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PRZEMYSŁAW MŁYNARCZYK*, GRZEGORZ DZIATKIEWICZ**

NUMERICAL MODELLING OF THE OPTICAL DEMULTIPLEXER PHOTONIC STRUCTURES

MODELOWANIE NUMERYCZNE STRUKTUR FOTONICZNYCH OPTYCZNEGO DEMULTIPLEKSERA

Abstract

Photonic structures and their application are one of the most intensively studied areas of modern optics. They are used in devices such as blue lasers, optical fibres or optical add-drop multiplexers. The paper describes the possibility of designing the photonic structure of the optical demultiplexer using the application written by the authors.

Keywords: *photonic crystals, optical demultiplexer, numerical modelling*

Streszczenie

Kryształy fotoniczne oraz ich zastosowania są jednymi z najintensywniej badanych obszarów współczesnej optyki. Znajdują zastosowanie w takich urządzeniach jak niebieskie lasery, światłowody fotoniczne czy optyczne multipleksery sumująco-selekcjonujące. Artykuł opisuje możliwość projektowania struktury fotonicznej optycznego demultipleksera przy zastosowaniu napisanej przez autorów aplikacji.

Słowa kluczowe: *kryształy fotoniczne, optyczny demultiplekser, modelowanie numeryczne*

* M.Sc. Eng. Przemysław Młynarczyk, Institute of Thermal and Process Engineering, Faculty of Mechanical Engineering, Cracow University of Technology.

** PhD. Eng. Grzegorz Dziatkiewicz, Institute of Computational Mechanics and Engineering, Faculty of Mechanical Engineering, Silesian University of Technology.

1. Introduction

The concept of photonic crystals was formed at the same time in 1987 in two research centres in the USA. One of the first scientists who dealt with photonic structures was Eli Yablonovitch from Bell Communications Research in New Jersey who was working on the materials for photonic transistors. The second one was Sajeev John from Princeton University who was working on increasing the efficiency of lasers used in telecommunication. Both scientists discovered and formulated the concept of photonic band gap which became the basis of this structures applicability. In the 1991 Yablonovith created the first photonic crystal and in 1997 a method of mass production of these structures was developed [1]. A natural prototype of the photonic crystal is an opal, a mineral derived from the cluster of silicates, found in many places around the world including Poland, mainly in the lower Silesia where the former was located in nickel ore mines, and which is a component of green opals (chrysoprases). Nowadays an intensive study of photonic structures are conducted which reveals more and more new applications. The paper shows the application of numerical calculations for designing a optical photonic demultiplexer. The Helmholtz equation of electromagnetic propagation in the one-dimensional heteregenous photonic structure is solved numerically to obtain the transmittance characteristics. The resultant complex linear system of equations gives complex amplitudes of the incident and reflected waves on each interlayer. The written computer code allows to perform the basic design of the various 1D photonic structures.

2. Photonic structures

The photonic crystal is a periodic structure composed of different dielectric materials. By changing the differences between the refractive indices of materials the effect of "trapping" different wavelengths of light can be achieved, this phenomenon is called the photonic band gap. In general, the properties of the photonic crystal depend on the size, number of layers, the geometry and individual properties of the materials forming the crystal. There are three structures of photonic crystals: one-, two-, and three-dimensional. In the modelling of the electromagnetic field in the photonic crystal many methods known in the optics or electrodynamics are used. For example: the plane wave method and the finite difference time domain method, which are used for solving the time-dependent Maxwell equations of both electric and magnetic fields, the moments method and its numerous varieties as well as semi-analytical and analytical methods. So far, the analytical solutions of Maxwell's equations were found only for the simplest one-dimensional photonic crystal [3, 4].

2.1. One-dimensional photonic crystals

The simplest example of a one-dimensional photonic structure is the form of periodic multi-layer dielectric stacks called the Bragg mirror as it is shown in Fig 1.

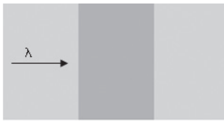

Fig. 1. Simple Bragg mirror

If the electromagnetic wave with a ω frequency drops on such a structure, a part of the wave energy is reflected. This property is used in typical signal filters. Bragg mirrors are designed with respect to the reflection spectrum for a selected wavelength range. So designing one-dimensional photonic crystals is a process of an appropriate selection of a number of layers, their thickness and materials with appropriate refractive indices. One-dimensional photonic crystals are used in such systems like optical demultiplexers, optical filters, the so called: "blue lasers", ultra-white pigments, photonic semiconductors etc.

