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| Citation       | Chakraborty, Uttara et al. “Cryogenic operation of silicon photonic modulators based on the DC Kerr effect.” Optica 7, 10 (October 2020): 1385-1390 © 2020 Optical Society of America under the terms of the OSA Open Access Publishing Agreement |
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| As Published   | http://dx.doi.org/10.1364/optica.403178                                                                                                                                                                                                                         |
| Publisher      | Optical Society of America (OSA)                                                                                                                                                                                                                                   |
| Version        | Final published version                                                                                                                                                                                                                                             |
| Citable link   | https://hdl.handle.net/1721.1/128923                                                                                                                                                                                                                              |
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Cryogenic operation of silicon photonic modulators based on the DC Kerr effect

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Received 28 July 2020; revised 13 September 2020; accepted 14 September 2020 (Doc. ID 403178); published 8 October 2020

Reliable operation of photonic integrated circuits at cryogenic temperatures would enable new capabilities for emerging computing platforms, such as quantum technologies and low-power cryogenic computing. The silicon-on-insulator platform is a highly promising approach to developing large-scale photonic integrated circuits due to its exceptional manufacturability, CMOS compatibility, and high component density. Fast, efficient, and low-loss modulation at cryogenic temperatures in silicon, however, remains an outstanding challenge, particularly without the addition of exotic nonlinear optical materials. In this paper, we demonstrate DC-Kerr-effect-based modulation at a temperature of 5 K at GHz speeds, in a silicon photonic device fabricated exclusively within a CMOS-compatible process. This work opens up a path for the integration of DC Kerr modulators in large-scale photonic integrated circuits for emerging cryogenic classical and quantum computing applications.

1. INTRODUCTION

Photonic integrated circuits (PICs) have emerged as a promising platform for a wide range of integrated optical computing and signal processing applications. PICs are a highly attractive candidate for quantum technologies due to the ease with which they can generate, manipulate, and detect quantum states of light in a compact architecture [1]. These systems can now be accessed through commercial photonics foundries [2], paving the way for a new paradigm in large-scale photonic quantum information processing [1,3] and quantum key distribution [4,5]. The CMOS compatibility and large refractive index contrast of the silicon-on-insulator platform make it particularly well suited for large-scale quantum photonics [6,7] and optical data transmission.

However, integration of silicon photonics with key quantum componentry—including single photon emitters [8–10], quantum memories [11], and single photon detectors [12,13]—will likely require operation at cryogenic (<10 K) temperatures. Silicon photonics provides an efficient platform for electro-optic interconnects, which can reduce passive heat loading and provide a high-speed, low-loss solution to limitations on electrical connections in cryogenically cooled circuits [14,15]. Low-power cryogenic systems for classical computing, such as superconducting optoelectronic circuits [16], must also be operated at temperatures below 10 K [17].

The major challenge in the operation of silicon quantum photonics at cryogenic temperatures is the absence of fast, low-loss, phase-only modulation technology, which is required for active multiplexing [18] and high-fidelity quantum gates [19]. To date, silicon photonics typically rely on the plasma dispersion effect [20–22] or the (typically slow) thermo-optic effect [23]. At cryogenic temperatures, thermo-optic modulators suffer from a decrease in the thermo-optic coefficient of silicon by four orders of magnitude [24]. Plasma dispersion modulators can suffer from large carrier-induced losses and can be bandwidth-limited by low-temperature carrier freeze-out [25,26].

