Switching a plasma-like metamaterial via embedded resonant atoms exhibiting electromagnetically induced transparency

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We theoretically demonstrate control of the plasma-like effective response of a metamaterial composed of aligned metallic nanorods when the electric field of the incident radiation is parallel to the nanorods. By embedding this metamaterial in a coherent atomic/molecular medium, for example silver nanorod arrays submerged in sodium vapor, we can make the metamaterial transmissive in the forbidden frequency region below its plasma frequency. This phenomenon is enabled by having Lorentz absorbers or other coherent processes like stimulated Raman absorption in the background medium which provide a large positive dielectric permittivity in the vicinity of the resonance, thereby rendering the effective permittivity positive. In particular, processes such as electromagnetically induced transparency are shown to provide additional control to switch and tune the new transmission bands.

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OCIS codes: 160.3918, 270.1670.
Metamaterials displaying novel electromagnetic properties at predetermined frequencies have generated considerable interest [1]. The geometric structure of the metamaterial units support localized electromagnetic resonances that is at the heart of their unique and enhanced response. This has resulted in novel phenomena such as negative refractive index [1, 2], electromagnetic invisibility [3], subwavelength imaging using superlenses [4] etc. As metamaterials rely on their geometric configuration for their enhanced properties, they suffer from the drawback that once the structure is fabricated the properties are fixed. Futuristic applications of these structured materials would require frequency agile, reconfigurable metamaterials with dynamic control [9].

Recently, there have been a few proposals for the dynamic control of metamaterial response using various physical processes. These include using Kerr nonlinearities [5], photoconductivity of semiconductor inclusions [6], magnetostrictive effects [7], liquid crystal inclusions [8], coherent control schemes [9] and optical gain [10]. Parametric control of the metamaterial via embedded atomic/molecular media driven to coherence offers unique possibilities, in that, the dispersion and dissipation of the metamaterial can be dramatically transformed by applied electromagnetic radiation [9]. Coherent control schemes exploit the quantum mechanical response of the embedded atoms/molecules by carefully creating interfering pathways within the atoms. This has been used to show various counter-intuitive effects such as Electromagnetically Induced Transparency (EIT) [11], ultra-slow light [12] to superluminal light [13], enhancement of the index of refraction [14], etc. in homogeneous atomic gases and vapours. We have recently shown that appropriate inclusion of resonant atomic/ molecular media within the metamaterial units can enable dynamic parametric control of the metamaterial properties [9].

In this letter, we consider a periodic array of parallel metallic nanorods with subwavelength periodicity that effectively behaves like a plasma at optical and near infra-red (NIR) frequencies for the radiation with the electric field aligned along the rods as shown in Fig. 1. When this metamaterial is embedded in an appropriate resonant medium, its plasma-like response can be switched and a transmission band opens up below the cut-off (plasma) frequency. Resonant processes such as EIT are used to tailor the properties of this transmission band.

It is well-known that the low frequency plasma-like response of sparse, conducting subwavelength thin wire meshes [15] arises due to (i) a lowered effective electron density ($N_{\text{eff}}$)
as the conducting medium is sparse, and (ii) an enhanced effective electronic mass ($m_{\text{eff}}$) that owes to the large inductance of the thin wires. The resulting effective plasma frequency $\omega_p^2 = (N_{\text{eff}}e^2)/(\epsilon_0 m_{\text{eff}})$ can range from a few gigahertz to a hundred terahertz depending on the geometry. At optical and NIR frequencies, however, most bulk metals behave dominantly as plasmas rather than as Ohmic conductors. As the electromagnetic fields penetrate well into the metal wires, any effects arising due to the enhanced effective mass become less pronounced and the plasma frequency depends only on the volume fraction occupied by the metal (filling fraction, $f$). This behaviour as a dilute metal is evidenced by the band structures shown in Fig. 2(a) for an array of silver nanorods. A higher metallic filling fraction results in a larger plasma frequency ($\text{Re}(\epsilon_{\text{eff}}) > 0$ for $\Omega > \omega_p$ in Fig. 2(a)).

