Title

Simulations of Silicon-on-Insulator Channel-Waveguide Electrooptical 2×2 Switches and 1×1 Modulators Using a $Ge_2Sb_2Te_5$ Self-Holding Layer

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Abstract

2×2 switches and 1×1 loss modulators based upon GST-embedded SOI channel waveguides

10-nm GST film sandwiched between doped-Si waveguide strips

1.3 to 2.1-μm wavelength range

2×2 Mach–Zehnder and directional coupler switches

1×1 EO waveguide has application as a variable optical attenuator and as a digital modulator for 1.3-2.1 μm

Highlight

The design presented here is new in two ways:
(1) the thin film is placed midway in the body of the waveguide where it has a much stronger effect upon the mode indices;
(2) the phase change—rather than being optically triggered—is electrically induced. (3)utilize both the electro-refraction (ER) and the electro- absorption (EA) component of the induced phase change

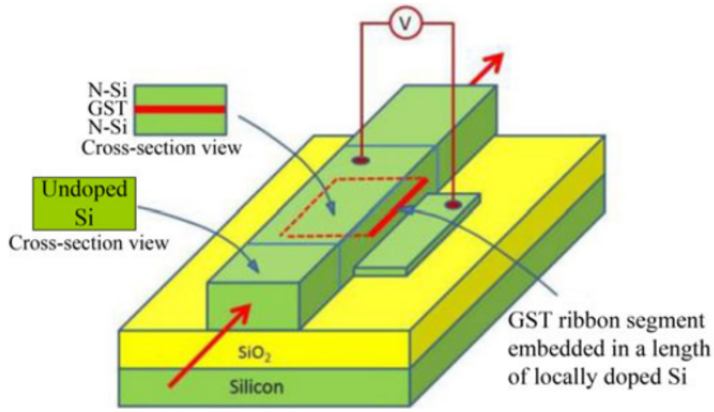
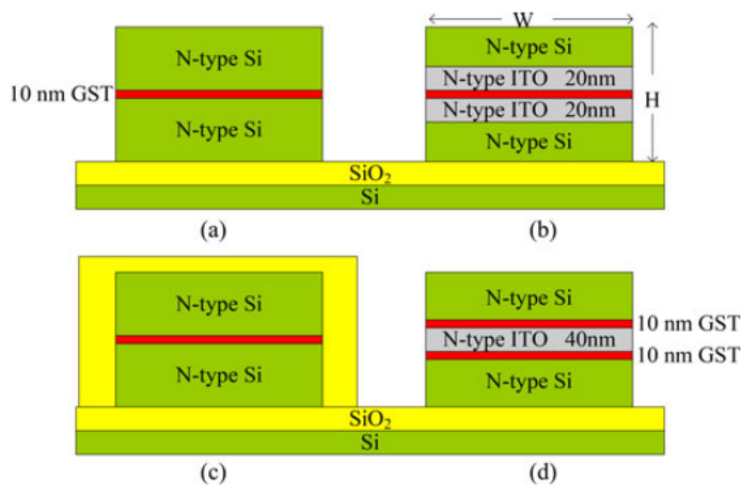


Fig. 1. Perspective view of proposed 1 × 1 SOI EO channel waveguide modulator employing a wavelength-scale segment of "buried" GST ultrathin ribbon.



Unexpectedly, the TE-polarized light is particularly sensitive to the induced change of GST complex index $\Delta n + i\,\Delta k$, more so than in TM. Unexpectedly, the ratio $\Delta n/\Delta k$ is consistently higher in TM than TE. The loss suppression in TM indicates that ER dominates in TM. Thus, with the anti-slot, TM is more favorable for low-loss 2 × 2 switching, whereas TE is the most natural mode polarization for 1 × 1 EA applications.

ELECTRICALLY INDUCED PHASE CHANGE

In detail, the recrystallization requires an applied set voltage pulse of 100-ns duration that induces temperature rise above **413 K** but below **819 K** (the melting point).

As for the changing process from crystalline to amorphous state, a shorter reset voltage pulse of typically 1 to 10 ns duration is employed, and there the GST film temperature must be raised above the melting point(above the **891 K** as desired) and then quenched rapidly by the pulse falling to zero in < 1 ns.

The voltages (5V and 15V) that we applied in both simulations might be considered as "*relatively high*"; however, this is a trade-off we are willing tomake to achieve optimum optical performances in the coming sections.