While silicon’s intrinsic third-order $\chi^{(3)}$ nonlinearity makes it an excellent candidate for nonlinear processes such as four-wave mixing [27–29], silicon’s crystal centro-symmetry precludes the existence of a native second-order $\chi^{(2)}$ nonlinearity. Thus, unlike non-centro-symmetric materials such as lithium niobate (LiNbO$_3$) and gallium arsenide (GaAs), silicon cannot be a natural candidate for Pockels-effect-based electro-optic modulators. One approach is to integrate materials that possess a strong second-order nonlinearity such as LiNbO$_3$ [30] or barium titanate (BaTiO$_3$) [31] into the silicon photonics platform. Such hybrid integration techniques, however, typically require non-standard fabrication procedures and complex material compatibility, thus motivating the need for a “zero-change” phase-only modulator in silicon.
such, the change in relative permittivity with an applied DC field
where \( \chi \) is negligibly small (on the order of \( 10^{-2} \)).

The absence of an intrinsic \( \chi^{(2)} \) in silicon had, until recently, precluded the development of phase-only modulators in pure silicon. While some prior experiments [32,33] have suggested that a large second-order nonlinearity can be induced by straining silicon waveguides, more recent studies [34,35] have deduced that the reported second-order nonlinearities were overestimates, and that the observed nonlinear effects arose from interfacial charge defects rather than strain as originally believed. Alternatively, it has now been shown [36–39] that a second-order nonlinearity can be generated in silicon by means of an applied DC electric field, producing an effective \( \chi^{(2)} \) from the third-order nonlinear susceptibility \( \chi^{(3)} \). This approach leads to efficient electric-field-induced second-harmonic (EFISH) generation in silicon as well as a large electro-optic DC Kerr effect that can be leveraged in optical phase shifters.

The index shift in silicon due to an applied DC field is derived using the following approach, where \( E_0 \) denotes the magnitude of the static applied electric field and \( E_{ω} \) the amplitude of the optical mode field with frequency \( ω \). Since \( \chi^{(2)} = 0 \) in silicon, the nonlinear polarization [40] is given by

\[
P = \varepsilon_0(\chi^{(1)}(E_0 + E_{ω}e^{jωt}) + \chi^{(3)}(E_0 + E_{ω}e^{jωt})^3 + \cdots). \tag{1}
\]

Retaining only the terms proportional to \( E_{ω} \), we have

\[
P = \varepsilon_0(\chi^{(1)} + 3\chi^{(3)}E_0^2)E_{ω}e^{jωt} + \cdots, \tag{2}
\]

where \( \chi^{(1)} + 3\chi^{(3)}E_0^2 \) is the effective relative permittivity \( \varepsilon_r \). As such, the change in relative permittivity with an applied DC field \( E_0 \) is given by

\[
\Delta\varepsilon_r = 3\chi^{(3)}E_0^2. \tag{3}
\]

Since the refractive index \( n \) equals \( \sqrt{\varepsilon_r} \), we obtain the electric-field-induced refractive index shift as

\[
\Delta n = \frac{3\chi^{(3)}E_0^2}{2n}. \tag{4}
\]

The performance of DC-Kerr-effect-based modulators incorporated into Mach–Zehnder interferometers (MZIs) has been demonstrated at room temperature [36]. The use of such DC-Kerr-effect-based modulators at cryogenic temperatures is highly desirable in PICs for classical and quantum information processing. Based on Eq. (4), given that the thermo-optic decrease in the refractive index of silicon between room and cryogenic temperatures is negligibly small (on the order of \( 10^{-2} \) [24,41]), the refractive index shift at cryogenic temperatures is expected to be on the same order of magnitude as that at room temperature for the same externally applied DC electric field. In the present work, we demonstrate the cryogenic operation of integrated DC-Kerr-based silicon modulators, showing that the effective refractive index shifts observed at a temperature of 5 K are indeed comparable to those observed at room temperature.

