Quantum receiver for phase-shift keying at the single photon level

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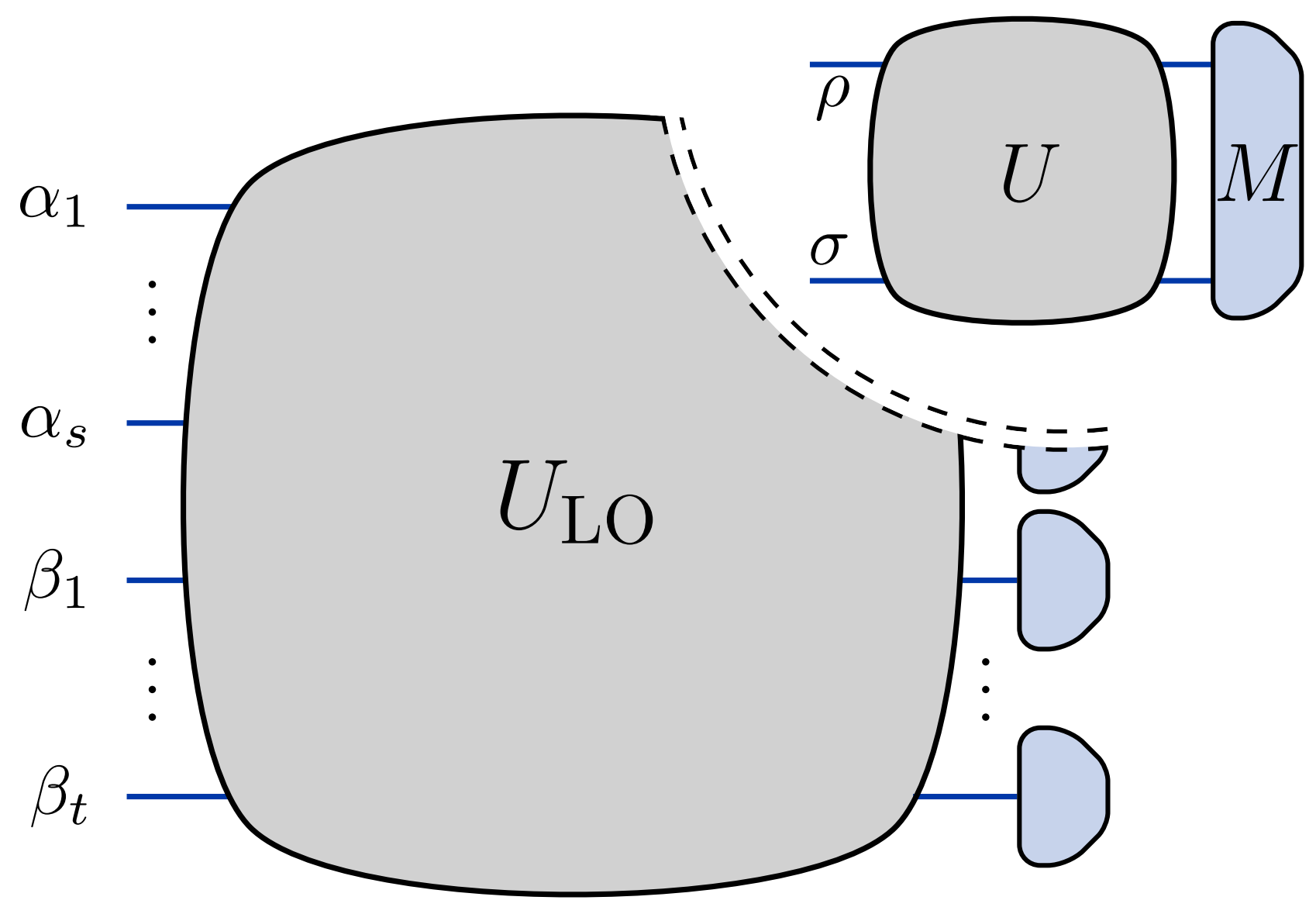
Motivation

Quantum enhanced receivers provide improved discriminatory capabilities for multiple non-orthogonal quantum states. We propose and experimentally demonstrate a new decoding scheme for quadrature phase-shift encoded signals. Our receiver surpasses the standard quantum limit and outperforms all previously known non-adaptive detectors at low input powers [1].

