GENERALISED DECOY-STATE SCHEME FOR RIGOROUS CHARACTERIZATION OF SINGLE-PHOTON DETECTORS

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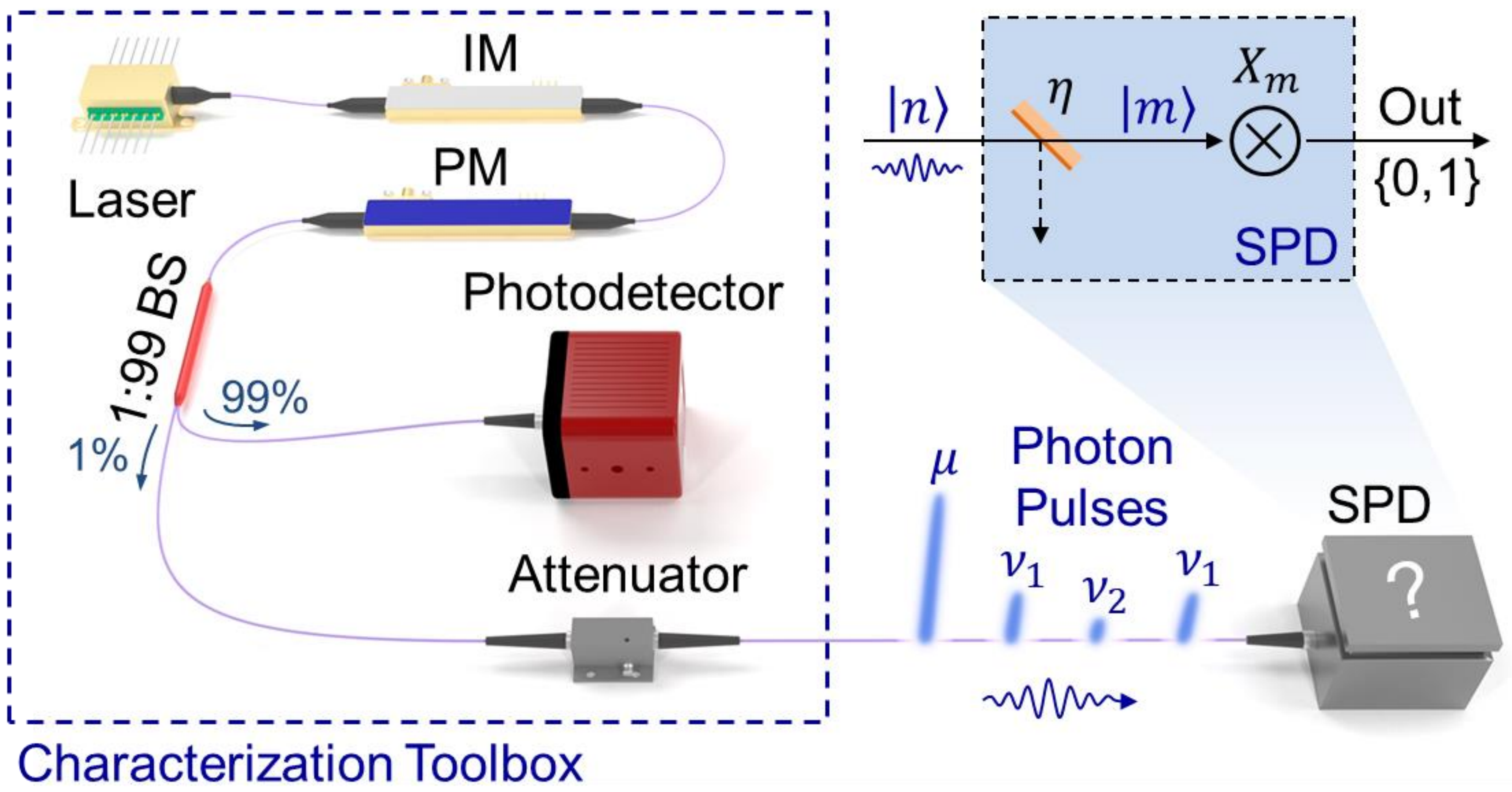
INTRODUCTION AND KEY CONTRIBUTIONS

Conventional single-photon detectors (SPDs) characterization methods require detailed detector models, which are not always available. The decoy-state scheme can provide rigorous bounds on the background noise and single-photon detection efficiency (SPDE) without the need for any prior knowledge of the detector model. This work provides a new and generalized toolbox for rigorous SPDE characterization with relaxed assumptions on the detector model, which could open up new possibilities in device calibration standards and quantum information applications.

