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An integrated optical modulator operating at cryogenic temperatures

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Integrated photonic circuits (PICs) operating at cryogenic temperatures are fundamental building blocks required to achieve scalable quantum computing, and cryogenic computing technologies^{1,2}. Silicon PICs have matured for room temperature applications, but their cryogenic performance is limited by the absence of efficient low temperature electro-optic (EO) modulation. Here we demonstrate EO switching and modulation from room temperature down to 4 K by using the Pockels effect in integrated barium titanate (BaTiO₃)-based devices³. We investigate the temperature-dependence of the nonlinear optical (NLO) properties of BaTiO₃, showing an effective Pockels coefficient of 200 pm/V at 4 K. The fabricated devices exhibit an EO bandwidth of 30 GHz, ultra-low-power tuning which is 10⁹ times more efficient than thermal tuning, and high-speed data modulation at 20 Gbps. Our results demonstrate a missing component for cryogenic PICs. Our results remove major roadblocks for the realisation of cryogenic-compatible systems in the field of quantum computing, supercomputing and sensing, and for interfacing those systems with instrumentation at room-temperature.

Cryogenic technologies are becoming essential for future computing systems, a trend fuelled by the world-wide quest to develop quantum computing systems and future generations of high-performance classical computing systems^{4,5}. While most computing architectures rely solely on electronic circuits, photonic components are becoming increasingly important (Supplementary Note, SN 1). First, PICs can be used for quantum computing approaches where the quantum nature of photons is exploited as qubits^{1,2}. Second, optical interconnects can overcome limitations in

bandwidth and heat leakage that are present in conventional electrical interconnect solutions for digital data transfer between cryogenic processors and the room temperature environment⁶ (SN 2). In addition, due to their low interaction with the environment, photons are the only viable carriers to transport quantum states over large distances. Optical interfaces are therefore essential for true quantum communication, necessary to connect multiple quantum computers^{7,8} and for secure remote operation of quantum computers⁹. Recently, integrated photonics have also been exploited in quantum computing architectures based on trapped ion qubits¹⁰. The scalability of such a system is directly reliant on integrated cryogenic electro-optic modulators. The need for cryogenic photonics is not limited to computing systems, but covers a wide range of technical fields, such as radio astronomy¹¹, particle physics¹², and THz sensing¹³.

Today, the realisation of such photonic concepts is hindered by the lack of switches and modulators that operate at cryogenic temperatures with low-loss, high bandwidth, and low static power consumption. So far, only two concepts for cryogenic EO switches have been investigated, based either on the thermo-optic effect¹⁴ or the plasma-dispersion effect¹⁵. Both mechanisms have physical limitations which intrinsically restrict the low-temperature performance of such devices. Thermo-optic phase shifters exploit Joule heating with large static power consumption and exhibit a bandwidth of less than a few MHz¹⁶. Plasma-dispersion-based devices require very high doping levels to compensate for carrier freeze-out at cryogenic temperatures and are intrinsically incapable of pure phase modulation. The high doping leads to large propagation losses and devices are limited to a bandwidth of <5 GHz in micro-disk modulators¹⁵. Both of these technologies are fundamentally limited from providing low-loss, low-power, high-speed switching and tuning as is fundamentally required for e.g. photonic quantum computing^{1,17}. InP-on-Si modulators have also been explored for cryogenic use¹⁸ but with limited performance and only to temperatures of 77 K, not reaching the few K or below as required by cryogenic applications.

The use of EO switches based on the Pockels effect has been shown to offer low propagation losses and high-bandwidth, combined with low static power consumption at room temperature^{3,19–21}. While the Pockels effect has no intrinsic physical limitations for use at cryogenic temperature²², making a Pockels devices requires an integrated material which retains a large Pockels coefficient and which does not suffer from additional spurious effects at low temperature. No integrated cryogenic Pockels modulator has previously been reported, but room temperature devices have

recently been demonstrated using organics²³, $\text{PbZr}_x\text{Ti}_{1-x}\text{O}_3$ ¹⁹, LiNbO_3 ²⁰, and BaTiO_3 ³. Among them, BaTiO_3 stands out due to having the largest Pockels coefficients³ and exhibiting compatibility with advanced silicon photonics platforms²⁴. We complete this triumvirate by demonstrating that BaTiO_3 is also an ideal candidate for cryogenic EO integration.

