HIGH SELECTIVE ABSORPTION BY A PLANAR MULTILAYER STRUCTURE WITH TWO LOW ABSORBING MATERIALS IN THE CORE

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The necessary conditions are established for the thicknesses of two layers of the planar absorbing structure at which zero reflectance can be achieved. Using these conditions, a numerical procedure was developed for finding the thicknesses of three layers of the structure, which makes it possible to achieve close to zero values of the reflectance and transmittance for the chosen wavelength. This made it possible to propose a method for designing narrow-band absorbers based on such structures.

Key words: absorber, zero reflectance, selective absorption, multilayer structure.

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I. INTRODUCTION

Most of the developed design methods for narrow- and broadband absorbers are based on the use of metamaterials [1–6] or planar multilayer structures [7–11]. Such absorbers are widely used as sensors, photodetectors, filters, solar collectors, etc. A large number of narrowband and ultra-narrowband absorbers have been designed using metamaterials. A limitation of this type of absorbers is their impracticality for many large-scale optical and optoelectronic devices [7].

In this paper, we have proposed a method for designing narrow-band absorbers based on plane-parallel structures. A feature of this method is the use of only two low absorbing materials for such an absorber. To ensure selective absorption, we used a method of varying the thickness of several layers of the structure such as an interference mirror. This approach was previously successfully used to design narrow-band filters based on two transparent [12,13] or low absorbing materials [14]. A feature of all these methods is the use of analytical conditions for zero reflectance. Such conditions were previously obtained for structures based on transparent materials [15–17] and structures based on low absorbing materials [14].

II. NECESSARY CONDITIONS FOR ZERO REFLECTANCE

It is known that at normal incidence, the amplitude reflectance for the k-layer structure bounded by semi-infinite media with refractive indices of n_0 and n_{k+1} (Fig. 1) can be written as [18]

$$\tilde{r}_{0,k+1} = \frac{\tilde{r}_{0,s} + \tilde{r}_{s,k+1}\tilde{h}_{0,s}e^{-2i\tilde{\delta}_s}}{1 - \tilde{r}_{s,0}\tilde{r}_{s,k+1}e^{-2i\tilde{\delta}_s}}. \quad (1)$$

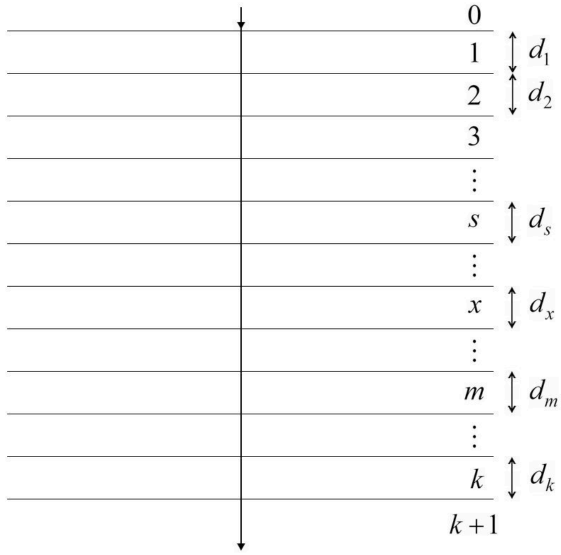

Fig. 1. Parameters of the multilayer structure $0, 1, 2, \ldots, k+1$

Here, $\tilde{r}_{s,k+1} = \frac{\tilde{r}_{s,m}+\tilde{r}_{m,k+1}\tilde{h}_{s,m}e^{-2i\tilde{\delta}_m}}{1-\tilde{r}_{m,s}\tilde{r}_{m,k+1}e^{-2i\tilde{\delta}_m}}$; s, m are the numbers of two arbitrary layers ($s < m$) whose thicknesses d_s and d_m are to be determined; $\tilde{\delta}_j$ is the phase thickness of the layer j ($j = 1, 2, \ldots, k$); the complex value $\tilde{h}_{j,p}$ is defined as: $\tilde{h}_{j,p} = \chi_{j,p}e^{i\gamma_{j,p}} = \tilde{t}_{j,p}\tilde{t}_{p,j} - \tilde{r}_{j,p}\tilde{r}_{p,j}$; $\tilde{r}_{j,p} = \sigma_{j,p}e^{i\phi_{j,p}}$, $\tilde{t}_{j,p} = \tau_{j,p}e^{i\theta_{j,p}}$ are amplitude reflectance and transmittance of the part of the structure $j, j+1, \ldots, p-1, p$, when $p > j$, or $j, j-1, \ldots, p+1, p$, when $p < j$; $\chi_{j,p}$, $\sigma_{j,p}$, $\tau_{j,p}$ and $\gamma_{j,p}$, $\phi_{j,p}$, $\theta_{j,p}$ are, respectively, moduli and phases of the next complex quantities: $\tilde{h}_{j,p}$, $\tilde{r}_{j,p}$ and $\tilde{t}_{j,p}$. Complex amplitude reflectance $\tilde{r}_{j,p}$ and transmittance $\tilde{t}_{j,p}$ are determined according to the formulae:

