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Optical properties of 1D photonic crystals with correlated and uncorrelated disorder

Seng Fatt Liew[1] **and Hui Cao**[1,2]

[1] Department of Applied Physics, Yale University, New Haven, CT 06511, USA
[2] Department of Physics, Yale University, New Haven, CT 06511, USA

E-mail: sengfatt.liew@yale.edu

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Abstract
We introduce both correlated disorder and uncorrelated disorder to one-dimensional dielectric periodic structures and investigate their effects on light transmission, localization length, density of photonic states and decay rate of resonant modes. The photonic bandgaps are more robust against uncorrelated disorder due to the preservation of long-range structural order. While correlated disorder enhances light localization near the band edges, uncorrelated disorder causes a divergence of localization length near the gap edges. The correlated disorder induces a larger fluctuation of decay rates for the bandgap modes than the pass band modes. In contrast, the resonant modes near the pass band center experience the strongest fluctuation of decay rates in the presence of uncorrelated disorder.

Keywords: photonic band gap, correlated disorder, uncorrelated disorder

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Since its invention 20 years ago [1, 2], photonic crystals have attracted a great deal of attention with the promise of full control of light propagation and localization [3–5]. Rapid developments in nanotechnology have made the fabrication of photonic crystals operating at optical frequencies possible. However, structural disorder which is introduced unintentionally during the fabrication process limits the widespread application of photonic crystals [6]. The performance of two-dimensional (2D) photonic crystal waveguides for slow light applications is degraded by scattering loss from the fabrication disorder [7–9]. The omnidirectional photonic bandgap (PBG), which allows ultimate control of the spontaneous emission of atoms, is sensitive to the non-uniformity in three-dimensional (3D) inverted opal structures [10, 11]. Hence, a thorough understanding of the effects of structural disorder is essential for improving photonic crystal devices.

Recently, there have been many experimental and theoretical studies on how disorder influences light propagation and localization in one-dimensional (1D) [12–15], 2D [16–18] and 3D photonic crystals [19–25]. The types of disorder depend on the fabrication processes. The 'top-down' approach including lithography and etching has been widely used in fabrication of 2D photonic crystals. The typical disorder is random variation in size and shape of building blocks, and the randomness is usually uncorrelated. The 'bottom-up' approach, such as self-assembly, introduces randomness in both position and size of building blocks. The positions of neighboring building blocks are often correlated in the closely packed structures. Most theoretical studies on disorder in photonic crystals are focused on uncorrelated disorder. Recently it has been shown that correlation of disorder may result in strong anomalies of light localization [26–29]. The difference between correlated and uncorrelated disorder is not well understood, except in metallic photonic crystal slabs [30].

In this paper, we introduce both correlated randomness and uncorrelated randomness in position and size of building blocks, and study how they modify light transmission, localization length, density of photonic states and decay rate of resonant modes in 1D dielectric photonic crystals. The results highlight the different effects that correlated disorder and uncorrelated disorder have on photonic crystals. The photonic bandgaps are more robust against uncorrelated disorder due to the preservation of long-range structural order. The dips in the spectra of transmission and density of photonic states that correspond to PBGs become narrower in the presence of uncorrelated disorder, but wider in the case of correlated disorder. Correlation of disorder enhances light localization near the band edges, while uncorrelated disorder causes a divergence of localization length near the gap edges. The resonant modes near the pass band center experience the strongest fluctuation of decay rates in the presence of uncorrelated disorder. In contrast, the correlated disorder induces a larger fluctuation of decay rates for the bandgap modes than the pass band modes.

2. Correlation of disorder

Our structures consist of N dielectric layers separated by air gaps. In the absence of disorder, the period of 1D photonic crystal is a. The position of the mth dielectric layer is $x_m = ma$. The thickness of each dielectric layer is d. Randomness is introduced to either position or thickness of the dielectric layers. In the case of position disorder, the position of each dielectric layer is perturbed while its thickness remains constant. If every dielectric layer is shifted randomly from its position in the periodic system, the positions of neighboring dielectric layers are uncorrelated. The position of the mth dielectric layer is $x_m = ma + \delta x_m$, where δx_m is a random number distributed uniformly between $-\Delta a$ and Δa, and Δ represents the degree of disorder. Alternatively, the positions of neighboring dielectric layers can be correlated by introducing randomness to their spacings. Namely, $x_m = x_{m-1} + a + \delta x_m$. Thus x_m includes all position variations of the preceding layers, $x_m = ma + \sum_{j=1}^{m} \delta x_j$.

