High-performance and Ultra-compact Endless Automatic Polarization Controller based on Thin-film Lithium Niobate

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Abstract: Based on thin-film lithium niobate platform, we experimentally demonstrate an endless automatic polarization controller which only requires a driving voltage range of 10 V, and achieves a polarization tracking speed of 10 Krad/s.

1. Introduction

State of polarization (SOP), as one of the fundamental properties of light, plays an important role in the optical communication system. For example, the transmission capacity can be increased by using the polarization-division multiplexing technology.[1] In the coherent communication system, a complex digital signal processing (DSP) is often performed to compensate the rapid change of SOP in the fiber.[2] The DSP will meet some challenges in the future ultra-high speed data transmission. A high-performance automatic polarization controller can significantly relieve pressure on DSP.

To date, most of the polarization controllers are based on moving machine parts, such as rotating wave-plates with rotation motors, pushing fiber with piezo-electric actuators, but these solutions are slow and may introduce instabilities from mechanical vibrations.[3] However, some polarization controllers without moving parts also have been proposed.[4] For example, a polarization controller based on the titanium diffused lithium niobate (Ti:$LiNbO_3$) has been reported that it can achieve the fastest control speeds.[5] Although the Ti:$LiNbO_3$ devices are attractive for fast polarization control, the current off-the-shelf Ti:$LiNbO_3$ polarization controller is still bulky in size (> 5 cm) and suffer from high drive voltage range (> 100 V), which severely limit the achievement of higher SOP tracking speed.[5]

Recently, with the advantages of low drive voltage, high speed, and small size, the thin-film lithium niobate (LN) has emerged as a promising platform for future electro-optic (EO) integrated devices.[6, 7] Here we propose and experimentally demonstrate an endless automatic polarization controller based on the thin-film LN platform. It can achieve an on-chip insertion loss of 0.92 dB, a footprint of 15 mm × 3 mm, a SOP tracking speed of larger than 10 Krad/s. The SOP tracking speed of 10 Krad/s is by far the highest endless tracking rate reported in integrated photonics and limited by our electrical control system. Note that, in theory, the SOP tracking speed of the proposed device can reach up to 628 Mrad/s according to a response time of <5 ns.

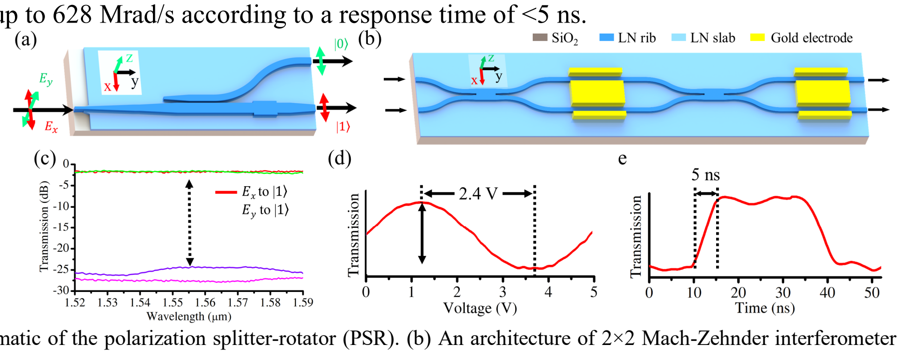

Fig. 1 (a) A schematic of the polarization splitter-rotator (PSR). (b) An architecture of 2×2 Mach-Zehnder interferometer (MZI), composed of two electro-optic (EO) phase shifters. (c) The measured transmissions of the fabricated PSR (including the off-chip coupling loss) when injecting horizontal polarization and vertical polarization, respectively. (d) The normalized transmission of a MZI as a function of the applied voltage. (e) The normalized transmission of a MZI as a function of time when applying rectangle wave signals.

2. Basic Building Blocks

The proposed endless automatic polarization controller is based on two fundamental building blocks (Fig. 1). The first one is the polarization splitter-rotator (PSR) which consists of a mode evolution taper, an asymmetric directional coupler, and an edge coupler for off-chip coupling. It can couple and split two orthogonal linearly polarized states of the off-chip of light, E_x and E_y, into two waveguides, respectively, and simultaneously rotate the transverse magnetic (TM) polarization to the transverse electric (TE) polarization (Fig. 1a). Therefore, only TE polarization of light propagates in our chip. The second one is a 2×2 Mach-Zehnder interferometer (MZI), composed of two voltage-controlled EO phase shifters and two 3-dB multi-mode interferometer (MMI) couplers (Fig 1b). The relative amplitude and phase between two arms can be controlled by the first and second EO phase shifters.

