Controllable Passive Multi-polarization-states Generator based on Silicon Photonics for Quantum Communication

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Abstract: We demonstrate a silicon-based controllable multi-polarization-states generator for quantum key distribution. Our device can effectively generate various sets of well-defined four-polarization states using the thermo-optics effect and combine them into one port at a telecom-wavelength.

1. Introduction

One of the promising methods for secure communication is quantum key distribution (QKD) that applies the quantum mechanical properties of light to the distribution of secret keys, in which a sender and a receiver share keys that cannot be eavesdropped on [1,2]. Over the past decades, QKD has been evolved from demonstrations to practical implementations and is expected to be one of the first commercial quantum technologies [3]. Despite the maturity of QKD, there are barriers to technology adoption such as mass production and integration of functional photonic devices toward commercialization.

Silicon photonics platform, which allows photonic devices with multiple functions to be integrated into a single photonic circuit, have been introduced for QKD system [4–7]. Such a platform is based on a technology that can be commercialized and mass-produced by mature semiconductor fabrication processes [8]. Recently active polarization state generators for QKD using silicon photonics technology have been reported [4,6]. Such an active device can be used as a polarization encoder in QKD, but it may not be easy to generate accurate polarization states due to the degradation of the optical modulation amplitude.

In this paper, we introduce a passive multi-polarization-states beam combiner (MPSBC) for QKD based on silicon photonics to avoid the generation of inaccurate polarization states by free-carrier dispersion. Our MPSBC is composed of a two-dimensional (2D) grating coupler (GC), multi-mode interferometer (MMI), phase shifter, and 1D GC. We note that our device can continuously generate various sets of well-defined four polarization states, and can combine them into one port.

2. Theory

Figure 1(a) shows a MPSBC consisting of 1D GCs, a 2D GC, MMIs, and phase shifters. The MMI is used for a 50:50 beam splitter that converts the input state of $|P\rangle$ to output states of $|l\rangle$ and $|r\rangle$, as shown in Fig. 1(b). A photon is coupled to each 1D GCs used as input ports of the MPSBC from single-mode fibers (SMFs). The input photon in the MPSBC has transverse electric (TE) polarization on a plane parallel to the MPSBC, and the polarization direction is perpendicular to the propagation direction of the photon in the waveguide. After passing through the MPSBC, the output photon through 2D GC is coupled to an SMF. In Fig. 1(a), the $|P_1\rangle$ ($|P_4\rangle$) photon state coupled to 1D GC propagates to 2D GC with a $\pi/2$ phase difference through the MMI of H_T (H_B). The photon, $|t\rangle$ ($|b\rangle$), arriving at the 2D GC is converted to the $|D\rangle$ state with 45° polarization ($|A\rangle$ state with -45° polarization) and then coupled to the output fiber. We can describe as follows:

$$UH_T\,|P_1\rangle \rightarrow U\frac{1}{\sqrt{2}}i\,|t\rangle = \frac{1}{\sqrt{2}}i\,|D\rangle\,,$$

$$UH_B\,|P_4\rangle \rightarrow U\frac{1}{\sqrt{2}}i\,|b\rangle = \frac{1}{\sqrt{2}}i\,|A\rangle\,,$$

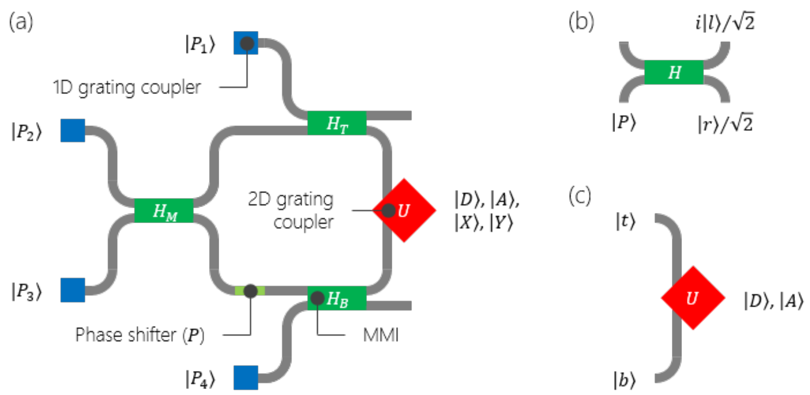

Fig. 1. (a) Schematic of the MPSBC with 1D GCs, a 2D GC MMIs, a phase shifter, and waveguides, (b) 2×2 MMI, and (c) 2G GC

where U is an operator that can describe 2D GC and $|t\rangle$ and $|b\rangle$ denote input states of 2D GC, as shown in Fig. 1(c).

The $|P_2\rangle$ photon state coupled to 1D GC is split into two states with a $\pi/2$ phase difference by the MMI of H_M. One of two states transforms into $|t\rangle$ state through the MMI of H_T, while the other transforms into $|b\rangle$ state with a $\pi/2$ and φ phase through the phase shifter of P and the MMI of H_B. On arriving at the 2D GC, $|t\rangle + ie^{i\varphi}|b\rangle$ photon state then convert to $|X\rangle$ photon state. Similarly, the transformation of $|P_3\rangle$ to $|Y\rangle$ can be understood using a method similar to that of $|P_2\rangle$ and described as follows:

$$UH_TPH_M|P_2\rangle \rightarrow \frac{1}{2}\left(|D\rangle + ie^{i\varphi}|A\rangle\right) \equiv |X\rangle,$$
$$UH_BPH_M|P_3\rangle \rightarrow \frac{1}{2}\left(i|D\rangle + e^{i\varphi}|A\rangle\right) \equiv |Y\rangle.$$

