

# All-optical Quantum State Engineering for Rotation-symmetric Bosonic Codes

Rajveer Nehra<sup>1\*</sup>, Miller Eaton<sup>2\*</sup>, Olivier Pfister<sup>2</sup>, and Alireza Marandi<sup>1,†</sup>

<sup>1</sup> Department of Electrical Engineering, California Institute of Technology, Pasadena, California 91125, USA

<sup>2</sup> Department of Physics, University of Virginia, Charlottesville, VA 22904, USA.

\*These authors contributed equally to this work

†marandi@caltech.edu

**Abstract:** We propose a resource-efficient scheme to generate various non-Gaussian states including binomial code states and truncated Schrödinger cat code states using coherent photon subtraction from a two-mode squeezed state followed by photon-number-resolving measurements. © 2022 The Author(s)

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Continuous-variable quantum information processing through quantum optics offers a promising platform for building the next generation of scalable fault-tolerant information processors. To achieve computational advantages and fault tolerance with quantum error correction, non-Gaussian resources are essential [1]. Non-Gaussianity can be achieved with photon-number-resolved measurements (PNRD) [2,3], non-Gaussian gates such as the cubic phase gate [4], or by the inclusion of non-Gaussian quantum states such as binomial states [5], Schrödinger cat states [6], and Gottesman-Kitaev-Preskill (GKP) states [7]. While the binomial codes and truncated Schrödinger cat codes have been proposed and demonstrated in the microwave domain to protect against finite photon loss errors, their implementations in the optical domain have remained elusive. Such codes belong to a large class of rotation-symmetric bosonic codes, which have been shown to implement fault-tolerant universal quantum computation [8]. Here, we introduce an all-optical method to generate rotationally symmetric states with 4-fold and 2-fold symmetry in the phase space, in particular, the binomial code states and truncated cat code states [9].

Our method, shown in Fig. 1, starts by preparing a two-mode squeezed vacuum (TMSV) state by interfering two orthogonal single-mode squeezed vacuum (SMSV) states produced by optical parametric amplifiers (OPAs) at the first balanced beamsplitter labeled as BS1 in Fig. 1. This is followed by two highly unbalanced

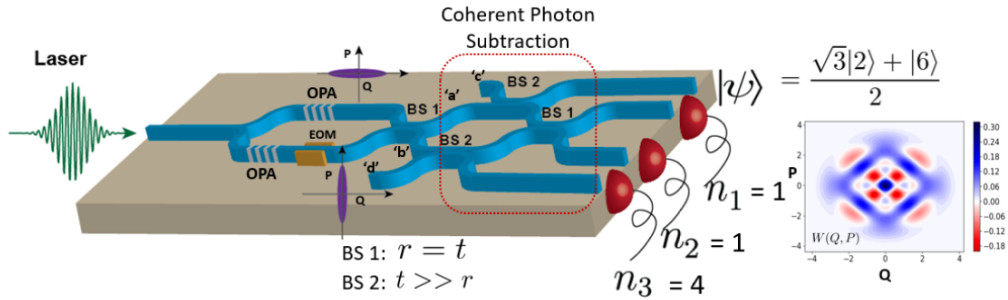


Fig. 1. The proposed scheme for generating rotation-symmetric error-correcting codes. A two-mode squeezed vacuum (TMSV) state is generated by combining two orthogonal single-mode squeezed vacuum (SMSV) states at the first balanced beamsplitter (BS1). Photons are subtracted from each modes of the TMSV state using highly unbalanced beamsplitters (BS 2). The subtracted photons are then interfered at the second balanced beamsplitter followed by PNR measurements on three output modes, which prepares the fourth mode in the desired code state for a certain measurement combination of  $n_1, n_2$ , and  $n_3$ . The dotted red box represents the coherent photon subtraction process. A particular case shown here considers  $[n_1, n_2, n_3] = [1, 1, 4]$ , resulting in  $|\psi\rangle \propto |2\rangle + |6\rangle$  with 4-fold rotational symmetry as evident in the displayed Wigner function. OPA: Optical parametric amplifier. BS1: Balanced beamsplitter. BS2: Unbalanced beamsplitter for photon subtraction. EOM: Electro-optic modulator.