$$\tilde{r}_{j,p} = \frac{\tilde{n}_j - \tilde{n}_p}{\tilde{n}_j + \tilde{n}_p}, \qquad \tilde{t}_{j,p} = \frac{2\tilde{n}_j}{\tilde{n}_j + \tilde{n}_p}$$

if $|j-p|=1$, or using recurrence relations

$$\tilde{r}_{j,p}=\frac{\tilde{r}_{j,j\pm1}+\tilde{r}_{j\pm1,p}\exp(-i2\tilde{\delta}_{j\pm1})}{1+\tilde{r}_{j,j\pm1}\tilde{r}_{j\pm1,p}\exp(-i2\tilde{\delta}_{j\pm1})},$$

$$\tilde{t}_{j,p}=\frac{\tilde{t}_{j,j\pm1}\tilde{t}_{j\pm1,p}\exp\left(-i\tilde{\delta}_{j\pm1}\right)}{1+\tilde{r}_{j,j\pm1}\tilde{r}_{j\pm1,p}\exp(-i2\tilde{\delta}_{j\pm1})}$$

if $|j-p|>1$. Here $+$ in the $\pm$ and $-$ in the $\mp$ refers to the condition $p>j+1$, and $-$ in the $\pm$ and $+$ in the $\mp$ refers to the condition $j>p+1$. The values $\tilde{r}_{j,p}$ and $\tilde{t}_{j,p}$ can also be calculated using the matrix method [19, 16]. Phase thicknesses of layers s and m are:

$$\tilde{\delta}_s=\frac{2\pi d_s\tilde{n}_s}{\lambda},\qquad \tilde{\delta}_m=\frac{2\pi d_m\tilde{n}_m}{\lambda},\tag{2}$$

where d_j is the thickness of layer j and $\tilde{n}_j=n_j-i\kappa_j$ $(j=1,2,\ldots,k)$ is its complex refractive index.

Based on (1), the condition of zero reflectance $(\tilde{r}_{0,k+1}=0)$ for structure $0,1,\ldots,k,k+1$ is

$$\tilde{r}_{0,s}+\tilde{r}_{s,k+1}\tilde{h}_{0,s}e^{-2i\tilde{\delta}_s}=0$$

or

$$\tilde{r}_{0,s}+\frac{\tilde{r}_{s,m}+\tilde{r}_{m,k+1}\tilde{h}_{s,m}e^{-2i\tilde{\delta}_m}}{1-\tilde{r}_{m,s}\tilde{r}_{m,k+1}e^{-2i\tilde{\delta}_m}}\tilde{h}_{0,s}e^{-2i\tilde{\delta}_s}=0,\tag{3}$$

If equation (1) is rewritten as

$$\tilde{r}_{0,k+1}=\frac{\tilde{r}_{0,m}+\tilde{r}_{m,k+1}\tilde{h}_{0,m}e^{-2i\tilde{\delta}_m}}{1-\tilde{r}_{m,0}\tilde{r}_{m,k+1}e^{-2i\tilde{\delta}_m}},$$

where

$$\tilde{h}_{0,m}=\tilde{t}_{0,m}\tilde{t}_{m,0}-\tilde{r}_{0,m}\tilde{r}_{m,0},$$

