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Thin heterogeneous optical silicon-on-insulator waveguides and their application in reconfigurable optical multiplexers

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***Abstract*. A new type of optical waveguides in silicon-on-insulator (SOI) nanostructures is proposed and studied. Their optical properties and the possibility of their application in tunable optical filters and reconfigurable multiplexers are discussed based on the results of numerical simulation by the BPM and FDTD methods. A new design of heterogeneous waveguide structures containing additional regions with a high concentration of free charge carriers in the form of a p – n junction, which are located at the edges of a multimode strip waveguide (the cross section of the silicon core being $\sim 0.22 \times 35$ μm), is proposed. This doping provides single-mode behaviour of the heterogeneous waveguide due to low optical losses in the fundamental mode and to enhanced losses in highest modes. Heterogeneous waveguides can be used for the fabrication of different photonic elements including new types of tunable optical filters and reconfigurable multiplexers based on the multireflection technology.**

Keywords: *integrated optics, optical waveguide, optical losses, silicon-on-insulator, reconfigurable optical add/drop multiplexer, multireflection technology, numerical FDTD and BMP methods.*

1. Introduction

Tunable optical filters and reconfigurable optical add/drop multiplexers (ROADMs) belong to the type of most popular photonic devices operating based on wavelength division multiplexing (WDM), which determine further possibility of increasing the flexibility and transmission capacity of fibreoptic communication lines. Although many different types of filters and WDM multiplexers [1] have been designed and patented, none of them possesses sufficient potential to replace the others in all possible applications.

To reduce the cost of one spectral channel, which is required for a broader application of the WDM technology, we have proposed new types of tunable filters and reconfigurable multiplexers based on the planar technology of the integrated optics and new multireflection filtering technology [2 – 6]. The latter freshly employs the phenomena of waveguide light propagation, multiple reflections and constructive interference. It provides narrowband filtering of optical radiation due to spatial expansion of a narrow input optical beam with the help of a patented multireflection beam expander [2, 3] with a high dispersion. The specified optical wavelength and its filtration are controlled with the help of a set of tunable strip waveguides [4, 7 – 9] or due to Bragg diffraction on a surface acoustic wave [5, 6, 10 – 12] for many light microfluxes combined in output strip waveguides of other beam expanders. The multireflection technology allows tunable optical elements (not only multiplexers but also filters, lasers, etc.) to be designed by using different materials (silicon, polymers, lithium niobate, chalcogenide glass, etc.) [7 – 11], which can be used to fabricate partially transmitting reflectors and single-mode waveguides with low losses (less than 1 dB cm^{-1}) to control the phase or direction of an optical wave.

The aim of this paper is the search for new approaches to the fabrication of reconfigurable optical multiplexers based on thin silicon-on-insulator (SOI) structures. New heterogeneous optical strip waveguides [12] based on SOI nanostructures are chosen as basic ones for investigation, in which regions with a high concentration of two types of free charge carriers (electrons and holes) have been additionally produced providing low optical losses and an uncharacteristic single-mode behaviour of very wide (larger than 10 μm) high-contrast SOI waveguides with a silicon core of thickness ~ 220 nm. In this paper we also consider the possibility of application of heterogeneous waveguides for fabricating tunable filters and ROADMs based on the multireflection technology in thin SOI structures [13, 14] compatible with the standard CMOS technology [13]. The advantages of the new design of optical elements based on the heterogeneous waveguides are confirmed by model calculations. Calculations were performed by the beam propagation method (BPM) and the finite difference time domain (FDTD) method by using commercial software Beam-PROP and FullWAVE packages developed by RSoft Design Group Inc. [15] for the needs of integrated optics. To speed up the calculations, we have used the effective index method (EIM) [16], which replaces a three-dimensional waveguide into its two-dimensional planar counterpart. In this case, the quasi-TE mode of a 3D waveguide corresponds to a quasi-TM mode of an equivalent 2D waveguide.

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2. Quasi-single-mode optical strip waveguides based on thin SOI layers

It has been recently proposed to use diffraction 2D gratings [17] produced in SOI structures to couple radiation along the normal from the optical fibre into a thin silicon waveguide. These gratings usually represent circular grooves of diameter 300 nm etched into depth of 90 nm with a step of 580 nm in a strip silicon waveguide of thickness 220 nm on a buried oxide layer of thickness 1 μm. Two-dimensional gratings are very promising for the combined usage with the multireflection filtering technology because they simplify the coupling of light into the optical waveguide and provide an additional possibility of polarisation independence of devices [18]. It was shown in [17] that optical modes of two orthogonal polarisations are coupled into a waveguide by a 2D grating with the same efficiency and propagate at different (perpendicular) directions in the form of quasi-TE-polarisation waves. The spatially separated optical signals are then simultaneously processed by two (even polarisation dependent) elements; at the output from the devices these signals can be again combined at the output 2D grating [18]. All the above allows one not to employ additional polarisation-rotation elements, which are often used to make a polarisation-independent device [8].

