Cooperative Asymmetry Induced Transparency in Ensembles of Interacting Plasmonic Resonators

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Abstract

We develop a theory of Cooperative Asymmetry Induced Transparency (CAIT) in a finite array of interacting meta-molecules. An asymmetry in the meta-molecule geometry provides an effective coupling between system modes opening a transparency window in the material. In contrast with similar EIT like phenomena in meta-materials that can be described by meta-molecules acting independently, CAIT relies on cooperative interactions to form the high quality modes on which the transparency depends. The sensitivity of CAIT on collective modes is consistent with recent experimental observations.

1. Introduction

An otherwise opaque or reflective material can be made transparent by coupling two material states. An incident probe field excites one of these states which would scatter the light in the absence of coupling; while the other is stable and cannot be directly addressed by the probe. In a transparency window, the coupling induces excitation of the stable state at the expense of the optically active excitation, thereby suppressing scattering of the probe. The most well-known example of this phenomenon is electromagnetically induced transparency (EIT), in which a control laser field provides the inter-state coupling. Such coupling induced transparency has also been proposed [1] and observed [2, 3, 4] planar metamaterials. Rather than atoms as the constituent electromagnetic (EM) resonators, sub-wavelength arrangements of circuit elements, or meta-molecules, serve as the building blocks of these metamaterials. Each meta-molecule supports two modes of current oscillation: one of which is driven by the probe, and one which is blind to the probe. An effective coupling between these two modes can be achieved by engineering the meta-molecules' geometry [4, 1], and in particular can be induced by breaking of the meta-molecules' symmetry [2, 3]. The models [1, 2, 4], however assume the blind mode of a single meta-molecule is itself radiatively stable. For some meta-molecules, notably asymmetric split rings (ASR)s, this assumption does not hold. Here, we develop a model for an array of meta-molecules where the stable excitation responsible for coupling induced transparency emerges from a *collective* mode distributed over the entire metamaterial. We arrive at this model from the framework to describe large numbers of discrete scatters in a metamaterial presented in Ref. [5]. The dependence on the collective mode explains the experimentally observed sensitivity of the transparency window to system size [6] and disorder in the array [7]. Whereas both modes of a single meta-molecule radiate, the interactions between them form a stable collective mode blind to the incident field which facilitates CAIT.

2. Model Description: Collective modes in a sheet of asymmetric split rings

We consider an ensemble of N asymmetric split rings arranged in a lattice in the xy plane. Each ASR consists of two concentric circular arcs of nearly equal length separated by a distance a in the x-direction.

The right and left arcs, or meta-atoms labelled by indices r and l respectively, comprising the ASR support associated single modes of current oscillation producing electric dipoles with orientation $\hat{\mathbf{d}}_r = \hat{\mathbf{d}}_l = \hat{\mathbf{y}}$ and magnetic dipoles with opposite orientations $\hat{\mathbf{m}}_r = -\hat{\mathbf{m}}_l = \hat{\mathbf{z}}$. The electric and magnetic dipoles contribute respective radiative decay rates Γ_E and Γ_M to the total decay rate Γ of a single meta-atom in isolation. The asymmetry of the arcs manifests itself as a difference between single meta-atom resonance frequencies, with those of the right and left meta-atoms given by $\omega_r = \omega_0 + \delta\omega$ and $\omega_l = \omega_0 - \delta\omega$, where ω_0 is a reference frequency. A uniform EM probe field propagating in the $\hat{\mathbf{z}}$ direction with polarisation $\hat{\mathbf{y}}$ along the electric dipoles impinges on the sheet.

A single ASR possesses two modes arising from the interaction between the arcs. In the absence of asymmetry ($\delta\omega = 0$), these eigenmodes consist of equal excitations of the two arcs. In the symmetric mode the two halves oscillate in phase producing a net electric dipole. While in the other, they oscillate out of phase producing a net magnetic dipole. The probe field drives the symmetric mode leaving the magnetic dipole mode unaffected. These modes radiatively decay at rates $2\Gamma_E$ and $2\Gamma_M$ respectively. Introducing an asymmetry, $\delta\omega \neq 0$, produces an effective driving between the electric and magnetic dipole excitation [5].

