Optical biosensor based on a photonic crystal with a defective layer designed to determine the concentration of SARS-CoV-2 in water

I M Efimov¹, N A Vanyushkin¹, A H Gevorgyan¹ and S S Golik¹,²
¹ School of Natural Sciences, Far Eastern Federal University, 10 Ajax Bay, Russky Island, 690922 Vladivostok, Russia
² Institute of Automation and Control Processes, Far East Branch, Russian Academy of Sciences, Vladivostok, 690041 Russia
E-mail: Efimov.im@dvfu.ru

Keywords: optical, biosensor, photonics, crystal, layer, defect

Abstract
We propose a new optical biosensor based on a SiO₂/Si photonic crystal with a defect layer, which can determine the concentration of SARS-CoV-2 in water by the defect mode shift. Two models of the dependence of the refractive index of the defect layer on the concentration of the pathogen in water were considered. The optimal parameters of the photonic crystal in our device were determined such as the thickness of the SiO₂ and Si layers of the ideal photonic crystal of 0.720 and 0.275 μm, respectively, and the optimal thickness of the defect layer of 1.87 μm was also determined. It was also demonstrated that in the presence of absorption in the structure under study, it is much more advantageous to operate in the reflection mode compared to the transmission mode. Finally, the wavelength dependence of the defect mode on the SARS-CoV-2 concentration was obtained and the sensitivity of the sensor was determined to be 1020 nm/RIU.

1. Introduction

Pathogens are various microorganisms, such as viruses and bacteria, which can cause damage to the host organism. Throughout history, pathogens have accompanied humanity and the emergence of new species of infectious pathogens has caused various epidemics [1–3]. Many scientists of the last century saw antibiotics as a solution to the problem, but antibiotic-resistant pathogens, which significantly complicate treatment and recovery of patients, are also a real threat. The next step in solving this problem is the timely detection and isolation of pathogen vectors.

The rapid development of genetics and biochemistry has led to the expansion of various medical and biomedical tools to detect various pathogens with great accuracy. There are now many methods for detecting pathogens, including SARS-CoV-2. The best known and most used identification procedure is based on real-time reverse transcription polymerase chain reaction (RT-PCR) [4]. However, this diagnosis requires advanced laboratory testing, expensive equipment, and experienced personnel. Therefore, it is necessary to simultaneously simplify and automate the process of pathogen detection. Nowadays, various optical biosensors are being actively developed, because they are highly sensitive to changes in pathogen concentration, can operate in different modes, such as transmittance, reflection and absorption of light.

Currently, there are many types of optical biosensors. They include biosensors based on plasmon resonance spectroscopy [4]. Plasmons are collective fluctuations in the charge density of a free electron gas. The simplest system in which surface plasmons can be excited is a metal-dielectric boundary [4–15]. There are also biosensors based on the Raman effect, inelastic scattering of optical radiation on molecules of matter, accompanied by a significant change in the frequency of radiation. The number and location of lines appearing is determined by molecular structure of the substance [15–18]. Another type is fluorescence-based biosensors [7]. Their mechanism can be based on fluorescence quenching, fluorescence amplification or resonance fluorescence energy transfer.

In recent years, biosensors based on photonic crystals (PCs), including those with a defect in the structure, have been of great interest [18–24]. PC is a periodic structure of layers with different refractive index. PCs have a
unique property of having a certain range of frequencies, called a photonic bandgap (PBG), in which electromagnetic waves cannot propagate through the PC [25]. In practice, this means that if radiation with a wavelength inside the PBG is incident on the PC, it experiences strong reflections from the PC. Thus, the PC can act as a mirror or an optical filter. If a defective layer is added to the periodic structure of the PC, the periodicity of the structure is violated, which leads to changes in the transmission and reflection spectra in the entire region. This manifests itself in the appearance of a narrow transmission band inside the PBG, which is called a defect mode (DM). The position and shape of the DM depends on the parameters of the defect layer, such as the thickness and refractive index of the defect layer. It is this property that underlies our biosensor. In this work, the defect layer is composed of water with the addition of SARS-CoV-2. Changing the concentration of the pathogen leads to a change in the refractive index of the defect layer, which in turn shifts the position of the DM, which can be detected by the sensor. As a result, the SARS-CoV-2 concentration in the defect layer is determined by this wavelength shift.