An important drawback of this coupling element is the necessity to use waveguide structures with a high contrast of the refractive indices ($n = 3.478$ for silicon and $n = 1.447$ for oxide), which makes it impossible to fulfill simultaneously mutually exclusive requirements to the optimal geometric size of the silicon core in the SOI structure. Indeed, to decrease the level of parasitic signals, the waveguide should be a single-mode one, i.e. it should have submicron dimensions. In the transverse direction, this condition is fulfilled due to the optical thickness ($\sim$ 220 nm) of a high-quality silicon layer. At the same time, the width of such strip waveguides should be large enough ($\sim$ 10 μm) to provide admissible matching with the optical fibre, therefore, the waveguides will be compulsory multimode ones. Upon their excitation, strong intermode interference leading to the distortions of the optical beam shape can be observed, which is especially illustrative in the case of a mismatch of the spatial distribution and position of the exciting optical beam with the fundamental mode of the waveguide (Fig. 1a). Thus, to establish the single-mode regime, the adiabatic narrowing of the waveguide core is proposed to be used (approximately by 25 times), which results in additional losses and is not always admissible. Note that it is reasonable to employ wide optical waveguides in order to provide low losses and low parasitic scattering upon their mutual intersection.

Therefore, a search for a design of SOI waveguides is required so that they could be simultaneously large and single-mode. For thick 3 – 8-μm ridge waveguides, this is achieved by using a ridge with the optimal thickness and height above the planar base [19, 20]. In this case, only the fundamental mode can propagate with low losses and all other modes radiate as they propagate. For 2D gratings on thin SOI layers this technology is not applicable, hence, it has been recently proposed [12] to use heterogeneous quasi-single-mode strip waveguides at the edges of which heavily-doped p^+ regions are located. The principle of their operation is based on the dispersion of free charge carriers

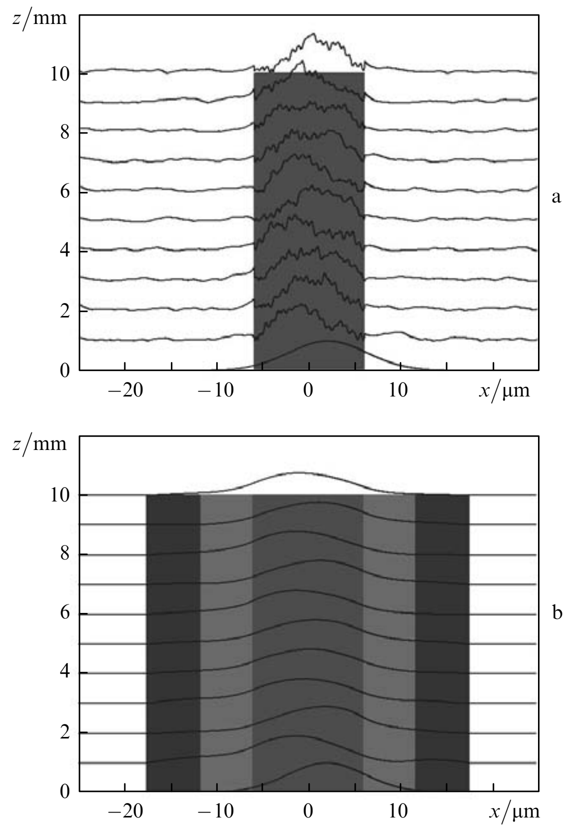

Figure 1. Propagation of a Gaussian optical beam displaced by 2 μm with respect to the axis of a wide SOI waveguide. Spatial distribution of a magnetic TM-mode field for a standard multimode waveguide ($W =$ 12 μm) (a) and the same for a heterogeneous quasi-single-mode waveguide ($W =$ 12 μm, $W_0 =$ 35 μm) (b).

to select the fundamental mode (due to the production of high losses for all highest modes).

In this paper we consider for the first time heterogeneous optical waveguides with heavily-dopes regions in the form of p – n junctions in which both types of free charge carriers – electrons and holes – play a significant role. Such a design of the heterogeneous waveguides provides not only total electric neutrality in the doping region but also a higher level of mode selection compared to the case when only one type of the charge carriers is used.

