Quantum Electronics **51** (11) 1044–1050 (2021)

https://doi.org/10.1070/QEL17645

High-frequency electric field intensity sensor based on double-slot waveguides filled with electro-optical polymer

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Abstract. **We consider the structure of a high-frequency external electric field sensor based on microring resonators using waveguides with two horizontal or vertical slots filled with an electro-optical polymer. The method of lines is used to calculate the propagation constants and mode field distributions of such waveguides. It is shown that double-slot waveguides filled with an electro-optical polymer exhibit higher optical radiation intensity in the slot region compared to single-slot waveguides, which makes it possible to increase the sensor sensitivity. The distances between the slots and the values of their widths at which a maximum sensor sensitivity is achieved are determined. The sensor allows alternating electric fields with frequencies up to 10 GHz to be measured in the range of $100-16\times10^6$ V m^{-1} with an accuracy of 150 V m^{-1}.**

Keywords: *microring resonator, slot waveguide, optical sensor, electro-optical polymer, effective refractive index, electric field intensity.*

1. Introduction

Electric field sensors are widely in demand for detecting ultrahigh frequency waves and electromagnetic pulses, analysing external electromagnetic interference, checking electromagnetic compatibility, diagnosing high-frequency electronic circuits, studying the effect of electromagnetic radiation on human health, etc. [1–3]. In the field of electromagnetic research, the determination of the characteristics of high-frequency electric fields is an important method for evaluating the effectiveness of electromagnetic protection [4–6]. For high-frequency electric field measurement systems, both high-speed sensor modules and high-frequency signal detection modules are required [7, 8].

Optical electric field sensors have significant advantages over their electronic counterparts due to their small size, lower weight, high sensitivity, wide spectral range, and protection from electromagnetic interference [2, 5]. The operation principle of all-optical electric field sensors is based on the use of the electro-optical effect. The applied high-frequency electric field changes the refractive index of the electro-optical medium, which leads to modulation of the test optical signal. Thus, information about the electric field parameters is converted into an optical format [9]. In terms of reliability, simplicity of design and compactness, sensors based on waveguide structures are superior to sensors based on bulk optical elements [10–13].

The most sensitive are optical electric field sensors based on Mach–Zehnder interferometers or ring resonators [12, 14–16]. Electric field sensors based on microring resonators using optical waveguides with horizontal and vertical slots filled with a liquid crystal (LC) [16] allow the electric field intensity to be measured with an accuracy of 1 V m^{-1} in the range $1-10^6$ V m^{-1}. The operation speed of the sensors is limited by the LC response time and varies from tens to hundreds of microseconds. This makes it possible to use them for measuring alternating electric fields with frequencies up to tens of kilohertz.

The sensor operation speed can be increased by using electro-optical polymers instead of LCs, which make it possible to measure alternating electric fields with a frequency of 1–10 GHz [11, 17]. In particular, in work [11], the possibility of determining the alternating electric field intensity with a frequency of up to 8.4 GHz using a SEO125 active organic polymer was experimentally demonstrated.

We have proposed a high-frequency electric field sensor using microring resonators based on slot waveguides, the slots of which are filled with a SEO125 electro-optical polymer [18]. The sensor allows measuring alternating electric fields with a frequency of up to 10 GHz. The sensor sensitivity is limited by the photodetector parameters, in particular, by the dark current value. When using a photodetector with a dark current of 20 nA, the sensor makes it possible to measure changes in the electric field intensity of the order of 300 V m^{-1} (with a signal-to-noise ratio of 10). Thus, the sensitivity of a sensor with an electro-optical polymer is an order of magnitude lower than that of a similar device with an LC [16]. This is due to the fact that the changes in the polymer's refractive index under the electric field action are several orders of magnitude smaller than those in an LC.

A number of works have shown theoretically and experimentally that the use of waveguides with several vertical [19–23] or horizontal [19, 24, 25] slots allows one to increase the localisation of optical radiation in the slot region, resulting in increased sensor sensitivity. In particular, Feng et al. [19] indicated that the use of a waveguide with several horizontal slots increases by 56% the localisation coefficient of optical radiation power in layers with a low refractive index. Vivien et al. [21] found that the variations of the effective refractive index of a waveguide mode in a waveguide with several vertical slots are 20% larger than in the case of a single-slot waveguide. Kazanskiy et al. [23] showed the possibility of increasing the sensitivity of the refractive index sensor by a factor of 2.5 due to the use of a grating double slot waveguide.

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Received **5** August 2021; revision received 14 September 2021
Kvantovaya Elektronika **51** (11) 1044–1050 (2021)
Translated by M.A. Monastyrskiy

In this work, we consider the possibility of increasing the sensitivity of a high-frequency electric field sensor based on microring resonators using optical waveguides with two horizontal or vertical slots filled with an electro-optical polymer.

