Cryogenic operation of a polarisation cinverter and directional coupler in $\mathrm{LiNbO_3}$ for quantum circuits

(student paper)

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ABSTRACT

Many quantum photonic technologies, such as single photon emitters and superconducting detectors, require cryogenic temperatures at which to operate. Therefore, developing integrated quantum optical components at these temperatures is crucial. We demonstrate an electro-optic polarisation converter and a directional coupler for $1550\,\mathrm{nm}$ at 0.8 K in titanium in-diffused lithium niobate waveguides. The main operation parameters of these integrated devices are preserved, despite the presence of pyro-electric charge build-up. The operation of the polarisation converter preserves the modulation depth of $30-35\,\mathrm{dB}$, increases the modulation voltage from 13 V to 20 V and shows operation up to $25\,\mathrm{MHz}$ at cryogenic temperatures. The splitting ratio of the directional coupling remains virtually unchanged over the entire temperature range.

Keywords: electro-optics, lithium niobate, cryogenic, polarisation converter, directional coupler

1 INTRODUCTION

Integrated quantum photonics offers significant promise in the field of quantum communication. However, many quantum photonic technologies require cryogenic temperatures at which to operate. For example, major advancements have been made recently in the integration of superconducting detectors and quantum dot sources [1], [2], both of which require operating temperatures around 1-5 K. For this purpose, the design and operation of well-known functional integrated optic elements are needed at cryogenic temperatures. Active and passive integrated components have been developed in titanium-indiffused lithium niobate waveguides [3], [4]. This platform offers the advantage of a high second order non-linearity, electro-optic properties and low waveguide losses. Multiple components can be integrated in one platform, including superconducting detectors (SNSPDs) and electro-optical devices [1], [5], [6]. Efficient and stable optical access can be established with pigtailing optical fibres directly to the platform [7]. However, active and passive integrated components lack the realisation in lithium niobate at cryogenic temperatures.

We present results of a polarisation converter and a directional coupler at cryogenic temperatures, compatible with quantum communication and quantum photonic applications [5]. The polarisation converter converts incident polarised light between orthogonal linear polarisation modes, controlled via an externally applied bias voltage. Despite the presence of pyro-electric field accumulation in the device, we were able to characterise the conversion in the temperature range from room temperature to $0.8\,\mathrm{K}$.

The directional coupler splits incident TE-polarised light comparable to a 50:50 beam-splitter into two parallel waveguide channels via evanescent coupling. The waveguide geometry was designed in the telecommunication range of around $1550\,\mathrm{nm}$. Temperature reduction shows no significant variation of the splitting ratio.

2 METHOD

The polarisation converter and directional coupler are realised in z-cut lithium niobate in titanium diffused waveguides. Both independent devices were characterised over the temperature range from 300 K to 0.8 K in a closed-cycle Helium sorption cryostat. To achieve stable light coupling, single mode fibres were butt-coupled to the endfaces of the waveguides and attached with UV-cured optical adhesive. The optical coupling technique achieves total efficiencies of 55% for the polarisation converter and 40% for the directional coupler at room temperature. The optical losses in the waveguides are determined to be in range of $0.15\,\mathrm{dB/cm}$ at a wavelength of 1550 nm (TE).

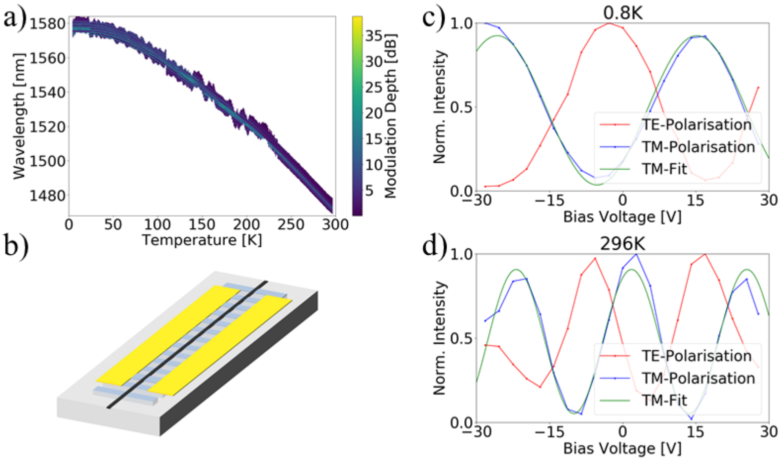

Figure 1. a): Heat map of the modulation depth determined at every wavelength and temperature. The modulation depth is the ratio of the minimum and maximum intensity in the voltage sweep. c),d): voltage dependent intensity modulation at 0.8 K and 296 K, respectively.