As shown earlier in [12], based on the analysis of classical works [21, 22], free electrons in silicon provide a relatively higher level of optical losses than holes. Therefore, we propose in this paper to employ doping with donors in immediate proximity from the waveguide core and with acceptors at the waveguide edges (Fig. 2). The widths of all doping regions were chosen the same (W_g) and to provide the electric neutrality, the concentrations of free electrons and holes are also considered equal. It is important for us to study the optical properties of heterogeneous waveguide structures and, therefore, for convenience but without the loss of generality this paper considers homogeneous distribution of charge carriers over the SOI structure. In addition, one can obtain from [21, 22] a convenient empiric relation between the achievable change in the real part of the refractive index (Δn) and the additional absorption ($\Delta\alpha$) by free charge carriers, which appears in this case. For the wavelength $\lambda_0 = 1.55$ μm in silicon, this relation has the form [12]:

$$\Delta\alpha_e = 0.12|\Delta n_e|,\ \Delta N_e = 1.14\times10^{21}|\Delta n_e|,$$
$$\Delta\alpha_h = 0.16|\Delta n_h|^{5/4},\ \Delta N_h = 2.18\times10^{21}|\Delta n_h|^{5/4}. \quad (1)$$

Here, ΔN_h and ΔN_e are the volume (in cm^{-3}) concentrations of holes and electrons; the losses $\Delta\alpha_e$ and $\Delta\alpha_h$ are measured in cm^{-1}. It is assumed in this case that the total change in the complex refractive index due to the light dispersion by free charge carriers is described by the expression [21]:

$$\Delta n = \Delta n_h + \Delta n_e + i\Delta\alpha\lambda_0/4\pi, \quad (2)$$

where $\Delta\alpha = \Delta a_h + \Delta\alpha_e$; $\Delta n_e = -8.8\times10^{-22}N_e$; $\Delta n_h = -8.5\times10^{-18}(\Delta N_h)^{4/5}$.

These equations allow the complete characterisation of optical properties of heterogeneous waveguides at arbitrary increments Δn_h in the real part of the refractive index due to the presence of free holes and the search for optimal parameters of waveguide structures (in our case $\Delta N_h = \Delta N_e$ and, hence, $\Delta n_e = 1.91|\Delta n_h|^{5/4}$) as well as the concentration of free charge carriers necessary for it to be determined from (1).

Consider a strip SOI-based waveguide (Fig. 2) of width $W_0 = W + 4W_g$, whose edges have heavily-dopes p^+ and n^- regions of width W_g in which the refractive index is smaller than in the waveguide core of width W due to dispersion by free charge carriers. Therefore, due to heavily-doped regions, a heterogeneous optical waveguide is formed (Fig. 3a) in which three additional strongly-coupled weak-contrast optical waveguides are produced based on multimode high-contrast waveguide (silicon – oxide). By selecting $|\Delta n_h| \approx 0.002$ (for $\Delta N_h \sim 9.2\times10^{17}$ cm^{-3}), it is easy to provide the concentration of the main fraction of the fundamental mode energy in the central part of the waveguide of width W. In general the properties of this fundamental mode, except lower optical losses, are similar to those of the zero mode of a standard semiconductor waveguide produced due to the gradient of the free charge carriers [23].

Fundamental differences appear for all other modes of the heterogeneous waveguide, whose effective refractive indices are close or smaller than those of the doped region. Their optical fields occupy all the region of the waveguide W_0, therefore, the energy fraction falling into the dissipative region is manifold larger than that of the fundamental mode (Fig. 3a). Thus, these modes inevitably strongly decay by free carriers, which increases with the mode number. These assumptions were confirmed by direct calculations with the help of the BPM method [15]. Figure 3b illustrates the dependence of optical losses in two first waveguide modes as a function of Δn_h for widths W_0 and W. One can clearly see that the high selection of the fundamental mode is achieved for rather wide optical waveguides ($W_0 \sim 35$ μm), its optical losses being very low (−2.1 dB and −1.4 dB for $W = 10$ and 12 μm, respectively). We can assert that the use of the p – n junction leads to a substantially better selection of the fundamental mode with respect to the higher-order modes. In particular, for an optical waveguide with the characteristic length ($W_0 \sim 35$ μm) providing −3-dB optical losses in the fundamental mode, an additional decay for the first mode by free charge carriers with respect to the decay level of the fundamental mode in the case of the p – n junction is −20.4 and −15.8 dB for $W = 10$ and 12 μm, respectively, compared to −10.5 and −11.8 dB for the case of p^+ doping only.