2. Schematic of the sensor

The sensor consists of a closed microring resonator based on strip waveguides. Straight strip waveguides connected to the resonator waveguide by damped fields are used to input/output optical radiation into/from the resonator. If the wavelength of optical radiation propagating along the input waveguide coincides with the resonant wavelength of the microresonator, the radiation is launched into the ring waveguide. Radiation at other wavelengths continues to propagate along the input waveguide. The radiation branching off into the ring waveguide passes from it into the output waveguide. Thus, radiation enters the output waveguide in a narrow spectral range, the centre wavelength of which corresponds to the resonant wavelength of the microresonator. The range width is set by the coupling coefficient of the ring and straight waveguides and by the microresonator parameters.

Any changes in the effective refractive index for the ring waveguide mode lead to a change in the resonant wavelength. As a result, the output signal intensity changes at the carrier wavelength, which coincides with the resonant wavelength of the unperturbed resonator.

The microring resonator can be designed on the basis of a slot waveguide, which consists of strips of material with a high refractive index, separated by a region of material with a low refractive index – a slot. The slot dimensions are less than the wavelength of optical radiation propagating through the waveguide. Such slots can be arranged vertically [26, 27] or horizontally [28, 29] in the form of a layered structure. Since electric fields are continuous at the interface between materials with different refractive indices, the mode field in the slot region is relatively large. Thus, a change in the refractive index of the slot material significantly affects the guiding properties of the waveguide, which makes it possible to increase the sensor sensitivity.

To measure external electric fields, the waveguide slots can be filled with an electro-optical substance, for example, an electro-optical polymer. If such a waveguide is introduced into an external electric field, the refractive index n of the electro-optical polymer changes in proportion to the electric field magnitude:

$$n = n_0 - \frac{1}{2} n_0^3 r_{33} E_{\rm ext},$$

where n_0 is the polymer's refractive index in the absence of an electric field; r_{33} (m V^{-1}) is the electro-optical coefficient of the polymer; and $E_{\rm ext}$ (V m^{-1}) is the applied electric field intensity [9]. For a SEO125 polymer, the refractive index n_0 for a wavelength of 1550 nm is 1.63, and the estimated value of the electro-optical coefficient r_{33} is 100 pm V^{-1} [11]. A change in the refractive index of an electro-optical polymer, in turn, leads to a change in the effective refractive index $n_{\rm eff}$ for the guided mode of the slot waveguide, which leads to a change in the output signal intensity at the carrier wavelength coinciding with the resonant wavelength of the unperturbed resonator. Thus, by measuring the intensity of the output optical signal at the resonator output, the external electric field can be determined.

A schematic of the ring waveguide of a micro-resonator with vertical and horizontal slots filled with an electro-optical polymer is shown in Fig. 1. The slot waveguide is made of Si_3N_4 or silicon and is located on a silicon substrate. To implement the total internal reflection condition, a SiO_2 buffer layer with a refractive index lower than that of the waveguide is placed between the waveguide and the substrate. The SEO125 active organic polymer fills the vertical or horizontal slots of the ring waveguide. Such a polymer has a low optical loss for radiation with a wavelength of 1550 nm, a large electro-optical coefficient, and good temporal stability [11]. The total width of the slot waveguide is 1000 nm, and the height is 300 nm.

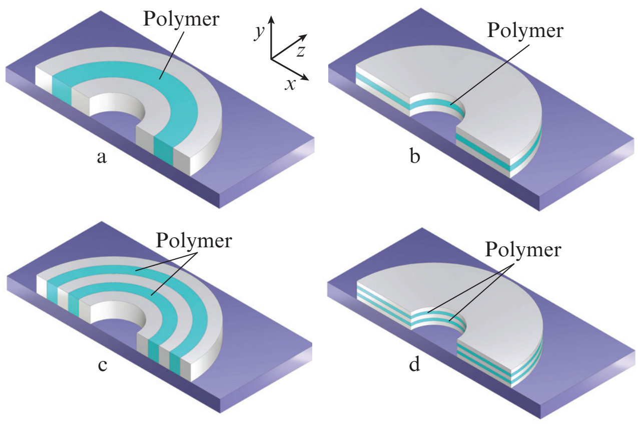

Figure 1. (Colour online) Structures of a microring resonator based on waveguides with a single and two vertical (a, c) and horizontal (b, d) slots filled with an electro-optical polymer.

