Adaptive two-phase estimation on a photonic integrated device

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Abstract: Efficient adaptive multiphase estimation has been demonstrated experimentally on an integrated three-arm interferometer injected by single photons. Bayesian learning and Sequential Monte Carlo approximation have been employed as machine learning tools to achieve this goal.

1. Introduction

The use of quantum resources to improve classical precision in parameter estimation is the goal of quantum sensing and metrology [1]. In this context, phase estimation represents a benchmark scenario [1, 2], since other physical problems can be mapped into it. While single parameter estimation has been extensively studied, this is not the case of multiparameter estimation, which still requires major investigations and whose experimental realizations are very few so far [2].

Here, we experimentally realized a photonic quantum sensor able to handle multiple optical phases simultaneously. Two independent phases shifts are identified as parameters to be estimated, while additional phases act as control parameters to be changed during the estimation process. Adaptively changing the device to improve the estimation can be an important solution, especially when the number of resources available for estimation is limited [1]. We first studied different adaptive strategies to optimally tune the control parameters. Then, we selected the best one to demonstrate efficient adaptive two-phase estimation in a limited data regime, by injecting the system with single-photon states [3].

2. Description of the device

The device is a three-mode interferometer (Fig. 1a) – the generalization of a Mach-Zehnder interferometer – fabricated using the femtosecond laser writing technique [4]. A similar device has demonstrated the capability to achieve quantum-enhanced performance in two-phase estimation [2]. Several optical phase shifters provide reconfigurability to the device, enabling it to be used as a quantum sensor for multiparameter quantum metrology investigation in adaptive regimes. Through a suitable calibration procedure, we are able to set the unknown and control optical phases by applying specific currents on certain ohmic resistors. Different calibration procedure can be designed in order to control the device. Notably, we have also obtained important results using a neural network approach [5].

3. Strategies for adaptive estimation

The adaptive strategies we tested adopt machine learning techniques as tool for changing the quantum sensor during the estimation process. In particular, we exploited a Bayesian learning algorithm designed to work with multiple parameters, capable of computing high-dimensional integrals using a sequential Monte Carlo approximation [6]. In this framework the initial knowledge of the unknown phases x_1, x_2 is encoded in the *a priori* probability distribution $P_0(x_1, x_2)$. After, a sequence m of experimental measurement results, this knowledge is updated via Bayes' rule: $P(x_1, x_2|m) \propto P(m|x_1, x_2)P_0(x_1, x_2)$. Bayesian estimators have been shown to be efficient with large measurements by reaching the Cramér-Rao Bound (CRB) [1], which provides the ultimate limit of the estimate. However, non-asymptotic saturation of the lower bound is also crucial, such as when the number of available resources is limited [1]. According to the sequential Monte Carlo approximation [6], the probability distribution is divided into a discrete support of N points $\{x_1^{(p)}, x_2^{(p)}\}$ — called particles — each with its associated probability weight w_p. This discrete support can be used to approximate all continuous expectation values by replacing integrals with sums over the discrete distribution. In this way, the expectation values of the parameters are given by $\hat{x}_i = \int x_i P(x_1, x_2|m) dx_1 dx_2 \approx \sum_p x_i^{(p)} w_p$ with $i = 1, 2$, and the covariance matrix reads $\mathrm{Cov}_{ij} = \int (x_i - \hat{x}_i)(x_j - \hat{x}_j) P(x_1, x_2|m) dx_1 dx_2 \approx \sum_p (x_i^{(p)} - \hat{x}_i)(x_j^{(p)} - \hat{x}_j) w_p$. Several methods can be used to compute the optimal control parameters to be applied during the estimation cycle. We tested different possibilities by simulating their performance on our apparatus. The results show that the best algorithm is based on computing controls that optimize a specific figure of merit, for each step of the estimation cycle. In our case, we select the overall variance as the quantity to be minimized, since the goal of the estimation cycle corresponds to its minimization. The results of the simulated strategies are reported in Fig. 1b.

4. Experimental adaptive multiphase estimation

To demonstrate the actual performance of the selected algorithm, we performed an experimental adaptive two-phase estimation using the integrated three-arm interferometer (Fig. 1a). The experimental results of our implementation show that all the terms of the matrix CRB are saturated and a similar accuracy is achieved for both parameters (Fig. 1c). This demonstrates that the integrated platform employed and the algorithm implemented are largely suitable for adaptive multiphase estimation problems. Indeed, our approach is versatile and can easily scale to more complex integrated platforms and systems, for example by including additional unknown and control parameters, or adopting multi-photon quantum states as probes.

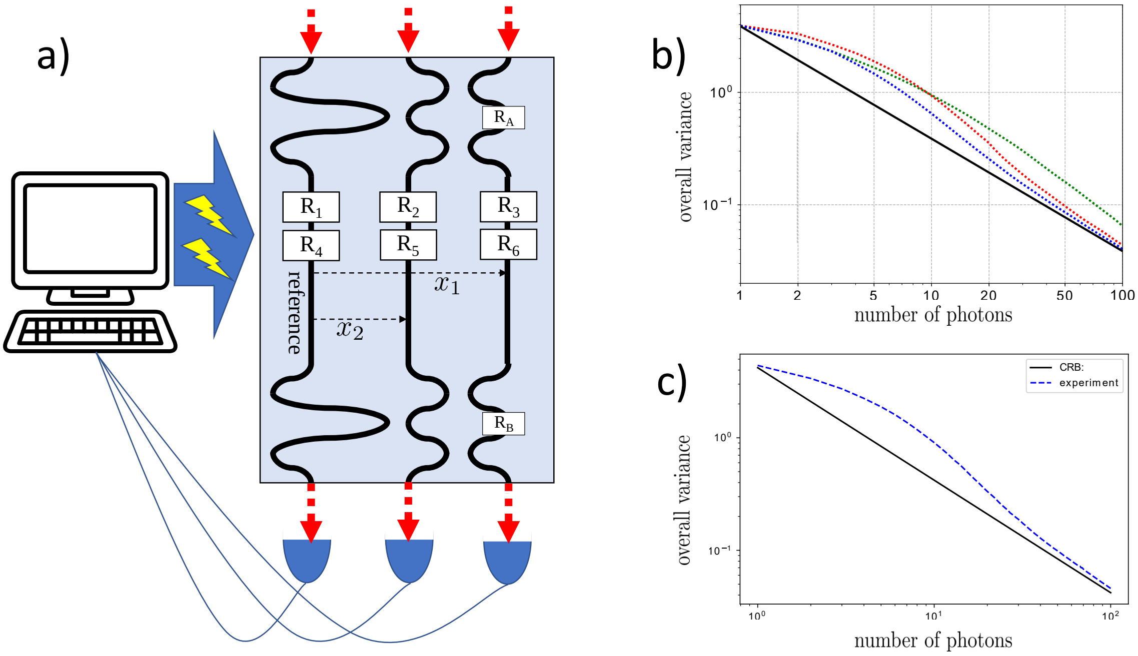

Fig. 1. a) Integrated photonic device employed for multiphase estimation in adaptive regime. Optimal control parameters are computed after each measurement result and applied on the chip using thermo-optical phase shifters. b) Simulated performance of the tested adaptive algorithms. c) Experimental results of adaptive two-phase estimation using the best performing algorithm.

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