Therefore, a wide heterogeneous SOI waveguide takes properties of a single-mode waveguide. In particular, this is clearly demonstrated upon its off-axial excitation by a Gaussian optical beam (Fig. 1b). One can see its fundamental difference from the case of excitation of a multimode waveguide when large amplitude oscillations of the transverse field distribution are observed (Fig. 1a). Independent

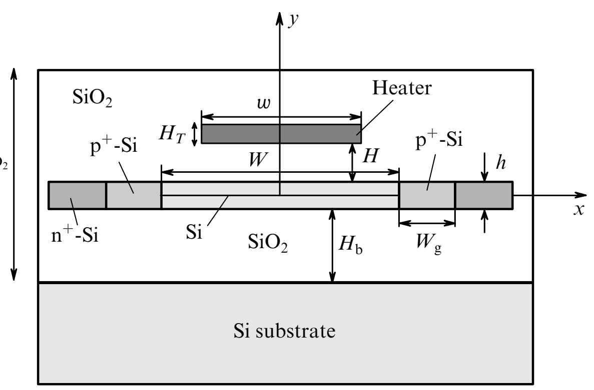

Figure 2. Principal scheme of a heterogeneous optical SOI waveguide with a local heater.

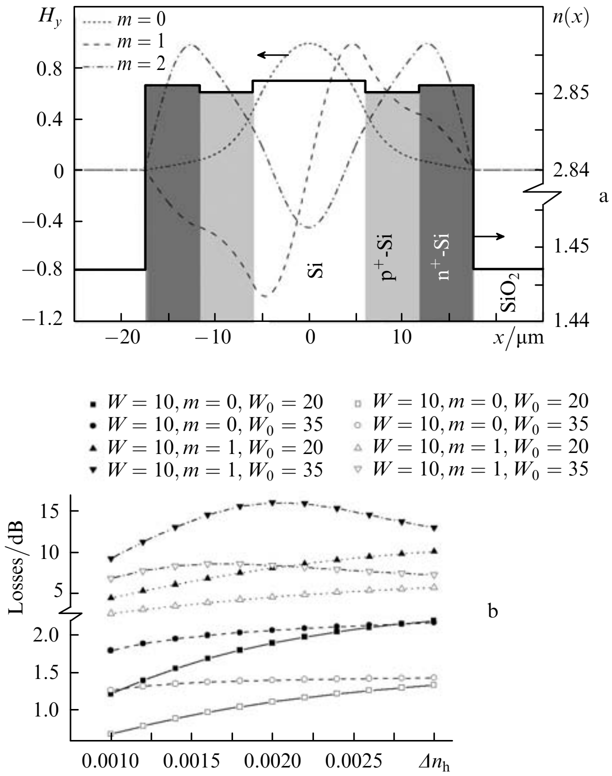

Figure 3. Optical properties of heterogeneous strip waveguides on thin SOI layers. Distribution of the real part of the refractive index and optical fields of the first three modes (W = 10 μm, W_0 = 35 μm) (a) and additional optical losses on free charge carriers in a strip optical waveguide for different waveguide modes as a function of the increment of the real part of the refractive index in the p^+ region for W = 10 and 12 μm, m = 0 and 1 as well as W_0 = 20 and 35 μm (b). Calculation is performed by the 2D-BPM method.

of the excitation character, at the output from a heterogeneous waveguide only the fundamental mode with substantially lower losses than all other modes, which can be present in a waveguide at the instant of its excitation, is produced.

The obtained results clearly demonstrate that a heterogeneous waveguide with a silicon core $\sim 0.22 \times 35$ μm can be a quasi-single-mode one with optical losses less than 1.5 dB cm^{-1}. An additional advantage of heterogeneous waveguides is a weak dependence of optical losses on the roughness of its side boundaries due to a large width of the heterogeneous waveguide and isolation of the fundamental mode field from the dissipation sources with the help of p – n regions. Thus, its optical losses are expected to be lower than those (~ 2.4 dB cm^{-1}) for a single-mode strip SOI waveguide of a smaller cross section (0.22×0.50 μm) manufactured by using the CMOS technology [13].

