Strong edge effect in photonic graphene

S. R. Zandbergen[1] and M. J. A. de Dood [1]

[1] Huygens Laboratory, Leiden Universtiy, Niels Bohrweg 2, 2333 CA Leiden, The Netherlands

Photonic graphene consists of a triangular lattice of strongly scattering dielectric rods and shows a characteristic conical singularity in the photonic bandstructure. We use a two-dimensional lattice of 5 mm diameter alumina rods (n = 3.1) with a lattice constant of 8 mm to demonstrate a pseudo-diffusive transport regime. In this case, the transmission of microwaves in an ordered structure scales inversely with thickness. We show that the transmission through graphene-like materials depends critically on the configuration of the edges: no modulation of the transmission occurs for straight edges, while zig-zag edges lead to a strong modulation of the transmission.

Introduction

Graphene is a novel electronic material that consists of a two-dimensional layer of carbon atoms arranged in a hexagonal lattice. The interesting properties of graphene are related to conical singularities in the bandstructure that occur at the K-point on the edge of the Brillouin zone. These singularities are referred to as Dirac points; the dispersion relation of the electrons around these points is linear and the electrons can be described by the Dirac equation for relativistic particles. The existence of a conical singularity in the bandstructure is a direct consequence of the triangular symmetry of the lattice, and therefore is not limited to the electronic case. In fact, similar Dirac points can be found in the photonic bandstructure of rods on a triangular lattice [1,2].

The advantage of designing an experiment in the optical domain is that the relevant dimensions of the crystal structure scale with the wavelength. Many of the theoretically predicted effects in graphene depend critically on the atomic arrangement of the edges and seem to be out of reach with current technology. By choosing an appropriate microwave wavelength, the fabrication of photonic graphene samples with well-defined edges and size becomes feasible and form an excellent model system to study physical effects related to the Dirac point in a photonic rather than an electronic system [3,4].

Using Dirac Maps in the Design of Photonic Graphene

An experimental demonstration is greatly facilitated if the Dirac point is isolated in the sense that the singularities at the K-point are the only allowed modes in the crystal. Figure 1 shows an example of a photonic bandstructure calculated for a triangular lattice of dielectric rods. The rods have a dielectric constant $\varepsilon = 12$ (e.g. Si or GaAs) and a radius-to-lattice constant ratio $r/a = 0.30$. The bandstructure features an isolated Dirac point at a normalized frequency of 0.461 as indicated by the dashed line.

In order to design photonic crystal structures with such an isolated Dirac point, we introduce the concept of a photonic Dirac map. These Dirac maps are an extension of

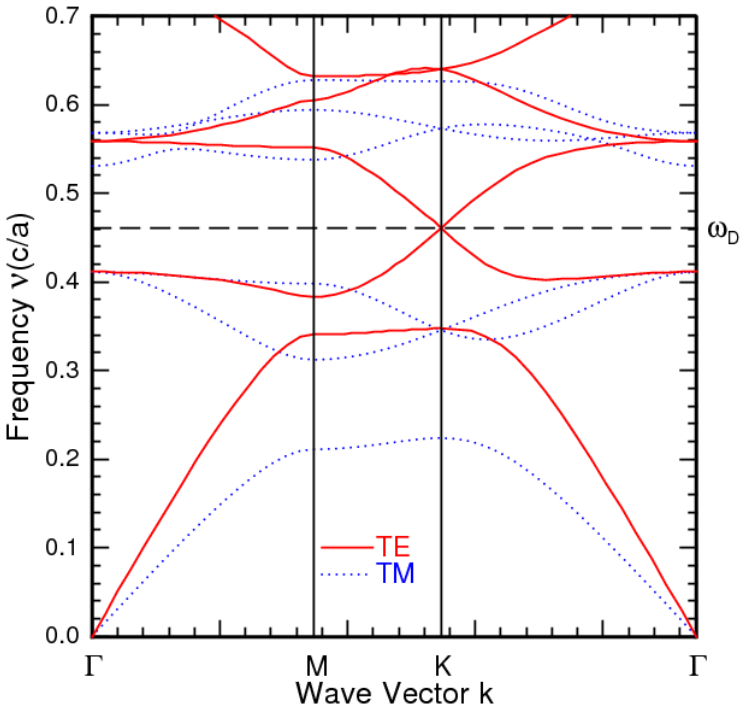

Figure 1: Calculated photonic bandstructure for a triangular lattice of pillars with a dielectric constant ε = 12. The bandstructure for TE polarization (solid lines) shows an isolated Dirac point at the K-point for a normalized frequency of 0.461, indicated by the horizontal dashed line.

