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# Analysis of a Shielding Approach for Magnetic Field Tolerant SFQ Circuits

Rodwell S. Bakolo<sup>1</sup>, Joey A. Delport<sup>1</sup>, Pascal Febvre<sup>2</sup> and Coenrad J. Fourie<sup>1</sup>

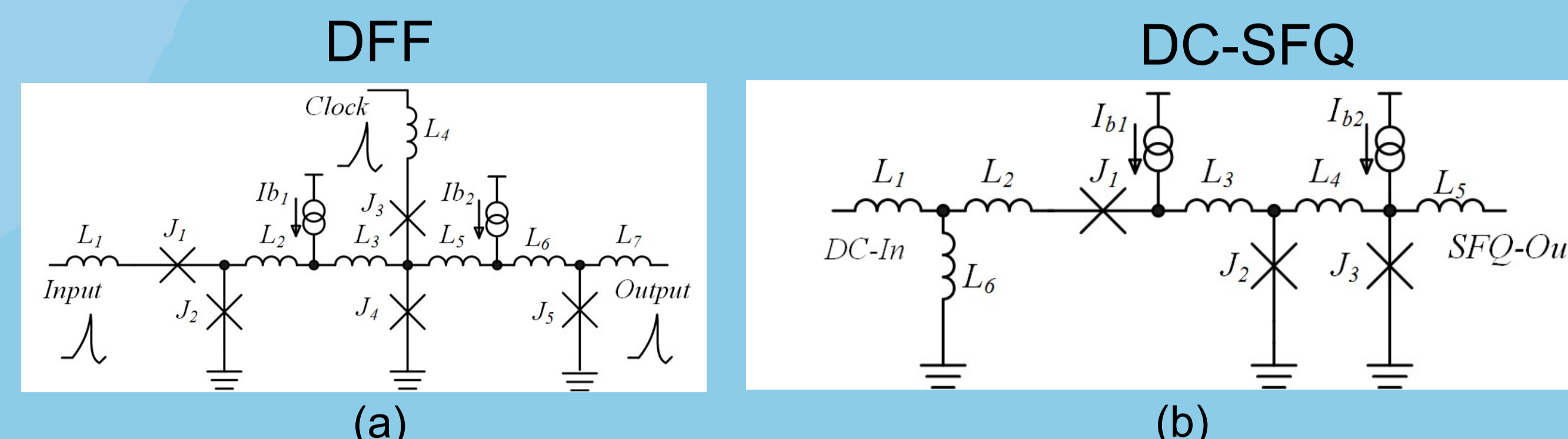
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## 1. Introduction

- SFQ circuits remain vulnerable to magnetic fields from external sources and bias lines, such that small quantities can cause malfunction [1], [2].
- SFQ circuits require shielding to be protected from external magnetic field sources and simple shielding solutions have been proposed before [3].
- The normal solid shielding causes a reduction in circuit inductance and redesigning and re-optimisation are a must.
- We present an analysis of a grid patterned shield that offers adequate shielding while affecting circuit inductance less.
- Two SFQ cells, DFF and DC-SFQ were considered in the analysis and both showed similar results.
- Selected circuit parameters can be changed to restore circuit operation beyond operating field margins.

## 2. DFF and DC-SFQ Cells



$L_1 = 1.86$  pH,  $L_2 = 1.59$  pH,  $L_3 = 7.73$  pH,  $L_4 = 1.50$  pH,  $L_5 = 2.13$  pH,  $L_6 = 1.30$  pH,  $L_7 = 1.91$  pH,  $J_1 = J_4 = 200$   $\mu$ A,  $J_3 = 150$   $\mu$ A,  $J_2 = J_5 = 250$   $\mu$ A,  $I_{b1} = 230$   $\mu$ A and  $I_{b2} = 135$   $\mu$ A  
 $L_1 = 0.56$  pH,  $L_2 = 0.52$  pH,  $L_3 = 1.0$  pH,  $L_4 = 4.78$  pH,  $L_5 = 2.2$  pH,  $L_6 = 4.1$  pH,  $J_1 = J_2 = 225$   $\mu$ A,  $J_3 = 250$   $\mu$ A,  $I_{b1} = 275$   $\mu$ A and  $I_{b2} = 175$   $\mu$ A

