THz metamaterials made of polaritonic materials

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Abstract

In this paper we demonstrate through simulations a variety of phenomena and possibilities that can be realized in THz metamaterials made of polaritonic materials. Such phenomena include hyperbolic dispersion relation, sub-wavelength imaging using backward propagation and backward radiation, and total transmission, reflection and subwavelength guiding exploiting subwavelength Mie resonances. The particular systems that we use to demonstrate these phenomena are two-dimensional periodic systems of μm-scale rods in a host, where both rods and host are made of polaritonic alkali-halide materials.

1. Introduction

The emerging technologies of the THz sources along with the unique properties and capabilities of the THz radiation, especially in security, sensing and communications, increase more and more the demand for the realization of components for the manipulation of THz waves.

Since the majority of natural materials do not show strong response to the THz waves, and so they do not offer themselves for a straightforward THz component realization, metamaterials, which possess geometry induced resonances that can be easily adjusted by adjusting the size of the metamaterial basic building block, can offer an excellent solution of the problem. Moreover, the richness in the phenomena and properties achievable with metamaterials (like, e.g. giant, near zero or negative permittivity and/or permeability, negative refractive index, giant chirality etc.) lead to a variety of capabilities for the metamaterial-based systems (e.g. perfect absorption, subwavelength resolution imaging, polarization filtering and control, spatial and temporal filtering, etc.)

The majority of today's THz metamaterials have been made by using metal as the basic material for the metamaterial elements. An alternative category of materials that can replace metal, but can also lead to additional phenomena and capabilities are polaritonic materials. Polaritonic materials are polar crystals where the incident radiation excites optical phonon in the crystal. The coupling of the radiation with the optical phonons results to the so called phonon-polariton modes in the crystal, and is described by a resonant permittivity response of the Lorenz type:

$$\varepsilon = \varepsilon_\infty - \frac{(\varepsilon_0 - \varepsilon_\infty)\omega_T^2}{\omega^2 - \omega_T^2 + i\omega\gamma} \tag{1}$$

In Eq. (1) ω_T is the angular frequency of the optical phonons in the crystal, which falls in THz or far-infrared regime, γ is the damping factor and ε_0, ε_∞ are the limiting values of the permittivity for zero and high frequencies respectively.

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The dielectric function (1), in the regime just above the resonance, shows a response similar to that of the dielectric function of metals in the optical regime. This indicates that all the effects that can be observed in metal optics can be transferred to the THz using polaritonic materials. Moreover, the high positive values of the dielectric function just below the resonance frequency can be exploited in a variety of phenomena where high-index materials are required. A particular example is for the achievement of dielectric metamaterials with negative permeability and/or permittivity due to Mie resonances in subwavelength frequency regimes.

Another interesting and rich variety of effects can result from the combination of polaritonic materials, which are resonant in the THz regime, with metamaterial approaches, i.e. the combination of material resonances and geometry resonances. Such a way, phenomena like subwavelength resonances, high field confinement, broad-band epsilon near zero regimes, strong field enhancement etc, are also possible.

In this work we demonstrate the potential of two-dimensional metamaterials made of polaritonic rods periodically placed in a polaritonic host medium to give a variety of rich phemonena and structures. These include: (a) structures with hyperbolic dispersion relation in the THz regime [1], which offer great potential for subwavelength imaging (more details in Section 2), (b) superlenses based on the principle of backward propagation and backward radiation [2] (more details in Section 3), (c) total transmission, total reflection and sub-wavelength guiding exploiting Mie resonances in epsilon near zero frequency regimes of the polaritonic host material [3] (more details in Section 4).

2. Hyperbolic dispersion relation in THz metamaterials

Structures with hyperbolic dispersion relation have been recently proven a very important category of metamaterials, as they give the ability of sub-wavelength resolution imaging without the need of any resonant response (which implies high losses), or magnetic response (which is not easy to be achieved), and are relatively simple structures which can be easily fabricated. The ability of hyperbolic metamaterials (HMM) for subwavelength resolution imaging is based on the fact the HMM do not have an upper limit to the magnitude of wave vectors that they can support, so they can transmit arbitrarily large (in principle) parallel (to the air-HMM interface) wave vector components, which in free space are evanescent components and carry the subwavelength details of a source object. Moreover, the hyperbolic dispersion is associated with high density of electromagnetic (EM) modes, which can greatly affect the performance of EM sources placed in such a medium.