photonic bandgap maps that are routinely used to optimize the photonic bandgap of a structure. An example of a Dirac map is given in Fig. 1, that shows the Dirac map for a triangular lattice of rods with a dielectric constant ε = 12. Separate maps are given for TE (left) and TM (right) polarization. The color coding in the figures indicates the existence of a mode in the ΓM (grey areas) or ΓK (yellow areas). The white areas in the figure correspond to photonic bandgaps. The frequencies of the photonic bands at the special K point are indicated by the blue lines. Isolated Dirac points are found whenever the blue lines are within the yellow areas.

Using the newly developed concept of “Dirac maps”, we find that the minimum value of the dielectric contrast needed to create an isolated Dirac point is close to 9. Similarly, for a given dielectric constant, the range of the parameter r/a for which a Dirac point exists can be identified. We find that up to two isolated Dirac points exist for both TE and TM polarized modes and that Dirac points can be found for all basic triangular and honeycomb lattices (holes and rods). We note that the use of these graphical maps is not limited to Dirac points, but can be adapted to search for other special points in a photonic bandstructure as well, such as the degenerate points in k-space needed for one-way waveguides [5].

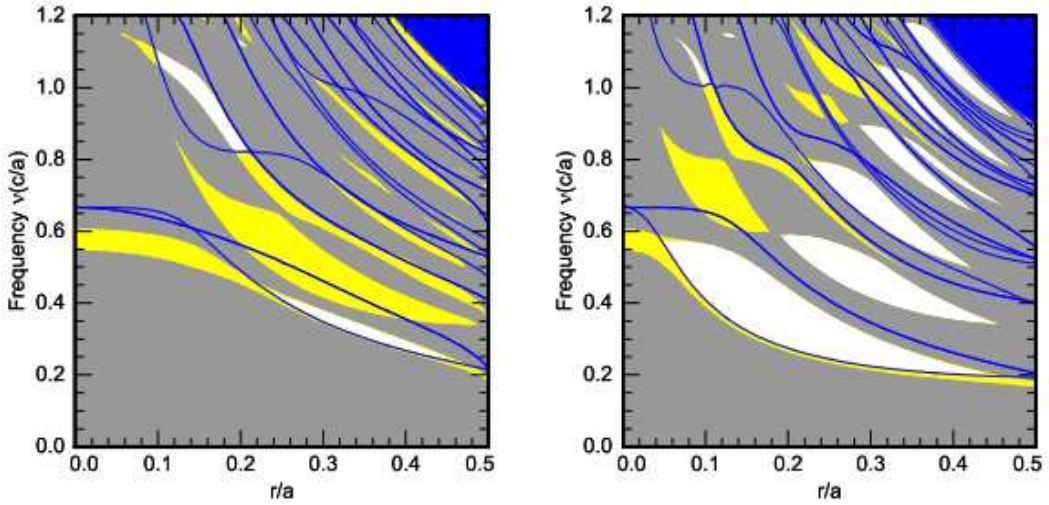

Figure 2: Dirac map of a photonic crystal structure consisting of a triangular lattice of pillars with a dielectric constant ε = 12 for TE polarization (left) and TM polarization (right). The colors indicate the existence of a mode in the ΓM direction (grey area) or the ΓK direction (yellow area). The blue lines correspond to the frequencies of the bands calculated at the K-point. Isolated Dirac points are found whenever these lines are inside a yellow region.

References

[1] M. Plihal and A. A. Maradudin, "Photonic band structure of two-dimensional systems: The triangular lattice", Phys. Rev. B **44**, 8565 (1991)

[2] S. Raghu and P. Haldane, "Analogs of quantum Hall effect edge states in photonic crystals", Phys. Rev. A **78**, 033834 (2008)

[3] R.A. Sepkhanov, Ya. B. Bazaliy and C.W.J. Beenakker, "Extremal transmission at the Dirac point of a photonic bandstructure", Phys. Rev. A **75**, 063813 (2007)

[4] J.L. Garcia-Pomar, A. Cortijo and M. Nieto-Vesperinas, "Valley polarized electronic beam splitting in graphene", Phys. Rev. Lett. **100**, 236801 (2008)

[5] Z. Wang, Y.D. Chong, J.D. Joannopoulos, and M. Soljacic, Phys. Rev. Lett. **100**, 013905 (2008).