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Temperature sensor on base of pne-dimensional photonic crystal with defect

© A.I. Sidorov[1,2], Yu.O. Vidimina[2]

[1] ITMO University,
197101 St. Petersburg, Russia
[2] t. Petersburg State Electrotechnical University„LETI",
197376 St. Petersburg, Russia
e-mail: sidorov@oi.ifmo.ru

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The results of computer simulation of optical properties of one-dimensional ($1D$) photonic crystal with defect, based on semiconductor-dielectric layers are presented. As semiconductor silicon and germanium were used. The influence of temperature on spectral position of defect transmission band was studied. It was shown that for photonic crystal based on silicon temperature sensitivity is 0.07 nm/K and 2.6 dB/K. For photonic crystal based on germanium — 0.37 nm/K and 7.8 dB/K. This makes such photonic crystals promising for use in temperature sensors as sensitive element.

Keywords: temperature sensor, photonic crystal, photonic bandgap, transfer matrix.

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Introduction

The temperature measurement is ubiquitous in industrial processes, allowing to choose the optimal mode of operation or monitor changes in the state of the material. The temperature mode is equally important both in everyday life and in the chemical, food industry, medicine and other areas of human activity. The deviation from the process modes may result in accidents and injury to people. Therefore, the development of new measurement methods and new temperature sensors is an important applied task.

The use of photonic crystals and optical fiber to create temperature sensors is based on thermooptical effects. For example, this can be a spectral shift of the luminescence band or its quenching with a change in temperature [1], a temperature change in the absorption coefficient [2] or the refractive index [3]. The sensors with a sensitive element based on optical fibers [2] have a high temperature sensitivity (up to 20 nm/K). Various types of interferometers are used to measure temperature, for example, a Mach-Zehnder interferometer [4]. The paper [5] describes a temperature sensor, which is a ring resonator based on a photonic crystal, made of polycrystalline silicon. The sensitivity of such a sensor is 0.0653 nm/K. A Sagnac interferometer based on photon-crystalline fibers [6] can be used as a sensitive element of the temperature sensor. One-dimensional photonic crystals were used in the papers [7,8] to measure cryogenic temperatures. The temperature sensor described in [7] has a sensitivity of 0.15375 nm/K. Long-period Bragg lattices formed in an optical fiber, which are a $1D$-photonic crystal, are used as sensitive elements in temperature sensors [8]. The $1D$-photonic crystals with a defect are promising for sensor applications due to their simplicity, processibility and spectral sensitivity of the defect bandpass to external influences [9–12]. The study [13] shows the prospects of using a $1D$-photonic crystal with a defect as a sensitive element of a temperature sensor.

$1D$-photonic crystals with a defect can be used not only to measure temperature, but also to measure other characteristics of media, for example, to measure the refractive index of an analyte [14,15].

The purpose of this work was to study, by numerical simulation, the optical characteristics of a one-dimensional photonic crystal with a defect, from the point of view of the possibility of its use as a sensitive element in a temperature sensor.

Photonic crystal geometry and numerical simulation technique

The geometry of a $1D$-photonic crystal for the near-IR range is shown in Fig. 1, *a*. It consists of four alternating semiconductor and $10\,\mu$m dielectric layers. The central $200\,\mu$m semiconductor wafer forms a photonic crystal defect. This wafer can be made of monocrystal silicon ($n = 3.4$, $dn/dt = 1.62 \cdot 10^{-4}\,\mathrm{K}^{-1}$) or germanium ($n = 4$, $dn/dt = 6 \cdot 10^{-4}\,\mathrm{K}^{-1}$). The choice of the thickness of the layers and the defect, which significantly exceed $\lambda/4$, is based on the following. In the case of a large period of a photonic crystal not one, but several band gaps are formed in it. This simplifies the choice of the operating wavelength of the probing radiation source. In addition, with a large thickness of the defect and semiconductor layers, the sensitivity of the temperature sensor increases.

