Repository Istituzionale dei Prodotti della Ricerca del Politecnico di Bari

Optical properties of new wide heterogeneous waveguides with thermo optical shifters

This is a post print of the following article

Original Citation:
Optical properties of new wide heterogeneous waveguides with thermo optical shifters / DE LEONARDIS, Francesco; Tsarev, Av; Passaro, Vittorio. - In: OPTICS EXPRESS. - ISSN 1094-4087. - 16:26(2008), pp. 21333-21338. [10.1364/OE.16.021333]

Availability:
This version is available at http://hdl.handle.net/11589/2251 since:

Published version
DOI:10.1364/OE.16.021333

Terms of use:

(Article begins on next page)

28 April 2024

Optical properties of new wide heterogeneous waveguides with thermo optical shifters

Francesco De Leonardis [1], Andrei V. Tsarev [2], Vittorio M. N. Passaro [3*]

[1] *Photonics Research Group, Dipartimento di Ingegneria dell'Ambiente e per lo Sviluppo Sostenibile, Politecnico di Bari, viale del Turismo n. 8, 74100 Taranto, Italy*
f.deleonardis@poliba.it
[2] *Institute of Semiconductor Physics, Siberian Branch Russian Academy of Sciences Prospect Lavrenteva, 13, Novosibirsk, 630090, Russia*
tsarev@.isp.nsc.ru
[3] *Photonics Research Group, Dipartimento di Elettrotecnica ed Elettronica, Politecnico di Bari, via Edoardo Orabona n. 4, 70125 Bari, Italy*
** Corresponding author: passaro@deemail.poliba.it*

Abstract: We present analysis and simulation of novel silicon-on-insulator (SOI) heterogeneous waveguides with thermo-optic phase shifters. New structure design contains a p-n junction on both sides of SOI ridge waveguide with 220 nm×35 μm silicon core. Strongly mode-dependent optical losses (by additional free charge absorption) provide quasi-singe-mode behavior of wide waveguide with mode size ~10 μm. Local heater produces an efficient phase shifting by small temperature increase (ΔT ~ 2K), switching power (< 40 mW) and switching time (< 10 μs). Mode optical losses are significantly decreased at high heating (ΔT ~ 120 K).

©2008 Optical Society of America

OCIS codes: (060.1810) Couplers, switches, and multiplexers; (130.0130) Integrated optics; (130.5990) Semiconductors; (160.6840) Thermo-optical materials.

References and links

1. G. T. Reed, *Silicon Photonics. State of the art* (John Wiley & Sons, Ltd, 2008).
2. W. Bogaerts, R. Baets, P. Dumon, V. Wiaux, S. Beckx, D. Taillaert, B. Luyssaert, J. Van Campenhout, P. Bienstman, and D. Van Thourhout, "Nanophotonic waveguides in silicon-on-insulator fabricated CMOS technology," J. Lightwave Technol. **23**, 401-412 (2005).
3. D. Taillaert, H. Chong, P. Borel, L. Frandsen, R. De La Rue, and R. Baets, "A compact two-dimensional grating coupler used as a polarization splitter," IEEE Photon. Technol. Lett. **15**, 1249–1251 (2003).
4. W. Bogaerts, D. Taillaert, P. Dumon, D. Van Thourhout, and R. Baets, "A polarization-diversity wavelength duplexer circuit in silicon-on-insulator photonic wires," Opt. Express **15**, 1567-1578 (2007).
5. A. V. Tsarev, "New type of heterogeneous nanophotonic silicon-on-insulator optical waveguides," Quantum Electron. **37**, 775-776 (2007).
6. A. V. Tsarev, F. De Leonardis, and V. M. N. Passaro, "Thin heterogeneous SOI waveguides for thermo-optical tuning and filtering," Opt. Express **16**, 3101-3113 (2008).
7. A. V. Tsarev, "Thin heterogeneous optical silicon-on-insulator waveguides structures and their application in reconfigurable optical multiplexers," Quantum Electron. **38**, 445-451 (2008).
8. A. V. Tsarev, V. M. N. Passaro, and F. Magno, "Widely Tunable Reconfigurable Optical Add/Drop Multiplexers in Silicon-on-Insulator Technology: a New Approach," in Silicon Photonics, V.M.N. Passaro Ed., Research Signpost Publ., Trivandrum, Kerala, India: ISBN: 81-308-0077-2, 47-77 (2006).
9. A. V. Tsarev, "Tunable optical filters," United States Patent No 6,999,639, February 14, 2006.
10. A. V. Tsarev, "Beam-expanding device," United States Patent No 6,836,601, December 28, 2004.
11. Comsol Multiphysics by COMSOL ©, ver. 3.2, single license (2005).
12. www.rsoftdesign.com, Rsoft Photonic CAD Suite, ver. 8.0, single license (2007).
13. R. A. Soref and B. R. Bennett, "Electrooptical Effects in Silicon," IEEE J. Quantum Electron. **QE-23**, 123-129 (1987).