Both the NLO properties and structural behaviour of BaTiO_3 thin-films are entirely unknown at temperatures below 300 K. In fact, even in bulk BaTiO_3 crystals the NLO behaviour below 270 K is not known, and the room temperature NLO behaviour of BaTiO_3 thin-films has only recently been thoroughly investigated³. The phase transitions of thin-films are expected to differ from bulk crystals²⁵ due to the structural mismatch and thermal stress that exists between the substrate and the BaTiO_3 layer^{26,27}. They are entirely unknown for BaTiO_3 on Si. Predictions of the Pockels tensor at cryogenic temperatures based on data at higher temperatures is not possible because in complex oxide materials the functional properties can change drastically with temperature. Here, we determine the cryogenic behaviour of BaTiO_3 thin films by analysing the performance of BaTiO_3 -based EO switches at temperatures down to 4 K. Our results show that efficient EO switching at cryogenic temperature is indeed possible and with bandwidths beyond 30 GHz. We also demonstrate the applicability of such devices for low-power switching and tuning as well as high-speed data modulation at 20 Gbps at 4 K.

In this work, we use two waveguide designs (Figure 1a) fabricated on single crystalline BaTiO_3 layers bonded to SiO_2 -buffered silicon substrates (see Methods). In the first design, silicon nitride (SiN)-based waveguides (Figure 1d) allowed us to study the pure NLO properties of BaTiO_3 in absence of mobile charge carriers which could result in an additional, non-Pockels EO response. In the second, silicon (Si) waveguides served as more efficient devices (Figure 1e) to demonstrate high-speed data modulation. The enhanced efficiency originates from a larger optical-mode overlap with the BaTiO_3 layer (41 %, Figure 1c) than with the SiN waveguides (18 %, Figure 1b). We found that the propagation losses (5.6 dB/cm, SiN device) were not affected by the presence of BaTiO_3 in the active section (SN 3) throughout the temperature range studied.

To characterise the NLO behaviour of BaTiO_3 at 4 K, we measured the induced resonance shift in a racetrack resonator as a function of the DC bias (Figure 1f), from which we determined the refractive index change of BaTiO_3 (Δn_{BTO}) as a function of the applied electric field (see Methods). This dependence allows us to study two of the three expected features of Pockels-based switching³:

NLO hysteresis and angular anisotropy, the third being the persistence of the Pockels effect at high frequencies (>10 GHz)³.

The NLO response with a hysteretic behaviour (Figure 2a) indicates that a non-vanishing Pockels effect is preserved in BaTiO₃ down to a temperature of 4 K. We determine the effective Pockels coefficient, r_{eff} , by analysing the hysteretic behaviour of the refractive index change (SN 4). The dependence of r_{eff} on device orientation (Figure 2b) reveals the second signature of the Pockels effect, its anisotropy. The reduced magnitude at 4 K compared to room temperature is due to a temperature dependence of the Pockels effect, as discussed below. While r_{eff} is reduced with temperature, the EO response is expected to be present at high frequencies also at low temperature. Indeed, we observe a constant EO response in racetrack resonators with a low Q factor ($Q \sim 1,800$) up to 30 GHz (Figure 2b). This constitutes the highest bandwidth for any cryogenic modulator reported to date. The frequency response is expected to remain flat at even higher frequency but could not be measured in our experiment (see Methods). The hysteretic behaviour, anisotropy, and high-speed response prove the presence of the Pockels effect in BaTiO₃ at 4 K.

We performed electrical characterisation of the material at low temperature using dedicated electrical test structures (SN 5). The resistivity of BaTiO₃ at 4 K is very high, $>10^9$ Ωm . In fact, the measured current is dominated by capacitive charging and ferroelectric switching currents (Figure 2d). The field-dependent capacitance shows clear hysteretic characteristics (Figure 2e), consistent with ferroelectric domain switching.

