New thin heterogeneous optical waveguides on SOI for reconfigurable optical add/drop multiplexers

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Abstract: *This paper presents the new type of heterogeneous optical waveguide on silicon-on-insulator (SOI) and its application for ROADM. The side p-n-doping of 220 nm×35 μm silicon core provides quasi-single-mode behavior due to small optical losses for fundamental mode with 10 μm mode width and increasing losses for the higher modes.*

1. Introduction

Optical waveguides based on thin silicon-on-insulator (SOI) nanostructures are widely used in various photonic elements [1] whose production technology can be compatible with the standard CMOS technology. On the base of thin SOI one can manufacture photonic crystals, nano-scale two-dimensional (2D) diffraction gratings for coupling light from optical fibers or/and for polarization diversity of photonic devices [2].

However, due to a high contrast of the refractive index of the silicon core (n = 3.478) and surrounding oxide (n = 1.447), it is impossible to fulfill simultaneously incompatible requirements imposed on the optimal geometrical dimensions of the waveguide silicon core that have the best fit with 2D grating. To reduce parasitic signals, the waveguide should be single-mode, i.e. it should have the submicron size. In the direction perpendicular to the waveguide axis, this condition is fulfilled due to the small optical thickness (~ 220 nm) of a high-quality silicon layer. At the same time, the width of such strip waveguides should be large enough (about 10 μm) to provide the acceptable matching with the optical fiber, and hence, these waveguides are necessarily multi-mode, containing tens of modes. Traditional way to eliminate this problem is based on the use of adiabatic waveguide coupler that has to change waveguide width about 20 times (from submicron silicon wire to multi-micron grating region).

In this paper, we describe alternative way, that is based on the use of the new thin heterogeneous SOI waveguides with large transverse dimensions (mode size ~ 10 μm), being at the same time a single-mode. The new design contains additionally heavily doped *p-n*-regions on the sides of a multi-mode strip waveguide (with silicon core cross section ~ 220 nm × 35 μm). Such doping provides the quasi-single-mode behavior of the heterogeneous waveguide due to the small optical losses for the fundamental mode and increase in losses for the higher-order modes. This heterogeneous SOI waveguide provides low propagation and waveguide crossing losses and is preferable for jointly use with 2D grating couplers, reconfigurable optical add/drop multiplexers (ROADMs) [2] and multi-reflector filtering photonic devises [3].

New structure design is accomplished by a number of numerical simulations using beam propagation method (BPM) and finite difference time domain (FDTD) method [4]. To have faster simulations, 3D structure has been replaced by its two-dimensional analogy using the effective index method (EIM), which decomposes 3D strip waveguide into two

2D slab waveguides. We use the same width and concentration for p^+ and n^+ - doped regions that provides charge equilibrium of the structure. Besides, the width of *p-n* junction is assumed very small in comparison with the waveguide width that makes possible to use a step shape approximation of the refractive index across the structure.

II. Optical properties of heterogeneous optical waveguide in thin SOI

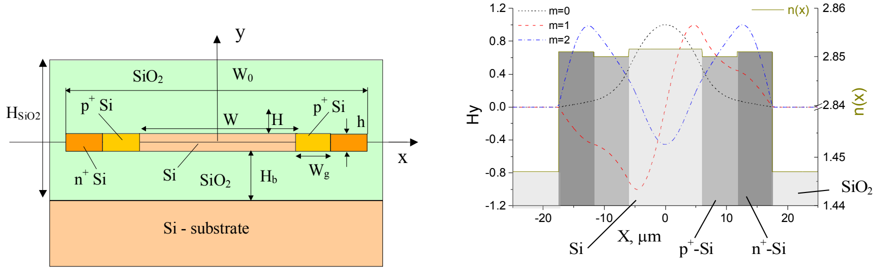
Recently, we propose heterogeneous optical waveguide that contains p^+- doping of sides of wide silicon core [3, 5]. Here we extend this approach for the more preferable case of *p-n* side doping (see Fig.1) that provides even better results. Optical properties are studied on the base of simple relation obtained from the well-known paper by Soref et al. [6]. It describes the change in refractive index (Δn) and absorption ($\Delta\alpha$) at the wavelength of interest ($\lambda_0 = 1.55$ μm) due to presence of free electron (N_e) and hole (N_h) concentration in silicon [3, 5]:

$$\Delta\alpha_e = 0.12\cdot|\Delta n_e| \qquad (1)$$
$$\Delta\alpha_h = 0.16\cdot|\Delta n_h|^{5/4}$$

