WAVEGUIDES

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Optical properties of wide single-mode strip and grating loaded channel waveguides

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***Abstract*.** **New wide single-mode strip and grating loaded (SGL) channel waveguides made of silicon nitride on the oxide buffer layer of a planar silicon-on-insulator waveguide are studied. The central 10-μm-wide strip produces a multimode channel waveguide and diffraction gratings with a period 0.6 μm built on the structure edges produce mode-dependent additional losses due to radiation to the surrounding medium. The optical properties of these waveguides are discussed using the results of a three-dimensional numerical simulation by the FDTD and BPM methods. It is shown that a wide SGL waveguide is quasi-single-mode one because it has a small propagation loss (~ 0.3 dB cm^{-1}) for the fundamental mode and a high (up to -20 dB cm^{-1}) loss for the higher order modes. The new SGL waveguides are CMOS compatible and can become basic for fabricating new photonic elements, including tunable optical filters and multiplexers based on the multireflector technology.**

Keywords: *integrated optics, optical waveguide, optical loss, silicon-on-insulator, numerical FDTD and BPM methods, multireflector technology*.

1. Introduction

Recently, intensive investigations have been performed in the field of silicon photonics [1], which has an enormous potential for mass production of various functional CMOS-compatible devices as well as for integration of optical and electronic components on a single substrate. In many photonic devices, optical interference effects are used; therefore, to reduce the level of intermode parasitic signals during their operation, it is expedient to use single-mode optical waveguides. In silicon photonics, two types of single-mode channel waveguides, produced in silicon-on-insulator (SOI) structures, are basically used: ridge [2], etched in 'thick' (3 – 5 μm) silicon layers, and silicon nanowires [3 – 5] on 'thin' (200 – 300 nm) silicon layers. Thick waveguides are convenient for efficient matching with the standard waveguides (with the mode field size of 10 μm). Thin silicon wires, due to the inconsistency in their size, are matched more complicatedly with the optical fibre but have a significant advantage resulting from their compatibility with the manufacturing CMOS technology [3].

Optical radiation along the normal from the fibre can be coupled into a thin silicon waveguide by using two-dimensional gratings [6], which not only simplify the coupling but also provide polarisation independence of the devices [7]. To ensure optimal matching with the fibre, the two-dimensional grating is produced in a wide (~ 10 μm) multimode waveguide region, which, using the adiabatic tapered element, is connected to a single-mode silicon wire ~ 450 nm in size. Note that it is also necessary to use wide waveguide regions for providing low scattering losses during the intersection of channel waveguides in various optical circuits [8]. Wide single-mode waveguides are very important for developing optical filters and tunable multiplexers based on the multireflector filtering technology [9, 10].

Thus, there exist many urgent physical and technological problems which require the use of wide single-mode waveguides on thin SOI layers. Unfortunately, the large difference in the refractive indices of silicon and the surrounding oxide make the problem of their manufacturing laborious.

We have proposed recently wide strip and grating loaded (SGL) channel waveguides [11]. Preliminary investigations have shown [11] that these waveguides have small losses and a high level of selection of the fundamental mode with respect to all other modes, which makes them quasi-single-mode ones. The aim of this paper is a detailed study of new wide SGL waveguides on thin SOI layers.

2. Single-mode optical strip and grating loaded channel waveguides in a thin SOI layer

To meet the mutually contradicting requirements to a single-mode waveguide with a broad transverse dimension of the mode field in thin SOI layers, we will use the approach successfully working in the case of heterogeneous waveguides [12, 13]. Namely, based on a silicon core, we will form a channel waveguide and locate the additional regions with a high attenuation coefficient of optical waves so that, due to the different transverse field distribution, the fundamental mode have small losses and all the other modes – very large losses [11 – 15]. To produce the basic waveguide structure, we will use the idea of constructing a channel waveguide with the help of a guiding strip located above the planar waveguide [16].

Note that in real devices the channel waveguides are often separated by deep grooves in silicon [17], intended for thermal insulation of phase-shifting thermooptical elements.