The device operation speed is determined by the time of reaching the stationary regime in the microring resonator and the response time of the electro-optical material. The time of reaching the stationary regime for a ring waveguide with a curvature radius of 32 μm is approximately 25 ps, which corresponds to a frequency of 40 GHz [30]. At the same time, electro-optical polymers allow measuring alternating electric fields with a frequency of 1 – 10 GHz [11, 17], and, consequently, their response time limits the operation speed of the sensor.

3. Sensor sensitivity

The effective refractive index and the distribution of the mode fields of curved slot waveguides with slots filled with an electro-optical polymer were calculated using the method of lines [31, 32] modified for the structure under study. The calculations did not take into account losses during the input of optical radiation into the waveguide and extraction from it, as well as material losses.

To assess the sensor sensitivity, we analysed the dependence of the signal intensity at the resonator output on the external electric field intensity for various resonator parameters. The parameters of an FU-68PDFV510M semiconductor laser with an output optical power of 15 mW at a wavelength of 1550 nm were used as the initial parameters of optical radiation. Optical radiation at the ring resonator output was converted into an electrical signal by an FD161 InGaAs pin photodiode. The current sensitivity of the photodiode at the oper-

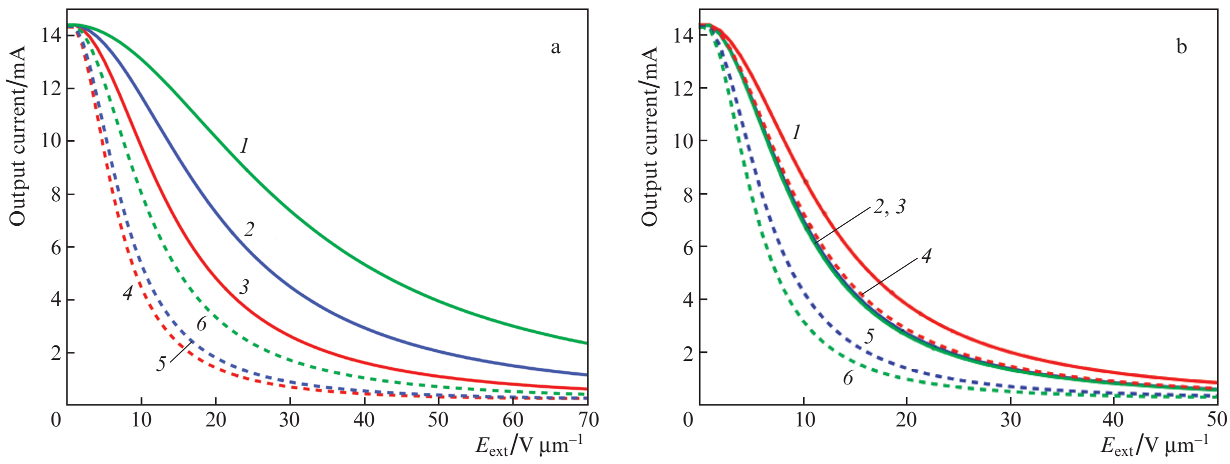

Figure 2. (Colour online) Dependences of the signal at the output of a ring resonator with a radius of 32 μm, based on a waveguide with a single and two vertical (a) and two horizontal (b) slots filled with an electro-optical polymer on the electric field intensity: (a) curves *1*–*3* correspond to a waveguide with a single slot 50 , 100, and 200 nm wide; and curves *4*–*6* correspond to a waveguide with two slots spaced by 200 nm and, respectively, 25, 50, and 100 nm wide; (b) curves *1*–*3* correspond to a waveguide with a single slot 100, 200, and 300 nm wide; and curves *4*–*6* correspond to a waveguide with two slots spaced by 100 nm and, respectively, 50, 100, and 150 nm wide.

ating wavelength of 1550 nm was no less than 0.8 A W^{-1}, and the dark current did not exceed 20 nA [16].

Figure 2 shows the signals at the output of the resonators based on curved waveguides with a single and two vertical (Fig. 2a) and two horizontal (Fig. 2b) slots filled with an electro-optical polymer at various external electric field intensities. The slope of the curves describing the dependence of the output signal on the electric field intensity characterises the sensor sensitivity. For correct comparison, the slot width in single slot waveguides is assumed to be equal to the total width of the slots in double slot waveguides, which provides the same volume of the electro-optical material.

As can be seen from the Figure, the sensitivity of a sensor based on a double slot waveguide is higher than that of a sensor based on a single slot waveguide at the same filling with an electro-optical polymer. This pattern is typical for both horizontal slot and vertical slot waveguides.

4. Optimisation of sensor parameters

We evaluated the sensitivity and measurement range of the sensor at various slot widths and spacings for vertical and horizontal slot waveguides.