$$\tilde{t}_{0,m}=\frac{\tilde{t}_{0,s}\tilde{t}_{s,m}e^{-i\tilde{\delta}_s}}{1-\tilde{r}_{s,0}\tilde{r}_{s,m}e^{-2i\tilde{\delta}_s}},\qquad \tilde{t}_{m,0}=\frac{\tilde{t}_{m,s}\tilde{t}_{s,0}e^{-i\tilde{\delta}_s}}{1-\tilde{r}_{s,m}\tilde{r}_{s,0}e^{-2i\tilde{\delta}_s}},$$

$$\tilde{r}_{0,m}=\frac{\tilde{r}_{0,s}+\tilde{r}_{s,m}\tilde{h}_{0,s}e^{-2i\tilde{\delta}_s}}{1-\tilde{r}_{s,0}\tilde{r}_{s,m}e^{-2i\tilde{\delta}_s}},\qquad \tilde{r}_{m,0}=\frac{\tilde{r}_{m,s}+\tilde{r}_{s,0}\tilde{h}_{m,s}e^{-2i\tilde{\delta}_s}}{1-\tilde{r}_{s,m}\tilde{r}_{s,0}e^{-2i\tilde{\delta}_s}},$$

then the condition of zero reflectance $(\tilde{r}_{0,k+1}=0)$ for the structure $0,1,\ldots,k,k+1$ is

$$\tilde{r}_{0,m}+\tilde{r}_{m,k+1}\tilde{h}_{0,m}e^{-2i\tilde{\delta}_m}=0$$

or

$$\begin{aligned}\frac{\tilde{r}_{0,s}+\tilde{r}_{s,m}\tilde{h}_{0,s}e^{-2i\tilde{\delta}_s}}{1-\tilde{r}_{s,0}\tilde{r}_{s,m}e^{-2i\tilde{\delta}_s}}\ &+\ \tilde{r}_{m,k+1}\left[\frac{\tilde{t}_{0,s}\tilde{t}_{s,m}e^{-i\tilde{\delta}_s}}{\left(1-\tilde{r}_{s,0}\tilde{r}_{s,m}e^{-2i\tilde{\delta}_s}\right)}\frac{\tilde{t}_{m,s}\tilde{t}_{s,0}e^{-i\tilde{\delta}_s}}{\left(1-\tilde{r}_{s,m}\tilde{r}_{s,0}e^{-2i\tilde{\delta}_s}\right)}\right.\\ &\left.-\ \frac{\left(\tilde{r}_{0,s}+\tilde{r}_{s,m}\tilde{h}_{0,s}e^{-2i\tilde{\delta}_s}\right)}{\left(1-\tilde{r}_{s,0}\tilde{r}_{s,m}e^{-2i\tilde{\delta}_s}\right)}\frac{\left(\tilde{r}_{m,s}+\tilde{r}_{s,0}\tilde{h}_{m,s}e^{-2i\tilde{\delta}_s}\right)}{\left(1-\tilde{r}_{s,m}\tilde{r}_{s,0}e^{-2i\tilde{\delta}_s}\right)}\right]e^{-2i\tilde{\delta}_m}=0\end{aligned}\tag{4}$$

The solution of the system of equations (3) and (4) can be defined as a relation for the phase thicknesses of two layers:

$$\tilde{\delta}_s=\frac{1}{2i}\ln\left(-\tilde{r}_{s,m}\frac{\tilde{h}_{0,s}}{\tilde{r}_{0,s}}\right)+\pi j_s,\qquad j_s=1,2,\ldots;\tag{5}$$

$$\tilde{\delta}_m\ =\ \frac{1}{2i}\ln\left(\tilde{r}_{m,k+1}\frac{\tilde{r}_{0,s}\tilde{r}_{s,0}\tilde{r}_{s,m}\tilde{r}_{m,s}+\tilde{h}_{0,s}\tilde{h}_{s,m}}{\tilde{r}_{s,m}\tilde{t}_{0,s}\tilde{t}_{s,0}}\right)+\pi j_m,\qquad j_m=1,2,\ldots;\tag{6}$$

