Localization and isotropic gap formation in chip-scale Yukawa potential metastructures

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Abstract: Amorphous photonic structures generated using Yukawa-potentials are examined numerically and experimentally. Unique isotropic and asymmetric bandgaps are demonstrated. Urbach band tails are analyzed to prove Anderson-like localization in amorphous structures. © 2023 The Author(s)

1. Introduction:

It has been believed for a long time that the disorder has a deteriorating effect on any light propagation in the medium [1]. However, it is shown that specifically engineered disorder in photonic media can lead to exquisite phenomena for novel photonic devices [2]. Such structures are called amorphous photonic structures and have a tremendous potential to study Anderson-like localization and related effects such as enhanced wave transport, random lasing, coherent backscattering, and, recently, quantum effects [2, 3]. Furthermore, it is shown that owing to their inherent short-range order; amorphous photonic structures can possess photonic bandgaps that can be used for photonic integrated circuit components by replacing photonic crystals[4-6]. One advantage of amorphous structures is that they enable flexible circuit designs without being confined to specific symmetry axes, as in photonic crystals due to their random-like nature.

In this abstract, we aim to explore the unique features of amorphous photonic structures that can be used for flexibly designed photonic structures. We have engineered random-like refractive index distributions using Yukawa potential to mimic crystalline-to-amorphous transition in solid-state systems. Yukawa potential is known to result in spatially homogeneous and isotropic frequency dispersion characteristics [6]. We have fabricated amorphous structures with different levels of disorder, and examined their bandgap isotropy and the change in transport properties due to increasing disorder. We have shown the formation of Urbach-like band tails and explored the degree of localization in the isotropic bandgaps to prove the Anderson-like localization of light in our structure.

2. Results and Discussion

We generated the amorphous refractive index distributions using the Metropolis Monte Carlo method [6]. The structures are modeled as a colloid of independent scatterers interacting with a Yukawa potential in a liquid-like structure. An essential parameter for the generation is normalized temperature, T*, which shows the degree of disorder in the lattice. Air holes are used as independent scatterers to generate random index distributions. An example of random hole distribution with an intermediate level of disorder, T*=0.4, is given in the SEM image in Fig 1a. We used a Si substrate with a thickness of 220 nm, a hole radius of 110 nm, and a 400 nm average distance between holes, selected to generate a telecommunications-regime bandgap (1.3-1.6 μm). The lack of long-range order is verified using the radial distribution function of holes given in Fig. 1b. The radial distribution function shows a short-range order up to 5 times the average distance between nearest neighbors, leading to bandgap formation. In contrast, the distribution becomes uniform at longer distances, evident by the lack of Bragg peaks [7]. Figure 1c shows the simulated spectrum for the configuration shows an isotropic bandgap of around 1.5 μm, which enables all-angle light propagation within the structure by creating longitudinal defects. We should note that there is a slight asymmetry

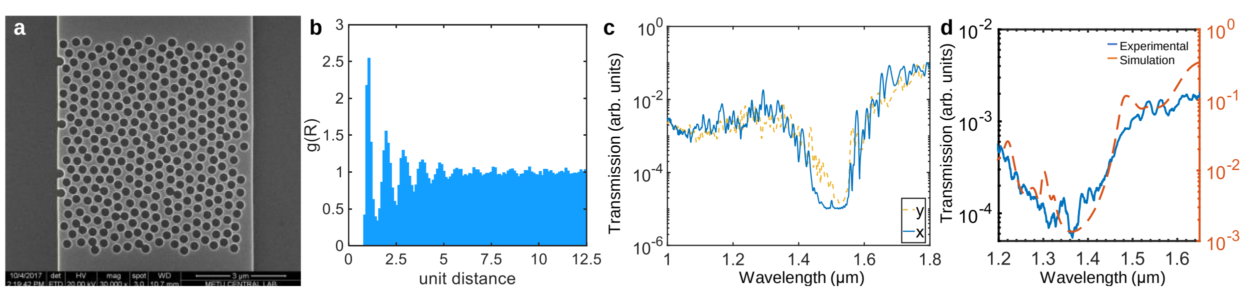

Figure 1: Isotropic bandgaps of amorphous photonic structures. a. SEM image of an amorphous photonic structure with T*=0.4 **b.** Radial distribution function of the amorphous structure with T*=0.4 indicating short range order. **c.** Simulated transmission spectrum of the amorphous with T*=0.4 in x and y directions showing isotropic bandgap. **d.** Measured transmission spectrum versus the simulation for the structure in panel a.

between dielectric and air band edges caused by the Urbach-like band tails formed due to inherent disorder. These band tails have different susceptibilities against increasing disorder, leading to a different slope, which is also examined in Fig 2b. Figure 1d confirms these features experimentally, with a good match against the simulation.