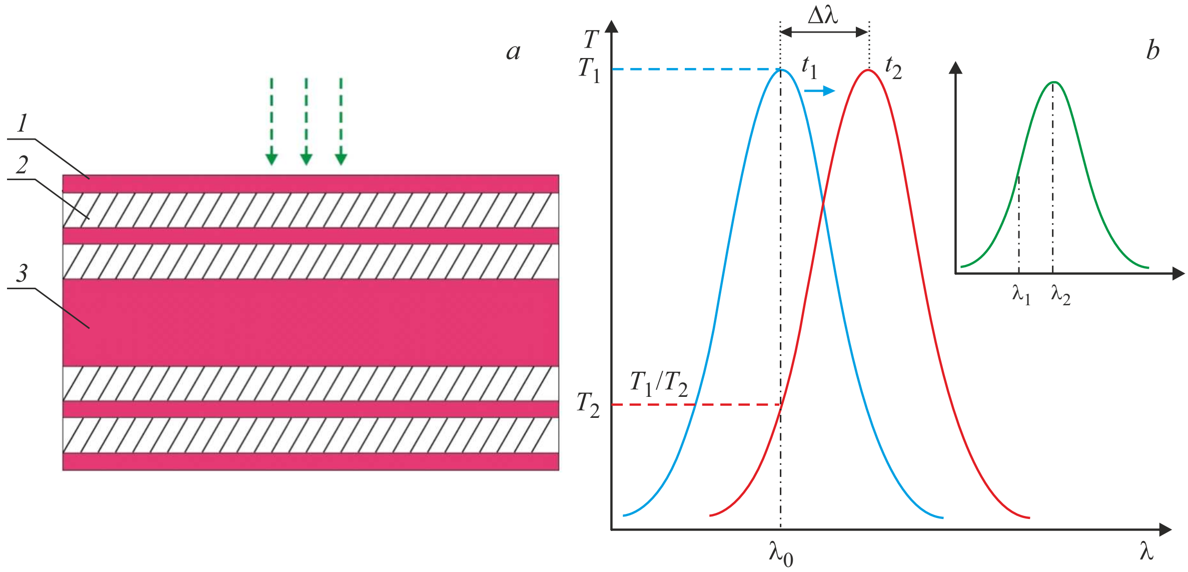

Figure 1. (*a*) Geometry of a 1*D*-photonic crystal with a defect. *1* — semiconductor, *2* — dielectric, *3* — defect (semiconductor); (*b*) methods of temperature measurement (explanations in the text).

Polycrystalline silicon ($n = 3.15$, $dn/dt = 1.6 \cdot 10^{-4}\,K^{-1}$) and germanium ($n = 3.9$, $dn/dt = 6 \cdot 10^{-4}\,K^{-1}$) were used as semiconductor layers forming a photonic crystal, polycrystalline silicon. In the first case, SiO_2 ($n = 1.46$) was used as the dielectric layer. When using germanium, which is transparent to $\lambda > 2\,\mu$m, CaF_2 ($n = 1.42$) was used, since SiO_2 already has noticeable absorption. In the numerical simulation the optical constants of the materials from [16,17] were used. The temperature coefficients of the refraction indices of the dielectric layers were not taken into account in the calculations. As can be seen from the above data, when these materials are used in a photonic crystal, a high contrast between the refraction indices of semiconductor and dielectric layers is provided. This allows to reduce the number of pairs of semiconductor-dielectric layers in a photonic crystal to 4 without damage to the optical characteristics of the photonic crystal. The vacuum deposition method can be used to construct semiconductor and dielectric layers. In this case the semiconductor wafer forming the defect will serve as a substrate.

Figure 1, *b* shows the methods of measuring temperature using this photonic crystal. Since the spectral shift of the defect bandpass occurs with a change in temperature, the value of this shift $\Delta\lambda$ can be determined to determine the temperature. For these purposes a spectrophotometer can be used. However, to increase the sensitivity and reduce the dimensions of the measuring part of the sensor, it is preferable to use narrow-band tunable DFB (Distributed Feedback) semiconductor lasers as radiation sources. In this case a photodiode can be used as a radiation receiver. The second method is to measure the change in the transmission at a fixed wavelength (the wavelength of the probing laser λ_0). However, in this case there is uncertainty in determining the sign of the temperature change. To eliminate this uncertainty two probing lasers with wavelengths slightly different from each other can be used (see the insert in the Fig. 1, *b*).

