Supplementary Information

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Abstract

Supplementary information for manuscript entitiled "A Fast, Tuneable Coupler for Superconducting Qubits"

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I. COUPLER RESET PROTOCOL

A direct-current connection between the coupler and qubits requires the coupler to be reset. Because the Josephson inductance of the qubit junctions is much larger than the shunt inductor L, current flowing from the coupler mostly flows through L. As a result, the coupler junction is effectively shunted by two loops with net inductance $(L_M + L_s + L)/2$, as shown in Supplementary Figure 1a. A junction with shunt inductance can have multiple stable operating points [1] if $\beta = 2\pi I_0^c(L_s + L_M + L)/2\Phi_0 > 1$; here $L_s + L_M + L \simeq 4.2$ nH and $I_0^c \simeq 1.6\mu A$, giving $\beta \simeq 20/2 = 10$. For these parameters, Supplementary Figure 1b shows the expected behavior of the internal flux in the loop Φ versus external current bias I_{cb}, where the stable operating points are branches with positive slope A, B, C, D and E (solid lines), and unstable operating points are given by dashed lines. When the coupler is set to the bias labeled I_{cb}^{ON}, it can randomly assume any of the flux values given by the intersection of the gray dotted line with the stable branches A-E. The branch must be precisely reset to

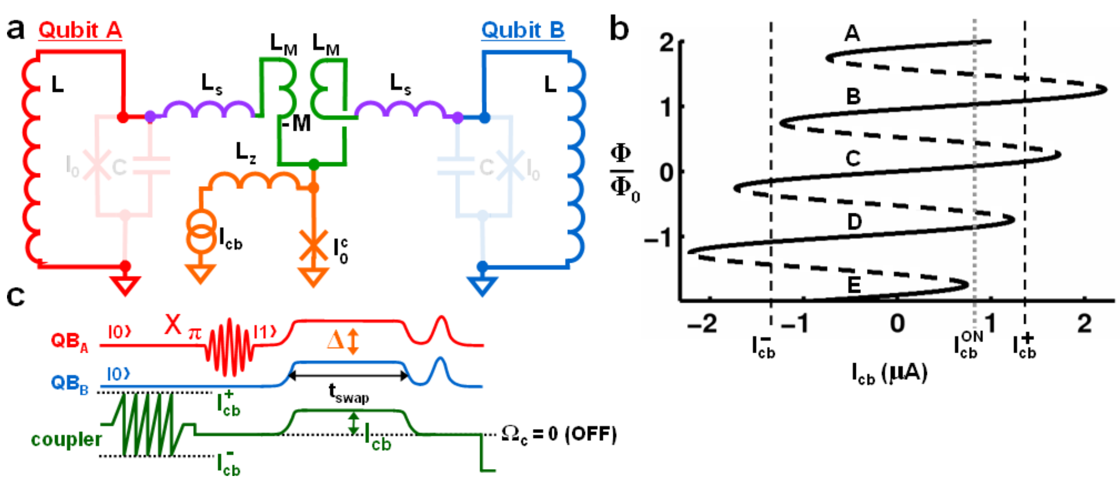

FIG. 1. (a) Unshaded parts of the circuit reveal the path from the coupler bias, through the qubit inductors, to ground, forming a Josephson junction in a loop which is known to display multi-stable behavior. (b) Schematic depiction of multi-stability of coupler circuit. (c) Pulse sequence for coupler reset.

place the coupler to a known bias. This may be accomplished using a technique developed for junction-shunted phase qubits [2]. For example, to place the coupler on branch C, the coupler bias is repeatedly varied between the two values I_{cb}^+ and I_{cb}^-. As occupation in any other branch will result in a switch out of that branch, with enough trials the coupler will eventually finds itself in C, the only stable branch. Supplementary Figure 1c shows how this reset protocol is simply integrated into the swap experiment. To determine I_{cb}^{+} and I_{cb}^{-}, a

