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Dual nature of localization in guiding systems with randomly corrugated boundaries: Anderson-type versus entropic

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ABSTRACT

A unified theory for the conductance of an infinitely long multimode quantum wire whose finite segment has randomly rough lateral boundaries is developed. It enables one to rigorously take account of all feasible mechanisms of wave scattering, both related to boundary roughness and to contacts between the wire rough section and the perfect leads within the same technical frameworks. The rough part of the conducting wire is shown to act as a mode-specific randomly modulated effective potential barrier whose height is governed essentially by the asperity slope. The mean height of the barrier, which is proportional to the average slope squared, specifies the number of conducting channels. Under relatively small asperity amplitude this number can take on arbitrary small, up to zero, values if the asperities are sufficiently sharp. The consecutive channel cut-off that arises when the asperity sharpness increases can be regarded as a kind of localization, which is not related to the disorder *per se* but rather is of entropic or (equivalently) geometric origin. The fluctuating part of the effective barrier results in two fundamentally different types of guided wave scattering, viz., inter- and intramode scattering. The intermode scattering is shown to be for the most part very strong except in the cases of (a) extremely smooth asperities, (b) excessively small length of the corrugated segment, and (c) the asperities sharp enough for only one conducting channel to remain in the wire. Under strong intermode scattering, a new set of conducting channels develops in the corrugated waveguide, which have the form of asymptotically decoupled extended modes subject

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to individual solely intramode random potentials. In view of this fact, two transport regimes only are realizable in randomly corrugated multimode waveguides, specifically, the ballistic and the localized regime, the latter characteristic of one-dimensional random systems. Two kinds of localization are thus shown to coexist in waveguide-like systems with randomly corrugated boundaries, specifically, the entropic localization and the one-dimensional Anderson (disorder-driven) localization. If the particular mode propagates across the rough segment ballistically, the Fabry–Pérot-type oscillations should be observed in the conductance, which are suppressed for the mode transferred in the Anderson-localized regime.

1. Introduction

The multiple scattering of quantum and classical waves in disordered systems is at the heart of many interesting physical phenomena. Among them the best known and thoroughly studied are the Anderson localization of current carriers and waves of different types, quantum corrections to conductivity (weak localization), metal–insulator transitions in solid state systems, and the coherent retro-reflection of waves (the backscattering enhancement) [1–3]. Recently, Bose-condensed systems with numerous manifestations of state localization, which are in one way or another related to random potentials, have also become the subject of active research (see Refs. [4–7] and references therein).

In recent years, however, there has been an increasing tendency for obtaining the experimental results that either were not in good conformity with conventional theories of disorder-induced localization or even substantially inconsistent with them (see, e.g., Ref. [8] and references therein). The observed inconsistencies may have different origins, to which one can attribute, for instance, uncommon refractive properties of propagation media [9], specific correlation properties of scattering potentials [10], the availability of absorption or amplification sources [11], and other possible factors. The non-trivial topology of propagation medium may also play a major role. The latter factor manifests itself in diverse phenomena such as Aharonov–Bohm and quantum Hall effects [12,13], non-homogeneous concentration of energy in randomly filled cavities [14], unusual properties of current carrier transport in wires both with isolated bends (in Ref. [15], the "bent resistance" has been detected experimentally) and in ballistic conductors with randomly distorted boundaries [16,17].

The random nature of systems of waveguide configuration (quantum conductors and classical waveguides) and the consequent scattering results in waveguide state attenuation commonly characterized by the *extinction* length [18], and also in spacial localization of those states, which has the interference nature and is specified by the *localization* length. Strictly speaking, the theory of such a localization is valid for systems that are infinitely large in the direction of waveguide axis. In the present study we concentrate on the problem of electron (as well as classical wave) transport across a *finite* (in the direction of current) disordered systems whose random nature is ensured by random roughness of their side boundaries.

Any deformation of the waveguide system boundaries is known to result in the appearance of the so-called *entropic barriers* [19], whose notion is closely associated with the definition of *quantum channels* in the information transfer theory [20]. In contrast to energetic barriers, which are originally present in the Hamiltonian, the entropic barriers are not of the potential relief nature. A possible way to take them into account in practice is to introduce the emulating potential terms into the Hamiltonian, whose effect would be the same as in strictly considering the scattering in systems with destroyed boundaries [21]. Yet another approach, which is more correct mathematically, was applied in Refs. [22,23], where boundary irregularities were converted into the scattering potentials