The measured r_{eff} at 4 K is lower than at room temperature (Figure 2b), which has two causes. First, the Pockels effect itself is generally temperature dependent due to changes in strain and polarisation of the crystal²⁸. Second, the non-zero elements of the Pockels tensor depend on the crystal symmetry, which can change abruptly with temperature due to structural phase transitions. BaTiO₃ bulk crystals are known to transition from a tetragonal phase at room temperature to orthorhombic and rhombohedral phases at lower temperatures (~ 270 K and ~ 200 K respectively)²⁵. Such transitions change the elements of the Pockels tensor and modify the magnitude of the effective Pockels coefficients²⁸. Because phase transitions of thin-film materials can be drastically affected by substrate strain^{26,27,29}, studying the properties of thin-film BaTiO₃ becomes critical when considering cryogenic applications. To investigate the effects of possible phase transitions, we measured r_{eff} in a range from 4 to 340 K. Indeed, the magnitude of r_{eff} is

strongly temperature-dependent (Figure 3). A peak around 240 K, with $r_{\text{eff}} > 700$ pm/V, is consistent with the reported divergence of the r_{42} element of the Pockels tensor close to the tetragonal-orthorhombic transition²⁸. Consistently, the permittivity of the BaTiO₃ layer (see Methods) also shows a peak in the same temperature range (SN 6), confirming that the abrupt change in r_{eff} is caused by a phase transition. Below 240 K the magnitude of r_{eff} decreases gradually to around 200 pm/V at 4 K. In addition to the phase transition at 240 K, a second phase transition occurs above 100 K causing a rapid change in r_{eff} of 90° devices. This phase transition is also observed in the qualitative behaviour of the NLO hysteresis which shows that the transitions is induced by the electric field (SN 6). While r_{eff} of BaTiO₃ is reduced at 4 K compared to room temperature, the value of ~200 pm/V is still larger than most other material systems at room temperature^{19,20}. The effect of a reduced Pockels coefficient on the energy efficiency of EO switching is partially compensated for by a simultaneous reduction of the permittivity of BaTiO₃ (SN 6). Additionally, the conductivity of BaTiO₃ is reduced by more than four orders of magnitude (SN 5), resulting in a negligible static power consumption of BaTiO₃-devices in cryogenic environments. No material instability or drift, as could for example be caused by pyroelectric effects, were observed at cryogenic or room temperature in any experiment.

We have reported the first ever measurement of the cryogenic NLO properties of BaTiO₃, and indeed of any oxide thin-film material. The methods used to characterize these properties will enable further research to improve the cryogenic performance through engineering of the material properties²⁹. However, already today we can use BaTiO₃ to demonstrate cryogenic devices with outstanding performance.

We demonstrate the applicability of BaTiO₃ for cryogenic photonic applications by two examples: low-power EO switching and high-speed data modulation. For switching we use a 500 μm Mach-Zehnder interferometer with 2×2 multimode interference splitters, applying a voltage to one arm. Because the leakage current through BaTiO₃ at 4 K is 10⁴ times lower than at 300 K, less than 10 pW static power is consumed when inducing a π phase shift to switch between the two optical outputs using an electric field of 6×10⁶ V/m (Figure 4a,b), corresponding to a voltage of ~50 V in the given device geometry ($V_{\pi}L = 5$ Vcm). Compared to state-of-the-art technology based on thermo-optic phase shifters¹⁴, static tuning using BaTiO₃ is one billion times more power efficient. The dynamic energy of the switch is ~30 pJ, which could be reduced to ~2 pJ, at a voltage of <5 V,

150 in an optimised device geometry (SN 7). Another important metric for EO switches is the losses
151 in the device. Based on the measured propagation losses (5.6 dB/cm) and the device geometry we
152 estimate an insertion loss of <1 dB (SN 3). The propagation losses are dominated by scattering
153 losses in the SiN waveguide which can be reduced significantly by using a state-of-the-art
154 fabrication process. SiN waveguides with propagation losses as low as 1 dB/m have been
155 reported³⁰.

