Wide-band perfect absorption in optically thin layers composed of indefinite media with tilted optical axes

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Abstract

In this paper we discuss new property of indefinite media, namely, a capability of the perfect absorption in optically ultrathin layers. Example of a perfectly absorbing layer for the near-infrared range, made of silver nanowires, is described.

1. Introduction

Recently perfect absorption was demonstrated at far-infrared [1], mid-infrared [2], near-infrared [3] and visible [4] frequencies. Different artificial resonant structures were utilized in each region. In the present paper we propose a general approach for design of optically ultrathin perfect absorbers and illustrate its operation in the near-infrared range. It is based on exploitation of thin slabs of indefinite media (IM), whose optical axes are tilted with respect to interfaces. As example, we consider indefinite media made of silver nanowires absorbing light in the near-infrared range. The cross-section of a slab of IM with the optical axis, tilted by the angle ϕ with respect to the Z-axis, is shown in Fig. 1. The thickness of the slab is h.

2. Conditions for the perfect absorption

Let us consider TM-polarized waves propagating in a medium with the tilted optical axis and fixed transversal component of the wave vector k_x. Then the vertical component of the wave vector reads as

$$k_z = \frac{k_x \varepsilon_{xz} \pm \sqrt{(\varepsilon_{xz}^2 - \varepsilon_{xx}\varepsilon_{zz})(k_x^2 - k_0^2 \varepsilon_{zz})}}{\varepsilon_{zz}} \tag{1}$$

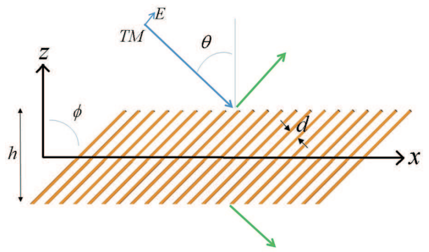

Fig. 1: Schematic view of an indefinite medium slab with the tilted optical axis.

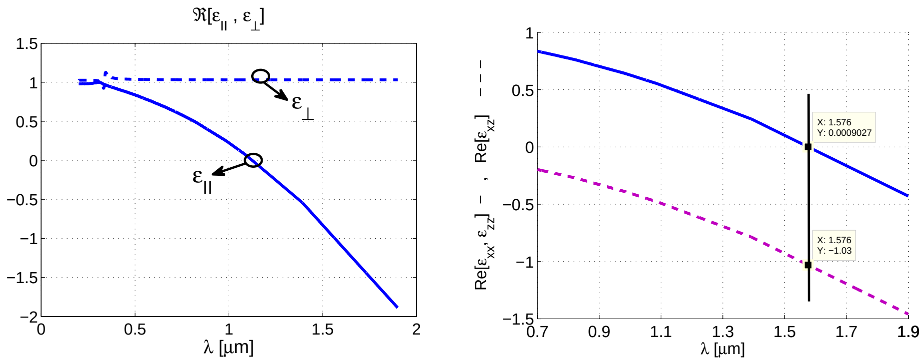

Fig. 2: Left: real parts of $\varepsilon_{||}$ and $\varepsilon_{\perp}$, calculated at $p = 0.015$. Right: real parts of ε_{zz} and ε_{xz}. Vertical line indicated wavelength at which $\varepsilon_{xz} = -1$ and $\varepsilon_{xx} = \varepsilon_{zz} \simeq 0$.

where k_0 is the wavenumber in free space. The transversal wave impedance reads as

$$Z_t = \frac{-E_x}{H_y} = \frac{\eta}{k_0} \frac{k_x^2 - k_0^2 \varepsilon_{xx}}{k_z \varepsilon_{zz} - k_x \varepsilon_{xz}} \tag{2}$$

where $\eta = 120\pi$ Ohm.

Let us consider the idealized lossless case and assume that the axial and transversal components of the permittivity tensor of the IM are the following: $\varepsilon_{||} = -1$, $\varepsilon_{\perp} = 1$. If the optical axis is tilted by the angle 45°, we obtain the following tensor components

$$\varepsilon_{xx} = \varepsilon_{zz} = 0, \qquad \varepsilon_{xz} = \varepsilon_{zx} = -1. \tag{3}$$

Then we have $k_{z1} \to \infty$ and $k_{z2} = 0$. Here k_{z1} corresponds to the wave whose electric field vector is parallel to the optical axis. If the incidence angle θ equals to -45°, then the transversal wave impedances for the wave in IM Z_t and in free space Z_{0t} read:

$$Z_t = \eta k_x / k_0 = \eta \sin 45^\circ = Z_{0t} = \eta \sqrt{k_0^2 - k_x^2} / k_0 = \eta \cos 45^\circ. \tag{4}$$

Thus, if the considered IM possess small losses, then $Z_t \simeq Z_{0t}$ and $k_z \to \infty$, so the incident wave enters the slab without reflection and propagates attenuating in the medium with a very small wavelength that provides perfect absorption within an ultrathin layer.