2.2. Two-dimensional photonic crystals

Light propagating in the two-dimensional photonic crystal can be separated into two independent polarized waves, for which there is no longer a common photonic band gap. Trapping or controlling photons is possible by the use of two-dimensional forbidden gaps in the expected direction of wave propagation and by obtaining a high refractive index in the perpendicular direction. Two-dimensional photonic structures may become the most important component of modern optical technology. Integration of these structures with electronic systems is crucial for constructing a new generation of computers based on electro-optical chips.

Nowadays the most popular use of this type of photonic structures are optical add-drop filters which are a combination of two devices: multiplexer and demultiplexer. The main feature of such a filter is to isolate (drop) a band of an electromagnetic wave (EM) or the addition (add) band of the EM wave to the desired light beam. Two dimensional structures are mainly produced by using two-dimensional lithographic [5].

2.3. Three-dimensional photonic crystals

Three-dimensional photonic structures have periodicity in all three directions. The main advantage of such a structure is inhibiting and directing the photons resulting from the phenomenon of spontaneous emission. Three-dimensional structures can be produced using techniques known from electronic industry. There is still a lot of unanswered questions about the three-dimensional photonic crystals, and the main aim will be to complete inhibition of spontaneous emission which is theoretically possible by using infinitely thick crystals [5].

3. Electromagnetic wave propagation in 1D structure

The relationship between electric and magnetic fields are described by Maxwell's equations. These four equations are the basis for electromagnetic wave propagation modelling [6].

Considering only the propagation of the electric field in the vacuum, one dimensional wave equation can be obtained:

$$\frac{\partial^2 E}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = 0 \qquad (1)$$

where:

- E – the electric field vector,
- x – spatial coordinate,
- c – the speed of light in the vacuum,
- t – time.

Referring to the Helmholtz solution of this equations it is possible to model the harmonic wave in photonic crystals. Assuming the solution in the form of a harmonic wave propagation through the materials with different coefficients of dielectric permittivity, and thus with other factors of wave refraction, according to [1, 7] the following harmonic solution is obtained:

$$E_{pr} = E_p e^{ik_0 r} + E_r e^{-ik_0 r} \qquad (2)$$

where:

- E_{pr} – the amplitude of the propagating wave electric field,
- E_p – the amplitude of the incident wave electric field,
- E_o – the amplitude of the reflected wave electric field,
- r – spatial coordinate,
- i – the imaginary unit,
- k_0 – the wave vector dependent to medium refractive index.

For the photonic structure consisting of *m*-layers, as shown in Fig. 2, the solution of Helmholtz equation for m-th layer becomes:

$$E_m(x) = A_m e^{in_m k x_m} + B_m e^{-in_m k x_m} \qquad (3)$$

where:

- n_m – a refractive index for the m-th layer,
- x_m – an coordinate position in the m-th layer,
- A_m – the amplitude of the wave incident on the m-th layer,
- B_m – the amplitude of the wave reflected on the m-th layer,
- k – a wave vector.

Introducing the continuity conditions for every interlayer:

$$E_m(x_m) = E_{m+1}(x_m) \qquad (4)$$

$$\frac{\partial}{\partial x}E_m(x_m) = \frac{\partial}{\partial x}E_{m+1}(x_m) \qquad (5)$$

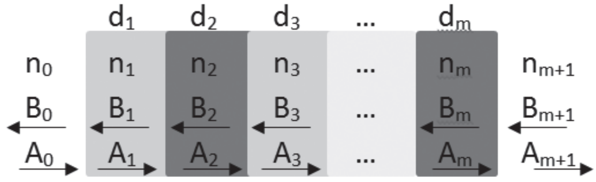

Fig. 2. Photonic structure consisting of m layers

the system of equations for each surface between the layers is obtained:

$$A_m e^{in_m kx_m} + B_m e^{-in_m kx_m} = A_{m+1} e^{in_{m+1} kx_m} + B_{m+1} e^{-in_{m+1} kx_m} \tag{6}$$

$$in_m kA_m e^{in_m kx_m} - in_m kB_m e^{-in_m kx_m} = in_{m+1} kA_{m+1} e^{in_{m+1} kx_m} - in_{m+1} kB_{m+1} e^{-in_{m+1} kx_m} \tag{7}$$

For the structure with N layers, the system of 2N+2 equations with 2N+4 unknowns is built by applying the continuity conditions (4) (5) for each interlayer and for the first and the last surface of the structure. The unknowns are complex amplitudes of the incident and reflected waves on each interlayer. It is a system of complex linear algebraic equations, with respect to A_i and B_i.

