THE USE IN PRINTING OF THE PHOTONIC BAND GAP AS A PARTICULAR FEATURE OF PHOTONIC CRYSTALS

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Abstract
The photonic crystals are macroscopic structures. They exhibit many properties over which numerous tests are conducted. These crystals, thanks to the presence of so-called photonic band gap, cause conscious control of the course of electromagnetic waves. This property allows the conscious design of colors, because the color is not created by additive or subtractive synthesis, such as RGB or CMY, but through photonic changes taking place in the structure. The change in color may change due to changes in the viewing angle of the print or other external stimuli applied to the printed substrate.
Photonic crystals, thanks to their introduction to pigments, are used in printing mainly as a kind of security for documents or product brand. It is difficult to fake such documents because they can not be scanned or copied. After some time, the possibility of producing photonic paper, which would solve the problem of environmental pollution, was also considered. The recorded image would disappear after some time and the paper could be re-used.
Conducting experiments related to acquiring knowledge about the properties of photonic crystals is very expensive. The conditions for mass production have not yet been developed. It is expected that the structure of these crystals provides a new approach to light issues.

1. General information

The photonic crystals consist of dielectric layers with alternating values of the refractive index. This feature allows you to consciously control the course of electromagnetic wave in the structure of these crystals, that is, for conscious transmission of light.

These crystals exhibit a photonic band gap, which is a spectral gap for a certain length and frequency of the electromagnetic wave . A structure consisting of alternating variable values of the refractive index prevents the propagation of waves for a given range of their spectrum. In view of this - due to its periodicity – the relation of light wave dispersion in photonic crystals shows some gaps in the energy bands [1]. The thickness of the active layers forming the crystal is 200 ÷ 300 nm, which means that the linear construction elements are comparable to the length of the electromagnetic wave.

The photonic crystals are mostly artificially produced materials, but an example of their natural occurrence are: Paua sea snail shell, living in New Zealand, Blue Morpho butterfly wing, from South American regions, chameleon and opal, which is a precious stone from Australia [2].

The photonic crystals cause any change in color. This is due to the photonic changes occurring in their structure. This means that the color is not formed as a result of an additive mixture of basic RGB colors, or a mixture of subtractive primitive colors CMY.

Currently, numerous studies are conducted in special centers dealing with this subject. Premonitions of scholars allow to conclude that it is worth focusing on photonic crystals because it is a future material.

1.1. Types of photonics crystals

The change in the refractive index may occur in three directions, which is why photonic crystals stand out:

- one-dimensional,
- two-dimensional,
- three-dimensional [3]

One-dimensional crystals are characterized by a change in the refractive index in only one direction. In two-dimensional crystals, this change can occur in two directions, and in three-dimensional in all. Examples of these crystals are shown in Figure 1.

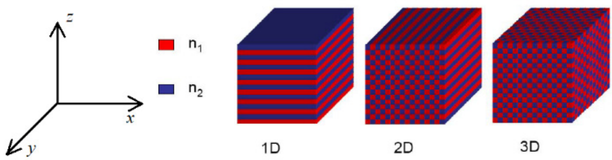

Fig. 1. Photonics crystals: 1D, 2D, 3D [4]

The direction of the change in the refractive index determines the direction of the spectral interruption, i.e. the photonic band gap. For example, if the photonic crystal is one-dimensional and the change in the value of the refractive index occurs in the z direction, then only in this direction the said spectral break may occur.

1.2. Configurations of photonic crystals

The layers forming the photonic crystal, i.e. those with alternating variable refractive index values, are arranged in a square or triangular configuration [3], which is shown in Figure 2.