2. The theory

The transverse structure of the PC we are considering is shown in figure 1.

- $E_R$ – Reflected wave; $N$ – Number of unit cells;
- $E_0$ – Incident wave; $\theta_0$ – Angle of incidence;
- $E_T$ – Transmitted wave; $DL$ – Defect Layer.

Our structure consists of a defective layer sandwiched between two perfect PCs, each of which consists of $N$ periodic cells. Each cell is a pair of layers with thickness $h_{1,2}$ and refractive index $n_{1,2}$. The refractive indices were determined by the materials of the layers. To select suitable materials that can be used as cell layers, the following conditions were set: the materials should provide a high difference between the refractive indices of the $n_1$ and $n_2$ layers, be relatively inexpensive and easy to manufacture, and transparent in the spectral range of interest. The thicknesses of the layers were determined from the quarter-wave criterion

$$\text{Re} \left[ n_1(\lambda_0) \right] h_1 = \text{Re} \left[ n_2(\lambda_0) \right] h_2 = \lambda_0/4,$$

where $\lambda_0$ is the center wavelength of PBG. When this condition is met, we get the maximum width of PBG.

Next, let us consider the defect layer. The defect layer is a medium of host material with particle inclusions. In our case the host material is water, and the inclusions are SARS-CoV-2 pathogens. Two models were used to determine the refractive index of the defect layer through the parameters of the constituent substances: the Maxwell-Garnett effective medium approximation (EMA) and the simple proportional dependence of the dielectric permittivity. EMA refers to analytical or theoretical medium modeling that describes the macroscopic properties of composite materials [26, 27]. This method is applicable if the macroscopic system is homogeneous, and the sizes of all particles are much smaller than the wavelength. The calculation of the dielectric permittivity of the composite by EMA is represented by the equation:

$$\varepsilon_m = \varepsilon_M + 2\gamma \left( \varepsilon_i - \varepsilon_M \right) \frac{\varepsilon_i + 2\varepsilon_M}{4\varepsilon_M + \varepsilon_i - \delta_i(\varepsilon_i - \varepsilon_M)},$$

where $\varepsilon_m$ is effective permittivity of the composite, $\varepsilon_i$ is dielectric constant of inclusions, $\varepsilon_M$ are dielectric constants of the inclusions and the host material, respectively, $\delta_i$ is volume fraction of the inclusions.

Figure 1. Schematic diagram of the analyzed structure.
The proportional dependence is based on the assumption that the dielectric permittivity depends linearly on the volume fractions of the host material and inclusions. The dependence is represented by the equation:

\[
\varepsilon_m = \varepsilon_M (1 - \delta_l) + \varepsilon_i \delta_i,
\]

In this paper we used the transfer-matrix method \[28–30\] to calculate the transmission and reflection spectra of the structure under study. The transfer matrix for the j-th layer in the structure can be written as:

\[
M_j = \begin{pmatrix} \cos k_j h_j & -i \frac{p_j}{p_j} \sin k_j h_j \\ -ip_j \sin k_j h_j & \cos k_j h_j \end{pmatrix},
\]

where \(k_j = \frac{2\pi}{\lambda} n_j \cos \theta_j\), \(\theta_j\) is the angle of refraction in the j-th layer, which is determined from Snell’s law as:

\[
\theta_j = \cos^{-1}\left(1 - \frac{n_0^2 \sin^2 \theta_0}{n_j^2}\right),
\]

\(p_j = n_j \cos \theta_j\), \(n_0\) is the refractive index of the external medium to the left of the PC, \(\theta_0\) is angle of incidence.

