Silicon-on-Insulator Modulators for Next-Generation 100 Gbit/s-Ethernet

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Abstract *Novel SOI modulator schemes with unprecedented electrical bandwidth and compactness are proposed and investigated. We find that 100 Gbit/s modulation at 3 V peak-to-peak voltage is possible with ultra-compact devices of less than 2 mm length.*

Introduction

Optical 100 Gbit/s-Ethernet requires a new generation of low-cost electro-optic modulators that can be mass-produced and integrated into silicon-based electronic microprocessor circuitry. These devices should exhibit low power consumption and bandwidths of several tens of Gigahertz.

So far, the fastest modulation in silicon-on-insulator (SOI) waveguides was achieved by free-carrier injection. Modulation at 20 GHz in a silicon-based device was recently demonstrated in a reverse-biased pn-junction, allowing data transmission up to 30 Gbit/s [1]. The size and power consumption of such devices can be considerably reduced by exploiting slow light in photonic crystal (PhC) waveguides [2]. However, the speed of is inherently limited by the dynamics of the free carriers.

On the other hand, bandwidths of 110 GHz have been demonstrated in modulators based on the linear electro-optic effect (Pockels effect) in polymers [3]. Electro-optic coefficients of such organic materials can exceed 500 pm/V [4]. A first interesting attempt to deploy electro-optic polymers on SOI has been published [5], but the bandwidth is still limited to the low MHz-regime by large RC-time constants.

In this paper, we propose novel schemes for compact SOI-based modulators with large electrical and optical bandwidth and low power consumption. We exploit electro-optic interaction in a cover material that is deposited onto a prestructured silicon waveguide. Our calculations show that these devices can work at and above bitrates of 100 Gbit/s.

Novel SOI Modulator Schemes

Figures 1 and 2 show schematic views of the three novel modulator schemes. In Fig. 1, the light is guided by silicon strips which are embedded in the electro-optic material (EO). Field discontinuities at the high index-contrast interfaces lead to field enhancements that provide strong interaction of the guided mode with the electro-optic material, see field plots in Fig. 1 .

In the scheme of Fig. 1 (a) the microwave field is applied via two aluminum conductor paths running in parallel to the optical strip waveguide. The spacing is chosen large enough (typically 1 µm) to avoid optical loss. For the slot waveguide, Fig. 1 (b), both silicon strips are doped and connected to the aluminum conductors by thin silicon slabs. Arsenic doping with a density of $n_D \approx 2\times10^{16}\ \mathrm{cm}^{-3}$ yields sufficient electrical conductivity $\sigma_{Si} \approx 10\ (\Omega\mathrm{cm})^{-1}$, but does not induce relevant optical loss.

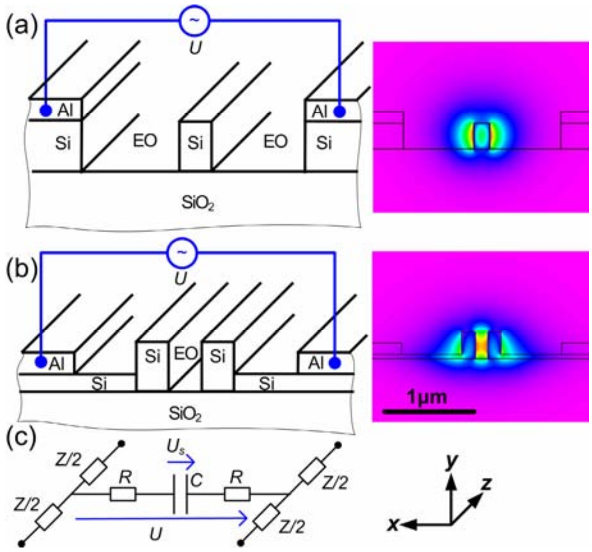

Fig. 1 *Novel waveguide-based SOI modulator schemes. The optical slot waveguides consist of silicon ribs on top of the buried oxide (SiO_2) and are covered with an electro-optic material EO. For both structures, the optical mode fields are depicted on the right. (a) Strip waveguide structure (b) Slot waveguide structure (c) Lumped-element model of the slot waveguide structure*

Fig. 1 (c) depicts a lumped element model of a short segment of the slot waveguide configuration: Z denotes the series impedance per unit length for each of conductor tracks, whereas R and C define the shunt admittance of the silicon slabs and ribs. For a DC signal, the applied voltage $U = U_S$ drops over the narrow slot (typical width: 150 nm), where high field strengths can be easily achieved. If fed with an AC signal, the capacity of the slot has to be charged via the resistive slab regions, $U_S < U$. This leads to an RC-limited bandwidth $f_{RC} = \sqrt{3}/(4\pi RC)$.

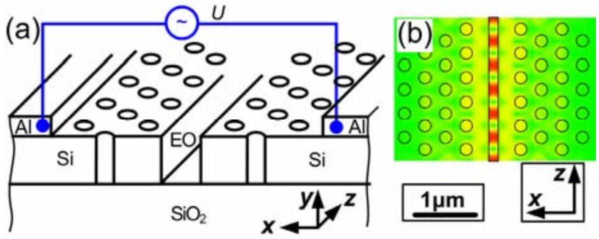

Fig. 2 *PhC-based modulator scheme: A PhC line defect waveguide with a slot is etched into the SOI device layer. The structure is covered with an electro-optic material EO. The doped PhC regions are electrically connected to the aluminum conductor paths.*

The optically isolating slab regions in Fig. 1 (b) can be replaced by a photonic crystal (PhC) structure. This scheme is depicted in Fig. 2(a). The optical intensity is high in the electro-optic material EO that fills the slot, see Fig. 2 (b). As for the slab structure, the modulation frequency is limited by the RC time constant. The group velocity of the optical signal can be significantly reduced by an appropriate design of the PhC. The interaction time with the electro-optic material can thus be increased; this decreases the operating voltage and/or the device length.