beamsplitters (BS 2) used for photon subtractions from each mode of the TMSV state. Next, a balanced beamsplitter (BS 1) is placed to interfere the subtracted photons in order to erase the information about from which mode the subtracted photons originated. As a result, this combination of photon subtractions and the balanced

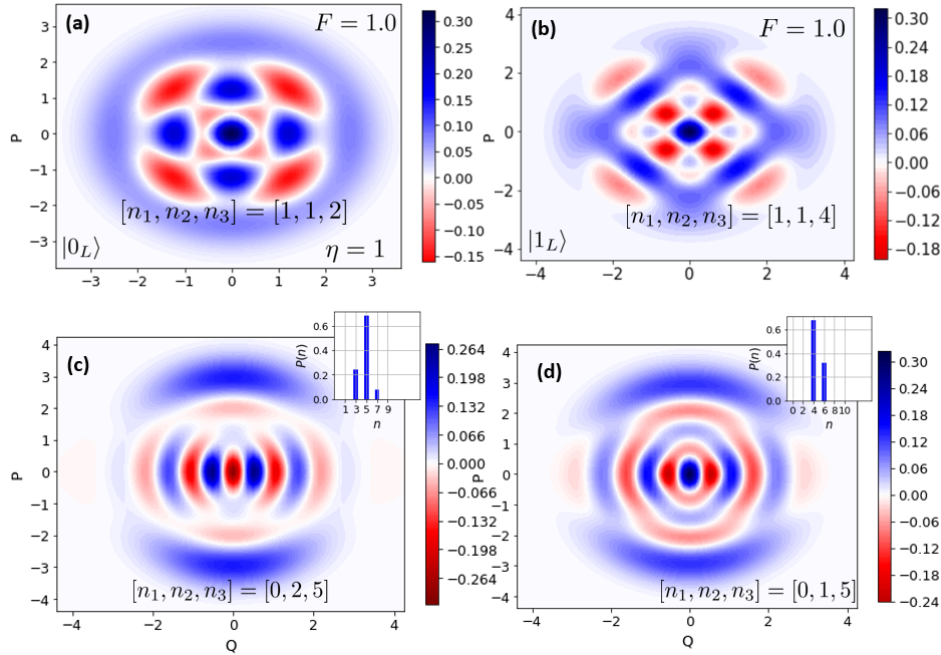


Fig. 2. Wigner functions and photon-number distributions of codewords with 4-fold and 2-fold phase space symmetry. (a) and (c) are the binomial codewords generated for logical states  $|0_L\rangle$  and  $|1_L\rangle$  with fidelity  $F = 1$ , when  $[n_1, n_2, n_3] = [1, 1, 2]$  and  $[n_1, n_2, n_3] = [1, 1, 4]$ , respectively. (c) and (d) are two orthogonal codewords with mean photon-number  $\bar{n} \approx 4.6$  for the measurement outcomes of  $[n_1, n_2, n_3] = [0, 2, 5]$  and  $[n_1, n_2, n_3] = [0, 1, 5]$ , respectively.

interference allows one to coherently subtract photons from the TMSV state. Finally, photon-number-resolving (PNR) measurements are performed on three output modes which prepares the desired state  $|\psi\rangle$  in the fourth mode for a certain configuration of PNR measurement outcomes.

In Fig. 2, two particular cases with 4-fold and 2-fold symmetry are considered with perfect PNR measurement, i.e., the quantum efficiency  $\eta = 1$ . In (a) and (b), we show the Wigner functions of the generated binomial codewords  $|0_L\rangle \propto |0\rangle + |4\rangle$  and  $|1_L\rangle \propto |2\rangle + |6\rangle$ , where the initial TMSV state has squeezing of 10.63 dB and 6.08 dB, respectively. In (c) and (d), truncated cat code words are generated with 6.42 dB of initial squeezing with shown PNR distributions. The Wigner functions exhibit strong negativity, which will be required for fault-tolerance, and both of these codes offer to correct for single-photon losses, a prominent source of error in optical quantum information processing. Such error correcting codes have exact orthogonal codewords in a finite dimensional Hilbert space, which makes them hardware-efficient and amenable for high fidelity unitary operations.

Our proposal allows one to generate these code words with rates of KHz-MHz by pairing up with state-of-the-art PNR detectors and can be readily realized with already demonstrated squeezing levels and high quantum efficiency PNR detection [2, 10].

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