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In this case, this type of the strip SOI waveguide [16] becomes multimode one at any parameters of the guiding strip. To provide selection of the fundamental mode with respect to other modes of a wide waveguide, we will place two more analogous strips along the sides of the main strip forming the waveguide [11] in which diffraction gratings are additionally produced to couple radiation out of the waveguide (Fig. 1a). To simplify the technology, it is assumed (but not obligatory) that the strip forming the waveguide and diffraction gratings are fabricated during one production step, i.e. they have the same thickness d and are separated from the silicon core of the planar base by the oxide layer of thickness h_c. In this case, the diffraction grating has grooves, which are oriented perpendicular to the propagation direction of optical radiation and etched over the entire thickness of the strip, while the whole structure after fabrication is addtionally covered by the same oxide layer. This technological procedure allows one to exclude the influence of the oxide etching below the strip on the optical properties of the waveguide.

Note that the properties of this optical waveguide strongly depend on the refractive index, the thicknesses and spatial position of the elements forming the structure. To demonstrate the high optical properties of the proposed waveguide structures, we used, as an example, the strips made of the silicon nitride (Si_3N_4) on the silicon dioxide sublayer. This technology is widely used in photonics [18]. As in the case of application of two-dimensional grating input–output elements, we consider here only TE-polarised waves whose electric field vector lies in the waveguide plane. In the analysis we used the following refractive indices: 1.447, 2.0, and 3.478 for oxide, silicon nitride, and silicon, respectively. The SOI structure had the parameters standard for the silicon photonics: the silicon core thickness of 220 nm, the oxide buffer depth of 2 μm. This makes it possible to neglect the effects of the optical leakage through the thick buffer oxide layer from the waveguide to the silicon substrate.

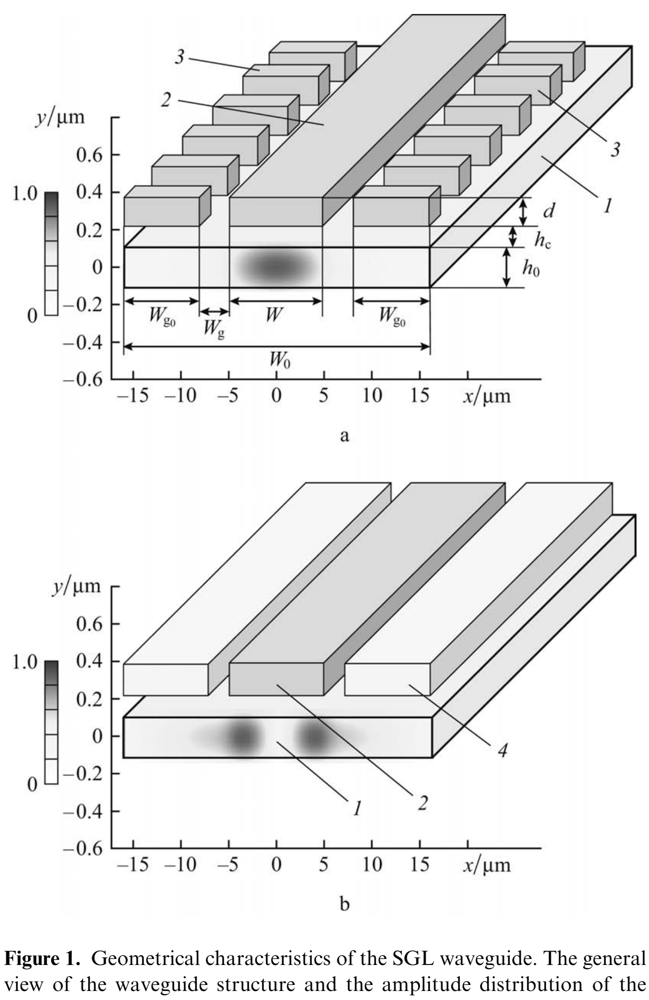

Figure 1. Geometrical characteristics of the SGL waveguide. The general view of the waveguide structure and the amplitude distribution of the electromagnetic field of the fundamental mode (a), the general view of the equivalent waveguide and electromagnetic field distribution of the first waveguide mode (b); (*1*) planar base of the silicon waveguide; (*2*) silicon nitride strip above the buffer oxide layer; (*3*) silicon nitride diffraction grating; (*4*) attenuation region of the equivalent waveguide; W and d are the strip width and thickness; W_{g_0} is the diffraction grating width; W_g is the region width between the strip and the grating; W_0 is the total width of the planar base of the waveguide; h_c is the buffer layer thickness.

