Strain-induced electro-optical effect in silicon Mach-Zehnder modulators

(Student paper)

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ABSTRACT

Due to the strong evolution of data transmission worldwide, silicon photonics needs to provide low power consuming and ultra-fast modulators. Pockels effect is known to answer both these demands. However, silicon is a centrosymmetric crystal, which makes it inadequate to use Pockels effect. Nonetheless, by straining a silicon waveguide, it is possible to unlock second order nonlinear optics effects, enabling electro-optic modulation through Pockels effect. In our work, we experimentally demonstrated a high-speed strain-induced Pockels effect based electro-optic modulation in a Mach-Zehnder silicon modulator. We also present a complete analysis of Pockels, Kerr, and free carriers effects.

Keywords: Silicon photonics, Pockels effect, nonlinear optics, modulation.

1 INTRODUCTION

Silicon photonics is considered a centerpiece in a global approach of reducing the power consumption of communication technologies [1]. In particular, electro-optic modulators draw great attention. Indeed, numerous studies have shown plasma dipsersion based modulators or electro-absorption based modulators[2], [3], but these solutions are still limited in bandwidth and are quite power-hungry. To answer this issue, Pockels effect, a second order nonlinear optical effect is a perfect candidate as it is an instantaneous effect providing pure phase modulation under a low electric field. Yet, silicon (Si) is a centrosymmetric material, meaning no second order nonlinearities. Nonetheless, by applying a stress involving strain gradients in a silicon waveguide, the centrosymmetry is broken and then Pockels effect can arise [4], [5]. During the last decades, numerous studies have been done in this direction, but most of them were flawed. In fact, silicon is a semiconductor material, resulting in free carriers plasma dispersion effect, responsible for additional modulation behavior. As most of the first attempts of characterizing the strain induced $\chi^{(2)}$ were performed in DC regime, these carriers effects were far from being negligible, leading to strong overestimations of the nonlinear susceptibility [6]. To paliate this hurdle, we performed high speed modulation experiment using a strained silicon Mach-Zehnder modulator for in this regime, free carriers are too slow to entail any additional modulation response. It permitted us to properly characterize the second order susceptibility arising from the strain gradient in the structure [7].

2 THEORY

For electro-optic modulation, several effects can be used. Here we focus on electro-refraction effects. In a medium with a non-zero second order susceptibility $\chi^{(2)}$, Pockels effect can be achieved. It is a linear electro-optic effect, which means that the effective index change Δn_{eff} is proportional to the modulating electric field applied on the structure. It is important to notice that this is a pure phase modulation process (the phase modulation is not accompanied by amplitude modulation). Pockels effect can only be achieved in a non-centrosymmetric material. This implies that silicon cannot be used for this purpose. However, by stressing the silicon lattice in a way that a strain gradient is achieved, the crystal symmetry is broken, which makes this restriction vanish. The strain in a silicon waveguide is usually obtained by depositing a silicon nitride (SiN) stressing layer.

On the orther hand, silicon is a semiconductor, so free carriers effects can also be present. In particular, free carrier plasma dispersion effect (FCPDE) implies an additional effective index change through variations of electrons and holes concentrations inside the silicon structure. It appears that Pockels effect and free carrier plasma dispersion effect are competing, which makes it difficult to analyze them. Furthermore, the free carriers move in a way that it reduces the effective modulating electric field inside the waveguide, leading to a decrease of the Pockels effect. As to avoid FCPDE and field screening effect, it is possible to modulate at high frequency (>3 GHz) in order to have a period shorter than the free carrier lifetime ($\simeq$1 ns).