After that, the matrix \(M\) of one unit cell in the periodic part of the structure is obtained by multiplying the transfer matrices \(M_j\) of the layers in the cell:

\[
M = M_2 M_1,
\]

Since \(M\) is unimodular (\(\det M = 1\)), the power matrix \(M^N\), for \(N\) period structure, can be written from Chebyshev polynomials \[28, 29\] as:

\[
M^N = \left(\begin{array}{cc} U_N(X) - U_{N-2}(X) & M_{12} U_{N-1}(X) \\ M_{21} U_{N-1}(X) & M_{22} U_{N-1}(X) - U_{N-2}(X) \end{array}\right),
\]

\(U_N\) denotes Chebyshev polynomials of the second kind and they are given by:

\[
U_N(X) = \frac{\sin[(N + 1) \cos^{-1}X]}{\sqrt{1 - X^2}}, \quad X = \frac{1}{2}(M_{11} + M_{22})
\]

Finally, the transfer matrix of the whole structure has the following form:

\[
m = M^N M_d M^N = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix},
\]

where \(M_d\) is transfer matrix of the defective layer.

Carrying out some mathematics then the transmission and reflection coefficients are given as:

\[
t = \frac{2p_0}{(m_{11} + p_j m_{12})p_0 + (m_{21} + p_j m_{22})},
\]

\[
r = \frac{(m_{11} + p_j m_{12})p_0 - (m_{21} + p_j m_{22})}{(m_{11} + p_j m_{12})p_0 + (m_{21} + p_j m_{22})},
\]

Energy transmission and reflection coefficients:

\[
T = \frac{p_f}{p_0} |t|^2,
\]

\[
R = |r|^2,
\]

where indices 0 and f, \(f\) is indices denote the parameters of the environment bordering the PC on the left and on the right, respectively.

3. The results and discussion

In our work, silicon oxide (SiO\(_2\)) (first layer) and silicon (Si) (second layer) layers were used as materials for the PC unit cell. The dielectric permittivity of Si\[31\] and SiO\(_2\) \[31\] as a function of wavelength is shown in figure 2.

In the following, we considered the case of normal incidence (\(\theta_0 = 0\)) and each perfect PC in our structure had \(N = 8\) unit cells. The external environment is vacuum (\(n_0 = n_f = 0\)).

Now let us consider the defect layer. The dielectric permittivity of the matrix \[32\] and the inclusions \[33, 34\] is shown in figure 3.

Figure 4(a) shows the difference in the permittivity of the defect layer components

\[
\Re(\Delta \varepsilon) = \Re(\varepsilon_{\text{Coral}}) - \Re(\varepsilon_{\text{H,O}}),
\]

and figure 4(b) shows the sum of the imaginary parts of the refractive indices of all materials of our structure

\[
\Im(\sum \varepsilon) = \Im(\varepsilon_{\text{Coral}}) + \Im(\varepsilon_{\text{H,O}}) + \Im(\varepsilon_{\text{SiO}_2}) + \Im(\varepsilon_{\text{Si}}).
\]
Obviously, the higher the difference in the refractive indexes of the defect layer components, the higher the sensitivity to changes in the pathogen concentration, but at the same time, as it will be shown below, high imaginary component values of all materials reduce the DM amplitude. Therefore, we were faced with the choice of which spectral range to work in. In the 10–15 μm range, the defect layer components have a high refractive index contrast, but all materials except Si strongly absorb radiation. On the other hand, in the 5–8 μm range, the situation is the opposite.

As noted above, models (1), (2) were used to determine the refractive index of the defective layer. Figure 5 shows the dependences of the real and imaginary components of the refractive index as a function of the pathogen concentration at wavelength λ = 5 μm, calculated using EMA.
Figure 6 shows the difference between the refractive indices calculated by the EMA method and the proportional relationship at different wavelengths, \( \Delta n = \text{Re}((n_{EMA} - n_P) / n_{EMA}) \).