Arrays of metal nanorods comprise one of the simplest optical metamaterials that display plasma-like behaviour. Large scale ordered and aligned silver nanowire arrays can be obtained, for example, by pulsed electrodeposition in porous alumina [16]. Alternatively,
vertically aligned columnar silver nanorods as schematically suggested in Fig. 1 have been grown on substrates using glancing angle e-beam deposition [17]. The effective dielectric permittivity of the *dilute metal*, for radiation with the electric field along the nanorods, is given by

$$\varepsilon_{\text{eff}} = f \varepsilon_m + (1 - f) \varepsilon_b$$  \hspace{1cm} (1)

Here, the filling fraction $f = \pi r^2 / a^2$, where $r$ is the radius of the circular rods and $a$ is the periodicity of the square lattice, $\varepsilon_m$ and $\varepsilon_b$ are the dielectric permittivities of the metal and the nonconducting background medium, respectively. The effective plasma frequency ($\omega_p$) of the metamaterial is obtained by the condition $\varepsilon_{\text{eff}} = 0$. It is seen in Fig. 2(a) that propagating modes arise only when $\text{Re}(\varepsilon_{\text{eff}}) > 0$, and in Fig. 2(b) that $\text{Re}(\varepsilon_{\text{eff}})$ given by Eq. (1) reproduces the transmittance through a slab of two layers of silver nanorods with reasonable accuracy. This agreement assumes significance in view of the ongoing debate on the nature and applicability of homogenization theories to such thin-wire metamaterials at optical frequencies [18, 19, 20]. The field maps calculated by finite elements method with perfectly matched boundary layers confirm the plasma-like behaviour where there is very little penetration within the rod arrays below $\omega_p$, while the fields are transmitted across the nanorod array above $\omega_p$ (see Fig. 2, bottom panels).

Usually $\text{Re}(\varepsilon_m)$ is a negative number with a large magnitude at optical and NIR frequencies and a small filling fraction of the metal is sufficient to render $\varepsilon_{\text{eff}} < 0$, as can be deduced from Eq. (1). If the embedding medium, however, had a resonance below the effective plasma frequency, the resonant enhancement of the $\text{Re}(\varepsilon_b)$ in the positive regime could offset the negative contribution of the metal. The metamaterial as a whole would now act as a positive dielectric medium and display a transmission band at frequencies within the width of the resonance below the resonance frequency. Note that the transmission band occurs below the plasma frequency of the bare plasma metamaterial. It is, indeed, counter-intuitive that introduction of a lossy resonance can induce the medium to be more transmissive.

Resonant enhancement of the positive permittivity of the background material can be achieved by various means: Examples range from off-resonant Raman transitions to simple resonant absorption by the atoms / molecules and coherent processes like EIT. Let us consider a specific and realistic case of silver nanorods submerged in a background of atomic sodium gas that is readily accomplished by placing the nanorod array within a vacuum cell infused with sodium vapor. For the frequencies of the $D_1 - D_2$ lines of sodium, we construct
Fig. 2. Top panels: (a) Bandstructure of the silver nanorod metamaterial and (b) Transmittance from an array containing four layers of nanorods, for various filling fractions of silver calculated using the transfer matrix method. The polarization is such that the electric field is along the rod axes. The Re(\(\varepsilon_{\text{eff}}\)) and transmittance calculated for a homogeneous slab of effective medium as given by Eq. (1) are also shown by thin lines in (a) and (b) respectively. Bottom panels: The electric fields (in arbitrary units) within the rod array for a plane wave incident from the bottom. The radiation does not penetrate for frequencies (left, 535 THz) below the plasma frequency5 (middle, 537 THz) while it propagates across for higher frequencies (right, 540 THz).
a *dilute metal* (nanorod array) with a plasma frequency $\omega_p > \omega_{D_1, D_2}$. A filling fraction of $f = 0.174$ completes the prescription for a silver nanorod array. For example, we consider a metamaterial with a square unit cell of $a = 120 \text{nm}$ and consisting of four square silver nanorods with sides of $b = 25 \text{nm}$ per unit cell. It is estimated that one can achieve a maximum of $\epsilon_b \sim 2.2$ near the resonance for pressure broadened sodium with a number density of $\sim 1 \times 10^{17} \text{cm}^{-3}$ \cite{22}. Using such a background medium, our formula predicts a maximum of $\epsilon_{\text{eff}} \sim 0.86$, i.e., it leads to a positive dielectric permittivity band below $\omega_p$.