We designed and fabricated the proposed devices on an X-cut LN-on-insulator (LNOI) platform. The wafer consists of a 360 nm thin-film LN layer on a 500 µm thick silicon handle with a 4.7 µm buried oxide layer. Fig. 1c shows that the performance of the fabricated PSR. It can achieve a polarization cross talk of ~ 23 dB, an operation 3dB-bandwidth of > 70 nm, and an on-chip insertion loss of 0.12 dB, an off-chip coupling loss of 1.7 dB. The half-wave voltage and extinction ratio of the fabricated MZI are equal to 2.4 V and 22.6 dB, respectively (Fig. 1c). With a switching speed of <5 ns, in theory, the SOP tracking speed of the proposed device can achieve up to 628 Mrad/s.

3. Results

Fig. 2a presents a schematic of the proposed endless automatic polarization controller. It consists of a PSR, a flip-chip bonded photodetector, and four EO phase shifters. Actually, two phase shifters are sufficient to transfer an arbitrary input polarization state to a single TE polarization, but two additional phase shifters are required in order to realize an endless control (we will compare the cases of non-endless and endless in the following). The incoming light is injected from the PSR side, and there are two output ports located on the output side. One of the output ports connects with the photodetector, which is used as a feedback to control the voltages applied onto the four EO phase shifters. A gradient algorithm was implemented in a field-programmable gate array (FPGA) for fast execution. The algorithm was designed to ensure the optical power received by the photodetector maintains minimum under all possible input SOPs. Therefore, all of the optical power of the input signal with arbitrary SOP would be transferred to the other output port with TE polarization (port 1 in Fig. 1a).

Fig. 2b depicted the micrograph of the fabricated devices. θ_1, θ_2, θ_3 and θ_4 mark the different phase shifters. The device is folded to reduce the total length, and the footprint is about 15 mm × 3 mm. An on-chip insertion loss of 0.92 dB of the fabricated device was measured.

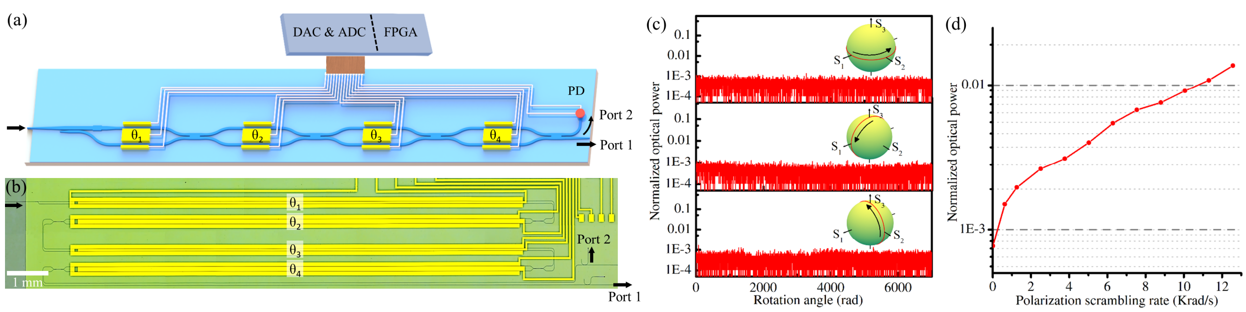

Fig. 2 (a) The schematics of the proposed endless polarization controller. (b) The microscope image of the fabricated device. (c) The normalized optical power of the feedback signal as a function of the rotation angle of the input polarization. Insets: the rotation trajectories of the input polarization states. d The normalized optical power of the feedback signal as a function of the polarization scrambling rate.

We used a commercial polarization scrambling device (General Photonics, PSY 201) to characterize the performance of our polarization controller. To quantify the control system, the feedback signal, including the deviations caused by the voltage change, was recorded every 5.1 µs. Firstly, we demonstrate the endless operation capability of our device by programing the input SOPs to endlessly rotate around three different orthodromes on the Poincaré sphere (Fig. 2c insets). We perform tracking experiment for more than 7000 rad for each great orthodrome. Fig. 2c shows that the normalized optical power received by the photodetector was always kept at a low level of < 0.1%, indicating the successful endless tracking operation.