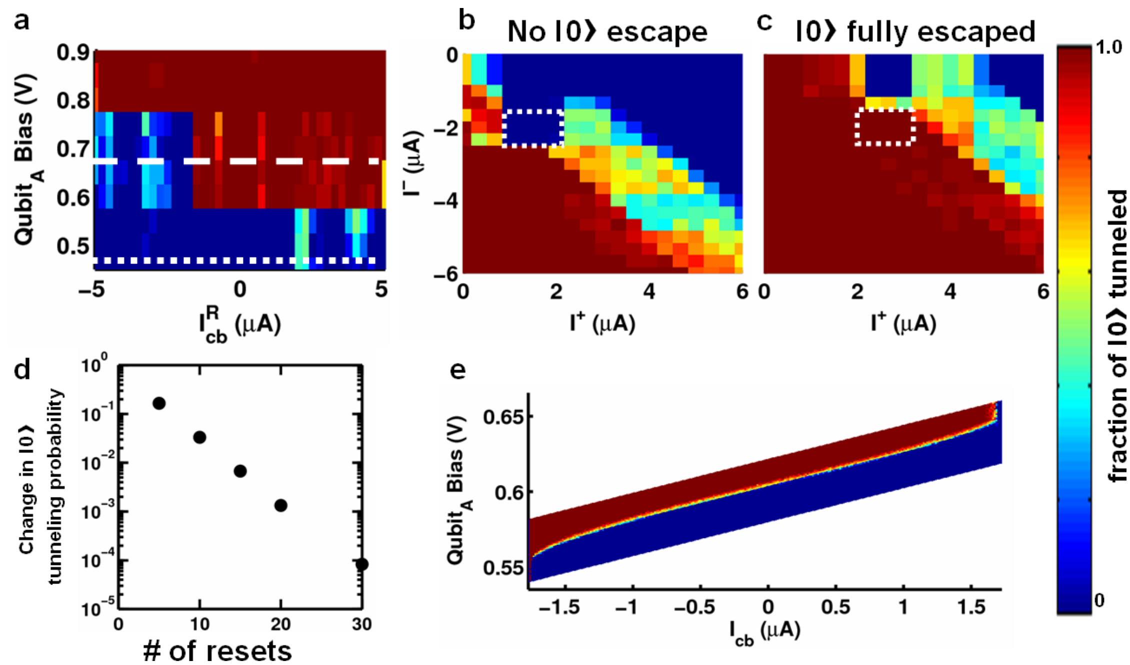

FIG. 2. (a-c) Calibration of reset amplitudes for coupler bias. (d) Measurement of qubit error versus the number of required coupler resets. (e) Verification of proper coupler reset.

qubit can be used to detect when the coupler switches to a different branch. When switching happens, the direct-current coupling between the coupler and qubit causes a qubit bias shift, which in turn can be measured by monitoring the escape of the qubit $|0\rangle$ state. For this measurement, we must first map out the onset and completion of the escape of the $|0\rangle$ state as a function of coupler and qubit bias. In Supplementary Figure 2a, we show the escape probability for the $|0\rangle$ state as a function of reset offset $I_{cb}^{R} = I_{cb}^{-} = I_{cb}^{+}$ and the bias of qubit A. We take the dotted line as the condition where the $|0\rangle$ state had not escaped, and the dashed line as when the $|0\rangle$ state had fully escaped. We then plot in Supplementary Figures 2b and 2c these conditions versus the two coupler biases I_{cb}^{+} and I_{cb}^{-}. The data for the former case is shown in Supplementary Figure 2b, where the region enclosed by the dashed box gives the values of I_{cb}^{+} and I_{cb}^{-} where the coupler is properly reset, *i.e.* when the qubit does not escape from the $|0\rangle$ state due to changing of a branch. Supplementary Figure 2c shows a check of this condition, as this same region should always have the $|0\rangle$ state fully escaped. For optimal reset, I_{cb}^{+} and I_{cb}^{-} were chosen at the center of the dashed box. Repeating these measurements for qubit B gave similar values.

Because a number of reset cycles must be used to reliably reset the coupler, the reset probability must be measured versus the number of resets. As shown in Supplementary Figure 2d, we found that 30 cycles produced an acceptable error of $\sim 1.5 \times 10^{-4}$.