As can be seen from figure 6, the maximum difference between the obtained refractive indexes at different concentrations is achieved at equal concentrations of the pathogen and water \([27]\). It is also worth noting that at extremely high and extremely low concentrations, the values of the refractive index of the defect layer are practically the same. For this reason, the simpler proportional model can be used in practice as the concentration of covid is expected to be low under real conditions. Nevertheless, further in our work we will use the EMA method because it is more precise at all concentrations.

At the beginning of our study, we considered the wavelength range from 5 \( \mu m \) to 15 \( \mu m \) in which the optical properties of SARS-CoV-2 are known \([33, 34]\). Figure 7 shows a series of R and T spectra at different PBG positions without pathogen particles in the defect layer. Spectra series a, b shows the negative influence of high SiO\(_2\) absorption, spectra series c, d shows the negative influence of H\(_2\)O absorption, and series e, f shows the variant with minimal negative influences.

Further in our study, we considered the range from 5 \( \mu m \) to 7.5 \( \mu m \). This range was chosen because the minima of \( \text{Im}(n) \) of all components of the structure, which is responsible for absorption and reduces the amplitude of the DM, are observed in this range. This effect can be seen in figure 7. The main contribution to absorption at the selected wavelengths is made by water, so it is optimal to choose the operating wavelength near a water absorption minimum. We chose the water absorption minimum near 5.3 \( \mu m \). When comparing a series of spectra with and without a defective layer, it can be observed that when a defective layer is added, not only DM appears, but also the splitting of the edge modes outside the PBG occurs (see also \([35]\)). In figures 7(a) and (c) a deep reflection minimum can be observed at 9.3 \( \mu m \) (shown by blue dash arrow). This minimum is due to high

---

**Figure 5.** Dependences of the refractive index of the defect on SARS-CoV-2 volume fraction, at a wavelength of \( \lambda = 5 \mu m \), (a) Real part, (b) Imaginary part.

**Figure 6.** Difference in calculated values of the defect’s real part of refractive index between EMA and the proportional dependence.
absorption by SiO₂ (see figure 2(b)). Figure 8 compares the R spectra in the case shown in figure 7(e) with and without the defective layer in the vicinity of the left PBG boundary.

It is also worth noting the appearance of a slight shift of the PBG boundary. In the case of adding a defective layer δ₁ = 0.15 μm, the left boundary of the PBG has experienced a blue shift by the value of Δλ = 0.06 μm.

To view the full picture of the influence of the defect layer thickness on the DM, the reflection and transmittance spectra of our structure depending on the thickness of the defect layer were plotted in figure 9. For clarity, the reflection spectrum was depicted as 1 − R, which is equivalent to the sum of transmission and absorption T + A.

The arrows indicate the first DM, which has the highest sensitivity. As can be seen, the DM appears stronger at the boundaries of the PBG, especially at the longwave one, while in the center of the PBG the influence of the defect is practically not observed. This can be explained by the strong influence of absorption in the structure on the amplitude of the defect mode near the center of the PBG. One can also note the higher amplitude of DM on the reflection spectrum. The sensitivity of the DM to changes in the optical thickness of the defect δ₃ = δ₄ is maximum at the center of the PBG (see the slope of the curve showing the mode position in figure 9), but as we approach the center of the PBG the amplitude of the DM, as noted above, drops, so we sought a compromise...
Figure 8. Reflection spectra near the left PBG boundary at different thicknesses of the defect layer: (a) \(h_d = 0.15 \mu m\); (b) \(h_d = 0 \mu m\).
The other parameters: \(h_1 = 1.30 \mu m\), \(h_2 = 0.49 \mu m\), \(\delta_i = 0\).

Figure 9. Transmittance (a) and reflectance (b) spectra with varying thickness of the defect layer, \(h_1 = 0.700 \mu m\), \(h_2 = 0.268 \mu m\), \(\delta_i = 0\).
between sensitivity and amplitude. Based on figure 9, only the reflection spectra will be considered, due to higher amplitude of DM.

