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► **To cite this version:**

Coenrad Fourie, R. Collot, P. Febvre, J. Lesueur, J. Kunert, et al.. Mutual inductances in superconductive integrated circuits. Institute of Electrical and Electronics Engineers (IEEE). 14th International Superconductive Electronics Conference (ISEC 2013), Jul 2013, Boston (MA), United States. Curran Associates, Inc., 2013 IEEE 14th International Superconductive Electronics Conference, 2013. hal-04909561

HAL Id: hal-04909561

<https://hal.science/hal-04909561v1>

Submitted on 23 Jan 2025

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Mutual inductances in superconductive integrated circuits

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Introduction

Inductive coupling in superconductive integrated circuits (ICs) becoming more important, especially with inductively biased circuits.

The effects coupling between bias inductors and circuit components need to be established to ensure that circuit operating margins do not deteriorate due to layout.

We analyzed the coupling between a control line and a SQUID loop for several structures manufactured with the FLUXONICS foundry at IPHT. This included coplanar lines over a ground plane.

We also analyzed mutual inductance for a YBCO ion-irradiated nanocircuits in a monolayer process [1], and conclude that coupling problems (and performance degradation) will be much more severe for circuits in such processes.

Previous work

We have already demonstrated that mutual inductance for complex layouts, such as an SFQ pulse transfer cell with isolated ground planes and ground plane holes (Fig. 1, FLUXONICS foundry [2]) can be modeled with InductEx (Fig. 2) and extracted (with calibration [3]). The difference between measurements and calculations were < 3 % for self and mutual inductances.

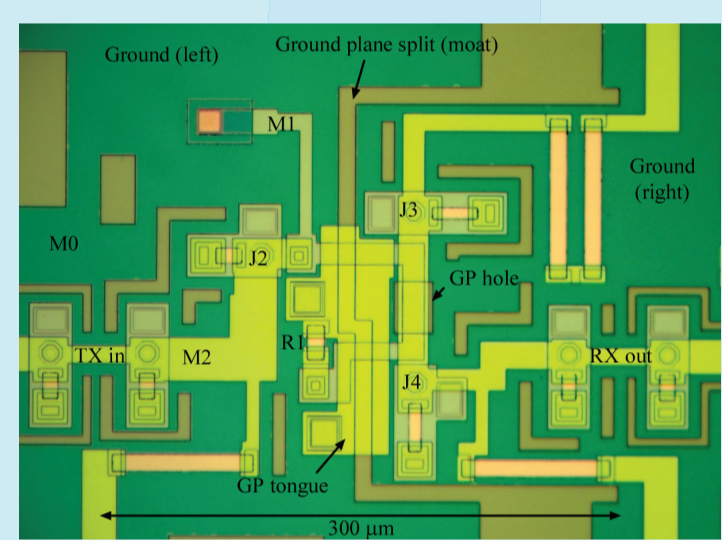


Fig. 1: Microphotograph of SFQ pulse transfer circuit [2]).

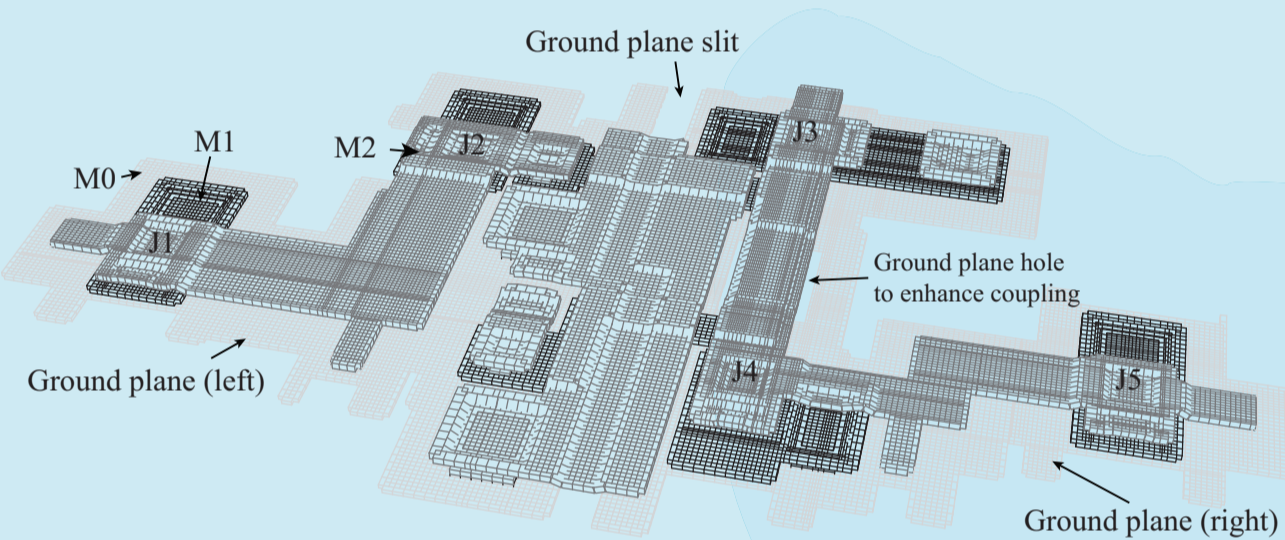


Fig. 2: Inductance calculation model of SFQ pulse transfer circuit in Fig. 1.

