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Course 16 - Prospects for Strong Cavity Quantum Electrodynamics with Superconducting Circuits

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Introduction

Cavity quantum electrodynamics (cQED) studies the properties of atoms coupled to discrete photon modes in high Q cavities. Such systems are of great interest in the study of fundamental quantum mechanics of open systems, the engineering of quantum states and the study of measurement-induced decoherence [1, 2, 3], and have also been proposed as possible candidates for use in quantum information processing and transmission [1, 2, 3]. Ideas for novel cQED analogs using nano-mechanical resonators have recently been suggested by Schwab and collaborators [4, 5]. We present a realistic proposal for cQED via Cooper pair boxes coupled to a one-dimensional (1D) transmission line resonator as shown in Fig. 1, within a simple circuit that can be fabricated on a single microelectronic chip. As we discuss, 1D cavities offer a number of practical advantages in reaching the strong coupling limit of cQED over previous proposals using discrete LC circuits [6, 7], large Josephson junctions [8, 9, 10], or 3D cavities [11, 12, 13]. Besides the potential for entangling qubits to realize two-qubit gates addressed in those works, we show that the cQED approach also gives strong and controllable isolation of the qubits from the electromagnetic environment, permits high fidelity quantum non-demolition (QND) readout of multiple qubits, and can produce states of microwave photon fields suitable for quantum communication. The proposed circuits therefore provide a simple and efficient architecture for solid-state quantum computation, in addition to opening up a new avenue for the study of entanglement and quantum measurement physics with macroscopic objects. We will frame our discussion in a way that makes contact between the language of atomic physics and that of electrical engineering, and begin with a brief general overview of cQED before turning to a more specific discussion of our proposed architecture.

Section snippets

Brief review of cavity QED

In the optical version of cQED [2], one drives the cavity with a laser and monitors changes in the cavity transmission resulting from coupling to atoms falling through the cavity. One can also monitor the spontaneous emission of the atoms into transverse modes not confined by the cavity. It is not generally possible todirectly determine the state of the atoms after they have passed through the cavity because the spontaneous emission lifetime is on the scale of nanoseconds. One can, however,…

Circuit implementation of cavity QED

We now consider in more specific detail the cQED setup illustrated in Fig. 1. A number of possible superconducting quantum circuits could function as the ‘atom’. For definiteness we focus on the Cooper pair box [16, 6, 17, 18]. Unlike the usual cQED case, these artificial ‘atoms’ remain at fixed positions indefinitely and so do not suffer from the problem that the coupling g varies with position in the cavity. An additional advantage is that the zero-point energy is distributed over a very…

Zero detuning

For the case of zero detuning and weak coupling $g < \kappa$, the radiative decay rate of the qubit into the transmission line becomes strongly *enhanced* by a factor of Q relative to the rate in the absence of the cavity [15] because of the resonant enhancement of the density of states at the atomic transition frequency. In electrical engineering language, the $\sim 50\ \Omega$ external transmission line impedance is transformed on resonance to a high value which is better matched to extract energy from the…

Large detuning: lifetime enhancement

For the case of strong detuning, the coupling to the continuum is substantially reduced. One can view the effect of the detuned resonator as filtering out the vacuum noise at the qubit transition frequency or, in electrical engineering terms, as providing an impedance transformation which strongly *reduces* the real part of the environmental impedance seen by the qubit. For large detuning the qubit excitation spends only a small fraction of its time as a photon [15] so that the decay rate into…

Dispersive QND readout of qubit

For large detuning, making the unitary transformation $U = \exp\left[\frac{g}{\Delta}\left(a\sigma^{+} - a^{\dagger}\sigma^{-}\right)\right]$and expanding to second order in g, approximately diagonalizes the Hamiltonian (neglecting damping for the moment) $UHU^{\dagger} \approx \hbar\left[\omega_{r} + \frac{g^{2}}{\Delta}\sigma^{z}\right] a^{\dagger}a + \frac{1}{2}\hbar\left[\Omega + \frac{g^{2}}{\Delta}\right]\sigma^{z}$.We see that there is a dispersive shift of the cavity transition by $\sigma_{z}g^{2}/\Delta$, that is the qubit pulls the cavity frequency by $\pm g^{2}/\kappa\Delta = \pm 2.5$ line widths for a 10% detuning. Exact diagonalization [15] shows that the pull becomes power dependent and decreases in…

Resonator as quantum bus: entanglement of multiple qubits

Finally, the transmission-line resonator has the advantage that it should be possible to place multiple qubits along its length (~ 1 cm) and entangle them together, which is an essential requirement for quantum computation. For the case of two qubits, they can be placed closer to the ends of the resonator but still well isolated from the environment and can be separately dc biased by capacitive coupling to the left and right center conductors of the transmission line. Any additional qubits…

