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COMMENTARY

Controlling electromagnetic metamaterials

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The last two decades have been witness to two exciting and independent developments that have forever changed our conventional view of how light interacts with matter. One relates to coherent control via quantum interference, wherein the possibility of making an otherwise opaque medium transparent [1], now known as electromagnetically induced transparency (EIT), set off intense research activity. EIT essentially requires careful creation of atomic coherence, that results in diverse effects varying from almost freezing light in its tracks (slow light) to freezing atoms to nanoKelvin temperatures via velocity-selective coherent population trapping. The second development relates to metamaterials whose origins are very *classical* in nature. In electromagnetics, these designer materials were originally proposed for realizing a super-lens wherein the evanescent field becomes the work horse that accords sub-wavelength resolution in imaging [2]. Since then a variety of metamaterials have been proposed, where even the propagating fields can be dramatically controlled, as in electromagnetic cloaks wherein the fields are maneuvered around an obstacle so as to make it invisible. The biggest technological contraints in realizing large-scale device applications of metamaterials have been two. The first is the large dissipation associated with an inherently resonant phenomenon. The second arises due to the very design of metamaterial; once the metamaterial structures (inclusions) are fabricated, they offer little maneuverability in terms of the operating frequency.

However, both EIT and metamaterials have truly lifted the tedium associated with the *usual* classical linear phenomena involving light. It is commonly believed this is just the beginning of a long journey, where our inherent drive to control gainfully these and many other wondrous effects will be the prime mover of future developments. The marriage of these two diverse developments is highlighted here, with a word of caution: one can only naively guess the surprises this relationship will bring forth.

In order to achieve a composite material combining the attributes of EIT and metamaterials, one simple design involves immersing the metamaterial in a dilute atomic gas whose frequency-selective absorption can be exploited to manipulate the metamaterial response [3]. Furthermore, a combination of light fields accords extra control over the metamaterial via the absorption and dispersion of the atomic gas through the atomic coherence (quantum) route, based on effects like EIT. The price of working at near-resonant conditions is the large dispersion with frequency accompanied by large loss. EIT-based control exploits the large frequency-dispersion and yet provides substantially decreased loss which is even lower than the metallic losses in a narrow-bandwidth regime. The large variation of the refractive index of the EIT medium results in the freezing of currents in the metallic inclusions of the metamaterial, thereby lowering loss.

The most critical issues that govern this alliance arise from the very nature of the two partners. EIT is a quantum phenomenon, whereas metamaterials are described classically. Quantum phenomena are extremely susceptible to the surroundings, and using a solid or liquid medium severely restricts the performance of the quantum partner. For example, rare-earth ions implanted in crystals have been shown to exhibit EIT only at extremely low temperatures where the phonon noise is sufficiently suppressed such that the ground-state

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coherence is carefully preserved to exhibit EIT. Proposals involving an EIT layer near the interface of a dielectric and a negative-refractive-index metamaterial promise low loss as well as spatial confinement to store light pulses [4]. However, other resonant phenomena which are not as susceptible to the environment can also be used, a summary of various paradigms of control discussed in this commentary are schematically indicated in Fig. 1.