Theoretical framework

Ambiguous discrimination of ρ_x from set $\{\rho_j\}$ with prior probabilities $\{p_j\}$ using ancillary states σ, a unitary transformation U, and measurement M [2, 3].



Discrimination of multiple coherent states

The best guess for input x, given output y is the one that maximises,

$$p_{U,\sigma}(\hat{x}|y) = \max_x p_{U,\sigma}(x|y) = \frac{1}{p_{U,\sigma}(y)} \max_x p_{U,\sigma}(y|x)p(x).$$

The average success probability is given by

$$p_{U,\sigma} = \sum_y p_{U,\sigma}(y) p_{U,\sigma}(\hat{x}|y).$$

Choose ancillary states and measurements to optimise the success probability:

$$p_s = \sup_{U\in\mathcal{U},\sigma\in\mathcal{S}} p_{U,\sigma}.$$

Linear optics toolbox

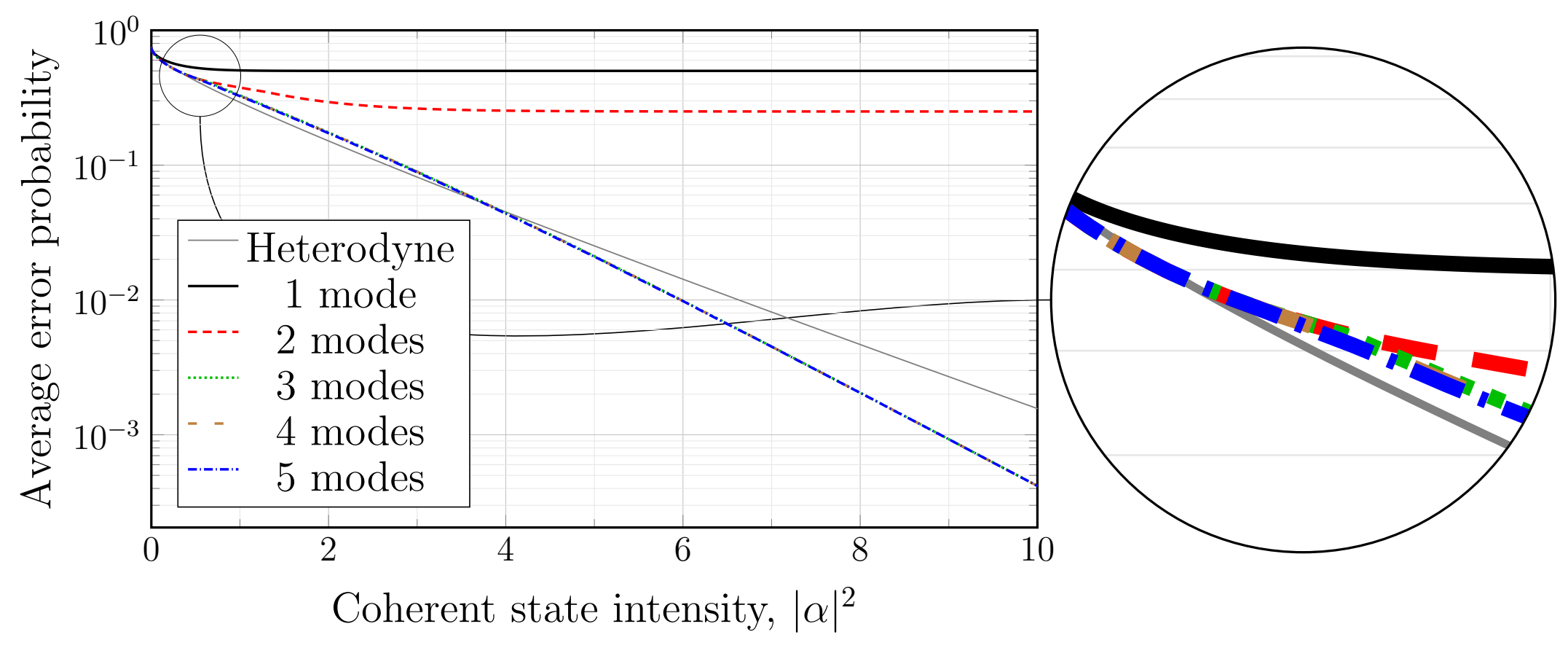
Mix α_x with $N-1$ auxiliary coherent states β_j through an N-mode passive, linear optical unitary U, followed by mode-wise displacements δ_j:

