Experimental and simulation results of a symmetrical pad to reduce a stray ground current in superconducting integrated circuits

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Abstract. The method of extracting bias current is widely used in large scale SFQ circuits to avoid harmful effect by spreading the bias return current on a ground plane, which causes malfunction or degrading the operating margin by the stray magnetic field. Although extracting the bias current is effective, we found that the extraction using a normal pad structure with a bias pad and a current extracting pad still produces a large stray ground current (magnetic field) for its asymmetric structure. We proposed a bilaterally symmetrical pad structure, which can reduce the stray ground current significantly in superconducting circuits. The bias current is extracted from a nearby ground pad of a bias pad in usual method, whereas the bias current is extracted from two of the symmetrical ground pads which are arranged both sides of the bias pad in the symmetrical structure. Then, the bias current is extracted on halves from each of the two pads symmetrically, reducing the stray ground current. First, we have simulated the ground current by using FastHenry program. The results showed that the symmetrical pad structure outside of ground plane reduced spread of the ground return current significantly. Next, we have designed a test chip and confirmed the effectiveness of the symmetrical structure experimentally.

1. Introduction
Integration level of superconducting circuits has been increased step by step, especially in single flux quantum (SFQ) circuits [1]–[4]. In the SFQ LSI circuits with several to ten thousand junctions, the bias currents exceed 1 A. The bias currents are applied to circuit elements through bias lines from bias supply pads and returned through a ground plane in SFQ circuits. The return current induces undesirable magnetic field, which causes harmful effect in the circuit operation [5]–[7]. Several methods are used for reducing the effect [8]–[12]. One of the methods is extracting the bias current from the neighboring pad of the bias current supply pad. This improved the stability and the bias current margins in the circuit operations. However, the harmful effect of the ground current seems to be still existed, especially in large-scale circuits.

We have analyzed the current distribution on the ground plane by using 3D inductance calculation program, FastHenry [13]. Then, we have found that relatively small difference of the position of the pads for supplying and extracting bias current produces large spread of the ground current. To avoid...
the spread, we proposed a symmetric pad structure outside of the ground plane for extracting bias current symmetrically [14]. According to the simulation using FastHenry program, the current on the ground plane in this symmetrical structure was reduced more than one order of magnitude than that of the usual asymmetric pad structure with bias extraction in practically usable circuit area.

To verify the results of the simulation, we have designed a test chip and confirmed the effectiveness of the symmetric pad structure experimentally.

2. Basic analysis of bias current extraction using FastHenry program

2.1. Model for FastHenry analysis

Usually, bonding pads are arranged peripherally in a chip and bias current is applied from a bias pad through a bias line to circuit elements. We made a simple analysis model with extracting the bias return current as shown in figure 1. The bias current is applied from Port1 and is flowed to the ground plane (GP) at Port2 through the bias line. Then, the current is extracted from Port3 connecting to the GP. The ground plane was 5 mm × 5 mm in size which is usually same as the die size, and the bias line was 50 µm in width. Port2 was located in the center of the chip. The number of filaments and the ratio of adjacent filaments along the thickness, Z, were set to five and two, respectively, as shown in figure 1. The number of segments for X and Y direction in ground plane was set to 200 or 400 in the following analysis. The London penetration depth of the bias line and ground plane was set to 87 nm.

\[ \text{Figure 1. Basic analysis model of bias current and ground return current.} \]

2.2. Results in Bias Current Extraction

First, we have analyzed for the simple structure with bias current extraction. Figure 2 shows the color contour map of the return current in the top filament on the ground plane, in which the number of the segment is 400 × 400. The bias current was normalized with 1 A, which was flowed on the 50 µm-wide bias line. The numerical number in the legend such as $2.940 \times 10^7$ means current density parallel to X and Y plane of the top filament with thickness of 0.03 µm on GP in units of A/m². Note that the ground current of three or four orders less current should be considerable because the critical current and operating current is several hundred micro amperes in SFQ circuits.
The ground return current is color contour mapped with 12 levels in four orders of log scale. The return current initially flows back under the bias line and then spreads over the ground plane in near Port1 and Port3. The area flowing larger than 1/1000 of the maximum current which is the current under the bias line was spread to around 1 mm far from Port1 and Port3. Moreover, the area larger than 1/10000 of the maximum current extend to more than half of the chip. In figure 2(a), the bias current extracting position, Port3, was 200 \( \mu m \) apart from the bias current supplying position, Port1, which seemed to be relatively small. However, the small difference produced widely spread ground current. In figure 2(b), Port3 and Port1 were placed in the same position. This ideal case showed no current spread on a ground plane in the Ports. Note that the current spread is large even with relatively small difference of 200 \( \mu m \) between current supplying and extracting points.

