A brief discussion on the physical properties of one-dimensional periodic structures

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Abstract

In this paper we present a brief discussion on the properties of one-dimensional (1D) photonic structures. We will show the light transmission through periodic structures, i.e. photonic crystals, random structures, and quasicrystals. We will discuss the possibility to describe other types of 1D structures.

Introduction

One-dimensional (1D) structures are very interesting in solid state physics. A remarkable case is the 1D photonic crystal [1,2]. In general, photonic crystals are periodic arrangements in 1D, 2D and 3D of the dielectric function. Owing to this periodicity, for certain energy ranges light is not allowed to travel through the crystals. A very simple example of a 1D photonic crystal is a multilayer of two different materials [3,4]. If the alternation of materials in the multilayer is made by following a deterministic series, the result is a 1D photonic quasicrystal [5,6]. If the alternation is random, the result is a 1D photonic random structure [7].

Griffiths and Steinke have described, in a very elegant way, the theory of the propagation of waves in one dimension [8], shedding light on the similarities among different physical problems, as vibrations in strings, electron wave functions, and light transmission in photonic crystals.

Here we present different example of one-dimensional photonic structures, as 1D photonic crystals, quasicrystals, and random structures. We also depict the possibility to use a formalism, similar to the Bragg law and the transfer matrix method employed for 1D photonic crystals, able to describe the kinetic energy of an object, with mass m and speed v, that is travelling through a 1D modulation of the gravitational interaction (that we call 1D gravitational crystal). Our description leads to a speculation: certain ranges of the kinetic energy of the object can not travel through the 1D gravitational crystal, resulting in a gravitational gap.

Results and Discussion

We simulated the light transmission of the 1D structures with transfer matrix method [9].

1D photonic crystals: we show in Figure 1 the transmission spectrum of a 1D photonic crystal of 7 bilayers. The two materials of the layers have refractive indexes n_1=2.1 and n_2=1.6, and both the layers have thickness d=120 nm.
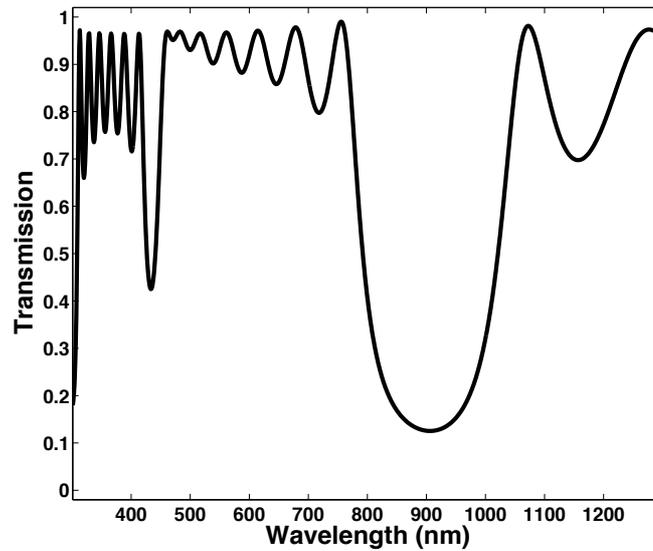
Figure 1. Transmission spectrum of a 1D photonic crystal of 7 bilayers.

In Figure 2 we show the photonic band gap of a 1D photonic crystal as a function of the number of bilayers (n_1=1.7 and n_2=1.5, both the layers have thickness d=100 nm).
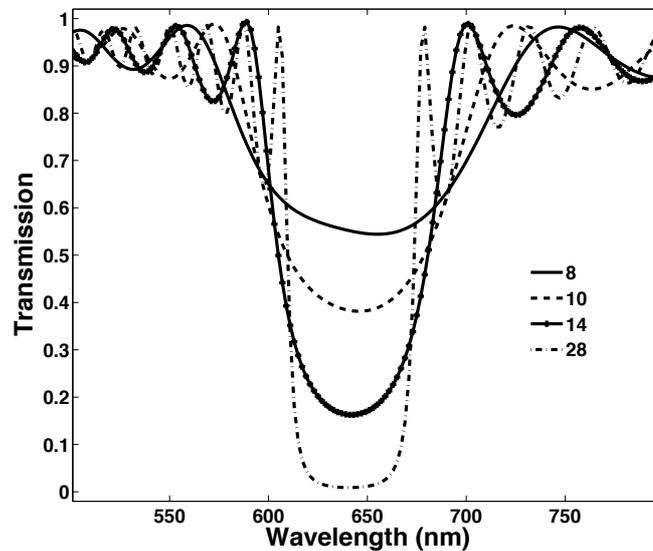

Figure 2. Transmission spectrum of a 1D photonic crystal as a function of the number of bilayers.