These SGL waveguides can have very small losses (less than 0.5 dB cm^{-1}) [11]; therefore, the dimensions of the three-dimensional waveguide structures to be analysed should be rather large. This creates certain difficulties when attempts are made to study them using the known numerical methods. At the same time, the general SGL waveguide structure (Fig. 1a) is very convenient for numerical simulations with the help of the beam propagation method (BPM) [19], except the regions with the submicron diffraction gratings, the potentials of this method being insufficient for the correct analysis.

It is physically obvious that when an optical wave propagates along the SGL waveguide, the presence of the diffraction grating will be revealed as a perturbation of the refractive index and as the appearance of additional optical losses caused by the grating coupling with the radiation modes. It is known that within the framework of the effective medium theory [20], the subwave three-dimensional periodic structure can be replaced by an anisotropic film whose optical axis is perpendicular to the groove axis and the ordinary and extraordinary refractive indices are determined from the expressions [20, 21]:

$$n_o^2 = (1-f)n_1^2 + fn_2^2,$$
$$n_e^2 = (n_1 n_2)^2/[(1-f)n_2^2 + fn_1^2], \quad (1)$$

where n_1, n_2 are the refractive indices of media 1 and 2; f is the filling coefficients of medium 2. Therefore, in the absence of resonances, it is proposed to simulate this three-dimensional periodic waveguide structure with the help of an equivalent waveguide (Fig. 1b) in which the diffraction grating is replaced by a strip with the complex refractive index. Its real part n_r is determined by the effective medium theory ($n_r = n_o$ for the TE polarisation), while the imaginary part n_i is found from the condition that radiation attenuation in the equivalent structure coincides with the losses L of the initial grating loaded waveguide. Thus, we assume that if the correspondence of the parameters of the equivalent and initial (grating loaded) waveguide is known, we can reliably describe the optical properties of arbitrary SGL waveguides using the BPM method.

3. Attenuation of optical waves in a grating loaded SOI waveguide

Propagation of an optical wave in a strip SOI waveguide under the diffraction grating can be analysed using different methods [22–24]. In this paper, we used the finite-difference time domain (FDTD) method [25, 26], which allows numerical solution of the problem of optical beam propagation in an inhomogeneous medium in the presence of a three-dimensional diffraction grating with arbitrary parameters (without any additional simplifying assumptions). From the convenience and technological expediency considerations, we assume that the grating is of a rectangular shape (Fig. 1a) with the groove width equal to the half the grating period ($f = 0.5$). When using the approach of equivalent waveguides, it is important that at the working wavelength $\lambda_0 \sim 1.55$ μm, we do not observe strong interference effects, which can lead to drastic changes in the attenuation coefficient. The effective refractive index of a typical waveguide on a thin SOI is 2.856; therefore, the grating period D is chosen equal to 0.6 μm, which leads to radiation coupling out at an angle slightly different from the normal to the waveguide surface. In this case, the spectral transmission of the grating loaded waveguide is a smooth function of the radiation wavelength in a rather broad (more than 40 nm) region, which makes it possible to describe it by the method of effective waveguides.

We found the parameters of the equivalent waveguide using a test three-dimensional structure representing a strip waveguide of width $W_0 = 10$ μm above which there was located a diffraction grating of length $l = 72$ μm, width $W_{g_0} = 9$ μm, thickness $d \sim 0.16$ μm, and period $D = 0.6$ μm. This structure contains the basic elements of the initial SGL waveguide; however, the structure is more convenient for the quantitative analysis by the FDTD method, which is very critical to the size of the numerical simulation region. We measured the optical signal using nine FDTD monitors (for overlap and power integrals) placed equidistantly at $l/8$ from each other. We averaged the signals from each monitor over the last 5000 values of calculated time intervals, plotted their dependences as a function of the corresponding coordinate, and determined the exponential attenuation coefficient.

