Effects of Superconducting Return Currents on RSFQ Circuit Performance

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***Abstract*—Complex RSFQ circuits are typically dc-biased with one or more current bias trees, with current returning through a superconducting ground plane. As the bias currents become larger in more complex circuits, it is increasingly critical to pay attention to the distribution of these return currents, and the effects of the resulting magnetic fields on the performance of the RSFQ circuits. We have modeled the current and field distributions, and found that magnetic field and flux are indeed significant. This has been confirmed by direct measurement using a distribution of SQUIDs. Furthermore, we have measured the performance of several RSFQ circuits, and have found that currents in the ground plane can significantly affect performance margins. Approaches to circuit and system designs that can reduce these problems are discussed.**

***Index Terms*—Current distribution, flux trapping, grounding, power distribution, shielding.**

I. Introduction

RSFQ logic forms the basis of the fastest digital and mixed-signal integrated circuits in any electronic technology. However, there are several fundamental issues that must be addressed as these circuits are scaled up in complexity and density. For one thing, although the individual Josephson junctions are biased at currents of order 0.1 mA, most of the junctions are biased in parallel, requiring total current biases of order 1 A in complex circuits with many thousands of junctions on a chip [1]. This requires the chip to distribute rather large currents, which in turn produce stray magnetic flux that can couple inductively into various locations in the circuits. At the same time, these circuits are built around elements that are essentially SQUIDs, which are well known as the world's most sensitive detectors of magnetic flux. This unfortunate combination of large currents and flux sensitivity creates a fundamental problem, that is becoming worse as the total current bias is increased. In particular, we suggest that stray flux coupling may be contributing to reduced bias margins in complex RSFQ circuits.

This problem is well known [2], [3], and methods of addressing this, such as the use of superconducting ground planes, are already well established. However, as we will describe below, these do not completely solve the problem, and there are several subtle related issues that have not been fully addressed in the literature of RSFQ circuits. In this paper we focus on return currents that are likely to be widely spread across the ground plane. We show by simulation and measurement that these currents can produce flux $\sim 0.1\Phi_0$ in standard RSFQ cells ($\Phi_0 = \mathrm{h/2e} = 2.07$ fWb is the flux quantum), which in turn can reduce bias margins substantially. Similar effects may be responsible for reduction in performance margins in a variety of complex RSFQ circuits. We conclude by discussing several approaches to improved circuit and system design that may reduce these problems.

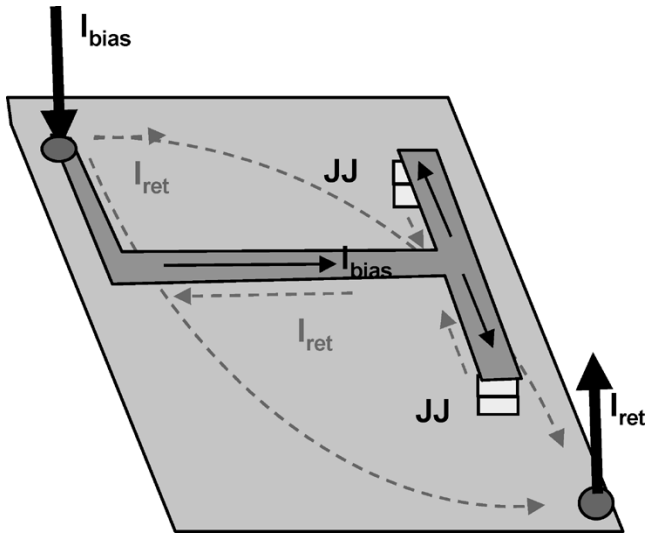

Fig. 1. Simplified representation of current biasing an RSFQ circuit with a superconducting groundplane. Here the current enters on the upper left and exits from the ground plane on the lower right. The two Josephson junctions (JJs) form a SQUID that can couple magnetic flux.

II. Current Distribution in Ground Plane

Typical design and layout approaches to RFSQ circuits involve the use of a superconducting ground plane that provides the common ground for all of the circuits on the chip. The current bias lines are fed into the circuit in a tree structure, with bias resistors acting to distribute the proper current in each leg. The lower electrode of each junction is typically connected directly to ground, and the ground current distribution is not directly confined to a particular path. A simplified picture of such a layout is shown in Fig. 1. Here, the current $\mathrm{I_{bias}}$ is fed into a contact in the upper left of the chip, and an equal return current $\mathrm{I_{ret}}$ is extracted through a ground contact in the lower right. The two Josephson junctions on the right represent a fragment of an RSFQ circuit, and the superconducting loop connecting them represents a SQUID that can couple magnetic flux.

