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Two-dimensional Penrose-tiled photonic quasicrystals: is there a pure photonic band gap?

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Abstract. We report measurements of the diffraction pattern of a two-dimensional photonic quasicrystal structure and use the set of plane-waves defined by the diffraction pattern as the basis of a theoretical approach to calculate the photonic bandstructure of the system. An important feature of the model is that it retains the essence of the rotational and inflational properties of the quasicrystal at all levels of approximation; properties lost in approximate models which artificially introduce elements of periodicity. The calculated density of modes of the quasicrystals is found to display a weakly depleted region analogous to the band gap that occurs in a periodic system.

Introduction

The properties of quasicrystals [1, 2] have become of considerable interest since Shechtman *et al.* [3] observed the long-range aperiodic arrangement of atoms in AlMn alloys. The concept of quasicrystals can be extended to other physical systems such as dielectric structures with feature size at the length scale of a micrometer or less, which are often called photonic microstructures. Photonic quasicrystals are of interest because a pseudogap, or near vanishing minimum in the density of all modes, might be more readily achieved for all propagation directions in such structures as a result of their high degree of rotational "symmetry". Indeed, a "sizeable spectral gap" has been predicted theoretically for a two-dimensional photonic structure defined by the periodic repetition of a "supercell" with local octagonal quasisymmetry [4]. Photonic microstructures can provide a number of advantages in the investigation of the physical properties of quasicrystal-like system because the structure can be designed to study particular phenomena and can be investigated by well developed optical techniques.

Here we report a study of the optical diffraction properties, optical eigenmode spectrum.

The structure considered is essentially a two-dimensional Penrose-tiled [1] dielectric slab, where the tiles are two kinds of rhombus: a thin tile (with vertex angles of 36° and 144°) and a fat tile (72° and 108°) as illustrated in Fig. 1(a).

The experimental and model structures are formed by air cylinders, which are positioned at the vertices of the tiles. The experimental sample (quartz substrate with 121 air cylinders, shown in Fig. 2(b)) was fabricated using electron-beam lithography. The tile side $d = 10\,\mu$m and the hole diameter is about 3 μm, the depth of the cylinders is about 700 nm.

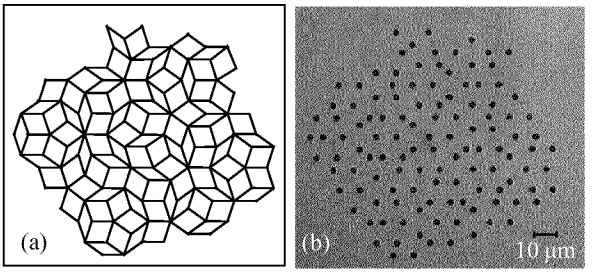

Fig. 1. (a) Penrose tiling with thin and thick tiles. (b) Microphotograph of the sample, used in the diffraction experiment.

1. Diffraction pattern

A He–Ne laser with a gaussian shaped beam and wavelength 633 nm was collimated to provide a beam diameter of about 130 μm, matching the size of the patterned area. The laser beam was incident normal to the sample, thus leading to the appearance of the diffraction pattern on the screen, placed 24 cm behind the sample as shown in Fig. 2(a). Note that although the experiment is carried out on a finite system with only 121 cylinders the pattern is remarkably similar to that reported for essentially infinite atomic quasicrystals [1],

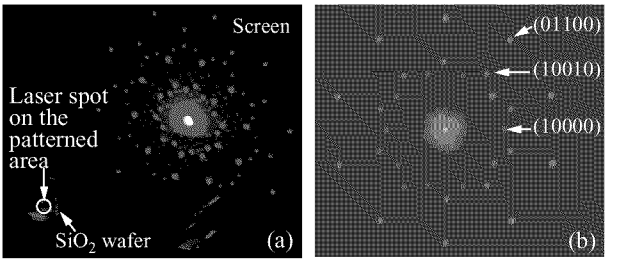

Fig. 2. (a) General photograph of the experimental diffraction pattern. (b) Photograph of the most pronounced peaks on the experimental diffraction pattern and indexing of the diffraction pattern.

