Holographic assembly of quasicrystalline photonic heterostructures

Yael Roichman and David G. Grier
Department of Physics and Center for Soft Matter Research, New York University, New York, NY 10003
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Quasicrystals have a higher degree of rotational and point-reflection symmetry than conventional crystals. As a result, quasicrystalline heterostructures fabricated from dielectric materials with micrometer-scale features exhibit interesting and useful optical properties including large photonic bandgaps in two-dimensional systems. We demonstrate the holographic assembly of two-dimensional and three-dimensional dielectric quasicrystalline heterostructures, including structures with specifically engineered defects. The highly uniform quasiperiodic arrays of optical traps used in this process also provide model aperiodic potential energy landscapes for fundamental studies of transport and phase transitions in soft condensed matter systems.

Quasicrystals have long-ranged orientational order even though they lack the translational periodicity of crystals. Not limited by conventional spatial point groups, they can adopt rotational symmetries that are forbidden to crystals. The resulting large number of effective reciprocal lattice vectors endows quasicrystals’ effective Brillouin zones with an unusually high degree of rotational and point inversion symmetry [1]. These symmetries, in turn, facilitate the development of photonic band gaps (PBG) [2] for light propagating through quasicrystalline dielectric heterostructures [3, 4, 5], even when the dielectric contrast among the constituent materials is low. Photonic band gaps have been realized in one- [6] and two-dimensional [7] lithographically defined quasiperiodic structures. Here we demonstrate rapid assembly of arbitrary materials into two- and three-dimensional quasicrystalline heterostructures with features suitable for photonic device applications.

Our approach is based on the holographic optical trapping technique [8, 9, 10] in which computer-generated holograms are projected through a high-numerical-aperture microscope objective lens to create large three-dimensional arrays of optical traps. In our implementation, light at 532 nm from a frequency-doubled diode-pumped solid state laser (Coherent Verdi) is imprinted with phase-only holograms using a liquid crystal spatial light modulator (SLM) (Hamamatsu X8267 PPM). The modified laser beam is relayed to the input pupil of a 100× NA 1.4 SPlan Apo oil immersion objective mounted in an inverted optical microscope (Nikon TE-2000U), which focuses it into traps. The same objective lens is used to form images of trapped objects, using the microscope’s conventional imaging train [10].

We used this system to organize colloidal silica microspheres 1.53 μm in diameter (Duke Scientific Lot 5238) dispersed in an aqueous solution of 180 : 12 : 1 (wt/wt) acrylamide, N,N’-methylenebisacrylamide and diethoxyacetophenone (all Aldrich electrophoresis grade). This solution rapidly photopolymerizes into a transparent polyacrylamide hydrogel under ultraviolet illumination, and is stable otherwise. Fluid dispersions were imbibed into 30 μm thick slit pores formed by bonding the edges of #1 coverslips to the faces of glass micro-
creates a compact three-dimensional quasicrystal. (d) Opti-

cal diffraction pattern showing ten-fold symmetric peaks. T

e three-dimensional configuration. The shaded region identi

fies quasicrystalline lattice. (b) Particles displaced into th

e fully embedded icosahedron. (c) Reducing the lattice constan

t gives a monolayer above the coverslip. This sequence also re

calls earlier reports [20, 21] that holographic traps can suc

cessfully organize spheres into vertical stacks along the

optical axis, while maintaining one sphere in each trap.

The icosahedron itself is the fundamental building block of a class of three-dimensional quasicrystals, such as the example in Fig. 3. Building upon our earlier work on holographic assembly [22], we assemble a three-dimensional quasicrystalline domain by first creating a two-dimensional arrangement of spheres correspond-
ing to the planar projection of the planned quasicrystalline domain, Fig. 3(a). Next, we translate the spheres along the optical axis to their final three-dimensional coordinates in the quasicrystalline domain, as shown in Fig. 3(b). One icosahedral unit is highlighted in Figs. 3(a) and (b) to clarify this process. Finally, the separation between the traps is decreased in Fig. 3(c) to create an optically dense structure. This particular do-

main consists of 173 spheres in roughly 7 layers, with typical inter-particle separations of 3 µm.

The completed quasicrystal was gelled and its optical diffraction pattern recorded at a wavelength of 632 nm by illuminating the sample with a collimated beam from a HeNe laser, collecting the diffracted light with the microscope’s objective lens and projecting it onto a charge-coupled device (CCD) camera with a Bertrand lens. The well-defined diffraction spots clearly reflect the quasicrystal’s five-fold rotational symmetry in the projected plane.

Holographic assembly of colloidal silica quasicrystals in water is easily generalized to other materials and sol-

vents. Deterministic organization of disparate compo-
nents under holographic control can be used to embed gain media in PBG cavities, to install materials with nonlinear optical properties within waveguides to form switches, and to create domains with distinct chemical functionalization. The comparatively small domains we have created can be combined into larger heterostruc-
tures through sequential assembly and spatially localized photopolymerization. In all cases, this soft fabrication process results in mechanically and environmentally sta-

tble materials that can be integrated readily into larger systems.