It is well known that a superconducting ground plane will screen out magnetic fields that are perpendicular to the plane of

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the film. It does this by inducing "image currents" that oppose the applied field, cancelling out the perpendicular component. This works well in screening out the field produced by a bias current that enters the chip in a line above the ground plane. As in standard microstrip at higher frequencies, a return current is induced directly underneath the strip, with a matching current. This confines the magnetic field between the strip and the ground plane, with fringe fields that decay from the edges as a dipole field, approximately as $(\mathrm{d}/\mathrm{r})^3$, where d is the separation of the line from the ground plane and r is the distance from the edge of the line. For a typical $\mathrm{d} \sim 0.3\ \mu\mathrm{m}$, this edge field is completely negligible more than $\sim 10\ \mu\mathrm{m}$ from the edge.

But the situation becomes more complicated near the input contact for the bias current. In particular, the return current $\mathrm{I_{ret}}$ that had been traveling underneath the input line now has to find its way to the ground contact, which in Fig. 1 is on the opposite corner of the chip. In doing so, it is no longer narrowly confined, and can spread out across the chip. In effect, the ground plane beneath the current input contact becomes a virtual current source with a radial spread, coupled with a virtual current sink at the ground contact on the other side. These spreading and converging currents can also be viewed as image currents for the vertical insertion and extraction wires.

It is also important to note that most of the unconstrained current in a superconducting film does *not* flow near the outer edge, contrary to common belief. It is certainly true that the current *density* J peaks sharply near the edge (on the scale of the magnetic penetration depth λ), but if one integrates J across a wide film, most of the total current I flows straight across the interior of the film. Since we are most concerned about the magnetic field in the interior (since that is where the RSFQ circuits are located), we can estimate the surface current density to a first approximation by $\mathrm{J} = \mathrm{I}/\mathrm{r}\theta$, where r is the radial distance and θ the appropriate spreading angle. The magnetic field H produced by this spreading current is equal to the surface current density J, but perpendicular, pointing in the azimuthal rather than the radial direction. There is, of course, no vertical component of field.

The key point of this crude estimate is that the magnetic fields and fluxes induced by these spreading currents can be quite large. For example, if one considers a 100 mA ground return current crossing a 0.5 cm chip, the surface current density in the middle of the chip would be $\mathrm{J} \sim 0.1\ \mathrm{A}/0.5\ \mathrm{cm} = 20\ \mathrm{A/m}$. This produces $\mathrm{H} = 20\ \mathrm{A/m}$ and $\mathrm{B} = \mu_0\mathrm{H} = 25\ \mu\mathrm{T}$. This is about half the earth's magnetic field (50 μT). Given the great pains that are taken to screen out the earth's field in RSFQ cryoprobes, it is clear that a field of this magnitude is unacceptable. This is also evident for a typical area of flux coupling, say for two junctions 20 μm apart, with an effective interlayer height of 0.5 μm. If this area is oriented to couple the maximum flux, 25 μT gives a flux $\Phi \sim 0.25\ \mathrm{fWb} = 0.12\ \Phi_0$. Although the details would depend on the specific circuit, a flux change in a critical loop of order 10% of Φ_0 would be expected to affect bias currents of an RSFQ circuit by a similar factor. This is comparable to critical margins in complex circuits, and might prevent proper functioning of some circuits.

Of course, the configuration in Fig. 1 is rather oversimplified. In a more typical RSFQ chip, there are multiple current bias inputs and multiple ground contacts around the chip. A somewhat more realistic model is indicated in Fig. 2. Now there are two bias sources, with a common ground, and 8 ground contacts around the chip. The return currents extracted through each ground contact are not specifically constrained; only the total ground current is constrained to match the total bias current. The distribution of the return current among the ground contacts is determined by small, largely parasitic resistances to the off-chip ground. (The superconducting inductances are important only in determining distributions on the ground plane itself.) For similar resistances, this return current extraction may be approximately symmetrical around the chip. On the other hand, the bias currents are typically not symmetrical around the chip. This mismatch creates excess bias currents crossing the ground plane, coupling flux into RSFQ circuit elements and reducing bias margins. Since the total bias current in a complex RSFQ circuits can approach 1 A, significant mismatches requiring cross-chip currents of order 100 mA are quite likely. As discussed earlier, this can lead to flux coupling in some of the internal SQUID loops in RSFQ circuits, and consequent narrowing of critical margins.