PERFORMANCE GUIDELINES FOR 2 × 2 SWITCHES

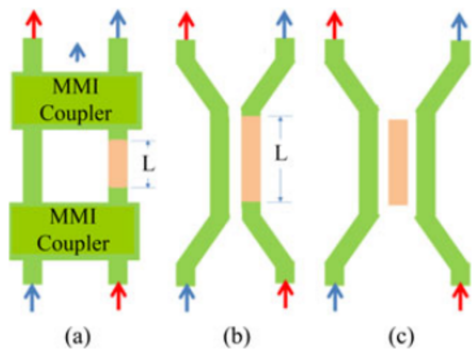


Fig. 3. Top view of proposed non-resonant 2 × 2 SOI EO channel waveguide spatial routing switches: (a) MZI, (b) two-waveguide directional coupler, and (c) three-waveguide directional coupler. The orange-shaded region indicates an embedded electrically addressed GST ribbon segment.

The GST indices are written for the amorphous phase $\mathrm{n_{am}} + \mathrm{i\,k_{am}} = \mathrm{n_1} + \mathrm{i\,k_1}$, and for the crystalline phase $\mathrm{n_{cr}} + \mathrm{i\,k_{cr}} = \mathrm{n_2} + \mathrm{i\,k_2}$, while the channel waveguide has a mode effective index in each state written as $\mathrm{n_{1e}} + \mathrm{i\,k_{1e}}$ and $\mathrm{n_{2e}} + \mathrm{i\,k_{2e}}$. Looking at the extinction coefficient k, let us denote α as the absorption loss of the waveguide in decibel per micrometer in each state, $\alpha = 4.34(4\pi\mathrm{k}/\lambda)$. The IL of an amorphous active waveguide of length L is proportional to the product αL, that is *IL* (dB) $= 4.34(4\pi\mathrm{k_{1e}L}/\lambda)$ and the crystalline-phase loss is $4.34(4\pi\mathrm{k_{2e}L}/\lambda)$. The extinction ratio of a loss modulator discussed below is then *ER* (dB) $= (\mathrm{k_{2e}}\check{\ }\mathrm{k_{1e}})(4.34)(4\pi\mathrm{L}/\lambda)$.

Loss modulation utilizes EA, while ER is mostly neglected: 2 × 2 switching relies upon ER, with additional requirements that: (1) ER >> EA, and (2) absorption loss in the initial cross state is low.

In switches, it is the product of the phase factor $\Delta\beta$ with L, that affects the transfer of light from the input guide to the output guide, where $\Delta\beta L = (2\pi/\lambda)(n_{2e}$˘$n_{1e})$. Values of $\Delta\beta L$ from 3 to 18 are required, depending upon the switch geometry and upon whether the device is resonant or non-resonant. Specifically the Mach–Zehnder interferometer (MZI) requires $\Delta\beta L = \pi$ rad, while the two-waveguide directional coupler needs $\Delta\beta L = 5.4$ rad, and the three-waveguide directional coupler requires $\Delta\beta L = 18$ rad.
To minimize *IL* and crosstalk (*CT*) in both switching states, we generally desire n_{2e}˘$n_{1e} >> k_{2e}$˘k_{1e} with the ratio $\rho = (n_{2e}$˘$n_{1e})/(k_{2e}$˘$k_{1e})$ being as high as possible.

RESULTS OF NUMERICAL SIMULATIONS

PREDICTED 2 × 2 SWITCHING PERFORMANCE:

TABLE I
VALUES OF THE N AND K INDICES THAT WERE UTILIZED IN THE PRESENT SIMULATIONS

Material	$\lambda = 1310$ nm		$\lambda = 1550$ nm		$\lambda = 2100$ nm	
	n	k	n	k	n	k
GST(Amorphous)	4.68	0.33	4.60	0.12	4.05	0.006
GST(Crystal)	7.51	2.38	7.45	1.49	6.80	0.40
N-Silicon	3.50	0.0001	3.48	0.0002	3.45	0.0003
N-Germanium	—	—	—	—	4.09	0.0003
N-ITO	0.96	0.002	1.94	0.002	1.92	0.003
Silicon Dioxide	1.45	0.0	1.44	0.0	1.44	0.0