1. Introduction

Silicon photonics belongs to rapidly growth science and technology [1]. Optical ridge waveguides based on thin (~ 220 nm) silicon core in silicon-on-insulator (SOI) structures are very suitable as their technology is compatible with semiconductor CMOS technology [2].

#102194 - $15.00 USD Received 29 Sep 2008; revised 29 Oct 2008; accepted 30 Oct 2008; published 10 Dec 2008

Besides, nano-size two-dimensional gratings [3] etched in thin SOI waveguides can be used as fiber-to-ridge waveguide coupler and provide the possibility of polarization diversity [4] without polarization rotators. This 2D-grating element is very compact and couples orthogonal modes from a single-mode optical fiber into two quasi-TE modes of two crossed ridge waveguides, which could be connected to the photonic integrated circuit input/output. However, the grating area in the ridge waveguide can be rather large, i.e. 10 μm, so experiencing a strongly multi-mode behavior, due to high index contrast. Thus, real devices contain adiabatic couplers that transform wide ridge waveguides to single-mode silicon photonic wires, ~ 450 nm wide.

Recently, we proposed the new heterogeneous waveguides [5-7], very suitable for silicon photonics devices. Advantage of heterogeneous waveguide is based on the use of additionally doped regions at both sides of wide (~ 20-35 μm) single-mode silicon rib waveguide with mode size ~10 μm (having mode dependent optical losses by free charge dispersion absorption). These heterogeneous waveguides could represent the base for multiple photonic devices, containing wide waveguide sections for fiber-to-ridge waveguide coupling or low loss waveguide crossing. Recently, new heterogeneous waveguides were tested [6-7] for the application in reconfigurable optical add/drop multiplexers (ROADMs) based on multi-reflector filtering technology [8-9] using waveguide beam expanders [10]. We have performed preliminary thermal simulations [6] of p^+ side doped heterogeneous waveguides by finite element method (FEM) [11], demonstrating their high perspective for ROADMs applications. Later, more advanced heterogeneous waveguides [7] with both n^+ and p^+ doping to provide charge equilibrium of the structure, were proposed and studied. The last structure gives the better fundamental mode selection in comparison with p^+ doped waveguides.

This paper presents for the first time results of numerical simulations of new advanced heterogeneous SOI waveguide with p-n junctions and thermo-optical phase shifters. To provide more general analysis with better accuracy, we have studied local heating of heterogeneous waveguide by FEM [11] and used these results as a refractive index perturbation for beam propagation method (BPM) simulations [12]. To have faster simulations, 3D structure has been replaced by its 2D analogy using the effective index method (EIM), that decomposes 3D strip waveguide into two 2D slab waveguides.

2. Heterogeneous waveguides in thin SOI

A general view of new heterogeneous waveguide is presented in Fig. 1(a). Analysis of classical work [13] discussed in [5-7] shows that free electrons in silicon provide a relatively higher level of optical losses than holes. Therefore, we currently propose to employ doping with donors at the immediate proximity from the waveguide core and doping with acceptors at the waveguide edges (see Fig. 1(a)). The widths (W_g) of all doping regions are chosen as equal and the concentrations of free electrons and holes are also considered equal to assure the electric neutrality. In order to study the optical properties of heterogeneous waveguide structures, we consider homogeneous distribution of charge carriers over the SOI structure.

