Scaling in one-dimensional localized absorbing systems

Lev I. Deych,1 Alexey Yamilov,2 and A. A. Lisyansky2

1Physics Department, Seton Hall University, South Orange, New Jersey 07052
2Physics Department, Queens College of CUNY, Flushing, New York 11367
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Numerical study of the scaling of transmission fluctuations in the one-dimensional localization problem in the presence of absorption is carried out. Violations of single-parameter scaling for lossy systems are found and explained on the basis of a new criterion for different types of scaling behavior derived by Deych et al. [Phys. Rev. Lett., 84, 2678 (2000)].

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I. INTRODUCTION

The single-parameter scaling (SPS) hypothesis is the cornerstone of the current understanding of the localization phenomena. It was originally formulated in terms of the scaling behavior of the conductance of disordered conductors, where it was suggested that when the length, L, of a disordered conductor increases, the evolution of the conductance, g(L), is determined by a single parameter, g itself. For one-dimensional (1D) systems the Landauer’s formula expresses the electron conductance in terms of electron reflection, R(L), and transmission, T(L), coefficients as 

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and thereby allows considering of electron transport on an equal footing with, for example, propagation of light. It was recognized later that SPS must be understood in terms of properties of the entire distribution of g (or T), and that the most appropriate quantity to deal with is the

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\[ \gamma(L) = (1/2L)\ln(1 + 1/g(L)) = (1/2L)\ln[1/T(L)]. \]

In the limit of large L, this parameter is normally distributed with the average \( \gamma = \langle \gamma(L) \rangle = \lim_{L \to \infty} \gamma(L) \) and the variance \( \sigma^2(L) = \langle \gamma^2(L) \rangle - \gamma^2. \) The limiting value of \( \gamma(L) \) is known in the theory of products of random matrices as the Lyapunov exponent (LE). The inverse quantity, the localization length, \( l_{loc} = \gamma^{-1} \), determines the main length scale in the localization regime. SPS in this context means that the variance of \( \gamma \) is not an independent parameter, but it is determined by \( \gamma \) itself implying a simple relationship between two quantities:

\[ \sigma^2 = \gamma L. \] (1)

This expression was obtained for the one-dimensional model in Ref. 3 assuming complete randomization of the phases of complex transmission and reflection coefficients over a microscopic length scale \( l_{ph} \ll l_{loc} \) (phase-randomization hypothesis). Later the phase-randomization hypothesis was used by many different authors to rederive Eq. (1) (see, for instance, Refs. 5,6), and the inequality \( l_{ph} \ll l_{loc} \) came to be regarded as the criterion for SPS. However, there were earlier signs that the phase-randomization hypothesis is neither necessary nor sufficient condition for SPS to occur. For instance, numerical simulations of Ref. 6 and analytical calculations of Ref. 7 showed that in the center of a conductivity band of the 1D Anderson model, SPS holds even though the phase is not randomized, provided that the disorder is weak. Later, numerical simulations of a random, periodic-on-average model demonstrated a strong violation of SPS in the band gaps of the spectrum of the underlined system without disorder, which existed even for weak disorder and, actually diminished, when disorder increased. This was contrary to the behavior found for states from the original conducting band, for which minor deviations of the variance from Eq. (1) occurred when disorder becomes strong enough.

The final realization of the fact that the phase randomization hypothesis has nothing to do with SPS came in Ref. 9. In that paper, the variance of LE was calculated exactly for the Lloyd model and the SPS equation (1) was derived without ad hoc assumptions. It was found that the emergence of SPS is governed by a new length scale \( l_s \), related to the integral density of states with the new criterion for SPS being

\[ \kappa = l_{loc} / l_s \gg 1. \]

On the basis of the exact solutions it was conjectured that in the region of the spectrum close to its original boundary, the parameter \( l_s \) can be defined in a generic case as

\[ l_s = a\sqrt{N(E)}, \] (2)

where \( a \) is the lattice constant and \( N(E) \) is the number of states between the closest genuine boundary of the spectrum of the disordered system and \( E \), normalized by the total number of states in the band [such that \( 0 < N(E) < 1 \)]. It follows from the established criterion that the violation of SPS occurs in the regions of the spectrum with the depleted differential density of states. It is well known that these regions correspond to fluctuation states arising outside the initial spectrum of the system. Therefore, the deviations from SPS must occur at the gap sides of initial boundaries of the spectrum as was observed in Ref. 8. Numerical studies undertaken in Ref. 9 evidenced that the criterion based upon the definition of \( l_s \) given by Eq. (2) was valid for the periodic-on-average model with rectangular distribution of random parameters. An additional implication of the results of Ref. 9 is that the random-matrix theory approach, which also reproduces Eq. (1), does not apply to spectral regions with depleted differential density of states.

The objective of this paper is to show that two different scaling regimes governed by the parameter \( l_s \) found in Ref. 9 exist also in disordered systems with absorption. Having in mind applications to light propagation in random photonic band-gap materials, we consider how the inclusion of small absorption affects scaling properties of transmission.
show that the conjectured definition of \( l_s \) in terms of the integral density of states can also be applied to disordered systems with absorption.