TABLE II
SIMULATION RESULTS FOR THE FIG. 2(A) WAVEGUIDES

Geometry	Claddings	λ(nm)	W × H(nm)	Mode	Δn_e	Δk_e	ρ	α_{1e}(dB/μm)	α_{2e}(dB/μm)	$\alpha_{2e} - \alpha_{1e}$(dB/$\mu$m)
SGS	3 air 1 oxide	1310	524x262	TE(TM)	0.248(0.039)	0.355(0.006)	0.700(6.704)	1.166(0.314)	15.923(0.555)	14.757(0.240)
		1550	620x310	TE(TM)	0.255(0.031)	0.190(0.005)	1.341(5.906)	0.302(0.090)	6.990(0.274)	6.687(0.183)
		2100	840x420	TE(TM)	0.17(0.027)	0.033(0.002)	5.179(15.311)	0.015(0.012)	0.879(0.058)	0.864(0.045)

TABLE III
SIMULATION RESULTS FOR THE FIG. 2(B) WAVEGUIDES

Geometry	Claddings	λ(nm)	W × H (nm)	Mode	Δn_e	Δk_e	ρ	α_{1e}(dB/μm)	α_{2e}(dB/μm)	$\alpha_{2e} - \alpha_{1e}$ (dB/μm)
SIGIS	3 air 1 oxide	1310	524x 262	TE(TM)	0.212(0.015)	0.317(0.005)	0.667(3.336)	1.024(0.176)	14.236(0.365)	13.212(0.189)
		1550	620x 310	TE(TM)	0.225(0.014)	0.171(0.005)	1.315(3.020)	0.273(0.074)	6.287(0.233)	6.015(0.159)
		2100	840x 420	TE(TM)	0.155(0.015)	0.030(0.001)	5.147(11.724)	0.020(0.037)	0.803(0.070)	0.783(0.033)

TABLE IV

SIMULATION RESULTS FOR THE FIG. 2(C) AND (D) WAVEGUIDES AS WELL AS GERMANIUM IN FIG. 2(A)

Geometry	Claddings	λ(nm)	WxH (nm)	Mode	Δn_e	Δk_e	ρ	α_{1e} (dB/μm)	α_{2e} (dB/μm)	$\alpha_{2e} - \alpha_{1e}$ (dB/μm)
SGS	4 oxide			TE(TM)	0.167(0.025)	0.032(0.002)	5.160(16.038)	0.015(0.012)	0.856(0.053)	0.841(0.041)
SGIGS	3 air 1 oxide	2100	840 × 420	TE(TM)	0.317(0.029)	0.062(0.007)	5.136(4.202)	0.026(0.039)	1.631(0.219)	1.605(0.180)
GeGGe	3 air 1 oxide			TE(TM)	0.147(0.052)	0.028(0.002)	5.178(15.878)	0.014(0.015)	0.751(0.100)	0.736(0.085)

TABLE V

ESTIMATED AND SIMULATED PERFORMANCES OF 2 × 2 SWITCHES USING THE TM-POLARIZED ACTIVE SGS SEGMENT

λ(nm)	PCM	MZI L (μm)	MZI Cross IL(am) dB	MZI Cross CT(am) dB	MZI Bar IL(cr) dB	MIZ Bar CT(cr) dB	2WGDC L (μm)	2WGDC Cross IL(am) dB	2WGDC Cross CT(am) dB	2WGDC Bar IL(cr) dB	2WGDC Bar CT(cr) dB
1550	GST	25	2.3	–15	3.4	–9.9	43	3.9	–15	1.0	–17
2100	GST	38	0.5	–15	1.1	–16	67	0.8	–15	0.4	–22

PREDICTED 1 × 1 MODULATOR AND VOA PERFORMANCE:

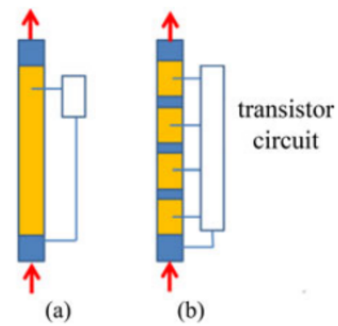


Fig. 10. Top view, schematic, of 1 × 1 EO waveguide (a) loss modulator, (b) VOA with discretized control.

Related work

- Ultra-small self-holding, optical gate switch using $Ge_2Sb_2Te_5$ with a multi-mode Si waveguide
- Small-sized Mach-Zehnder interferometer optical switch using thin film $Ge_2Sb_2Te_5$ phase-change material
- Mid-infrared 2 × 2 electro-optical switching by silicon and germanium three-waveguide and four-waveguide directional couplers using free-carrier injection
- An all-optical non-volatile, bidirectional, phase-change meta-switch

- Self-holding optical switch using phase-change material for energy efficient photonic network