The obtained phase thicknesses of layers s and m (5), (6) correspond to complex thicknesses expressions for which can be written using (2):

$$\tilde{d}_s^{\pm}=\frac{\lambda}{2\pi\tilde{n}_s}\left[\frac{1}{2i}\ln\left(-\tilde{r}_{s,m}\frac{\tilde{h}_{0,s}}{\tilde{r}_{0,s}}\right)+\pi j_s\right],\qquad j_s=1,2,\ldots;\tag{7}$$

$$\tilde{d}_m^{\pm} = \frac{\lambda}{2\pi\tilde{n}_m}\left[\frac{1}{2i}\ln\left(\tilde{r}_{m,k+1}\frac{\tilde{r}_{0,s}\tilde{r}_{s,0}\tilde{r}_{s,m}\tilde{r}_{m,s}+\tilde{h}_{0,s}\tilde{h}_{s,m}}{\tilde{r}_{s,m}\tilde{t}_{0,s}\tilde{t}_{s,0}}\right)+\pi j_m\right], \qquad j_m = 1, 2, \ldots . \tag{8}$$

For such complex thicknesses, zero reflectance is reached, but if $\mathrm{Im}(\tilde{d}_{s,m}) \neq 0$, then they have no physical meaning. To achieve a close-to-zero reflectance, the thickness of another layer d_x can be used as a variable parameter. By changing this parameter, you can choose its value so that the imaginary parts of the expressions for the complex thicknesses become close to zero ($\mathrm{Im}(\tilde{d}_{s,m}^{\pm}) \approx 0$). In this case, the reflectance $R = \tilde{r}_{0,k+1}\tilde{r}_{0,k+1}^{*}$ calculated for positive thicknesses

$$d_{s,m}^{\pm} = \mathrm{Re}(\tilde{d}_{s,m}^{\pm}) \tag{9}$$

takes a value close to zero.

III. NUMERICAL EXAMPLES

Let us analyze the multilayer structure such as a dielectric mirror on the glass substrate with the refractive index $n_{k+1} = 1.52$ that is in the air ($n_0 = 1$):

$$1\,|(HL)^p\,|1.52 \tag{10}$$

Such a structure consists of k layers ($k = 2p$) of two low absorbing materials with refractive indices $\tilde{n}_H = n_H - i\kappa_H$ and $\tilde{n}_L = n_L - i\kappa_L$. First, we choose all layers to be quarter-wavelengths for the chosen wavelength λ_0, whose thicknesses are equal to $d_H = \frac{\lambda_0}{4n_H}$ and $d_L = \frac{\lambda_0}{4n_L}$. In such structures with a large number of layers, the transmittance $T = \frac{n_{k+1}}{n_0}\tilde{t}_{0,k+1}\tilde{t}_{0,k+1}^{*}$ in a certain spectral range, which includes λ_0, is close to zero. Our task is to maximize the value of the absorptance

$$A = 1 - R - T \tag{11}$$

at the wavelength λ_0 so that a narrowband absorber can be obtained. In accordance with the method considered in Sec. 2, in order to achieve the reflectance close to zero, the thicknesses d_s and d_m of the layers s and m should be calculated using formulas (9), and the thickness d_x of the layer x should be considered as a variable parameter.

Fig. 2 shows the dependence of the reflectance R on d_x for the sixteen-layer structure (10), in which $\tilde{n}_H = 3.6 - i\,0.001$, $\tilde{n}_L = 1.35 - i\,0.001$, $s = 5$, $m = 12$, $x = 6$, and the thicknesses d_s, d_m are determined using (9).

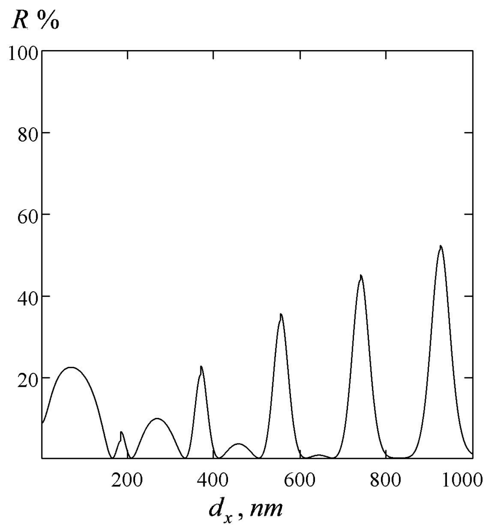

Fig. 2. Reflectance R of the sixteen-layer structure (10) with changed thicknesses of three layers x, s, m versus thickness d_x ($x = 6$). The thicknesses d_s and d_m ($s = 5$, $m = 12$), which depend on d_x, are calculated using (9) at $\tilde{n}_H = 3.6 - i\,0.001$, $\tilde{n}_L = 1.35 - i\,0.001$, $\lambda_0 = 500$ nm

