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Towards a spin-ensemble quantum memory for superconducting qubits

Vers une mémoire quantique à ensemble de spins pour qubits supraconducteurs

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ABSTRACT

This article reviews efforts to build a new type of quantum device, which combines an ensemble of electronic spins with long coherence times, and a small-scale superconducting quantum processor. The goal is to store over long times arbitrary qubit states in orthogonal collective modes of the spin-ensemble, and to retrieve them on-demand. We first present the protocol devised for such a multi-mode quantum memory. We then describe a series of experimental results using NV (as in nitrogen vacancy) center spins in diamond, which demonstrate its main building blocks: the transfer of arbitrary quantum states from a qubit into the spin ensemble, and the multi-mode retrieval of classical microwave pulses down to the single-photon level with a Hahn-echo like sequence. A reset of the spin memory is implemented in-between two successive sequences using optical repumping of the spins.

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R É S U M É

Cet article porte sur la réalisation d'un nouveau type de dispositif quantique, dans lequel un ensemble de spins électroniques avec des temps de cohérence longs est associé à un processeur quantique supraconducteur à quelques qubits. Le but est de stocker les états des qubits dans les degrés de liberté collectifs de l'ensemble de spins, et de les récupérer à la demande, bénéficiant ainsi d'une meilleure protection contre la décohérence. En première partie, nous présentons le protocole mis au point pour une telle mémoire quantique multi-mode. Nous décrivons ensuite une série de résultats expérimentaux utilisant des centres NV dans le diamant, démontrant les briques de base de ce protocole : le transfert d'états quantiques arbitraires d'un qubit vers l'ensemble de spins, et la récupération de champs micro-ondes classiques au niveau du photon unique par application d'une séquence de refocalisation de type écho de Hahn. La réinitialisation de la mémoire entre deux séquences successives est réalisée par repompage optique des spins.

1. Introduction

Superconducting qubits are attractive candidates for quantum information processing because of their flexibility and rapid single- and two-qubit gates [1], but compared to microscopic systems they suffer from short coherence times. This suggests to combine the two types of systems in a hybrid quantum device, where microscopic entities with long coherence times act as a quantum memory to complement a small-scale quantum processor made of superconducting qubits [2,3]. To be truly useful in a quantum computer, a quantum memory should behave as an ideal n-qubit register, with $n \gg 1$. It should be possible to re-initialize the memory (reset step), to transfer arbitrary qubit states $|\psi_i\rangle$ into each register (write step), store them over long times, and finally transfer back on-demand one of the states into the processor when needed for running the algorithm, while keeping the others in the memory (read step).

Spins in crystals are ideally suited to implement these ideas, as already demonstrated in optical quantum memories [4]. Large ensembles of N spins offer as many orthogonal degrees of freedom, which can be exploited to store many qubit states in parallel. Various different systems are being investigated for this purpose: rare-earth ions in silicate crystals [5], donor spins in silicon [6]... In this work, we will focus on nitrogen-vacancy (NV) color centers in diamond as the storage medium. NV centers have coherence times that can reach seconds [7] and can be actively reset in the spin ground state by optical repumping [8]. In our quantum memory project, the interaction between the qubits and the NV ensemble is mediated by a superconducting resonator used as a quantum bus, which is electrically coupled with the qubits, and magnetically coupled with the spins (see Fig. 1). The goal of this article is to review the experimental progress towards the implementation of the memory protocol [9] described below.

2. Quantum memory protocol

Our memory protocol [9] is inspired by related work on optical quantum memories [10,11], adapted to the requirements of a circuit quantum electrodynamics (cQED) setup (see also [12,5]), which implies in particular working at millikelvin temperatures and microwave frequencies. As shown in Fig. 1, the qubit and spin ensemble are embedded inside the quantum

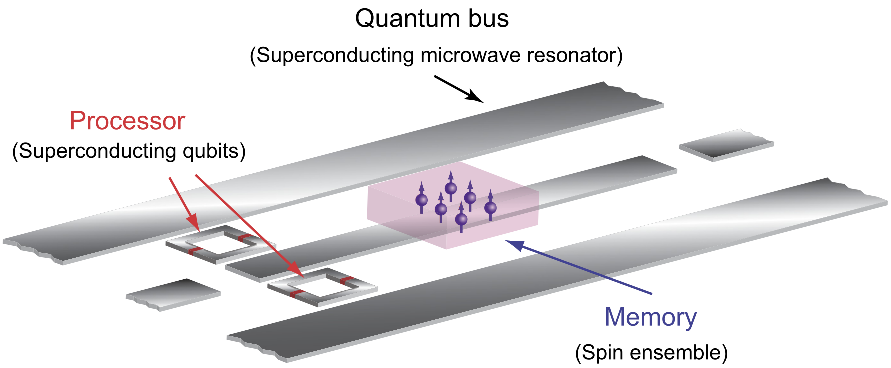

Fig. 1. Concept of a hybrid quantum processor combining a two-qubit processor and a spin ensemble multimode quantum memory. The exchange of quantum states between the processor and the memory is implemented by a superconducting microwave resonator used as a quantum bus, which is coupled electrically with the qubits and magnetically with the spins.