Fundamental Passivity and Causality Bounds on Metamaterial Cloaking

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In the last decade, metamaterials and plasmonics have been introduced and developed in the electromagnetic community, bringing new exciting findings and potential applications of this technology in a variety of applied fields. The application of these new ideas to the hundred-year-old field of electromagnetic scattering has led to the discovery of anomalous and, often, counterintuitive effects. Most notably, huge interest has been devoted by the broad scientific community to the realization of a long-sought invisibility, or cloaking, device and a plethora of different ideas have been proposed. Now, after some years from the first theoretical works on cloaking, and some proof-of-concept realization of these concepts, researchers are realizing that bandwidth is the fundamental issue limiting the practical applicability of this technology, and a better understanding of these limitations is of vital importance. Several authors have pointed out that, in general, broadband invisibility may pose serious problems in terms of causality. Still, most of the available papers on cloaking, even some of the most recent ones, present scattering reduction at a single frequency, without analyzing the frequency dependence of this phenomenon.

Some attempts to derive bandwidth limitations on cloaking have been recently proposed, using delay-bandwidth considerations. These results are however limited to certain classes of invisibility devices and appear too restrictive in the general sense. Here we propose a new approach to establish fundamental and completely general bounds on the bandwidth of cloaking, borrowing concepts from microwave engineering. In particular, we apply the rigorous Bode-Fano theory of broadband matching to the reflection and scattering coefficients of planar and spherical scatterers, in both the quasi-static and dynamic regimes. This allows us to derive, for the first time, very general physical bounds valid for any passive cloaking scheme. These theoretical limitations are ultimately deduced from passivity and causality and only depend on the characteristics of the scatterer to be hidden. Therefore, given the object to be cloaked, our approach allows to check the realizability of given cloaking specifications and can calculate the optimal tradeoff between available bandwidth and total scattering reduction.

We believe that these results are of fundamental scientific significance and represent a pivotal achievement in the general area of metamaterials and more specifically in understanding the realistic applicability of cloaking devices to real-world applications, such as camouflaging, non-invasive sensing and energy applications.