Here, we assume that the ASRs are separated by less than a wavelength, thus enhancing the role of interactions mediated by the scattered fields. The regularity of the lattice results in collective modes of oscillation distributed over the metamaterial, each at a particular frequency and radiative damping. The incident EM field preferentially drives modes to which it is phase matched, *i. e.* those in which all meta-molecules oscillate in phase. For sufficiently large arrays [5], the material supports two such modes: the phase matched electric (PME) mode consisting of electric dipole excitations with resonance frequency ω_E and decay rate γ_E, and phase matched magnetic (PMM) mode with frequency ω_M and a suppressed decay rate $\gamma_M < \Gamma_M$. The PME mode largely emits out of the plane and therefore causes reflection of the incident probe field. The radiation from the magnetic dipoles comprising the PMM mode, on the other hand, tends to remain trapped as it is repeatedly scattered between meta-molecules in the plane. This leads to a decay rate of that mode which becomes ever more suppressed with larger arrays [5]. Furthermore, the electric dipole amplitudes in the PME mode closely match the corresponding magnetic dipole amplitudes of the PMM mode. The presence of the asymmetry, $\delta\omega \neq 0$, therefore provides an effective coupling between these two modes. While in principle, the asymmetry also couples the phase matched modes to other collective modes, for sufficiently large arrays, this additional coupling is minimal and can be neglected. The amplitudes of the PME c_E and PMM c_M modes obey the equations of motion

$$\frac{dc_E}{dt} = \left[-i\omega_E - \frac{\gamma_E}{2}\right] c_E - i\delta\omega\, c_M + F(t), \tag{1}$$

$$\frac{dc_M}{dt} = \left[-i\omega_M - \frac{\gamma_M}{2}\right] c_M - i\delta\omega\, c_E, \tag{2}$$

where $F(t)$ is the driving of the PME mode induced by the probe field.

3. Results

To illustrate how the coupling between these collective modes results in CAIT for the probe field, we examine how the PMM and PME modes respond to monochromatic driving. Fig. 1 shows that when the inter-ASR interactions result in a sufficiently small γ_M, a window opens in which the incident field excites the high quality PMM mode at the expense of the PME mode. Since the PME mode is not excited, the electric dipoles responsible for reflection and scattering or the field are not active and the material becomes transparent to frequencies within that window. It was shown in Ref. [5] that γ_M decreases with the number of ASRs in the lattice. By examining the response for two values of γ_M, one sees that the higher decay rate associated with smaller arrays qualitatively accounts for the dependence of transmission resonance's width on system size observed in Ref. [6]. The influences of non-phase matched modes on the dynamics may become important in certain circumstances, particularly for smaller systems. Their effects are under investigation, and the results will be presented elsewhere.

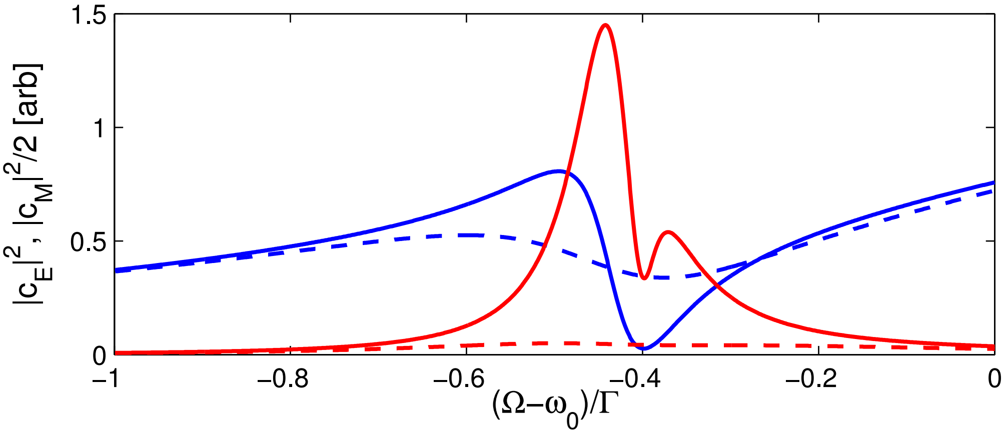

Fig. 1: The energy of the Phase-matched electric mode $|c_E|^2$ (blue) and the scaled energy of the phasse matched magnetic mode $|c_M|^2/2$ (red) as a function of driving frequency Ω. The frequency and spontaneous emission rate of the PME mode are $\omega_E = \omega_0 + 0.4\Gamma$, and $\gamma_E = 2\Gamma$ respectively, while the frequency of the magnetic mode is $\omega_M = \omega_0 - 0.4\Gamma$. The asymmetry parameter $\delta\omega = 0.25\Gamma$. The energies are shown for two values of PMM mode decay rates: $\gamma_M = 0.025\Gamma$ (solid lines) and $\gamma_M = 0.25\Gamma$ (dashed lines). This demonstrates that a high quality PMM mode is required in order to obtain a transparency window, and that in the transparency window, the PMM mode is excited at the expense of the PME mode.

4. Conclusion

We developed a theory of Cooperative Asymmetry induced transparency in a finite lattice of interacting asymmetric split ring meta-molecules. Unlike typical EIT, which is formed through coupling to a stable excitation in a single emitter, CAIT depends on cooperative interactions between meta-molecules to form a stable collective mode distributed over the entire system. This model provides insight into recent experimental results [6].

References

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