Within the phase-randomization hypothesis approach, statistics of the transmission in lossy one-dimensional dielectrics was considered analytically in a number of papers. Following Ref. 13 the relation between the variance and the localization length in the presence of absorption can be presented in the form

\[
\tau = \tau_0(\beta) = 1 + 2 \beta e^{2\beta} E i(-2 \beta),
\]

where \( \tau = \sigma^2 L/\gamma \), \( \beta = l_{loc}/l_a \), and \( l_a \) is the absorption length in the absence of randomness.

\[
E i(x) = \int_{-\infty}^{\infty} dt \exp(t/t)
\]

is the exponential integral. In the absence of absorption, Eq. (3) reduces to the regular SPS form \( \tau = 1 \). In the two limiting cases Eq. (3) gives the asymptotes \( \tau = 1 - 2 \beta \ln(1/\beta) \), \( \beta \ll 1 \) and \( \tau = 1/2\beta \), \( \beta \gg 1 \).

Presuming that the length scale \( l_s \) retains its meaning in the case under consideration, we expect that the parameter \( \tau \) deviates from the phase-randomization hypothesis prediction \( \tau_0(\beta) \) [Eq. (3)] in the vicinity of the boundaries of the spectrum in accordance with the same criterion \( l_{loc} \gg l_s \) as in Ref. 9. Using numerical simulations of a periodic-on-average one-dimensional lossy system, we show that, indeed, the parameter \( \kappa = l_{loc}/l_s \) sets a valid criterion for validity of Eq. (3). As an additional benefit, we demonstrate that within the range of its validity, Eq. (3) represents a universal, model independent relation between the variance and the mean value of LE. The deviations from the phase-randomization-based results of Ref. 13 studied in our paper must be clearly distinguished from results of Ref. 15. In the latter paper, brake down of the phase randomization was obtained in the case of very strong disorder and strong absorption for states at the center of the original band. The results of our paper indicate that (i) violation of the generalized single-parameter scaling occurs at weak disorders for states close to the band edge of the original spectrum, (ii) this violation is not related to the phase randomization but is controlled by the parameter \( l_s \).

II. MODEL AND THE METHOD OF CALCULATIONS

We consider a classical transverse electromagnetic wave propagating normally through a stack of alternating dielectric slabs with dielectric constants \( \varepsilon_1 \) and \( \varepsilon_2 \). The widths of the stacks of the first kind is distributed uniformly in the interval \( (d_1 - \delta, d_1 + \delta) \) while the width of the others is being kept constant, \( d_2 \). The propagation of the waves in the superlattice consists of free propagation in the slabs and scattering at the interfaces, where the boundary conditions should be satisfied. It can be described using the transfer-matrix formalism for the vector \( v_n = (E_n, E'_n/k)(\text{where} \ E_n, E'_n \ \text{are the electric field and its derivative at} \ n \ \text{th interface} \), and \( k = \alpha/c \). The presence of absorption can be accounted for by adding a constant complex part to the dielectric functions: \( \varepsilon_n = \varepsilon_n^0(1+i\alpha) \) and \( \varepsilon_s = \varepsilon_s^0(1+i\alpha) \), where \( \alpha \) is a damping coefficient. Vectors on neighboring interfaces are connected via the transfer matrix

\[
\mathcal{T}_n = \begin{pmatrix}
\cos k_n d_n & (1/k_n)\sin k_n d_n \\
-k_n \sin k_n d_n & \cos k_n d_n
\end{pmatrix},
\]

where \( k_n = k \sqrt{\varepsilon_n} \). The transfer matrix of the entire system is \( \mathcal{T}(\alpha, L) = \prod_{n=1}^{N} \mathcal{T}_n(\alpha, L) \), where \( L = N(d_1 + \langle d_2 \rangle) \). LE is defined through the transmission coefficient for the superlattice:

\[
\gamma(L, \alpha) = -\frac{1}{2L} \ln |(\mathcal{T}(\alpha, L) v_0)\rangle = -\frac{1}{2L} \ln \left[ \frac{1}{2} \left( \left| \mathcal{T}_{11}(\alpha, L) + \mathcal{T}_{22}(\alpha, L) \right| - i \left[ \mathcal{T}_{12}(\alpha, L) - \mathcal{T}_{21}(\alpha, L) \right] \right)^2 \right],
\]

where \( \gamma \) is the Coulomb-gapped deformation potential energy density.

\[
\gamma(L, \alpha) = \frac{1}{2L} \ln \left| \frac{\mathcal{T}(\alpha, L) v_0)}{v_0} \right|^2.
\]