1D random photonic structures: A way to realize a 1D random photonic structure is to make a layered structure in which each layer has a 50% possibility to make the material 1 or the material 2. In Figure 3 we show the transmission spectrum of a 1D random structure of 15 bilayers (solid line), compared with the one of the 1D photonic crystal (dashed line). For these

structures, n_1=2.2 and n_2=1.8, and the layer thicknesses are d_1=(100/n_1) nm for the material 1 and d_2=(100/n_2) nm for the material 2, respectively.
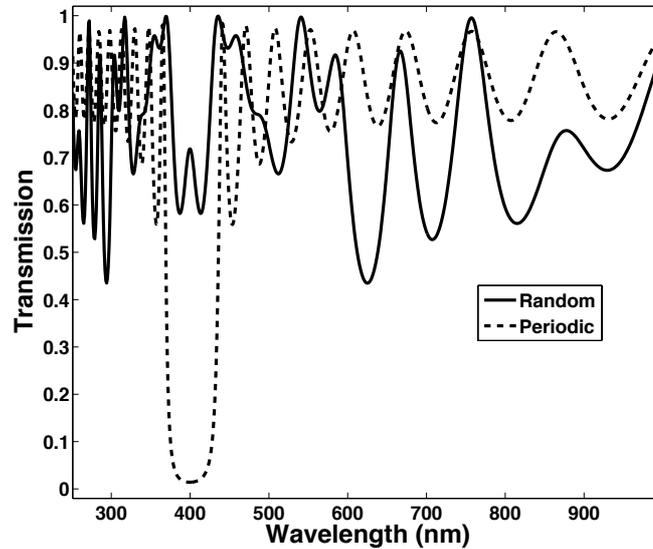

Figure 3. Transmission spectra of 1D random photonic structure (solid line) and a 1D photonic crystal (dashed line).

It is very interesting the decrease of the light transmission (Figure 4) all over the studied spectral range by increasing the number of layers of the 1D random structure (n_1=2.2 and n_2=1.8, and the layer thicknesses are d_1=90 nm for the material 1 and d_2=100 nm for the material 2, respectively).
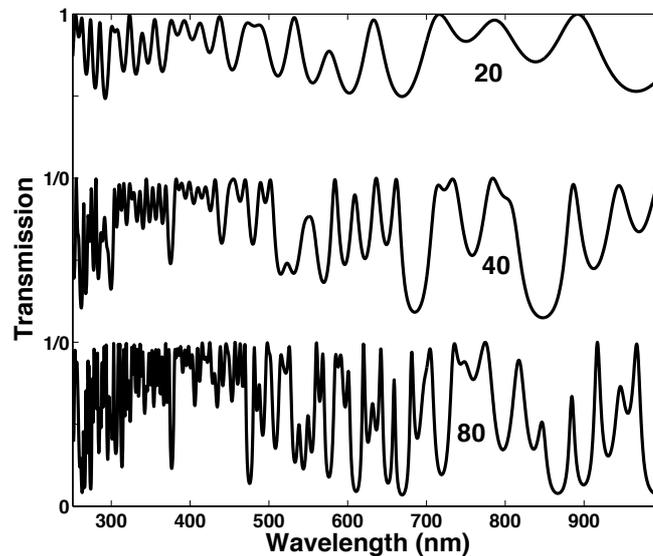

Figure 4. Transmission spectrum of a 1D random photonic structure as a function of the number of layers.

1D photonic quasicrystals: A 1D photonic structure that is realized by following a deterministic series is 1D photonic quasicrystal. In Figure 5 we show