In the case of size disorder, the thickness of dielectric layers is varied, while their positions do not change. If the thickness of each dielectric layer is varied independently from d, the size disorder is uncorrelated. The thickness of mth dielectric layer is given by $d_m = d + \delta d_m$, where δd_m is a random number distributed uniformly between $-\Delta d$ and Δd. The size disorder becomes correlated if the thickness of the mth dielectric layer is fluctuated around that of the $m - 1$th layer, $d_m = d_{m-1} + \delta d_m = d + \sum_{j=1}^{m} \delta d_j$.

For structural characterization of the disordered photonic crystals, we computed correlation functions and spatial Fourier spectra. The spatial correlation function is $C(\Delta x) \equiv \langle \delta n(x) \delta n(x + \Delta x) \rangle$, where $\delta n(x) = n(x)/\bar{n} - 1$, $n(x)$ is the refractive index at position x, $\bar{n}$ is the average refractive index for one configuration and $\langle \cdots \rangle$ represents averaging over many configurations with the same degree of disorder Δ. Figures 1(a) and (b) show the correlation functions for position disorder and size disorder. In the case of uncorrelated disorder, $C(\Delta x)$ is independent of Δx as long as $\Delta x \neq 0$. Hence, the structure has a long-range order. With increasing disorder Δ, the value of $C(\Delta x)$ decreases, indicating the structural correlation is reduced by disorder. In the case of correlated disorder, $C(\Delta x)$ decays with increasing distance Δx. Thus the structural correlation or order is short-ranged. For the same value of Δ, the structural correlation in the presence of size disorder is larger than that of position disorder. This suggests the position disorder reduces structural correlation more dramatically.

A Fourier transform of $n(x)$ gives the spatial Fourier spectrum (figures 1(c) and (d)). The peaks in Fourier spectra correspond to the spatial periods of structures. The peak height reflects the strength of spatial periodicity and the peak width is inversely proportional to the dimension of ordered regions. In the case of uncorrelated disorder, we find the Fourier peak height decreases as Δ increases while the peak width remains nearly constant. This behavior reflects long-range order of the structure. In the case of correlated disorder, the peak height decreases more quickly and the peak width increases with Δ. The peak broadening indicates the ordered regions shrink in size and the structural order becomes short-ranged.

3. Transmission and localization length

We used the transfer matrix method to calculate the transmission spectra of 1D disordered photonic crystals. The parameters in the numerical simulations are $n = 1.05$, $N = 81$, $a = 300$ nm and $d = 100$ nm. Scattering is weak due to small refractive index contrast. For each type of disorder, the transmission spectra are obtained by averaging over 10^3–10^4 configurations with the same degree of disorder. We focus on the transmission dip that corresponds to the fundamental PBG and investigate how disorder changes the gap width and depth. D is the depth of transmission dip normalized to that in the absence of disorder (inset of figure 2(a)) and W is the full width at half-minimum (FWHM) of the transmission dip normalized to that without disorder (inset of figure 2(b)).

With the introduction of disorder, the transmission dip becomes shallower. For both position disorder and size disorder, the reduction of D is larger if the disorder is correlated. Figure 2(a) shows that the correlated disorder causes a rapid drop of D when $\Delta < 0.3$. Once Δ exceeds 0.3, the falling of D slows down. The uncorrelated disorder leads to a different behavior, D decreasing slowly at smaller Δ then faster at larger Δ.

Figure 2(b) shows that the gap width W evolves in the opposite way between the correlated disorder and uncorrelated disorder. For both position and size disorder, the correlated disorder makes the gap wider, while the uncorrelated disorder makes it narrower. The position disorder causes a larger change of W than the size disorder for the same Δ. We attribute the larger effect of position disorder to the relatively small refractive index contrast in our structures. For larger n, the trend may be different [10].

We also calculated the variation of transmission T with structure length L. In the case of correlated disorder, T decreases with increasing L both inside and outside the PBG. Figure 3(a) shows the transmission spectra for various lengths L of structures with a fixed degree of correlated position disorder, $\Delta = 0.3$. The frequency ω is normalized to the center frequency ω_0 of the fundamental PBG. From the decay of T with L, we obtained the localization length, $\xi = -L/\langle \ln T \rangle$ [31]. Figure 4(a) is a plot of ξ versus ω/ω_0 for several values of Δ. The vertical lines mark the edges of the fundamental PBG. With increasing disorder, ξ increases inside the gap and decreases in the pass bands. Near the band edges, ξ first decreases then increases with Δ. Therefore, correlated