For convenience, we use the empiric relation (based on [13]) between changes of the real part of both refractive index (Δn) and additional absorption ($\Delta\alpha$), due to free charge carriers at optical wavelength λ_0 =1.55 μm in silicon [5]:

$$\Delta\alpha_e = 0.12|\Delta n_e|,\ \Delta N_e = 1.14\times10^{21}\ |\Delta n_e| \qquad (1)$$

$$\Delta\alpha_h = 0.16|\Delta n_h|^{5/4},\ \Delta N_h = 2.18\times10^{21}\ |\Delta n_h|^{5/4}$$

Here, ΔN_h and ΔN_e are the volume concentrations (in cm^{-3}) of holes and electrons, respectively, and the losses $\Delta\alpha_h$ and $\Delta\alpha_e$ are measured in cm^{-1}. It is assumed that the total change of complex refractive index due to light dispersion by free charge carriers is described by [13]:

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

#102194 - $15.00 USD Received 29 Sep 2008; revised 29 Oct 2008; accepted 30 Oct 2008; published 10 Dec 2008
(C) 2008 OSA

where $\Delta\alpha = \Delta\alpha_h + \Delta\alpha_e$, $\Delta n_e = -8.8\times10^{-22}\,\Delta N_e$; $\Delta n_h = -8.5\times10^{-18}\,(\Delta N_h)^{4/5}$. These equations characterize the optical properties of heterogeneous waveguides at arbitrary increases Δn_h of the real part of refractive index, due to the presence of free holes. To provide charge equilibrium conditions, Eq. (1) gives a simple relation for structure parameters, namely, $\Delta N_e = \Delta N_h$ and $\Delta n_e = 1.91|\Delta n_h|^{5/4}$. Thus, one can examine arbitrary waveguide structures for different concentration of free charge carriers in each doped sections.

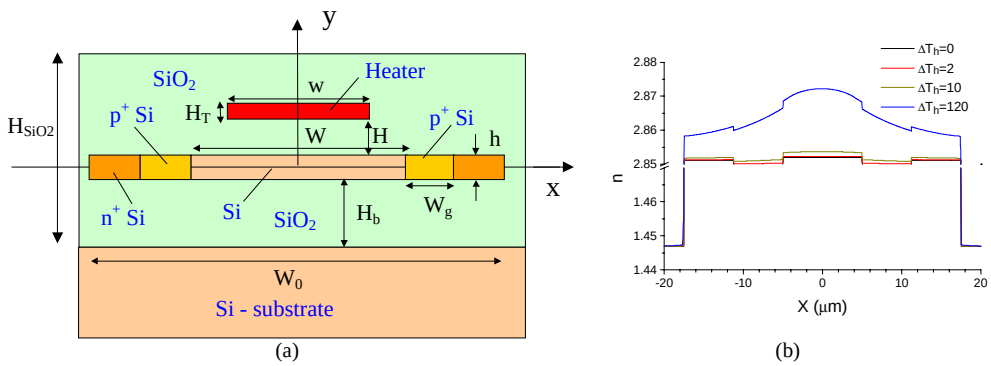
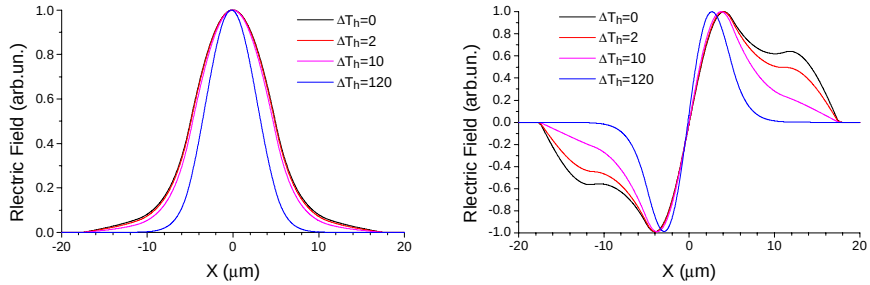


Fig. 1. Heterogeneous SOI waveguide. (a) General view; (b) Refractive index distribution across heterogeneous waveguide for different temperature change (ΔT_h) in the center of waveguide core. h = 220 nm, H_b = 4 μm, w = 8 μm, W = 10 μm, W_0 = 35 μm, H = 0.1 μm, H_T = 0.2 μm. Joint 2D BPM and FEM (for $\Delta T_h > 0$) simulations.

Let us consider a heterogeneous SOI-based waveguide (see Fig. 1(a)) with total width $W_0 = W + 4\cdot W_g$. Waveguide edges have heavily-doped 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. Thus, these two p-n junctions form a heterogeneous optical waveguide (see Fig. 1(b)), in which three strongly-coupled low-contrast optical waveguides are built in the multimode high-contrast waveguide (silicon-oxide).