$$\gamma_j = U_{j1}\alpha_x + \sum_{k=2}^{N} U_{jk}\beta_{k-1} + \delta_j .$$

Optimising p_s scales quadratically with the number of modes N. We reduce this to a linear complexity by instead mixing α_x with $N-1$ vacuum modes at the same unitary. Hence, $\gamma_j = u_j\alpha_x + \epsilon_j$ with u a unit vector. Now determine optimal choice for u and ϵ to maximise p_s.

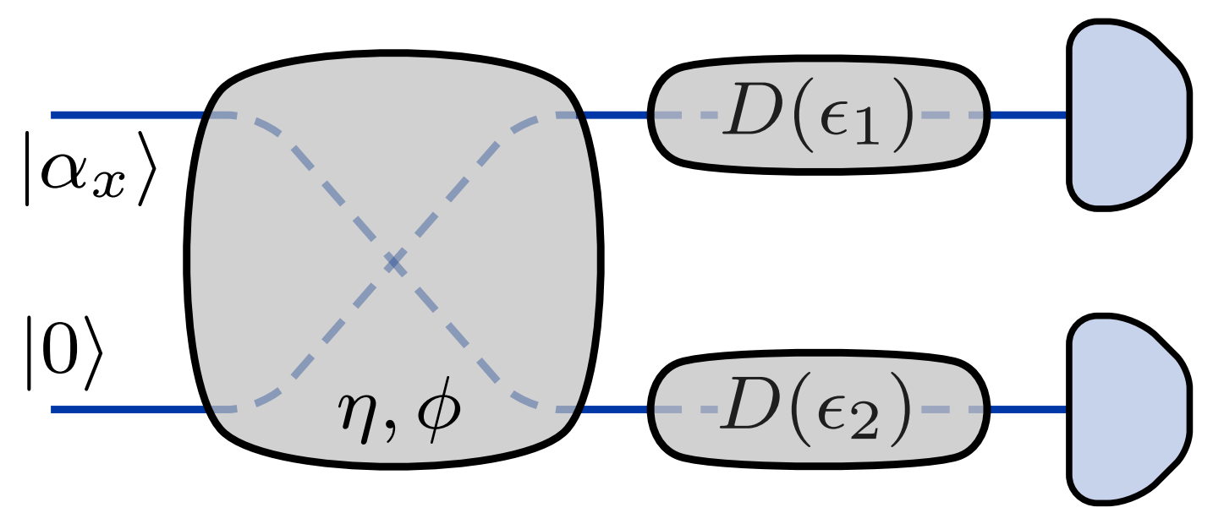
Quadrature phase-shift key

To optimisation the success probability, first fix the number of ancillary modes.



Average error for QPSK for different N

Additional ancillary modes increase the complexity of the decoder with minimal improvements. For the weak amplitude regime, we consider only one ancillary mode ($N = 2$).



