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Figures-of-merit of Anderson localization cavities in membrane-based periodic-on-average random templates

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ABSTRACT

Anderson localization of light is an exotic mesoscopic phenomenon sustained in disordered systems through the self-interference of multiply scattered light. The localized modes are essentially eigenfunctions of the structural disorder, and define the resonances in the system. In this paper, we report on the computed figures-of-merit of Anderson cavities in two-dimensional membrane based structures, in which the disorder is written on a periodic-on-average template. We propose a disorder parameter that better reflects the randomization of the lattice points as compared to the conventionally used percentage disorder strength. Our results investigate the viability of such cavities in applications such as random lasing and cavity quantum electrodynamics.

1. Introduction

Wave transport in disordered systems is a fundamental subject of research and has relevance to a large range of topics ranging from atmospheric physics to advanced nanophotonic systems [1,2]. In the absence of interference effects, the light intensity obeys the diffusion equation and realizes ohmic transport across a disordered sample. In the presence of strong disorder, the finite diffusion coefficient tends to vanish, with the manifestation of Anderson localization of light, created by the self-interference of partial waves scattered throughout the volume of disorder. This phenomenon was initially proposed to explain the metal-insulator transition in disordered metallic crystals [3], and was later observed in light [4,5] and sound [6] waves, more recently in matter waves also [7]. Of all these systems, perhaps the largest activity has happened in optical systems [8], perhaps due to the advancement in the experimental achievements. In recent years, a large amount of literature has been published in low-dimensional systems [9–12], which include the situations wherein transverse localization [13] was observed [14,15].

The recent years have seen a surge of activity in specialised optical designs called periodic-on-average random systems (PARS). A PARS design is based on an underlying periodic lattice, PARS implies a deliberate randomization of periodic lattice points so as to perturb the Bloch modes of the erstwhile periodic system. Indeed, the significance of PARS design is evident from the fact that this configuration was discussed in the earliest seminal works on localization [16]. PARS systems have been discussed in several theoretical and experimental developments [17–21], with particular emphasis on their localization properties. In recent years, the phenomenon of optical localization has been seen through two vantage points, namely, cavity quantum electrodynamics (CQED) and random lasing. Basically, CQED relates to the modifying effects on the lifetimes of an emitter that is placed within a cavity. The cavity controls the density of states available to the emitter. Anderson localized states are resonant states realized by accidental cavities formed due to disorder. Their ability to modify the surrounding of an emitter has been recently studied in works on one-dimensional localization in disordered waveguides [10]. It was observed that the lifetimes of quantum dots tuned in and out of an Anderson cavity were different, thus revealing the promise of these unusual systems to study CQED within various coupling regimes. A second field of interest in PARS are random lasers. Random lasers are interesting optical devices that generate temporally coherent lasing emission using disorder-mediated feedback [22–29]. Lasing in Anderson localized cavities aim to utilize the high quality factor of the localized modes [19,11,25,26,30].

The CQED properties of the resonators are quantified through the Purcell factor, which is based on two figures-of-merit, namely, the quality factor and the mode volume. Similarly, in the case of random lasing, the lasing depends on the mode volume of the cavity which determines the gain, and also the quality factor which determines the feedback. Waveguides in disordered photonic crystals are examples of one-dimensional localizing systems. The confinement in the propagating dimension occurs due to the modification in the waveguide mode characteristics due to disorder in the neighbouring lattice. The localized modes in a disordered photonic crystal waveguide case have a very small mode volume, even for the smallest disorder. While this implies

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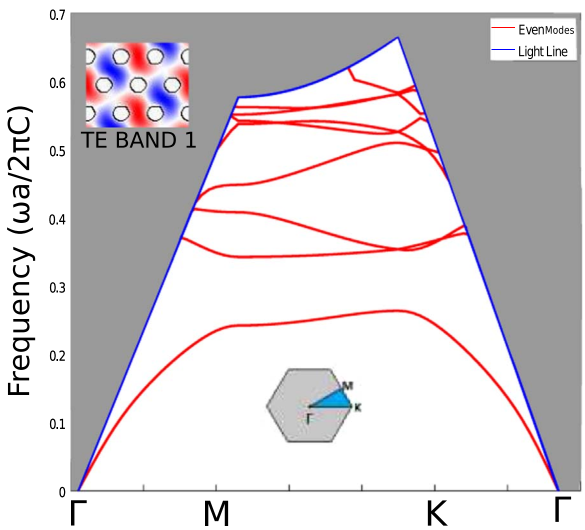

Fig. 1. Energy band structure of the quasi-two dimensional photonic crystal with a triangular lattice, r/a=0.23. The inset shows the TE Band 1 field profile at the K point.

strong Purcell factor, it also indicates a stringent need of perfect placement of quantum emitters in the system. However, apriori prediction of the spatial location of the localized mode is very difficult. Although computational methods can predict the location for a given configuration, the inherent uncertainty in fabrication of the actual sample may realize a shift in position which is larger than the mode size. It is, therefore, of interest to study the behavior of a two-dimensional system where the confinement is totally due to disorder in the photonic crystal lattice. Experimental activity till now has reported correlations in the light transport in such systems, wherein multiple quantum dots emitted at various wavelengths under optical excitation [31] were used. In this manuscript, we treat the situation differently. We numerically investigate a two dimensional system that is illuminated with a monochromatic source and the light is coupled to a localized mode if it exists. We then compute the Purcell factor for the resonator, and investigate the evolution of the Purcell factor as a function of the disorder strength. We find that at high disorder, the Purcell factor is large enough to motivate quantum optical experimentation in such systems.

