Perfect absorbers on curved surfaces and their potential applications

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Abstract: Recently perfect metamaterial absorbers triggered some fascination since they permit the observation of an extreme interaction of light with a nanostructured thin film. For the first time we evaluate here the functionality of such perfect absorbers if they are applied on curved surfaces. We probe their optical response and discuss potential novel applications. Examples are the complete suppression of back-scattered light from the covered objects, rendering it cloaked in reflection, and their action as optical black holes.

OCIS codes: (050.6624) Subwavelength structures;(160.3918) Metamaterials; (310.3915) Metallic, opaque, and absorbing coatings.

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1. Introduction

Metamaterials are composite materials engineered on a sub-wavelength scale that allow to control the light propagation [1]. Once these composite materials are at hand, unprecedented optical devices appear to be in reach for which the perfect lens [2] or the cloaking device [3, 4] usually serve as referential examples. To enable an optical response which cannot be achieved with natural materials, resonances are usually exploited in the design of a unit cell of the composite material. In the visible, this can be achieved by using metallic nanostructures which support surface plasmon polaritons. Potentially the most intensive response is witnessed while considering perfect absorbers. They are made of nanostructured thin films designed to perfectly annihilate the incident light. The functionality of perfect absorption has been explained while relying on different terminologies, e.g., discussing it in terms of an impedance matching [5], using a transmission lines formulation [6], or while evoking the concept of critical coupling [7]. Perfect absorbers have been investigated both numerically and experimentally at gigahertz [5], terahertz [8], infrared [9, 10], and optical frequencies [11, 12]. The research on perfect absorbers was triggered by applications with a major impact such as thermal emitters [13] or plasmonic sensors [14].

Thus far, only perfect absorbers on planar substrates were investigated. This is, especially from the theoretical side, a grateful configuration since the numerical discussion can be restricted to a single unit cell. However, much more applications, as we will see further below, will come in reach if this restriction is lifted and perfect absorbers are integrated onto curved surfaces. Such configuration can be realized by current technologies. The fabrication of plasmonic nanostructures on thin membranes suitable for being arranged on curved surfaces [15], the exploitation of self-assembly strategies that roll-up thin-films [16], the bottom-up fabrication of plasmonic nanostructures directly on spherical beads [17] or by using the high resolution nanofabrication method based on nanostencil lithography (NSL) [18] are technologies that can cope with that challenge. Alternatively, in other spectral domains, e.g. at THz frequencies, it is reasonable to fabricate the relevant structures directly as flexible films from where they can be deposited on arbitrary surfaces [19, 20]. Such techniques might equally provide a path to make structured surfaces available on cylinders or even spheres.

To motivate the fabrication of perfect absorbers on curved surfaces it has to be proven that they preserve their functionality in this specific configuration. The simulation challenge consists in considering an entire macroscopic object since a restriction to a single unit cell ceases to be meaningful. Here we shed light on that issue by discussing perfect absorbers on curved surfaces for the first time. Moreover, we intimately connect the verification of the functionality with the exploration of two applications.

The first application is the suppression of spurious back-scattered light. This makes the object to be covered by the perfect absorber invisible in reflection. Although, the object is not entirely cloaked, the complete suppression of back-scattered light allows to conceal the object in many configurations of practical importance, i.e. those where the emitting and the receiving element of an observer that tries to probe for the presence of the object are spatially close, e.g. in radar applications. Since the functionality of the cloaking device we suggest is not restricted to the quasi-static limit, as it holds for most cloaking strategies that compensate the scattering response, the back-scattering from arbitrarily large objects can be suppressed.

The second application is an optical black hole. Such a device has been suggested by Narimanov *et al.* relying on a transformation optics approach [21]. An optical black hole captures the entire light arriving from all directions. We will show that the perfect absorber on curved surface possesses identical properties. Although the optical black hole as previously suggested does not require any magnetic material for its implementation, a sufficiently thick shell of an absorbing material with a gradient in the permittivity is necessary. This makes its fabrication for the visible spectral domain challenging. In contrast, the structure suggested here only requires a single nanostructured thin film.