Summary and conclusions

In summary, we propose that the combination of one-dimensional superconducting transmission line resonators, which confine their zero point energy to extremely small volumes, and superconducting charge qubits, which are electrically controllable qubits with large electric dipole moments, constitutes an interesting system to access the strong-coupling regime of cavity quantum electrodynamics. This combined system constitutes an advantageous architecture for the coherent control, entanglement,…

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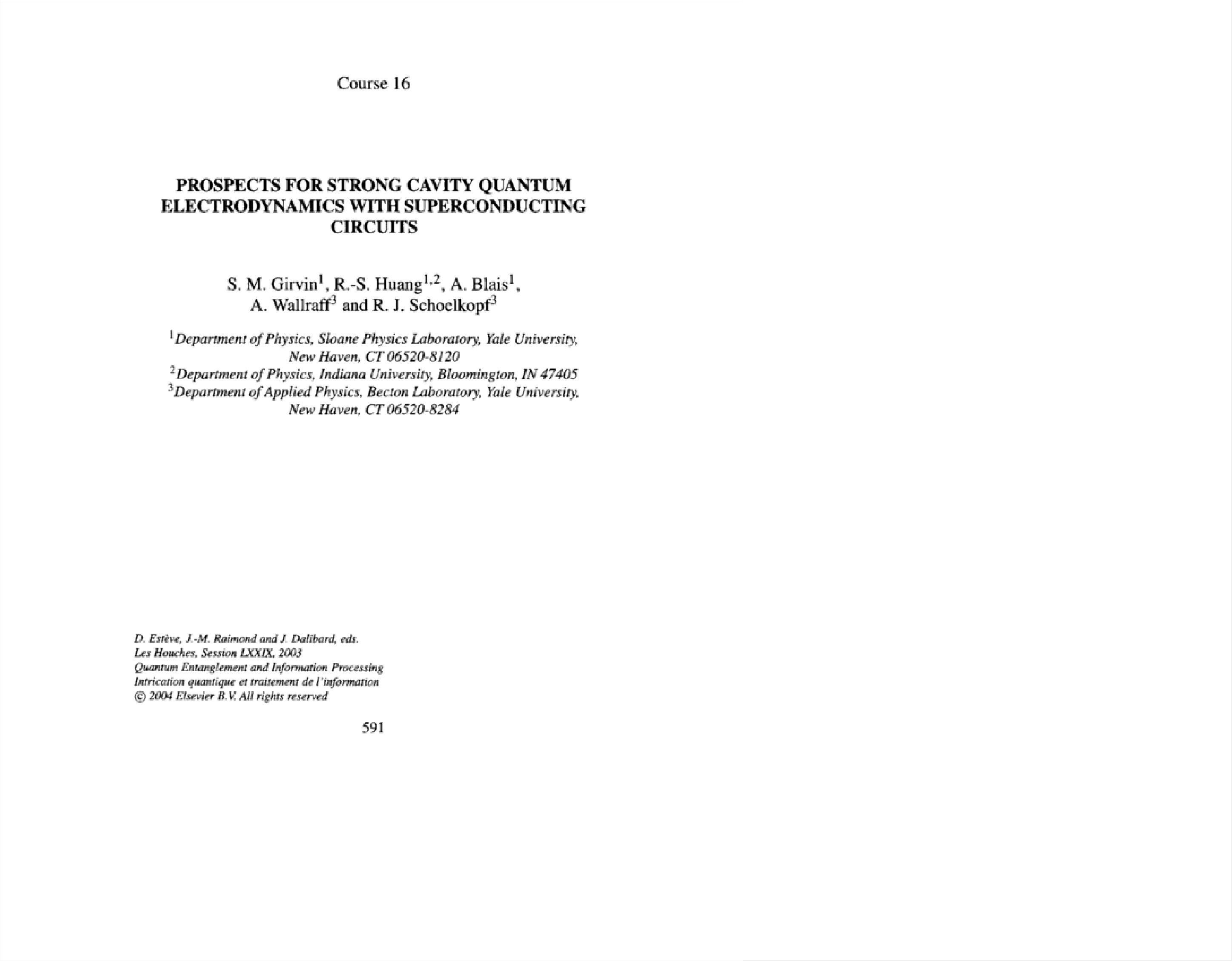

Course 16

PROSPECTS FOR STRONG CAVITY QUANTUM ELECTRODYNAMICS WITH SUPERCONDUCTING CIRCUITS

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