By adjusting the phase, φ, of the phase shifter (P) on the MPSBC, $|P_2\rangle$ and $|P_3\rangle$ of input photon states can be transferred to the two orthogonal polarization states on the circle defined by $|H\rangle$, $|V\rangle$, $|R\rangle$, and $|L\rangle$ on the Poincaré sphere surface, where $|H\rangle$, $|V\rangle$, $|R\rangle$, and $|L\rangle$ denote horizontal, vertical, right circular, and left circular polarization state, respectively. In particular, when the phase of the phase shifter is 0° and 90°, the input photon states set $\{|P_2\rangle, |P_3\rangle\}$ is converted to the set of $\{|X\rangle, |Y\rangle\}$, corresponding to $\{|R\rangle, |L\rangle\}$ and $\{|V\rangle, |H\rangle\}$, respectively. Therefore, our MPSBC can be used as the polarization encoder for polarization-based QKD.

3. Experiments and results

The MPSBC is fabricated by using a standard complementary metal-oxide-semiconductor compatible process. We employ a deep ultraviolet photolithography process with a 220 nm thick Si on a 2 µm thick buried oxide.

Figure 2(a) shows an optical microscope image of our proposed MPSBC which consists of 2×2 MMIs, a heater, and 2D GC, and the size is approximately 1900 × 1000 µm^2, where the heater is used as a phase shifter. Input light is coupled into and out of the MPSBC by SMFs. To obtain a high coupling efficiency from SMFs to the MPSBC for TE mode, the 1D GCs are used. The 2D GC is used for the conversion from two path states in TE mode, to $|D\rangle$ and $|A\rangle$ polarization states, and for effective fiber coupling from the MPSBC. Two heaters with the length of 200 µm not only adjust the phase of propagating light in the other two paths, but also compensate for the phase errors occurring in the fabrication process. The current is applied only to the lower heater in Fig. 2(a), and the upper heater is used to give the same loss as that of the lower heater. We note that only four ports are used as input ports for the MPSBC. The insertion losses for each port (P_1, P_2, P_3, and P_4) of the MPSBC are -15dB, -16.4dB, -16.2dB, and -14.8dB, respectively.

Figure 2(b) shows the measurement data of output polarization states of MPSBC at a wavelength of 1550 nm. When input light is coupled to P_1 and P_4 ports in Fig. 2(a), $|D\rangle$ and $|A\rangle$ polarization states are measured, respectively. As predicted in theory, when the current applied to the heater is swept, the two perpendicular output polarization states corresponding to P_2 and P_3 inputs are rotated on the Poincaré sphere. When input light is coupled to P_2 (P_3) at 1.2 mA (1.8 mA) current applied to the heater, $|R\rangle$ ($|V\rangle$) and $|L\rangle$ ($|H\rangle$) polarization states are measured. Thus, multiple pairs of 4-polarization states can be generated by the proposed MPSBC which applies

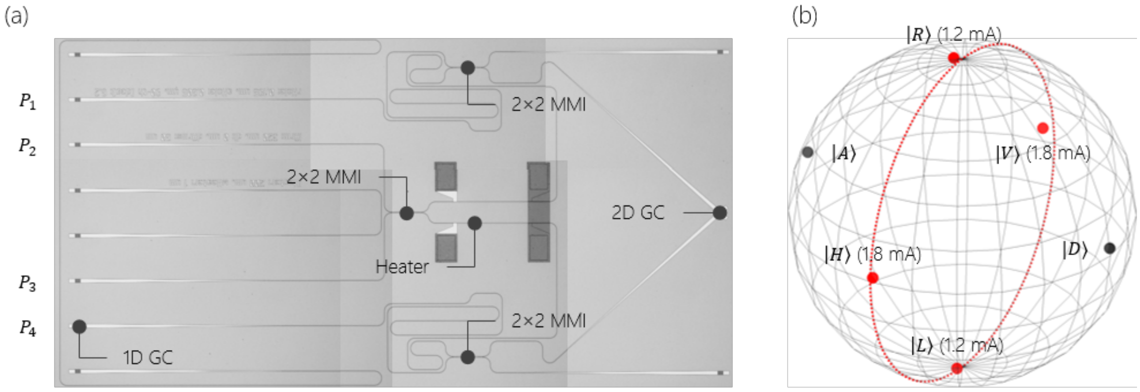

Fig. 2. (a) Microscope image of silicon-based MPSBC. (b) Measured polarization states, $|D\rangle$, $|X\rangle$, $|Y\rangle$, and $|A\rangle$, on the Poincaré sphere at a wavelength of 1,550 nm. When the applied currents to the heater are 1.2 and 1.8 mA, measured set $\{|X\rangle, |Y\rangle\}$ is corresponding to the set of $\{|R\rangle, |L\rangle\}$ and $\{|V\rangle, |H\rangle\}$. Dashed-lined indicates $|X\rangle$ and $|Y\rangle$, corresponding to the P_2 and P_3 inputs in the ideal case when the applied current is increased.

to the polarization-based BB84 protocol as the polarization encoder.

4. Conclusions

We have demonstrated a silicon-photonics-based multi-polarization states beam combiner. The proposed MPSBC is consists of simple passive components and can generate various 4-polarization state sets by varying the current applied to the heater used as phase shifters. Therefore, the MPSBC can be used as a polarization encoder for BB84 QKD with the well-defined four polarization states. Additionally, our device can be used as a polarization decoder when the output port is exchanged for the input port.

5. Acknowledgements

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