3. Analysis of ground return current for four pad structures

The distribution of the ground current for the four structures shown in figure 3 was simulated by FastHenry. In figure 3, (a) and (c) have asymmetrical pad structure, whereas (b) and (d) symmetric structure. In addition, pads are place on the ground plane in (a) and (b), whereas (c) and (d) outside of the ground plane. The simulation condition was the same as that described in Section 2. The number of the segment was set to 200 \( \times \) 200 to save the calculation time, since there was no obvious difference for that of 400 \( \times \) 400 segments. Figure 4(a)–(d) show color contour maps of the ground current, which correspond to the structure shown in figure 3(a)–(d). All the pad size is 100 \( \times \) 100 \( \mu m \) and the distance between the bias pad and the extraction pad is also 100 \( \mu m \). The width of the bias line is 50 \( \mu m \) in width. When compared asymmetric pad structures, (a) and (c), with symmetric ones, (b) and (d), the spread of the ground current was reduced obviously for the later ones. Moreover, when compared the pads on GP, (a) and (b), to the pads outside of GP, (c) and (d), the latter ones can reduce the current spread.
Figure 3. Four pad structures for simulation; (a) normal asymmetrical pad structure on a ground plane, (b) symmetrical pad structure on a ground plane, (c) asymmetrical pad structure outside of a ground plane, and (d) symmetrical pad structure outside of a ground plane.

Figure 4. Simulated colour contour maps in (a) normal asymmetrical pad structure on a ground plane, (b) symmetrical pad structure on a ground plane, (c) asymmetrical pad structure outside of a ground plane, and (d) symmetrical pad structure outside of a ground plane.
We have quantitatively compared the ground current distribution in the four pad structures. The calculations were performed without a bias line to eliminate the effect from the bias line and clarify the contour map, since the contour map without the bias line had no special difference from that with the bias line. Figure 5 shows the dependences of the ground current on the distance from the center of bias current supply pad. The data were obtained with drawing contour lines on the ground current color map, which fitted well with circle lines. The ground current was normalized with 1 A as with other results, so a current of $10^{-3}$ corresponds to flowing 1 mA in 50 μm-wide ground plane. In the normal pad structure, circuits must be placed 0.5 mm away from the bias supply pad for reducing the ground current to less than $10^{-3}$. When considering a 2 μm-wide inductive line in SFQ circuit, the ground current under the line corresponds to be as large as 40 μA in $10^{-3}$. It seems to affect the operation of SFQ circuits. Although the ground current should be reduced less than $10^{-4}$, it is impractical in the normal pad structure. The bilaterally symmetrical pad structures on a ground plane and outside of a ground plane structure can reduce well the spread of the ground current as shown in figure 5. Especially, one can see that the symmetrical pad structure outside of GP is superior to reduce the ground current than that on GP. In particular, the normalized ground current can be reduced to $10^{-4}$ at $d \sim 0.5$ mm. Furthermore, the ground current can be reduced to more than one order of magnitude less than that of the normal structure at $d > 0.5$ mm.

![Figure 5](image)

**Figure 5.** Dependencies of normalized ground current on distance from bias pad for four pad structures, where distance between bias pad and extraction pad is 100 μm. Fitting curves are also drawn for the asymmetric and symmetric pad structures outside of ground plane.

Fitting curves for the asymmetric and symmetric pad structures outside of GP are also drawn in figure 5. According to approximate expression for current elements from the bias pad to the extraction pads by using Biot-Savart law, the magnetic field was decayed with proportional to $d^{-2}$ in the asymmetric structure and $d^{-4}$ in the symmetric structure. On the other hand, the simulated results are well fitted with $d^{-1.5}$ and $d^{-3}$ in respectively. In the approximation, we assumed that the distance from the bias pad, $d$, is large enough compared to the pad-to-pad distance, $S$. The difference seems that the assumption $d \gg S$ is not enough for the simulated results. It is also possible that the difference is due to Meissner effect on ground plane, which cannot be included in the approximate expression. However, the fitting curves are well represents a feature of the difference of the symmetric and asymmetric pads.