Optimal QPSK receiver

A near optimal receiver is attained through

$$u = \frac{1}{\sqrt{2}}(1,1) \quad \text{and} \quad \epsilon = \frac{1}{2}(i+1, i-1) .$$

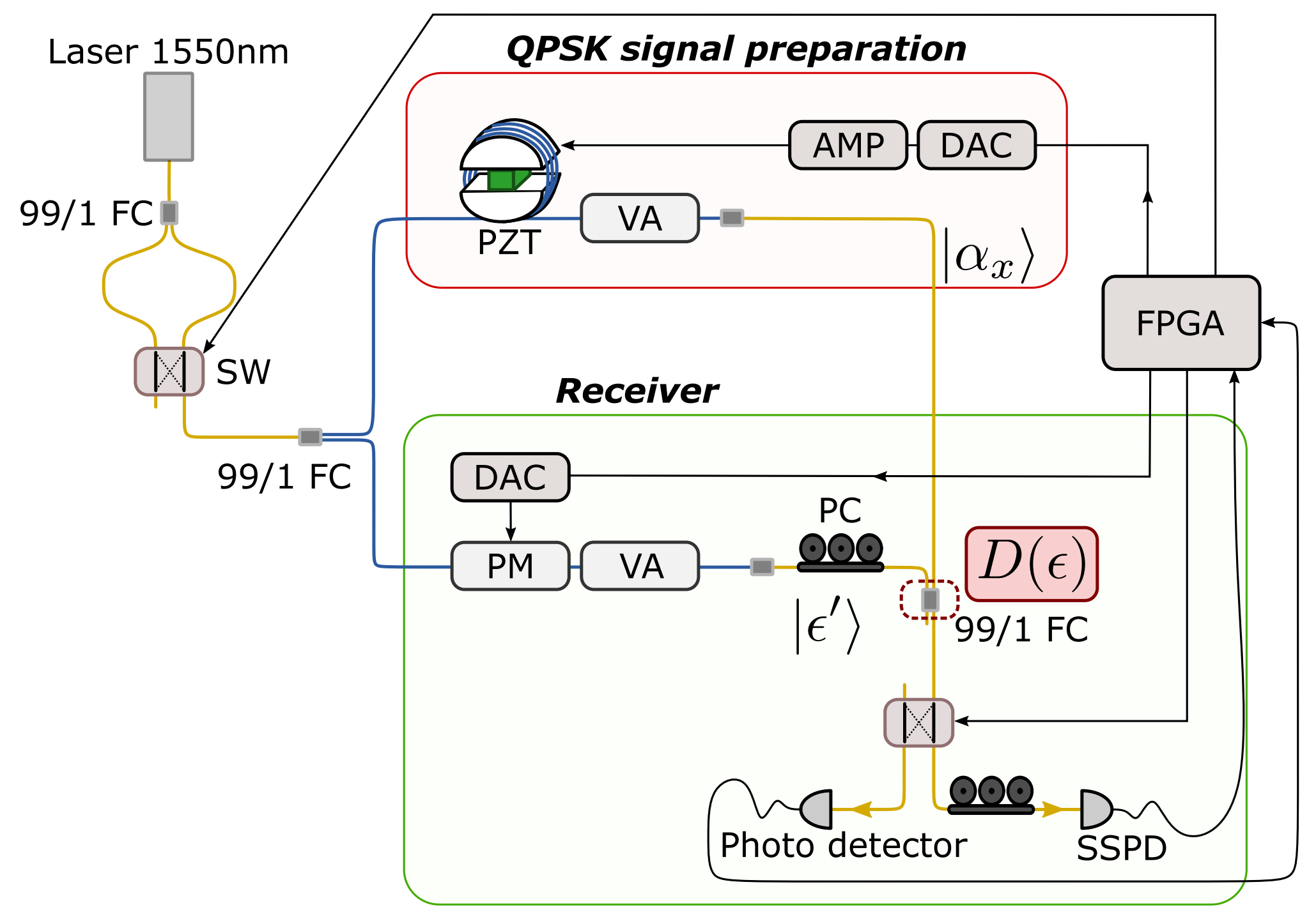
Physically, this is realised by mixing the input and ancilla modes on a 50% beam splitter before being displaced. For these parameters, we obtain the following analytical expression for the average success probability:

$$p_s = \frac{1}{4}\left(1 + 2\,\exp\left[-\frac{1+\alpha^2}{2}\right]\sinh\left[\frac{\alpha}{\sqrt{2}}\right]\right)^2 ,$$

which is close to the numerically optimised success probability. Note that the independence of the success probability, and hence the optimal parameters, on $|\alpha|$ is only valid in the weak amplitude regime.