Monolayer inductance

For a monolayer high- T_C process (70 nm YBCO with ion-irradiated junctions), we established the validity of a modeling technique through the comparison of calculations with SQUID modulation measurements [1].

SQUIDs with coupling lines (Fig. 5) are modeled with a partial-element equivalent circuits (PEEC) technique [4] (no ground return path provided) as shown Fig. 2.

As seen in Table II, the absence of a ground plane leads to strong coupling even when lines are separated by large distances.

Table II: Calculated mutual inductance for monolayer coplanar lines in YBCO high- T_C process. The loop inductor and co-planar coupling lines have width = 10 μm , thickness = 70 nm and penetration depth = 185 nm. The SQUID loop inductance is 38 pH.

Gap s [μm]	Calculations	
	M [pH]	k
2.5	19.8	0.43
5	17.7	0.38
10	14.8	0.32
20	11.2	0.24

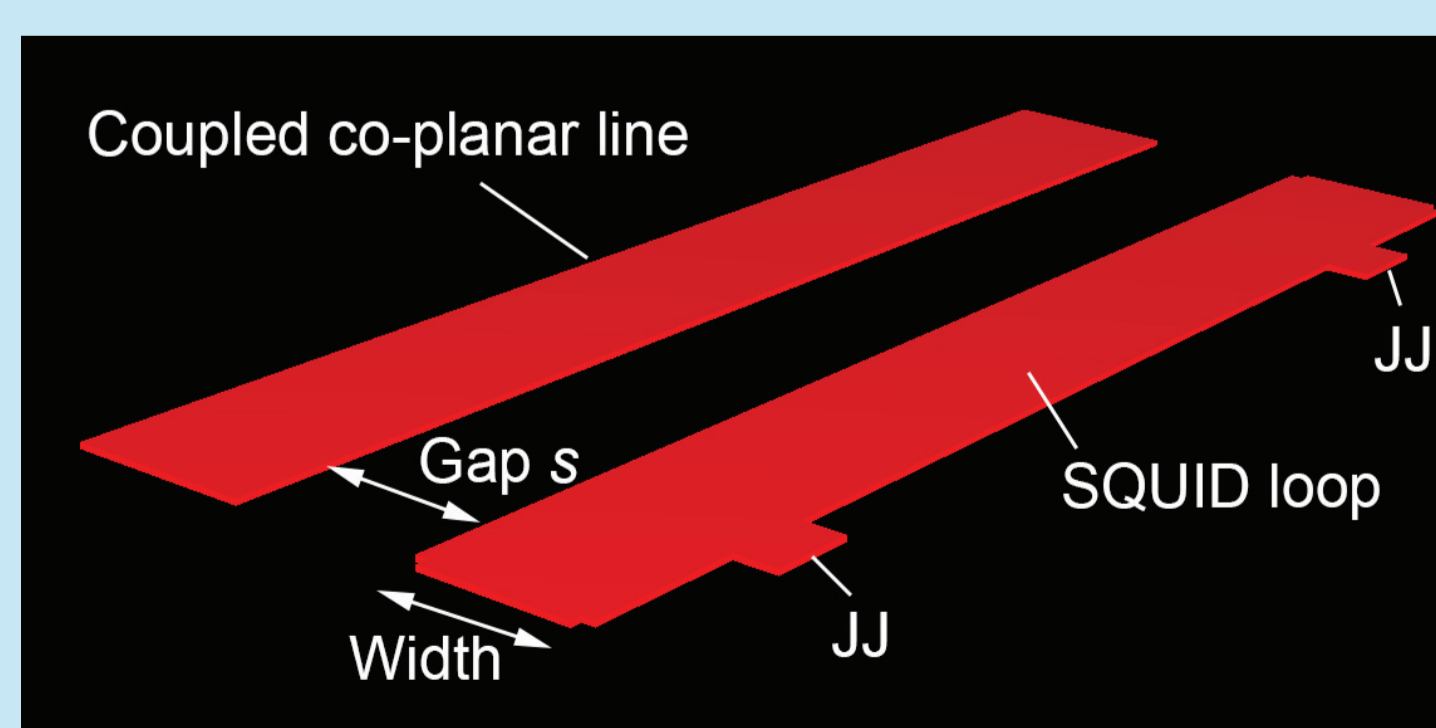


Fig. 5: Monolayer SQUIDs (with ion-irradiated junctions) and coupled co-planar line. A PEEC inductance modeling method is used with InductEx.

Stray coupling in a monolayer RSFQ circuit

For possible high- T_C monolayer RSFQ circuits [1], we investigated the coupling between bias non-perpendicular bias lines and circuit elements. As an example, consider the SFQ circuit in Fig. 6, which comprises a DCSFQ and JTL.

