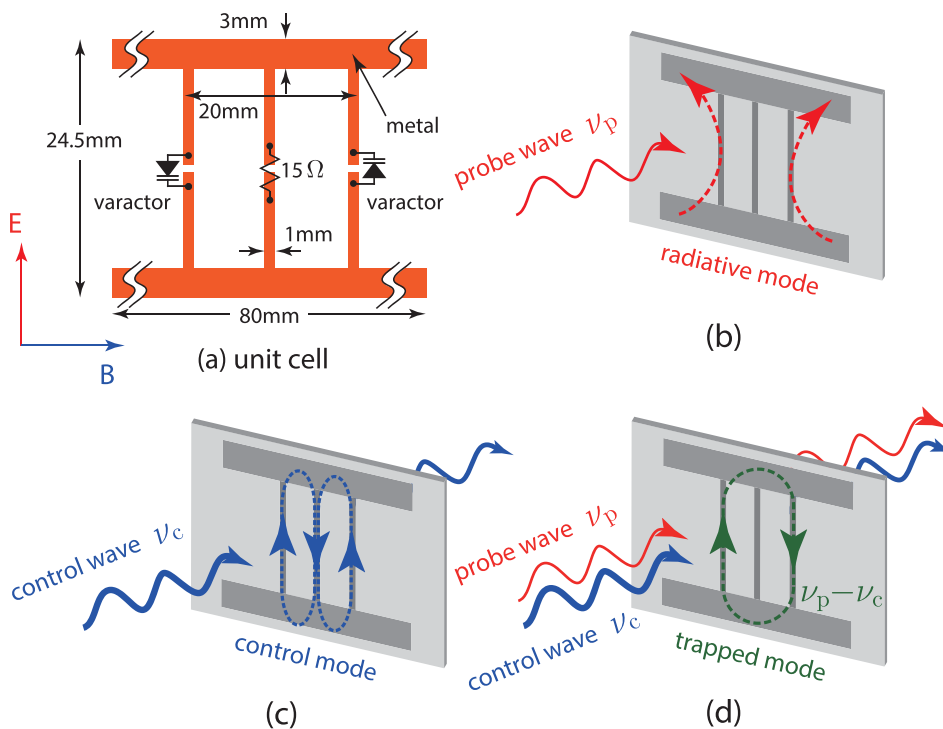

FIG. 1. (a) Structure of a meta-atom and current flow for the (b) radiative, (c) control, and (d) trapped modes.
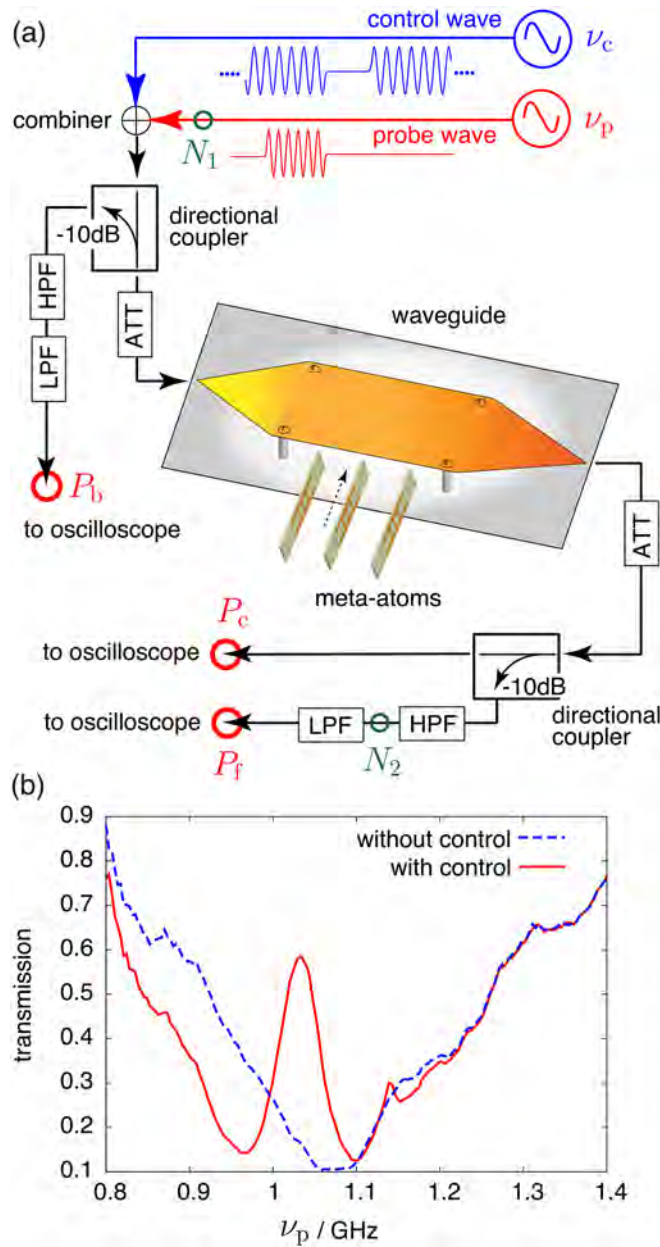
FIG. 2. (a) Overview of the experimental setup. Directional couplers pick up 10% of the transmitted or reflected signal. ATT: 5 dB attenuator. LPF: low-pass filter with an insertion loss of 10 dB at 1.07 GHz. HPF: high-pass filter with an insertion loss of 10 dB at 0.865 GHz. (b) Transmission spectra for the probe wave in the presence or absence of the control wave.