the transmission spectrum of a 1D photonic quasicrystal of 21 layers made following the Fibonacci series, i.e. ABAABABAABAABABAABABA [10,5] (n_A=2.1 and n_B=1.6, and the layer thicknesses are d_A=(125/n_A) nm for the material A and d_B=(125/n_B) nm for the material B, respectively). In Figure 5a the plot is in wavelength, while in Figure 5b in energy.
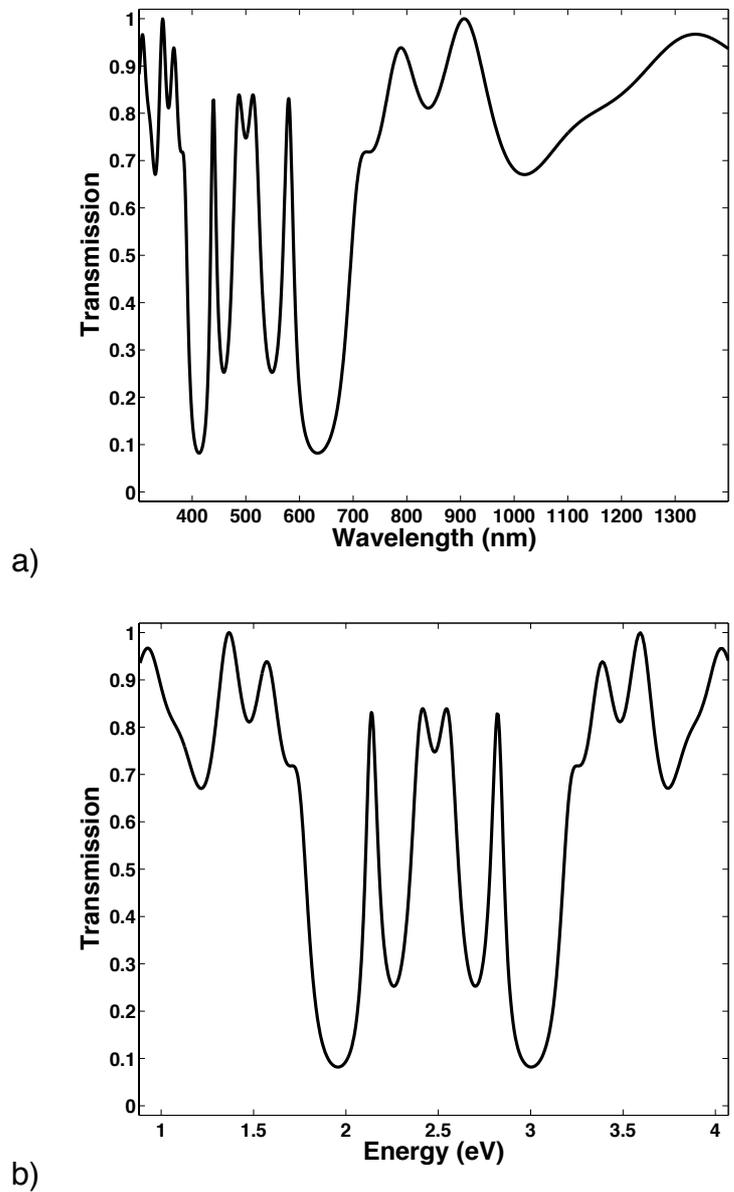

a)

b)

Figure 5. Transmission spectrum of a 1D photonic Fibonacci quasicrystal.

An other type of series is the sequence of prime numbers. In Figure 6 we show the transmission spectrum of a structure with the following sequence: ABBAAABBBBBAAAAAAABBBBBBBBBBB.
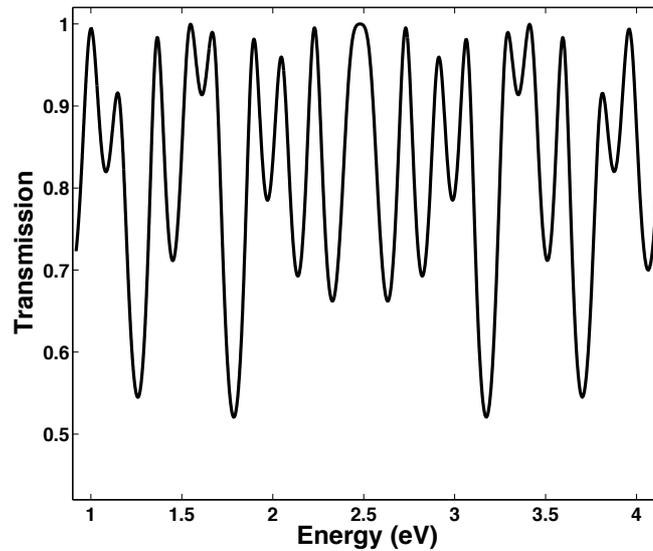
Figure 6. Transmission spectrum of a photonic structure made following the series of prime numbers (i.e. 1, 2, 3, 5, 7, 11).

We show the simulation of a 1D gravitational crystal and stress its similarity to a 1D multilayer photonic crystal, depicted in Figure 7a. In a 1D structure as sketched in Figure 7b, pairs of blocks made of Aluminium (size 5x5x5 cm, mass m_{Al}=0.3375 kg) and of Iron (size 5x5x5 cm, m_{Fe}=0.9950 kg) are alternated.
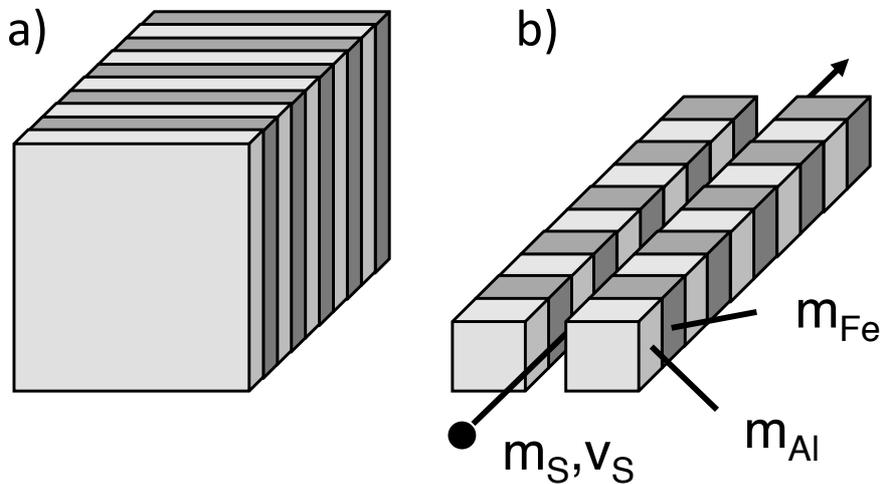