HMM have been realized so far in the IR and optical regime using metallic rods in a host or metallic layered systems, and subwavelength resolution imaging (known as hyperlensing) has been demonstrated, even associated with image magnification. Here we show that the same effects can be observed in the THz regime using rods made of a polaritonic material, and exploiting the negative permittivity response of the rods in combination with the structure geometry [1]. Such systems of polaritonic rods in a host can be easily realized using a self-organization approach known as eutectics directional solidification [1].

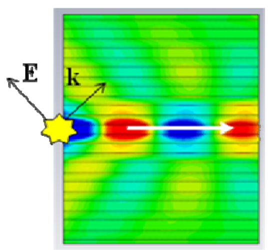

Fig. 1: Propagation of a TM wave emitted from a point source through a polaritonic material of LiF circular rods in NaCl, in hexagonal lattice. The rod radius and the periodicity are of the order of few μm. The wave has frequency ~10 THz, where the system shows hyperbolic dispersion relation.

In Fig. 1 we show the subwavelength resolution imaging (of resolution ~λ/4) in a system of polaritonic LiF rods embedded in NaCl host due to the hyperbolic dispersion relation in the system. The hyperbolic dispersion relation in this case had been concluded by detailed numerical simulations and by the

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results of the Maxwell-Garnett effective medium model (the validity of the Maxwell-Garnett model has been confirmed comparing experimental reflection data with corresponding prediction of the model).

3. THz superlensing based on backward radiation in negative permittivity waveguides

It has been shown recently that in waveguides with small negative permittivity values ($-1<\varepsilon<0$) there is the possibility of backward guided modes (i.e. modes of opposite phase and group velocity) which show quite strong "attenuation" (leakage) leading to backward radiation from the side-walls of the guide. Exploiting such modes one can achieve subwavelength tunnelling of electromagnetic waves in a system of parallel waveguides, which can be a two-dimensional periodic system of rods (guides) in a host, or a layered system. In this work we show [2] that similar phenomena can be achieved in the THz regime in systems of polaritonic LiF rods (acting as waveguides) in NaCl host, as shown in Fig. 2.

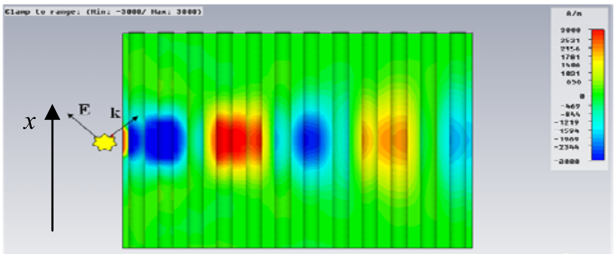

Fig. 2: Sub-wavelength propagation in a system of LiF rods (of small negative permittivity) in NaCl. The propagation along *x*-direction in the LiF rods is backward leading to convergence of the leaked radiation in the NaCl host due to negative refraction.

4. Epsilon near zero based phenomena in polaritonic systems

As was mentioned in the introduction, one can achieve interesting phenomena (like negative permeability and permittivity, subwavelength guiding) exploiting subwavelength Mie resonances in high-index dielectrics. The presence of epsilon near zero regimes in polaritonic materials allows the observation of such phenomena in systems of dielectric rods in a polaritonic host without the need of very high index values for the rods. In such systems we can achieve subwavelength and strongly confined Mie resonances in frequency regimes where host shows $\varepsilon\sim0$ response. Exploiting the coupling between such resonances in arrangements of closely placed rods (such as the system of Fig. 3) one can achieve, under special conditions, phenomena like total transmission, total reflection or subwavelength guiding.

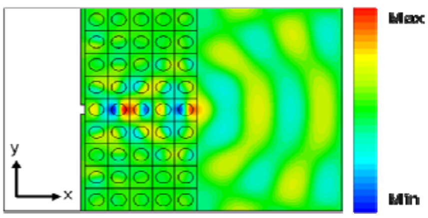

Fig. 3: Sub-wavelength guiding exploiting the Mie resonances of LiF rods in NaCl, in the frequency regime where NaCl has permittivity near zero.

References

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