Direct Detection of Quantum Phase Errors in Spatially Multiplexed Transmission Channels

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Abstract: We introduce a protocol for direct detection of arbitrary continuous phase errors in transmission of multi-photon spatially entangled quantum states, and present a design and experimental evidence for its realization in an integrated photonic circuit.

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The appearance of errors is a key problem restricting the performance and scalability of quantum systems for information processing, computing, and communications. Thereby the development of quantum error detection and correction protocols [1] is of particular importance. The rapid advances in integrated photonic technologies can facilitate a versatile range of quantum applications taking advantage of the fast photon propagation at the speed of light over long distances. Yet unlike the widely used solid state quantum particles (e.g. trapped ions) where a π-phase flip error is often present [1], photons in their propagation channels (e.g. fibers or free-space) can suffer from arbitrary phase fluctuations spanning the whole 2π range [2]. A possibility to directly detect such arbitrary continuous phase errors, without relying on additional classical communication channels [3], would be of fundamental interest for research and applications, yet it so far remained an open problem.

Here we formulate and demonstrate experimentally, for the first time to our knowledge, a new approach for the direct detection of arbitrary continuous phase errors in spatially multiplexed optical transmission channels. We show a conceptual scheme in Fig. 1(a). The sender (Alice) performs a static transformation $\hat{T}$ that mixes an input multi-photon state $|\psi_{in}\rangle$ with vacuum inputs and thereby expands an input state to a larger number of modes (from 2 to 4 in the example in Fig. 1(a)). Then, the expanded photon state is transmitted through spatially multiplexed channels, which could suffer from continuous phase noise in each channel φ_n. At the receiver side (Bob), an inversion $\hat{T}^{-1}$ is performed to decode the information and obtain $|\psi_{out}\rangle$. We develop a systematic and rigorous mathematical procedure building on the theory of tomographic measurements [4] to design a fixed transformation $\hat{T}$ in such a way, that the presence of *photon counts from the auxiliary output ports* (3 and 4 in Fig. 1(a)) serves as a *sufficient and necessary condition to indicate the presence of phase errors* in transmission, see Fig. 1(b). In absence of errors, the output photons recombine and the input state is exactly recovered as $|\psi_{out}\rangle = |\psi_{in}\rangle$ with in principle zero photon loss. Importantly, the errors can be directly detected during the transmission of arbitrary and a priori unknown quantum states. Our scheme is equally applicable to both single- and multi-photon states based on simple photon counting, without correlation measurements.

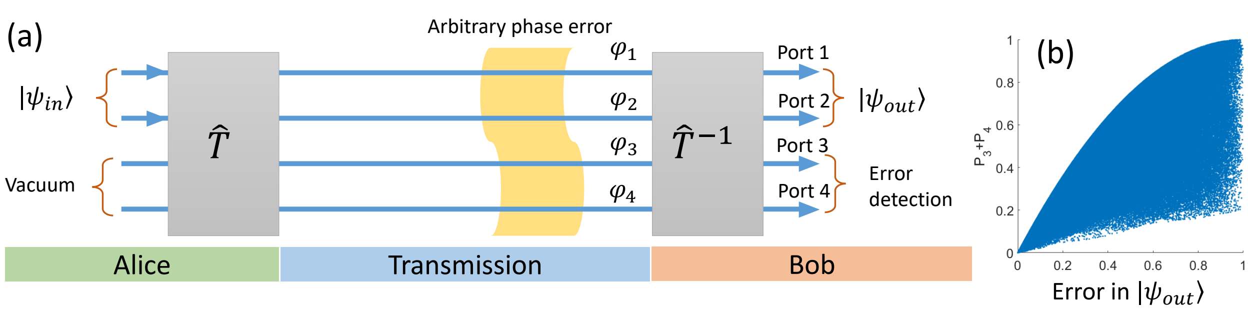

Fig. 1. (a) Sketch of the working principle for detecting continuous phase errors φ_j in spatially multiplexed transmission channels. (b) Modelling of the photon fraction exiting the detection ports 3 and 4 vs. the relative output state error for different inputs states and realizations of phase errors.

