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SiGe/Si capacitive modulator design optimization for datacom applications

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Abstract

Capacitive modulators constitute an appealing approach to reduce modulator footprints for datacom transceivers. We develop an accurate and fast model to estimate the optimum capacitive modulator performances for datacom applications.

1. Introduction

Silicon photonics has become an industrial reality for the datacom market. Among the various components found in the transmitter section, modulators are a corner stone. Commercial modulators mainly rely on free plasma dispersion effect within a Mach-Zehnder Interferometer (MZI). Several electronic configurations are possible to achieve electro-refraction. PN-junctions are the most used thanks to the high bandwidths and low propagation losses. Nevertheless, PN-modulators suffer from a low efficiency, leading to few-mm long footprints. This paper focuses on the optimization methodology of a semiconductor-insulator-semiconductor capacitive (SISCAP) junction to improve modulator efficiency, including the use of strained-SiGe to even more improves efficiency. As a result a model is developed to estimate optimum reachable performances of SiGe/Si SISCAP for datacom applications at λ=1.31µm.

2. Modeling method

Studied SISCAP

The studied SISCAP modulator is based on stacking a P-doped SOI layer, a strained-SiGe layer, a gate oxide and a N-doped Si layer as shown on Fig. 1.

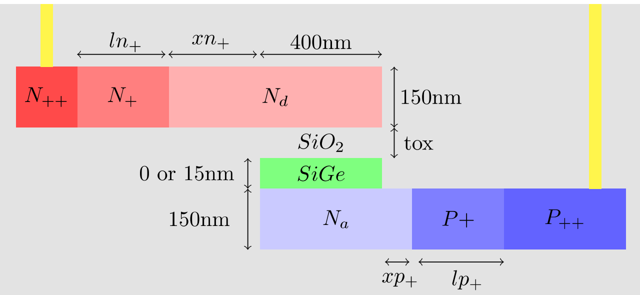

Fig. 1 Design of the studied SISCAP with 12 optimization parameters.

Here we assume a 150nm-thick SOI and polySi layers, a 15nm-thick SiGe-layer matching the Debye length extension of carriers, and a 400nm-wide waveguide. As a consequence, the capacitor oxide thickness, the Ge-content in the SiGe and the doping levels and positions are the remaining variables. This let us with 12 optimization parameters. Finding the optimum design using 2D numerical tools is challenging considering so many degrees of freedom with interactions. In order to estimate optimum achievable performances, a fast but accurate model is developed.

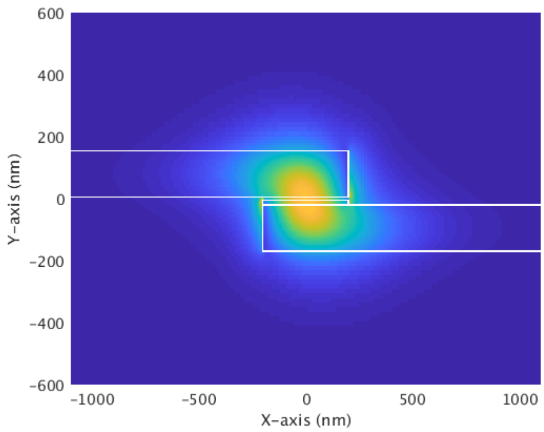

Fig. 2 Optical mode in the SISCAP computed on Lumerical MODE.

SISCAP modelling

The SISCAP model relies on the perturbation theory. Only one optical simulation is performed on Lumerical [1], assuming a 10nm-thick gate oxide and 20% Ge-fraction for the strained-SiGe layer. Then electronic simulations are performed on Matlab, by solving 1D-Poisson equation within the waveguide. Finally, the optical and electronic outputs are combined thanks to the perturbation theory with Si and strained-SiGe electro-refractive coefficients [2][3]. The Matlab computations of efficiency, losses and electro-optical bandwidth are done in 6s. This is fast enough to allow optimization for the 12 parameters. To do so, a genetic algorithm is used.

When considering amplitude modulators, Optical Modulation Amplitude (OMA) is a convenient figure of merit (FoM) to maximize. OMA takes into account both phase-shift and optical losses. Fig. 3(a) shows a MZI set in quadrature. Considering ON-OFF Keying (OOK) operation, the intensity differences between the different symbols should be maximized. This FoM corresponds to OMA as shown in Fig. 3(b).

