Josephson junction qubit network with current-controlled interaction

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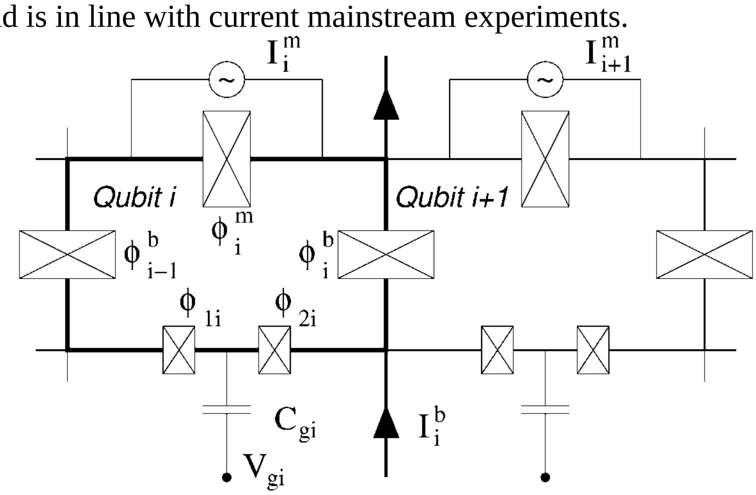
After several years of great experimental achievements on Josephson junction (JJ) qubits [2-4], coupling of qubits is now becoming feasible. A few challenging experiments with coupled JJ-qubits have been reported [5]. However, so far experiments on coupled JJ qubits have been performed without direct physical control of the qubit-qubit coupling.

We present a new solution for controllable physical qubit-qubit coupling [1]. The network has the following properties: (a) nearest-neighbour qubit-qubit coupling controlled by external bias current, (b) qubits parked at the degeneracy points, also during qubit-qubit interaction, (c) separate knobs for controlling individual qubits and qubit-qubit coupling, (d) scalability. An important feature is that the network is easily fabricated, and is in line with current mainstream experiments.



Network of loop-shaped SCPT charge qubits, coupled by large Josephson junctions. The interaction of the qubits (i) and (i+1) is controlled by the current bias I_{bi} or by simultaneous current biasing of readout junctions. Individual qubits are controlled by voltage gates, $n_{gi}=C_{gi}V_{gi}$. The Josephson energies of the coupling JJs, E_J^b, and the readout JJs, E_J^m, are much larger than the charging energies, $E_J^{b(m)} >> E_C^{b(m)}$.

The network under consideration consists of a chain of charge qubits - Single Cooper Pair Transistors (SCPT) - with loop-shaped electrodes coupled together by current biased coupling JJs at the loop intersections. The loop design creates an (inductive) interface to the qubit by means of circulating currents [4]. We employ these current states in the qubit loops to create controllable coupling of neighbouring qubits. Left without any external current biasing of the coupling and readout JJs, the network acts as a quantum memory of independent qubits (neglecting a weak residual interaction [1]). When a bias current is sent through the coupling JJ, the current-current interaction between the neighbouring qubits is switched on and increases with increasing bias current. Moreover, if both of the readout JJs of the same qubits are biased well below threshold, again there is nearest-neighbour coupling via the circulating currents. However, if one of the readout JJs is current biased, this only affects that particular qubit and allows readout of individual qubits. Thus the bias currents serve as the interaction control knobs. The loop inductances are assumed to be sufficiently small to neglect qubit-qubit coupling via induced magnetic flux, as well as undesirable qubit coupling to the magnetic environment. In addition, we assume negligible capacitive coupling between the islands, which are well shielded by the injection leads.

The qubit network dynamics in the charge qubit regime E_C>>E_J is described by the Hamiltonian

$$H = \sum_{i=1}^{N} [\frac{E_{Ci}}{2}(1-n_{gi})\sigma_{zi} - E_{Ji}\cos\bar{\theta}_i\sigma_{xi} + \eta_i\sigma_{xi}\sigma_{x(i+1)}] + \sum_{i\neq j}\kappa_{ij}\sigma_{xi}\sigma_{xj},$$

which consists of the individual qubits, where $\bar{\theta}_i$ is the mean phase difference induced by current bias in the coupling and readout JJs, the controllable interaction, and finally a weak residual coupling. The residual coupling effectively connects all the qubits, but is a factor $\hbar\omega_p / E_J^b << 1$, where ω_p is the coupling JJ plasma frequency, smaller than the maximum controllable coupling.

In order to couple exclusively the qubits (i) and (i+1) one should apply a current bias I_i^b , while $I_{i\pm1}^b = 0$. In this case the qubit coupling amplitude is given by the equation

$$\eta_i = \frac{E_{Ji}E_{J(i+1)}}{4E_J^b\cos\bar{\phi}_i^b}\sin^2\frac{\bar{\phi}_i^b}{2}.$$

The coupling is quadratic, $\sim \left(I_i^b / I_c^b\right)^2$, for small currents and diverges when the current approaches the critical current I_c^b. An alternative way to switch on the qubit interaction is to apply current bias (below the critical current) simultaneously to two neighbouring readout JJs, which will give a similar but weaker interaction.

By applying current bias pulses with controlled amplitude and duration it is possible to perform quantum gates on the qubit network, eg. control-NOT and cNOT-SWAP gates. Readout can be performed either using the readout JJ:s [6] or by measuring the charge on the qubit islands [7].

Finally we emphasize that the present analysis and design is equally relevant in the region of E_C~E_J, characterizing the ”Quantronium” [4].

In conclusion, the present scheme provides a realistic solution for easy local control of the physical coupling of charge qubits via current biasing of coupling Josephson junctions or, alternatively, pairs of readout junctions. The design is in line with experimental mainstream development of charge qubit circuits and can easily be fabricated and tested experimentally. The tunable coupling of the qubit chain allows easy implementation of CNOT and CNOT-SWAP operations.

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