Photonic Crystals: from Bloch Modes to T-Matrices

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The study of photonics crystals properties is often based on Bloch modes dispersion diagrams. But in practical applications, the crystal has a finite size and is illuminated by an incident field. A priori, this problem is different from the study of Bloch modes propagating in an infinite crystal. Bloch theory only consider propagative modes, whereas in a finite crystal there also exists evanescent modes. It is well known in grating theory that the evanescent modes play an important role and cannot be neglected in a quantitative analysis. Can they be neglected in a first approach of photonic crystals studies?

In this presentation, we make the link between the dispersion relation of Bloch modes for an infinite crystal, which describes the intrinsic properties of the photonic crystal in the absence of any incident field, and the diffraction problem of a grating (finite photonic crystal) illuminated by an incident field. We develop the relationship between the translation operator of the first problem and the elementary transfer matrix of the second one, and we put forward the links between the incident field, the eigensolutions of this matrix, and the Bloch modes of the associated infinite structure. Indeed, the eigenvalues of this transfer matrix hold all the information about the dispersion relations.

Then we show how we can take advantage of the previous tools in order to understand and anticipate the qualitative behavior of limited crystals. Many interesting properties can be deduced from a somewhat unconventional representation of the Bloch modes dispersion diagram, which informs us about the possible energy propagation directions. In this case of monochromatic studies, the constant frequency dispersion diagrams are deduced easily from the transfer matrix eigensolution.

This approach is applied to the study of anomalous refraction properties of photonic crystals. It enables us to answer questions such as: when does ultrarefraction occur? Can the photonic crystal simulate a homogeneous and isotropic material with low effective index? It enables us to find suitable parameters to obtain spectacular ultrarefractive or negative refraction properties and to design optical devices such as highly dispersive microprisms and ultrarefractive microlenses. Rigorous computations demonstrate the relevance of our approach, and add a quantitative aspect by giving the amount of energy transported by the different beams.

There also exists circumstances where evanescent modes govern the behavior of the crystal. The simplest case is obtained inside a bandgap. In this case, we show how the field decay is related to the eigenvalues of the elementary transfer matrix.