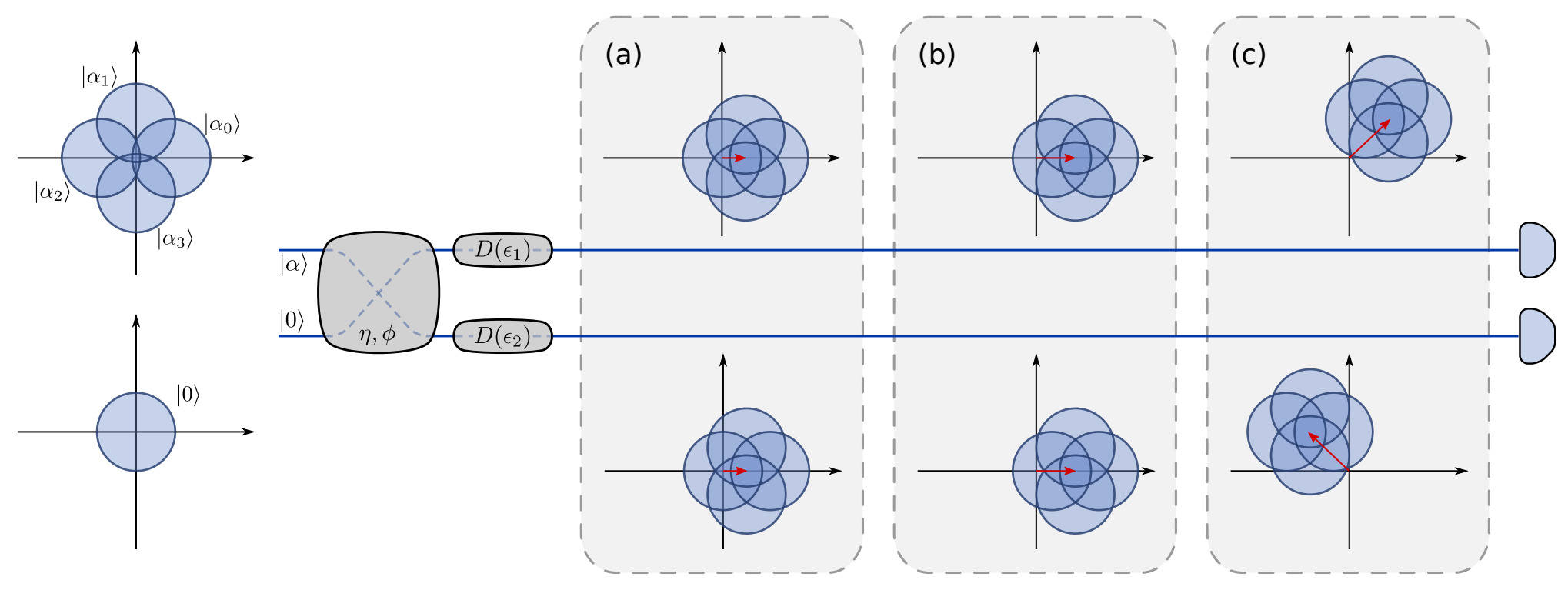
Experimental demonstration

We realise our QPSK decoder in temporal mode representation [4], allowing detection of two optical modes with one detector.