2. Perfect absorber on planar and curved surface

Our analysis starts by investigating and optimizing the performance of a perfect metamaterial absorber similar to that reported in Ref. [7]. For the sake of a general validation of the proposed concept, we focus on a two-dimensional geometry here. The geometry under consideration is shown in Fig. 1(a). The perfect metamaterial absorber consists of metallic nanowires above a metallic ground plate separated by a dielectric spacer. The structure is periodic in y-direction with periodicity P and is infinitely extended in z-direction. We assumed that the dielectric deposited onto the metal is characterized by $\varepsilon = 2.25$ reflecting the properties of SiO_2. The ground plate and the metallic wires are assumed to be made from silver [22]. The legend of Fig. 1(a) also contains all geometrical parameters. They were purposely chosen such that the perfect absorber achieves critical coupling [7]. At critical coupling, the incoming energy of an incident plane wave is entirely dissipated without reflection. Transmission through the structure is entirely suppressed ($T = 0$) by choosing a sufficiently thick ground plate. Since the operational domain should be in the near-infrared, the thickness of the ground plate is set to be 200 nm. The perfect absorber is optimized such that reflection is negligible ($R \simeq 0$) when an anti-symmetric resonance is excited in the coupled system made from the nanowire and the ground plate. Therefore, the absorption of the perfect absorber is close to unity ($A = 1 - T - R \simeq 1$) [9].

Moreover, Fig. 1(b) shows the proposed ultimate device. It is made from a dielectric cylinder that is covered by the plasmonic metamaterial absorber. The structures are always illuminated by a transverse magnetic (TM) polarized plane wave. A finite element electromagnetic solver [23] has been used to explore the physics of the omnidirectional perfect absorber.

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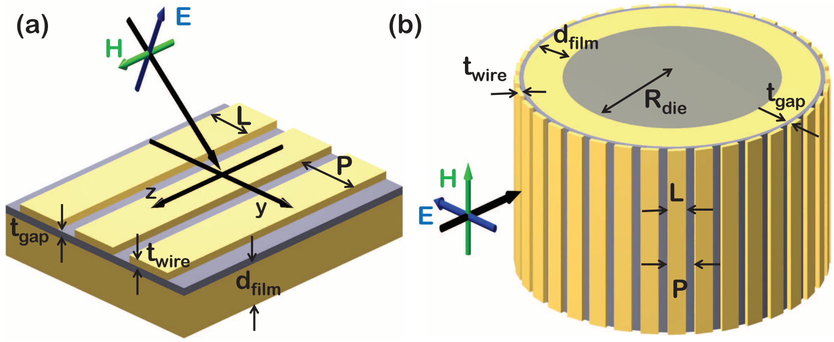

Fig. 1. Geometry and illumination under consideration (a) Schematic of a planar perfect metamaterial absorber. (b) Schematic of the perfect metamaterial absorber on a curved surface. Geometrical parameters are chosen according to $d_{\text{film}} = 200\,\text{nm}$, $t_{\text{gap}} = 10\,\text{nm}$, $t_{\text{wire}} = 10\,\text{nm}$, $L = 125\,\text{nm}$, $P = 200\,\text{nm}$, $R_{\text{die}} = 8.2\ \mu\text{m}$. The structure illuminated by TM polarized plane wave and the magnetic filed is always along the infinite nanowires i.e. z-direction.

In order to design the perfect absorber on the curved surface we first study the optical response of the planar perfect absorber as shown in Fig. 1(a). The spectrally resolved absorption as a function of the incidence angle is shown in Fig. 2(b). The results clearly indicate that for angles less than 65 degrees the absorption is almost unity at the resonance frequency. The absorption changes only marginally for larger angles of incidence where the resonance is shifted to higher frequencies. Hence, we expect that the black hole formed by this absorber will capture all light from a large range of incidence angles. The magnetic field distribution H_z at the resonance frequency $f = 232\,\text{THz}$ is displayed in Fig. 2(a). There the scattered field corresponds to that of a magnetic dipole located in the center of the absorber. The inset of Fig. 2(a) shows the current distribution of the perfect absorber at resonance frequency. The response is clearly associated with an antisymmetric current distribution excited in the nanowire and the ground plate [9, 10]. Such an antisymmetric resonance is necessary to perfectly dissipate the incident radiation in the metal.