156 As a second example, we performed data modulation experiments by sending a pseudo-random
157 bit-sequence to a ring modulator ($Q \sim 6'000$) fabricated with BaTiO₃-Si waveguides and recording
158 the optical eye-diagram (Figure 4c,d). Data transmission at rates up to 20 Gbps are achieved with
159 our experimental setup using a drive voltage (V_{pp}) of just 1.7 V, resulting in an extremely low
160 energy consumption of 45 fJ/bit.

161 In conclusion, we have shown that BaTiO₃ thin films can be used to realise electro-optic switches
162 and modulators for efficient cryogenic operation of silicon photonic integrated circuits. We have
163 demonstrated low-power switching, as well as high-speed data modulation. Combining BaTiO₃
164 with silicon photonic integrated circuits, we make a building block available that was previously
165 inaccessible for any cryogenic circuits. We anticipate that these components are a milestone for a
166 versatile platform of cryogenic photonics for applications as diverse as quantum computing and
167 communication^{1,8}, astronomy¹¹, fundamental physics¹², and cryogenic sensing concepts¹³.

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Competing interests

F.E., J.F., and S.A. are involved in developing barium titanate technologies at Lumiphase AG. M.G.T. is involved in developing photonic quantum technologies at PsiQuantum Corporation.

Data availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Author contributions

F.E. and J.F. fabricated and structurally characterised the epitaxial BaTiO₃/SrTiO₃ layer stack with support from H.S.. F.E designed all photonic circuits and fabricated them with support from D.C.. F.E., P.S. and S.A. performed optical simulations for the device design. G.E.V-G., F.E., A.A.G., A.H., G.D.M. and J.B. characterised the EO performance at different temperatures including low-speed and RF measurements. The EO data was analysed by F.E. and A.A.G.. F.E. and P.S. performed all electrical measurements. The concept for this work was defined by S.A., G.D.M. and M.G.T. and implemented by F.E. with support of S.A. and J.B.. F.E., J.F., and S.A. wrote the manuscript with contributions from all authors.

Methods

Device design and fabrication. Single crystalline BaTiO₃ was deposited on top of an epitaxial 4-nm-thick SrTiO₃ seed layer by molecular beam epitaxy on 8" silicon-on-insulator (SOI) wafers with 220-nm-thick device silicon layer for SiN-based devices, and on 2" SOI wafers with 100-nm-thick device silicon for Si-based devices, following a process described elsewhere³. Direct wafer bonding was used to transfer the BaTiO₃ and device Si layers onto high-resistivity Si wafers capped with a 3-μm-thick thermal oxide. Specifics of the direct wafer bonding process can be found in ref. ³.

For SiN-based waveguides the device Si layer was removed by dry etching, followed by chemical vapor deposition of SiN. The waveguide layer (Si or SiN) was patterned by dry etching. After waveguide patterning, a combination of SiO₂ cladding deposition, via etching, and metallisation was used to form the final cross-section. Intermediate annealing steps at 400°C under O₂ atmosphere were used to reduce propagation losses²¹.

The SiN-based waveguides use an 80-nm-thick BaTiO₃ layer, and 150-nm-thick SiN layer. The strip-waveguide width is 1.1 μm. The SiN thickness and waveguide width were chosen to ensure guiding of a single TE mode, and to maximize the overlap of that mode with the BaTiO₃ layer. The electrode-to-electrode gap is 9 μm to ensure no added losses caused by metal absorption. The racetrack resonators have a bend radius of 50 μm and straight sections of 75 μm length. The coupling gap (0.53 μm) between the access waveguide and the resonator was optimized for critical coupling.

The Si strip-waveguides were fabricated using 225-nm-thick BaTiO₃ and 100-nm-thick Si. The waveguide width is 0.75 μm. As for the SiN-based waveguides the waveguide dimension, including the Si thickness, were designed for TE single mode operation, with an optimized optical overlap with the 225-nm-thick BaTiO₃ layer. The racetrack resonator that was used has a bending radius of 15 μm and straight sections of 30 μm, and the electrode-to-electrode gap is 2.3 μm. The small electrode gap causes additional propagation losses in the resonator ensuring a Q-factor allowing >30 GHz bandwidth. The coupling gap of ~0.1 μm was optimized for critical coupling.

