Perfect absorption in uniform and nanostructured media

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Abstract—**We consider the conditions for perfect absorption in uniform thin-films and in thin gratings. We find that perfect absorption of TE polarized light can occur in gratings composed of weakly absorbing materials.**

The quest for thin perfect absorbers is interesting in its own right but is particularly important for applications such as photodetectors and solar energy. It is well-understood that the maximum absorption in a negligibly thin layer (i.e. for which $nd \ll \lambda$, where n is the refractive index, d is the thickness and λ is the wavelength) is 50% when the layer is in a uniform background and light is incident from a single side. The reason is simple [1]: the light can be decomposed into an even and an odd mode, the latter of which has a node coinciding with the layer. For a thin layer the absorption of this mode vanishes, which means that the maximum absorption is achieved when the even mode is fully absorbed, corresponding to a total absorption of 50%. Complete absorption is possible when the radiation is incident symmetrically or when a layer with half the thickness is placed on an ideal mirror. These two cases are equivalent, and here we only consider the second of these.

Perfect absorption in a uniform structure has been considered by many authors (see, e.g., [1],[2],[3],[4]). A layer with (complex) refractive index $n = n' + in''$, and thickness $d/2$, with air on one side and a perfect mirror on the other (see Fig 1a), exhibits perfect absorption when $r + \delta = 0$ where $r = (1-n)/(1+n)$ is the (Fresnel) reflection from air into the layer and $\delta = e^{i\frac{2\pi}{\lambda}nd}$. Solving this for normal incidence in the limit $nd \ll \lambda$ while $n \gg 1$ it is found that, to lowest order, $n = \sqrt{i\lambda/(\pi d)}$, so that $n' = n'' \propto d^{-\frac{1}{2}}$. This unusual dependence arises because the Fresnel coefficients and δ depend on refractive index in opposite ways. It is easy to show that this condition corresponds to that for critical coupling [5], when the time constant associated with losses and that associated with transmission out of the structure are equal. The absorption A, for a fixed $d = 20$ nm but various n values can be found in Fig 2a—it confirms unit absorption near the diagonal and shows a uniform decrease away from the optimum value. All results are for $\lambda = 700$ nm.

The problem with the result for a uniform film is that it demands exotic materials for which $n' \approx n''$. Alternatively it has been shown that perfect absorption can be achieved with nanostructures composed of common materials. Most of these rely on exciting resonances in metamaterials or plasmonic particles. Structure have been successfully fabricated that target microwave, terahertz and infrared frequencies [6], but creating the smaller meta-atoms that would be required for operation in the infrared or visible range is unfeasible.

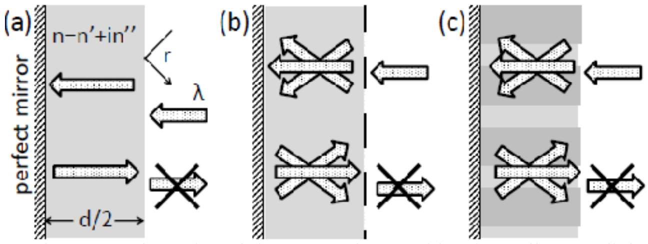

Figure 1: Schematics of the geometries considered. In all cases, light of wavelength $\boldsymbol{\lambda}$ is normally incident on a layer of thickness $\boldsymbol{d/2}$ with (complex) refractive index $\boldsymbol{n}$ and a perfect mirror at the back. Perfect absorption is equivalent to the reflection vanishing. (a) Uniform structure; (b) Uniform structure with surface grating; (c) Periodic structure.

Here we consider two dielectric based structures. The first is shown in Fig. 1b and consists of a uniform film augmented by a dielectric surface grating of negligible thickness. The second, shown in Fig 1c, is a volume grating in the entire structure. In both cases the period of the grating is chosen so that only the specular order and the ± 1 orders in the medium are relevant, while all others are evanescent.

We have derived an algebraic equation that predicts the conditions for perfect absorption for the geometry in Fig 1b. The expressions are analytic but require the various reflection and transmission coefficients and the δ-type parameters defined earlier, which must be calculated numerically. We expect the solution to be quite different from that of a uniform film since the grating can couple light into waveguide modes. This increases the path length in the film layer and hence the absorption.