Figure 7. a) Scheme of 1D photonic crystal. b) Scheme of 1D periodic structure where pairs of blocks made of Aluminium and Iron are alternated (i.e. 1D gravitational crystal). A sphere with mass m_S and speed v_S travels between the pairs of blocks (the distance between the blocks is 1 cm, the diameter of the sphere is 0.8 cm).

In this periodic structure a modulation of the gravitational interaction is obtained. In analogy with other 1D physical problems, we do a speculation: the kinetic energy, of a sphere of mass (m_S=0.005 kg and speed v_S) interacting with the

block of Aluminium and Iron, obeys a law that is similar to the Bragg law. The law is of the form $E_K = 2(F_1 d_1 + F_2 d_2)$, with $F_1 = G m_S m_{Al}/d_{S-Al}^2$, $F_2 = G m_S m_{Fe}/d_{S-Fe}^2$, and $E_K = \frac{1}{2} m_S v_S^2$. G is the gravitational constant (6.67×10^{-11} Nm^2/kg^2).

In a transfer matrix method formalism, analogous to the one employed for photonic crystals [9],

$$M_j = \begin{bmatrix} cos\phi_j & -\frac{i}{m_j} sin\phi_j \\ -im_j sin\phi_j & cos\phi_j \end{bmatrix},$$

with $\phi_j(E) = E/(\xi F_j d_j)$, is the characteristic matrix of each layer. ξ is a parameter (the value of ξ is 3.5). From the product of all the matrixes that correspond to the layers of the 1D structure, $M = \prod_j M_j$, we can determine its transmission coefficient, that is $t = 2/M_{11} + M_{12} + M_{21} + M_{22}$, and leads to the transmission $T = |t|^2$.

In Figure 8 we show the calculated transmission spectrum, for the lattice depicted in Figure 7b, where the first and the second order of the gap are observed.
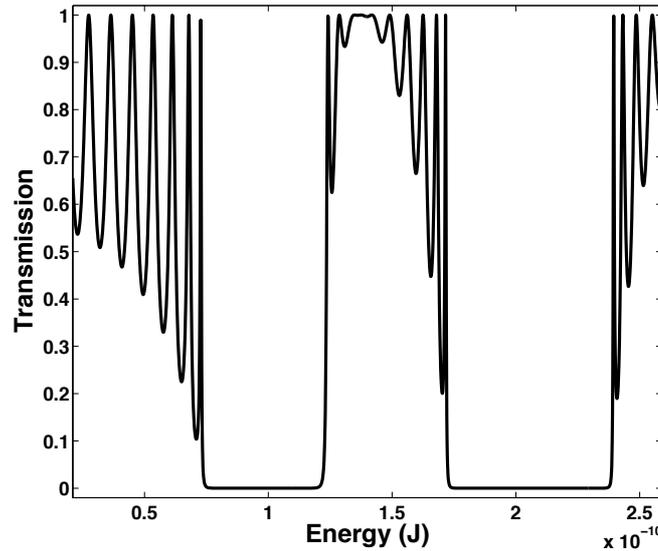

Figure 8. Transmission spectrum of a 1D structure made by the alternation of Aluminium and Iron blocks.

The centre, in energy, of the gap for the 1D structure is at about 9.88×10^{-11} J, and such energy corresponds to a speed of the sphere of about 1.99×10^{-4} m/s (the result is in agreement with the one obtained with the above mentioned equation $E_K = 2(F_1 d_1 + F_2 d_2)$).

A possible development of this description of a 1D gravitational crystal is the accurate derivation of the formalism.

The experimental observation of the suggested phenomenon can be obtained in three different ways: i) the study of systems with very small values of speed v_S; ii) the study of systems with a high volumetric mass density; iii) the highly precise fabrication of the 1D structure in order to be able to observe the higher orders of the gap (corresponding to higher values of speed v_S).

Conclusion

In this work we presented, with well-established theoretical tools, the optical properties of 1D photonic crystals, random structures, and quasicrystals. We also speculate the possibility to describe the physical properties of 1D gravitational crystals.

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