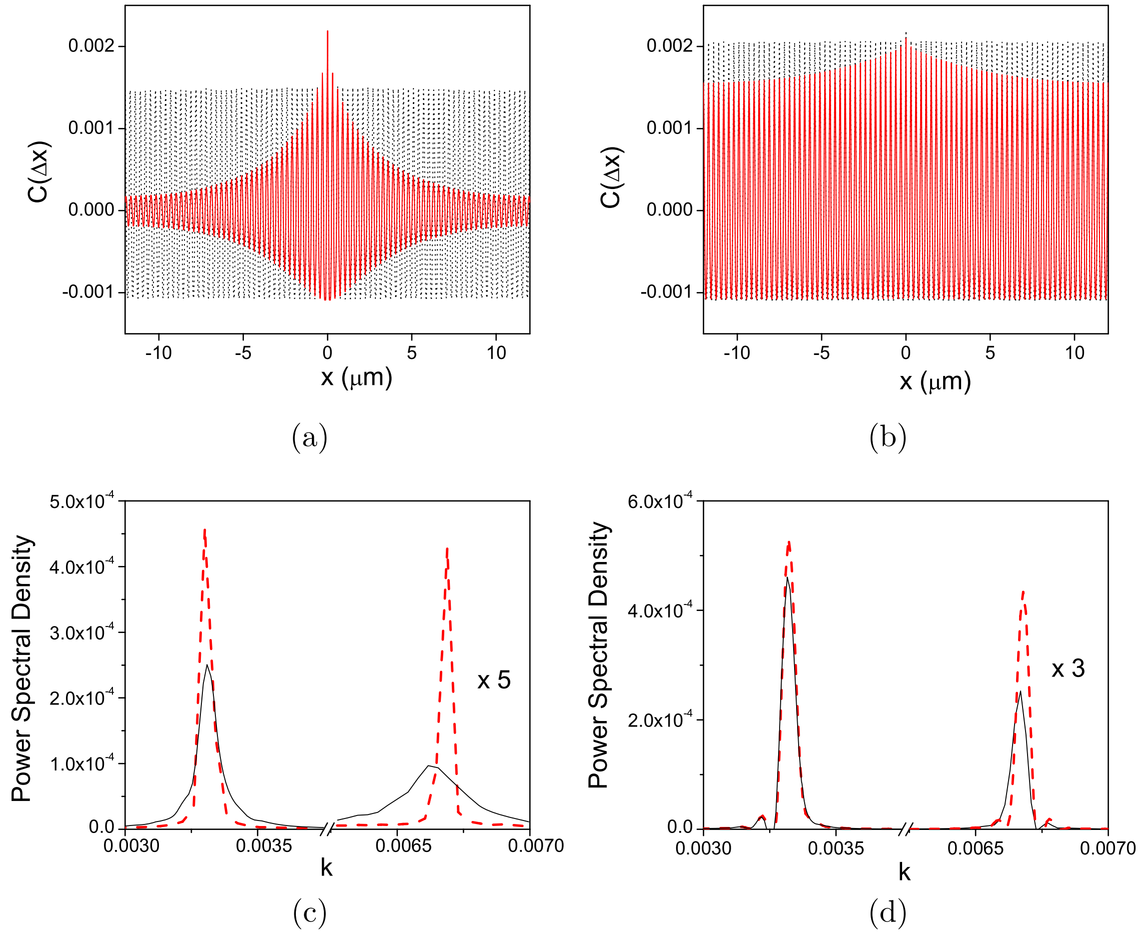

Figure 1. Spatial correlation functions $C(\Delta x)$ and Fourier spectrum for 1D photonic crystals with position disorder (a), (c) or size disorder (b), (d). The solid curves represent correlated disorder, while the dashed curves show uncorrelated disorder. The degree of disorder $\Delta = 0.1$. Note that the second peaks in spatial Fourier spectra are magnified.

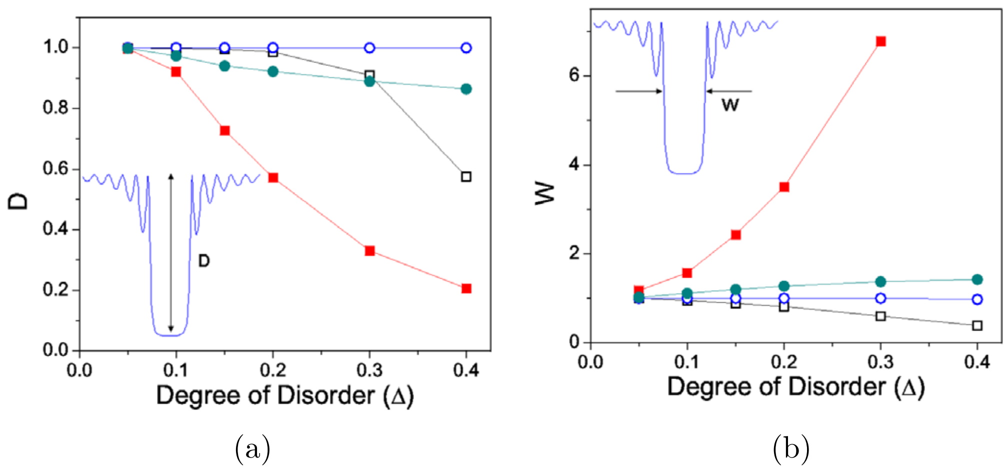

Figure 2. Depth D (a) and width W (b) of the transmission dip as a function of degree of disorder Δ. Squares and circles represent position disorder and size disorder, respectively. Solid symbols are for correlated disorder and open symbols for uncorrelated disorder.