3. Optical multiplexers based on heterogeneous optical waveguides

Unique properties of heterogeneous optical waveguides make them promising for many applications in photonics and integrated optics. In particular, it is reasonable to use them during the development of tunable optical filters and multiplexers based on the multireflection technology (Fig. 4). Multireflection beam expanders form the basis of this technology [2, 3]. They can be produced by forming a set of partially reflecting elementary reflectors with variable values of the reflection coefficient (usually 0.1 % – 1 % [7 – 9]) along a strip optical waveguide.

It is known [8, 9] that an oblique position of the waveguide in the multiplexer (Fig. 4a) increases the slope of the temperature wavelength tuning ($\delta\lambda/\delta T$), which can achieve record-high values (~ 0.6 nm $°C^{-1}$) without the use of the Vernier principle [24] for the angle $\theta = 60°$. The geometrical factors characterising the multiplexer are determined by two parameters [8]:

$$\sigma_r = (1 - \sin\theta)^{-1}, \qquad \sigma_x = \cos\theta(1 - \sin\theta)^{-1}, \tag{3}$$

where θ is the orientation angle of the beam expander with respect to the y axis (Fig. 4a). The parameters σ_r determines a relative increase in the period d_r of the reflector position along the beam expander and specifies the magnification factor of the slope of the temperature wavelength tuning with respect to the case of a multiplexer with orthogonal orientation ($\theta = 0$). Similarly, the parameter σ_x determines a relative increase in the period d_x of the connecting waveguide position along the x axis (Fig. 4a):

$$d_r = \sigma_r d_0, \quad d_x = \sigma_x d_0, \quad d_0 = \mathrm{Integer}(\lambda_0/\Delta\lambda)\lambda_0/(2N_m), \tag{4}$$

where Integer is an integer part; $\lambda_0 \sim 1.54$ μm is the central wavelength of the multiplexer; $\Delta\lambda \sim 40$ nm is the bandwidth of the multiplexer tuning; $N_m \sim 2.85$ is the effective refractive index of the fundamental mode of a SOI waveguide. The main geometric parameters of the multiplexer are presented in Table 1. One can see that due to a small refractive index and low thermal conductivity of the silicon oxide, the SOI waveguides are not optically or thermally coupled for a gap of 3 μm between them. Therefore, for $\theta \sim 60°$ the geometrical dimensions of

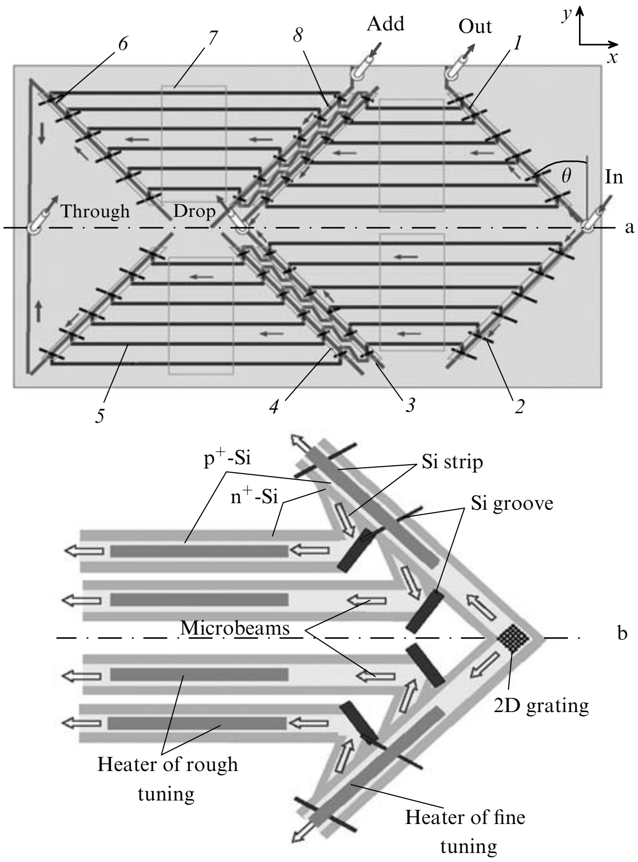

Figure 4. Principal scheme of a multireflection SOI multiplexer. The general scheme of the multiplexer (a) and the scheme of the multiplexer region near the input element from the fibre to the waveguide with the help of a 2D grating (b): (*1*) input beam expander (In) with a control output (Out); (*2*) elementary reflector; (*3*) strip waveguide of a beam expander of the filtration channel (Drop); (*4*) phase-shifting elements of fine tuning; (*5*) array of transverse coupling waveguides; (*6*) strip waveguide of a beam expander of the propagation channel (Through); (*7*) phase-shifting elements of the rough tuning; (*8*) strip waveguide of a beam expander for adding a signal (Add).

wide heterogeneous optical waveguides meet the requirements to the parameters of multireflection multiplexers. In this case, a more than seven-fold increase in the slope of the wavelength tuning is provided compared to the slope, when other tunable multiplexers are used, for example, based on ring resonators.

