Circuit Modeling of Flux Qubits Interacting with Superconducting Waveguides

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MOTIVATION

Superconducting quantum circuits emerged as a promising candidate for quantum computer 'hardware', mainly because their quantum behavior can be engineered by the appropriate choice of their circuit parameters. In the implementation outlined in [1], the interrogation of the qubit is obtained via coupling to a one-dimensional cavity. Since such electromagnetic environment has a decisive role in the quantum dynamics of the qubit, it is crucial to simulate a qubit together with the write-in and read-out circuitry. This is a complex task, which requires different levels of modeling: quantum-mechanical simulations for the qubit itself, classical and quantum electrodynamics for the cavity around the qubit and extensive microwave simulations of the read-out apparatus.

DESCRIPTION OF WORK

Equivalent circuit construction is a promising approach to simulate different physical phenomena in a unified environment. As earlier work [2][3] has demonstrated, simple few state quantum systems can be numerically simulated in a standard circuit simulator such as SPICE, using an equivalent circuit shown in Fig 1. A 'modes-to-nodes' conversion is used to construct equivalent lumped circuits of microwave components and state of the art electromagnetic simulators (such as the HFSS code by Ansoft [4]) perform this conversion automatically. To understand the electromagnetic behavior of superconducting components, we employ the Comsol Multiphysics software suite [5] which allows us to couple Maxwell's equations to London's equations that describe superconducting materials. Lumped superconducting circuits (with Josephson junctions) could also be simulated by their equivalent circuits (see Fig, 2).

Once all circuit models are built and verified separately, they are interconnected in SPICE, which simulates the mixed quantum-classical dynamics of the entire measurement apparatus. The results are directly comparable with experiments.

RESULTS

We concentrate on the structure proposed by [6], and sketched in Fig 3. We investigate the dynamic behavior of this circuit, optimize its circuit parameters and geometry and investigate how the noise of the electromagnetic environment influences decoherence of the qubit. Detailed results will be presented at the conference.

Modeling of the interaction between quantum systems and their (classical) electromagnetic environment is a fundamental point of nanoelectronics and quantum technology – we hope this work brings us closer to the understanding of such structures.

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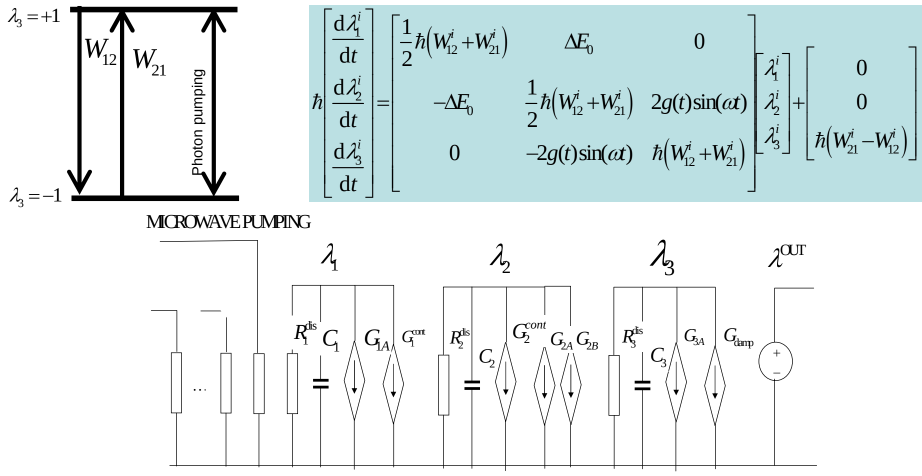

Figure 1. The Bloch equations (a dynamical model of a two-state quantum system, sketched in part a)) can be modeled by the equivalent circuit shown above. The voltages of the capacitors exhibit the same dynamic behavior as the components of the coherence vector for the two-state quantum system. This makes it possible to simulate quantum mechanics in circuit simulators.

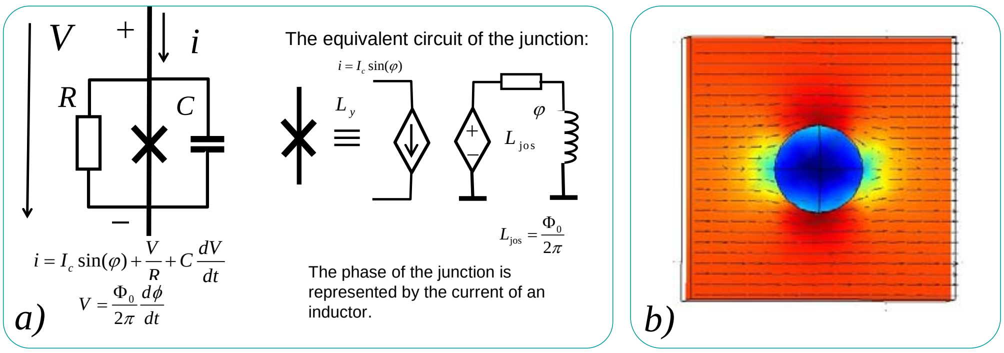

Figure 2. Non-linear classical circuits, built from Josephson junctions are modeled by the equivalent circuit shown in part a). Part b) illustrates the textbook example of magnetic field distribution around a superconducting sphere. This figure was made by Comsol Multiphysics, in which we implemented the models of superconducting electrodynamics.

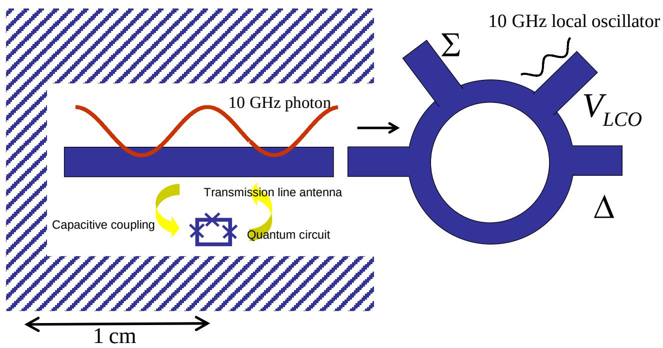

Figure 3. Sketch of the experimental setup of a qubit interacting with a microwave read-out circuitry [6]. The quantum circuit is coupled to a transmission line resonator, which is capacitively connected to a microwave hybrid. We will demonstrate our simulation approach on this circuit.