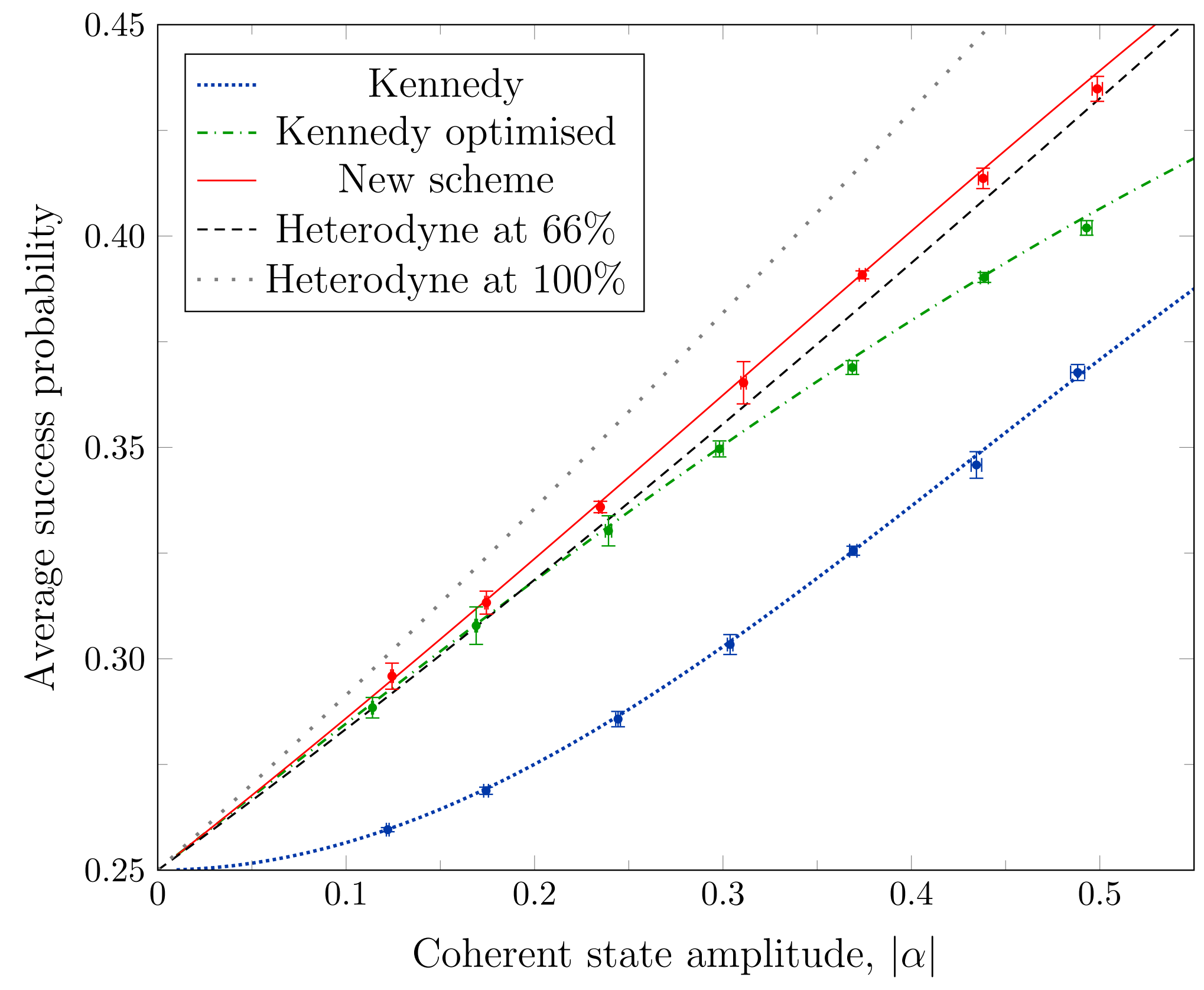
Experimental setup

We implement three two-mode Kennedy receivers based on different displacement operations before photon detections: nulling operations, optimised displacement amplitude, and optimised displacement phase operations.



Different displacement operations

Count rates obtained from 10^4 trials. Error bars denote one standard deviation from five realisations for each mean photon number.



Success probability for QPSK coherent states

References

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