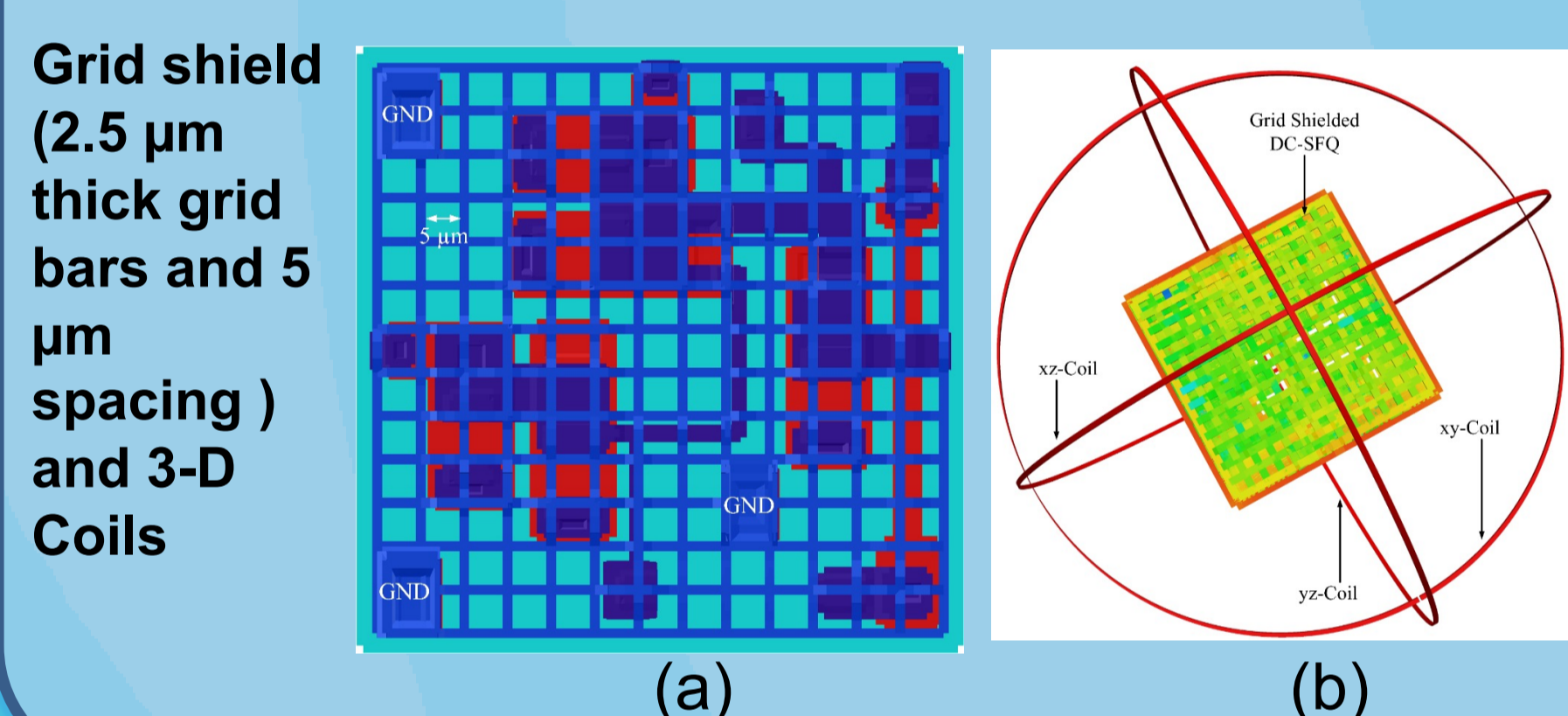
Optimized bias margins in the absence of external magnetic fields