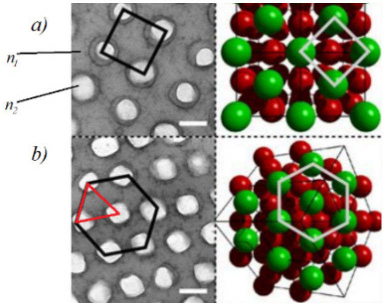

Fig. 2. Photonic crystal with a) square, b) triangular configuration [5]

Changing the color causes:

1) changing the network configuration from square to triangular or vice versa,,
2) changing the distance between cells with the same refractive index,
3) even slight changes in geometry in the photonic crystal, e.g. cell shape.

2. Photonic band gap

One of the most important properties of photonic crystals is the occurrence of a photonic band gap, i.e. a spectral break for a specific length and frequency of electromagnetic waves. About photonic crystals, it is said that these are materials „trapping" light [6].

Brillouin zone

The photonic band gap is closely related to the presence of the Brillouin zone. In the case of semiconductor crystals in this zone, the potential energy changes in the crystalline space in a periodic manner, and the electrons in the crystal arrange themselves into energy bands. Permissible energy states are quantized, and their levels are grouped into appropriate bands of conductors, which are separated from each other by band intervals, i.e. those in which energy states cannot be sown [7]. The Brillouin zone in semiconductor crystals is the dependence of the electron energy on the wave vector, and in the case of photonic crystals is the dependence of the frequency of the circular phonon on the wave vector, as shown in Figure 3.

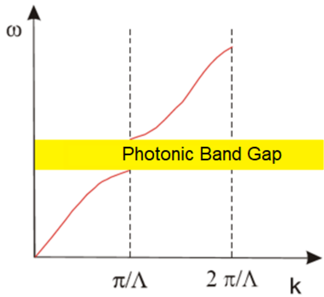

Fig. 3. The dependence of the circular frequency of the phonon on the wave vector [8]

It can be seen that this function is not continuous for wave numbers with the values expressed by the formula (1):

$$k = \left\{ \frac{\pi}{\Lambda}; \frac{2\pi}{\Lambda} \right\} \tag{1}$$

where:
k – a wave number ,
Λ – a length of the electromagnetic wave
For these values, a photonic break is created. The circular frequency, called pulsation, is a quantity that determines how quickly a given periodic phenomenon is repeated. It is presented as the product of the circumference of the circle and the frequency of vibrations. The photonic paused break allows the light to be transmitted for only selected wavelengths.

The width of the break depends very much on the large difference in the refractive index.

Summarizing:

- change in the width of the spectral break affects the color change,
- the greater difference is shown by the relative dielectric permittivity values of the layers on which their refractive index values depend, the wider the gap is,
- the presence of a photonic band gap depends on the type of photonic crystals, i.e.: 1D, 2D and 3D and from the crystal network configuration,
- the color change process, i.e. the manipulation of the band gap width, is reversible.

Greater control over the transmission of light in the crystal, and thus the design of the color, allows a 3D crystal, consisting of layers with a large difference in the refractive index.

3. The use of photo crystals

The photonic crystals find application in many fields of science and technology. Artificially manufactured, previously used as a kind of document security and to protect the product brand, because reproducible production conditions have been developed in this field. The product is printed with a ink whose pigment contains photonic crystals.

Optical properties and the perception of color change depending on:

- lighting conditions,
- the angle of observation of the object,
- an applied electric or magnetic field,
- mechanical, thermal and chemical stimuli.

Opalux, headquartered in Toronto, patented Photonic inks using the properties of photonic crystals with a security function activated by RFID (Radio-Frequency Identifications). The construction of such a system and the principle of its operation consists in the fact that special objects are attached to the objects, which contain electronic circuits with encoded data and a transceiver antenna. Using the RFID reader together with the antenna, data are read and written using radio waves [9]. The ink changes its color under the influence of the RFID field and as a result is optically variable. Printed with photonic ink, the object changes its color near the reader, and after moving away from the reader, the object's color returns to the original one [10]. The photonic ink reverses and shrinks, depending on the voltage or current applied. It is also able to maintain static images with low energy. Figure 4 shows the change in color, depending on the voltage applied to the film printed with such a photonic ink.