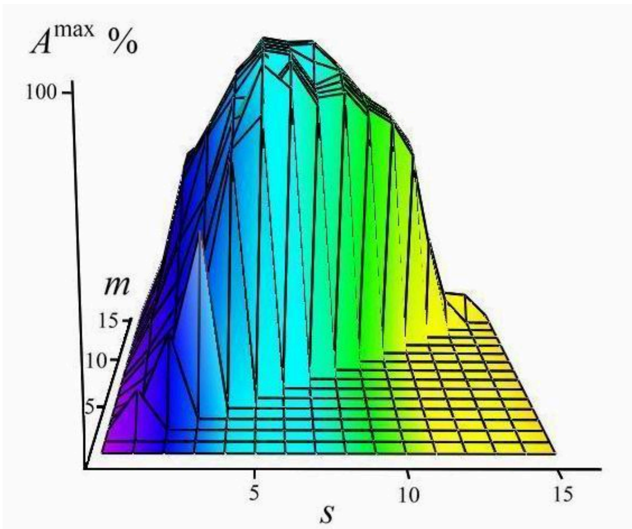

Fig. 3. Maximum absorptance $A^{\max}$ (among the absorptances A of sixteen-layer structures (10) with thicknesses $d_{s,m,x}$ calculated for all possible numbers x) versus numbers s, m at $\tilde{n}_H = 3.6 - i\,0.001$, $\tilde{n}_L = 1.35 - i\,0.001$, $\lambda_0 = 500$ nm

Here, the layer numbers s, m, x are chosen arbitrarily. This dependence shows the existence of many solutions for the thickness d_x at which the reflectance R at the wavelength $\lambda_0 = 500\,\mathrm{nm}$ reaches a value close to zero. In order to determine the optimal numbers of layers s, m, x, the thicknesses of which must be calculated, it is necessary to analyze the dependence of the maximum absorptance $A^{\max}$ on the numbers s, m at the chosen wavelength λ_0 (Fig. 3). Here, by the value $A^{\max}$ we mean the maximum value among the absorptances of k-layer structures with the layer x and two layers s, m with thicknesses $d_{s,m}$ (9) calculated for all possible numbers x. In turn, the thickness d_x, which depends only on the refractive indices of the layers and numbers s, m, is determined from the condition $R = 0$ (Fig. 2). As an example, consider a multilayer structure (10) consisting of sixteen layers ($k = 16$) with complex refractive indices $\tilde{n}_H = 3.6 - i\,0.001$, $\tilde{n}_L = 1.35 - i\,0.001$ for $\lambda_0 = 500$ nm. From fig. 3, we can conclude that the value of the absorptance A close to the maximum is achieved for the structure with numbers s, m, which take the values $s = 5$, $m = 12$ at $x = 6$. The calculation of all thicknesses gives the next values: $d_s = 85.0$ nm, $d_m = 92.9$ nm, $d_x = 209.7$ nm, $d_2 = d_4 = \cdots = d_L = 92.6$ nm, $d_1 = d_3 = \cdots = d_H = 34.7$ nm.

A feature of such solutions for thicknesses is that they correspond to the narrow band of low reflection at λ_0 and a much wider band of close to zero transmission (Fig. 4,a). The existence of two such bands leads to the appearance of the narrow absorption band (Fig. 4,b) due to the fulfillment of condition (11). In this case, the maximum absorptance reaches a value close to 100%.