-53% ~ 42%

-56% ~ 34%

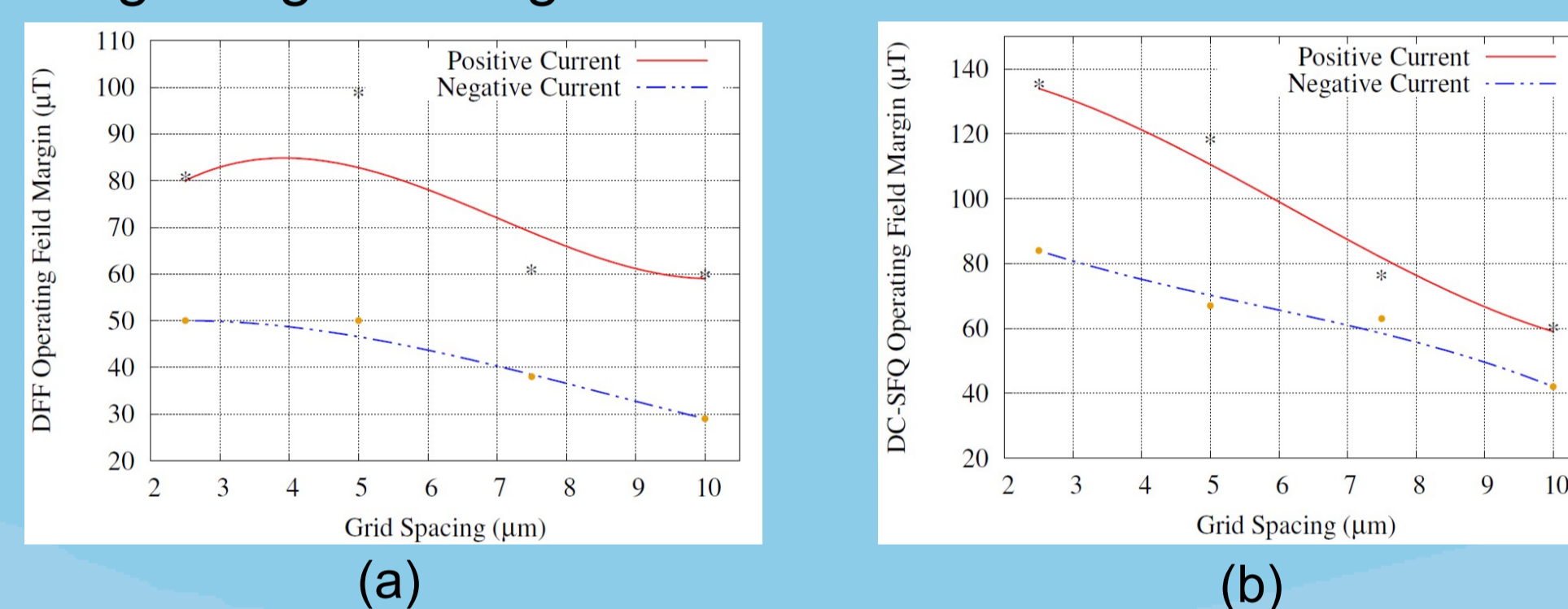
## 3. The Grid Patterned Shield

- Grids of chosen thickness and equal spacing.
- Placement of ground (marked GND in (a)) contacts is crucial for better shielding.
- Magnetic fields were modelled with 3-D coils (xy, xz and yz) in *InductEx*.
- Coils generate roughly uniform magnetic fields over the entire DFF and DC-SFQ cells.
- A current density plot, in (b), shows the effectiveness of the grid shield.



## 4. Operating Field Margins (OFMs)

- Analysis of DFF and DC-SFQ operating field margins with varying spacing of grid bars in a grid shield.
- Coil current sweeps from negative to positive were used.
- The smaller the grid spaces, the better the shielding, as represented by higher operating field margins. With a solid shield the OFMs were 50  $\mu$ T & 86  $\mu$ T (DFF) and 59  $\mu$ T & 113  $\mu$ T (DC-SFQ) – for negative and positive coil currents.
- Both the DFF and DC-SFQ showed lower operating field margins against negative coil currents.

