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Coherent perfect absorption of electromagnetic wave in subwavelength structures

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ABSTRACT

Electromagnetic (EM) absorption is a common process by which the EM energy is transformed into other kinds of energy in the absorber, for example heat. Perfect absorption of EM with structures at subwavelength scale is important for many practical applications, such as stealth technology, thermal control and sensing. Coherent perfect absorption arises from the interplay of interference and absorption, which can be interpreted as a time-reversed process of lasing or EM emitting. It provides a promising way for complete absorption in both nanophotonics and electromagnetics. In this review, we discuss basic principles and properties of a coherent perfect absorber (CPA). Various subwavelength structures including thin films, metamaterials and waveguide-based structures to realize CPAs are compared. We also discuss the potential applications of CPAs.

1. Introduction

Perfect absorption of light is of great importance in a variety of applications ranging from sensing to stealth technologies [1–6]. Achieving perfect absorption at subwavelength scale is particularly important for nanophotonic and electromagnetic applications. In recent years, various approaches of designing ultrathin perfect absorbers have been proposed, including thin films, metamaterials and metasurfaces [7–13]. In a common absorber, the incident energy is delivered to the systems via a single channel, for instance by a plane wave illuminated on one side of the absorber. However, it was found that the incident energy could be perfectly absorbed under incidence on opposite sides of an absorber [14–18]. This interference-assisted absorption is known as "coherent perfect absorption", and was experimentally demonstrated in a silicon slab under coherent monochromatic illumination [14,15]. In a coherent perfect absorber (CPA), two counterpropagating input beams of identical amplitudes and phases interfere destructively outside a cavity and dissipate their energy completely by interacting with the intra-cavity losses of the absorber, resulting in perfect absorption. Such a CPA provides a new way for the control of electromagnetic absorption.

In this review, we first discuss the concept and the theoretical basis of a CPA. Then, we outline various subwavelength structures used for coherent perfect absorption. These structures includes thin films, metamaterials and waveguides-based structures. Lastly, we discuss the properties of CPAs and their promising applications in all-optical data processing and photocurrent enhancement, etc. The concept of coherent perfect absorption can also be extended to other contexts apart from classical optics, such as acoustics [19–21], plasmonics [22], and quantum optics [23].

2. Theoretical analysis

Fig. 1(a) shows a typical planar CPA structure. Two coherent beams normally illuminate from two opposite sides. An input beam (A_1 or A_2) of this two-port system is partially transmitted and partially reflected, while an output beam (B_1 or B_2) consists of reflected and transmitted components. To analyze this system, one can solve the Maxwell's equations by using scattering matrix (**S** matrix) [24]. In general, the relationship between input and output can be described by

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = S\begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = \begin{bmatrix} r_{11} & t_{12} \\ t_{21} & r_{22} \end{bmatrix}\begin{bmatrix} A_1 \\ A_2 \end{bmatrix}, \quad (1)$$

where r_{ij} and t_{ij} are the reflection and transmission coefficients of an input beam (A_1 or A_2), respectively. The scattering matrix **S** depends on operating wavelength, geometry of the structure and material properties. For simplicity, we consider a two-port structure which

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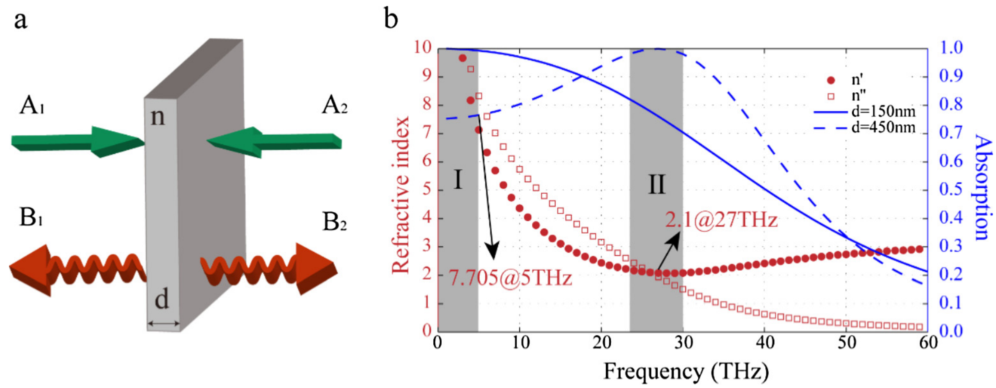

Fig. 1. Concept of coherent perfect absorption. (a) Sketch of a coherent perfect absorber. A_1 and A_2 represent the amplitudes of the input waves, while B_1 and B_2 represent the amplitudes of the output waves. The output beams consist of reflected and transmitted components. The thickness of the slab is d and refractive index is n. When d and n are properly designed, the output waves can destructively interfere on each side, resulting in perfect absorption. (b) Refractive index of doped silicon described by Drude model and the absorption curves for different thicknesses. The two absorption regions are highlighted as Zone I and Zone II. The theoretical refractive indexes are calculated using Eqs. (11) and (13) for 5THz and 27THz, respectively [17].