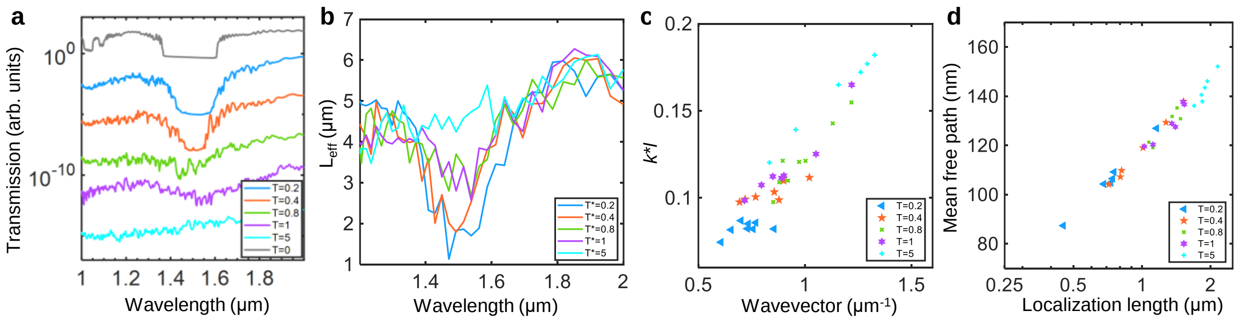

Figure 2. Anderson-like localization in amorphous photonic structures. a. Simulated transmission spectra of amorphous structures with different T* showing the evolution of photonic bandgap **b.** Effective length versus wavelength for amorphous structures with different T*. **c.** Modified Ioffe-Regel condition versus shifted wavevector for amorphous structures with different T* **d.** Mean free path versus localization length for the modes shown in panel c.

We have examined the effects of disorder level (T*) on light propagation and looked for traces of Anderson-like localization. Fig 2a shows the change in the bandgap with increasing T* from 0.2 (low disorder) to 5 (very high disorder). We observe that the gap broadens and disappears, creating a wavelength regime where all the propagation is halted due to increased coherent backscattering after T*=1. Fig 2b investigates the effective length of the local field distribution, which varies linearly with the available density of states. It shows that the effective length at the midgap changes from 1.1 μm (three times the average hole distance) to 5 μm, indicating the transition from strong to weak localization of modes and the final stage of diffusive transport at T*=5, where the effective length is near constant over all the regime.

Furthermore, effective length provides insights about the bandgap asymmetry, where the air-band edge has a smaller length, confirming the highly dispersive behavior. Figure 2c shows the Ioffe-Regel factor versus the normalized wavevector examined close to the dielectric band tail, which is an essential condition to determine the presence of Anderson-like localization [1]. We have selected possible modes for different values of T*, which revealed that at all T*, the modified Ioffe-Regel factor is much smaller than the original condition, k*l ~ 1 required for Anderson-like localization [8]. Furthermore, the relation between the mean free path and the localization length for each selected mode is given in Fig 2d. The localization length is within the short-range order length when the photonic bandgap is present, while the mean scattering-free length is much less than the average hole distance, further strengthening the localized nature of the modes.

3. Conclusion

In this abstract, we have summarized the unique properties of light transport in amorphous photonic structures generated using Yukawa potential. Using a Si slab with air holes, we have numerically and experimentally demonstrated the isotropic bandgap formation at the telecommunications band. We have analyzed the effect of disorder on the localization and light propagation, where we proved the strongly localized nature of band tails and midgap modes, with a localization length less than short-range order and a scattering free length less than inter-hole distance. These structures can be used as a platform to design integrated photonic devices free of any symmetry constraints [7], to study topological and complex phenomena originating from coherent backscattering and Anderson-localization, and to examine novel usage areas in nonlinear (random lasing), quantum optics, and cavity QED [1,2].

4. References

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