Interplay of Bloch waves and scattered waves in real photonic crystals

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Light propagates inside an ideal and infinite photonic crystal when the Bloch condition is satisfied and any allowed light wave is decomposed in a basis of propagating Bloch waves [1]. In real photonic crystals, light propagation is modified due to unavoidable fabrication-induced structural imperfections in size, positions, and permittivity of the building blocks, as well as the finite size of the crystal. The unavoidable deviations from perfect periodicity result in scattering [2, 3]. Here, we seek to understand the nature of waves inside a real photonic crystal since inevitable disorder plays a significant role in wave propagation.

We investigate experimentally three-dimensional (3D) opals and two-dimensional (2D) silicon photonic crystals. We measured reflected intensity from the crystals with a high numerical aperture. The statistics of the reflected intensity differs from that of uncorrelated scattered waves typical of statistically homogeneous media (disordered ZnO nanoparticles). Thus, the reflected intensity is correlated, which is caused by the presence of correlated Bloch waves. We quantify the optical correlations by measuring the position-dependent degree of correlation across each crystal surface. We find that the correlation coefficient depends on disorder in different regions within the opal photonic crystal (see Fig. 1(a)). In contrast, the CMOS-fabricated 2D crystal shows a very high correlation of about 0.9 over a large range as shown in Fig. 1(b). We propose a model that assumes that spherical waves are generated due to disorder and are superimposed with propagating Bloch waves. By comparing our model with experimental result in Fig. 1(b), we extract that the ratio of the intensity of the scattered spherical waves and Bloch waves is 0.36, which is in agreement with 0.32 from the sample parameters. Our results therefore reveal the actual form of wave propagation in real photonic crystals, which are crucial in several applications [4, 5] and fundamental research [6].

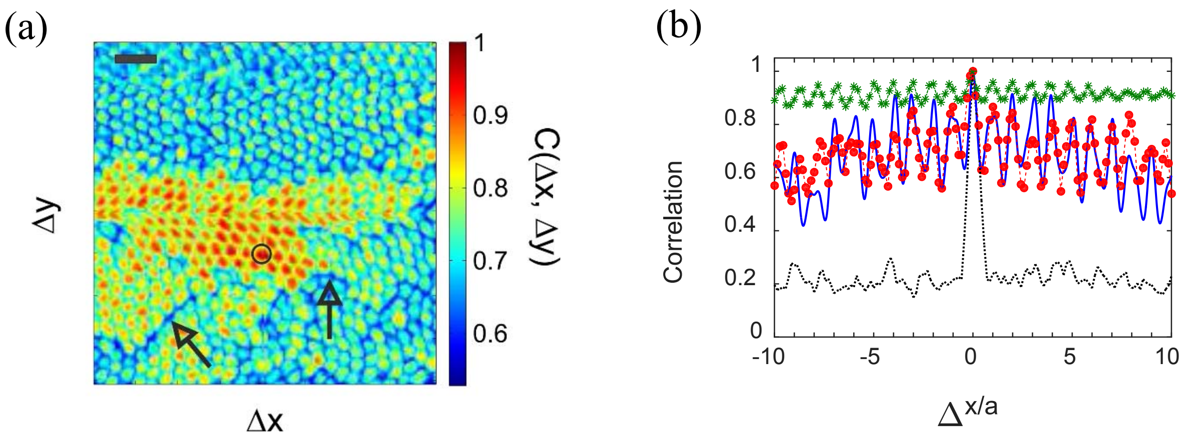

Fig. 1 (a) A 2D map of correlation of reflected intensities from an opal photonic crystal. The black circle is the reference position of the correlation and the black arrows indicate grain boundaries due to crystal mosaic spread that occurs during self-assembly of opals. The scale bar is 1 micron (b) Intensity correlation versus x-translation. The red dots are a cross-section at a fixed y through the reference position in (a) and the blue straight line is our model that describes scattered waves due to disorder as spherical waves. The green star and black dashed line are the measured data for a 2D Si photonic crystals and a completely disordered sample of ZnO nanoparticles, respectively.

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