control wave is switched off, so that the probe wave is captured in the metamaterial. This happens because the energy in the trapped mode cannot escape via the radiative mode in the absence of three-wave mixing. After some time period τ, called the storage time, the EIT effect is recovered by reintroducing the control wave. Then, the energy stored in the trapped mode is released into the waveguide through nonlinearity-assisted coupling with the radiative mode. These procedures are notably identical to that for an atomic EIT system.

By way of experimental demonstration, we placed a three-layered metamaterial with a separation of 7.5 cm in the waveguide. The amplitude of the control wave, tuned to $\nu_c = 0.45$ GHz, could be varied using an external controller within several nanoseconds. We prepared a probe pulse of 30 ns duration and carrier frequency of 1.035 GHz, which corresponds to the transparency window in the presence of the control wave. The amplitudes of the probe and control waves at the input port of the waveguide were 260 mV and 1.2 V, respectively. Output signals were acquired using a high-speed oscilloscope connected to ports P_c and P_f in Fig. 2(a). The signal at port P_c was used to monitor the control wave in the absence of the probe wave, and the signal at port P_f (having passed through two filters to remove the control wave and unnecessary harmonic waves) was used to monitor the probe wave. The timing of the control-wave modulation was adjusted to allow the capture of the rear part of the probe pulse.

