Sagnac-loop phase shifter with polarization-independent operation

Tien Tjue Ng, Darwin Gosal, Antía Lamas-Linares and Christian Kurtsiefer
Centre for Quantum Technologies and Department of Physics,
National University of Singapore, 3 Science Drive 2, 117543 Singapore

Abstract—A bulk-optics, polarization-independent phase shifter for photonic quantum information applications is demonstrated. A transverse mode electro-optic modulator using lithium niobate is placed in a Sagnac-like loop containing Faraday rotators. This direction-dependent polarization rotation in the loop is combined with a Mach-Zehnder interferometer to form an optical switch with an on/off contrast of 96% and a switching time of 1.6 ns.

Index Terms—phase modulation, amplitude modulation, polarization, photonic qubits, quantum information

I. INTRODUCTION

Fast optical phase shifters or switches based on electro-optical materials are in widespread use. Switch devices that operate on a sub-nanosecond timescale are a core building block of photonic technologies, in particular in optical communications [1], [2]. For most typical applications, the devices work for only one particular polarization and can tolerate large insertion losses. The situation is very different in quantum information science. Here, losses are much more important, and a convenient degree of freedom to encode information is the polarization of single photons, since it is particularly easy to manipulate and measure. This implies that this degree of freedom should be left untouched by any external operation, such as switching. The availability of a device which can rapidly switch light with low losses and without affecting polarization opens a new range of applications: conditional measurement schemes, combined polarization state–time bin encoding, quantum computing with optical qubits [3] and device–independent quantum cryptography [4]. For a qubit encoded in the polarization state of a photon, the device would add an overall phase without affecting the quantum information encoded. In Dirac notation, this is expressed by

$$|\psi\rangle = \alpha |H\rangle + \beta |V\rangle \rightarrow e^{i\phi} \alpha |H\rangle + \beta |V\rangle = e^{i\phi} |\psi\rangle , \quad (1)$$

where $|H\rangle$ and $|V\rangle$ represent horizontal and vertical polarization states, $\alpha$ and $\beta$ are the relative amplitudes, and $\phi$ is the global phase. A device adding a global phase to a polarization qubit therefore must preserve not only the relative amplitudes of the polarization components, but also the relative phase.

Electro-optic modulators (EOM) vary the phase of transmitted light with a transverse or longitudinal electric field (with respect to the propagation direction) by inducing a refractive index change in a crystal. While devices based on a longitudinal field can be polarization independent, the typical high driving voltages renders them impractical for fast operation. To achieve an overall non-birefringent operation of transverse EOMs, a series of crystals can be combined [5], [6], [7]. This makes fast operation more difficult, and complicates the setups and fabrication. Alternatively, the three electro-optic coefficients can be simultaneously used [8]. Such elements, however, exhibit an undesirable phase dependent beam deviation. Our aim was to make a device that can be implemented in bulk optics, is appropriate for integration in typical photonic quantum information setups, and can operate in a ns timescale relevant to such experiments.

II. DESIGN CONCEPT

The basic idea is to split the two polarization components into two counterpropagating beams in a Sagnac-like loop (for a related device based on a similar concept see [9]). These beams are then manipulated such that in one section of the loop they have the same polarization; in this section they both experience an identical phase shift within a single modulator crystal. Further manipulation of the polarization allows the recombination of the two counterpropagating beams such that the original relative amplitudes of the polarization components are maintained and a global phase has been added to the state.
The first step is to separate the two polarization components into counterpropagating beams by a polarizing beam splitter (PBS). To ensure that the two components have the same polarization at the modulator position in the loop, we need to rotate the polarization of the clockwise beam by 90° twice, while the counterclockwise beam is not affected. This direction-dependent rotation is achieved with a combination of Faraday rotators (FR) and half wave plates (HWP). By siting the modulator crystal in the symmetric point in the loop, we avoid geometric limitations in operation speed from propagation speeds within the device. Figure 1 schematically shows how the two counterpropagating polarization components are split, manipulated, and eventually recombined by the same PBS that performs the original splitting. In contrast to [9], the Faraday rotators in this design allow for the phase shifted light to exit through a different port of the loop than the input light.