To characterize the SOP tracking speed of our device, we reprogrammed the commercial polarization scrambler to generate rapidly and randomly varying SOPs at different scrambling rate, and then we use our device to track and stabilize the scrambling SOPs. As shown in Fig. 2d, the normalized power received by the flip-chip bonded photodetector could still maintain at around 1% in the case of the SOP changing rate of 10 Krad/s. This is by far the highest endless tracking rate reported in integrated photonics and limited by our electrical control system. Note that the theoretical SOP tracking speed of the proposed device can achieve up to 628 Mrad/s according to a switching speed of <5 ns of a single MZI.

Next, we compare the difference between the non-endless and endless operation. A polarization controller (called as single-stage PC), consisting of two optical phase shifters (Fig. 3a), was used for exhibiting the non-endless operation. Although the single-stage PC also can be used to track and transfer the input polarization state, it cannot realize the endless operation. As shown in Fig. 3b, with the change of the input SOP, the voltage applied to the single-stage PC is easy to exceed the voltage range of the digital-to-analog converter. During the period of exceeding the voltage range, the single-stage PC cannot track the input SOP. While the voltages applied to the endless polarization controller never achieve the voltage range of the digital-to-analog converter (Fig. 3c and 3d).

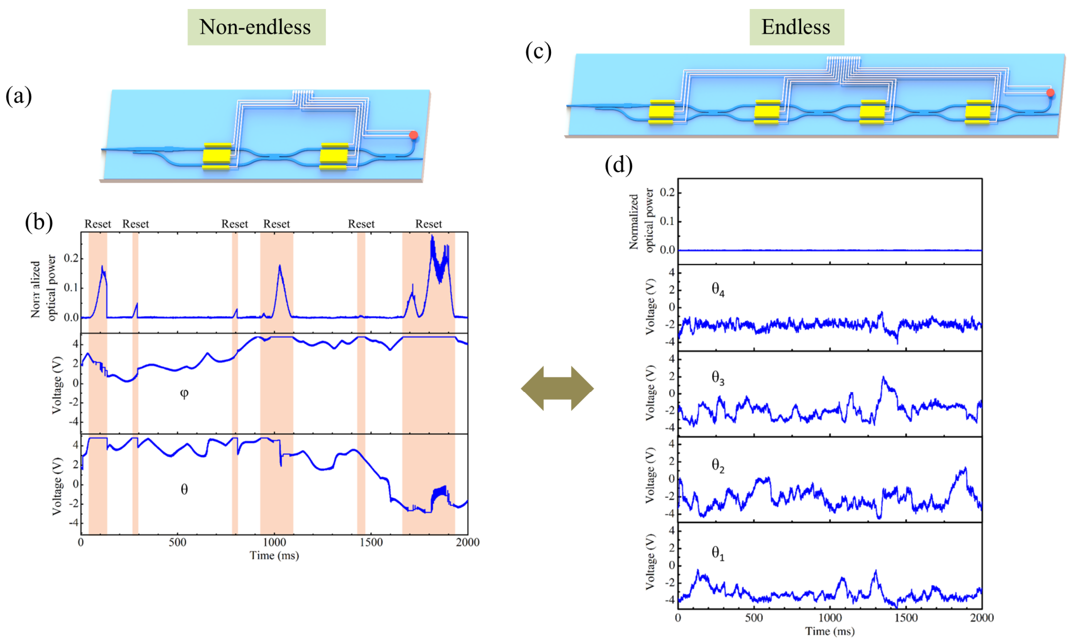

Fig. 3 (a) a schematic of a polarization controller which only consists of two optical phase shifters, and is used for exhibiting the case of non-endless. (b) The optical power received by the photodetector, and the voltages applied to the phase shifters as a function of time when using the polarization controller shown in (a) to track the incoming polarization state. (c) A schematic of an endless polarization controller. (b) The optical power received by the photodetector, and the voltages applied to the phase shifters as a function of time when using the endless polarization controller shown in (a) to track the incoming polarization state..

4. Conclusion

In this work, we proposed and experimentally demonstrate an endless polarization controller based on the LNOI platform. With the advantages of low driving voltage range and high response speed, the proposed device will open a new path for the polarization management.

5. References

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