Demonstration of High-Speed Pockels Effect in Strained Si Waveguides

Christian Lafforgue, Mathias Berciano, Lucas Deniel, Guillaume Marcaud, Xavier Le Roux, Carlos Alonso-Ramos, Daniel Benedikovic, Vladyslav Vakarin, Alicia Ruiz-Caridad, Paul Crozat, et al.

► To cite this version:

Christian Lafforgue, Mathias Berciano, Lucas Deniel, Guillaume Marcaud, Xavier Le Roux, et al.. Demonstration of High-Speed Pockels Effect in Strained Si Waveguides. Conference on Lasers and Electro-Optics OSA Technical Digest (Optical Society of America, 2020), Optical Society of America, 2020, Washington, United States. 10.1364/CLEO_SI.2020.SM2J.1 . hal-02941661

HAL Id: hal-02941661

<https://hal.science/hal-02941661>

Submitted on 17 Sep 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Demonstration of High-Speed Pockels Effect in Strained Si Waveguides

Christian Lafforgue, Mathias Berciano, Lucas Deniel, Guillaume Marcaud, Xavier Le Roux, Carlos Alonso-Ramos, Daniel Benedikovic, Vladyslav Vakarin, Alicia Ruiz-Caridad, Paul Crozat, Delphine Marris-Morini, Eric Cassan, Laurent Vivien

Centre for Nanoscience and Nanotechnology (C2N), Université Paris Saclay CNRS, UMR 9001, 91120 Palaiseau, France

Author e-mail address: laurent.vivien@c2n.upsaclay.fr

Abstract: We report on the first demonstration of high-speed optical modulation based on Pockels effect in strained silicon waveguides. Bandwidths higher than 20GHz and low insertion loss have been achieved at a wavelength of 1550nm.

1. Introduction

The explosion of data demand imposed new requirements in terms of bandwidth and functionalities reducing the overall power consumption of the photonic circuits. In this context, silicon photonics is considered as the most adapted solution to address the major limitations of optical communication systems. Indeed, the high index contrast provided by the silicon-on-insulator (SOI) platform allows the fabrication of compact devices through the strong know-how from the complementary metal-oxide semiconductor (CMOS) technology used in microelectronics. In addition, high yields and low costs can be envisaged and are necessary for massive deployment of silicon photonics-based integrated circuits for many applications including Datacom, quantum technology and sensing, to name a few. Among all building blocks for the development of integrated circuits, the electro-optic modulator for the conversion of data carried by an electric signal to an optical carrier is essential at wavelengths from 1300nm to 1600nm. Many approaches have been considered to achieve high-speed and low loss optical modulators in Si photonics platform including electro-refraction based on free carrier plasma dispersion effect to induce phase changes of the light propagating through a Si waveguide-based PIN junction and electro-absorption based on Franz-Keldysh effect in Ge waveguide or Quantum Confined Stark Effect in Ge quantum wells. These approaches have demonstrated state-of-the-art optical modulation performance. However, no one induces a pure phase optical behavior (no variation of absorption) relied on Pockels effect. Indeed, this effect, which is dominant in optical modulators based on ferroelectric materials like Lithium Niobate (LiNbO_3) and Barium Titanate (BaTiO_3), is essential for advanced modulation formats circuits but also for emergent application such as quantum optics or microwave photonics. A lot of efforts have thus been performed to obtain such effect in Si photonics platform based on hybrid integration of doped polymer, epitaxial BaTiO_3 , lead zirconate titanate (PZT), and LiTaO_3 [1-4]. Even if these hybrid configurations demonstrated good results, a pure silicon approach will insure a better compatibility with Si technology, and will fulfil the constraints in terms of reliability, durability and temperature. However, as silicon is a centro-symmetric semiconductor, there is not second-order optical susceptibility ($\chi^{(2)}$). Nonetheless, this limitation can be relaxed by applying deformations to the Si lattice by means of stress in order to break its inversion symmetry [5-6]. In this work, we demonstrated, for the first time, high-speed behavior, beyond 20GHz due to Pockels effect in strained Si waveguides inserted in Mach-Zehnder interferometers.