Now after having identified the planar absorber that supports almost unity absorption which is largely independent on the incidence angle, we will cover exemplary a dielectric cylinder with this absorber in order to make this cylinder invisible in reflection [see Fig. 1(b)]. The chosen dielectric cylinder has a radius of $R_{\text{die}} = 8.2\ \mu\text{m}$ with a permittivity of $\varepsilon_{\text{cyl}} = 5$. The proposed device is illuminated by a TM-polarized plane wave. The z - component of the magnetic field at resonance frequency is shown in Fig. 2(c). It has to be stressed that, although difficult to realize due to the disparate length scales, the perfect absorber was rigorously simulated while taking its detailed geometry precisely into account. From the field distribution it can be recognized that the back-scattered field of the dielectric cylinder covered by the perfect absorber at resonance frequency $f = 232\,\text{THz}$ is almost vanishing. The incident plane wave is unperturbed in the region in front of the cylinder. This is a clear indication that the impinging illumination is completely absorbed by the nanostructured thin film. A scattered field is only observed in forward direction in Fig. 2(c). The origin can be traced back to the incomplete absorption at grazing incidence but also to free space diffraction that occurs from the modified amplitude distribution of the incidence plane wave. The most visible feature is the shadow at the right of the cylinder that is a consequence of the perfect absorption.

To quantify the optical response, the two-dimensional scattering cross sections (SCSs) of the cylinder with and without perfect absorbing cover are shown in Fig. 2(d). The total SCS of the

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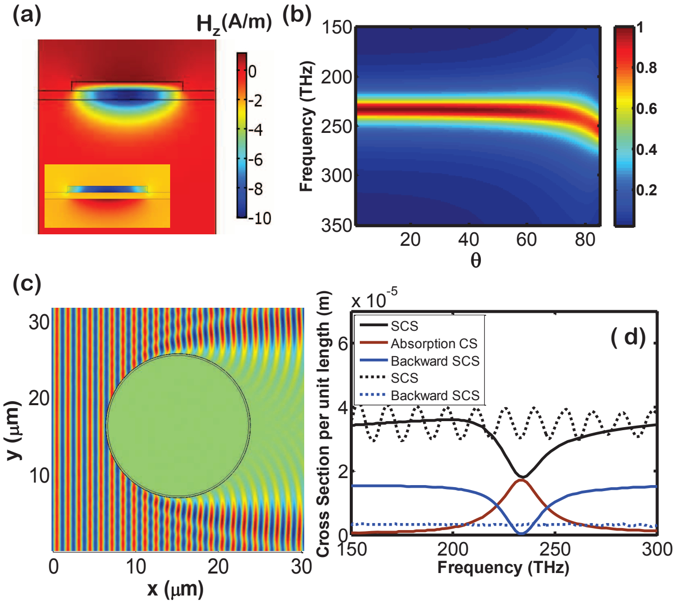

Fig. 2. Optical response of the perfect metamaterial absorber on planar and curved surface. (a) H_z- component and J_y- component (inset) at resonance frequency $f = 232$ THz for a unit cell of the planar absorber [see Fig. 1(a)]. (b) Absorption of the planar absorber as a function of frequency and the angle of incidence. (c) H_z- component at resonance for a plane wave incident at an absorber on curved surface. (d) Cross sections per unit length of the absorber on curved surface (solid lines) and a referential dielectric cylinder with permittivity of $\varepsilon_{\mathrm{cyl}} = 5$ (dashed lines). The figure shows the total and the backward scattering cross section as well as the absorption cross section (all per unit length).

cylinder coincides with the absorption cross section at resonance frequency as suggested by the principle of critical coupling [7]. The back-scattering cross section of the covered cylinder compared to the dielectric cylinder is significantly suppressed at resonance and even indistinguishable from zero on a linear scale. Hence, the proposed device can reduce the back-scattering significantly at the design frequency. Obviously, the total SCS at resonance frequency is then equal to the forward SCS that can be easily extracted while subtracting the backward SCS from the total SCS. At non-resonant frequencies the total SCS for the absorber-covered cylinder is almost identical to a metallic cylinder with same radius (not shown here). In passing we note that the total SCS for the covered cylinder is decreased by a factor of 2 when compared to the dielectric cylinder without absorber.

3. Performance of absorber on curved surface

In order to verify the functionality of the suggested optical black hole, the absorption efficiency for a Gaussian beam excitation (waist of $3\,\mu$m) is shown in Fig. 3. The beam width suggests that it will excite approximately 14 unit cells. The absorption efficiency of the optical black hole for a Gaussian beam is defined as the ratio of the absorbed power per unit length by the optical black hole to the incident power per unit length of the Gaussian incidence beam [24,25]. Figures 3(a)-3(c) show the magnetic field for illumination with a Gaussian beam for some selected off-sets from the center of the cylinder. For no or only a slight off-set, e.g. $y_0 = 0$ or $3\,\mu$m, the scattered magnetic field is negligible and the incident beam is entirely absorbed by the optical black hole.

