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Coherent perfect absorption of light in a single nanowire

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Abstract: Whereas absorption of travelling waves is an inherently stochastic process, standing waves can be deterministically absorbed by a flat thin absorber – a phenomenon known as coherent perfect absorption (CPA). Here, we extend CPA to absorbers of lower dimensionality and report that, upon reflection in a conical mirror, radially polarized light can be deterministically absorbed in a single nanowire. Conversely, azimuthally polarized light can be fully reflected. Such phenomena are of interest for energy harvesting and for the detection of topologically structured light, including “Flying Donuts” and orbital angular momentum-carrying beams.

Coherent perfect absorption (CPA) is based on the interference of two counterpropagating beams that form a standing wave [1]. By placing a thin 2D absorber in the standing wave antinodes, full absorption of both beams can be achieved. Here, we expand CPA to 1D absorbers under illumination with vector polarized light and develop an analytical description of the process. We investigate the conditions for selective absorption of radially or azimuthally polarized light and discuss the corresponding physical limitations.

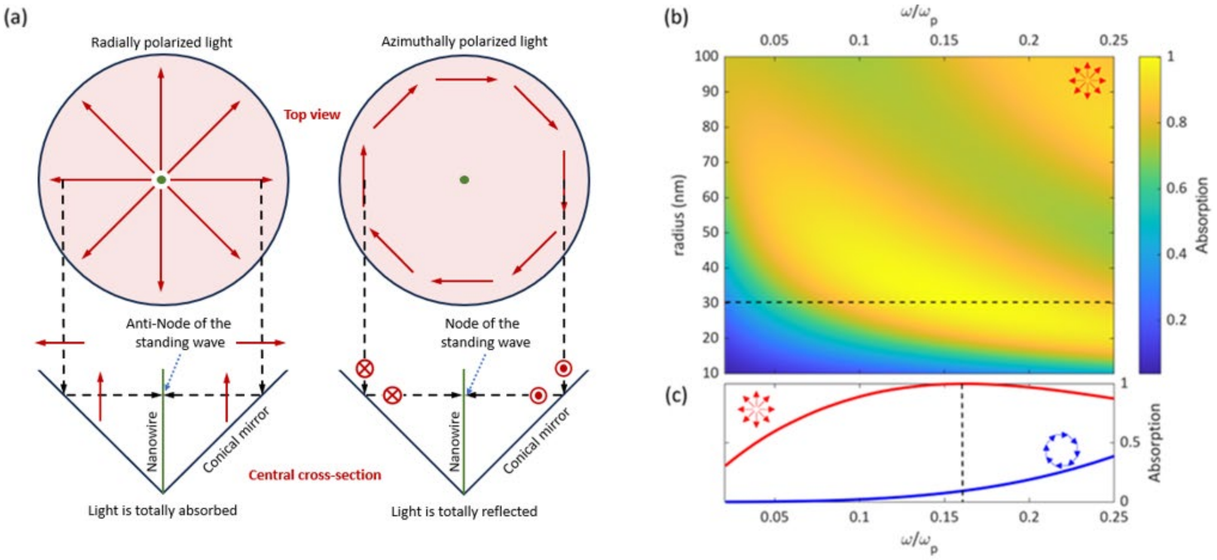

Figure 1. (a) Schematic of a 1D coherent perfect absorber. A conical mirror transforms a vector polarized beam to a cylindrical wave converging to a thin absorbing nanowire at the centre of the mirror. Depending on the incident polarization (radial or azimuthal), reflected waves from antipode positions on the mirror interfere constructively or destructively at the position of the nanowire, enhancing or suppressing absorption, respectively. (b) Nanowire absorption under illumination with radially polarized light as a function of frequency and wire radius. (c) Absorption spectra of a nanowire with a 30 nm radius (indicated by the horizontal dashed line in (b)) under illumination with radially (red) or azimuthally (blue) light. The vertical dashed line marks the frequency of CPA. In (b) & (c), the nanowire is described by a Drude conductivity with ω_p=3×10^{16} rad/s.