At the first stage, we found the attenuation coefficients of the waves of the grating loaded waveguide at different h_c and d (Fig. 2). Then, we determined the values of n_i, which provide for the equivalent strip waveguide the same attenuation as that for the test waveguide. In this case, the attenuation of the equivalent strip waveguide was found from the imaginary part of the complex effective refractive index n_{eff} determined by using the 3D BPM method [20, 26]:

$$L = \mathrm{Im}(N_{eff}) \cdot 545750/\lambda_0. \quad (2)$$

The obtained values of n_i as a function of d and h_c are shown in Fig. 2. They represent smooth functions with a strong dependence on the coating thickness and a weak ($\sim 0.5\,\%$) change when the distance from the strip to the silicon core is increased.

4. Numerical analysis of optical properties of a strip and grating loaded channel waveguide

Note that the exact quantitative analysis of optical properties of three-dimensional waveguide structure (Fig. 1a) with the strip and grating loaded coating is a difficult and unsolved problem. In this paper, we propose a rather correct approximate analysis based on the equivalent three-dimensional waveguide (Fig. 1b), which requires, however, an additional scientific substantiation. For this purpose, we selected a

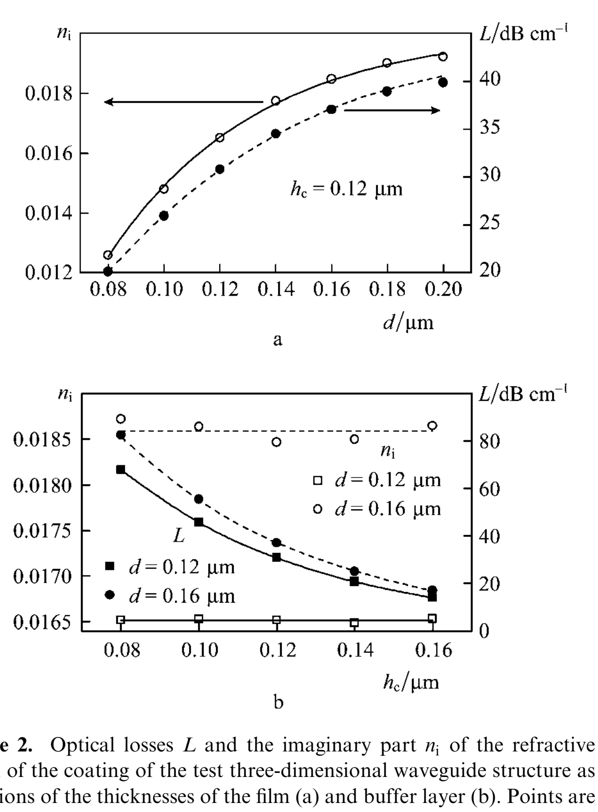

Figure 2. Optical losses L and the imaginary part n_i of the refractive index of the coating of the test three-dimensional waveguide structure as functions of the thicknesses of the film (a) and buffer layer (b). Points are the calculation of the test strip and grating loaded waveguide by the 3D FDTD method, curves are the calculation of the equivalent waveguide by the 3D BPM method.