The results for TM and TE polarization, again for normal incidence and $d = 20$ nm for the geometry in Fig, 1b, are shown in Fig 2b and Fig. 2c, respectively. The other parameters are given in the figure caption. While in both cases perfect absorption can be achieved, the nature of the solution has changed: for TM polarization the solution is close the imaginary (vertical) axis, corresponding to a metallic medium. In contrast, for TE polarization the optimum is close to the real (horizontal) axis, corresponding to a medium with low intrinsic absorption. This difference can be explained as follows: for TM polarization, metallic media support surface plasmon polaritons (SPPs), excitations which propagate along the surface of the medium and which decay exponentially into each of the media. Phase matching requirements forbid the excitation of SPPs from vacuum, which is why it does not occur for uniform films. In the case considered here excitation is possible since the surface grating acts as a grating coupler. Since SPPs have TM polarization, this solution is not available for TE-polarized incident light. For TE-polarization the grating couples light into guided TE-modes of the film region, leading to an optimum which is positioned close to the real (horizontal) axis. This solution for materials with low intrinsic loss is very promising for energy harvesting applications. Though guided TM modes exist, the coupling into those modes is inefficient since it relies on the modes' minor, longitudinal electric field component, which is why this solution is absent for TM polarization.

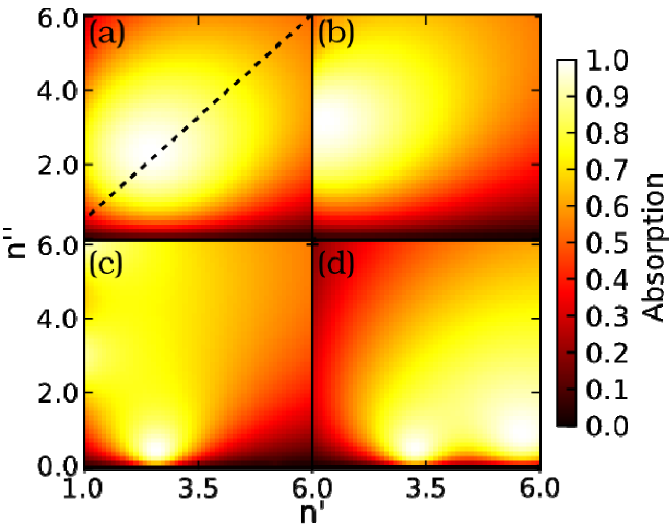

Figure 2: Absorption versus the he real and imaginary parts of the refractive index of the film layer for four cases. (a) Uniform layer (as in Fig. 1a); (b) Uniform layer with surface grating and TM polarization (as in Fig. 1b); as (b) but for TE polarization; (d) volume grating and TE polarization. The parameters are $\boldsymbol{d} = \mathbf{20}$ nm, λ=*700* nm. The grating has a period of 640 nm and a fill fraction of 50%. The surface grating has a thickness of 1 nm and a (real) refractive index $\boldsymbol{n} = \mathbf{20}$. In the volume grating the low refractive index is air and the high refractive index indicated on the axes.

While the result in Fig 2c, showing perfect absorption in a low-loss film with an optical thickness which is much less than the wavelength, is promising, it is perhaps not realistic because of the difficulty of fabricating the required grating, whichin the example given, has a refractive of $n = 20$. We therefore consider a geometry, fabrication of which is realistic and which is illustrated in Fig 1c. The functions of the grating and of the absorber are now combined. Thus the thin-film now also acts as a volume grating, which can couple incident light into a waveguide mode can be supported by the thin film, even though its refractive index is modulated. The properties of such structures cannot be calculated using a simple model. We used the Finite Element Method to calculate the properties of the periodic structure, particularly its Bloch functions, which are then used to construct reflection and transmission scattering matrices [7], as implemented in the freely available EMUstack package [8].

The result, again for $d = 20\,nm$ and other parameters given in the figure caption, is given in Fig 2d. There are now multiple optima near the real axis while the optimum near the vertical axis has disappeared, and does not show for any structure with a volume grating. The various maxima correspond to coupling into the fundamental waveguide mode with the higher reciprocal lattice vectors of the grating. The key observation is that perfect absorption occurs for weakly absorbing media (*i.e.*, with refractive indices close to the real axis), and with realistic real part of the refractive index. With small changes in the parameters this optimum can be shifted to a significant degree.

Based on the idealized geometry in Fig 1c we have designed a thin structure ($d \ll \lambda$) that should exhibit perfect absorption and which can be fabricated using standard processes.

In conclusion, we have shown that very thin layers with $nd \ll \lambda$ and refractive index close to the real axis (*i.e.*, with low intrinsic loss) can act as perfect absorbers if combined with a dielectric grating This shows that metallic inclusions, which lead to large parasitic losses, are not required. These geometries, such as that in Fig. 1c can be fabricated by standard processes. While the structures discussed here have strong polarization dependence because of the presence of a grating, the generalization to two-dimensional gratings should reduce this dependence considerably.

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