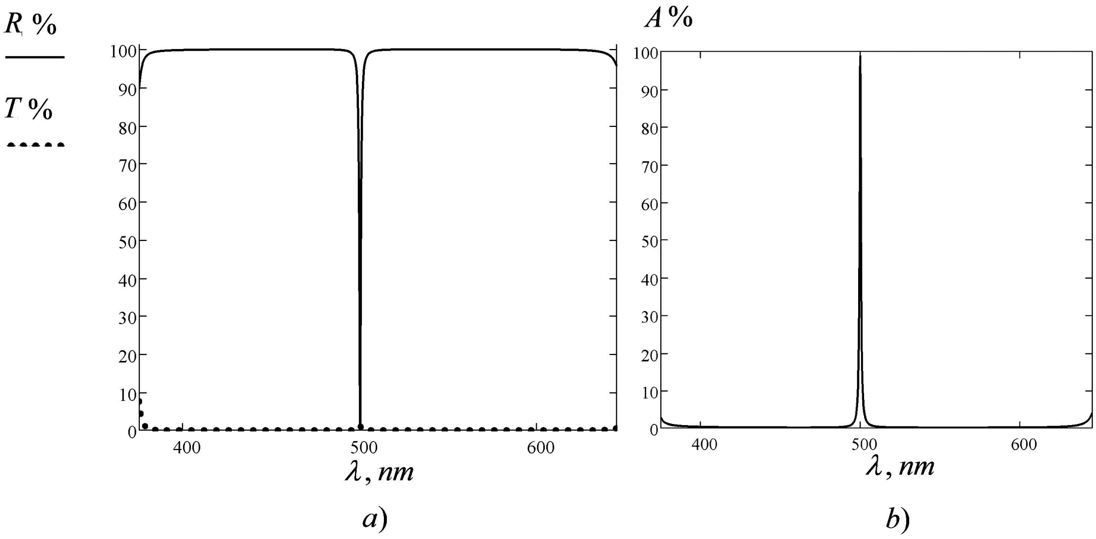

Fig. 4. Reflectance R, transmittance T and absorptance A of the sixteen-layer structure (10), in which new values of the thicknesses of three layers x, s, m are calculated: $d_s = 85.0$ nm, $d_m = 92.9$ nm, $d_x = 209.7$ nm ($s = 5$, $m = 12$, $x = 6$) at $\tilde{n}_H = 3.6 - i\,0.001$, $\tilde{n}_L = 1.35 - i\,0.001$, $\lambda_0 = 500$ nm, $d_2 = d_4 = \cdots = d_L = 92.6$ nm, $d_1 = d_3 = \cdots = d_H = 34.7$ nm