Cryogenic measurements. The cryogenic electro-optic measurements were performed in a Lakeshore CPX cryogenic probe station, fitted with RF (40 GHz BW, K-type connectors) and

optical feedthroughs. DC and RF signals were applied to the devices using RF probes, and optical coupling was achieved using a fibre array with polarisation maintaining fibres for 1550 nm. A tuneable laser (EXFO T100S-HP) and power meter were used to record transmission spectra (EXFO CT440). The cryogenic electrical measurements were performed in a Janis cryogenic probe station equipped with DC probes. Current-voltage and capacitance-voltage measurements were performed using a parameter analyser. Both cryogenic probe stations were cooled by liquid helium to a base temperature of 4.2 K.

DC EO characterisation. The DC electro-optic response was extracted by applying a voltage to the electrodes of a racetrack resonator and measuring the shift in resonance wavelength ($\Delta\lambda$), compared to the unbiased case, as a function of the applied voltage. From the measured wavelength shift, the change in BaTiO₃ refractive index (Δn_{BTO}) can be estimated as

$$\Delta n_{\text{BTO}} = \frac{\lambda_0 \cdot \Delta\lambda}{\text{FSR} \cdot L_{\text{E}} \cdot \Gamma_{\text{BTO}}}$$

where Γ_{BTO} is the optical confinement in BaTiO₃, FSR is the free spectral range of the resonator, L_{E} is the electrode length, and λ_0 is the resonance wavelength with no voltage.³ The effective Pockels coefficient, r_{eff} , was then determined according to the procedure described in SN 4.

RF frequency response. To measure the EO frequency response (EO S_{21}) a vector network analyser (VNA, Keysight PNA 50 GHz) was used to apply the electrical stimulus to a BaTiO₃ ring modulator. The modulated optical signal was applied to a photodiode (Newport 1024) and the response recorded by the VNA. Electrical calibration was performed before the measurement, and the response of the photodetector was compensated for the data analysis. While the VNA could generate signals up to 50 GHz, the bandwidth of the photodetector was 26 GHz, which in combination with large frequency-dependent electrical losses in the cryogenic probe station (SN 8) makes it impossible to measure the bandwidth beyond 30 GHz.

Data modulation experiments. For the data modulation experiment, a racetrack resonator modulator with a Si strip-waveguide was used. The electrical signal was generated using an arbitrary waveform generator. A pseudo-random bit stream of 2^7-1 bits was used for modulation. The electrical signal was pre-distorted to compensate for the finite time-response of the electrical signal path (SN 8). The signal was amplified using a RF amplifier and sent to the cryogenic setup, with an estimated voltage swing on the device of 1.7 V (SN 8). A Pritel FA-23 EDFA was used to

312 amplify the modulated optical signal which was applied to a photo diode and recorded on an
313 oscilloscope.

314

Figure 1. BaTiO₃ electro-optic device concept. **a**, Schematic cross-section of the devices. A silicon or silicon nitride layer forms a strip-waveguide (grey) on top of an BaTiO₃ layer (blue). A thin Al₂O₃ layer (red) was used to improve adhesion (Methods). Lateral electrodes fabricated with W (green) are used to apply an electric field across the BaTiO₃. The devices are embedded in SiO₂ (yellow) layers on top of silicon substrates (black). The refractive indices of BaTiO₃ and SiN were measured using spectroscopic ellipsometry. **b**, **c**, Simulations of the Pointing vector, $|S_z|$, of the transverse electric (TE) mode of the SiN waveguide geometry and the Si waveguide geometry, respectively. The two waveguide geometries show an optical confinement in BaTiO₃, Γ_{BTO} , of 18 % and 41 %, respectively. **d**, **e**, Optical micrographs of BaTiO₃-SiN and BaTiO₃-Si racetrack resonators, respectively, used to characterise BaTiO₃ and demonstrate device functionality. The phase shifter section is embedded in the resonator which is evanescently coupled to access waveguides. The signal electrodes are connected to pads and the ground electrodes to a ground plane, for contacting using electrical probes. **f**, Characterisation principle of resonant electro-optic switches, showing example data of the shift in resonance wavelength between no applied field (solid line) and 16.7 MV/m (dashed line), which in this device corresponds to 150 V resulting in a shift of 4.3 pm/V. The shift in resonance wavelength, $\Delta\lambda$, is measured for an applied electric field and converted to the material properties of BaTiO₃ (see Methods).