In numerical simulation, the transfer matrix method [18] was used for the normal incidence of radiation. In this method the field amplitudes at the input (E_1, H_1) and output (E_2, H_2) of the layers boundaries are generally described by the following matrices:

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -i\,\frac{\sin\alpha}{U} \\ -iU\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} E_2 \\ H_2 \end{bmatrix} = M_1 \begin{bmatrix} E_2 \\ H_2 \end{bmatrix},$$

$$U = n\sqrt{\varepsilon_0/\mu_0}\cos\theta.$$

Here n — layer refraction index, θ — angle of incidence (in our case $\theta = 0$), $\alpha = 2\pi/\lambda nd\cos\theta$ — phase delay, when the wave passes through the layer, d — layer thickness. The transfer matrix M of the entire multilayer structure with N layers is described as $M = M_1 \cdot M_2 \cdot M_3 \cdot M_{2N}$.

Results and discussion

Figure 2 shows a general view of the photonic band gap for a photonic crystal with a defect based on $Si{-}SiO_2$. The spectral band gap is $0.15\,\mu$m. The defect bandpass is located inside the band gap, and its width at half maximum is approximately equal to 0.1−0.2 nm. It should be noted, that since the thickness of the semiconductor layers significantly exceeds the operating wavelength, additional interference fringes, caused by interference inside these layers, appear on the spectrum outside the band gap. In the absence of absorption in the photonic crystal, the transmission coefficient at the maximum of the defect bandpass is 100%. On the reflection spectrum a minimum with a reflection coefficient equal to 0 will correspond to the a defect.

Figure 3 shows the effect of temperature change Δt on the spectral position of the defect bandpass for a photonic crystal on the basis of Si–SiO_2. The width of the defect bandpass at a half maximum in this case is equal to 0.1 nm. It can be seen from the figure, that as the temperature increases, the defect bandpass shifts spectrally toward longer wavelengths. The defect bandpass amplitude does not change in this case. The reason for its spectral shift is an increase in the refraction index of the semiconductor layers and the defect. After the defect bandpass reaches the long-wavelength edge of the photonic bandgap, a new defect bandpass appears on its opposite edge. This can lead to ambiguity in determining the temperature.

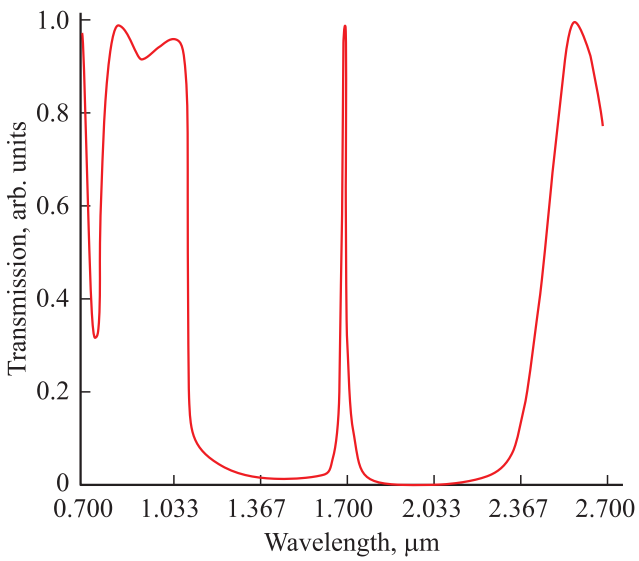

Figure 2. General view of the photonic band gap for the photonic crystal geometry shown in Fig. 1, *a*.