We next confirmed that I_{cb}^{+} and I_{cb}^{-} properly reset the coupler for all coupler and qubit bias values up to the critical current of the coupler junction. As shown in Supplementary Figure 2e, we plot the escape probability of qubit A as a function of coupler and qubit bias. The slope in the curve is expected and is due to the direct current connection between the coupler and qubit as discussed below. The increase in slope at the two ends of the curve arises from the non-linearity of the qubits Josephson inductance as the critical current is approached.

II. COMPENSATION FOR QUBIT BIAS SHIFT DUE TO COUPLER BIAS

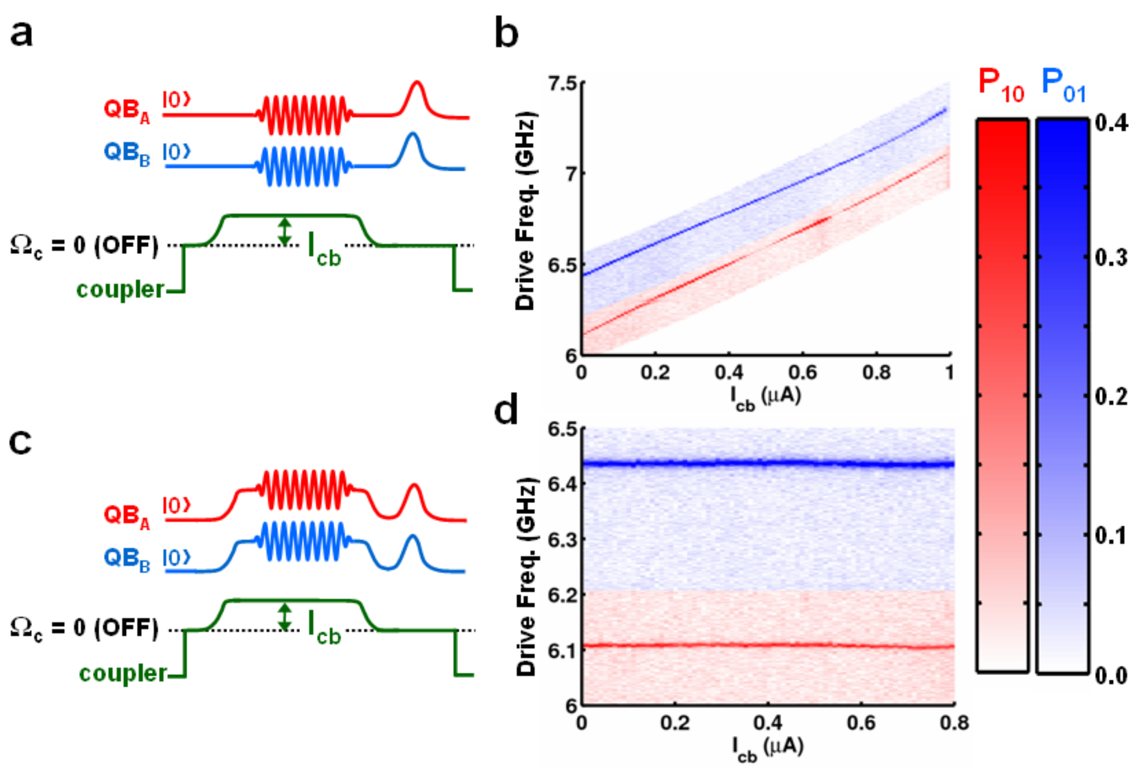

FIG. 3. (a) Pulse sequence and (b) spectroscopy data without compensation for shift due to coupler bias. (c-d) Same, but now with compensation for coupler bias shift.

As mentioned above, the coupler and qubit biases are connected via a direct-current path. As a result, a bias applied to the coupler also shifts the qubit biases. This can be seen in Supplementary Figures 3a and 3b, which show the pulse sequence and data for two-qubit spectroscopy as a function of coupler bias. As the coupler bias I_{cb} increases, the qubit biases shift in a direction that increases the qubit resonance frequencies. The shifts are approximately the same for both qubits, and can be easily compensated for as shown in Supplementary Figures 3c and 3d. Here, the pulse sequence and spectroscopy data are the same except the qubit biases also contain a compensation pulse. With compensation, the qubit frequencies are constant as a function of coupler bias, indicating the shifts have been minimized.

