Supplementary Materials for

Programmable and sequential Gaussian gates in a loop-based single-mode photonic quantum processor

Yutaro Enomoto, Kazuma Yonezu, Yosuke Mitsuhashi, Kan Takase, Shuntaro Takeda*

*Corresponding author. Email: takeda@ap.t.u-tokyo.ac.jp

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**Supplementary Text**

**Electro-optic modulators**

We use three different types of electro-optic modulators (EOMs). EOM-1 and EOM-2 (Fig. 2A) are bulk polarization modulators, RTP-X-4-20-AR650-1000-HV from Laysop Ltd. For driving them, we use high voltage drivers, custom-made versions of PCD-bpp, from Bergmann Messgeräte Entwicklung KG. They rotate the polarization angle of the incoming beam depending on the applied voltage. EOM-3 is a bulk phase modulator, RTP-PM-X-4-20-AR650-1000-HV from Laysop Ltd. We use the same driver for driving it. It shifts the optical phase of the incoming beam. EOM-4 and EOM-5 are fiber-coupled phase modulators, NIR-MPX800-LN-05-P-P-FA from iXblue Photonics, which do not require a special driver.

EOM-2 is a variable polarization rotator and sandwiched with two polarization beam splitters (PBSs), constituting the variable beam splitter (VBS) (29). While a set of EOM-2 and two PBSs alone serves as a VBS, we also place a quarter-wave plate between two PBSs. This is intended to set the initial reflectivity of the VBS to 50% with no voltage applied to EOM-2, making it easy for us to control the optical path length of the loop part; the optical path length can be sensed by a modulation and demodulation technique since the loop part can be seen as an optical ring cavity whose input coupler has a reflectivity of 50%. We choose 50% because it is realized simply by inserting a quarter-wave plate though any reflectivity but 0% or 100% is acceptable for the control. The path length is corrected by a mirror equipped with a piezoelectric actuator.

With the current driver for EOM-2, two independent values of the voltage, $V_1$ and $V_2$, can be programmed so that four different values of 0, $V_1$, $V_2$ and $V_1 + V_2$ are applied to EOM-2 (29). One degree of freedom, namely $V_1$, is used to make the reflectivity of the VBS be 0% when the loop imports the input state or exports the output state. Thus the number of the remaining degree of freedom is one. This is the reason why we choose to apply the same squeezing gates over the multiple steps for the demonstration. However, this is not a fundamental limitation. As discussed in the reference (29), it can be overcome by developing a more sophisticated driver or cascading the same EOMs.

EOM-4 is used to vary the homodyne angle by changing the applied voltage when LO shift is ON (Fig. 2). This function is necessary for the quantum tomography of the output state of the processor. The applied voltage ranges between −4.59 V and +0.86 V corresponding to −135 degrees and +30 degrees, respectively. For each homodyne angle, we repeat the measurement sequence 1000 times, as a representative one is shown in Fig. 2B.

**Displacing beam**

The displacing beam (Fig. 2A) has two functionalities. One is the optical feedforward to finalize the quantum operations. The other is the preparation of the input coherent state. In our demonstration, instead of externally injecting coherent states from Switch-1, we internally prepare the coherent states in the loop part, where the displacing beam displaces the vacuum state taken in from Switch-1. When the displacing beam is used for the feedforward, the
electrical switches are configured so that the outcome of the homodyne detector is sent to EOM-5 ((v) in Figs. 2A and 2B). On the other hand, when it is used for the input state preparation, the constant voltage source is connected to EOM-5 ((iii) in Figs. 2A and 2B). Since the mode function (Eq. 3) is anti-symmetric with respect to its center, constant displacement over the whole time bin results in no net displacement. Thus, we enable the displacement only for 20 ns within the first half of the time bin (Fig. 2B (iii)) to produce coherent states from the vacuum state.

The Mach–Zehnder interferometer (MZI) in the path of the displacing beam removes the carrier field of the displacing beam by a destructive interference. The carrier field produces an offset in the outcome of the homodyne detector. Ideally, the carrier field will not affect the experimental results thanks to the insensitivity of the mode function (Eq. 3) to the overall offset. However, it does affect to some extent in reality since the amplitude of the carrier field is too large without the MZI. Moreover, due to the dynamical change of the reflectivity of the VBS and thus the offset level originating from the carrier field, the offset cannot be removed simply by applying a high-pass filter to the outcome of the homodyne detector. This is the reason why we implement the MZI to reduce the carrier field to mitigate its undesired effect.

Preliminary measurements for time synchronization and parameter calibration
The synchronization of each component is adjusted by preliminary measurements. The timing of each switching is adjusted in the following way. The classical light fields are introduced into the optical circuit, and the fields are measured by detectors at the output port. A pulse-like switching signal to each component produces a pulse in the time series of the outcome of the detectors. By measuring the timing of the pulse in the time series with respect to the trigger pulse, we can infer when to send switching signals to each component. As the timing controller can create pulse signals with controlled delays, it sends the switching signals at the inferred timings with one nanosecond precision. The electrical delay between the homodyne detector and EOM-5 is adjusted by the length of the coaxial cable transmitting the feedforward signal.

The reflectivity of the VBS is calibrated in advance in a similar way with the classical light field from the injection port for the ancillary states. By measuring the optical power at the output port with the voltage applied to EOM-2 varied, the correspondence between the reflectivity and the voltage level is obtained. The amounts of the phase shift by EOM-3 and -4 are also calibrated in the similar way. By sinusoidal fittings of the outcome of the detector, the correspondence between the phase shift and the voltage level applied to EOM-3 or -4 is obtained.
Fig. S1.

Wigner functions of input and output states of the single-step squeezing gates ($r = 0.44$ and $0.69$) shown with the same rule as Fig. 3. (A), (C), and (E) show the experimental results while (B), (D), and (F) show the theoretical predictions. (A) and (B) are for the vacuum input state, (C) and (D) are for the X-coherent input state, and (E) and (F) are for the P-coherent input state.
Fig. S2.
Wigner functions of input and output states of the single-step quadratic phase gates ($\kappa = 0.46$ and 0.75) shown with the same rule as Fig. 4. (A), (C), and (E) show the experimental results while (B), (D), and (F) show the theoretical predictions. (A) and (B) are for the vacuum input state, (C) and (D) are for the X-coherent input state, and (E) and (F) are for the P-coherent input state.
Fig. S3.

Wigner functions of input and output states of the multi-step squeezing gates shown with the same rule as Fig. 5. A squeezing gate with $r = 0.44$ is applied $n$ times ($n = 1, 2, \text{ and } 3$). (A), (C), and (E) show the experimental results while (B), (D), and (F) show the theoretical predictions. (A) and (B) are for the vacuum input state, (C) and (D) are for the X-coherent input state, and (E) and (F) are for the P-coherent input state.