2. Results

To demonstrate optical modulation based on Pockels effect in Si waveguides, an asymmetric Mach-Zehnder interferometer (MZI) was designed and fabricated for the quasi-TE modes at a wavelength of 1550nm. To break the crystal symmetry of Si, a silicon nitride (SiN) stressed thin film with -1.3 GPa internal stress was deposited onto the Si waveguides. Contact electrodes were then deposited to apply vertical RF signal. Figure 1 presents schematic views of two electrode configurations: coplanar RF and micro-strip electrodes, we considered in the study of Pockels effect in strained silicon photonics in order to dissociate the origin of the electro-optics behavior.

Each MZI modulator was characterized in DC and RF regimes and analyzed to dissociate the contribution of all electro-optic effects: Pockels, Kerr or plasma dispersion effects. First, we compared the RF characteristics of both modulator with coplanar and microstrip electrodes (Fig. 1). A significant gain in terms of RF response of about 13 dB around 10 GHz has been achieved for the same MZI length and the same stress level. This difference is explained by the stronger electric field induced within the silicon waveguides thanks to the microstrip

configuration of the electrodes. Furthermore, we observe a drop of the modulation efficiency after 10 GHz due to the group velocity mismatch (GVM) between the optical and microwave propagated signals.

Combining Multiphysics simulations including optical mode propagation, strain induced Pockels effect, microwave propagation and carrier effects, and experimental results, we were able to determine the theoretical response of each MZI modulator. We have also determined an effective value of the $\chi^{(2)}$ coefficient (xxy component) of -1.8 ± 0.2 pm/V. Furthermore, from these measurements, we have dissociated the contribution of all possible effect which may induce an electro-optical effect and we are able now to enhance Pockels effect in silicon and to reduce other contributions.

Fig.1: Modulation response as a function of the frequency for both coplanar electrode (dashed green) and microstrip electrode (blue line) configurations.

3. Conclusion

The Pockels effect is known to be an ultra-fast electro-optic effect and is extensively used in high-speed and efficient modulators. However, because silicon possesses an inversion symmetry within its crystal structure, all second-order nonlinearities vanish, thereby depriving silicon photonics to benefit from the Pockels effect. Nevertheless, inducing strain gradients into silicon by a stressed material was proved to overcome this limitation. We characterized the strain-induced $\chi^{(2)}$ tensor in silicon through the measurements of Pockels responses in the microwave regime. An effective value of -1.8 ± 0.2 pm/V was determined for the $\chi^{(2)}$ (xxy) component.

An experimental demonstration of electro-optical bandwidth higher than 20GHz was achieved as well as a 10 Gbps data modulation rate based on the Pockels effect in strained silicon waveguides at C-band wavelengths. These results pave the way for the development of high-speed and low power consumption pure phase modulators in silicon photonics.

Acknowledgements: This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (ERC POPSTAR - grant agreement - 647342). The fabrication of the devices was performed at the technological nanofabrication center of the C2N, which was partially funded by the Conseil Général de l'Essonne, France. This work was supported by the French RENATECH network.

4. References

- [1] Koeber et al, Femtojoule electro-optic modulation using a silicon–organic hybrid device, *Light: Sc. & Appl.* 4, e255 (2015).
- [2] S. Abel, et al., Large Pockels effect in micro- and nanostructured barium titanate integrated on silicon, *Nat. Mater.* 18, 42–47 (2019).
- [3] Alexander et al., Nanophotonic Pockels modulators on a silicon nitride platform, *Nat. Comm* 9, 3444 (2018).
- [4] M. He et al., High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gbit s⁻¹ and beyond, *Nature Photonics* 13, 359 (2019).
- [5] P. Damas et al., Comprehensive description of the electro-optic effects in strained silicon waveguides. *J. Appl. Phys.* 122, 153105 (2017)
- [5] M. Berciano et al., Fast linear electro-optic effect in a centrosymmetric semiconductor, *Communications Physics* 1, 64 (2018)