4.1. Microring resonator based on a vertical slot waveguide

To analyse the effect of the distance between the slots on the sensitivity and measurement range of the sensor, we calculated the effective refractive indices for guided modes of curved waveguides with a constant width of the slots and various distances between them, as well as the signal intensity at the output of microring resonators based on such waveguides. As an example, Fig. 3 shows the dependences of n_{eff} for waveguides with two vertical slots 100 nm wide, spaced by 100, 200, 300, and 400 nm, and the signals at the output of resonators on the external electric field intensity.

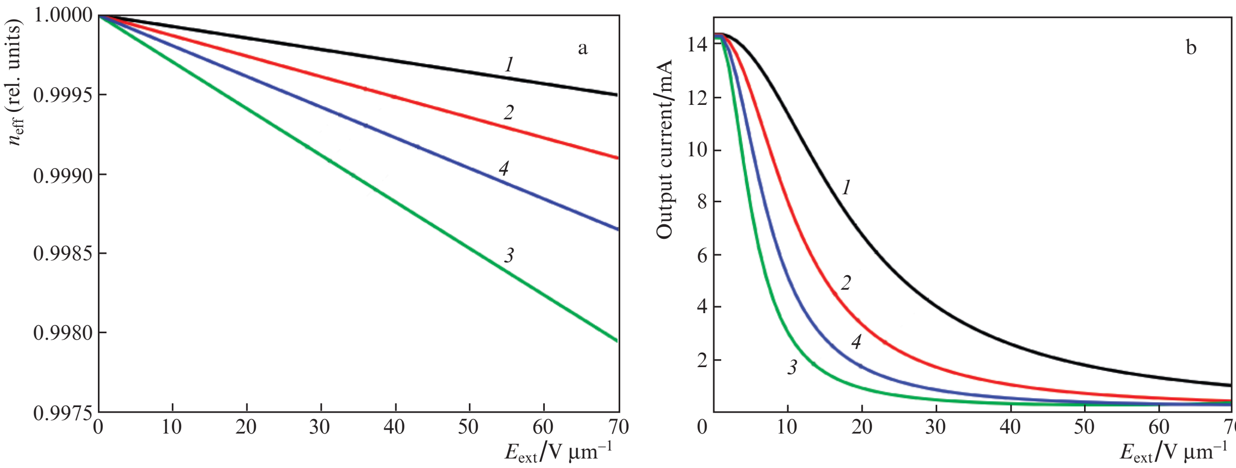

Figure 3. (Colour online) (a) Normalised effective refractive indices for guided modes of the curved waveguides with two vertical slots 100 nm wide, filled with an electro-optical polymer and spaced by (*1*) 100, (*2*) 200, (*3*) 300, and (*4*) 400 nm, and (b) signals at the output of resonators based on such waveguides as functions of the external electric field intensity.

As can be seen from the Figure, the effective refractive index for a waveguide mode with slots spaced by 300 nm reacts most sharply to a change in the external electric field. As a result, sensors based on such waveguides have the highest sensitivity (1.25 mA V^{-1} μm^{-1}). Refined calculations show that the optimal distance between vertical slots in the waveguide is 330 nm. In this case, the sensitivity of sensors with slots spaced by 300–350 nm varies in the range 1.25–1.29 mA V^{-1} μm^{-1}, i.e., it differs by an insignificant value, which indicates the stability of the ring resonator design with two vertical slots to imperfections in its manufacture.

For waveguides with two slots 25, 50, and 150 nm wide, the maximum sensitivity is achieved at a distance of 300, 320, and 335 nm between the slots, respectively. The presence of the optimal distance between the slots can be explained by means of analysing the amplitude distributions of the electric fields of the modes in the ring waveguide cross section (Fig. 4).

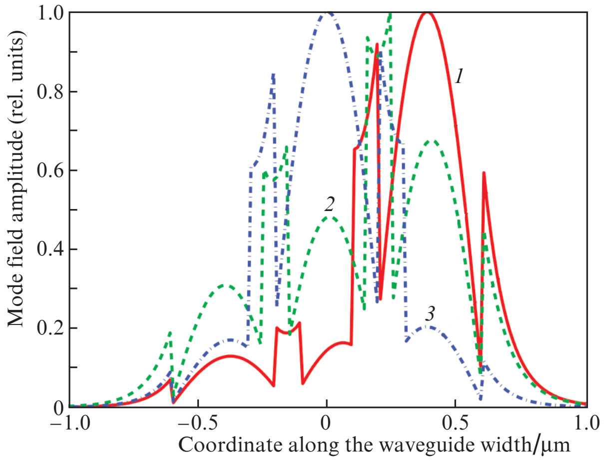

Figure 4. (Colour online) Distributions of the electric field amplitudes of the guided modes in the cross section of waveguides with two vertical slots 100 nm wide, filled with an electro-optical polymer and spaced by (*1*) 200, (*2*) 300, and (*3*) 400 nm.

