Homogeneous magnetic metamaterials due to extreme coupling

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Abstract

We introduce an approach to design metamaterials that may be self-consistently described by effective material parameters. The key is the exploitation of an extreme coupling regime which arises if plasmonic particles exhibit only nm separation. This tiny separation can be achieved by atomic layer deposition techniques. In this regime, the wavelength-to-cell size ratio exceeds easily a factor of 10 at resonance. This results in effectively homogeneous magnetic metamaterials with negligible spatial dispersion. We extend our studies towards depositing these structures on curved surfaces. This allows e.g. for perfect absorbers that make an object invisible in reflection.

1. Introduction

Since the advent of metamaterials a much effort was focused on obtaining artificial magnetic and, in particular, left-handed metamaterials. Although some promising work was done to achieve such structures with small losses, the correct assignment of a genuine effective negative refractive index (spherical or elliptical iso-frequency surfaces) could not be achieved. This failure is equivalent to the non-existence of a local, angular-independent effective permittivity and permeability [1]. Quite contrary, most of the structures show an undesired complex dependency on the angle of incidence [2]. The assumption of locality, however, is very often a prerequisite for the integration of metamaterials into applications and the exploitation of metamaterial based devices. One of the major reasons why the complex response cannot be expressed by local effective parameters is simply the size of the unit cells. Unfortunately, if artificial magnetism is required they are only slightly smaller than the resonance wavelength. Hence, to design and fabricate magnetic metamaterials where the unit cell size is much smaller than the resonance wavelength is a major issue that needs to be addressed.

In this contribution, we will show that the resonance frequency, in particular for the desired artificial magnetic resonance, can be shifted to wavelength-cell size ratios of about 20 [3]. Such ratios become possible by exploiting the regime of *extreme coupling* where the plasmonic particles used to build up the structure are placed very close to each other, i.e. on the scale of a few nanometers. We will show that in this regime the optical response can be described by local effective material parameters very well, i.e. enabling the first truly effectively homogeneous magnetic metamaterial at 75-90THz.

The large wavelength to cell size ratio in the extreme coupling regime also allow to place metamaterial structures on curved surfaces, where the curvature is not negligible compared to the wavelength but compared to the unit cells, without observing any performance degradation. We will show that a perfect metamaterial absorber [4] can be placed e.g. on a cylindrical object to make it invisible in reflection. Such a flexible metamaterial structure allows for cloaking objects on a macroscopic scale.

2. Homogeneous magnetic and negative index metamaterials

At first, we consider exemplarily the well -known cut-wire or cut-plate pair magnetic metamaterial. By suitably choosing the period P_z to be 120nm and the thickness of the ALD layer to be 1nm (see Fig. 1), we obtain a structure that can be fully described in terms of the properties of the fundamental Bloch mode. This is a prerequisite for the calculation of local material parameters with the S-parameter retrieval [5], where one assumes that subsequent functional layers or unit cells are uncoupled. We observe an antisymmetric resonance that leads to an artificial magnetic response at 75THz. This finally leads to a ratio of wavelength to cells size (P=200nm) of 20. By investigating the angular dependency of the response of the single layer and applying the S-parameter retrieval again, we find that the set of effective material parameters shown in Fig. 1 (b)-(c) is valid for all angles of incidence and all polarizations and only negligible deviations are observed. The retrieved properties therefore are local material properties.

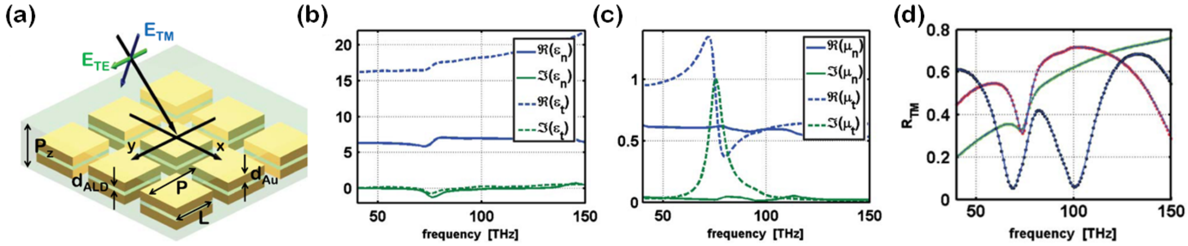

Fig. 1: (a) Artists view of the cut-plate-pair structure. (L=140nm, d_{Au}=40nm). (b) and (c) show the real and the imaginary parts of the tangential (x,y) and normal (z) components of the effective permittivity and permeability tensors, respectively. (d) To prove the applicability of the effective local parameters shown in (b) & (c) we calculated reflection and transmission for different angles of incidence, polarization and, most importantly, different number of layers (1-green, 2-red, 4-blue). Exemplarily we have shown the reflection at 57 degrees and TM polarization. The values calculated from the local parameters and with a thin-film transfer matrix technique (dotted curves) coincide perfectly with the rigorous results (solid curves).

