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Non-scattering Systems for Field Localization and Emission Enhancement

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Abstract: We propose invisible cavities which do not scatter electromagnetic waves under normal incidence but strongly enhance or suppress the fields inside. They can be used for cloaking sensors and emission enhancement of wave sources.

OCIS codes: (160.3918) Metamaterials; (230.5750) Resonators

1. Introduction

Localization of electromagnetic waves plays central role for applications in various fields of applied physics such as in lasers, resonators, optical fibers, nonlinear devices, and so forth [1]. During last decades, it became also a rapidly growing subject of nanophotonics where achieving high quality factors in optically compact systems is of paramount importance. A simple example of wave localization is the echo inside a cave. Sound waves created by an object inside the cave cannot escape outside and experience multiple reflections from its hard walls before getting eventually absorbed. Meanwhile, the sound can be strongly enhanced in this cavity due to wave interference. A pertinent question arises whether it is possible to create wave localization in a space region without isolating it and, moreover, without disturbing the waves outside of this region. Such space region would appear for an external observer as free space (fully imperceivable), while it would operate as a resonant cavity for an observer inside it.

In this work, we discuss and develop the design of such invisible cavities based on two parallel planar metasurfaces with contrasting electric properties separated by a certain distance [2]. We demonstrate both numerically and experimentally unidirectional invisibility of the cavity at the operating frequency. Simultaneously, the field inside the cavity exhibits enhancement and suppression regions. These properties can be used for cloaking sensors and obstacles, emission enhancement of sources located inside the cavity, etc.

2. Invisible cavities

The proposed and studied "invisible cavity" is formed by two infinite metasurfaces parallel to the xy-plane located at $z = 0$ and $z = d$ in the Cartesian coordinate system (d is the distance between the metasurfaces). The medium filling the space outside and inside the cavity is vacuum characterized by wave impedance η_0 and wave number k_0. The structure is illuminated by a normally incident plane wave propagating in the $+z$ direction with the electric field $E_{\rm I}$. The incident wave induces uniform electric currents in both metasurfaces J_1 and J_2 which scatter secondary plane waves in the surrounding space. Using the boundary conditions at each metasurface, one can determine their required sheet impedances $Z_1 = E(0)/J_1$ and $Z_2 = E(d)/J_2$ ($E(z)$ is the total electric field tangential to the surfaces) which provide zero reflection and full transmission with zero phase lag [2]. We find that the sheet impedances of the two metasurfaces can be *arbitrary* but *opposite* to one another, satisfying the relation $Z_1 = -Z_2$. The distance between the metasurfaces must be a fixed value with respect to the wavelength expressed as $d = n\lambda_{\rm op}/2$, where n is an integer and $\lambda_{\rm op}$ is the operational wavelength. Here, we focus on the lossless case when $Z_{1,2} = i\eta_0\tilde{X}_{1,2}$, where $\tilde{X}$ is the normalized sheet reactance. The field inside the cavity corresponds to that of a standing wave.

Figure 1(a) depicts analytical and simulated results for the field distribution outside and inside the invisible cavity. While the field outside the cavity volume at each point is equal to that of the incident wave, the fields inside it reach extreme values of approximately $10E_{\rm I}$ and $0.1E_{\rm I}$ at different locations (for the case of $\tilde{X}_1 \approx 0.101$). Therefore, by positioning arbitrary thin planar objects inside the cavity at the location of the electric field minimum, one can drastically suppress scattering from the object or in other words cloak the object. Naturally, such an object cannot be a perfect electric conductor. On the other hand, positioning a very small sensor at the location of the field maxima, one will be able to sense the incident wave without significantly disturbing it.

3. Reciprocity and emission enhancement

Due to reciprocity of the designed metasurface system, if the source of the incident waves (current sheet) is placed inside the cavity, one should expect reciprocal enhancement or suppression of waves outside the system.

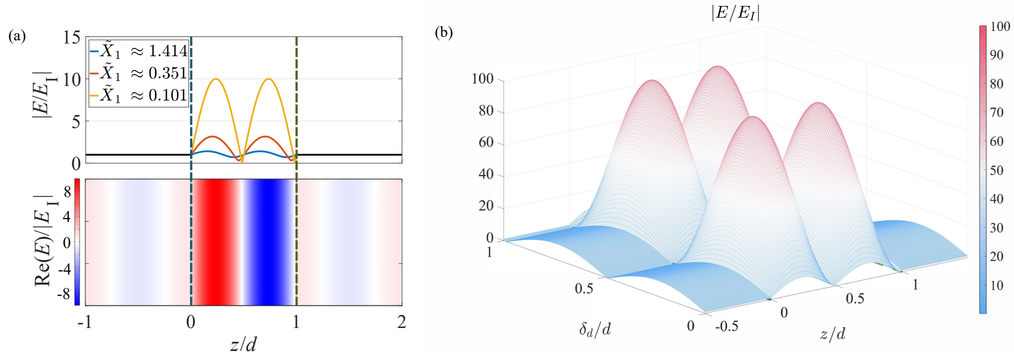

Fig. 1: (a) Up: Distribution of the total electric field normalized by the incident one for metasurface cavities with different reactances of the two sheets. The dashed lines denote the positions of the two metasurfaces, distance between which was chosen to be $d = \lambda_{\mathrm{op}}$. Bottom: Full-wave simulation of the total electric field distribution across the metasurface cavity. The reactances of two metasurfaces are $\tilde{X}_1 = -\tilde{X}_2 \approx 0.101$. (b) Electric field across a resonator with $\tilde{X}_1 \approx 0.101$ as a function of the position of the current sheet placed inside δ_d.

Figure 1(b) plots the total electric field across the cavity for different distances of the current source δ_d from the first metasurface, which is at $z = 0$. The surface current density amplitude in the sheet was chosen $J_\mathrm{s} = -2E_\mathrm{I}/\eta_0$ (in free space, it would excite a plane wave with the electric field amplitude E_I). One can see that by positioning the current sheet at the locations of the maxima (minima) of the cavity shown in Fig. 1(a), the field outside it reaches the value of $10E_\mathrm{I}$ ($0.1E_\mathrm{I}$). Thus, the cavity allows enhancement and suppression of emission from a source located in it [3]. To further demonstrate this capability, we have simulated wave radiation of a dipole source in free space and inside the finite-size cavity (see Fig. 2). We observe 11-fold enhancement of the radiated power by the source.

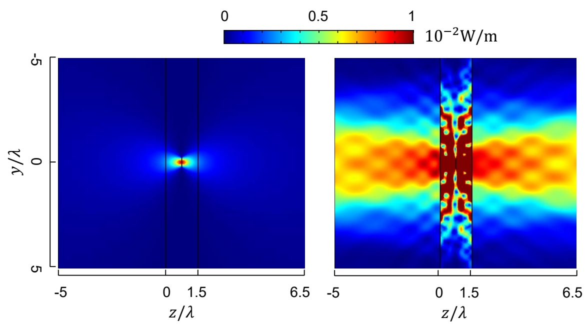

Fig. 2: Linear power density for a dipole source located in free space (left) and in the maximum of the invisible cavity (right). The system has continuous symmetry along the x-axis. The surface current density in the source follows a sine distribution $J_\mathrm{s}(y) = 0.021\cos[2\pi y/\lambda_{\mathrm{op}}]$ A/m.

4. Conclusions

In conclusions, we have proposed and discussed invisible cavities that can be used for cloaking sensors and obstacles as well as emission enhancement of wave sources. During the presentation, we will discuss in more details possible applications of these cavities and experimental results.

References

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