The pattern possesses 10-fold rotational symmetry, and contains a series of spots of different intensity, surrounding the central undiffracted beam. These spots can be associated with vectors in the reciprocal space which we will call "reciprocal vectors" (RVs). Contrary to the case of a periodic crystal, the indexing of the diffraction pattern of aperiodic quasicrystals is not a trivial task, due to the self-similarity of the structure. The RVs of a periodic structure form the periodic reciprocal lattice and we can always find a set of primitive RVs of minimal magnitude whose linear combinations generate the entire reciprocal lattice. However, in aperiodic quasicrystals the RVs densely fill all reciprocal space, and it is not possible to choose any RVs of minimal magnitude. Nevertheless, it turns out to be convenient to choose some basic RVs that correspond to relatively intense peaks in the diffraction pattern, and have magnitudes that are related to the inverse of certain lengths in the structure, such as a tile side [2]. Figure 2(b) shows a photograph of the diffraction pattern of the experimental structure, whith only three series of the most intensive peaks visible. The magnitude and orientation of the RVs of the internal series correspond to the inverse of half the long diagonal of the thin tile, and choose these RVs as basic set.

Similarly, the middle series corresponds to half the long diagonal of the thick tile and the external series corresponds to half of that tile side length.

2. Band structure

Our approach is based on the belief that the spatial distribution of the electromagnetic field of any mode of the quasicrystal will reflect the distribution of the dielectric constant, and can be represented by a Fourier expansion based on the set of plane waves defined by diffraction pattern, see [5] for details. With Fourier expansions for the inverse dielectric constant and electromagnetic field the allowed modes can then be found by solving the usual matrix eigenvalue problem [6]. For our calculation we have considered the model structure with the following parameters: the dielectric constants of the cylinders and surrounding media are 1.0 and 9.0 respectively, the radius of the cylinders is 0.309 of a tile side. The bands have been obtained in the decagon in reciprocal space defined by the lines bisecting the basic RVs — the pseudo-Jones zone [2], shown in Fig. 3 (inset). In a crystal the pseudo-Jones zone becomes the first Brillouin zone. The solid lines in Fig. 3 show the calculated (neglecting the RVs with which magnitude is less then magnitude of the basic RV, since we do not see it in the diffraction pattern) bands along symmetry directions in the pseudo-Jones zone, together with the associated density of modes, derived from the entire area of the zone. The results presented are for H-polarized modes (magnetic field parallel to the cylinders), which exhibit the largest gap. Note the complete gap in the band structure near a frequency of 0.3 (in units of c/d, where c is the light velocity), which originates from the Bragg reflection of electromagnetic waves associated with basic RVs. In quasicrystals, RV densely fill all reciprocal space. Therefore we have to take into account RVs of magnitude less than basic RV. The dotted line in Fig. 3 shows the band structure, calculated taking into account additionally the RVs of the type (10001), of the magnitude 0.618.... The inclusion of these RVs results in the formation of a "minigap" in the bands, and related dips and spikes in the density of modes. However, the most significant feature is the appearance of allowed states inside the gap. These modes are characterized by small wave vector and can be considered to be due to diffraction from the inflated basic elements of the (self-similar) quasicrystals.

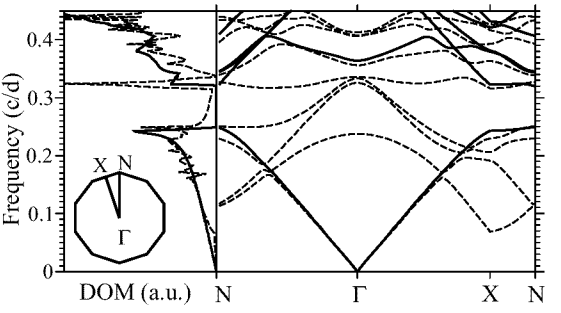

Fig. 3. Band structure for H-polarization calculated using 301 Fourier coefficients and plane waves and the related density of modes (solid line). Corresponding results calculated using an additional 10 plane waves of smaller magnitude such as (10001) (dotted line). Inset: symmetry points of the pseudo-Jones zone.

3. Conclusions

The distribution of matter in quasicrystals can be described using a rather small number of Fourier coefficients; The most substantial Fourier coefficients are related to RVs obtained by taking the sum of a few basic RVs; Quasicrystals possess a strongly depleted density of modes around the frequency defined by the strongest Fourier coefficients; The modes in that part of the spectrum are characterized by wavevectors, corresponding to the self-similar inflated elements of the basic structure, but at all frequencies, these modes experience Bragg reflection; Thus, the band structure and density of states of quasicrystals exhibit fractal behavior.

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