To prove this we compared the reflection and transmission for arbitrary angles of incidence calculated with the parameters shown in (b) and (c) with the rigorous ones. The results are in astonishing agreement as can be seen in Fig. 1(d).

We then modified the structure such that a fishnet as shown in Fig. 2(a) is obtained. From Fig. 2(b) it becomes clear, that the fundamental Bloch mode again describes the optical response correctly, since its effective refractive index ($n_{FM}=k/k_0$) coincides with the one determined by the S-parameter retrieval (n_{eff}). Clearly, a negative index resonance is obtained at 90 THz. Again the structure can be described by local effective material parameters where only one permeability component is shown here.

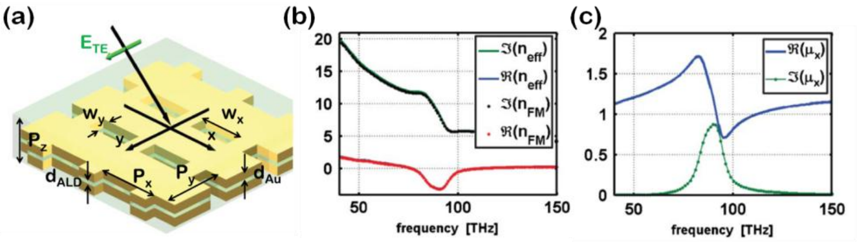

Fig. 2: (a) Artists view of the fishnet with principal axes and illumination scheme. (w_x=175nm, w_y=25nm $P_x=P_y$=200nm, P_z=120nm, d_{ALD}=1nm.) Note, that the fishnet is designed such that the negative index resonance can be probed by TE-polarization only. Just results for the design-polarization are discussed here. (b) Effective refractive index as obtained by S-Parameter retrieval n_{eff} from a single function layer of the fishnet and from the fundamental Bloch mode n_{FM}. The real and the imaginary part of both quantities are shown. A difference between the curves is only hardly visible due to the almost perfect coincidence. (c) Real and imaginary part of the x-component of the local effective permeability tensor. The fishnet shows the expected artificial magnetism leading to the negative index resonance at 90 THz.

3. Perfect Absorbers on Curved Surfaces

Whereas in the first part we were interested in homogeneous metamaterials by extremely coupling of identical plasmonic nanostructures, in this second part we are interested in a marginally modified geometry, i.e. the plasmonic nanostructure is extremely coupled to a metallic ground plate. This causes the structure to act as perfect absorber. The geometry as shown in Fig. 3 (a) is well known. The gold ground plate is chosen sufficiently thick to prevent any transmission. Resonant gold stripes on top are used to suppress reflection. This structure features almost 100% absorption for almost all angles of incidence in TM-polarization. By reducing the thickness of the dielectric spacer to values as small as 10 nm, the resonance again shifts to much larger wavelengths, leading to an increased ratio of wavelength to cell size. This large ratio allows placing the planar metamaterial absorber on curved surfaces without performance degradation, where the curvature is not negligible compared to the wavelength but compared to the unit cells. This is done, exemplarily, for a dielectric cylinder as shown in Fig. 3 (b). The cylinder is then illuminated by a TM-polarized plane wave. As can be seen from Fig. 3 (c), there is almost no light reflected from the cylinder, i.e. the backscattering cross section is almost zero at resonance. Therefore the cylinder covered with the perfect absorber is invisible in reflection.

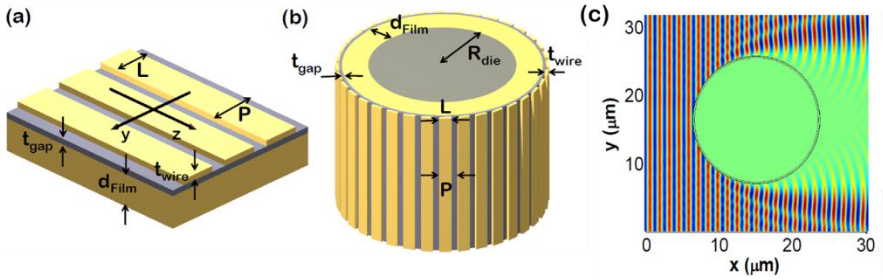

Fig. 3: (a) Artists view of the perfect absorber as designed on a planar substrate (d_{Film}=200nm, t_{gap}=10nm, t_{wire}=10nm, L=125nm, P=200nm, R_{die}=8.2µm). (b) Perfect absorber placed on the surface of a dielectric cylinder. (c) Field distribution of the magnetic field H_z when illuminated with a plane wave (TM).

4. Conclusion

In this contribution we discussed the versatility of using extremely thin dielectric spacers to shift the resonance of plasmonic based metamaterials to long wavelengths such that the ratio of resonance wavelength to cell size is very large. On one hand, this approach paves the way towards genuinely effectively homogeneous magnetic metamaterials that can be characterized by local effective material parameters. On the other hand, increasing the wavelength to cell size ratio also allows for placing metamaterials on curved surfaces without performance degradation. This allows for new applications. Here we suggested covering arbitrarily shaped objects with such a perfect absorber to make it invisible in reflection.

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