A schematic of CPA in a 1D absorber is shown in Fig. 1a. A thin absorbing nanowire is placed at the centre of a conical mirror oriented along the mirror axis. Upon reflection on the conical mirror, an incident vector polarized beam is transformed to a cylindrical standing wave. The nanowire lies on the antinode or node of the standing wave depending on the polarization of the incident beam. For example, in the case of radial polarization, the electric field lies in the plane of incidence at each cross-section of the mirror and as such its component normal to the mirror surface reverses. As a result, parts of the incident beam with anti-phase electric fields will interfere constructively along the axis of the mirror. In contrast, the electric field of an incident azimuthally polarized beam will be normal to the plane of incidence, resulting in destructive interference on the nanowire. We note that this effect can also be interpreted in terms of geometric (Berry-Pancharatnam) phase, where reflections from antipode positions on the conical mirror experience a relative π or 0 phase shift for radially and azimuthally polarization, respectively.

We have developed an analytical theory to describe CPA in 1D absorbers based on Mie theory for cylindrically symmetric problems. For simplicity, we consider infinitely long nanowires and exclude effects at the apex of the conical mirror. We expand the electric field outside and inside the nanowire in terms of outward and inward propagating cylindrical waves, represented by Hankel functions of the 1st and 2nd kind. By taking into account the interface conditions at the nanowire boundary, we can derive expressions for the reflected electric field of azimuthally and radially polarized waves:

$$E_{az} = \frac{nJ_0(nk_0a)J_0'(k_0a) - J_0'(nk_0a)J_0(k_0a)}{nH_0^{(1)\prime}(k_0a)J_0(nk_0a) - J_0'(nk_0a)H_0^{(1)}(k_0a)} J_0(k_0r) + 0.5H_0^{(1)}(k_0r) \tag{1}$$

$$E_{rad} = \frac{nJ_0(k_0a)J_0'(nk_0a) - J_0'(k_0a)J_0(nk_0a)}{nH_0^{(1)}(k_0a)J_0'(nk_0a) - J_0(nk_0a)H_0^{(1)\prime}(k_0a)} J_0(k_0r) + 0.5H_0^{(1)}(k_0r), \tag{2}$$

where n and α is the complex refractive index and radius of the nanowire, k_0 is the free-space wavevector, J_0 and $H_0^{(1)}$ are the 0-th order Bessel and Hankel functions of the 1st kind, and J_0' and $H_0^{(1)\prime}$ are the corresponding derivatives with respect to the radial coordinate at $r=\alpha$. Equations (1-2) hold for arbitrary material parameters and radius of the nanowire.

In Fig. 1b&c, we present a characteristic case of a nanowire with radius in the range 10-100 nm and optical properties defined by Drude conductivity with plasma frequency $\omega_p=3\times10^{16}$ rad/s and relaxation time $\gamma=5\times10^{16}$ rad/s, under illumination with radially polarized light. Full absorption can be achieved over most of the considered spectrum ($\omega>0.1\omega_p$) by appropriate selection of the nanowire radius. In particular, for a nanowire with radius of 30 nm, absorption remains over 90% over an octave of bandwidth and reaches 100% at $\omega\sim0.16\omega_p$ (see red curve in Fig. 1c). At the same time, absorption of azimuthally polarized light is substantially suppressed (blue curve in Fig. 1c) with most of the incident light being reflected. The ratio between azimuthally and radially polarized light absorption here can be as high as 10^4.

In conclusion, we have introduced CPA in 1D absorbers and developed a full analytical theory for its description. We derived conditions for broadband and polarization selective absorption of light. Our work paves the way towards applications in energy harvesting and in the detection and manipulation of topological light (vector beams, toroidal light pulses, angular momentum beams).

[1] Y.D. Chong, L. Ge, H. Cao and A.D. Stone,“ Coherent perfect absorbers: time-reversed lasers,” *Phys. Rev. lett*, vol. 105, p.53901, 2010.