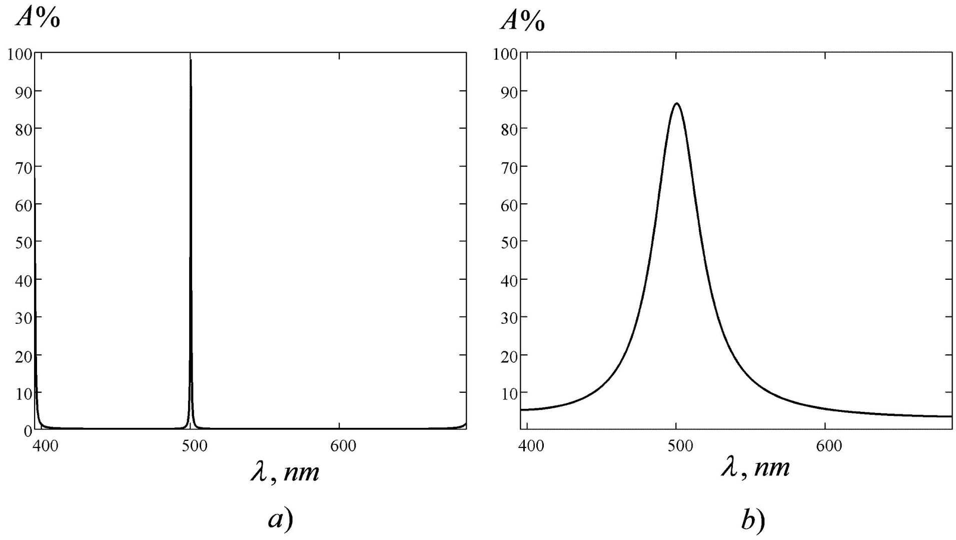

Fig. 5. Absorptance A of two k-layer structures (10), in which new values of the thicknesses of three layers s, m, x are calculated: a) $k = 14$, $s = 4$, $m = 12$, $x = 5$, $d_s = 99.4$ nm, $d_m = 85.7$ nm, $d_x = 172.8$ nm at $\tilde{n}_H = 4.3 - i\,0.001$, $\tilde{n}_L = 1.46 - i\,0.001$, $\lambda_0 = 500$ nm, $d_2 = d_4 = \cdots = d_L = 85.6$ nm, $d_1 = d_3 = \cdots = d_H = 29.1$ nm; b) $k = 6$, $s = 2$, $m = 5$, $x = 4$, $d_s = 171.8$ nm, $d_m = 30.1$ nm, $d_x = 80.0$ nm at $\tilde{n}_H = 4.3 - i\,0.03$, $\tilde{n}_L = 1.46 - i\,0.03$, $\lambda_0 = 500$ nm, $d_6 = d_L = 85.6$ nm, $d_1 = d_3 = d_H = 29.1$ nm

In the developed method, a high value of the absorptance is achieved by determining the thicknesses of three layers of the structure, which depend on the refractive indices of all layers. Therefore, the proposed method makes it possible to design a selective absorber using two arbitrary low absorbing materials with high and low refractive indices. Fig. 5,a shows the spectral dependence of the absorptance of the structure designed using other materials. The same algorithm can be applied to a thinner structure with fewer layers, but for this it is necessary to choose layer materials with higher values of the extinction coefficient κ. This, in turn, will lead to an increase in the width of the absorption band (Fig. 5,b), to a decrease in the absorptance in it, and to an increase in the absorptance in the rejection band.

IV. CONCLUSIONS

The established conditions for achieving zero reflectance of the planar low absorbing structure for the chosen wavelength λ_0 show the need to determine the thickness of three or more layers. On the other hand, the use of the same conditions for the structures such as an interference mirror makes it possible to maintain low transmittance for a wide wavelength range, which includes λ_0. Thus, the established analytical conditions made it possible to design narrow-band absorbers using two arbitrary low-absorbing materials. Such absorbers are characterized by broadband rejection with close to zero absorptance, and narrow-band absorption with a maximum close to 100%, which can be of practical use.

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ВИСОКЕ СЕЛЕКТИВНЕ ПОГЛИНАННЯ ПЛОСКОЮ БАГАТОШАРОВОЮ СТРУКТУРОЮ НА ОСНОВІ ДВОХ СЛАБОПОГЛИНАЛЬНИХ МАТЕРІАЛІВ

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Установлено необхідні співвідношення для товщин двох шарів поглинальної плоскопаралельної структури, за яких може досягатися нульове значення коефіцієнта відбивання. На основі цих співвідношень розроблено числову процедуру пошуку товщин трьох шарів структури, щоб одержати близькі до нуля значення коефіцієнтів відбивання та пропускання для вибраної довжини хвилі. Це дало змогу запропонувати метод проєктування вузькосмугового поглинача на основі таких структур. Його особливістю є використання лише двох слабопоглинальних матеріалів для створення такого поглинача. Для отримання таких поглиначів був використаний спосіб зміни товщин декількох шарів структури типу інтерференційне дзеркало. Такий підхід раніше успішно використовували для проєктування вузькосмугових фільтрів із потрібною кількістю смуг пропускання, розроблених на основі двох прозорих або слабопоглинальних матеріалів. Особливістю всіх цих методів є використання аналітичних умов нульового відбивання, які були раніше отримані для структур на основі прозорих або слабопоглинальних матеріалів. Установлені умови досягнення нульового коефіцієнта відбивання для вибраної довжини хвилі λ_0 слабопоглинальної плоскопаралельної структури вказують на необхідність визначення товщин щонайменше трьох шарів. З іншого боку, застосування цих самих умов для структур типу інтерференційне дзеркало зберігає низьке пропускання для широкого інтервалу довжин хвиль, який включає λ_0. Отже, встановлені аналітичні умови дали змогу проєктувати вузькосмугові поглиначі на основі таких структур. Розроблений метод дав змогу проєктувати поглиначі на основі двох довільних слабопоглинальних матеріалів із високим та низьким показниками заломлення. Особливістю цих поглиначів є наявність у них широкої смуги близького до нуля поглинання, усередині якої є вузька смуга високого поглинання, що може мати практичне застосування.

Ключові слова: поглинач, нульовий коефіцієнт відбиття, вибіркове поглинання, багатошарова структура.