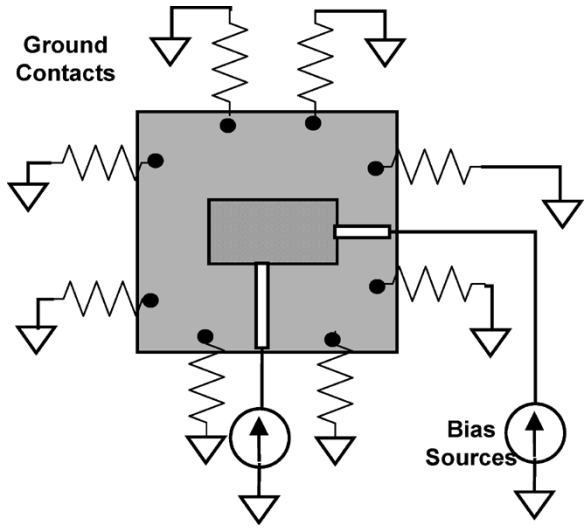

Fig. 2. Schematic of typical biasing scheme for RSFQ circuit, with a ground plane and a common ground for all bias lines. Current is injected into the circuit via multiple grounded bias sources. The return current is extracted through multiple ground contracts that are distributed around the periphery of the chip. The distribution of this extraction currents among the ground contacts is determined by parasitic resistances to a common off-chip ground. The spatial mismatches between local current sources and sinks can lead to significant cross-chip currents that may be of order 100 mA or more.

To provide further evidence of these ground-current distributions, we tested a particular 0.5-cm diagnostic chip (ak6_diag0ch03) fabricated using the HYPRES standard process [4] for 1 $\mathrm{kA/cm^2}$ Nb junctions (Fig. 3). This chip includes a number of independently biased SQUIDs, with geometries similar to those in standard RSFQ cells. Each of these SQUIDs permits direct injection of current $\mathrm{I_{con}}$ into the upper line of the SQUID, in order to calibrate the line inductance. In addition, this chip permits one to inject current $\mathrm{I_{inj}}$ directly into the ground plane in the corner. The measured results at 4.2 K for one particular SQUID are summarized in Fig. 3, for a fixed bias current placing the SQUID in the voltage state for $\mathrm{I} > \mathrm{I_c}$. Here the $\mathrm{V} - \Phi$ transfer characteristic of the

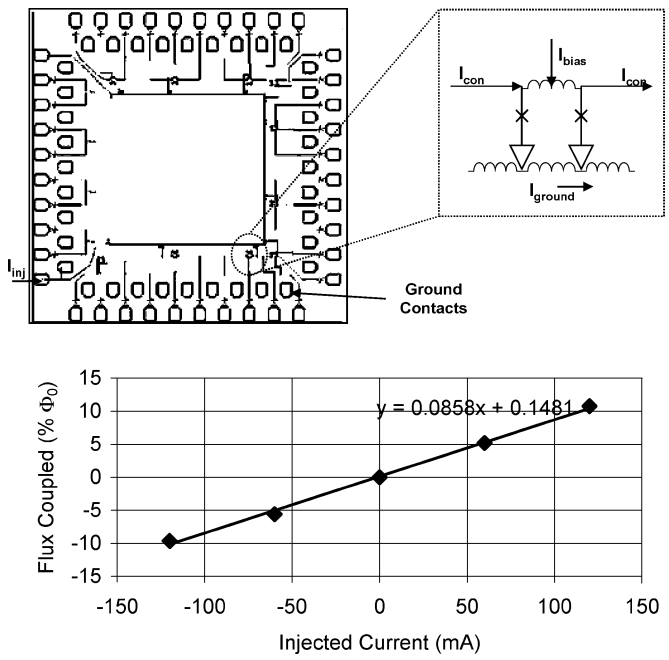

Fig. 3. Nb chip (5 mm × 5 mm) to demonstrate distribution of currents in superconducting ground plane. Top: chip layout showing array of SQUIDs around chip, focusing on a particular SQUID, with simplified circuit schematic also shown. Bottom: measured shift of $\mathrm{V}-\Phi$ transfer characteristic of SQUID with injected current $\mathrm{I_{inj}}$. The slope of this line corresponds to a mutual inductance $\mathrm{M}=1.8$ fH.