2. DEVICE STRUCTURE

Our test structures were two MZIs with input and output adiabatic couplers, 4.5-mm-long integrated PIN junction modulators in both arms (to balance propagation loss), and a path length difference of 37.4 \( \mu \)m between the arms (Fig. 1). (One arm of each MZI also had an embedded thermo-optic phase shifter, labeled in Fig. 1 as “Heater,” which was not used in this experiment owing to electrical connection limitations.) The devices were fabricated in a CMOS foundry (at SUNY Polytechnic Institute) using silicon-on-insulator wafers following the design in [36]. The modulators consisted of 500 nm × 220 nm silicon ridge waveguides with embedded PIN junctions. The widths of the intrinsic silicon regions of the waveguide core of the devices were 300 nm and 400 nm. The p and n regions were formed by boron difluoride (BF\(_2\)) and arsenic (As) implants with a target doping concentration of \( 10^{18} \) cm\(^{-3}\), and the p+ and n+ regions by BF\(_2\) and phosphorus (P) implants with a target doping concentration of \( 10^{20} \) cm\(^{-3}\). Tungsten vias contacting the n+ and p+ regions provided electrical connections to copper routing layers and on-chip copper contact pads. We present the experimental results from the 300 nm intrinsic silicon device in the main body of the paper and the results from the 400 nm intrinsic device in Supplement 1.

3. EXPERIMENTAL PROCEDURE

We affixed the chip with the test structures to a copper mount with conductive silver paint (Ted Pella) and wire-bonded it to a high-frequency printed circuit board (PCB). We mounted the package in a closed-cycle cryostat (Montana Instruments) and connected the PCB to the cryostat’s RF feed-throughs. Using piezo-driven positioners, we edge-coupled lensed single-mode fibers to the input and output adiabatic couplers (with a measured loss of \( \sim 6 \) dB per facet) of the Mach–Zehnder devices. The insertion losses (which decrease with increasing applied reverse bias) were less than 10 dB and less than 6 dB for the 300 nm and 400 nm devices, respectively. The experimental setup with the packaged chip mounted in the cryostat is described in Section 2 of Supplement 1.

Figure 2 shows the two experimental configurations for measurements conducted with DC reverse bias only and DC bias with AC small signal. We conducted transmission measurements at room temperature and at 5 K. An Agilent tunable telecom laser (1 mW) was coupled through the input lensed fiber onto the on-chip waveguide, and polarization rotators were used to match the input to the fundamental waveguide TE mode as closely as possible. For DC measurements, we applied voltages (with an Agilent DC power supply) to reverse bias the modulator on one arm of each device at a time, and measured (with an Agilent telecom power...
Fig. 2. Experimental configurations. Optical routing shown as single lines and electrical as double lines. (a) DC measurements: tunable laser input is polarization-matched to waveguide mode, and Mach–Zehnder output transmission is detected with a telecom photodetector. DC reverse bias is applied to one device at a time. (b) RF measurements: tunable laser input is polarization-matched to waveguide mode and amplified before being routed to Mach–Zehnder input. Through a bias tee, a DC bias is applied to operate each device at its quadrature point, and an AC small signal is simultaneously applied from the VNA. The Mach–Zehnder optical output is routed to a high-speed photodetector, and the photodetector electrical output is fed back to the VNA.

Experimental results for the 300 nm intrinsic silicon device are presented in Figs. 3 and 4, and the corresponding results for the 400 nm device in Section 1 of Supplement 1. Figures 3(a) and 3(b) show the transmitted power from both the cross and the bar arms at a representative wavelength of 1548 nm for the 300 nm intrinsic silicon MZI at room temperature and at 5 K, respectively. A thermo-optic shift toward lower reverse bias can be seen in the transmission curves as we go from room temperature [Fig. 3(a)] to 5 K [Fig. 3(b)]. As a result of this shift, we observe a decrease in the depth of the bar fringe at 5 K. This is expected since the insertion loss of the modulator is higher at lower reverse bias voltages, leading to a lower extinction ratio. The lower extinction ratio at lower voltages is also apparent from the decrease in the peak transmission meter) the transmitted power from one output arm of the adiabatic coupler at a time [Fig. 2(a)].