Such a system of equations can be solved assuming the boundary conditions for A_0, for example equal to 1, which is the amplitude of wave incident on the crystal, and $B_{n+1} = 0$ meaning that there is no reflections between the last layer and the surrounding medium. The reflection coefficient, which is the most important parameter of the photonic crystal, is determined by the relation [5]:

$$R = \left(\left| \frac{B_0}{A_0} \right| \right)^2 \tag{8}$$

4. Numerical model of optical demultiplexer

To solve the system of equations the Cramer method was used. This method is most convenient in the present case because it is important to find only one unknown B_0. The program calculates the reflection coefficient R in the loop sequence for each wavelength in a given range with a specific, defined difference for the subsequent two wavelength [8].

4.1. Optical demultiplexer

The optical add-drop multiplexer is a device used for separating the appropriate wavelength from the full range of optical wavelength propagating in a single optical fiber. At the same time such a device can add another pre-selected light to obtain expected range of the wavelength. The optical demultiplexer can be a part of the optical add-drop multiplexer or standalone device with many applications in networks and other optical devices. A key element of this device is a Bragg mirror with a defect. This is a typical 1D photonic crystal with a defect, which means that to the periodically stacked layers one layer with other parameter of refractive index or thickness is introduced. By proper selection of layers and defect parameter can be designed a structure with reflection coefficient equal to 1 for the entire range of the incident wave with the exception of one chosen length.

4.2. Numerical calculation results

The applied numerical method allows to define any photonic structures. Flexibility relates to the number of layers and their refractive indices and thicknesses. For the purpose of this article a simple structure shown in the Fig. 3 is considered. It is a five-layer structure, of a thickness equal to 1 μm, consisting of alternating layers of material with refractive index equal to 3.5 and air ($n = 1$).

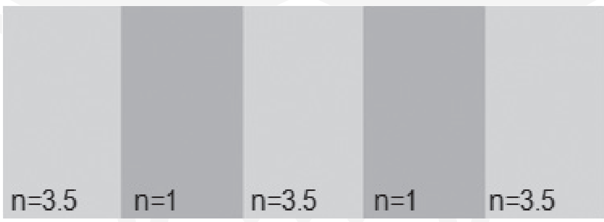

Fig. 3. Five-layer photonic crystal structure which is a part of the optical demultiplexer

For the structure shown in the Fig 3, without embedded defect, a complete wave reflection for the wavelength range from 1.24 to 1.32 μm (infrared light) is obtained. Numerical results are shown in the Fig. 4.

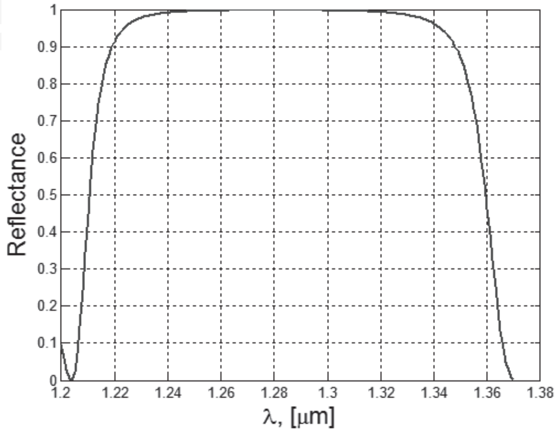

Fig. 4. Reflectance spectrum for the structure without defect

The defect into the central layer is introduced by the change of the thickness. The numerical result for thickness change by 312 μm is shown in the Fig. 5.