2. Computations and results

The system under study is a membrane photonic crystal of GaAs (dielectric constant 11.39) with an air-hole array overwritten on the membrane, with an r/a ratio of 0.23 that exhibited a large bandgap. For a wavelength of interest of $\lambda = 1.55\ \mu m$, which applies to telecommunications, the physical dimensions for typical structure work out to be as follows: thickness 240 nm, lattice constant 445 nm, and air-hole radius 102 nm. For lasing or QED applications, the design has to be made for quantum emitters, and one wavelength of interest is $1.3\ \mu m$ for InAs quantum dots [32]. For this case, the physical dimensions should be 201 nm, 373 nm and 86 nm respectively. Initially, the bandstructure of the periodic structure was computed using a plane-wave basis [33]. Fig. 1 depicts the band structure for different wavevectors along the $\Gamma \rightarrow$ M, M→K and K→Γ directions. The inset shows the TE Band 1 electric-field distribution at the K point. The blue line depicts the light line which separates the guided modes from the non-guided modes in the membrane. We exploit the large gap at $\omega \sim 0.3$ between which lies between the first and the second bands.

Subsequent calculations involved the realization of disorder, and the temporal evolution of fields were solved in the time domain, using finite difference time domain algorithms [34]. In this case, the virtual structure included an air padding on either side of the membrane in the Z direction, followed by perfectly matching layers (PML) in all directions, to emulate open boundary conditions. The spatial resolution was maintained to be 16 and the temporal resolution was 32. Disorder was introduced by randomly tweaking the centre of the holes of the erstwhile periodic triangular lattice structure by a calculated amount. The maximum allowed change M, such that the holes do not overlap each other, is given by $M = a - 2r$. Let the co-ordinates of the centre of the holes be (x, y). To realize a percentage disorder P, we choose pairs of random numbers $(\delta x, \delta y)$ such that $(\delta x)^2 + (\delta y)^2 < d^2$, where $d = \frac{M}{2} \times \frac{P}{100}$, $P \in [0, 100]$. The new co-ordinates of the centre of the holes are given by $(x + \delta x, y + \delta y)$.

In this treatment, we quantify the disorder strength using a different disorder parameter ζ_P, which is derived from the correlation coefficient between the refractive index profile of the disordered structure and that of the periodic structure. The definition is

$$\zeta_P = 1 - \frac{1}{N-1}\sum_{j=1}^{N}\left(\frac{A_j - \mu_A}{\sigma_A}\right)\left(\frac{B_j - \mu_B}{\sigma_B}\right). \quad (1)$$

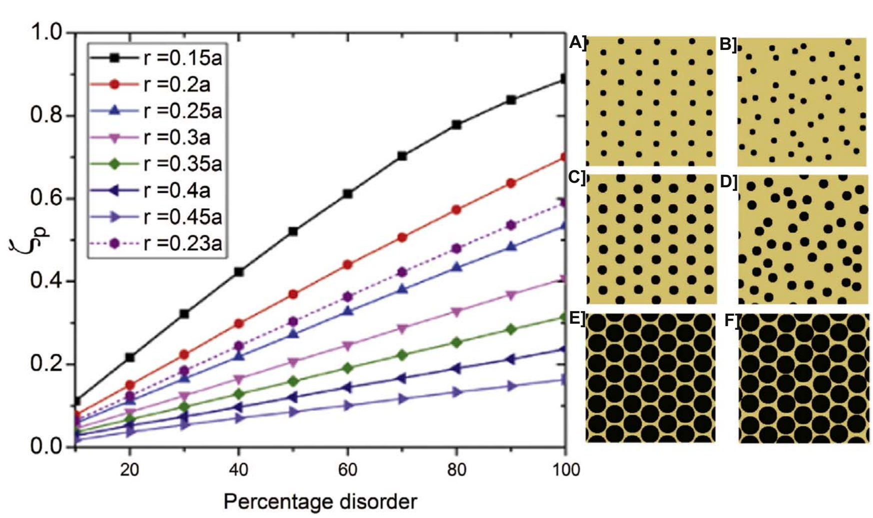

Fig. 2. Left panel: The variation of disorder parameter ζ_p as a function of percentage disorder at different hole radii. Right panel: A,C and E represent periodic structure for hole radii of $r = 0.15a$, $r = 0.23a$, $r = 0.45a$ respectively, where a is the lattice constant. B,D and F represent the structures at 100% disorder for $r = 0.15a$, $r = 0.23a$, $r = 0.45a$ respectively. It can be seen that, at a radius of $0.15a$, there is a large difference between the periodic and 100% disordered structure, while in $r = 0.45a$, the difference between the periodic and 100% disordered structure is not clearly evident. C and D ($r = 0.23a$) show the structures of interest in our calculations.