There are alternative proposals for the creation of a transmission band below the plasma frequency, but for homogeneous plasmas. Harris \cite{21} has proposed that processes analogous to EIT in atoms can be used to drive a longitudinal plasma oscillation in an ideal plasma, giving rise to a pass band below the plasma cutoff. Agarwal and Boyd \cite{22} have proposed the elimination of the negative dielectric bandgap in a resonant homogeneous optical medium by EIT effects. In contrast, we address plasma-like metamaterials that are inhomogeneous by construction and utilize the resonant enhancement of the positive dielectric permittivity of the background medium.

We now present numerical solutions for a plasma metamaterial consisting of silver nanorods immersed in a background vapour of sodium. We use nanorods of square cross-sections to avoid stair-casing effects on a square grid, while of course, maintaining the required filling fraction. The calculations are essentially two-dimensional within the plane perpendicular to the axes of the cylinders. Invariance along the cylindrical axes was assumed and the calculations were performed using the transfer matrix method \cite{23}. We have used experimentally determined values for the dielectric permittivity of silver \cite{24} and the sodium vapour \cite{25} in our calculations. In Fig. 3, new propagating bands below the effective plasma frequency ($\sim 650 \text{ THz}$), in the presence of the resonant sodium vapour, are shown. Fig.3(a) shows the band structure for the composite plasma metamaterial and Fig.3(b) shows the transmittance from a slab of four layers of this metamaterial. Narrow transmission bands are found to develop at $\sim 508.805 \text{ THz}$ and $509.335 \text{ THz}$ corresponding to the frequencies of the $D_1$ and $D_2$ lines of sodium respectively.

Application of another control radiation field can dramatically transform the dielectric response and the dispersion of the sodium lines via coherent processes like EIT. The control field for EIT can be readily applied in the scheme Fig. 1 that either propagates along the nanorod axis or co-propagates with the probe field, but with the magnetic field oriented
Fig. 3. (a) Band structure for s-polarized light with the metamaterial immersed in atomic sodium showing the new transmission band that develops below $\omega_p$, for the $D_1$ and $D_2$ lines. (b) The reflectance and transmittance corresponding to the band structure in (a). (c) along the nanorod axis. Application of a control field with a Rabi frequency $\Omega_c = 10\gamma$ is shown to tune and switch the transmittive bands of the $D_1$ and $D_2$ lines in Fig. 3(a) and 3(b). The intensity of the control field is used as a control parameter to switch the transmission. We find that the observed effects are reasonably independent of the exact location and distribution of the nanorods in the unit cell, as long as the filling fraction remains unaltered. We also note that plasma-like metallic metamaterials with even larger filling fractions can be also switched using a coherently enhanced refractive index for the background atomic gas [14]. Finally and crucially, we also would point out that the present proposal for switching the plasma metamaterial depends on making the effective permittivity positive through a bulk volume averaging process. This is very different from our previous work [9] on parametrically transforming the resonances of the metamaterial units via coherent processes.

In conclusion, we demonstrate the possibility of introducing a propagating band below the plasma frequency by coherent optical processes in a composite metallic nanorod array with a resonant atomic background. The resonant response of the positive permittivity of the background medium can be sufficient to cancel out the negative permittivity of the dilute plasma leading to a net positive effective medium permittivity. Coherent optical processes such as EIT are used to further engineer this new transmission band.
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