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Hybrid and optical implementation of the Deutsch-Jozsa algorithm

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A hybrid model of the Deutsch-Jozsa algorithm is presented, inspired by the proposals of hybrid computation by S. Lloyd and P. van Loock *et. al.* The model is based on two observations made about both the discrete and continuous algorithms already available. First, the Fourier transform is a single-step operation in a continuous-variable (CV) setting. Additionally, any implementation of the oracle is nontrivial in both schemes. The steps of the computation are very similar to those in the CV algorithm, with the main difference being the way in which the qunats, or quantum units of analogic information, and the qubits interact in the oracle. Using both discrete and continuous states of light, linear devices, and photo-detection, an optical implementation of the oracle is proposed. For simplicity, infinitely squeezed states are used in the continuous register, whereas the optical qubit is encoded in the dual-rail logic of the KLM protocol. The initial assumption of ideal states as qunats will be dropped to study the effects of finite squeezing in the quality of the computation.

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I. INTRODUCTION

The model proposed by Knill, Laflamme and Milburn [1, 2] presents an efficient way to implement a quantum computer using optical qubits, single-photon sources, linear devices and photo-detection, known as the KLM protocol. This well established model uses nonlinearities hidden in the measurement process to produce the interactions needed between the optical modes, together with offline state preparation and teleportation to enhance the probability of success of the conditional gates of the protocol, and error correction codes, achieving a scheme that is both fault-tolerant and robust against errors [3, 4].

On the other hand, the unconditional nature in which entanglement with continuous variables can be obtained, and thus the *unconditionalness* of the operations performed over CV together with the need of just single-mode nonlinearities for universal quantum computation, are two of the most prominent reasons to adopt this setting over a discrete-variable one [5, 6]. Besides, the idea of studying quantum algorithms, generally designed for qubits, in a CV setting is at the same time challenging and of great importance for the development of quantum information theory. This generalization may bring into light new algorithms with a more natural formulation using CVs. For example, any algorithm based on the quantum Fourier transform, such as the Deutsch-Jozsa algorithm or Shor's algorithm, is easily performed in a continuous setting, where such operation is a single-step operation [7].

Focusing on the Deutsch-Jozsa algorithm, it can be seen that its original discrete formulation [8] requires the production of superpositions of several qubit states via a quantum Fourier transform, a task that needs a lot of resources and computational power, even for a small number of qubits [9]. The translation of the algorithm into a CV setting seems more feasible and practical, due to the ability to produce the superpositions needed with a very low number of resources, nonetheless, how to implement the oracle in such continuous scheme is still an unresolved problem [10].

However, we can take advantage of both schemes by means of some sort of *hybrid* gates, i.e. a set of transformations that acts on both qubits and CV states [11]. In this paper we use a hybrid model of computation, in an all-optical setting, giving an explicit optical circuit for the action of the oracle on both registers involved in the computation. Such model is based on proposals by S. Lloyd [11] and P. van Loock *et. al.* [12], but differs from them by utilizing only linear optical devices, single-photon sources, offline squeezing and photo-detectors. In the first part of the work, we use idealized infinitely squeezed states as the computational CV basis for simplicity in our calculations. By the end, we shall drop such restriction to discuss the effects of realistic Gaussian states (that is states with finite squeezing) throughout the computational process.

The structure of the paper is as follows. First, in Section II we give a quick review of the original algorithm and its implementation in the continuous-variable case. Section III presents the algorithm in a hybrid and all-optical setting, paying special attention to the explicit implementation of the oracle. Section IV considers imperfect CV states in the hybrid model of the algorithm, in order to analyze the possible distortions at the end of the computation. Finally, Section V closes the paper with some concluding remarks.

II. FUNDAMENTALS OF THE DEUTSCH-JOZSA ALGORITHM

In this section we present a review of the basic aspects of the Deutsch-Jozsa problem according to its original

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