To conduct high-frequency measurements for determining the Mach–Zehnder modulator bandwidths, we amplified the input laser with an Oprel erbium-doped fiber amplifier (EDFA) to provide \( \sim 5 \) mW of on-chip power, and applied a 0.1 V AC small signal with frequencies up to 4 GHz using a Keysight vector network analyzer (VNA) [Fig. 2(b)]. The devices were biased at their quadrature points using the DC power supply. The transmitted optical signal was routed to a Discovery Semiconductors high-speed photodetector, the electrical output of which was in turn routed to the VNA to capture the RF bandwidth of the devices.

4. RESULTS

Experimental results for the 300 nm intrinsic silicon device are presented in Figs. 3 and 4, and the corresponding results for the 400 nm device in Section 1 of Supplement 1. Figures 3(a) and 3(b) show the transmitted power from both the cross and the bar arms at a representative wavelength of 1548 nm for the 300 nm intrinsic silicon MZI at room temperature and at 5 K, respectively. A thermo-optic shift toward lower reverse bias can be seen in the transmission curves as we go from room temperature [Fig. 3(a)] to 5 K [Fig. 3(b)]. As a result of this shift, we observe a decrease in the depth of the bar fringe at 5 K. This is expected since the insertion loss of the modulator is higher at lower reverse bias voltages, leading to a lower extinction ratio. The lower extinction ratio at lower voltages is also apparent from the decrease in the peak transmission.
of the cross fringe compared to the bar fringe, and the lower transmission contrast between bar and cross fringes at 2 V compared to 10 V in Fig. 3(b). The extinction ratios could be improved in future devices with better broadband adiabatic couplers approaching the ideal 50-50 splitting ratio, as well as finer control of dopant implantation process parameters to achieve more evenly balanced losses between the two arms of each MZI.

To determine the shift in the effective refractive index at each wavelength as a function of the DC reverse bias, we set the laser input to each wavelength and swept the DC reverse bias on one PIN modulator from 0 V to 12 V for the 300 nm device and 0 V to 17 V for the 400 nm device. The transmission curves showing both a peak and a trough in the applied voltage range were normalized and fitted to a cosine function to extract the differential phase shift as a function of the reverse bias voltage. From this empirically estimated differential phase shift \( \Delta \phi \), we calculated the effective index shift \( \Delta n_{\text{eff}} \) [corresponding to the integral of Eq. (4) over the fundamental mode profile] as \( \Delta n_{\text{eff}} = \frac{\Delta \phi}{\pi L} \), where \( \lambda \) is the input wavelength and \( L \) the PIN modulator length (4.5 mm).

In Fig. 3(c), we show the average effective index shift obtained from voltage sweeps at wavelengths of 1525–1575 nm for the 300 nm intrinsic silicon device at room temperature. Figure 3(d) shows the corresponding results at 5 K. The figure insets show, as a function of the applied DC reverse bias, the average relative loss (with respect to zero bias) arising from the PIN junction. With increasing reverse bias, the widening of the depletion region leads to a smaller overlap of the optical mode with free carriers, thus reducing the propagation loss. From our results for both devices, we observe that the magnitudes of the effective index shifts at 5 K remain comparable to those at room temperature, exceeding \( 2 \times 10^{-4} \) at the upper ends of the applied reverse bias ranges.

The order of magnitude of our experimentally obtained effective index shifts is in agreement with the simulations presented in Section 3 of Supplement 1. These experimental results indicate that the DC Kerr effect, as well as the plasma dispersion effect, continues to remain at work down to a temperature of 5 K.

