Universal wave phenomena in multiple scattering media

Ebrahimi Pour Faez, S.

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The main topic of this dissertation is studying the propagation of waves in disordered materials. More specifically, we have studied, theoretically and experimentally, the manifestations of Anderson localization in various systems using classical waves, such as light and ultrasound. Anderson localization refers to the suppression of wave diffusion in random media due to interference effects. This conductor to insulator transition was discovered fifty years ago by Philip Anderson in the context of electronic conductivity of metals.

Over the past decades, Anderson localization have attracted interest far outside its original scope of definition: as far as seismology and biomedical imaging. Most of the theoretical developments on the understanding of this phenomenon have been made by the condensed-matter physicists. Meanwhile, many important experimental achievement have been provided by the research on classical waves. However, a unified picture that captures both the experimental realities and theoretical descriptions of this phenomenon, for all types of waves, is still missing. Unfortunately, some existing interpretations of Anderson localization, even as reported next to experimental results, have been very mystified and sometimes superficial. Several claims have been made related to the observation of localization-related phenomena based on inadequate evidence or sometimes erroneous comprehension of the physics behind it.

On the theoretical side, two main approaches have been used, side by side, for studying Anderson localization. In the multiple scattering formalism, the propagation of waves is described in terms of scattering centers and Green functions. Light propagation in complex photonic structures can be described by a summation over several scattering paths. This summation is mathematically treated with diagrammatic techniques, which are commonly used in field theory. This approach successfully describes diffusion. It also sets the foundation for the self-consistent theory of localization, which includes the interference effects to an extent that the classical diffusion breaks down. This technique has proven to be very successful in describing several experimental transport measurements, which often approach localization transition from the diffusive side.

The second approach to studying waves in disordered media is to see the whole system as a matrix. This matrix can either be the Hamiltonian or the scattering matrix. For a disordered system, the entries of this matrix look like random. It is assumed that the statistical properties will not change if the entries are taken as completely random. This is the main concept behind random matrix theory (RMT). In contrast to the multiple-scattering formalism, which can be seen as the reductionist approach to studying waves in disordered...
media, random matrix theory is a holistic approach. In an RMT treatment, one often overlooks all the details of the system under investigation. Despite the apparently loose justification of RMT basic assumptions, the predictions are often generally applicable and surprisingly successful in reproducing the experimental results, even for very complicated systems.

The first two chapters of this dissertation are dedicated to introducing the basic foundations of multiple-scattering (chapter 2) and random matrix (chapter 3) theories. Books have been written about these subjects, and there was neither the intention nor the capacity of presenting a thorough introduction. Chapter 2 helps the reader to follow the derivation of two new theoretical results that are performed by us, using a multiple scattering approach. The first result is the equivalence of variations in frequency with variation in effective refractive index. This equivalence sets the basis for the method of Refractive Index Tuning, which is described in chapter 6 and supported by experimental results. The second theoretical result is the relation between so-called $C_0$ fluctuations and the efficiency of second-harmonic generation in random media. This equivalence was the motivation behind the experiments that are described in chapter 7. Both experiments were originally designed in relation with the idea of analyzing samples in the localized regime.

In chapter 4, the intensity distribution of electromagnetic polar waves in a chain of near-resonant weakly-coupled scatterers is investigated theoretically and supported by numerical analysis. Critical scaling behavior is discovered for part of the eigenvalue spectrum due to the disorder-induced Anderson transition. This localization transition (in a formally one-dimensional system) is attributed to the long-range dipole-dipole interaction, which decays inverse linearly with distance for polarization perpendicular to the chain. For polarization parallel to the chain, with inverse-squared long-range coupling, all eigenmodes are shown to be localized. A comparison with the results for Hermitian power-law banded random matrices and other intermediate models is presented. This comparison reveals the significance of non-Hermiticity of the model and the periodic modulation of the coupling.

The experimental observation of strong multifractality in wave functions close to the Anderson localization transition in open three-dimensional elastic networks is reported in chapter 5. The first observation of localization in these samples were reported in a prior publication. Our second look at the measurements provided the first experimental indication of multifractal structure of waves near the localization threshold and confirmed the nontrivial symmetry of the multifractal exponents, which was theoretically conjectured before.