As shown in figure 2, the distance between the bias pad and the bias extraction pad is important for reducing the spread of the GP return current. We simulated GP current for the four structures with several pad-to-pad distances as shown in figure 6. Figure 6(a) shows the results for pads on GP and
(b) shows that for outside of GP. It is obvious that the smaller the pad-to-pad distance, the smaller the GP current spread in all of the structure. In addition, the GP current is reduced by shortening pad-to-pad distance more effectively in the symmetrical pad structure than that in asymmetrical one.

![Graphs showing influence of pad size and distance on GP current](image)

**Figure 6.** Influence of pad size, distance between bias pads and bias extraction pads, on ground current; (a) pads are located on GP and (b) pads are located outside of GP.

### 4. Experimental results

To confirm the validity of the simulated results, we designed a test chip using AIST advanced process 2 (ADP2). Figure 7 shows the layout of the test circuit, where the symmetrical pad structure outside of GP is arranged on the left half and that on GP is arranged on the right half. The test circuit of 2.2 mm × 6.5 mm in size was placed near the edge on a die of 7 mm × 7 mm in size. To separate electrically and magnetically to other circuit area, 100 µm around of the ground plane was removed in the test circuit as shown in figure 7. X and Y direction SQUID pairs are placed on three different positions for measuring GP current on both structures. Each position to the pads are the same for both structures. The SQUIDs are shunted with resistors, where McCumber parameter, $\beta_c$, was set to 1. The width of the inductance line of the SQUID is 3 µm. The pad size is 100 × 150 µm and the distance between the bias pad and the extraction pad is 120 µm. The bias current is extracted equally from both of PAD A and PAD B for evaluating the symmetrical pad structure, while the bias current is extracted from either of them for evaluating the asymmetrical pad structure.

![Test chip layout](image)

**Figure 7.** Layouts of a test chip for evaluating symmetrical and asymmetrical pad structures. Pads are located outside of ground plane in left half, whereas they are located on ground plane on right half.
The ground current was measured using a shift of well-known $V - \Phi_{ext}$ ($I_{ctl}$) characteristic of the SQUID, where $V$ is the voltage of the SQUID, $\Phi_{ext}$ is the external magnetic flux induced by the control current, $I_{ctl}$. Bias current of 0.4 A was applied to the bias pad and extracted from PAD A and/or PAD B. Then, we measured the shift in $V - \Phi_{ext}$ ($I_{ctl}$) characteristic, $I_{shift}$, which was induced by the GP current. Square-root of sum of squares of the measured $I_{shift}$ for X and Y direction was calculated and was normalized to accorded with the simulated results. Figure 8 shows the experimental results, where the normalized GP current was divided by 2.5 so as to be fitted to the simulated value. The measured dependencies on the distance from the pads are well agreed with the simulated results except for the symmetrical pad structure on GP. We have not solved the discrepancy between the measured and the simulated results for the symmetrical pad structure on GP at present. Since another chip showed the same dependence, it seems that the experimental results are correct and the simulated result has lack of some factors. In either case, the symmetrical pad outside of GP structure is the best solution for reducing the spread of GP current.

![Figure 8](image_url)

**Figure 8.** Experimental results of ground current dependencies on the distance from the pads for the four pad structure. Simulated results are also shown for comparison.

5. Conclusion

We have investigated bias return current on a ground plane with simulation using FastHenry program and with experiment. Even extracting the bias current from the adjacent ground pad of the bias supply pad, the ground current spread extensively. We have found that the cause was due to the relatively small difference between the bias supply point and the extraction point. To solve the problem, we proposed the symmetrical pad structure, which has bilaterally symmetric bias current extraction pads to a bias pad. We simulated the ground current using FastHenry program and experimentally measured the ground current for the symmetrical and the asymmetric pad structures. Then, we confirmed the bias current extraction using the symmetric pad structure was able to reduce the spread of the ground current significantly. Moreover, we have found out that arranging the pad outside of ground plane was more effective than that on ground plane to reduce the ground current. The symmetrical pad structure outside of ground plane structure would improve the operation in large scale superconducting circuits.
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