disorder weakens the interference effect that suppresses light transmission in the gap of a periodic structure, leading to an increase of transmission. In the pass bands, the effect of disorder is opposite, it enhances light localization and reduces transmission. Near the band edge, a small degree of disorder improves localization but large disorder suppresses it.

The dependence of T on L is quite different in the case of uncorrelated disorder. Figure 3(b) is a log–linear

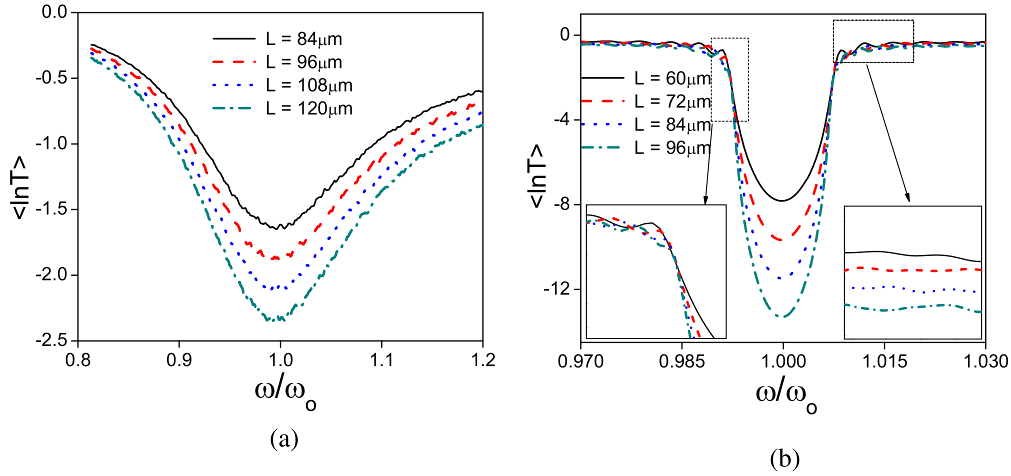

Figure 3. ln T versus ω/ω_0 for several lengths L of structures with a fixed degree of position disorder $\Delta = 0.3$. The randomness is correlated in (a) and uncorrelated in (b).

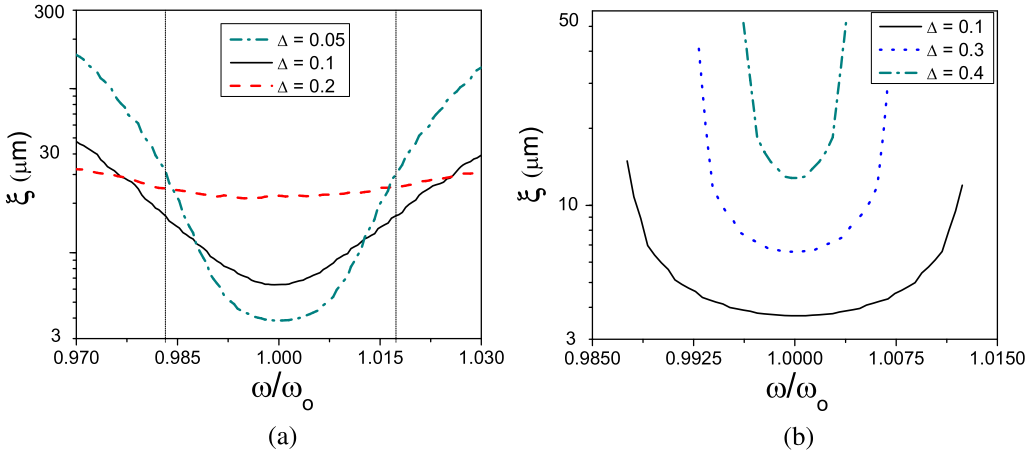

Figure 4. Localization length ξ as a function of normalized frequency ω/ω_0. The position disorder is correlated in (a) and uncorrelated in (b).