Figure 4 shows the electro-optic frequency response of the 300 nm intrinsic silicon device reverse biased at the quadrature point at room temperature and 5 K. \( S_{21} \) denotes the magnitude of the ratio of the transmitted output optical power from one MZI arm to the input optical power. The 3 dB bandwidths exceed 1.5 GHz at both room temperature and 5 K. For larger applied signals, we expect to be able to still achieve GHz-speed modulation since the DC Kerr effect is instantaneous and not carrier-lifetime limited [36]. Preliminary measurements conducted using an RF probe at room temperature (before the chip was wire-bonded to the PCB) yielded higher RC-limited bandwidths (~4 GHz), indicating that the chip-PCB packaging ultimately limits the speed of modulation in this experiment. The oscillations at lower frequencies are likely due to parasitic resonances from the electrical packaging. Modification of the electrical packaging in future experiments to overcome the PCB-induced limitation could allow the devices to be operated at higher speeds up to their full intrinsic bandwidths.

### 5. CONCLUSION AND OUTLOOK

In this work, we have demonstrated DC-Kerr-effect-based modulation in silicon at a cryogenic temperature of 5 K. We studied the electric-field-induced refractive index shift in Mach–Zehnder modulators with embedded PIN phase shifters, and showed that effective refractive index shifts greater than \( 2 \times 10^{-4} \) can be achieved at both room temperature and 5 K. The total index shift is the result of a combination of the DC Kerr and plasma dispersion effects.

Silicon DC Kerr modulators such as the ones demonstrated in this work can be fabricated in commercial silicon photonics foundries without the need for complex fabrication processes involving heterogeneous integration of electro-optic materials [42–44]. However, scaling up photonic quantum technologies to a level where they can tackle practical problems in quantum simulation [45] and machine learning [46] and ultimately demonstrate a quantum advantage [47,48] will likely require the co-integration of photonics with CMOS electronics [49,50]. The use of CMOS driving electronics will bring with it new challenges for the large-scale control of DC Kerr modulators. Rigorous engineering of modulator geometries will be essential for maximizing the induced effective \( \chi^{(2)} \) by the application of transverse electric fields approaching the breakdown field of silicon (~40 V/\( \mu \)m), along with the minimization of free-carrier absorption loss. The integration of DC Kerr modulators in MZIs in large-scale quantum photonic circuits will also require techniques to correct for the effect of balanced and unbalanced modulator losses on unitary transformations [51]. Approaches such as in situ unitary programming [52] or the inclusion of additional loss channels [53] may be used to mitigate loss-induced errors. Understanding how best to apply these techniques to our particular modulator architecture is an important future research direction. DC Kerr modulators in other CMOS-compatible platforms, such as silicon nitride (Si\textsubscript{3}N\textsubscript{4}), could also be explored as a pathway to cryogenic phase modulation in PICs. Recently, the photogalvanic effect in Si\textsubscript{3}N\textsubscript{4} microring resonators has been shown to build up a DC...
field that in turn induces a second-order nonlinearity for highly efficient second-harmonic generation [54]. A similar photogalvanic approach could potentially enable DC-Kerr-based phase modulation in Si$_3$N$_4$ or silicon-rich Si$_3$N$_4$ waveguides at cryogenic temperatures. Our low-temperature, high-speed DC Kerr modulator demonstration now paves the way for the use of such devices in cryogenic quantum and classical computing systems.

**Funding.** National Science Foundation (ECCS-1933556); National Defense Science and Engineering Graduate; H2020 Marie Sklodowska-Curie Actions (Grant Number 751016); Air Force Office of Scientific Research (Grant FA9550-16-1-0391); Defense Advanced Research Projects Agency (Grant No. HR0011-15-C-0056); The MITRE Corporation.

**Acknowledgment.** We are grateful to Matthew J. Byrd, Michael Fang, Michael Walsh, Ryan Hamerly, and Carlos Rios Ocampo for helpful discussions and comments. U.C. is supported by a National Defense Science and Engineering Graduate Fellowship. J.C. is supported by MSCA. Experiments were supported in part by AFOSR, supervised by G. Pomrenke. Devices were fabricated under DARPA DODOS. This work was supported by the National Science Foundation.

**Disclosures.** The authors declare no conflicts of interest.

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**Disclosures.** The authors declare no conflicts of interest.

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