Thus total change of complex refractive index due to the free charge dispersion effect is:

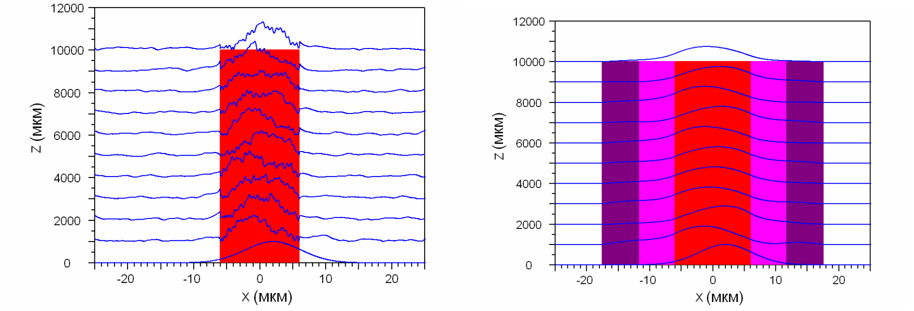
$$\Delta n_c = \Delta n + i\cdot n', \qquad (2)$$

where $n' = \Delta\alpha\lambda_0/(4\pi)$, $\Delta n = \Delta n_h + \Delta n_e$, $\Delta\alpha = \Delta\alpha_h + \Delta\alpha_e$.



a) b)

Fig. 1. Heterogeneous optical waveguide in SOI structure.
a) the structure design; b) distribution of the real part of a refractive index and optical fields of the first three modes (W=*10* μm, W_0=*35* μm, Δn = 0.002); Calculation by 2D BPM.



а) б)

Fig. 2. Propagation of the Gaussian optical beam that is displaced by 2 μm in relation to the axis of wide SOI waveguide. Spatial distribution of a magnetic field of TM polarization (that corresponds to TE in 3D case): a) in standard multi-mode waveguide (W=*12* μm); b) in heterogeneous quasi-single-mode waveguide (W = 12 μm, W_0 = 35 μm). 2D BPM simulation.

The principal difference of standard and heterogeneous optical waveguide is illustrated by the Fig.2 that demonstrates propagation of the Gaussian optical beam that is displaced by 2 μm relative to the core center. One can see that heterogeneous optical waveguide suppressed multi-mode interference that disturbs optical field of wide waveguide (compare Fig.2a and Fig.2b).
This positive effect produced by the *p-n* side doping ($N_h = N_e \sim 9.2{\cdot}10^{17}$ cm^{-3}, $|\Delta n_h| \sim 0.002$, see (1)) that changes the field distribution in those manner that the main part of the fundamental-mode energy in concentrated in the central region of the waveguide of width W (see Fig.1b), while only a very small part of this energy occupies the dissipative region with charge carriers. The optical fields of all other modes with effective refractive indices close to the refractive index in the doped region occupy the entire cross section of the waveguide. Therefore, the fraction of energy occupied the dissipative region increases by many times (Fig. 1b) and that produces considerable additional decay (see Fig.3) of these optical modes by free charge absorption. One can see from the data presented in Fig. 3 that fundamental mode of heterogeneous waveguide has negligible losses related to the losses of the high-order modes and that the losses could be controlled by the structure design.

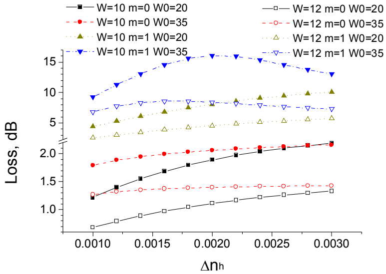


Fig. 3. Additional optical losses by free charge carriers (holes and electrons) in a strip optical waveguide for various modes as a function of real part of refractive index increment in p^+-doped regions. W = 10 μm and W = 12 μm, W_0 = 20 μm and W_0 = 35 μm. 2D BPM simulation.