plot of T versus ω/ω_0 for different lengths L of structures with a fixed degree of uncorrelated position disorder $\Delta = 0.3$. Unlike the case of correlated disorder where the shape of transmission spectra remains qualitatively the same with increasing L, the uncorrelated disorder modifies the shape of transmission spectra. The edges of transmission dip become much sharper at larger L. In the presence of long-range order, the interference effect becomes stronger in the larger system, making the transmission dip steeper. Near the gap center T decreases quickly with increasing L. The decrement slows down as the frequency moves away from the gap center. Close to the edges of PBG the transmission curves for different L cross (left inset of figure 3(b)). Around the crossing points, T changes little with L. Beyond the crossing points, T oscillates with frequency. Further away from the crossing points, the oscillation dies out and T again decreases with increasing L (right inset of figure 3(b)). The crossing points move towards the gap center with increasing Δ. Figure 4(b) shows the localization length ξ within the PBG. ξ increases with Δ, similar to the case of correlated disorder. The major difference is that ξ rises rapidly as ω moves towards the gap edges and diverges at the crossing points. This result reflects the underlying long-range order.

4. Density of photonic states

Next, we studied the effects of disorder on the density of photonic states $\rho(\omega)$. We follow the definition for density of states in a 1D finite-length structure in [32] and obtain $\rho(\omega)$ from the complex transmission coefficient $t = \sqrt{T}\exp(\mathrm{i}\phi)$ [32, 33]. The effective wavevector is $k_{\mathrm{eff}} = \phi/L$, where ϕ is the total phase accumulated by the light propagating through the structure and L is the total length of the finite structure. It gives $\rho(\omega) = \mathrm{d}k_{\mathrm{eff}}/\mathrm{d}\omega$. $\rho(\omega)$ is normalized by the density of states (DOS) for a homogeneous medium with an effective group velocity $v^{\mathrm{eff}} = c[f/n + (1 - f)]$, where f is the filling fraction of the dielectric material with refractive index n [32].

In a periodic structure, the DOS is depleted within the PBG and peaked near the band edges. Disorder creates defect states inside the gap. $\rho(\omega)$ is obtained by ensemble averaging over 10^3–10^4 configurations with the same type and degree of

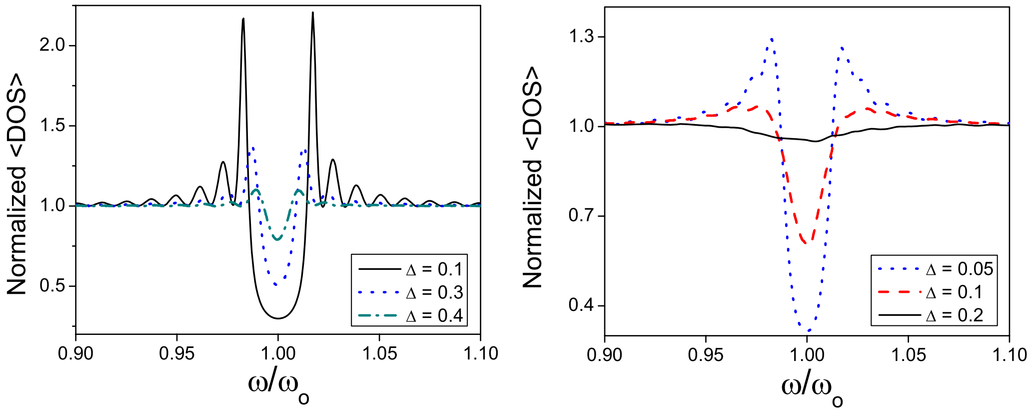

Figure 5. Normalized density of states (DOS) $\rho(\omega)$ versus ω/ω_0 in 1D structures with various degrees Δ of uncorrelated position disorder (a) and correlated position disorder (b).

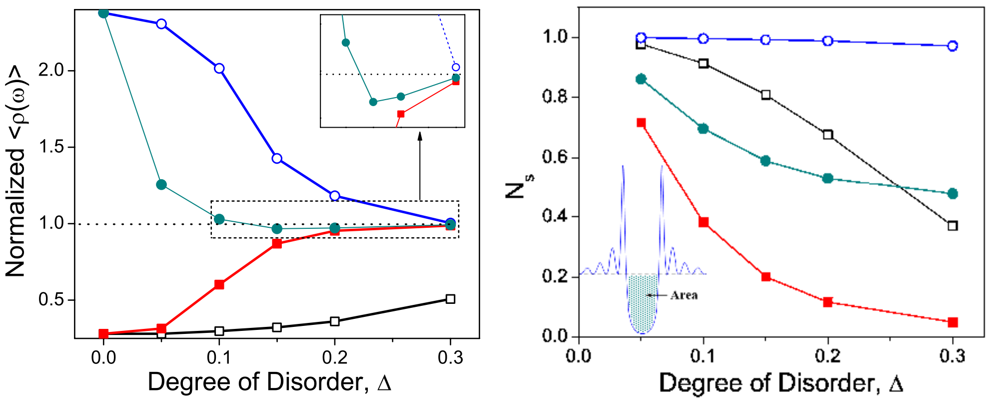

Figure 6. (a) Normalized $\rho(\omega)$ as a function of degree Δ of correlated position disorder (solid symbols) and uncorrelated position disorder (open symbols) at the frequency ω_1 of the PBG center (squares) and the frequency ω_2 of the largest DOS peak at the band edge (circles). (b) Total number of depleted states N_s as a function of Δ (symbol notation is the same as in figure 2).