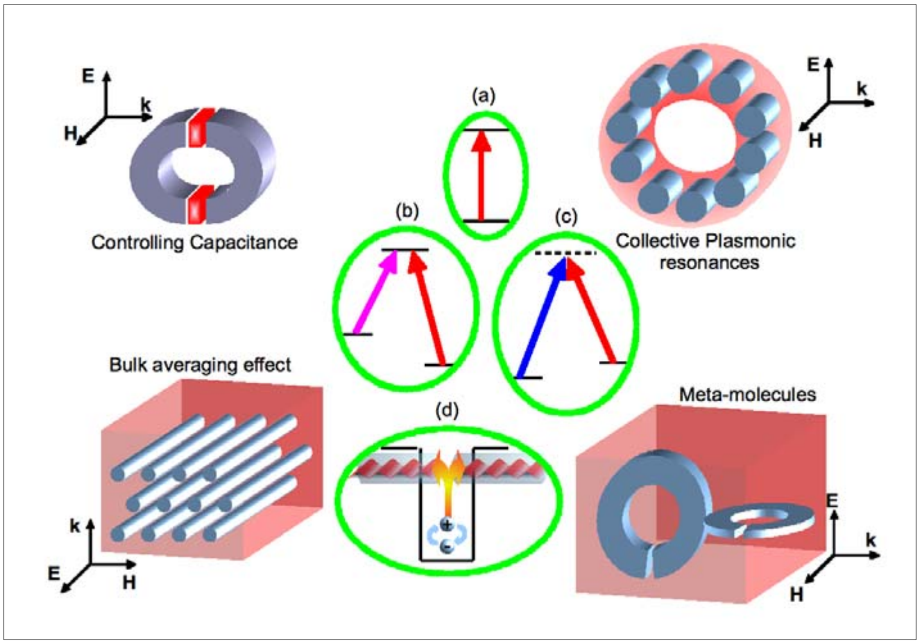

Fig. 1. A schematic of various control paradigms in metamaterials, where the inclusions are immersed in a background medium whose characteristics can be controlled by an external field thus transforming the response of the composite system. A variety of metamaterial characteristics—such as the capacitance of split-ring resonators (top left), the collective response of plasmonic nanorod arrays (top right), the bulk averaged permittivity of a dilute metal comprising nanorods (bottom left), or the classical-EIT like response of meta-molecules (bottom right)—can be completely transformed by making the background medium dispersive. Such a background medium, which transforms the response of the composite metamaterial, could consist of (a) entities—such as atoms, molecules or quantum dots—that provide a sharp resonant response at the propagating (probe) field frequency indicated in red color; (b) atoms that exhibit EIT at the probe frequency (red) in the presence of a control field (magenta); (c) atoms/molecules which can be driven by a Raman pump field (blue) thus offering a tunable response at the probe (red) frequency; or (d) semiconductor quantum wells coupled to individual metamaterial inclusions that rely on the exciton-plasmon excitation for control.

A further challenge arises is the manner of coupling between the two partners. By immersing a metamaterial—which comprises, for instance, split-ring resonators (SRRs)—in a dilute atomic gas, the *capacitance* of the gap in every SRR is modified because it is now occupied by the atomic gas. When the resonant response of the atomic gas matches (spectrally) well with the response of the SRR, the consequences are dramatic [3]. These include a host of effects resulting from the background atoms and include near-100% modulation of the dispersion and modification of the band structure.

Another way to control the composite response is to control the *inductance* and such ideas have been realized wherein the SRR structure is fabricated on a semiconductor material, whose conductivity controls the response of the metamaterial [5]. The resonance frequency of the metamaterial can be tuned within a 20% range by controlling the conductivity by photoexcitation of charge carriers within the semiconductor. The maturity of semiconductor technology makes this a preferred technique that offers flexibility of actively addressing individual metamaterial inclusions. However, this flexibility would come at a huge cost as addressing the subwavelength-sized SRRs individually is not only quite complex but the associated circuitry could also degrade the very nature of the metamaterial response.

At visible and near-infrared frequencies, the distinction between capacitance and inductance becomes obscure. Instead, the *plasmonic* resonances of nanoparticles provide the resonant response of a metamaterial. A regular arrangement of nanoparticles on the circumference of a circle allows coupling to the out-of-plane magnetic field via the collective excitation of their plasmonic resonances [6]. Again, a resonant background can effectively tailor this collective excitation. Ellipsoidal nanoparticles could be used for decreased inter-particle separation (with increased capacitive linkages), thereby enhancing the effect of the background resonance on the collective excitations. The materials could be fabricated using a host of techniques like ion-beam lithography, electron-beam lithography and laser-assisted etching. The materials could also be realized as stable arrays of colloidal nanoparticles, wherein the size, shape, and inter-nanoparticle separation can be controlled and the accompanying background can be doped with another resonant species.

The quality and extent of control largely depends on the background atomic medium: namely, the strength of its resonant response, the resonance linewidth, its spectral proximity to the metamaterial resonance, and the manner of coupling. For example, a dilute metal can be made to transmit light by immersing it in the right background medium. When an array of metallic nanorods (dilute metal) is immersed in a background resonant species, the resonant positive real part of the background permittivity offsets the negative contribution of the metal. Such simple juxtaposition of positive and negative contributions of materials with the right volumetric proportions can result in novel composite materials with control [7]. This scheme, which involves the introduction of excess loss in order to make a medium transparent, is rather counterintuitive. Note that any resonant phenomena that provides large positive permittivity can be exploited to achieve such control.

Yet another approach to control arises from coupled metamaterial units so as to classically mimic a response akin to EIT. Two metamaterial units with distinctly different linewidths are coupled to form a *meta-molecule* [8]. One unit couples to the free-space propagating mode of the radiation (radiative element), while the other is coupled *only* via the near field of the radiative element. The radiative element has typically a much larger linewidth than the one coupled via the near field. An interplay of the two units mimics the quantum EIT in the classical domain. Immersion of meta-molecules in a resonant background medium would offer additional control.

There are immense possibilities ahead and some of the promising directions are indicated here. The Raman (two-photon) resonance is particularly attractive as one of the Raman fields could be tuned so as to lie in the passband of the metamaterial and thus be far from any single-photon resonant band. This field would experience little attenuation and would provide a tunable (two-photon Raman) narrow linewidth resonance as the background control medium. Metamaterial inclusions which adsorb molecules that exhibit surface-enhanced Raman scattering could offer even larger oscillator strengths and could be effectively used for control. Furthermore, metamaterials could be used to enhance the semiconductor based plasmon-exciton mixed states which, in turn, could enhance the spontaneous emission rates and thus offer another promising avenue of control [9]. The nonlinear optics of metamaterials [10] is still a nascent area of research, and with the advantages of field enhancement, novel notions relating to phase matching of evanescent fields and the ability of phase reversal (phase engineering) could be cleverly exploited for control. Research activity in these directions would hopefully lead to realization of frequency agile, reconfigurable, low-loss, multifunctional metamaterials.

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