Figures 3(a) and 3(b) show the observed signals for storage times $\tau = 30$ and 50 ns, respectively, which correspond
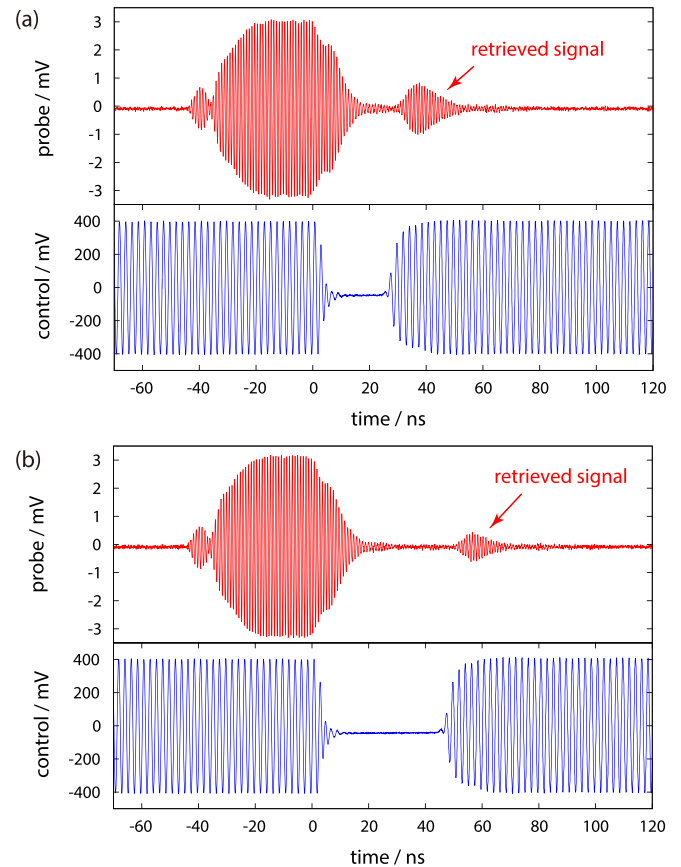
FIG. 3. Storage and retrieval of electromagnetic waves, for a storage time of (a) 30 ns or (b) 50 ns. The upper (lower) graph shows the probe (control) signal at port P_f (P_c).

spectrum in the presence of a continuous control wave with a fixed frequency of $\nu_c = 0.45$ GHz, which is located in the tail of the resonance of the control mode centered at $f_c = 0.4$ GHz and gives a transmission of 88% (not shown in the figure). The amplitude of the control wave is estimated to be 1.2 V at the waveguide input. The observed spectrum clearly exhibits a sharp transparency window around 1.035 GHz. In this case, the intense control wave connects the radiative and trapped modes and consequently induces the EIT effect in the metamaterial.

Next, we describe procedures for storage and retrieval of electromagnetic waves, which can be realized by dynamical modulation of the control wave. The EIT effect is initially activated by illuminating the control wave; the probe wave then travels slowly in the metamaterial. During propagation, the

to the periods without the control wave. The upper and lower graphs in each figure represent the time-domain waveforms at ports P_f and P_c, respectively. The modulation of the control wave can be confirmed in each lower graph. In both cases, the probe-wave signals were reduced when the control waves were switched off. This fact means that the probe waves were captured in the trapped mode, which was decoupled from the radiative mode in the absence of the control waves. After reintroducing the control waves, some signals return, corresponding to the probe waves being released from the metamaterial. The decay rate of the retrieved signals is determined by the lifetime of the trapped mode. In the experiment, ohmic loss in the nonlinear capacitors dominates.

If the metamaterial stores and retrieves the input pulse while preserving the spatial phase distribution, the retrieved signal is released in the forward direction; the backward wave can be suppressed. In order to confirm this effect, or "coherent" storage, we compared the retrieved waves propagating in the forward and backward directions for single- and three-layered metamaterials. The backward signal can be observed at port P_b in Fig. 2(a). The coupler and the filters introduced before port P_b were the same as those for the forward wave, and no calibration was necessary between the forward-propagating wave at port P_f and the backward-propagating wave at port P_b.

The experimentally observed retrieved signals for the storage time $\tau = 40$ ns are shown in Fig. 4. The upper (lower) graphs show the results for the single-layer (three-layered) metamaterial. The graphs in the left (right) column correspond to the forward (backward) waves observed at P_f (P_b).

For the single-layer metamaterial, the amplitudes of the retrieved signals observed in the forward and backward directions are almost the same, as shown in Figs. 4(a) and 4(b), because a single meta-atom releases the stored energy in both directions with equal intensity. For the three-layered metamaterial, the retrieved signal in the forward direction [Fig. 4(c)] is enhanced, while that in the backward direction [Fig. 4(d)] is suppressed. This result is attributed to the interference in the radiation emitted from the multiple meta-atoms. The fact proves that the metamaterial stores and reproduces the probe wave while preserving its phase distribution. The interference in the experiment is not complete because of the insufficient number of meta-atoms, incomplete transparency due to ohmic loss, and inhomogeneity in the control wave.