disorder. Figure 5(a) shows the normalized $\rho(\omega)$ for various degrees of uncorrelated position disorder. ω is normalized to ω_0. With increasing Δ, the depletion of DOS inside the PBG is diminished. Outside the PBG, the high peaks of DOS at the band edges are reduced, and at large disorder the normalized $\rho(\omega)$ approaches unity. Since $\rho(\omega)$ never reaches below one outside the PBG, the DOS dip gets narrower at larger Δ. The correlated disorder has a more dramatic effect on DOS. As shown in Figure 5(b), the DOS gap is quickly filled by defect states and the large peaks at the band edges diminish rapidly while being broadened. At certain Δ, the normalized $\rho(\omega)$ is reduced to below unity outside the PBG, resulting in a broadening of the DOS gap. Eventually at large disorder, the DOS dip disappears and the normalized $\rho(\omega)$ becomes unity at all frequencies.

Figure 6(a) plots the normalized DOS at the frequency ω_1 of the PBG center and the frequency ω_2 of the largest DOS peak at the band edge versus the degree of position disorder. The correlated disorder causes a much faster rise of $\rho(\omega_1)$ with Δ. $\rho(\omega_2)$ first decreases then increases with Δ for the correlated disorder, while it decreases monotonically with increasing Δ in the case of uncorrelated disorder. Similar behaviors are observed for the size disorder.

For a quantitative description of the depletion of photonic states, we computed the area of DOS dip (inset of figure 6(b)) to obtain the total number of depleted states N_s. Figure 6(b) is a plot of N_s, normalized by its value in the absence of disorder, as a function of Δ. With increasing disorder, more defect states appear in the gap and N_s is reduced. For both correlated position and size disorder, N_s decreases first rapidly with increasing Δ, then gradually at large Δ. The trend is opposite for uncorrelated position and size disorder. N_s decreases slowly at smaller Δ. Once Δ exceeds a critical value, N_s drops quickly. Hence, the PBG is more robust against small uncorrelated disorder. This is attributed to the preservation of long-range order.

5. Decay rates of resonant modes

Finally we investigated the modification of resonant modes by disorder. γ is the imaginary part of eigenfrequency that is calculated with the outgoing boundary condition [34]. In

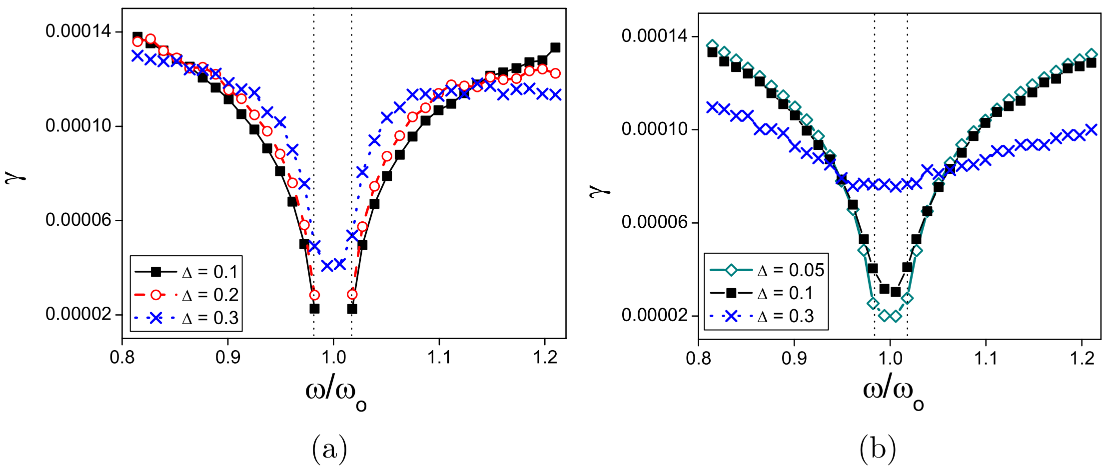

Figure 7. (a) Average decay rate of resonant modes in 1D structure with different degree Δ of uncorrelated position disorder (a) and correlated position disorder (b).

