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Physical bounds on electromagnetic invisibility and the potential of superconducting cloaks

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Abstract

The possibility of suppressing the scattering cross section of an object is subject to fundamental physical bounds imposed by causality and passivity. Global cloaking limitations have been recently derived, which imply that any linear, causal and passive cloak necessarily increases the global scattering, integrated over the whole electromagnetic spectrum, compared to the uncloaked object. Here, we expand on this topic, discussing in detail an interesting exception to this limit represented by cloaks with static diamagnetism. In this context, we explore the potential of superconducting materials to realize global and local reduction of the scattering cross section. The concepts of plasmonic and mantle cloaking are extended to superconductors, realizing strong and tunable invisibility, with some unique properties stemming from the peculiar electrodynamics of superconductors. We conclude by qualitatively discussing a possible method to derive more stringent local bounds on cloaking.

Keywords: Cloaking; Superconductors; Metamaterials

1. Introduction

In recent years, the new concepts introduced by metamaterials have determined an important paradigm shift in classical electrodynamics. The possibility to realize man-made materials with properties beyond what is readily available in nature has opened new venues in this broad area of research, with many exciting scientific proposals and practical applications [1]. The most notable example is, arguably, the possibility of realizing invisibility, or cloaking, devices [2–4]. This idea has triggered a lot of attention and excitement among engineers, scientists and the general public, as this topic "resonates" with a human dream that periodically resurfaces in literary works and movies. However, compared to their fictional counterparts, realistic invisibility cloaks designed and fabricated in recent years seem rather rudimentary in many aspects. Several theoretical, numerical and experimental works indeed agree in pointing out major challenges and limitations associated with cloaking technologies. The detrimental effect of Ohmic losses, for example, appears to severely limit the performance of several designs, a common problem in several metamaterial-based devices, which can be tackled by using low-loss materials or designs less prone to absorption (e.g., metasurface-based cloaking, or mantle cloaking [5]). A more fundamental problem is the typically narrow operational bandwidth of cloaking devices,

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which appears related to intrinsic limitations associated with causality, passivity and linearity of the scattering system (see, e.g., [6–9]). Besides, bandwidth issues generally worsen as the electrical size of the object to be cloaked increases [8], making broadband cloaking of large bodies very challenging.

Here, we base our discussion on a quantitative definition of cloaking, namely, the ability to restore the impinging field distribution around the cloaked object, in both amplitude and phase, by reducing its total scattering cross section (SCS). If the SCS vanishes, the cloaked object will become truly invisible for any illumination direction and observer's position. Some less stringent definitions of cloaking require, instead, to restore only the amplitude of the incident field, being able to produce a transparency effect to devices not sensitive to phase, such as the human eye. In this case, the bandwidth limitations are largely relaxed and a transparency effect can be more easily achieved, even by simply relying on smart optical tricks, working very well even for electrically large objects [10]. In this category of transparency devices, the great majority of proposed solutions work only for specific directions of excitation. For example, a "see-through" effect for a single direction can be achieved with simple mirror tricks [11]. A relevant exception is represented by the more advanced solution proposed in [12], based on transformation optics in a non-Euclidean space, which, in principle, may realize omnidirectional and broadband transparency effect, restoring the amplitude of the incident field (yet not the phase) all around the cloaked object.

Although such see-through effect may be sufficient in several applications, more in general restoring the phase distribution may matter since, if not restored, it may reveal the presence of a hidden object. Consider, for example, an object covered by a cloak that restores only the amplitude distribution of the incident field, but not its phase front. If two or more 'transparent' objects of this kind are brought in proximity of each other and illuminated, the perturbed waves can still largely interfere through their phase scattering patterns, revealing the presence of the overall system also in terms of amplitude. With cloaks designed to restore the impinging fields in both amplitude and phase, on the contrary, the objects become truly undetectable, irrelevant of what happens around them. In this paper we quantitatively analyze the performance of a cloaking device by assessing its ability to reduce the total scattered field over several frequencies.

Our scattering analysis allows drawing profound connections between the invisibility performance and general causality and passivity considerations. Global and local bounds on cloaking can then be derived on this basis, as we discuss in the following, indicating new avenues to improve cloaking technology, such as by exploiting diamagnetic/superconducting materials and active designs.

2. Global bounds on cloaking and diamagnetic cloaks

The derivation of global bounds on cloaking presented in [13] starts from a fundamental sum rule, first derived by Purcell [14], which directly relates the SCS of a given object, integrated over the entire electromagnetic spectrum, to its polarizability at zero frequency. Assuming only linearity, causality and energy conservation, it is possible to write [15–18]

$$\int_0^{\infty} C_{\text{scat}}(\lambda)\, d\lambda = \pi^2(\hat{p}_e^* \cdot \alpha_{e,s} \cdot \hat{p}_e + \hat{p}_m^* \cdot \alpha_{m,s} \cdot \hat{p}_m) \tag{1}$$

where $C_{\text{scat}}(\lambda)$ is the total scattering cross section as a function of wavelength λ; $\alpha_{\text{e,s}}$ and $\alpha_{\text{m,s}}$ are the static electric and magnetic polarizability dyadics; $\hat{p}_e$ and $\hat{p}_m = \hat{k} \times \hat{p}_e$ denote the polarization and cross-polarization unit vectors, respectively, and $\hat{k}$ indicates the incident direction. According to Eq. (1), if the static polarizabilities increase, an object will scatter more energy across the electromagnetic spectrum. In light of this, we may ask how the introduction of a generic cloak around the original object will modify the integrated scattering. To answer this question, we exploit a theorem derived in [19], and generalized in [20], which implies that, when we add matter around a given object, the static polarizabilities of the whole scatterer will necessarily increase if the static electric permittivity $\varepsilon(0)$ and magnetic permeability $\mu(0)$ of the cloak are, at all points, larger than unity (relative to the background material). Moreover, we note that, according to Kramers Kronig relations [15], the real part of the static electric permittivity is given by

$$Re[\varepsilon(0)] = 1 + \frac{2}{\pi}\int_0^{\infty} \frac{Im[\varepsilon(\Omega)]}{\Omega} d\Omega \tag{2}$$

which is *strictly larger than unity* if the material is passive, i.e., $\text{Im}[\varepsilon(\Omega)] \leq 0$. Conversely, as noted in [21], similar considerations are not applicable to $\mu(0)$, since the magnetic permeability ceases to be physically meaningful at moderately high frequencies, before converging to unity. As a result, materials with $\mu(0)$ between 0 and 1 are allowed, as confirmed by the existence of several diamagnetic materials in nature.

The above considerations imply that any linear, causal and passive cloak without diamagnetic properties