- Generalized method without the requirement for detector model
- Provide rigorous bound on SPDE and noise with finite-size analysis
- Precise measurement with weak coherent source
- Multiphoton response, nonlinear response, time-dependency does not affect the result

CHARACTERIZATION SCHEME AND GENERALIZED SPD MODEL



$$Y_n = \Pr(\text{click}|n) = \sum_m \binom{n}{m} (1-\eta)^{n-m} \eta^m X_m$$

$$X_m = \Pr(\text{click}|m)$$

Y_0 is dark count and Y_1 is the SPDE with noise included

Vacuum-insensitive SPD	Vacuum-sensitive SPD
SPAD, SNSPD, PMT	Threshold homodyne detector
$X_0 = Y_0$ = dark count	X_0 = noise + vacuum state
$X_1 = 1$	X_1 = noise + single photon
SPDE is defined as η	SPDE is defined as Y_1 [1]

[1] Grice, W. & Walmsley, I., J. Mod. Opt. 43, 795-805 (1996)

DECOY STATE MODEL

Gain: Probability of a detection event given input mean photon number μ [2-5]

$$Q_\mu = \sum_{n=0}^{\infty} Y_n \frac{\mu^n}{i!} e^{-\mu}$$

Considering statistic fluctuation in the experiment, the gain can be bounded using Hoeffding's inequality [6]

$$Q_\mu^\pm = Q_\mu \pm \sqrt{\frac{1}{2 l_\mu} \ln\left(\frac{1}{\varepsilon}\right)}$$

The input signal is mixed by three weak coherent states with different mean photon numbers μ, ν_1, and ν_2 ($0 \le \nu_2 < \nu_1, \nu_1 + \nu_2 < \mu$)

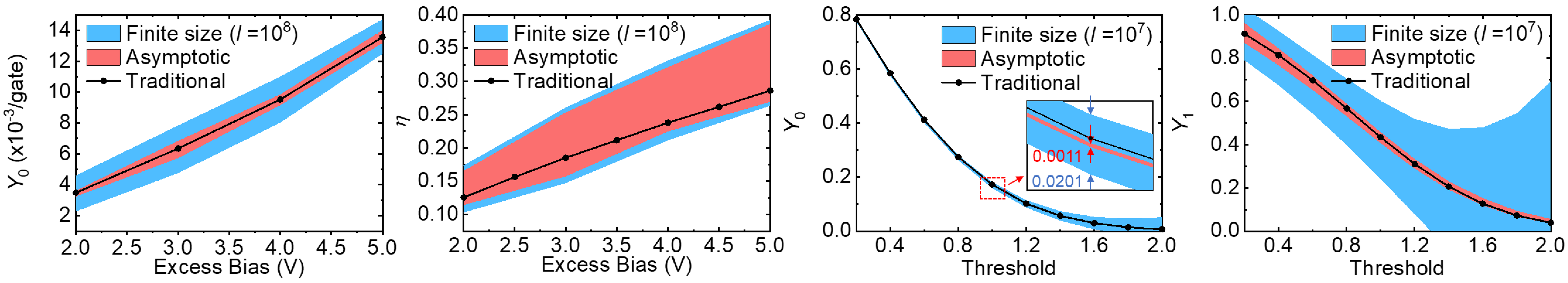
$$Y_0 \ge Y_0^L = \max\left\{\frac{\nu_1 Q_{\nu_2}^- e^{\nu_2} - \nu_2 Q_{\nu_1}^+ e^{\nu_1}}{\nu_1 - \nu_2}, 0\right\} \qquad Y_1 \le Y_1^U = \min\left\{\frac{Q_{\nu_1}^+ e^{\nu_1} - Q_{\nu_2}^- e^{\nu_2}}{\nu_1 - \nu_2}, 1\right\}$$

$$Y_1 \ge Y_1^L = \max\left\{\frac{\mu\left(Q_{\nu_1}^- e^{\nu_1} - Q_{\nu_2}^+ e^{\nu_2} - \frac{\nu_1^2 - \nu_2^2}{\mu^2}\left(Q_\mu^+ e^\mu - Y_0^L\right)\right)}{\mu\nu_1 - \mu\nu_2 - \nu_1^2 + \nu_2^2}, 0\right\}$$

$$Y_0 \le Y_0^U = \min\left\{\frac{\mu^2\left(\nu_1 Q_{\nu_2}^+ e^{\nu_2} - \nu_2 Q_{\nu_1}^- e^{\nu_1} + \frac{\nu_1\nu_2(\nu_1 - \nu_2)}{\mu^2}\left(Q_\mu^+ e^\mu - Y_1^L \mu\right)\right)}{(\nu_1 - \nu_2)(\mu^2 + \nu_1\nu_2)}, 1\right\}$$

[2] Lo, H.-K., Phys. Rev. Lett. 94, 230504 (2005). [3] Ma, X., Phys. Rev. A 72, 012326 (2005). [4] Wang, X.-B., Phys. Rev. Lett. 94, 230503 (2005). [5] Hwang, W.-Y., Phys. Rev. Lett. 91, 057901 (2003). [6] Hoeffding, W., (Springer, 1994).

EXPERIMENTAL RESULTS FOR AN SPAD AND A HOMODYNE DETECTOR



For SPAD, μ, ν_1, ν_2 = 0.960, 0.214, 0.007, sample size 10^8, protocol error $\varepsilon = 10^{-10}$

For homodyne detector, μ, ν_1, ν_2 = 1.156, 0.095, 0.028, sample size 10^7, protocol error $\varepsilon = 10^{-10}$

CONCLUSIONS

A generalized method based on the decoy-state scheme is proposed and experimentally demonstrated to accurately characterize single-photon detectors. Rigorous bounds for the background noise and SPDE are provided for both a SPAD and a homodyne detector. The resulting bounds are verified with the traditional methods. It shows great potential to become a standard toolbox for SPD characterization and be used in future quantum information applications.