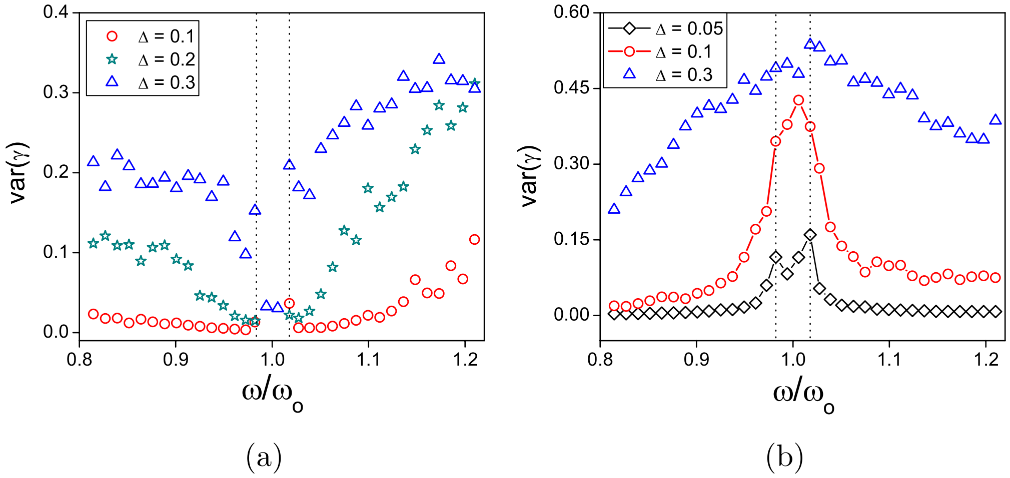

Figure 8. (a) Variance of decay rate of resonant modes in 1D structure with different degree Δ of uncorrelated position disorder (a) and correlated position disorder (b).

a finite-sized periodic structure, the modes at the band edges have the lowest decay rates. γ increases as the frequency moves towards the pass band center. Structural disorder perturbs both the frequency and decay rate of resonant modes. Their values fluctuate from one configuration to another. We ensemble-averaged the decay rates of modes within a small frequency window, $\Delta\omega_n = (\omega_{n+1} + \omega_n)/2 - (\omega_n + \omega_{n-1})/2$, centered at each mode of frequency ω_n in the periodic structure. Every data point in figures 7(a) and (b) represents the decay rate $\bar{\gamma}$ averaged over 10^3–10^4 configurations with the same degree of position disorder. In the pass bands the modes with frequencies around the band center have reduced $\bar{\gamma}$ with increasing Δ, while the modes near the band edges have higher $\bar{\gamma}$ at larger disorder. The defect modes appear inside the PBG, and they have lower $\bar{\gamma}$ than the modes outside the gap. At large disorder, the decay rate is nearly constant for all modes as the PBG disappears. The trends are similar for correlated disorder and uncorrelated disorder, though the latter modifies the decay rates more than the former. Similar results are obtained for the size disorder.

To quantify the decay rate fluctuation, we computed the variance of γ, $\mathrm{var}(\gamma) = \langle(\gamma/\bar{\gamma} - 1)^2\rangle$, where $\langle\cdots\rangle$ represents the ensemble average over modes within the small frequency window $\Delta\omega_n$. Figures 8(a) and (b) show the variance of decay rates for correlated and uncorrelated position disorder.

In the case of uncorrelated disorder, the modes close to the pass band centers have large var(γ). To explain the large fluctuation of decay rates, we plot in figure 9(a) the frequency and decay rate of all modes in 50 configurations with the same degree of uncorrelated position disorder $\Delta = 0.1$. It is evident that, deep in the pass bands, there are some very leaky modes, leading to large fluctuation of γ. Figure 9(b) shows the spatial distribution of electric field intensity for one such leaky mode. The mode is concentrated near one boundary of the system, leading to significant leakage of light from the boundary. It resembles the doorway state in an open cavity [35]. Hence, the decay rates of the majority of modes near the pass band center are reduced by disorder, resulting in an decrease of $\bar{\gamma}$. However, a few of them acquire extremely large decay rates, leading to an increase of var(γ). Such 'doorway states'