It follows from this Figure that at a small distance between the slots (less than 200 nm), the distribution of mode fields corresponds to the distribution of the super-mode field of two coupled waveguides. In this case, the field intensity of the waveguide mode in the slot region is small [curve (*1*)]. The distribution of mode fields in a waveguide with a large distance between the slots (more than 400 nm) is similar to the distribution of mode fields in a conventional strip waveguide, the role of which is played by the central part of a double slot waveguide [curve (*3*)]. Thus, in the region of slots filled with an electro-optical polymer, the mode field intensity is insignificant compared to the intensity in the central region of the waveguide. At the optimal distance between the slots (~300 nm), the distribution of the mode fields is similar to that of the super-mode fields of three coupled waveguides, while the intensity of the mode field in the slot region is very high [curve (*2*)]. This leads to the greatest change in the effective refractive index for the waveguide mode when the refractive index of the electro-optical polymer changes under the electric field action and provides the highest sensitivity of the sensor based on such a waveguide.

A further increase in the sensor sensitivity can be achieved by varying the slot widths. Figure 5 shows the dependence on the external electric field intensity of the refractive index n_{eff} for the modes of waveguides with vertical slots of various widths, filled with an electro-optical polymer with an optimal distance of 300 nm between them, and signals at the output of a ring resonator based on such waveguides. It can be seen that the effective refractive index for a waveguide mode with a slot width of 50 nm reacts most sharply to a change in the external electric field. As a result, sensors based on such waveguides reach maximum sensitivity (1.27 mA V^{-1} μm^{-1}). In this case, the sensitivity of sensors with a slot width from 50 to 80 nm differ by an insignificant value (0.005 mA V^{-1} μm^{-1}), which also indicates the stability of the analysed structure to manufacturing errors.

Figure 6 shows the amplitude distributions of the mode fields in waveguides with two vertical slots spaced by 300 nm. It can be seen that the mode field intensity in the narrow slot region (25 nm) is high. In this case, the polymer volume is

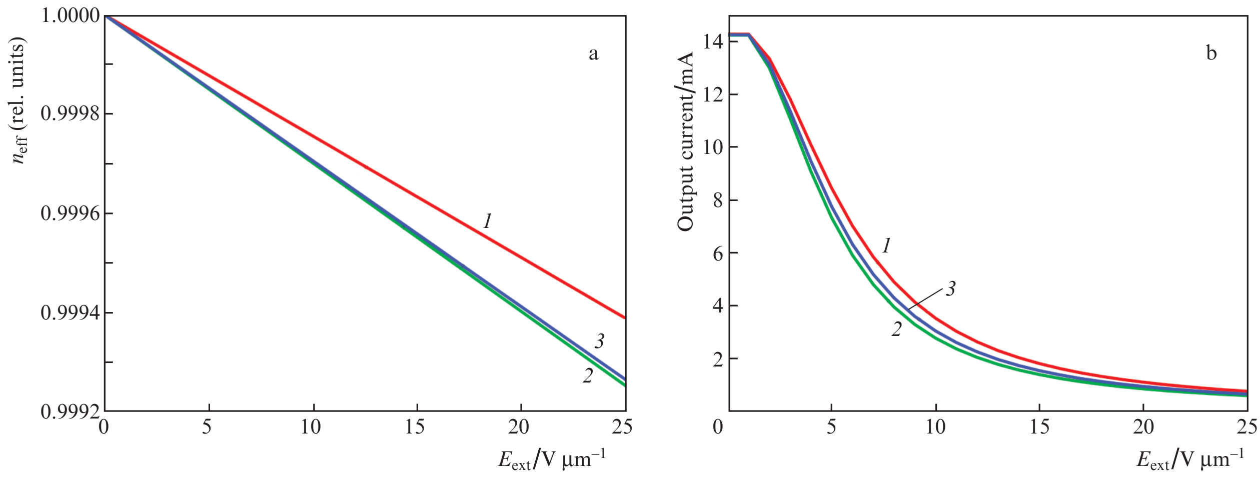

Figure 5. (Colour online) (a) Normalised effective refractive indices for guided modes of the curved waveguides with two vertical slots filled with an electro-optical polymer and spaced by 300 nm, with a width of (*1*) 25, (*2*) 50, and (*3*) 100 nm, and (b) signals at the output of resonators based on such waveguides as functions of the external electric field intensity.

small and the sensor sensitivity to electric field changes is insignificant. The volume of the electro-optical polymer filling the slots with a width of 100 nm is quite large. However, the mode field in the slot region is small, and the effective refractive index for the mode weakly depends on variations in the refractive index of the polymer. The combination of the mode field intensity and the electro-optical polymer volume is optimal for a slot with a width of 50 nm. In this case, with the refractive index of the polymer varying under the external electric field action, there occur the greatest changes in the effective refractive index for the mode.