In conclusion, we have experimentally demonstrated the storage and retrieval of electromagnetic waves by exploiting the EIT effect, implemented with a nonlinear metamaterial designed for operation in the microwave region. The storage of the probe wave was achieved by switching the control wave off during the propagation and the retrieval by recovering the control wave. We also confirmed that the coherence was preserved in the storage and retrieval processes by comparing the retrieved signals released in the forward and backward directions. These facts indicate that the metamaterial has the same ability as the atomic EIT medium. In principle, it should be possible to store the whole pulse more efficiently by increasing the number of meta-atoms and by reducing the undesired dissipation mainly caused by ohmic loss in the nonlinear capacitors. The nonlinear diodes can operate only at low frequencies (e.g., microwaves) but the extension to
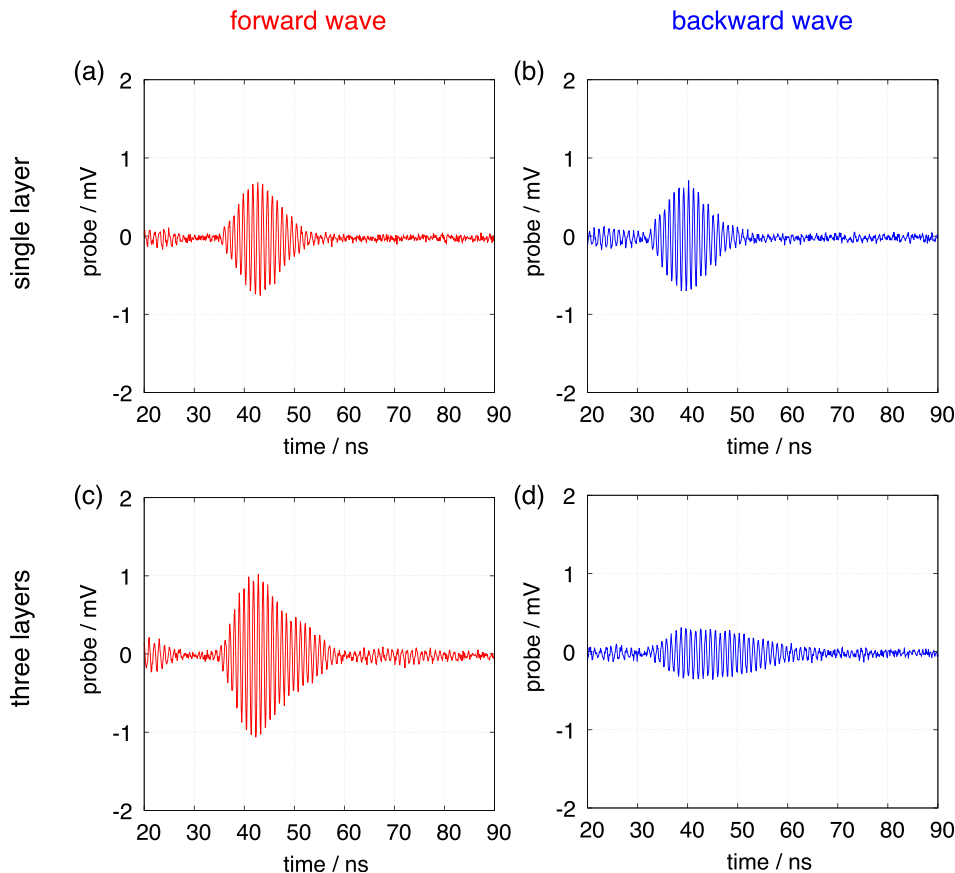

FIG. 4. Signals from a single-layer metamaterial retrieved in the (a) forward or (b) backward directions, and those from three-layered metamaterial retrieved in the (c) forward or (d) backward directions. The storage time is 40 ns.

higher frequencies (e.g., the optical region) can be made possible by incorporating other nonlinear optical effects into the metamaterial.

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