For OOK application assuming an input power

I_{in}=1mW=0dBm, OMA is found to be [4]:

$$\mathrm{OMA} = \exp\left[-\left(\alpha^{\mathrm{prop}} + 0.5.\left(\alpha^{\max} + \alpha^{\min}\right).\mathrm{L}\right].\sin(|\Delta\Phi.\mathrm{L}|)$$

With L the modulator length (mm), $\Delta\Phi$ the phase-shift (rad/mm), α^{prop} the scattering losses of an undoped waveguide (mm^{-1}), α^{Vmin} the linear losses due to material & free carrier absorption at the minimal voltage (mm^{-1}) and α^{Vmax} the linear losses due to material & free carrier absorption at the maximal voltage (mm^{-1}).
In the ideal case OMA should be equal to the input power, corresponding to lossless constructive and destructive interferences.

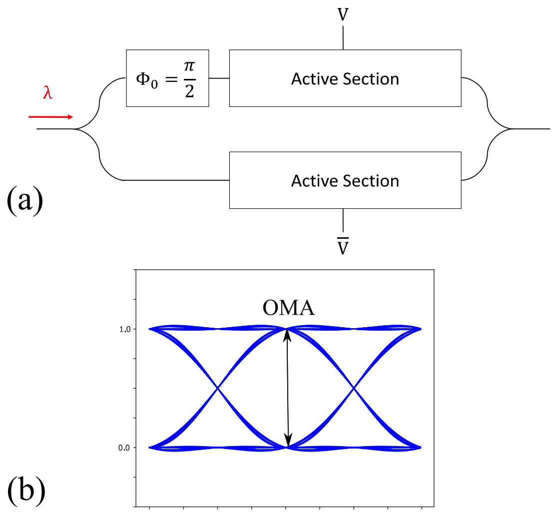

Fig. 3 (a) MZI set in quadrature. (b) OMA on a typical eye-diagram for OOK applications

2. Optimized results

The optimization algorithm is found to converge after 10000 modulator simulations. This corresponds to 17h of computation.

The model is then used to performed design optimization depending on the operating frequency. For each frequency, optimization is performed to maximize OMA for OOK applications assuming 1mm long device. The results are given in Fig. 4.

From this, it is clear that increasing frequency degrades OMA. At 50GHz, the maximum reachable OMA is found to be ~-2.3dB which corresponds to commercial PN modulator performances. This shows that capacitive modulators are relevant for datacom applications up to 50GHz applications. Furthermore, low Ge-contents (15% and 25%) strained-SiGe always improves OMA, meaning this CMOS-material may be more appealing for electro-refractive modulation than pure-Si for targeted frequency >20GHz.

Optimized capacitor oxides get thicker to increase the cut-off frequency, while the Ge-contents increase as well to compensate the phase-shift degradation. This makes sense since the modulator capacitance is inversely proportional to the capacitor oxide thickness.

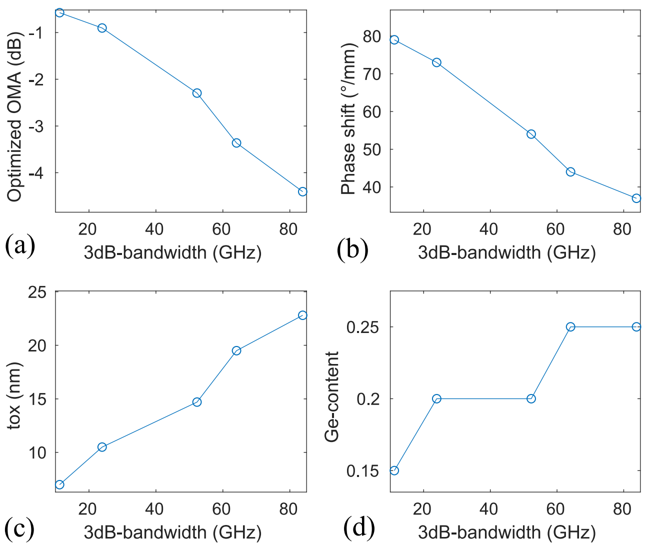

Fig. 4 Optimized design depending on the target cut-off frequency. (a) Optimized OMA. (b) Corresponding phase-shift. (c) Corresponding capacitor oxide thickness. (d) Corresponding Ge-content in the strained SiGe.

3. Conclusions

We develop a fast model followed by optimization algorithm to estimate optimal SiGe/Si capacitive modulator performances. We show that capacitive modulators should be relevant for datacom applications up to 50GHz, while being shorter than PN-junction. Besides, it is shown that using strained-SiGe is appealing for electro-refractive modulation at 1310nm. Low Ge-content between 15-25% are shown to be a fair trade-off between electro-refractive phase-shift and optical losses.

Acknowledgements

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