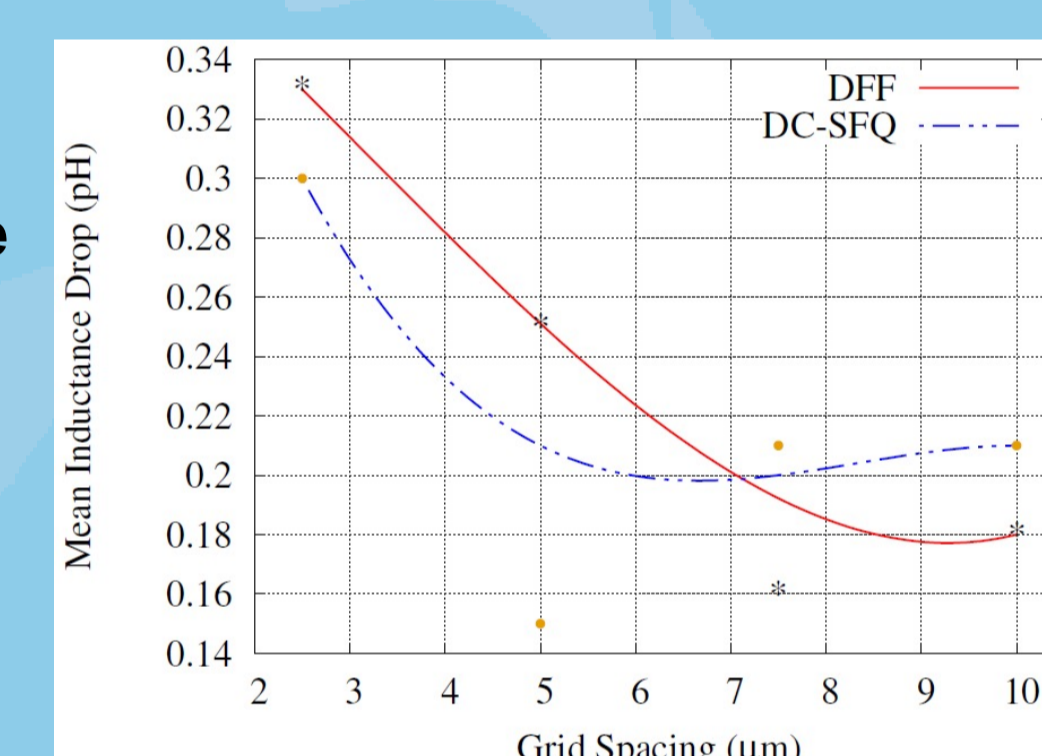


OFMs for the DFF and DC-SFQ cells – Grid bars with 2.5  $\mu$ m thickness

## 5. Parameter Variation

- Shielding causes circuit inductance to drop.
- Solid shielding had the most effect on circuit inductance with a mean reduction of 0.67 pH in the DFF and 0.5 pH in the DC-SFQ.
- A grid bar spacing of 5  $\mu$ m causes mean inductance drops of 0.15 pH and 0.25 pH for the DC-SFQ and DFF, respectively.
- Good shielding but less effect on inductance is often a good design approach.

Mean Inductance spread against grid spacing



## 6. Parameter Changes to Restore Operation

- Operating fields margins can be improved by changing selected circuit parameters as shown in the table – compare to the original values above in (2).
- Circuit functionality and bias margins, without of external magnetic fields, need to be recalculated before calculating new operating field margins.

The OFMs are quoted for negative & positive coil currents, in that order. The cells were under a grid of 2.5  $\mu$ m thick bars and spaced at 5  $\mu$ m

Cell	Initial OFMs	New Values	New OFMs
DFF	50 $\mu$ T & 98 $\mu$ T	$L_5=2.6$ pH	42 $\mu$ T & 126 $\mu$ T
DC-SFQ	67 $\mu$ T & 117 $\mu$ T	$L_6=3.5$ pH	67 $\mu$ T & 134 $\mu$ T
		$J_1=200$ $\mu$ A $J_3=275$ $\mu$ A	

- Notable improvement in operating field margins against fields from positive currents.

## 8. Further Observations

- Bias current tuning can be used to recover circuit operation, but only ideal at cell level. A big challenge to implement on a chip with cells of different biasing.
- Both DFF and DC-SFQ circuits showed different operating field margins to negative and positive currents. This can be attributed to the asymmetrical nature of the cell layouts.
- The 3-D Coils can cause coupling in the range  $-1 \leq k \leq 1$ , such that the coupled fields can induce a negative current in the target inductor, which results in higher operating field margins, especially for positive coil currents.
- By feeding all three coils with arbitrary currents, the magnetic field can be rotated in the 3-D orientations to determine shielding effectiveness further.
- SFQ circuits would attain higher operating field margins for single vector fields.

## 9. Conclusion

- Shielding can be implemented with grid patterned shields with grids of different thickness and spacing. Specifically, grid bars of 2.5  $\mu$ m thickness and 5  $\mu$ m spacing showed good results.
- A grid shield offers a good compromise to the designer to obtain the best possible shielding with minimal reduction on circuit inductance, suitable for legacy cells.
- The conventional solid shield offers comparable shielding but the effect on circuit inductance is large and circuits may require redesigning and re-optimization.
- We have shown a technique that can be used to analyze shielding effectiveness through the use of 3-D coils that generate external magnetic fields.
- It is possible to make changes to parameter values in order to recover circuit operation after a known operating field margins.

## Acknowledgements

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