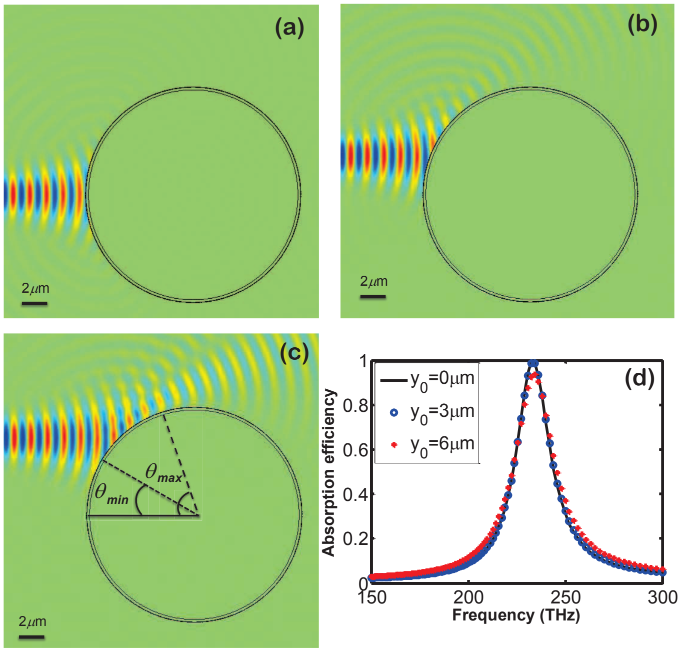

Fig. 3. (a), (b), and (c) show the H_z component of a Gaussian beam hitting the optical black hole for an off-set of $y_0 = 0, 3, 6$ μm, respectively. (d) Respective absorption efficiencies.

However, for Gaussian beams with an off-set that is only a little less than the cylinder diameter, i.e. $y_0 = 6$ μm, the absorption efficiency is slightly reduced. To understand the effect, one has to take into account that the illumination angle for the specific Gaussian beam with an off-set of $y_0 = 6$ μm varies between $\theta_{\min} = 30$ and $\theta_{\max} = 75$ degrees [see Fig. 3(c)]. As seen from Fig. 2(b), for larger incidence angles the absorption is less than unity and also the resonance frequency is slightly shifted to higher frequencies which explains the smaller absorption for a beam which is off-set by $y_0 \geq 6\,\mu$m. Quantitative results on the absorption efficiency as a function of the frequency and the illumination off-set are shown in Fig. 3(d). They clearly indicate that the efficiency of the optical black hole in resonance is well developed. For larger beam displacements naturally the efficiency at the resonance frequency diminishes since the illumination does not entirely hit the optical black hole.

In a final note we wish to stress that the proposed optical black hole made from a perfect absorber is narrow-band when compared to counterparts made from non-resonant metamaterials [21]. However, several approaches are documented to considerably increase the bandwidth of the perfect absorber, the essential ingredient for the proposed optical black hole. This is possible by using an array of metallic strips with different widths [26–28] or using trapezoidal shaped strips [11] instead of rectangular ones.

4. Conclusion

In concisely summing up, we have shown in this contribution that it is possible to hide an object in reflection by covering it by an appropriately designed perfect absorber. The object can be arbitrary in shape, assuming that it can fit into a cylindrical object on which the perfect absorber is applied. We have investigated and validated the proposed concept at near-infrared frequencies. However, the concept can be easily extended towards other frequency ranges by a proper

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design of the perfect absorber. Since the perfect absorber, placed here exemplary on a dielectric cylinder, captures all light coming from any direction, the device acts as an optical black hole. We have proven its functionality upon illumination with a Gaussian beam. Although detailed here for a deterministic nanostructure amenable for fabrication with top-down nano-fabrication methods, we are convinced that the functionality is entirely preserved for nanostructures fabricated by self-assembly processes. This opens applications for black-inks that are currently explored in the context of bottom-up metamaterials. Moreover, by using novel fabrication approach e.g. nanostencil lithography (NSL) it is in reach to fabricate perfect absorber on curved surfaces at optical frequencies. In fact, by this technique perfect absorber can be fabricated on flexible polymer films and then it can be used as a carrier to transfer to any curved surface.

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