Table 1.

Parameter	θ/deg				
	0	50	55	60	65
σ_x	1.000	2.747	3.172	3.732	4.511
σ_r	1.000	4.274	5.530	7.464	10.673
d_x/μm	10.61	29.14	33.64	39.58	47.84
d_r/μm	10.61	45.33	58.65	79.16	113.20

The incidence angle of light on the reflector equal to 75° corresponds to the case $\theta = 60°$. For this angle of incidence the reflection coefficients necessary for the optimal operation of the multiplexer are achieved due to insignificant changes in the refractive index of reflecting strips, which perform the function of elementary reflectors. Figure 5a shows the power dependence of the reflection and transmission coefficients for 0.7-μm wide reflecting strips obtained in the presence of doped p^+ regions in silicon. This allows one to design multireflection elements by controlling the concentration of charge carriers (holes) in a semiconductor.

An alternative approach to the production of multireflection elements is shown in Fig. 4b. In this case, the multiplexer is structured so that the optical microfluxes should be incident on elementary reflectors at an angle close to the Brewster one. Then, in the case of quasi-TE modes of a three-dimensional waveguide, the reflection coefficient can be rather small even in the case of a high contrast of the refractive index in the waveguide and reflector materials. This allows the design of elementary reflectors in the form of deep nanogrooves intersecting the core of the SOI waveguide. Figure 5b presents the results of the calculation of the TM_0-mode reflection coefficient (corresponds to the quasi-TE polarisation of the 3D waveguide) by the incidence angle of light on the reflector in the form of a deep groove of different widths by the 2D-FDTD method. One can see that by changing the angle of incidence (and the groove width) one can vary in a broad range the reflection coefficient from an elementary reflector. Therefore, the manufacturing technology of nanogrooves can be used to design multireflection multiplexers. The advantage of this technology consists in the possibility to exclude the filling in of the groove with a material with other optical properties, which is often required to provide a small reflection coefficient [8].

Note that for incidence angles close to the Brewster angle, the shape of the reflected beam is transformed. As a result, many high-order modes are present in the reflected beam, which is illustrated in Fig. 5b by light circles corresponding to the total energy of all modes in the reflected wave. Although this effect causes an increase in total losses in the multiplexer, it does not lead to the appearance of parasitic multimode oscillations because all highest modes rapidly decay upon their further propagation along a heterogeneous optical waveguide.

To confirm this, we performed a direct numerical simulation of a multireflection multiplexer by the 2D-FDTD method (Fig. 6). It is known that the FDTD method is critical to the dimensions of the calculation region. Therefore, taking into account the suitability and our computational capabilities for the analysis, we chose a multiplexer with a rectangular orientation of waveguides ($\theta = 0$) and three multireflection beam expanders, each of which contains 32 identical equidistantly-separated reflectors in the form of deep grooves of width 50 nm with a step of 7 μm. The presence of free carriers (holes) was simulated by introducing a complex refractive index of a material surrounding the strip waveguides.

Figure 6a shows the general scheme of the device and the amplitude distribution of the TM-mode field (H_y) during the propagation of an optical beam in the device. The optical wavelength of 1.526 μm corresponds to the maximum efficiency of filtration of optical radiation from the input beam expander (In) to the intermediate expander (Drop). One can see that a greater part of energy is filtered and,