Based on the reasoning above, let us consider the case near the water absorption minimum at wavelength $\lambda = 5.30 \, \mu m$. As it was shown earlier, approaching the center of the PBG increases the sensitivity, so we tried to achieve the highest sensitivity while maintaining the minimum DM amplitude at the level of at least 0.1 [36]. Figure 10 shows a series of reflection spectra with different defect layer parameters.

Let us consider each case in detail. In figures 10(a) and (c), the DM is close to the left and right boundaries of the PBG, respectively, and has a sufficient amplitude, so these options will be considered further. In figure 10(b), the DM is in the center of the PBG, and the DM does not have high enough amplitude, so this option will not be considered further. The DM amplitudes in figures 10(a) and (c) are almost identical. Let us consider the selected spectra when the concentration of inclusions in the defect layer changes. Figure 11 shows the dependences of the spectra $R$ on the volume fraction $\delta$ of SARS-CoV-2 in the range from pure water ($\delta = 0$) to pure SARS-CoV-2 ($\delta = 1$) with a step of the change in the volume fraction of 0.2.

In the spectra under consideration, as expected, there is a shift in the DM when the concentration of SARS-CoV-2 changes. In the two selected cases, the shift occurs to longer wavelengths. It is worth noting that the DM near the left edge mode of the PBG is shifted only slightly when the concentration changes, while the DM near the right edge mode of the PBG is shifted much more strongly. Another interesting fact is that the DM amplitude should increase with increasing SARS-CoV-2 concentration, as in figure 11(a), but we do not observe this effect in figure 11(b). As the pathogen concentration increases, the imaginary part of the refractive index of the defect layer decreases because the imaginary part of the SARS-CoV-2 refractive index is smaller than that of water in the selected wavelength range. On the other hand, the DM amplitude decreases as one approaches the center of the PBG. Apparently, in figure 11(b), the two described effects compensate each other, while in figure 11(a), on the

Figure 10. Reflectance spectra with defect layer with the following parameters: (a) $h_0 = 0.28 \, \mu m$, $\delta_1 = 0$, $h_1 = 1.26 \, \mu m$, $h_2 = 0.48 \, \mu m$; (b) $h_0 = 0.90 \, \mu m$, $\delta_1 = 0$, $h_1 = 1.00 \, \mu m$, $h_2 = 0.20 \, \mu m$; (c) $h_0 = 1.80 \, \mu m$, $\delta_1 = 0$, $h_1 = 0.72 \, \mu m$, $h_2 = 0.275 \, \mu m$. In all cases $\lambda_{DM} = 5.30 \, \mu m$. DMs are marked by black arrows.
contrary, the two effects are summed up, since in the two cases the direction of shift of the DM relative to the center of the PBG is different.

Let us consider the case with lower absorption; for this purpose, we will shift to the shortwave region, where the imaginary component of the refractive index of all components of our structure is close to 0. However, these spectra will be considered under the assumption that there are no SARS-CoV-2 absorption peaks in the chosen region. The reflection spectra at wavelengths $\lambda = 1 \mu m$ and $\lambda = 2 \mu m$ were considered. Figure 12 shows a series of R spectra with a concentration step 0.2.

Let us now consider the sensitivity of the DM. The characteristics of the obtained structures are shown in figure 13 and table 1.

Having analyzed the obtained data, we can come to the following conclusions:

1. The figures 11–12 show that the DM in the shortwave region has a narrow width and high Q-factor, which allows detecting even the smallest change in the concentration of pathogens, Q-factor was calculated according to the formula $Q = \frac{\lambda_{\text{res}}}{\Delta \lambda}$, where $\Delta \lambda$ is full width at half maximum (FWHM);

2. From the series of figure 13, we can see that the dependence of the DM displacement when the concentration changes is linear at different wavelengths;

3. Comparing the results a and b, we can confirm that the sensitivity of the DM near the right PBG boundary is higher than near the left boundary;

4. Considering the sensitivity of cases b, c, d the assumption was confirmed that the sensitivity, relative to the wavelength of the DM, is higher in the short-wavelength region than in the long-wavelength region, presumably due to the fact that in the long-wavelength region we cannot get as close to the center of the PBG as in the short-wavelength region without losing the DM amplitude.