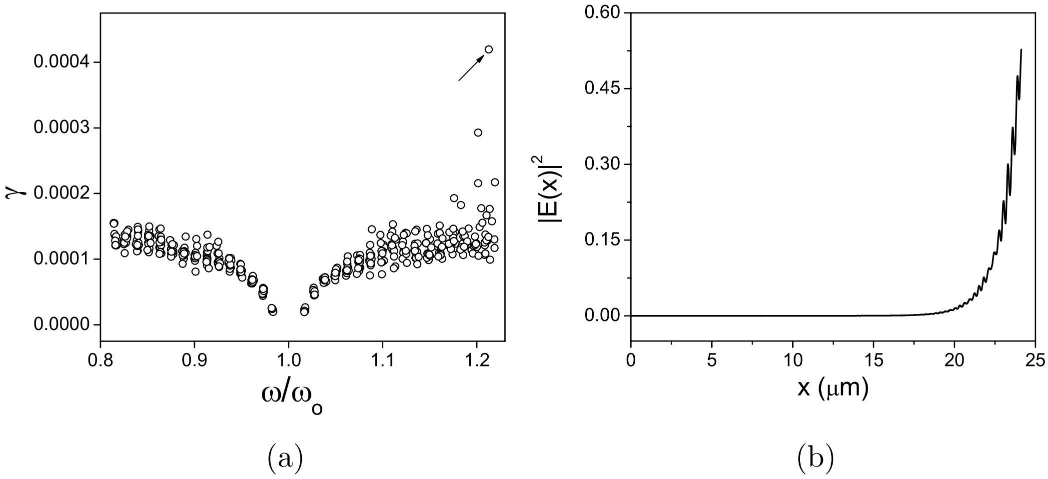

Figure 9. (a) Normalized frequency ω/ω_0 and decay rate γ of all modes in 50 configurations with the same degree of uncorrelated position disorder $\Delta = 0.1$. (b) Spatial distribution of electric field intensity for one leaky mode marked by an arrow in (a).

are mostly likely to be formed at a frequency close to the pass band center where the interference effect resulting from the structural periodicity is the weakest. As the frequency moves away from the pass band center, the interference effect becomes stronger due to the existence of long-range order. It is more difficult for the 'doorway states' to be formed by uncorrelated disorder, causing a decrease of var(γ). Near the band edges var(γ) rises again, indicating the band edge modes are very sensitive to disorder. This is because the band edge modes are formed via strong interference of multiply reflected light, and a small perturbation of structure can induce a large modification.

In the systems with correlated disorder, the very leaky modes can also be found near the pass band centers, leading to similar values of var(γ) as in the case of uncorrelated disorder. However, var(γ) does not decrease as the frequency moves towards the band edges. This is attributed to the lack of long-range order which is necessary to suppress the formation of very leaky modes. Near the band edges, var(γ) increases and exhibits double peaks for small Δ. With increasing disorder, the double peaks move towards the gap center and merge to a single peak at certain Δ. This behavior is consistent with the result in [14] and is related to the breakdown of single-parameter scaling. Therefore, the correlated disorder causes larger fluctuation of γ for the bandgap modes than the pass band modes, while the opposite is true for the uncorrelated disorder.

6. Conclusion

We introduce both correlated and uncorrelated randomness in position and thickness of dielectric layers in 1D periodic structures, and investigate their effects on light transmission, localization length, density of photonic states and decay rate of resonant modes. The systems with uncorrelated disorder maintain the long-range order, while the ones with correlated disorder have only short-range order. Our simulation results illustrate the differences between correlated disorder and uncorrelated disorder.

The correlated disorder diminishes the transmission dips that correspond to PBGs more quickly than the uncorrelated disorder. The robustness of PBGs against uncorrelated disorder is attributed to the preservation of long-range order of the structures. Another difference is that the uncorrelated disorder makes the transmission dips narrower while the uncorrelated disorder makes them wider than those in the perfectly ordered systems.

As the degree of structural disorder Δ increases, the localization length ξ increases inside the PBG and decreases outside the PBG. Unlike the case of correlated disorder, ξ diverges near the gap edges in the case of uncorrelated disorder. This divergence is attributed to edge sharpening of the transmission dips by increasing system length.

Like the dips in the transmission spectra, the dips in the photonic density of states are narrowed by uncorrelated disorder and widened by correlated disorder. The total number N_s of depleted photonic states within a PBG falls rapidly at small degree Δ of correlated disorder, then slowly at large Δ. The trend is just the opposite for the uncorrelated disorder: the drop of N_2 is gradual at small Δ, then accelerates at larger Δ.

The structural disorder not only produces defect states inside the PBG, but also reduces the decay rate of resonant modes in the pass bands. In the presence of uncorrelated disorder, the variance of decay rates is the highest near the pass band center due to the formation of very leaky modes. In contrast, the correlated disorder causes a larger fluctuation of decay rates for the bandgap modes than the pass band modes.

We think that the general conclusions presented in this paper can be extended to higher dimensions. However, caution must be exerted because in 2D and 3D connected networks structure can be formed which does not exist in 1D. It has been shown that a connected network can be more robust against disorder than a disconnected structure [36]. Therefore, further studies are needed to understand the effects of different types of disorders in higher dimensions.

Acknowledgments

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