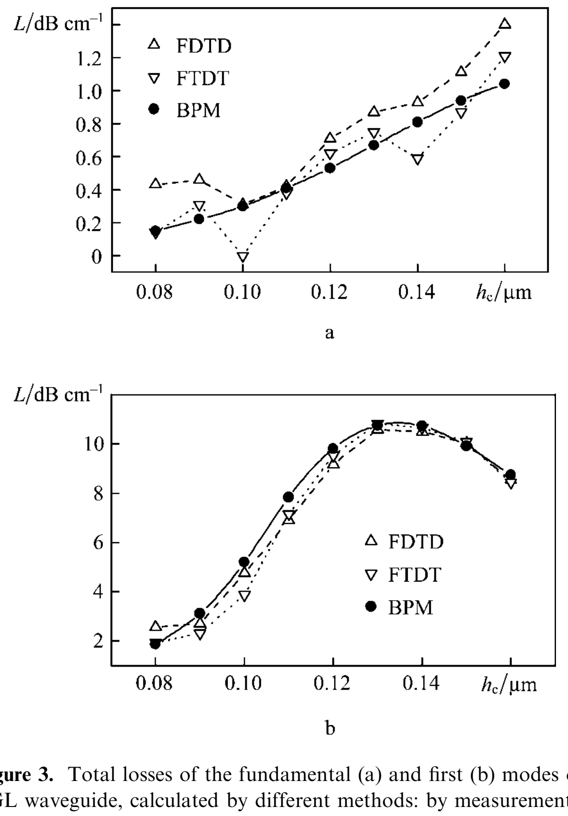

Figure 3. Total losses of the fundamental (a) and first (b) modes of the SGL waveguide, calculated by different methods: by measurement data of the overlap integral (△), power (▽) as well as of the effective refractive index by the BPM method (●); $d = 0.16$ μm, $W_0 = 32$ μm, $W = 10$ μm, and $W_g = 2$ μm.

three-dimensional numerical experiment based on the FDTD method for a series of waveguides with a strip and a diffraction grating containing 120 grooves.

The typical dependence of the attenuation coefficient for different thicknesses h_c of the buffer layer is presented in Fig. 3. One can see that within the ~ 0.5 dB cm^{-1} error, the calculation results of the optical losses in the equivalent waveguide and the initial strip and grating loaded waveguide well agree with each other.

Therefore, the data of the numerical simulations of the SGL waveguide by the 3D FDTD method (Fig. 3) allow one to confirm reliably the assumption about a strong difference in the attenuation levels of the fundamental and the first modes, which makes these waveguides almost single-mode ones. The light propagation in the strip and grating loaded waveguides can be described quantitatively by using the approach of equivalent waveguides.

5. Optical properties of a strip and grating loaded channel waveguide

As noted above, the optical properties of the SGL waveguide depend on many parameters such as the refractive indices, thicknesses, and the mutual position of all the elements forming its structure. In a real waveguide, a significant contribution in the optical losses can be introduce by scattering from the imperfect boundaries and by other mechanisms of losses which are taken into account by the introduced phenomenological parameter of scattering loss in a planar waveguide (L_{sc}) [11]. Our aim is to find such a combination of the mentioned parameters at which small losses of the fundamental mode and large losses for all other waveguide modes are achieved.

Calculations of the equivalent waveguides by the 3D BPM method showed that for almost all practically significant cases, only the first two modes ($m = 0$ and $m = 1$) have the minimum losses; therefore, we will consider only these two modes in the analysis of the waveguide structures. We assume that the SGL waveguides will be further used to develop tunable optical filters based on the multireflector technology [9, 10]. The studies performed earlier show [15] that of most interest are slanted structures of the filters and multiplexers with a large (more than 33 μm) step of the location of the bar of connecting waveguides. In this geometry of the device, high steepness of the temperature dependence of the wavelength tuning ($\delta\lambda/\delta T \sim 0.6$ nm K^{-1}) is achieved, which can exceed by five – ten times the analogous values for all other types of optical filters made of the same material. The analysis shows that the larger the total width $W_0 = W + 2(W_g + W_{g_0})$ of the waveguide structure presented in Fig. 1, the lower the optical losses and the high the selection of the fundamental mode. Therefore, in this paper, we analysed the suboptimal total width of the structure, $W_0 = 32$ μm, and observed how the optical properties of the SGL waveguide change with changing its most significant parameters.

Figure 4 presents the calculations of the optical losses by the 3D BPM mehod for an ideal SGL waveguide ($L_{sc} = 0$) as a function of the thicknesses of the film d and oxide buffer layer h_c at fixed widths of the region W_g, which separates the guiding strip from the diffraction grating. One can see that when the geometrical parameters of the structure change, propagation losses in the waveguide substantially change, these losses being significantly higher for the first mode ($m = 1$) than for the fundamental one ($m = 0$). We are interested in the search for the suboptimal parameters at which the minimum losses of the fundamental mode are accompanied by high losses of other structure modes. To this end, we used the parameter of additional losses L_{add} introduced earlier [12]:

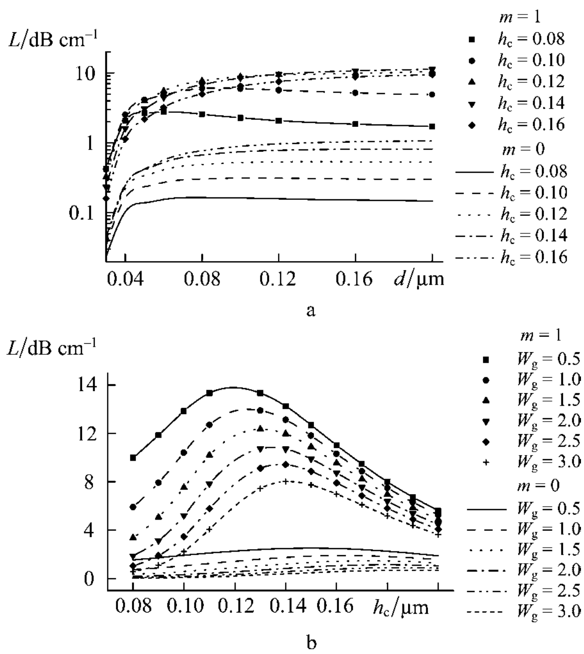

Figure 4. Optical losses of the fundamental ($m = 0$) and first ($m = 1$) modes of the SGL waveguide as a function of the film thickness at different thicknesses (in micrometers) of the buffer oxide layer h_c and $W_g = 2$ μm (a) and as a function of the buffer layer thickness at different thicknesses W_g (in micrometers) of the region between the strip and the grating and $d = 0.16$ μm (b); $W_0 = 32$ μm, $W = 10$ μm, $L_{sc} = 0$.

$$L_{add} = l_0 L_1 - 3\,\text{dB}, \tag{3}$$

where $l_0 = 3\,\text{dB}/L_0$ is the distance at which the fundamental mode attenuates by half; L_0 and L_1 are the losses of the fundamental and first modes. The physical parameter L_{add} is a measure of the fundamental mode selection because it shows the degree of the additional decrease in the signal of the first mode with respect to the fundamental mode in a waveguide with the characteristic length l_0.

The calculation results of additional losses are shown in Fig. 5 for different values of scattering losses and region widths W_g. One can see that at rather perfect wavguide boundaries ($L_{sc} \sim 0.1$ dB cm^{-1} [27]), suboptimal are the waveguides with the region width $W_g \sim 2-3$ μm, which provides the fundamental mode selection at the $-40 \div -60$ dB level and very small propagation losses (0.3 – 0.6 dB cm^{-1}). These values proved higher than those achieved in the case of heterogeneous waveguides [13] ($L_{add} \sim 20-30$ dB). Note that depending on the selected region width W_g, we can obtain a different loss level of the fundamental mode at a high degree of its selection, which is very important for the development of multireflector filters and multiplexers [9, 10, 12 – 15] with a different number of tunable channels, having the waveguides of various length. The large value of W_g (~ 3 μm) provides the best quality of selection at minimum losses. It is expedient to use it for very long structures (longer than 3 cm). For example, for the structure length of 3.1 cm, the total losses can be estimated at -1 dB and the first mode losses – at -20 dB. For shorter structures, it is better to use smaller values of W_g. For example,