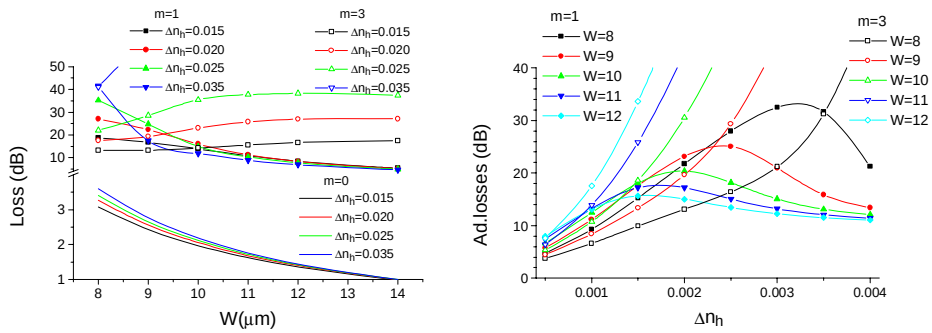
We have examined the optical properties of 3D heterogeneous waveguide by 2D BPM under effective index approximation [7]. Typical field distribution for two low-order guided modes are presented in Figs. 2(a)-2(b) (see case without heating ΔT_h=0 K). The main fraction of fundamental mode occupies the lossless part of waveguide central core with width W. The other modes of the heterogeneous waveguide, whose effective refractive indices N_{eff} are close or smaller than those of doped region, occupy the total region of the waveguide W_0, i.e. the energy fraction falling into the dissipative region is much larger than that of the fundamental mode (compare Fig. 2(a) with Fig. 2(b)). Thus, the higher-order modes must strongly decay by free carriers absorption with respect to the fundamental one. Optical losses for some guided modes (with the smallest optical losses) of heterogeneous waveguide are presented in Fig. 3(a)-3(b) for different structure parameters. It can be seen as heterogeneous waveguide has the strongly different optical losses for fundamental or other modes due to the presence of highly lossy regions. That fact makes heterogeneous waveguide as quasi-single-mode. Fig. 3(a) shows that optical losses for all modes strongly depend on the waveguide core width W, as well as on maximum refractive index increment in the doped region. Fig. 3(b) presents additional optical losses of higher modes with respect to TE_0 mode losses for a heterogeneous waveguide of characteristic length L_0, providing -3 dB losses for fundamental TE_0 mode. It is easily seen that for every core width W one can find a sub-optimal value Δn_h, providing better selection of the fundamental mode for the smallest optical loss.

#102194 - $15.00 USD Received 29 Sep 2008; revised 29 Oct 2008; accepted 30 Oct 2008; published 10 Dec 2008
(C) 2008 OSA



(a) (b)

Fig. 2. Optical field distribution of fundamental (a) and first order (b) modes at different temperature increase in the center of heterogeneous waveguide core. h = 220 nm, H_b = 4 μm, w = 8 μm, W = 10 μm, W_0 = 35 μm, H = 0.1 μm, H_T = 0.2 μm. Joint 2D BPM and FEM simulations.



(a) (b)

Fig. 3. Optical properties of heterogeneous waveguide. (a) Optical losses for different modes as a function of width W, for different Δn_h; (b) Additional optical losses for different modes of heterogeneous waveguide of the characteristic length L_0 as a function of Δn_h, for different center widths W. 2D BPM simulations.

3. Thermo-optic phase shifters in heterogeneous waveguide on SOI

We have analyzed parameters of thermo-optic phase shifter in heterogeneous waveguide by the use of an optimum heater length L_{eff} , corresponding to the phase shift π:

$$L_{eff} = \lambda/(2\cdot\partial n/\partial T\cdot\Delta T) \tag{6}$$

By means of the dynamic analysis [6], the time dependence of temperature and effective index has been evaluated, so estimating the thermo-optic response time and switching power of the analyzed structures as:

$$P_\pi = q_0\, w\, L_{eff} \tag{7}$$

where w is the heater width and q_0 is the heat flux used in the boundary condition for the heater. Results of heat simulations are presented in Fig. 4(a)-4(d). One can see that, due to very thin silicon layer, the heat spreads not only along the waveguide but also into the silica surrounding. Thus, the optimum heater size has to be optimized to the area of the fundamental guided mode (~W). Fig. 4(a) derives information on the switching time, similar both for heating and cooling case and strongly depending on the buffer height. Fig. 4(c) presents the temperature distribution across the waveguide. From the thermo-optic coefficient of silicon ($1.86\ 10^{-4}\ K^{-1}$), we have derived the refractive index change under heating condition (see Fig. 1(b)) and use it as a refractive index perturbation into the beam propagation method [12]. Thus