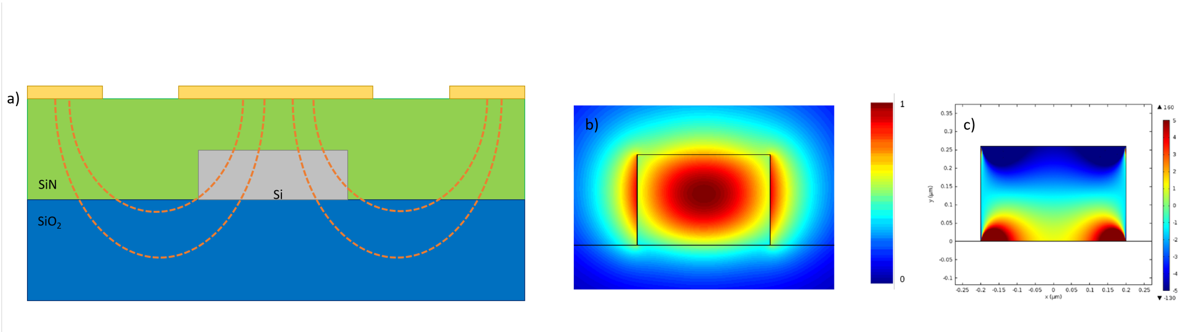

Figure 1. a) Schematic view of the cross-section of one MZM arm. Orange dotted lines represent the electric field lines. b) Distribution of the TE mode in the cross section (normalized). c) $\chi^{(2)}$ distribution (pm/V) in the cross section of the waveguide.

3 RESULTS

We fabricated a set of unbalanced silicon Mach-Zehnder modulators (MZM), strained by a SiN layer deposited through plasma enhanced chemical vapor deposition. It ended in a 1.3 GPa compressive stress in the SiN film. Coplanar electrodes were deposited on top of the SiN film to induce a vertical electric field is applied in the waveguide (see figure 1a).

High speed bandwidth measurments were then performed, with frequencies ranging from 100 MHz to 40 GHz. Additionally to the RF wave, a DC bias voltage was applied. An example of obtained response is represented on figure 2. For frequencies lower than 3 GHz, we observed a dependence of the modulator response with the bias voltage. This comes from the change of free carriers regime (from accumulation to inversion). Indeed, at these frequencies, free carriers are still fast enough to imply FCPDE and screening effect. However, at higher frequencies, this dependence vanishes and a constant response appears. This response is then associated to Pockels effect. The experimental results permitted to determine material properties describing the link between strain gradients and $\chi^{(2)}$. The local distribution of $\chi^{(2)}$ shows high values ($\simeq$160 pm/V) in the edges of the waveguide, yet the effective second order susceptibility is of the order of 1 pm/V. This relatively is due to a poor overlap between the optical mode, mainly located in the center of the waveguide, and the strain gradient distribution (see figure 1b and c).

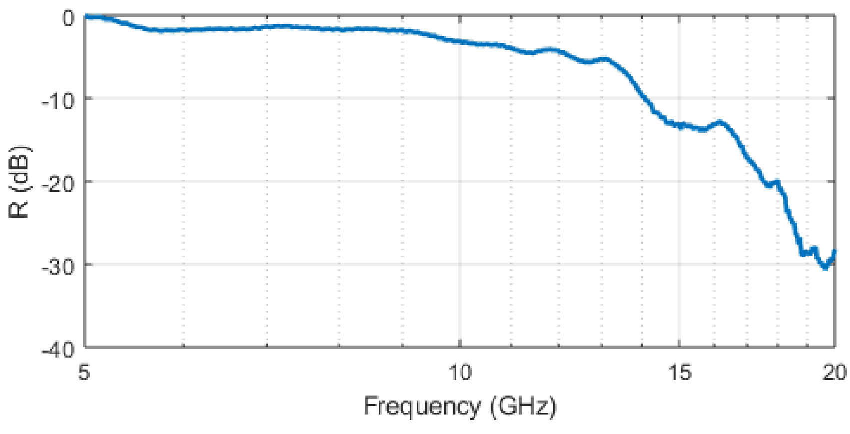

Figure 2. Modulator response for a -15V bias voltage (normalized).

4 CONCLUSION

In this study, we experimentally demonstrated strain-induced Pockels effect in a silicon modulator stressed by a silicon nitride layer deposited through PECVD. By measuring the modulator response at frequency higher than 3 GHz we were able to eliminate any free carriers effect that could play a role in the modulation. The experimental result permitted to determine the parameters of a theoretical model we previously established, pavin the way to further optimizations of the structure. Now, the perspective to improve the effective second order nonlinearity are to increase the overlap between the strain gradient profile and the optical mode.

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