Beyond the immediate application of holographic trap-
ing to fabricating quasicrystalline materials, the ability to create and continuously optimize such structures provides new opportunities for studying the dynamics [10] and statistical mechanics [23] of colloidal quasicrystals. The optically generated quasiperiodic potential energy landscapes developed for this study also should provide a flexible model system for experimental studies of transport [24] through aperiodically modulated environments.
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[1] S. E. Burkov, T. Timusk and N. W. Ashcroft. “Optical conductivity of icosahedral quasi-crystals.” *J. Phys.: Condens. Matt.* 4, 9447–9458 (1992).

[2] J. D. Joannopoulos, R. D. Meade and J. N. Winn. *Photonic Crystals* (Princeton University Press, Princeton, 1995).

[3] Y. S. Chan, C. T. Chan and Z. Y. Liu. “Photonic band gaps in two dimensional photonic quasicrystals.” *Phys. Rev. Lett.* 80, 956–959 (1998).

[4] S. S. M. Cheng, L. M. Li, C. T. Chan and Z. Q. Zhang. “Defect and transmission properties of two-dimensional quasiperiodic photonic band-gap systems.” *Phys. Rev. B* 59, 4091–4099 (1999).

[5] X. Zhang, Z. Q. Zhang and C. T. Chan. “Absolute photonic band gaps in 12-fold symmetric photonic crystals.” *Phys. Rev. B* 63, 081105 (2001).

[6] T. Hattori, N. Tsurumachi, S. Kawato and H. Nakatsuji. “Photonic dispersion-relation in a one-dimensional quasi-crystal.” *Phys. Rev. B* 50, 4220–4223 (1994).

[7] M. E. Zoorob, M. D. B. Charlton, G. J. Parker, J. J. Baumberg and M. C. Netti. “Complete photonic bandgaps in 12-fold symmetric quasicrystals.” *Nature* 404, 740–743 (2000).

[8] E. R. Dufresne and D. G. Grier. “Optical tweezer arrays and optical substrates created with diffractive optical elements.” *Rev. Sci. Instr.* 69, 1974–1977 (1998).

[9] D. G. Grier. “A revolution in optical manipulation.” *Nature* 424, 810–816 (2003).

[10] M. Polin, K. Ladavac, S.-H. Lee, Y. Roichman and D. G. Grier. “Optimized holographic optical traps.” *Opt. Express* submitted for publication (2005).

[11] U. Grimm and M. Schrieber. “Aperiodic tilings on the computer.” In “Quasicrystals: an Introduction to Structure, Physical Properties and Applications,” edited by J. B. Suck, M. Shrieber and P. Haussler (Springer, 2002).

[12] C. Jin, B. Cheng, B. Man, Z. Li, D. Zhang, S. Ban and B. Sun. “Band gap wave guiding effect in a quasiperiodic photonic crystal.” *Appl. Phys. Lett.* 75, 1848–1850 (1999).

[13] M. Bayindir, E. Cubukcu, I. Bulu and E. Ozbay. “Photonic band-gap effect, localization, and waveguiding in two-dimensional Penrose lattice.” *Phys. Rev. B* 63, 161104(R) (2001).

[14] M. J. Escuti and G. P. Crawford. “Holographic photonic crystals.” *Opt. Eng.* 43, 1973–1987 (2004).

[15] R. C. Gauthier and A. Ivanov. “Production of quasicrystal template patterns using a dual beam multiple exposure technique.” *Opt. Eng.* 12, 990–1003 (2004).

[16] R. C. Gauthier and K. Mnaymneh. “Photonic band gap properties of 12 fold quasi-crystal determined through FDTD analysis.” *Opt. Eng.* 13, 1985–1998 (2005).

[17] X. Wang, C. Y. Ng, W. Y. Tam, C. T. Chan and P. Sheng. “Large-area two-dimensional mesoscopic quasicrystals.” *Adv. Mater.* 15, 1526–1528 (2003).

[18] S. S. M. Cheng, L.-M. Li, C. T. Chan and Z. Q. Zhang. “Defect and transmission properties of two-dimensional quasiperiodic photonic band-gap systems.” *Phys. Rev. B* 59, 4091–4099 (1999).

[19] C. Jin, B. Cheng, B. Man, Z. Li and D. Zhang. “Two-dimensional dodecagonal and decagonal quasiperiodic photonic crystals in the microwave region.” *Phys. Rev. B* 61, 10762–10767 (2000).

[20] J. Leach, G. Sinclair, P. Jordan, J. Courtial, M. J. Padgett, J. Cooper and J. Laczik, Zsolt. “3D manipulation of particles into crystal structures using holographic optical tweezers.” *Opt. Express* 12, 220–226 (2004).

[21] G. Sinclair, P. Jordan, J. Courtial, M. Padgett, J. Cooper and Z. J. Laczik. “Assembly of 3-dimensional structures using programmable holographic optical tweezers.” *Opt. Express* 12, 5475–5480 (2004).

[22] P. T. Korda, G. C. Spalding, E. R. Dufresne and D. G. Grier. “Nanofabrication with holographic optical tweezers.” *Rev. Sci. Instr.* 73, 1956–1957 (2002).

[23] A. R. Denton and H. Löwen. “Stability of colloidal quasicrystals.” *Phys. Rev. Lett.* 81, 469–472 (1998).

[24] P. T. Korda, M. B. Taylor and D. G. Grier. “Kinetically locked-in colloidal transport in an array of optical tweezers.” *Phys. Rev. Lett.* 89, 128301 (2002).