Operating Voltage

For the case of an appropriately oriented second-order nonlinear material EO, e.g., a polymer, a microwave electric field induces a local change of the refractive index seen by the optical field. To a first approximation, the electric fields of both the microwave and the optical mode are predominantly aligned along the *x*-direction. The local refractive index change can be approximated by $\Delta n = -0.5\, r_{33} n_{\mathrm{EO}}^3 E_x$. The quantity r_{33} is the electro-optic coefficient of the polymer, n_{EO} denotes its refractive index and E_x is the x-component of the modulating microwave field. E_x is proportional to the applied voltage *U*. An optical signal propagating along the waveguide experiences a phase shift of $\Delta\Phi = k_0 \Delta n \Gamma L$, where the confinement factor Γ measures the overlap of the modulation field and the optical field in the electro-optic material, and $k_0 = 2\pi/\lambda$ is the wave number of the optical signal. For a Mach-Zehnder modulator in push-pull configuration, a phase shift of $\Delta\Phi = \pm\pi/2$ is needed for complete extinction.

Table 1 lists characteristic data for the three different device configurations. In the first column, the group velocity v_g for $\lambda = 1.55$ µm is specified in fractions of the vacuum speed of light c. Assuming a polymer with a moderate $r_{33} = 50$ pm/V [3], the normalized phase shift $\Delta\Phi/(UL)$ has been calculated for the strip and the slot waveguide, and for the PhC structure, see second column of Table 1. As expected, the slot waveguide structure has a higher normalized phase shift than the simpler strip due to more closely spaced electrodes. For the PhC modulator, the normalized phase shift is increased by the low optical group velocity. Assuming a peak-to-peak voltage of 3 V, the device lengths $L_{\pi/2}$ for a $\pi/2$ phase shift have been calculated, see third column of Table 1. We find that devices can be as short as 240 µm (1.7 mm) for the PhC (slot waveguide) configuration. In all cases, the refractive index change due to free carriers is much weaker than the electro-optic effect and can therefore be neglected.

Table 1: Characteristic data of the modulator based on a strip waveguide, slot waveguide, and a PhC (wavelength $\lambda = 1.55$ µm, electro-optic coefficient $r_{33} = 50$ pm/V). The lengths $L_{\pi/2}$ refer to a phase shift of $\Delta\Phi = \pi/2$ and a peak-to-peak voltage of U=3 V . The group delay-related roll-off frequency f_{gd} increases with U.

Configuration	v_g/c	$\Delta\Phi/(UL)$ [V mm]$^{-1}$	$L_{\pi/2}$ [mm]	f_{gd} [GHz]	f_{RC} [GHz]
Strip	0.30	0.16	6.5	-	-
Slot	0.35	0.61	1.7	-	**192**
PhC	0.05	4.44	0.24	**42**	340

Bandwidth Limitations

Apart from RC time constants, the modulation bandwidth of the devices is limited if the group velocity $v_{\mathrm{g,el}}$ of the electrical signal and the group velocity $v_{\mathrm{g,op}}$ of the optical signal differ: The corresponding spatial walk-off leads to a degradation of the modulator performance for high frequencies. For a modulator of interaction length *L*, the group delay difference $\Delta\tau_{\mathrm{g}} = L/v_{\mathrm{g,el}} - L/v_{\mathrm{g,op}}$ reduces the phase shift $\Delta\Phi$ as a function of the angular modulation frequency ω,

$$\Delta\Phi(\omega) = k_0\, \Delta n\, \Gamma\, L \,\mathrm{sinc}\left(\omega \Delta\tau_{\mathrm{g}} / 2\pi\right), \qquad (1)$$

where $\mathrm{sinc}(x) = \sin(\pi x) / (\pi x)$. The corresponding roll-off frequency is $f_{\mathrm{gd}} = 1.895/(\pi\,\Delta\tau_{\mathrm{g}})$. For a traveling-wave configuration where $\Delta\tau_{\mathrm{g}} = 0$, the phase shift does not degrade with frequency.

The group delay-related roll-off frequency f_{gd} and the RC bandwidth f_{RC} are listed in the last two columns of Table 1. For the strip waveguide, no RC limitation occurs. In the case of a traveling-wave configuration, there is no inherent limitation of the electrical bandwidth. For the slot waveguide in a traveling wave configuration, the RC limitation permits operation at and above 100 Gbit/s. For the slow-light PhC modulator, the electrical signal propagates always much faster than the optical signal, and traveling-wave operation is not possible. The electrical bandwidth is therefore limited by the transit time of the optical signal in the PhC section to about 42 GHz. RC limitations can be neglected. In this case, the bandwidth does not depend on the group velocity of the optical signal – if the group velocity is further reduced, the device can be made shorter, but still the transit time remains unaffected. On the other hand, if the operating voltage *U* is increased, both the device length *L* and the transit time can be reduced. The bandwidth of the PhC modulator is therefore proportional to the operating voltage and can be extended into the 100 Gbit/s region by using larger voltage swings.

Summary

We propose novel SOI modulator schemes. Operating voltages, device lengths and modulation bandwidths are predicted. We find that 100 Gbit/s modulation at 3 V peak-to-peak voltage is possible with devices having a length of less than 2 mm.

This work was supported by the Center for Functional Nanostructures (CFN) of the Deutsche Forschungsgemeinschaft (DFG) within projects A3.1 and A4.4.

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