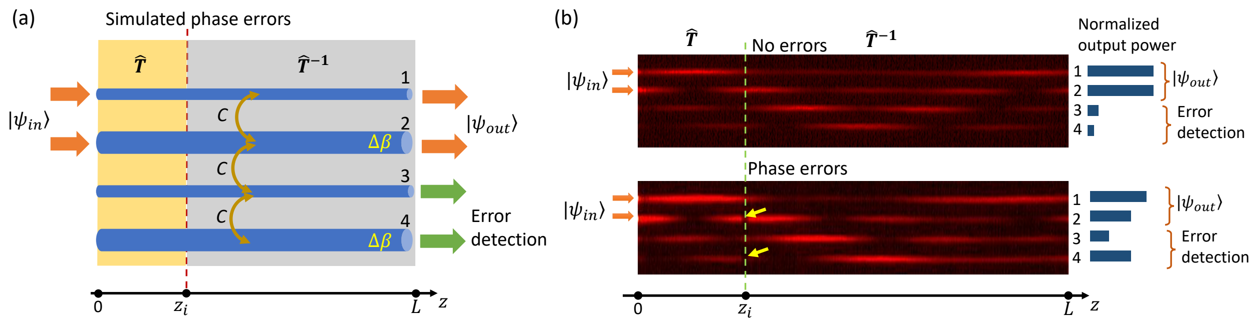

Fig. 2. (a) Scheme of the experimental realization using four coupled waveguides, with the propagation constants in waveguides 2 and 4 detuned by $\Delta\beta$. The phase errors are simulated with specially introduced phase shifts at $z = z_i$ cross-section. (b) Experimental fluorescence images that trace the light evolution in the waveguides: top – no phase errors and bottom – with introduced phase errors at the locations indicated with yellow arrows. Bar plots show the powers at the output.

Our scheme can be realized with static integrated photonic circuits, ensuring excellent stability and compactness. We designed a practical implementation using a coupled waveguide array, which provides a robust solution that is also more compact compared to photonic circuits with Mach-Zehnder-like units; yet the latter can also be used to achieve the same functionality. More specifically, as shown in Fig. 2(a), the structure consists of four equidistant waveguides with a coupling constant C. The propagation constants in the second and fourth waveguides are judiciously detuned with $\Delta\beta \simeq 1.2C$. Then, the device section $0 \leq z \leq z_i$ realizes the transformation $\hat{T}$, where the value $z_i \simeq 1.6\, C^{-1}$ is optimized for maximum sensitivity in quantum error detection. For the proof-of-principle demonstration, we simulate the transmission phase errors with specially introduced phase shifts inside the waveguides at the cross-section $z = z_i$. Then, the following section $z_i \leq z \leq L$ implements the inverse transformation $\hat{T}^{-1}$, where $L \simeq 7.3C^{-1}$.

We performed experiments to validate this scheme using coherent light emulating the single-photon regime, which is valid as our protocol only relies on photon counting. The waveguides are created in fused silica through femtosecond laser writing with the length $L = 67$mm and the experimentally-characterized coupling constant $C = 0.1026$ mm^{-1} at the laser wavelength of 633 nm. We set the detuning $\Delta\beta$ according to the analytical condition formulated above. We simulate the effect of transmission errors by incorporating segmented waveguide sections to introduce phase shifts [5] at $z_i \simeq 17$ mm. This position is chosen to achieve the best error-sensitivity. In Fig. 2(b) we show two representative cases of the experimentally observed light evolution. The input state is prepared with a spatial light modulator, $|\psi_{in}\rangle = [1,-1]/\sqrt{2}$. We show in Fig. 2(b, top) a case with no induced phase error at z_i, hence the input state is reconstructed at the output waveguides 1 and 2, while there is very little light exiting from waveguides 3 and 4. The very small power detected from ports 3 and 4 is due to fabrication imperfections and can be suppressed by more accurately calibrating the laser writing process. In contrast, when we add phase errors at z_i in some of the waveguides, as indicated with yellow arrows in Fig. 2(b, bottom), one can clearly observe a considerable light fraction exiting from the output ports 3 and 4, realizing the detection of phase errors in the transmission. Our approach can be simply generalized to photonic systems with a larger number of spatially multiplexed ports or waveguides. Moreover, by introducing tunable phase shifters at the end of the transmission channels, it may be possible to compensate the detected phase errors in real-time.

In summary, we developed and demonstrated with a proof-of-principle experiment a new protocol enabling direct quantum error detection associated with a practically important phase noise in spatially mutiplexed transmission channels. We anticipate that it will facilitate the development of more robust photonic devices for the processing and communication of quantum information.

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