Scaling Theory of Wave Confinement in Classical and Quantum Periodic Systems

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Completely controlling the propagation of waves in periodic media is a key challenge that is essential for a large variety of applications. An especially interesting type of propagation control is wave confinement, achievable by introducing disorder and functional defects into an otherwise periodic medium [1]. Based on the character of the introduced defect, such waves may exhibit various dimensionalities of confinement, as depicted in Fig. 1.

Due to the inherent complexity of wave propagation in these structures, distinguishing the waves of various confinement dimensionalities in the band structure becomes highly non-trivial. Here, we propose a new method of wave confinement analysis based on energy-density distribution [2], as opposed to heuristic band-structure analysis. Our method is based on scaling arguments [1] and may be seen as a more accessible and practical extension of the multifractality analysis [3]. This technique is applicable to waves of arbitrary type (elastic, acoustic, electronic, spin, etc.) in both classical and quantum systems of arbitrary dimension.

We demonstrate our method on the quantum system of electron confinement in a hexagonal BN layer with nitrogen vacancies [4] and on the classical system of a 3D diamond-like photonic band gap crystal [5] with a pair of crossing line defects. Already in this example, our method has uncovered 3D-confined acceptor-like bands, thereby disproving previous work [6]. We also discovered, for the first time ever, 2D-confined waveguiding bands even within the continuum states.

Fig. 1: Confinement of waves in various dimensions by defects of different geometries. (a) 3D confinement. (b) 2D confinement. (c) 1D confinement.

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