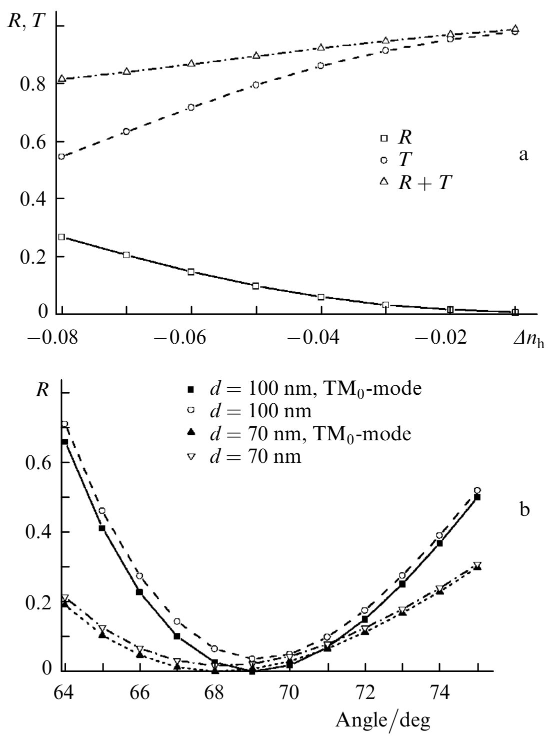

Figure 5. Dependences of the reflection and transmission coefficients as a function of increment of the real part of the refractive index caused by the presence of free charge carriers (holes) in the reflector strip of width 0.7 μm (a) and reflection coefficient as a function of the incidence angle of light onto the reflector in the form of a deep groove of thickness 70 and 100 nm, $W = 10$ μm (b). Calculation is performed by the 2D-FDTD method.

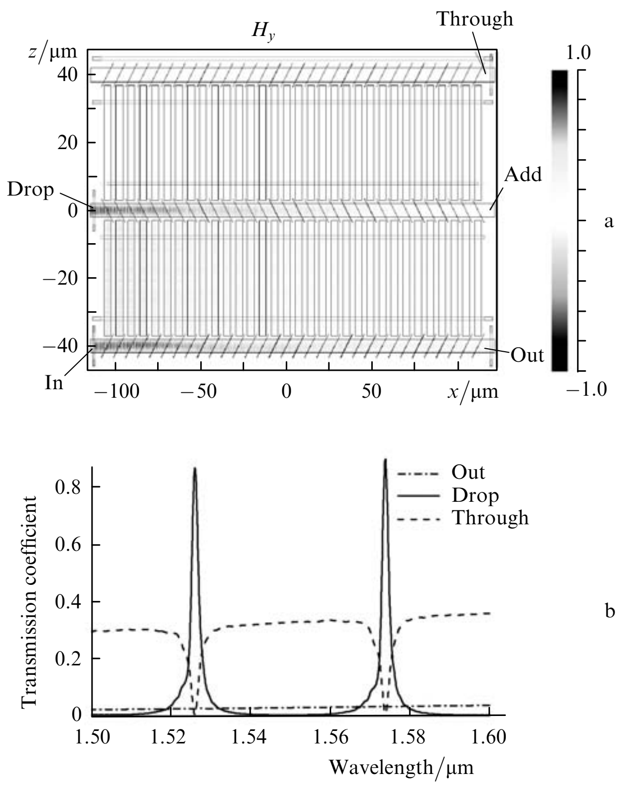

Figure 6. 2D-FDTD numerical simulation of a multireflection multiplexer with the rectangular orientation and three beam expanders with 32 reflectors in the form of a deep groove of thickness 50 nm and a step of 7 μm: the field amplitude distribution H_y during the propagation of an optical beam at a wavelength of maximum filtration (1.526 μm) in the multiplexer (a) and calculated power dependence of the transmission coefficient (b) (the waveguide length is 4 μm).

Table 2.

G/GHz	X/cm	Y/cm	ILt/dB		ILd/dB	
			$\alpha_{loss} = 1.5$ dB cm^{-1}	$\alpha_{loss} = 1.0$ dB cm^{-1}	$\alpha_{loss} = 1.5$ dB cm^{-1}	$\alpha_{loss} = 1.0$ dB cm^{-1}
25	8.45	1.73	18.6	14.2	13.9	10.7
50	4.53	0.92	12.1	9.7	9.6	7.9
100	2.60	0.62	9.4	8.1	7.6	6.5

hence, a small fraction of energy reaches the output of the first beam expander (Out) and the last beam expander of the propagation channel (Through). The dependences of the spectral transmission for different channels of the multiplexer presented in Fig. 6b show that the device does serve as an optical multiplexer and filter the specified wavelength to the Drop channel. All other unfiltered wavelengths pass to the output of the device to the Through channel. Based on the device symmetry, it is easy to illustrate that a signal at a 1.526-μm filtration wavelength can be coupled to the device through the right end (Add) of the intermediate beam expander and correspondingly, be redirected (with minimum losses) to the output of the Through device.

Better spectral resolution and suppression of parasitic signals in the multiplexer can be achieved due to an increase in the number of reflectors and an optimal choice of their reflection coefficient as well as due to the use of a separate beam expander for the Add channel (Fig. 4a). The spectral properties of such multiplexers intended for operation with a network of high-density frequencies are described earlier in [7, 8]. It is important to emphasise that although these results were obtained for ridge SOI waveguides, they can be used in multiplexers with heterogeneous optical waveguides.