To show the equivalency of Eqs. (5) and (7) we, first, diagonalize the transfer matrix \( \mathcal{T}(\alpha, L) \):

\[
\mathcal{T}(\alpha, L) = \hat{U}^{\dagger} \mathcal{T}^{(D)}(\alpha, L) \hat{U} = \begin{pmatrix} e^{\frac{i\alpha}{2}} & 0 \\
0 & e^{\frac{-i\alpha}{2}} \end{pmatrix} \hat{U}.
\]
here $\hat{U}$ and $\hat{U}^\dagger$ are some unitary matrices. For argument sake, we assume that $u_1(\alpha) > u_2(\alpha)$. Next, we notice the following relation between eigenvalues of the transfer matrix

$$n_1 \approx a^2 n_2 \approx a^2,$$

which follows simply from the reciprocity of our system. Indeed, propagation of the waves in the opposite-direction should be described by the matrix $\hat{T}^D(\alpha, L) = [\hat{T}(-\alpha, L)]^{-1}$, that leads to Eq. (9). Now, substituting $\hat{T}^D(\alpha, L)$ into Eqs. (5) and (7) (corrections due to matrices $\hat{U}$ and $\hat{U}^\dagger$ are negligible in the limit $N \to \infty$) one obtains $\gamma(L, \alpha) = -v_2(\alpha)$ and $\gamma(L, \alpha) = v_1(\alpha)$, respectively. Along with Eq. (9) this shows that these equations lead to the same value of LE. To make sure that the statistics of $\gamma(L, \alpha)$ given by both equations are also the same, we calculated numerically distribution functions for $\gamma(L, \alpha)$ using both Eqs. (5) and (7) for relatively short systems (such that Eq. (5) is still applicable) and found that they are identical.

III. RESULTS

In numerical simulations we used the following set of parameters $\epsilon_1 = 1.2$, $\epsilon_2 = 1$, and $\langle d_1 \rangle = d_2 = 1$. The disorder parameter, $\delta$, and the absorption rate, $\alpha$, were variable parameters. To calculate the moments of $\tilde{g}(L, \alpha)$, we averaged the characteristics of systems as long as 100 000 layers over 5000 realizations. The size of the stack was chosen to be at least five times the localization length or the absorption length. In the ordered system the first forbidden gap lies between $k = 1.456$ and $k = 1.543$. Since the localization length depends on the frequency of the wave, it is possible to study the function $\gamma(b(\nu))$ by changing the frequency. First, we compare our numerical results with the analytical formula of Ref. 13 in the region of frequencies well inside the first allowed band, where we expect these results to coincide. Figure 1 shows excellent agreement between the computed $\gamma(b)$ for $0.86 < k < 1.4$ and Eq. (3).

The localization length decreases rapidly when the frequency approaches the band edge, while LE, consequently, increases. As follows from Eq. (1), in the absence of absorption, $\sigma^2$ should follow the LE. Figure 2 depicts the depen-
At certain points the situation becomes more complicated, and we do not consider Eq. (3) at which the integrated density of states, in Eq. (2), becomes greater than the localization length. We assume that the disorder is not very strong so that the fluctuation boundaries inside former band gaps already be close to unity at the band edge. It reaches unity at the band edge, \( k = 1.456 \), SPS breaks down. Without absorption, we see the crossover to SPS in its pure form at \( \kappa = 1 \) reported in Refs. 8 and 9. When absorption is present, the crossover still occurs at \( \kappa = 1 \), but now to the modified SPS behavior \( \tau_0(\beta) \). We stress that the crossover occurs while \( a \ll l_{loc} \ll L \) and \( a \ll l_{a} \ll L \) so that the system remains in the meaningful scaling regime. This demonstrates that the condition \( 1 \ll \kappa \) establishes the criterion for modified SPS even in the presence of the absorption.

To check that our results are not model specific we also studied the Anderson model, with absorption introduced as a nonrandom imaginary part of the on-site random energy. In the Anderson model without disorder and absorption, there is a single allowed band form \( E = -2 \) to \( E = 2 \).

Figure 6 shows that \( \tau(\beta) \) deviates from \( \tau_0(\beta) \) at the edges of the allowed band as would be expected on the basis of the results presented for the periodic-on-average system. Inside the conductivity band, numerical and analytical results show excellent agreement. This is interesting in itself, since Eq. (3) was derived for a continuous model, and we see that in the SPS regime it holds also for the tight-binding discrete model.

In conclusion, we computed the Lyapunov exponent and its variance for a periodic-on-average layered system and for the one-dimensional Anderson model. We studied the deviation from the absorption-modified SPS expression for the variance. We showed that the new length scale, introduced in Ref. 9 in order to explain violation of SPS in the systems without absorption, retains its significance when absorption is present. We also showed that the same criterion \( \kappa = l_{loc}/l_s \gg 1 \) derived for lossless systems in Ref. 9 controls scaling behavior in lossy systems.

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10 The relation between $\sigma^2$ and $\gamma$ derived in Ref. 9 differs from Eq. (1) by a factor of 2. This discrepancy is due to the peculiar nature of the Cauchy distribution, whose moments, starting from the second one, diverge.