The polarisation converter works on the principle of transforming a polarised light beam via an electro-optic perturbation [8]. The conversion is induced in the waveguide by an electric field which is applied by gold electrodes deposited adjacent to the waveguide. The required phasematching of the nonlinear process is achieved by periodic poling in the range of $20\,\mu\mathrm{m}$. Bias voltages of 12 to 13 V achieve a complete polarisation conversion. During a temperature cycle, the conversion behaviour was monitored in the cryostat by modulating the bias voltage and operation wavelength. The characterisation is carried out as conversion maps around the phasematched wavelength in a 9 nm range in 0.3 nm increments while applying voltage sweeps in the range of -30 to 30 V in 1.5 V-steps. Polarisation maintaining fibres guide the TE-polarised light into the device and at the output the change in the output in the TM-polarisation is acquired.

The directional coupler transfers light from one adjacent waveguide to the other. The amount of the evanescent light coupling can be controlled by the separation distance, coupling length and index profile of the titanium diffused waveguides. With the use of refractive index simulations, an optimal geometry was selected for an even splitting ratio into both output waveguides for the TE-polarisation. The splitting of the directional coupler is monitored by continuously coupling TE-polarised light into the input waveguide. The changes in the splitting ratio are monitored at the output in both output waveguide channels during the cooling process. Dual-core fibre pigtails achieve a stable light coupling in and out of the waveguides.

3 RESULTS

We operated the polarisation converter in a temperature range from room temperature to $0.8\,\mathrm{K}$. A total coupling efficiency at room temperature of around 55% was achieved, which reduced slightly to 43% at cryogenic temperatures, which is highly promising for quantum communication applications at telecommunication wavelengths. Together with the high transmission, a modulation depth of the device was also maintained at $25 - 30\,\mathrm{dB}$ throughout the entire temperature range, as shown in Fig. 1 a). The large modulation depth clearly shows that the polarisation conversion effect is working at cryogenic temperatures. Close to the phase-matched wavelength, the modulation depth is highest, from which the phase-matched wavelength can be identified. As the temperature changes, the phase-matched wavelength shifts by about $100\,\mathrm{nm}$, which can be explained by the change in the temperature dependent refractive index. The conversion voltage required for a polarisation conversion increases during the cooling process. The voltage remains almost unchanged at room temperature around 13 V but at cryogenic temperatures an increase up to 20 V is observed for the 15mm long electrodes. We attribute this effect to the accumulation of pyro-electric charges, but it is straightforward to compensate by an additional d.c. bias voltage. The electrode design allows for fast electro-optical modulation. This polarisation modulator achieved a modulation speed of at least $25\,\mathrm{MHz}$ at a temperature of $0.8\,\mathrm{K}$.

We characterised the directional coupler at 1550 nm during the cooling process. The splitting started at room temperature around $52\pm2.5\%$ and increased to $55\pm2.5\%$ at cryogenic temperatures, as can be seen in Fig. 2 a). The total coupling efficiency at room temperature was around 40% but the transmission dropped to 2% at a temperature of 22 K. Below this temperature the coupling ratio remained the same. This indicates that the fibre incoupling was reduced due to thermal stress at the fibre coupled joins. Despite the change in transmission, a virtually temperature independent splitting ratio was achieved with a directional coupler in titanium diffused lithium niobate.

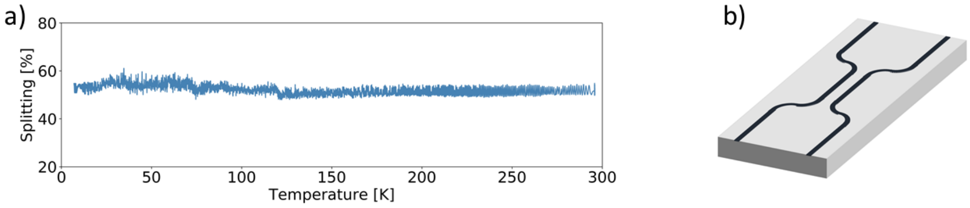

Figure 2. Splitting ratio of the directional coupler over the temperature range from 300-0.8 K. The ratio is determined as the relative power between the two output waveguides.

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