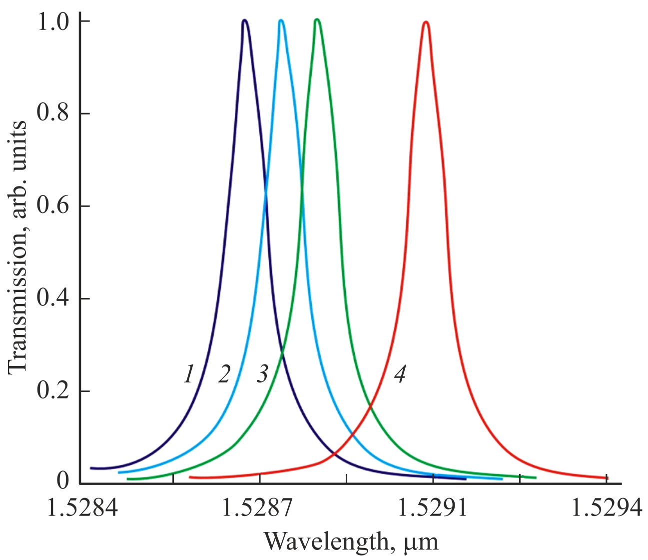

Figure 3. Effect of the temperature change Δt on the spectral position of the defect bandpass for a photonic crystal based on the basis of Si–SiO_2. Δt: *1* — 0°C, *2* — 1°C, *3* — 2°C, *4* — 5°C.

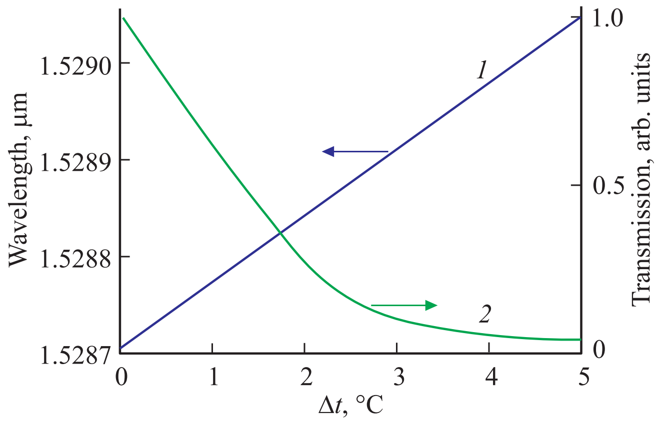

Figure 4. Effect of the temperature change on: *1* — spectral position of the defect bandpass maximum, *2* — transmission at a fixed wavelength. Photonic crystal based on Si–SiO_2.

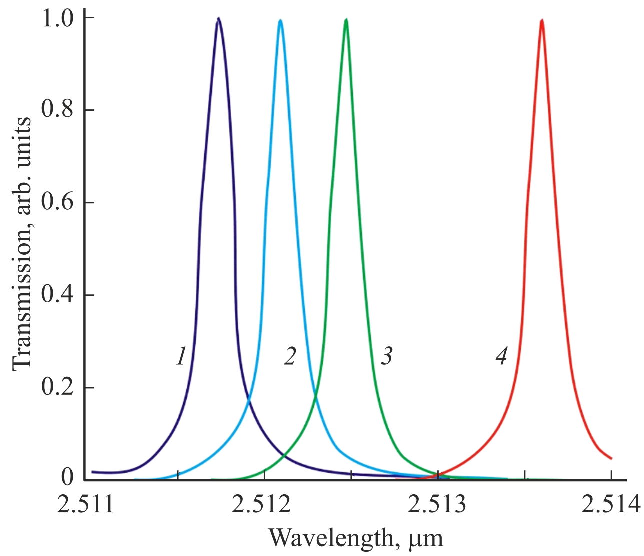

Figure 5. Effect of the temperature change Δt on the spectral position of the defect bandpass for a photonic crystal based on Ge–CaF_2. Δt: *1* — 0°C, *2* — 1°C, *3* — 2°C, *4* — 5°C.