III. MINIMUM RESOLUTION OF COUPLING STRENGTH FOR SWAP EXPERIMENT

For low coupling strengths, energy relaxation (T_1) makes the swap oscillations decay before the occurrence of a full swap. This decay limits the measurement of the minimum coupling strength that can be resolved. To determine the minimum coupling strength, corresponding to the OFF data repeated in supplementary Figure 4a, we performed simulations of a two-qubit coupled system that included the $T_1 \sim 350$ ns decay as measured for each qubit. We show in Supplementary Figures 4b-d the simulations for coupling strengths of 0.1 MHz, 0.3 MHz, and 0.5 MHz. The best fit to the data occurs at a simulated coupling strength of 0.1 MHz, as for coupling strengths < 0.1 MHz the oscillations cannot be resolved due to T_1 decay. We take the minimum coupling strength to be bounded as no greater than 0.1 MHz, giving a lower bound on the ON/OFF ratio of 100 MHz /0.1 MHz = 1000.

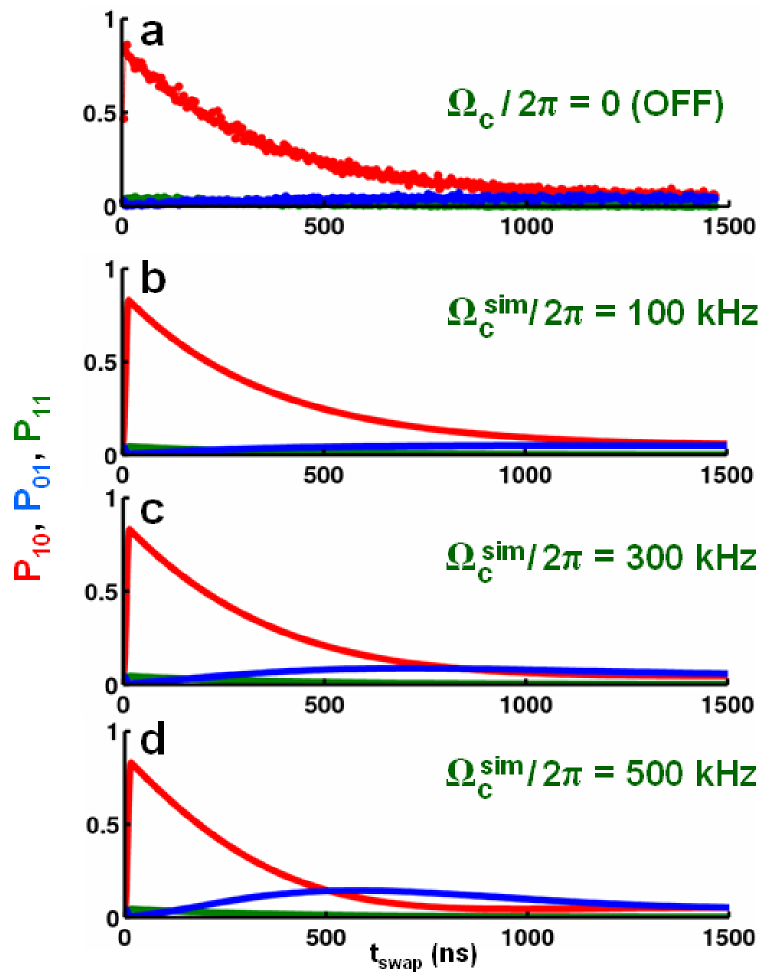

FIG. 4. Comparing the experimental data (a) with simulations for various coupling strengths (b-d) allows for the estimation of the minimum coupling strength.

[1] A. Barone and G. Paterno, *Physics and Applications of the Josephson Effect* (John Wiley and Sons, 1982).

[2] R. McDermott *et al.*, Science, **307**, 1299 (2005).