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# Strained silicon photonics for Pockels effect based modulation

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**Abstract** — We present on experimental results of strain-induced Pockels effect in silicon based on Mach-Zehnder interferometer modulators. We theoretically studied both Pockels effect and carrier parasitic effect in silicon under an electric field. We demonstrated high speed Pockels-based optical modulation up to 25 GHz.

**Keywords**— Pockels effect, silicon photonics, silicon-on-insulator, strained silicon, Mach-Zehnder interferometer

## I. INTRODUCTION

Since the last decade, numerous interests for strained silicon in photonics have grown given the potential of unlocking the Pockels effect, an ultra-fast electro-optic effect widely used in high speed and low-power consumption modulators for telecom and datacom applications. As silicon is a centrosymmetric semiconductor, second-order optical nonlinearities vanished. However, it has been proved [1] that mechanical stresses, provided by depositing a stressed overlayer (typically SiN), can generate strain gradients that break the crystal symmetry and eventually unlock second order nonlinear effects such as Pockels effect. Since then several studies have been performed [2-4] in order to improve this nonlinear effect. But a recent investigation [5] demonstrated that carriers have a great influence on the electro-optics measurements of Pockels effect. Indeed both plasma dispersion effect and Pockels effect act together which have led to an overestimation of the second order nonlinear susceptibility. One way to separate these effects consists in the increasing of the modulation speed [6] in order to minimize the impact of free carriers. Here, we report on experimental demonstration of a 25 GHz Pockels-based optical modulation in strained silicon Mach-Zehnder interferometers.

## II. DESIGN AND FABRICATION

The fabricated electro-optic modulators were a coplanar-waveguide-based electrode Mach-Zehnder interferometer (MZI) as represented in Fig. 1. Devices were implemented on SOI platform, with 260-nm-thick Si and 2- $\mu$ m-thick buried oxide (BOX) layers. Both interferometer arms were 4-mm length and a 60- $\mu$ m delay length was applied between them to naturally generate optical resonances. The silicon strip waveguide widths in each arm were 400-nm and operated in the single mode condition for the TE polarization. Silicon was strained with a highly stressed SiN

overlayer. Two identical coplanar waveguides were aligned with both MZI arms to carry a microwave electric signal that interacts with the optical mode to modulate its effective index.

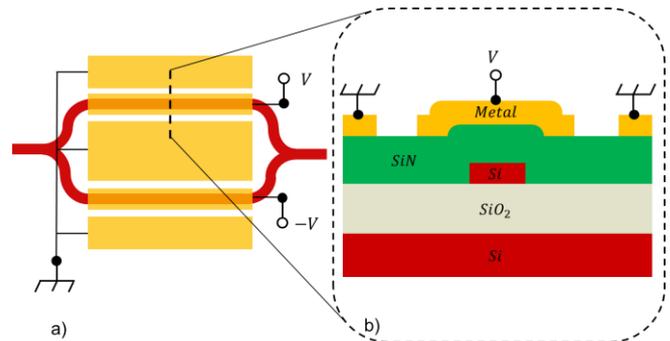


Fig. 1 (a) Schematic top view of the Mach-Zehnder modulator. (b) Cross-section of one arm of the Mach-Zehnder interferometer.

Our Mach-Zehnder interferometer modulators were first patterned using electron beam lithography with a 5 nm writing step size. The pattern was then transferred into silicon using inductively coupled plasma (ICP) etching technique in order to get fully etched structures. A 700-nm thick SiN stressed overlayer (with a -1 GPa internal stress) was deposited using plasma enhanced chemical vapor deposition (PECVD) process to strain the silicon waveguides underneath. Another electron beam lithography was then performed with a 5 nm writing step size to pattern the coplanar waveguides on top of the Mach-Zehnder interferometers. A 500-nm thick gold layer was thermally evaporated all over the sample followed by a lift-off to pattern the coplanar waveguides.

## III. ELECTRO-OPTIC MODULATION

The light coming from a tunable laser source (1520-1640 nm) was coupled to and from the edges of the cleaved sample with a TE polarization using lensed fibers. First, DC characterizations were performed to determine the variation of both Pockels and carrier effects. Then a microwave electric signal with a frequency swept between 100 MHz and 25 GHz was injected into one coplanar waveguide via RF probes. A DC block was used at the end of the coplanar electrodes. The modulated optical signal was detected by a photodiode and its power was normalized to the microwave signal power. The normalized response was directly

displayed on a spectrum analyzer as a function of the microwave frequency.

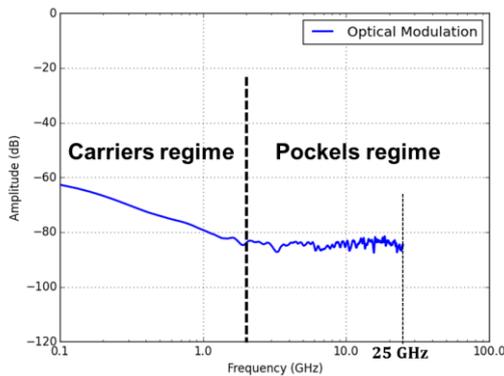


Fig. 2 Electro-optical response of the Mach-Zehnder modulator between 100 MHz and 25 GHz.

Figs. 2 shows the measured electro-optical response from the 4-mm long Mach-Zehnder modulator. Two regimes can be well identified. Between 100 MHz and 2 GHz the optical modulation is mostly due to plasma dispersion effect. A flat response is then observed from 2 GHz to 25 GHz (maximum frequency of our set-up) that should correspond to Pockels effect. Indeed at these frequencies, the carrier mobility and their recombination time prevent them from participating to the optical modulation.

The low optical modulation intensity value is a marker of a small interaction between the optical mode and the strain gradient region. We are working on improving the generation of stronger strain gradients on silicon waveguides to enhance the Pockels-based modulation efficiency.

#### IV. CONCLUSION

In this work, we have studied the effect of the stress layer on the modulation characteristics based on Mach-Zehnder interferometers. Our devices show an optical modulation up to 25 GHz corresponding to the Pockels effect.

#### ACKNOWLEDGMENTS

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