#102194 - $15.00 USD Received 29 Sep 2008; revised 29 Oct 2008; accepted 30 Oct 2008; published 10 Dec 2008
(C) 2008 OSA

we can analyze thermo-optic properties of heterogeneous waveguide by a fully integrated FEM-BPM joint approach. Fig. 2(a)-2(b) illustrates that, at small temperature increase ΔT_h=2 K and ΔT_h=10 K (corresponding to heat flux amplitude $0.2\times10^{+7}$ W/m^2 and $1\times10^{+7}$ W/m^2, respectively), optical field has not been changed enough, giving a small change in the optical losses (see Fig. 5). However, for a large heating when ΔT_h=120 K ($q_0 = 12\times10^{+7}$ W/m^2), one can see the change in optical modes (Fig. 2(a)-2(b)), as well as in optical losses (Fig. 5).

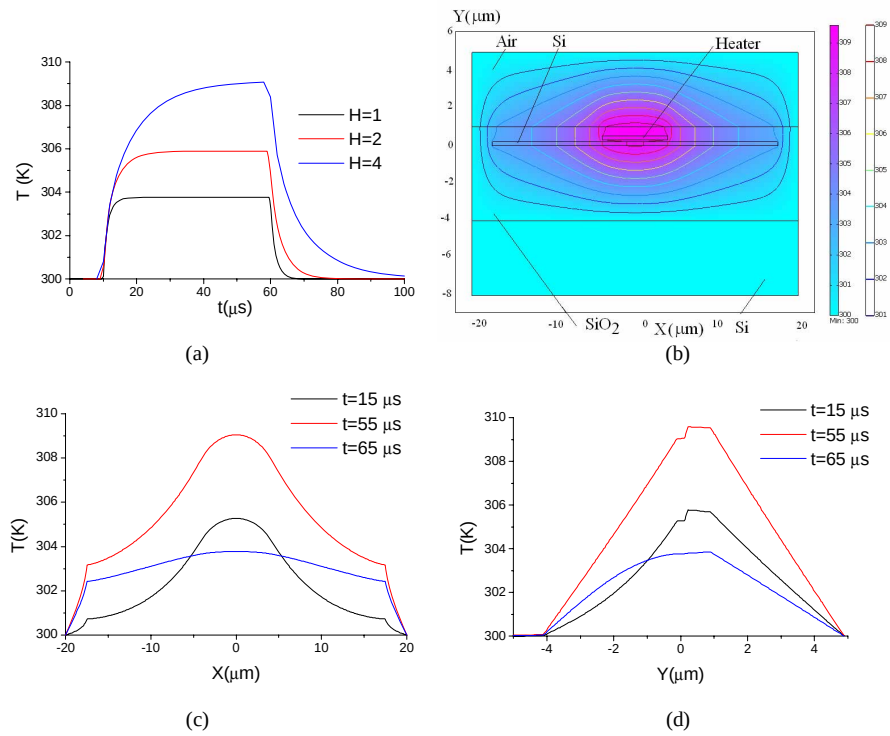


Fig. 4. Dynamic analysis by FEM of thermo-optic phase shifter in heterogeneous waveguide with aluminum heater (placed inside the silica on the top of silicon core). (a) Time response of temperature in the core center for different buffer heights (in μm); (b) Temperature distribution at time t =56 μs; (c) and (d) Cross temperature distribution at various times (5 μs, 45 μs, and 55 μs). Inward heat flux has a step impulse function of 50 μs duration, with amplitude 10^{+7} W/m^2.

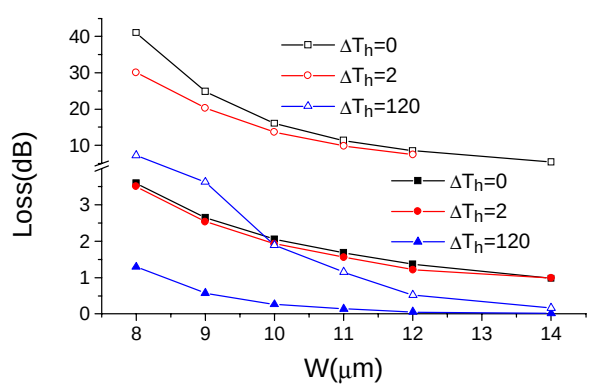


Fig. 5. Optical losses for different heater temperatures of sub-optimal heterogeneous waveguides as a function of core width W. h = 220 nm, H_b = 4 μm, w = 8 μm, W = 10 μm, W_0 = 35 μm, H = 0.1 μm, H_T = 0.2 μm. Joint FEM and 2D BPM simulations.