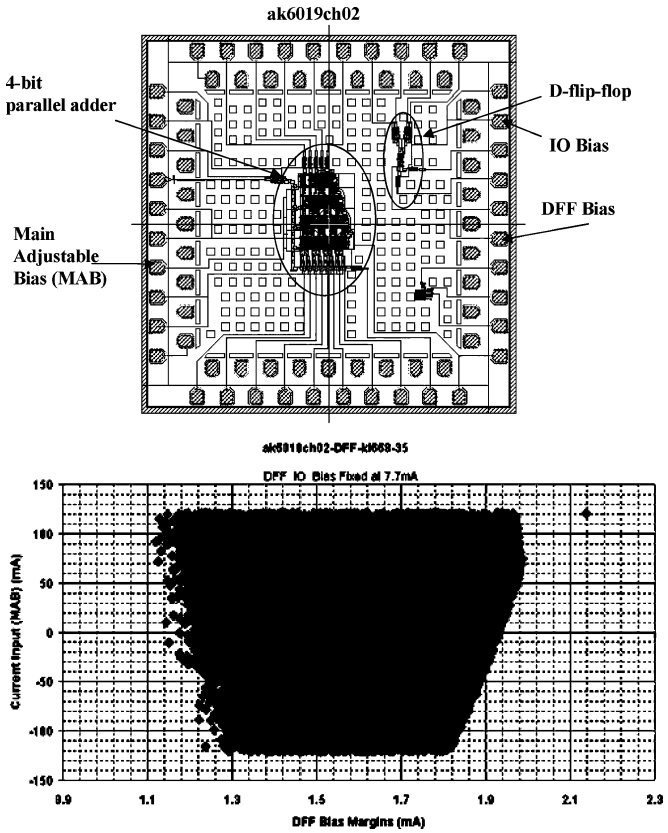

Fig. 4. Margins test of D-flip-flop (DFF). The top shows the layout of the chip, with a larger 4-bit parallel adder (center) and also a DFF (upper right). The bottom shows the measured values of DFF current bias (in mA) for proper (low-speed) operation of the circuit, for various values of the "main adjustable bias" (MAB) of the adder, of either sign. Note that for positive MAB bias, the operating margins of the DFF actually increased, while the margins shrank for negative bias.

SQUID shifts proportionally to the separate current (of either sign) $\mathrm{I_{inj}}$ injected into the ground plane in the lower left corner. The slope of this curve corresponds to a mutual inductance $\mathrm{M}=1.8$ fH. This seems like a rather small coupling, but it does in fact correspond to flux shifts of 10% of Φ_0 for currents of order 100 mA, as we suggested earlier.

One can compare the measured value $\mathrm{M}=1.8$ fH to a very simple model of radial spreading current, with $\mathrm{M}=\mu_0\mathrm{A}/\mathrm{r}\theta$, where A is the SQUID area, θ the spreading angle, and r the radial distance. Taking $\mathrm{A}=58\ \mu\mathrm{m}\times 0.33\ \mu\mathrm{m}$, $\mathrm{r}=4$ mm, and $\theta=\pi/2$, yields $\mathrm{M}=4$ fH. A more realistic calculation would take into account partial extraction of ground current (about half) through ground pads (the inner ring of 36 ground contacts) before the current reaches the SQUID, and also the misaligned flux coupling angle, both of which would reduce the effective coupling toward the measured value. Preliminary simulations with a two-dimensional finite-element program are consistent with this expectation.

III. Test of RSFQ Operating Margins

Finally, a direct test of RSFQ operating margins was made, using a 5-mm chip (ak6019ch02) containing two separate RSFQ circuits: a 4-bit parallel adder, and a D-Flip-Flop (Fig. 4). The only connection between the two circuits is through the ground plane. The bias current for the adder was much larger (∼100 mA) than that for the DFF (∼10 mA), so the bias margins of the DFF were tested for varying currents into the adder. Since operation of the adder was not checked, this "Main Adjustable Bias" (MAB) essentially provided a way to inject current in the ground plane. Automated low-speed operation of the DFF was carried out at 4.2 K using the "Octopux" programmable test system. A two-dimensional Monte-Carlo set of current parameters were chosen, with both the MAB and the DFF bias varied across relevant ranges, including both signs of MAB current. The points corresponding to proper operation of the DFF are shown in Fig. 4, indicating the operating margins of the circuit. It is clear that this margins plot is asymmetric, with positive MAB currents actually increasing the margins, at least for currents up to ∼50 mA. Negative currents, on the other hand, sharply decrease the operating margins.