In addition, we have considered the influence of error in values of the structural parameters on the performance of the sensor in the case a. It is important to consider this issue because these errors are unavoidable.
during the manufacturing process. When considering small deviation allowances of ±1%, it is worth noting the following point. The DM is mainly sensitive to changes in the defective layer parameters, so we considered the case where errors occur exactly in the defective layer.

Three cases were considered: the thicknesses of the defect layer were 1.85, 1.87, 1.89 μm, the resonance peaks at \( \delta = 0 \) were 5.285, 5.293, 5.302 μm, respectively, with the same parameters of the ideal PC. The sensitivity \( S_1 \) of the sensors was determined to be as follows: 1017.98, 1020.00, 1023.12 nm/RIU respectively. In case of real measurements, it is necessary to calibrate the device by pure water, so the deviations in structural parameters will only result in a sensitivity change.

In this work we considered the case when the system contains only water and SARS-CoV-2. It implies the absence of any other impurities which, for instance, can be identified by some other method. However, we can suggest that the selectivity for SARS-CoV-2 can be achieved, for example, by increase in the number of defect modes monitored simultaneously at different wavelengths. By doing this we can differentiate substances which have different refractive index spectra.

According to the results of the work, it was found that to increase the sensitivity of the sensor it is necessary to reduce the imaginary component of the refractive index, so it is recommended to move to the visible region, where the imaginary component of the refractive index of water is close to zero, but one needs to know the optical parameters of SARS-CoV-2 in the visible region to do this.

![Figure 13. Dependence of the defect mode peak on the pathogen volume fraction: (a) \( h_3 = 0.22 \) μm, \( h_1 = 1.26 \) μm, \( h_2 = 0.48 \) μm; (b) \( h_3 = 1.87 \) μm, \( h_1 = 0.72 \) μm, \( h_2 = 0.275 \) μm; (c) \( h_3 = 0.29 \) μm, \( h_1 = 0.14 \) μm, \( h_2 = 0.06 \) μm; (d) \( h_3 = 0.63 \) μm, \( h_1 = 0.275 \) μm, \( h_2 = 0.103 \) μm.]

**Table 1. Comparative characteristics of sensor sensitivity at different parameters.**

| № | \( \lambda_{DM} \) at \( \delta = 0 \), μm | \( S_1 \), nm/RIU | \( S_2 \), nm% | \( \frac{S_1}{\lambda_{DM}} \), RIU | \( \frac{S_2}{\lambda_{DM}} \), 10^{-3} nm% | Q factor, \( \delta = 0 \) | Q factor, \( \delta = 1 \) |
|---|---|---|---|---|---|---|---|
| a | 5.293 | 1020 | 1.14 | 0.193 | 0.21 | 300 | 594 |
| b | 5.295 | 80 | 0.15 | 0.015 | 0.03 | 962 | 1206 |
| c | 1.004 | 347 | 0.36 | 0.345 | 0.35 | 2004 | 2081 |
| d | 2.026 | 710 | 0.80 | 0.350 | 0.39 | 1864 | 1981 |
4. Conclusions

In conclusion, we have considered an optical biosensor capable of determining the concentration of the SARS-CoV-2 pathogen in water. Transmission and reflection spectra at different parameters of the unit cells and the defect layer were considered. It was found that the imaginary part of the refractive index negatively affects the amplitude of the defect mode.

The optimal spectral region near the water absorption minimum at 5.3 μm was found. The considered structure has the cell parameters for the perfect PC $h_1 = 0.720 \ \mu m$, $h_2 = 0.275 \ \mu m$ and has optimal thickness of defect layer $h_d = 1.87 \ \mu m$. In this case a compromise between the amplitude of DM and the sensitivity is achieved. The sensitivity of this sensor was determined to be 1.14 nm/% and 1020 nm/RIU.