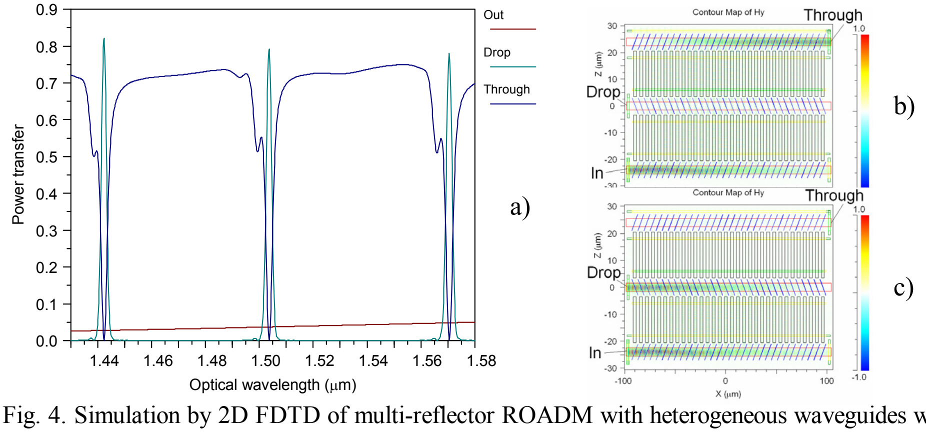


Fig. 4. Simulation by 2D FDTD of multi-reflector ROADM with heterogeneous waveguides with 32 slanted reflectors (φ = 45°) for TM polarization. W = 3 μm, n(reflector) = 1.7, period of reflectors d_x = 6 μm, beam expander period d_z = 24 μm. Variable reflector width from 40 nm to 90 nm. a) frequency response (FWHM = 2.4 nm, FSR = 67.1 nm); b) field map at through wavelength λ_0= 1.55 μm; c) field map at drop wavelength λ_0= 1.5036 μm.

Single-mode behavior and wide mode size, small propagation and waveguide crossing losses [3] make heterogeneous waveguides very suitable for multiple photonics applications. For example, they could be used for construction multi-reflector filtering devices [3]. For the illustration Fig.4 presents simulation by 2D FDTD [4] of typical frequency response of multi-reflector ROADM [3] with heterogeneous waveguides. We use variable reflectors width and position to provide proper apodization of the frequency response. The structure could be manufactured by modern nano-photonics technology.
These results show the need to conduct extensive investigation of novel nano-SOI waveguide structures and devices that utilizes *p-n*-doping, nano-grooves, and 2D-grating couplers. These arrangement could provide polarization diversity and better manufacturability of multi-reflector reconfigurable optical add/drop multiplexers [1-3].

Summary

This paper presents the first description and simulation of novel nano-photonic SOI heterogeneous waveguide structures. New structure design includes *p-n* doping on both sides of SOI strip waveguide with 220 nm × 35 μm silicon cross section surrounded by the silica cladding. It provides small crossing and propagation optical losses for fundamental mode and large losses for high-order modes due to different free charge absorption depending on the modes field distribution that is controlled by the structure design. For example, heterogeneous waveguide with equal level of p^+ and n^+ side doping ($N_h = N_e \sim 9.2{\cdot}10^{17}$ cm^{-3}, $|\Delta n_h| \sim 0.002$, $W = 10$ μm, $W_0 = 35$ μm) has the very different losses of fundamental and the first mode -2.1 dB and -20.4 dB, respectively. That is enough for single-mode optical beam propagation. Incorporation of these novel heterogeneous waveguides with 2D nono-grating couplers provides new opportunity for polarization diversity of ROADM. Thin and wide quasi-single-mode SOI heterogeneous waveguide provides better performance and manufacturability of multi-reflector ROADM that utilizes multi-reflector beam expanders. Multiple simulations by FDTD and BMP methods demonstrate the validity of the new SOI design that will be also interesting for implementation in other multiple nano-photonic optical elements.

Acknowledgments

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