3. Perfect absorption in the near-infrared range

Let us consider a composite of silver nanowires with the concentration p. Homogenization gives the following components of the permittivity tensor:

$$\varepsilon_{\perp} = \varepsilon_h \frac{1 + \frac{p(\varepsilon_i - \varepsilon_h)}{\varepsilon_i + \varepsilon_h}}{1 - \frac{p(\varepsilon_i - \varepsilon_h)}{\varepsilon_i + \varepsilon_h}} \tag{5}$$

and

$$\varepsilon_{||} = p\varepsilon_i + (1-p)\varepsilon_h \tag{6}$$

where ε_i is the the complex permittivity of bulk silver (values were taken from [5]) and $\varepsilon_h = 1$ is the permittivity of host medium. Real parts of the permittivity tensor components are shown in Fig. 2. Conditions (3) are satisfied at the wavelength $\lambda_0 = 1.576\,\mu$m.

Absorption is calculated using modification of the transfer matrix method which is applicable for the case when $|k_{z1}| \neq |k_{z2}|$ [6]. Fig. 3 illustrates absorption, calculated for different thicknesses of the slab. Even the slab thickness $h = 30$ nm provides the nearly 100% absorption with the bandwidth 100 nm and for $h = 180$ nm the perfect absorption takes place within the bandwidth 450 nm. It can be compared with results [3], where at the same frequency range 90% level of absorption was obtained within 825 nm.

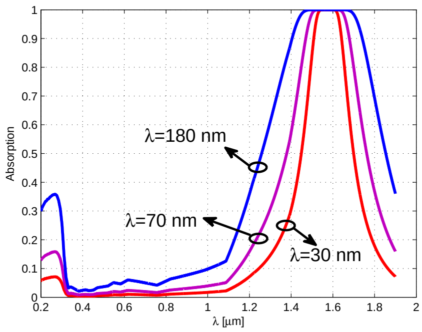

Fig. 3: Absorption, calculated for different thicknesses of the silver nanowire slab.

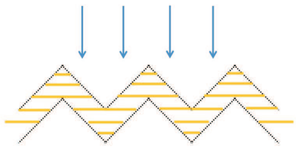

Fig. 4: Possible design of an absorbing layer.

3. Conclusion

We proposed new solution for design of optically thin absorbing layers. It is based on properties of a specially prepared indefinite medium, whose permittivity tensor has near-zero diagonal components and close to unity non-diagonal components. The wave, incident under the angle 45° onto such a medium, is not reflected and it strongly attenuates within the medium. Near-field radiation is totally absorbed even in optically ultrathin layers. Similar absorber for the mid-infrared range can be prepared of arrays of metallic carbon nanotubes, which possess properties of indefinite media in the terahertz range [7]. The discussed effect can find applications for such absorbers, where a range of incidence angles is confined.

References

[1] D.Yu. Shchegolkov, A.K. Azad, J.F. O'Hara and E. I. Simakov, Perfect subwavelength fishnet like metamaterial-based film terahertz absorbers, *Phys. Rev. B,* vol. 82(20), p. 205117, 2010.
[2] T.K.M. Diem and C. M. Soukoulis, Wide-angle perfect absorber/thermal emitter in the terahertz regime, *Phys. Rev. B,* vol. 79(3), p. 033101, 2009.
[3] K.B. Alici, A.B. Turhan, C.M. Soukoulis and E. Ozbay, Optically thin composite resonant absorber at the near-infrared band: a polarization independent and spectrally broadband configuration, *Opt. Express,* vol. 19, pp. 14260-14267, 2011.
[4] C.H. Lin, R.L. Chern and H.Y. Lin, Polarization-independent broad-band nearly perfect absorbers in the visible regime, *Opt. Express,* vol. 19(2), pp. 415424, 2011.
[5] P.B. Johnson and R.W. Christy, Optical constants of the noble metals, *Phys. Rev. B,* vol. 6, pp. 43704379, 1972.
[6] D.M. Pozar, *Microwave Engineering,* 3rd edition, Wiley India Pvt. Ltd., 2009.
[7] I. S. Nefedov and S.A. Tretyakov, Ultabroadband electromagnetically indefinite medium formed by aligned carbon nanotubes, *Phys. Rev. B,* vol. 84, p. 113410, 2011.