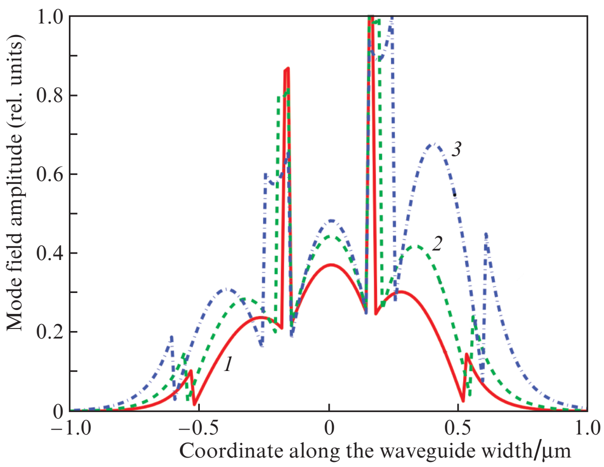

Figure 6. (Colour online) Distributions of the field amplitudes of the guided modes in the cross section of waveguides with two vertical slots filled with an electro-optical polymer and spaced by 300 nm, with a width of (*1*) 25, (*2*) 50 and (*3*) 100 nm.

Thus, the sensitivity of a sensor based on a ring resonator with a radius of 32 μm, based on waveguides with two vertical polymer-filled slots, can reach 1.30 mA V^{-1} μm^{-1}. A change in the electric field intensity by 1 V m^{-1} causes a change in the photodiode current in such a sensor by about 1.30 nA. Since the dark current of the photodetector is ~20 nA, it is obvious that such a sensor does not allow tracking changes in the external electric field intensity by less than 150 V m^{-1} (at a signal-to-noise ratio of 10). In this case, the range of measuring the intensity of external electric fields is $100-16\times10^6$ V m^{-1}.

4.2. Microring resonator based on a horizontal slot waveguide

A similar analysis was performed for sensors based on double horizontal slot waveguides. Figure 7 shows the dependences of the effective refractive indices for guided modes of curved waveguides with two horizontal slots 100 nm wide, spaced by 50, 100, and 150 nm, as well as signals at the output of resonators based on these waveguides, on the external electric field intensity.

As can be seen from the Figure, the effective refractive index of the mode of a waveguide with horizontal slots spaced by 100 nm reacts most sharply to a change in the external electric field. Sensors based on such waveguides have the highest sensitivity (~1.11 mA V^{-1} μm^{-1}). Refined calculations have shown that this distance between the slots in the waveguide is optimal. In this case, the sensitivity of sensors with a distance between the slots from 80 to 120 nm differs by an insignificant value (0.02 mA V^{-1} μm^{-1}), which indicates the stability of the ring resonator design with two horizontal slots to manufacturing defects.

For waveguides with a slot width of 50, 150, and 200 nm, the maximum sensitivity is achieved at the spacing of 90, 100, and 105 nm between the slots, respectively.

The presence of an optimal (in terms of sensor sensitivity) distance between the slots is explained similarly to the case of a vertical slot waveguide, which follows from Fig. 8, which shows the distributions of mode fields in a waveguide with two horizontal slots spaced by a distance of 100 nm. The mode field distributions in waveguides with small (less than 50 nm), medium (optimal, ~100 nm), and large (over 150 nm) distances between the slots are similar, respectively, to the distributions of the super-mode field of two coupled waveguides, three coupled waveguides, and the mode of a conventional strip waveguide, the role which is played by the central part of the double horizontal slot waveguide.