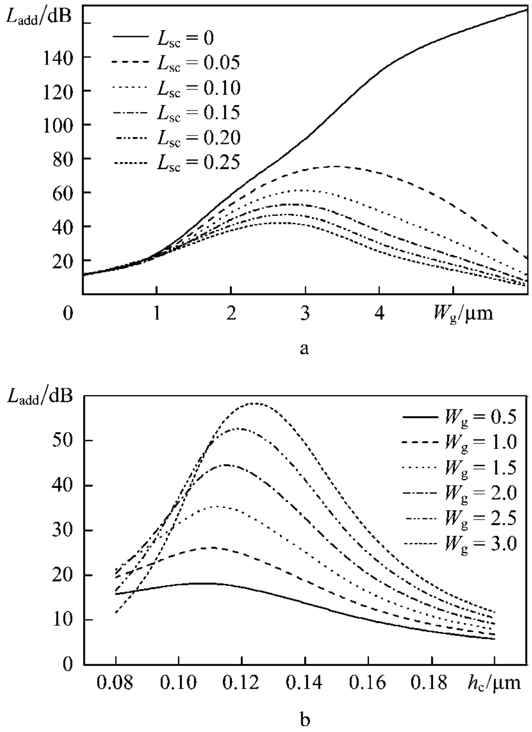

Figure 5. Additional optical losses of the SGL waveguide as a function of the buffer layer thickness at different optical losses L_{sc} (in dB cm^{-1}) in the planar waveguide (a) and as a function of the buffer layer thickness at different widths W_g (in micrometers) of the region between the strip and the grating and $L_{sc} = 0.1$ dB (b); $d = 0.16$ μm, $W_0 = 32$ μm, $W = 10$ μm.

the 1.6-cm-long waveguide with $W_g \sim 2$ μm will have small losses (-1 dB) and a relatively good selection level of the first mode (-14.5 dB).

The single-mode behaviour of wide strip and grating loaded waveguide is demonstrated in Fig. 6, which shows the propagation of a Gaussian beam, displaced by 20 % of the width with respect to the waveguide axis, through the waveguides on silicon of three types. One can see that in a standard channel waveguide (Fig. 6a) and in an ordinary strip waveguide (Fig. 6b), we observe the wave field distortion due to the intermode interference. The SGL waveguide provides strong suppression of all the modes except the zero mode, which leads to a smooth distribution of the optical field at its output. This makes the use of SGL waveguides very promising in any optical elements where wide waveguides are required and where the high level of the intermode interference suppression is necessary, for example, in optical filters and multiplexers based on the multireflector technology [9, 10, 12 – 15].

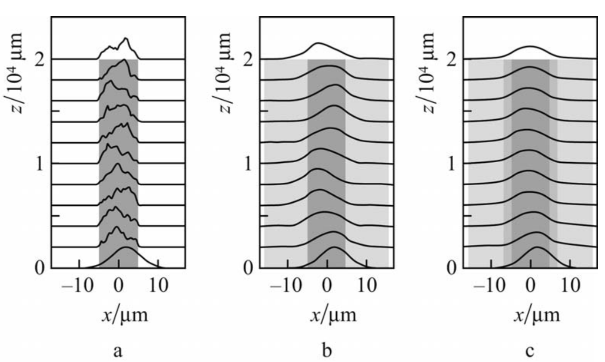

Figure 6. Propagation of a Gaussian beam displaced by 2 μm through different wide waveguides on thin SOI structures – silicon strip waveguide (a), silicon waveguide with a silicon nitride strip (b), and silicon waveguide loaded by a silicon nitride strip and grating (c); $d = 0.16$ μm, $h_c = 0.12$ μm, $W_0 = 32$ μm, $W = 10$ μm, $W_g = 2$ μm.

6. Conclusions

The optical properties of a new wide single mode strip and grating loaded waveguide have been described. These waveguides have been numerically analysed by the example of the silicon-on-insulator structure containing an additional coating in the form of an oxide layer and three thin (~ 0.12 μm) silicon nitride strips. The central strip serves to produce a multimode channel waveguide and the diffraction gratings etched on the two side strips – to select the fundamental mode due to the lattice coupling with the radiation modes. For the optimal choice of the structure parameters, we have observed small (~ 0.3 dB cm^{-1}) losses for the fundamental mode and high losses for all other modes, which makes the wide waveguide (with the transverse mode field dimension of ~ 10 μm) almost single-mode one. Additional losses of the first and further modes can achieve -60 dB in a waveguide of the characteristic length providing the attenuation of the fundamental mode at -3 dB. We have proposed the concept of equivalent waveguide to describe the optical properties of such three-dimensional waveguide structures, in which the diffraction grating is replaced by a strip with a complex refractive index; the parameters of the latter are taken from the equality condition of losses in the grating loaded waveguide and coated waveguide. This has allowed us to analyse different SGL waveguides by using the 3D BPM method. The correctness of this description has been verified by direct numerical 3D simulations using the FDTD method. Wide quasi-single-mode SGL waveguides are promising for the joint use with the diffraction elements of radiation coupling into thin waveguides, with the elements of intersection of wide and thin waveguides as well as for the development of new types of tunable optical filters and multiplexers based on the multireflector technology.

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