#102194 - $15.00 USD Received 29 Sep 2008; revised 29 Oct 2008; accepted 30 Oct 2008; published 10 Dec 2008
(C) 2008 OSA

Table 1 summarizes the results of thermo-optical analysis of different heterogeneous waveguides. Phase shifters with heterogeneous waveguides could be easily applied in multi-reflector filtering technology [8], as well as in other photonic devices. For example, phase shifters with small temperature increase could be used as wide tuning elements of ROADM and phase shifters with high temperature increase could be used as ROADM fine tuning elements [8]. The heating efficiency $\Delta N_{eff}/\Delta T_h$, switching power P_π and time τ are strongly dependent on heater width w and height H_b of the silica buffer, that mostly control the rate of the heat flux from the heater to the silicon substrate.

Table 1. Thermo-optic simulation of heterogeneous SOI structure ($q_0 = 2\cdot10^{+6}$ W/m^2).

Δn_h	H_b (μs)	w (μs)	W (μs)	W_0 (μs)	ΔT_h (heater) K	ΔT (core) K	Δn (core)	ΔN_{eff}	L_{eff} (μm)	P_π (mW)	τ (μs)
0.002	4	2	10	35	0.64	0.53	0.000098	0.000084	9.4	37	8.7
0.002	4	4	10	35	1.12	1.01	0.000187	0.000166	4.7	37	8.2
0.002	4	8	10	35	1.99	1.88	0.000337	0.000317	2.5	39	9.3
0.002	4	10	10	35	2.26	2.15	0.000400	0.000383	2.1	40	9.5
0.002	4	8	10	30	1.99	1.88	0.000350	0.000331	2.4	37	9.2
0.0015	4	8	12	25	2.10	1.99	0.000370	0.000340	2.3	36	9.6
0.002	4	8	10	25	2.10	1.99	0.000370	0.000351	2.2	35	9.6
0.0025	4	8	9	25	2.10	1.99	0.000370	0.000355	2.2	35	9.6
0.0035	4	8	8	25	2.10	1.99	0.000370	0.000359	2.2	35	9.6
0.0015	2	8	12	35	1.29	1.18	0.000219	0.000196	4.0	63	3.3
0.002	2	8	10	35	1.29	1.18	0.000219	0.000202	3.9	61	3.3
0.0025	2	8	9	35	1.29	1.18	0.000219	0.000205	3.9	60	3.3
0.0035	2	8	8	35	1.29	1.18	0.000219	0.000209	3.9	59	3.3
0.0015	1	8	12	35	0.86	0.75	0.000139	0.000119	6.5	104	1.4
0.002	1	8	10	35	0.86	0.75	0.000139	0.000124	6.4	100	1.4
0.0025	1	8	9	35	0.86	0.75	0.000139	0.000127	6.3	98	1.4
0.0035	1	8	8	35	0.86	0.75	0.000139	0.000130	6.3	95	1.4

4. Conclusions

This paper presents advanced simulations of novel heterogeneous SOI waveguide structures with thermo-optic phase shifters. New structure design includes *p*-*n*-doping on both sides of SOI ridge waveguide with 220 nm×35 μm silicon cross section, surrounded by silica cladding. It provides small optical losses for fundamental quasi-TE mode and large losses for higher order modes, due to different free charge absorption depending on mode field distribution. Local heaters above the waveguide core provide the highly efficient phase tuning in 10 μs range and several tens of switching power. Novel heterogeneous SOI waveguide structures are interesting for practical applications in multiple nanophotonic optical elements, including ROADMs based on multi-reflector beam expanders, 2D grating couplers and thermo-optic phase shifters.

Acknowledgments

The authors thank Company RSoft Design Group, Inc. for providing user license and technical support for Rsoft Photonic CAD Suite 8.0. This work was partially supported by II Engineering Faculty of Politecnico di Bari with funds by Provincia di Taranto, Italy.

#102194 - $15.00 USD Received 29 Sep 2008; revised 29 Oct 2008; accepted 30 Oct 2008; published 10 Dec 2008
(C) 2008 OSA