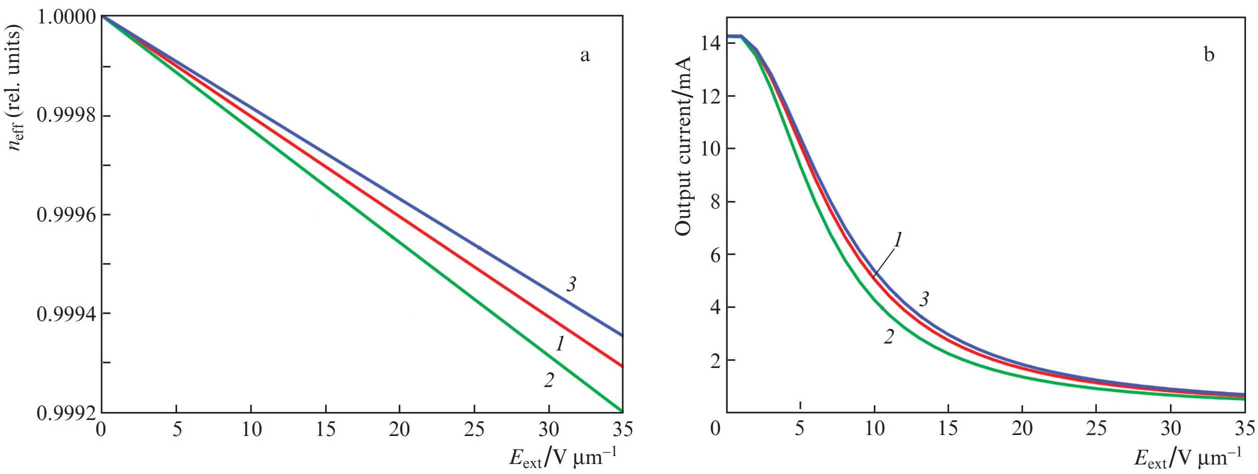

Figure 7. (Colour online) (a) Normalised effective refractive indices for guided modes of the curved waveguides with two 100 nm wide horizontal slots filled with an electro-optical polymer and spaced by (*1*) 50, (*2*) 100, and (*3*) 150 nm and (b) signals at the output of resonators based on such waveguides as functions of the external electric field intensity.

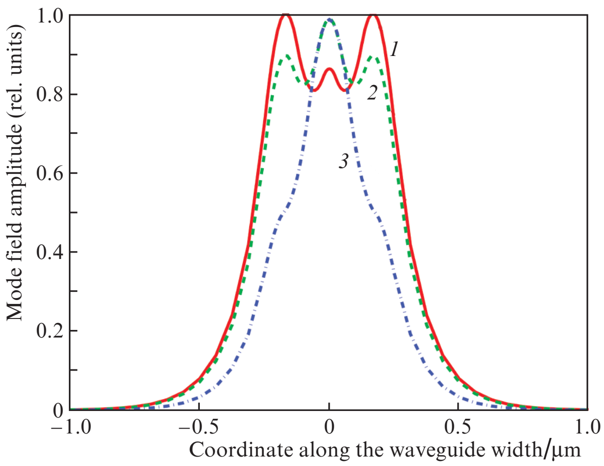

Figure 8. (Colour online) Distributions of the electric field amplitudes of the guided modes in the cross section of waveguides with two horizontal slots filled with an electro-optical polymer, with a width of 100 nm and spaced by (*1*) 50, (*2*) 100, and (*3*) 150 nm.

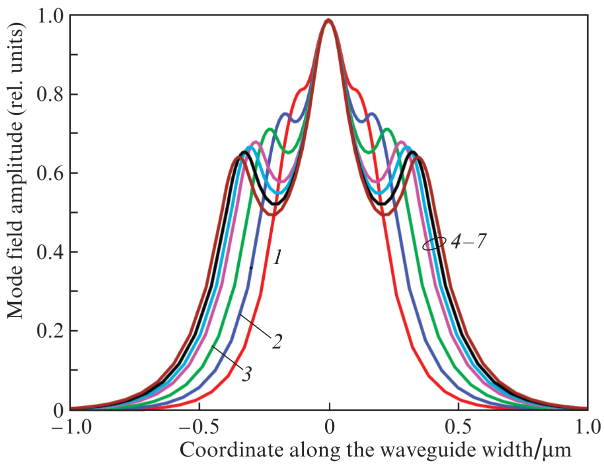

Figure 10. (Colour online) Distributions of the electric field amplitudes of the guided modes in the cross section of waveguides with two horizontal slots filled with an electro-optical polymer and spaced by 100 nm, with (*1*) 50, (*2*) 100, (*3*) 150, (*4*) 200, (*5*) 220, (*6*) 240, and (*7*) 260 nm.

Figure 9 shows the dependences of n_{eff} for modes of waveguides with horizontal slots of various widths, filled with an electro-optical polymer and optimal distances of 100 nm between the slots, as well as for signals at the output of a ring resonator based on such waveguides, on the external electric field intensity. It can be seen that with an increase in the slot width, the sensor sensitivity increases; however, starting from 200 nm, this change becomes insignificant. At a width of ~260 nm, the sensor sensitivity nearly reaches the limiting value (1.32 mA V^{-1} μm^{-1}). As follows from Fig. 10, at a slot width exceeding 200 nm, the mode field distributions in waveguides with a distance of 100 nm between the slots remain virtually unchanged.