A higher amplitude of the defect mode was observed in the spectrum of reflection compared to transmission. Spectra with different concentrations of SARS-CoV-2 were analyzed and wavelength dependences of the defective mode peak on pathogen concentration were obtained. Two methods of determining the refractive index of the defective mode, the proportion method and the EMA method, were compared, and no serious difference in the results obtained by the two methods was observed.

Acknowledgments

The work was supported by the Foundation for the Advancement of Theoretical Physics and Mathematics ‘BASIS’ (Grant № 21-1-1-6-1).

Data availability statement

No new data were created or analysed in this study.

Conflict of interest

No potential conflict of interest was reported by the authors.

ORCID iDs

IM Efimov https://orcid.org/0000-0001-6793-704X
N A Vanyushkin https://orcid.org/0000-0003-2338-680X
A H Gevorgyan https://orcid.org/0000-0002-0438-0069

References

[1] Li G et al 2020 J. Med. Virol. 92 424–32
[2] Khadke S et al 2020 J. Virology 17 154
[3] Thomas R 2007 Development of a Novel Based s. Cerevisiae Biosensor (Aberdeen: ProQuest)
[4] Calvo-Lozano O et al 2022 Anal. Chem 94 975–84
[5] Bouaana F and Labbani A 2021 J. Electromagnetics 117 239–49
[6] Hosseini E et al 2022 Plasmonics 17 639–46
[7] Aghaie A et al 2021 Appl. Phys. Rev. 8 031313
[8] Rende M et al 2021 J. Opt. Let. 46 4658–61
[9] Shiveshwari L and Awashti S 2015 Phys. Plasmas 22 092129
[10] Qi L and Zhang X 2011 J. Electromagn. Waves Appl. 25 539–52
[11] Cathy M et al 2015 J. Lab Chip. 3 711–7
[12] Akhilesh K et al 2021 J. Sensors. 21 22631–7
[13] Akhilesh K et al 2020 Phot. Tech. Let. 32 465–8
[14] Nunzio C et al 2021 MDPI Sensors. 21 1681
[15] Muhammad U and Menal K 2022 MDPI Sensors. 22 751
[16] Kneipp J 2017 J. ACS Nano. 11 1136–41
[17] Singh S et al 2021 J. PNAS 118 e2021339118
[18] Monkawa A et al 2021 Research Square 1
[19] Henriquez L, Acuna M and Rojas A 2020 Sensors 20 6926
[20] Samson R, Navale R and Dharne S 2020 Biotech 10 385
[21] Chaves F et al 2021 Optik 242 167161
[22] Taya A, Daher G and Colak I 2021 J Mater Sci: Mater Electron 32 28406–16
[23] Joannopoulos J D 1995 Photonic Crystals: Molding the Flow of Light (Princeton: Princeton Univ. Press) 305
[24] Shkondin E et al 2017 Opt. Mater. Express 7 1606–27
[25] Tinga W, Voss W and Blossey D 1973 J. Appl. Phys. 44 3897
[26] Markel V 2016 J. Opt. Soc. Am. 33 1244–56
[27] Bordo V.G. 2021 Theory of light reflection and transmission by a plasmonic nanocomposite slab: emergence of broadband perfect absorption arXiv:2101.09681
[28] Yeh P 1988 Optical Waves in Layered Media (New York, NY: Wiley)
[29] Yariv A and Yeh P 1984 Optical Waves in Crystals (New York, NY: Wiley)
[30] Vanyushkin N, Gervorgyan A H and Golik S S 2022 Scattering of a plane wave by an inhomogeneous 1D dielectric layer with gradient refractive index arXiv:2201.00557
[31] Kischkat J and Gruska B 2012 Appl. Opt. 51 6789–98
[32] Hale G M and Querry M R 1973 Appl. Opt. 12 555–63
[33] Li D et al 2021 J. Anal. Chem. 93 9437–44
[34] Valerio G et al 2021 J. Anal. Chem. 93 2950–8
[35] Belyakov V 2019 Diffraction Optics of Complex-Structured Periodic Media 2nd (Berlin: Springer)
[36] Domon B and Aebersold R 2006 Science 312 212–7