Figure 2. Electro-optic and electrical response of BaTiO₃-based optical switches at 4 K. **a**, Refractive index change of BaTiO₃ as a function of applied electric field for a device in the 11.25° direction (as defined in **b**). The hysteretic behaviour between increasing (blue) and decreasing (red) voltage originates from ferroelectric domain switching in the BaTiO₃, as illustrated schematically on top. P_{net} is the net polarization of all the domains. The arrows indicate the polarization of individual ferroelectric domains (blue) when a field is applied to lateral electrodes (green). **b**, Angular anisotropy of the effective Pockels coefficient in BaTiO₃ measured at 4 K and 300 K. The angle is defined relative to the BaTiO₃<100> direction. The same anisotropy as for BaTiO₃ at room temperature is observed but with reduced magnitude. The error bars show the combined standard error of the fit and from averaging measurements of multiple devices with the same orientation. **c**, Electro-optic S_{21} -parameter of BaTiO₃ ring resonator showing a flat response up to a frequency of 30 GHz at 4 K. The dashed line indicates 0 dB as a guide to the eye. **d**, Current measured as a function of electric field across the BaTiO₃ layer showing extremely low current flowing through the material. The current is dominated by capacitive charging, causing the offset between the sweep directions (indicated by the arrows), together with ferroelectric switching current resulting in the observed peaks (SN 5). **e**, Capacitance as a function of electric field, showing characteristic ferroelectric hysteresis and field-dependent permittivity.

Figure 3. Temperature dependence of the Pockels effect in BaTiO₃. The effective Pockels coefficient along different crystal orientations at temperatures from 4 K to 340 K. The peak around 240 K is the signature of a phase transition in BaTiO₃. A second, field-induced phase transition occurs around 100 K, causing a sharp drop of r_{eff} in 90° devices (indicated by horizontal dashed lines). This phase transition is also evident in the qualitative evaluation of the optical response (SN 6). The grey areas indicate the temperature ranges of the respective phase transitions. The error bars show the standard error of the fit used to extract the Pockels coefficients (SN 4).

Figure 4. Demonstration of low-power switching and high-speed data modulation with BaTiO₃-based devices at 4 K. **a**, Schematic of Mach-Zehnder (MZ) configuration used to switch between two ports. The yellow arrow indicates the input port and the red and blue arrows indicate output ports 1 and 2, respectively. Multi-mode interference splitters were used to split and combine the signal at the input and output ports. A voltage source, V, is used to apply an electric field, E, indicated by green arrows, across one arm of the MZ interferometer. The inset shows the waveguide cross-section. **b**, Transmission from both ports of a MZ switch as a function of applied electric field, along with the static power consumption. When fully switching between outputs, less than 10 pW static power is consumed, and only 30 pJ of dynamic energy. The field is kept below the coercive field of BaTiO₃ (SN 9) to exclude contributions from ferroelectric domain switching. **c**, Schematic of the experimental setup for data modulation. The data signal was generated using an arbitrary waveform generator (AWG) which was amplified and then combined with a bias voltage, V_{bias} , using a bias tee. A tuneable laser set to ~1550 nm provided the optical carrier. After modulation in the cryogenic probe station, the optical signal was amplified by a fibre amplifier and filtered before being detected by a photodiode. The electrical signal from the photodiode was amplified and then recorded on a real-time oscilloscope. The left inset show the waveguide cross-section and the right inset shows the electro-optic-electric (EOE) frequency response of the modulator. **d**, Eye diagrams recorded at 10 and 20 Gbps with $V_{\text{pp}} = 1.7$ V, corresponding to modulation energy of 45 fJ/bit. The opening of the eyes is limited by noise from amplified spontaneous emission of the amplifier used in the experiment (SN 8).