One can understand this asymmetry by noting that the positive self-bias of the DFF, ∼10 mA (including for the input and output circuits), would also be expected to produce spreading current in the ground plane near the circuit. We can crudely estimate that this current is spread across a distance ∼2 mm near the DFF, corresponding to a surface current density $\mathrm{J}\sim 10\ \mathrm{mA}/2\ \mathrm{mm}=5\ \mathrm{A/m}$. For a typical 10 $\mu\mathrm{m}^2$ coupling area, this corresponds to a flux ∼3% of Φ_0. For a circuit designed without taking this into account, one would expect a small but significant narrowing of operating margins, as is indeed observed. For a positive MAB current, however, the expected ground return currents, in the region near the DFF, would be expected to point in the opposite direction. In particular, if we consider a MAB current of +50 mA, and estimate that ∼20 mA remains uncollected when it is spread over ∼4 mm near the DFF, this also corresponds to $\mathrm{J}\sim 5\ \mathrm{A/m}$.

To the extent that this is properly oriented to oppose the current produced by the DFF bias, the net flux coupled would cancel out, and the operating margins would recover toward their ideal range. This, too, is observed. A further increase in MAB bias would then start to reverse the sign of the coupled flux, leading to a decrease in margin. Such a turnaround also seems to be present in the data of Fig. 4. For negative MAB currents, the flux will reinforce the self-flux that is already present, further reducing the margin. For example, for MAB current of -100 mA, we estimate that the surface current density near the DFF is $\mathrm{J} \sim -40\ \mathrm{mA}/4\ \mathrm{mm} = 10\ \mathrm{A/m}$, which corresponds to a flux $\Phi \sim -6\%$ of Φ_0. The data show a margin that is reduced from about 75% to about 50%.

This all presents a consistent picture, but agreement is semi-quantitative at best. We don't even really know which is the critical SQUID loop in the circuit responsible for these margins. A more accurate analysis would need to take into account detailed current distributions in the ground plane, flux coupling geometries, and models of the flux sensitivities of the various elemental cells of RSFQ circuits.

IV. Discussion and Conclusions

All of this provides strong evidence that these are important effects that must be taken into account for optimum performance of complex RSFQ circuits. It is worth emphasizing that these measurements were carried out inside two concentric mu-metal cans, in order to screen out the earth's magnetic field ($\sim 40\ \mathrm{A/m}$ or $50\ \mu\mathrm{T}$), and we believe that they were very effective at doing so. However, the local fields at the RSFQ circuits, produced by ground return currents, are almost as big, and are not effectively screened.

So other strategies must be employed to reduce these effects. These include balancing the locations of current biases and ground contacts around the chip, so that there is no need for large cross-chip currents and fields. One could also design a cryoprobe with separate dedicated return lines for each large bias current. If such a return line is connected to a ground contract right next to the corresponding bias contact on the chip, that would also reduce the need for such unbalanced currents. Of course, this approach requires that the return current be constrained closely to match the given bias current, which requires either transformer-isolated power supplies, or alternatively matched source-and-sink module pairs. One can also remove the ground plane where it is not directly needed (such as under bias lines, inductors, and transmission lines). This will tend to constrain the current flow away from the critical regions, although if one is not careful, this may simply make the problem worse elsewhere on the chip. Another important design strategy is to make use of "current recycling" [5], whereby repetitive circuit blocks are biased in series, thus reducing the total bias current to the chip.

Another important approach, which we have adapted in many of our RSFQ circuits, is the use of a double ground plane. In this approach, there is a top superconducting layer above the circuit elements, which is grounded to the lower layer with frequent superconducting vias. This creates a large number of flat superconducting loops around the SQUID loops. If the flux in any loop is initially zero, then it will remain zero. Therefore, any extended ground current will be split between the upper and lower ground planes, which should sharply reduce the flux coupled in a given SQUID loop. We have not yet carried out a systematic comparison of margin effects with and without the upper ground plane, but the preliminary evidence suggests that the ground-current effect is significantly reduced (but not eliminated). On the other hand, superconducting loops near critical circuit elements may also increase the likelihood of flux trapping, if one is not careful.

In conclusion, we have identified a serious problem with ground return currents in RSFQ circuits with total bias approaching 1 A, namely that magnetic flux coupled into internal SQUID loops can degrade circuit performance. This problem can be significantly reduced by a combination of strategies on the design, layout, and system levels. If these are properly implemented, further increases in integration scale of RSFQ circuits can continue to be achieved.

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