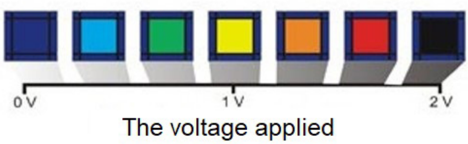

Fig. 4. Changing the color under the influence of the applied voltage [9]

It can be seen that the color gradually shifts in the visible range, along with increasing the voltage near the film. In the event of a voltage failure, the color is dark blue and changes to yellow when the voltage is 1 V and black when the voltage reaches 2 V. The photonic ink responds to the electric charge, so it can be used for both rigid and also and flexible surfaces [9].

Pigment, containing photonic crystals, caused that the possibility of producing paper, which in its structure would contain photonic crystals, began to be considered. Currently, work is underway to replace paper produced from cellulose with a matrix that swells under the influence of external factors. As a consequence, an image is created, the color change of which works analogously to the paint containing the photonic crystal in the pigment. It turned out that such a product would solve the problem of environmental pollution. Paper is a non-energy and long-term data carrier. It plays a key role in the storage and distribution of information. Over 90% of all information in companies is printed on paper, which is removed after a single reading without removing the ink. This causes negative environmental effects, such as air, water and soil pollution. The idea arose to create rewritable paper, i.e. one that can be used many times. Such a product is an attractive alternative to ensuring a perfect balance between economic development and environmental protection [11].

On this type of substrate different colors can be obtained by adjusting the particle size of the photonic coatings or writing on these substrates inks that are aqueous solutions with a certain pH. Photonic coatings can be repeatedly removed and transcribed without significant loss of color quality, while providing a lower burden for the ecosystem.

The structure of the rewritable paper consists of a nanoparticle photonic crystal based on oxides: carbon and iron, embedded in a bistable electroactive polymer, i.e. in which the once displayed image is maintained without any additional energy consumption for its maintenance. Electric excitation causes a large deformation in a given axis of the nanocomposite, which translates into a distinct change in color in the activated area. Images created in this way are of high quality [12].

The color created as a result of the reflection of light from the surface of the paper to be repeatedly recorded, in which the photonic crystals are occurred, is easily checked by changing the lattice constant of the crystal cell or the refractive index of the layers forming the photonic crystal. It is possible to achieve by controlling:

- pH of the aqueous solution,
- humidity,
- solvent swelling,
- temperature
- electric and magnetic fields.

Aqueous solutions, which are also inks that are applied to paper, cause a different degree of swelling of the polymer matrix. This leads to various changes in the geometry of the photonic crystal cells or the distance between them. As a result, patterns of different colors are created, because a different degree of swelling causes the human eye to reach a specific length.

Restrictions on the use of re-writable paper are:

- too quick evaporation of ink on the substrate,
- nuisance of moisture removal, which leads to degradation of paper,
- too slow printing speed, not comparable with the speed of printing on traditional paper.

Perhaps in the future, conventional printing methods will be replaced by the swelling method of the polymer matrix, on which aqueous solutions with different pH are applied.

Conclusion

The photonic crystals exhibit many properties over which numerous studies are conducted. Thanks to them, it is possible to consciously control the transmission of light, and thus thoughtful color design, because it is not formed by an additive or subtractive mixture, but thanks to photonic changes.

Conducting experiments related to the exploration of knowledge about photonic crystals is very expensive. It has not been possible - as before - to develop conditions for their mass production. It can be presumed that the structure of these crystals provides a new approach to light issues.

In polygraphs they are used as a kind of security, because photonic crystals are introduced into printing ink pigments. However, after some time, the possibility of creating photonic paper, which would replace the conventional methods of printing conventional paper, was also considered. The swelling method of the polymer matrix is used for this. Such a solution is environmentally friendly, because to obtain a multi-colored print, water solutions with a specific pH are sufficient.

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