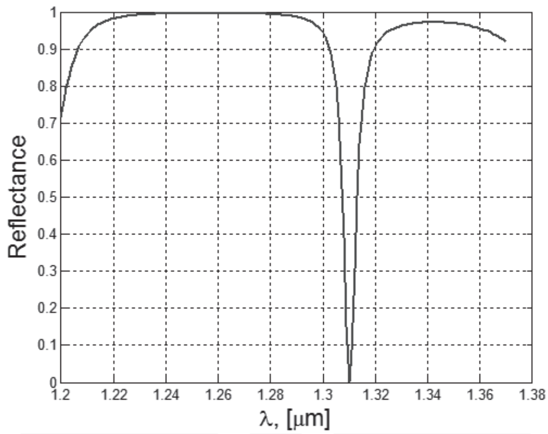

Fig. 5. Reflectance spectrum for the structure with defect

As can be seen in the Fig. 5. for the structure with defect, the complete transmission by the crystal was achieved for the wavelength of 1.310 μm. After several numerical simulations a graph which describes the Bragg defect thickness dependence on the length was plotted. The graph is shown in the Fig. 6.

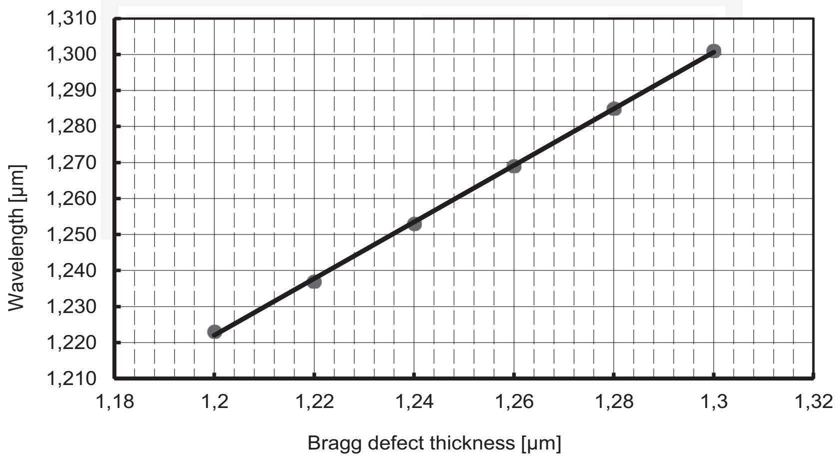

Fig. 6. Wavelength of transmitted wave vs. the Bragg defect thickness

The same calculations can be performed by changing the refractive index of the Bragg defect and the results are shown in the Fig. 7. However, such a design is problematic because each time a material with suitable refractive index should be found.

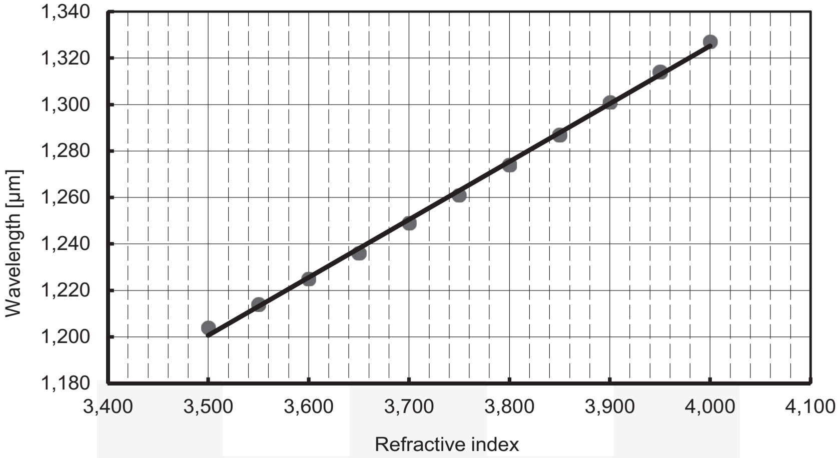

Fig. 7. Wavelength of transmitted wave vs. the refractive index

5. Conclusions

Photonic crystals have an increasing role in modern optic technology and every year there is more and more applications of such structures. The article described a possibility of designing the optical demultiplexer photonic structures using the numerical model. The numerical model allows to define all necessary parameters of the photonic crystal structure. The article shows that by such a program one can create tables and graphs serving as a quick and effective tool to design photonic crystal parameters. In the future, the use of photonic crystals will be increasing so the development of this type of applications will be necessary and unavoidable.

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