Metamaterial-Induced Transparency

Sharp Fano Resonances and Slow Light

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Inspired by the study of atomic resonances, researchers have developed a new type of metamaterial. Their work paves the way toward compact delay lines and slow-light devices.

Metamaterials—crystalline-like sub-wavelength arrangements of electromagnetic resonators—can exhibit exotic optical properties, such as negative refraction and cloaking, most of which have no counterpart in natural media. Metamaterial structures could one day be used to develop a wide variety of devices with enhanced and unusual functions, ranging from superlenses to electromagnetic cloaks. Metamaterials are also expected to play a key role in the development of all-optical data processing chips.

Now, a new direction has emerged in metamaterial research. Scientists are looking to realize narrow, low-loss resonances and strongly dispersive behavior in planar, two-dimensional structures of sub-wavelength thickness by using interference effects that suppress radiation leakage. These advances will greatly expand the metamaterial playground to encompass sensors, compact delay lines and coherent light-emitting devices.

At the core of this new approach lies an intriguing analogy with the famous quantum phenomenon of electromagnetically induced transparency (EIT). Following the first observation by Fedotov et al. that the electromagnetic response of certain metamaterials provides “another classical analog of the narrow resonances observed in electromagnetically induced transparency,” recent studies show that, by mimicking this quantum phenomenon, the dispersive properties of such planar metamaterials can lead to slow-light propagation and long pulse delays in the microwave, terahertz and optical parts of the spectrum.

Fano resonances: electromagnetically induced transparency and dynamical damping

A typical approach to achieving sharp spectral features involves the so-called Fano resonances that occur due to the interference of different excitation pathways. In the simplest case, Fano interference requires a quasi-bound state coupled to a continuum—which results in two channels of excitation, a direct one and an indirect one through the quasi-bound state. Constructive and destructive interference of these two channels leads to very narrow resonance lineshapes. Such resonances are used in the well-known phenomenon of EIT, where a pump and probe beam are applied at different dipole transitions of an atom vapor that share the same excited state; transitions between the two ground states are not allowed.
The resulting destructive interference of quantum probability amplitudes inhibits absorption and leads to a narrow transparency window in the spectrum of the otherwise opaque atomic medium. As a result, the probe beam can propagate without losses. This resonant transmission peak is accompanied by sharp normal dispersion, which can lead to a dramatic reduction in group velocity and a significant enhancement of nonlinear interactions.

However, scientists’ observations of EIT in atomic gases were restricted to the available atomic resonances, and the work necessitated optical pumping and often cryogenic temperatures. Such requirements severely hinder practical applications, particularly with respect to integration. These obstacles were soon overcome by the realization that the essential physics behind EIT are actually classical, and similar behavior can be observed in very simple systems, such as coupled spring-mass oscillators.

This insight led to the implementation of induced transparency effects in classical optical systems—for example, coupled optical resonators, photonic bandgap crystals and photonic crystal waveguides—that are robust and do not require special experimental conditions. The operation frequency is directly related to the geometry of the structure and can be varied in a wide spectral range through scaling. Nevertheless, in all approaches to classical EIT, the structure extends along the propagation direction of the incident wave, which imposes restrictions on the minimum dimensions of the medium.

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In the case of metamaterials, we used Fano resonances in a planar array of asymmetrically split-ring “metamolecules” that consist of two arcs with different lengths in order to minimize scattering losses and achieve high-quality resonances. Indeed, breaking the symmetry of the split-ring leads to two closely spaced resonances, each of which corresponds to strong excitation of one of the two arcs. When excited by an incident electromagnetic wave, the two arcs support currents oscillating in-phase, apart from a narrow frequency range, where an anti-symmetric current configuration is established due to the coupling of the two resonances.

As a consequence, these anti-symmetric currents radiate fields that interfere destructively, allowing the incident wave to propagate without losses, as signified by a narrow transparency window in the transmission spectrum of the metamaterial. This resonant mode has a long lifetime due to its weak coupling to free-space radiation and therefore appears to be “trapped” in the vicinity of the metamaterial surface—hence the term “trapped mode.” An important consequence of causality restrictions is that, at the metamaterial resonance, the transmission band is accompanied by steep normal dispersion, providing for low group velocities and slow light behavior.

In fact, we showed in a recent study that similar resonances can also be observed experimentally in a bi-layered structure. In this case, the two metamaterial layers can be either identical or very similar, and they are separated by a small sub-wavelength distance along the propagation direction. This displacement allows the two layers to be excited with opposite phases at a specific
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frequency, hence leading to the elimination of scattering losses by destructive interference of the re-radiated fields originating from each layer.