To make the multiplexer operable, it is important also to provide a possibility of a small-scale bent with low losses of optical waveguides (see, Fig. 4b). One of the advantage of waveguides with high-contrast refractive indices consists in the fact that they readily realise this bent [14]. The proposed heterogeneous waveguide structures preserved this important property. In particular, with the help of the 2D-FDTD method we studied the possibility of changing the direction of heterogeneous strip waveguides due to total internal reflection from deep grooves of width 1 μm. For the incidence angles of 30°, 45° and 60° additional rotational losses were 0.2, 0.13 and 0.04 dB, respectively. This allows one to change the direction of strip waveguides within $60^\circ - 120^\circ$ with low losses, which meets all the requirements of designing multiplexers with an inclined orientation.

As was shown earlier in [7, 8], the wavelength of the proposed multiplexers can be controlled with a thermooptic effect. Thermooptic phase-shifing elements placed along beam expanders can perform fine wavelength tuning whose tuning curve steepness for inclined structures increases by several times (see Table 1). Thermooptic phase-shifting elements for rough tuning are placed along the connecting strip waveguides. They allow one to tune discretely the wavelength in a broad spectral range upon small changes in the control temperatures. The consistent usage of fine and rough tunings provides wavelength tuning within telecommunication C or L bands at record-low control temperatures [7, 8].

The performed research allows us to offer a new design of tunable optical multiplexers, whose principal elements are schematically presented in Fig. 4. The basis of the optical scheme is heterogeneous optical waveguides on thin SOI structures. The regions with a high concentration of free charge carriers (in the form of p – n junction at the waveguide edges) provide low optical losses and quasi-mode behaviour of wide heterogeneous silicon waveguides. These regions serve to isolate optical modes of intersecting waveguides in order to provide simultaneously low losses due to the intersection.

To couple in and out optical radiation, two-dimensional nanogratings are used, which couple in optical radiation of two orthogonal polarisations and direct them as quasi-TE waves over two perpendicular directions along beam expanders of two parallel processing channels. The beam expanders are formed with the help of nanogrooves, the change in the width and angular orientation of which can provide the required values of the reflection coefficient. The direction of coupling waveguides also changes with the help of deep grooves but of a larger (of the order of a micron) width. The working wavelength of the multiplexer is controlled with thermooptic phase-shifting elements [7, 8] having local heaters at the top (see Fig. 2). Low energy and high switching rate are caused by the nanothickness of the silicon core of SOI waveguides and low thermal conductivity of the silicon oxide.

The estimates of characteristic parameters of proposed multiplexers for the orientation angle $\theta = 60^\circ$ are presented in Table 2 for different networks with different ITU grid frequencies G of the International Telecommunications Union. One can see that the proposed technology provides competitive technical parameters at reasonable dimensions of the multiplexer (X and Y), especially for 50- and 100-GHz frequency networks. While calculating the introduced losses for the filtration channel ILd and transmission channel ILt, we used the following characteristic parameters: input/output losses ~ 1.5 dB per input element, internal losses in the multiplexer ~ 1.5 dB, losses due to intersection of waveguides ~ 0.1 dB, control losses ~ 0.1 dB; waveguide losses α_{loss} were used in Table 2 as a parameter.

4. Conclusions

A new type of nanophotonic optical waveguide structures based on silicon-on-insulator technology have been proposed and studied. They represent heterogeneous optical waveguides with heavily-doped $p^+ - n^+$ regions at the edges of the silicon core (in the form of a strip of height 220 nm and width 35 μm surrounded by the silicon oxide). Additional doping provides quasi-single modeness of a heterogeneous waveguide due to low optical losses of the fundamental mode and an increase in the losses of higher-order modes (due to different decay by free charge carriers). The proposed waveguides allow one to design in a new way optical filters and multiplexers based on the promising multireflection filtering technology. Apart from heterogeneous waveguides such devices can include two-dimensional nanophotonic diffraction gratings for coupling light in/out of an optical fibre and for providing a polarisation independence (diversity) of the device, nanogrooves or strips with p^+ regions for the fabrication of multireflection beam expanders as well as local heaters for designing thermooptical control elements of a broadband filtering wavelength tuning within the telecommunication C and L band. Optical properties of heterogeneous optical waveguides and their possible applications in tunable optical filters and reconfigurable optical add/drop multiplexers have been studied based on the numerical simulation by the FDTD and BPM methods by using the commercial software developed by RSoft Design Group Inc.

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