is symmetric under a mirror reflection, i.e., $r_{12} = r_{21} = r$. If the system is in steady-state and linear regime and exclusive of magneto-optically gyrotropic medium, **S** matrix will be constrained by optical reciprocity [25,26], which suggests that **S** is symmetric. For the two-port cases, this constraint implies that $t_{12} = t_{21} = t$. In the following part, we will discuss coherent perfect absorption on the basis of optical reciprocity. Thus, the relationship between input and output beams can be written as

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = S \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = \begin{bmatrix} r & t \\ t & r \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}, \tag{2}$$

The reflection and transmission coefficients can be described by [17]

$$r = \frac{(n^2-1)(-1+e^{i2nkd})}{(n+1)^2-(n-1)^2 e^{i2nkd}}, \tag{3}$$

$$t = \frac{4ne^{inkd}}{(n+1)^2-(n-1)^2 e^{i2nkd}}, \tag{4}$$

where $k = \omega/c$, d is the thickness of the slab, and $n = n' + in''$ is the complex refractive index. Coherent perfect absorption occurs when output wave components vanish ($B_1 = B_2 = 0$) and corresponding inputs are so-called CPA eigenmodes. Due to the mirror symmetry of the system, coherent perfect absorption can only be achieved for symmetrical inputs ($A_1 = A_2$, $r + t = 0$) or anti-symmetrical inputs ($A_1 = -A_2$, $r - t = 0$). In both cases, the magnitude of reflection and transmission are equal, indicating that a CPA can act as a beam splitter when illuminated by a single beam. Using Eqs. (3) and (4), the CPA condition for normal incidence can be obtained

$$\exp(inkd) = \pm\frac{n-1}{n+1}. \tag{5}$$

Note that n should be replaced by the impedance Z for materials with magnetic response [27].

The $\pm$ sign corresponds to the symmetrical or anti-symmetrical inputs. An infinite number of discrete solutions of Eq. (5) has been obtained for $kd \gg 1$ [14]. The reflection and transmission coefficients for a single input beam can be written as

$$r_s = -\frac{1}{2}\left(\frac{n^2-1}{n^2+1}\right), \tag{6}$$

$$t_s = \pm\frac{1}{2}\left(\frac{n^2-1}{n^2+1}\right). \tag{7}$$

Apparently, a phase shift of π is added to the reflection wave for both symmetrical and anti-symmetrical CPAs. However, the phase shifts introduced by transmission for these two conditions are distinctive, i.e., either 0 or π. Thus, for two coherent input beams meeting the CPA condition, the transmitted wave of one beam and the reflected wave of the other beam will interfere destructively, resulting in total absorption of incident energy.

An important case of the above-mentioned two-port system is a film structure much thinner than the operating wavelength ($d \ll \lambda$, $|nkd| \ll 1$), such as a dielectric or a metal film. In this case, the left and right side of Eq. (5) can be approximated as $1 + inkd$ and $\pm(1 - 2/n)$. Since $|nkd| \ll 1$, only plus sign term in the right side should be selected. The real and imaginary parts of the refractive index (n' and n'') in Eq. (5) are approximately equal as

$$n' \approx n'' \approx \frac{1}{\sqrt{kd}} = \sqrt{\frac{c}{\omega d}}. \tag{8}$$

where c is the speed of light in vacuum. Thus $|nkd| \ll 1$ becomes $\sqrt{2kd} \ll 1$ and the corresponding refractive index should be much larger than unit ($|n| \gg 1$). Compared with the general CPA condition described by Eq. (5), the CPA condition for ultrathin film is clearer. Specifically, we can discuss the CPA condition for ultrathin film using metals or certain semiconductors (such as doped silicon) materials. Over a broad frequency range, the complex dielectric function can be explained by Drude model [28]

$$n^2 = \varepsilon_1 + i\varepsilon_2 = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\Gamma)}, \tag{9}$$

$$\varepsilon_1 = \varepsilon_\infty - \frac{\omega_p^2\tau^2}{1+\omega^2\tau^2}, \varepsilon_2 = \frac{\omega_p^2\tau^2}{\omega(1+\omega^2\tau^2)}. \tag{10}$$

where ε_∞ is the dielectric constant, $\Gamma = 1/\tau$ is collision frequency, and ω_p is the plasma frequency. In the very low frequency range, where $\omega \ll \tau^{-1}$, hence $\varepsilon_1 \gg \varepsilon_2$, and the real and imaginary parts of the refractive index are of comparable magnitude with

$$n' \approx n'' \approx \sqrt{\frac{\varepsilon_2}{2}} = \sqrt{\frac{\tau\omega_p^2}{2\omega}}. \tag{11}$$

Inserting Eq. (11) into Eq. (8), the thickness for CPA at this frequency range can be written as

$$d_w \approx \frac{2c}{\omega_p^2\tau}. \tag{12}$$