After performing an in-depth investigation of the associated dispersive effects, we demonstrated long pulse delays through a thin metamaterial slab by employing classical EIT. The sharp dispersion that occurred at the trapped-mode resonance allows for electromagnetic pulses to be significantly delayed with very weak distortion of the pulse shape. Remarkably, this effect is possible in a metamaterial layer with thickness many times smaller than the wavelength of the incident wave—which corresponds to a signal velocity within the metamaterial structure about 200 times smaller than the velocity of light in free-space.

Both in single- and double-layer trapped-mode metamaterials, the width of the resonance (and consequently the pulse delay) can be easily controlled through the geometry of the resonant elements. For instance, increasing the difference in arc length (i.e., the asymmetry) leads to further separation of the individual arc resonances, hence broadening the transparency window of the asymmetrically split-ring metamaterial. On the other hand, the properties of a double-layer structure can be tuned by changing the separation, and thus the coupling, of the two metamaterial layers with longer separation distances, leading to broader resonances and shorter lifetimes.

Intriguingly, the response of EIT metamaterials can be represented by a system of harmonic oscillators. In particular, the oscillating currents on the coupled metamaterial elements can be represented by two harmonic oscillators, with a small difference in their resonant frequencies. The oscillators are coupled through soft springs to a third lighter mass, which accounts for the far-field interference of the two layers.

The small mass is also subject to friction, while the two large-mass oscillators are lossless. The system is excited by an external force acting on both large-mass oscillators, representing the incident electromagnetic wave, while friction stands for the scattering losses in the metamaterial. Normally, the small mass will be forced by the large masses to oscillate, for all driving frequencies, leading to dissipation.

However, the difference in resonance frequencies allows for an antisymmetric
mode to be established at a specific frequency, where the two large masses oscillate with large amplitudes and opposite phases. As a result, the small mass experiences a zero net force and remains still. All the energy pumped by the external force is stored in the oscillations of the large masses; the dissipative losses in the system are thus minimized.

After the first demonstration of metamaterial EIT, a somewhat different approach was suggested by X. Zhang’s research group at Berkeley. Their strategy was based on a “plasmonic molecule” that consisted of a radiative element coupled to a sub-radiant “dark” element. More precisely, the radiative element is strongly coupled to free-space radiation and can be easily excited, while the dark element supports a resonant, perfectly anti-symmetric current configuration, which cannot be excited at normal incidence.

However, it becomes accessible through near-field coupling with the radiative element. In this instance, the two interfering pathways include the direct scattering from the radiative element and the indirect scattering mediated by excitation of the dark element. At a narrow frequency band, energy is efficiently stored in the dark element through its near-field coupling to the radiative element. It is re-radiated again through the latter, leading to strong resonant behavior. The width of the resonance is tuned by changing the distance, and subsequently the coupling strength, of the two elements. Finally, it was shown numerically that a 40-fold reduction in pulse velocity can be achieved in the suggested plasmonic metamaterial at the visible part of the spectrum.

H. Giessen’s group from Stuttgart confirmed experimentally the existence of an EIT-like response in the optical part of the spectrum that consisted of similar plasmonic molecules. The researchers used a meta-molecule that consisted of two coupled split-rings. Following the radiative-dark element approach, one of the split-rings was rotated by 90 degrees, so that when one resonator was strongly excited by a linearly polarized wave, the other remained weakly coupled to free-space. Again, the latter element can be excited by the radiative element through electric or magnetic inductance, leading to a situation very similar to EIT. This analogy was unambiguously demonstrated by the same group very recently, by employing a variant of the meta-molecule suggested by X. Zhang.

Theoretical investigations by P. Tasssin and C. Soukoulis’ group expanded the concept of EIT metamaterials in the mid-infrared part of the spectrum. Based on a circuit representation of metamaterial resonators, investigators suggested designs for low-loss, strongly dispersive metamaterials. Electric coupling was demonstrated using single-split and double-split rings lying on perpendicular planes allowed for magnetic coupling. Finally, R. Singh et al. provided further insights into the nature of spectral tunnelling between dark and radiative metamaterial elements in the terahertz domain, where the characteristic EIT behavior was observed experimentally.

Both metamaterial approaches—i.e., trapped-mode and coupled radiative-dark elements—can be considered classical analogs of EIT. Indeed, atomic transitions correspond to the resonances of the meta-molecules, and interference of quantum probability amplitudes translates to classical field interference. In particular, just as the transition amplitudes interfere in the EIT atomic media, the scattered electromagnetic fields from the trapped-mode metamaterial unit...
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In conclusion
Metamaterials are very attractive candidates for compact optical delay and slow-light devices. They combine the rigidity, practicality and scalability of other classical approaches with vanishing dimension along the direction of wave propagation; this makes them well-suited to manufacturing using existing planar fabrication technologies.

References and Resources

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[References and Resources]

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