III. IMPLEMENTATION

Lithium niobate is used as non-linear material for the modulator due to its excellent optical and electro-optical properties [11], [12], [13]. To implement the basic idea with free propagating beams we use an anti-reflection coated bulk 20 mm long y-cut LiNbO$_3$ crystal with a cross section of 1×1 mm$^2$ as a phase shifting element. The y-cut is selected to avoid beam deviations induced by the applied field.

The length of the crystal is chosen together with the cross section such that the beam can propagate through the material within the Rayleigh length of a transverse Gaussian mode, and the crystal is still reasonable easy to fabricate and manipulate, while keeping a large aspect ratio, as this results in a low half wave voltage.

The polarization of light at the modulator was chosen to be parallel to the optical axis for the lowest half wave voltage,

$$V_{1/2} = \lambda d/L r_{33} n_e^3,$$

(2)

where $d$ and $L$ are the thickness and length of the crystal, $\lambda$ the wavelength of the light, $n_e$ the extraordinary refractive index, and $r_{33}$ the relevant electro-optic coefficient. From our crystal geometry, we expect $V_{1/2} \approx 100$ V, which still can be switched with reasonable effort on a time scale compatible with our photon counter jitter ($\approx 1$ ns).

For half wave voltages on this order, the driving circuit becomes an essential part of the switch design (see Fig. 2). The main component of the driving circuit is a suitable MOSFET (BS131) located closely to the modulator crystal to keep parasitic capacitances small ($C = 50 \text{ pF}$, of which $\approx 5 \text{ pF}$ are from the crystal). While the MOSFET can quickly discharge the crystal, a resistor $R = 20 \text{ k}\Omega$ is used to recharge it again to the half wave voltage. Gate pulses with a rise time of 400 ps and an amplitude of 10 V were provided via an impedance-matched line. While the switching time of the modulator for one direction is limited by the discharge time of the crystal/MOSFET combination, the repetition rate for switch changes has a much larger time constant $\tau = RC$ for recharging the crystal. To maintain the full change of a half wave voltage across the switch after a recharge, we limited the repetition rate to 100 kHz.

This polarization-independent phase shifter is placed in a Mach-Zehnder interferometer to test the performance of our device as a switch, as shown in the small box in Fig. 1. The interferometer is adjusted for zero optical path length difference to allow for optimal operation over a large range of wavelengths. The effects of wavefront mismatch of the two paths are compensated via a divergent lens pair inserted in the reference path of the interferometer.

IV. EXPERIMENTAL PERFORMANCE

The performance of the switch was verified with a He-Ne laser at 632.8 nm. Applying a low frequency saw tooth voltage to the crystal electrodes, we checked the polarization-independency of the switch by measuring the interferometer visibility ($I_{on} - I_{off}$)/($I_{on} + I_{off}$) as a measure for the on/off contrast $I_{on}/I_{off}$ for several input polarization states. The 45° polarization is the most stringent test, since it clearly reveals any loss of a phase relationship between the two polarization components. Table 1 shows the measured half wave voltage and the visibility for different input polarizations of the laser beam after background correction.

Currently, the overall visibility is limited by wavefront matching in the interferometer. The reduced visibility of the 45° polarization is caused by an imperfect polarization compensation of the beam splitting element and the retro-reflectors in the interferometer.

The switching time of the phase shifter was characterized with a fast photodiode (G5842, Hamamatsu) located at one of the interferometer outputs; we observed a switching time (10% to 90% transition) of $1.6 \pm 0.2$ ns, following the limitation in the fall time of the voltage across transistor and crystal (see Fig. 3).