Thus, the sensitivity of a sensor based on a ring resonator with a radius of 32 μm, designed on waveguides with two horizontal slots filled with an electro-optical polymer, can reach 1.32 mA V^{-1} μm^{-1}. A change in the electric field intensity by 1 V m^{-1} causes a change in the photodiode current in such a sensor by about 1.32 nA. Consequently, a sensor based on a waveguide with two horizontal slots filled with an electro-optical polymer can be used to measure the intensity of external electric fields with an accuracy of 150 V m^{-1} in the range of $100 - 16 \times 10^6$ V m^{-1}.

5. Conclusions

We have shown that in double vertical or horizontal slot waveguides, a higher intensity of optical radiation is achieved in the region of slots filled with an electro-optical polymer, as compared to single slot waveguides. This makes it possible to increase the sensitivity of the sensor of high-frequency electric fields based on microring resonators by two to three times.

There is an optimal distance between the slots at which the sensor sensitivity attains it maximum. For vertical slot waveguides, this distance amounts to ~320 nm, for horizontal slot waveguides, to ~100 nm. A further increase in the sensor sensitivity can be achieved by varying the slot width. The maximum sensitivity of double vertical slot waveguides to the action of an external electric field is possible at a slot width of

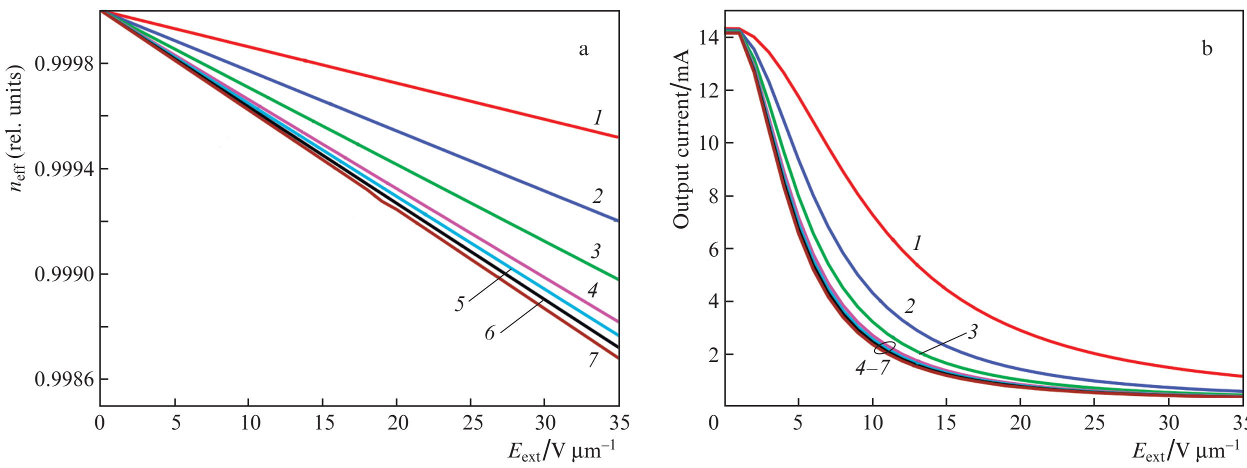

Figure 9. (Colour online) (a) Normalised effective refractive indices for guided modes of the curved waveguides with two horizontal slots filled with an electro-optical polymer and spaced by 100 nm, with a width of (*1*) 50, (*2*) 100, (*3*) 150, (*4*) 200, (*5*) 220, (*6*) 240, and (*7*) 260 nm, and (b) signals at the output of the resonators based on these waveguides as functions of the external electric field intensity.

50 nm. For horizontal slot waveguides, the maximum sensitivity is achieved at a slot width of 260 nm.

The sensitivity of sensors based on waveguides with two vertical slots spaced by 300 – 350 nm and having a width of 50 – 80 nm differs insignificantly. The sensitivity of sensors based on double horizontal slot waveguides differs insignificantly at a distance from 80 to 120 nm between the slots. This indicates the stability of the ring resonator design with two vertical or horizontal slots to manufacturing imperfections.

The sensor allows measuring alternating electric fields with a frequency of up to 10 GHz by using the SEO125 active organic polymer as a sensitive electro-optical material. The sensor sensitivity is limited by the photodetector parameters, in particular, by the dark current value. When using a photodetector with a dark current of 20 nA, the sensor can measure changes in the electric field intensity of the order of 150 V m^{-1}. In this case, the measurement range amounts to 100 – 16 × 10^6 V m^{-1}.

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