The spectral shift of the defect bandpass for a photonic crystal based on Si–SiO_2 depends linearly on the temperature change (Fig. 4, curve *1*). The sensitivity to temperature change of such a photonic crystal is 0.07 nm/K, that exceeds the sensitivity of a number of temperature sensors based on photonic crystals, described in the literature (for example, [5,13]). Figure 4 (curve *2*) shows the dependence of transmission on the temperature at a fixed wavelength corresponding to the maximum transmission of the defect bandpass at $\Delta t = 0$. It can be seen from the figure, that at $\Delta t < 2.5$°C the dependence is close to linear. When the temperature changes by 2.5°C, the transmission coefficient of the photonic crystal at a fixed wavelength decreases by a factor of 5. This corresponds to the temperature sensitivity of 2.6 dB/K. This value significantly exceeds the sensitivity of a number of temperature sensors described in

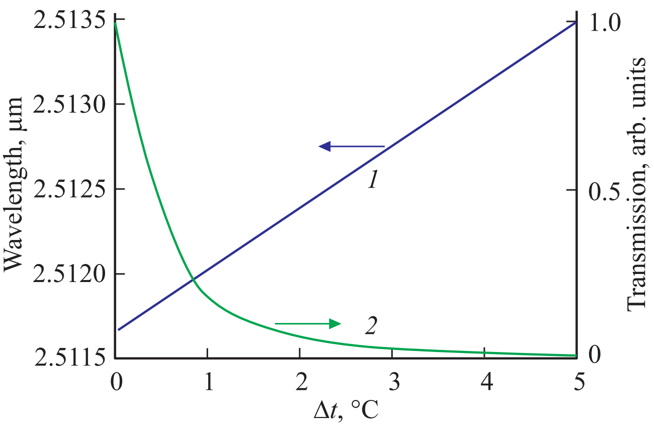

Figure 6. Effect of the temperature change on: *1* — spectral position of the defect bandpass maximum, *2* — transmission at a fixed wavelength. Photonic crystal based on Ge$-$CaF$_2$.

the literature (eg. [19]). Evidently, that using this method of temperature measurement, the temperature measurement range does not exceed 2.5°C. When two fixed wavelengths are used for measurements (see the insert in Fig. 1, *b*), the temperature measurement range increases by a factor of 2.

Figure 5 shows the effect of temperature change Δt on the spectral position of the defect bandpass for a photonic crystal based on Ge$-$CaF$_2$. The width of the defect bandpass at half maximum is 0.17 nm. As in the previous case, as the temperature increases, the defect bandpass shifts spectrally toward longer wavelengths. The defect bandpass amplitude does not change in this case.

The temperature dependence of the spectral shift of the defect bandpass for a photonic crystal based on Ge$-$CaF$_2$ is linear (Fig. 6, curve *1*). The temperature sensitivity of such a photonic crystal is 0.37 nm/K, that exceeds the sensitivity of a photonic crystal based on Si$-$SiO$_2$ by a factor of 5. The reason for this is the larger temperature coefficient of germanium compared to silicon. Figure 6 (curve *2*) shows the dependence of transmission on the temperature at a fixed wavelength corresponding to the maximum transmission of the defect bandpass at $\Delta t = 0$. It can be seen from the figure, that at $\Delta t < 1$°C the dependence is close to linear. When the temperature changes by 1°C, the transmission coefficient of a photonic crystal at a fixed wavelength decreases by a factor of 6. This corresponds to the temperature sensitivity of 7.8 dB/K, that exceeds the sensitivity of a photonic crystal based on Si$-$SiO$_2$ by a factor of 3. With this method of temperature measurement, the temperature measurement range does not exceed 1$-$2°C.

Conclusion

The numerical simulation has shown, that for a 1*D*-photonic crystal with a defect based on semi-conductor-dielectric layers the spectral position of the defect bandpass depends on the temperature. For the photonic crystal based on Si$-$SiO$_2$ the temperature sensitivity of the photonic crystal is 0.07 nm/K and 2.6 dB/K, depending on the measurement method. For a photonic crystal based on Ge$-$CaF$_2$ — 0.37 nm/K and 7.8 dB/K. This makes the described photonic crystals promising for use in the temperature sensors as a sensitive element. These photonic crystals with a defect can be used, for example, to maintain the temperature of chemical reactions in a narrow range. Temperature measurements can be made in both transmission and reflection measurement modes. The advantage of such a temperature sensor is that its sensitive element can be located separately and remotely from the measuring part of the sensor. For example, a photonic crystal can be located in a thermostated chamber equipped with windows for input and output of probing radiation.

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Conflict of interest

The authors declare that they have no conflict of interest.

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