The elements in the phase shifting loop (the two Faraday rotators and the LiNbO$_3$) are anti-reflection coated for operation in the near infrared. At the test wavelength of 633 nm

| Polarization | $V_{1/2}$ (V) | Visibility | on/off contrast |
|--------------|--------------|------------|----------------|
| 0°           | 93.9 ± 0.6   | 96.1 ± 1.7%| 30.3 (17.0 dB) |
| 45°          | 94.6 ± 0.4   | 93.3 ± 1.6%| 28.9 (14.6 dB) |
| 90°          | 94.9 ± 0.6   | 94.7 ± 1.7%| 38.2 (15.8 dB) |
we observe an insertion loss of 1 dB, and we expect a loss of 0.2 dB at the optimal wavelength.

V. Conclusions

We reported on a simple polarization-independent electro-optic modulator with a switching time of 1.6 ns which can be easily adapted to work with a range of different wavelengths. The on/off contrast ratio was between 14.6 and 17 dB, and showed residual polarization effects, which can be attributed to imperfect compensation of the external interferometer. Particular attention was paid to testing the device in complementary polarization bases, as the preservation of coherence between the polarization components is fundamental to our target application.

While currently implemented with free space optical components, the same basic idea could be used with waveguides for applications where the larger insertion loss is of less concern. There, switching times could be significantly improved due to the greatly reduced half wave voltages. Such a device has potential applications in photonic quantum communication experiments, e.g. for carrying out conditional measurements on entangled multi-photon states with polarization encoded qubits.

Acknowledgments

This work is supported by ASTAR SERC grant No. 0521010043, and the National Research Foundation and Ministry of Education, Singapore.

References

[1] Louay Eldada, “Advances in telecom and datacom optical components”, Opt. Eng., vol. 40, pp. 1165–1178, Jan. 2001.
[2] Wooten E.L. et al., “A review of lithium niobate modulators for fiber-optic communications systems”, IEEE J. Sel. Top. Quantum Electron., vol. 6, pp. 69–82, Jan. 2000.
[3] Prevedel et al., “High-speed linear optics quantum computing using active feed-forward”, Nature, vol. 445, pp. 65–69, Jan. 2007.
[4] A. Acin et al., “Device-independent security of quantum cryptography against collective attacks”, Phys. Rev. Lett. vol. 98, 230501, 2007.
[5] B. L. Davydov, A. A. Krylov, D. I. Yagodkin, “Polarisation-independent electrooptical switch based on LiNbO3 and LiTaO3 crystals”, Quantum Electron. vol. 37, pp. 484–488, 2007.
[6] W. K. Burns, T. G. Giallorenzi, R. P. Moeller, and E. J. West, “Interferometric waveguide modulator with polarization-independent operation”, Appl. Phys. Lett., vol. 33, pp. 944–947, Dec. 1978.
[7] H.-H. Oh, S.-W. Ahn, and S.-Y. Shin, “Polarisation-independent phase modulator using electro-optic polymer”, Electron. Lett. vol. 36, pp. 969–970, May 2000.
[8] Arkady Kaplan, and Shlomo Ruschin, “Layout for polarization insensitive modulation in LiNbO3 waveguides”, IEEE J. Sel. Top. Quantum Electron., vol. 6, pp. 83–87, Jan. 2000.
[9] M. L. Dennis and I. N. Duling, III, “Polarisation-independent intensity modulator based on lithium niobate”, Electron. Lett., vol. 36, pp. 1857–1858, Oct. 2000.
[10] L. Thylen, “Integrated optics in LiNbO3: recent developments in devices for telecommunications”, J. Lightwave Technol., vol. 6, pp. 847–861, Jun. 1988.
[11] V. G. Dmitriev, G. G. Gurzadyan, and D. N. Nikogosyan, Handbook of Nonlinear Optical Crystals 64, 119 (1999).
[12] A. Yariv, P. Yeh, Optical Waves in Crystals: Propagation and Control of Laser Radiation (John Wiley & Sons), (2003).
[13] Fernando Aguillo-Lopez et al., Electrooptics: Phenomena, Materials And Applications (Academic Press), 138 (1994).