We used a 10-port network as shown in the schematic to model the circuit for extraction

The bias line inductance L_1 couples very strongly (k close to unity) with L_2 and L_3 (the values vary as the current injection and extraction points for port 1 are moved, so that exact values cannot be given without more experiments). Coupling factor to L_4 is ~ 0.25 , to L_5 it is ~ 0.1 , and for the rest it is negligible.

The result shows that coupling in such circuits requires careful attention.

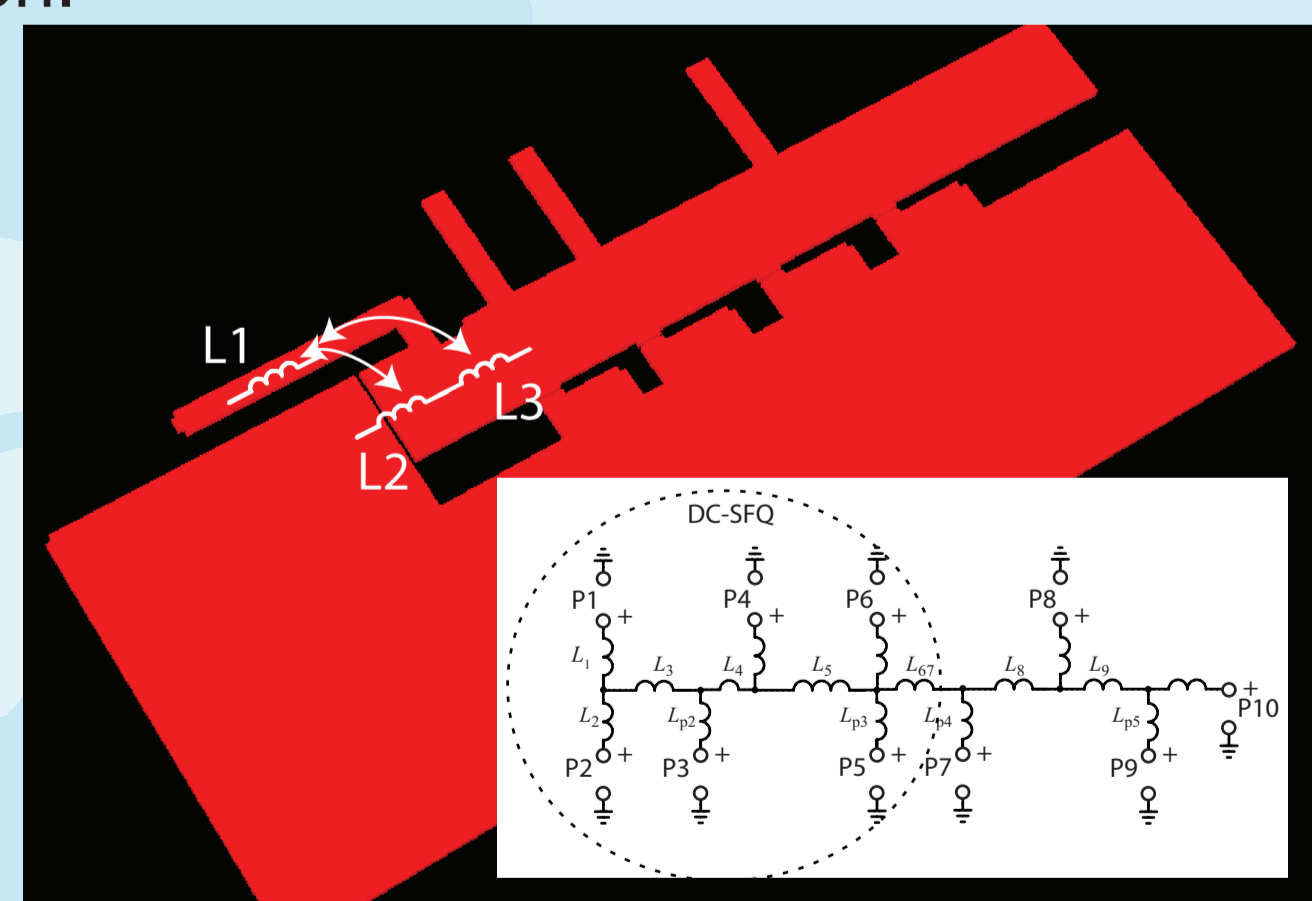


Fig. 6: Monolayer high- T_C RSFQ circuit schematic (inset) and extraction model showing physical locations of L_1 , L_2 and L_3 , and the coupling (arrows) between L_1 and L_2 , as well as L_1 and L_3 .

InductEx Homepage:
www.sun.ac.za/inductex

Mutual inductance experiments

We fabricated SQUIDs with coupling structures (Fig. 2) in with the FLUXONICS process to find mutual inductance when lines are fully over each other, are offset, or are separated by distance (coplanar). The control line is 8 μm wide, and the SQUID loop inductor is 5 μm wide. Offsets from the control line center are 0 μm , 3.8 μm and 11.4 μm .

We used no calibration. The results compared to measurements in Table 1 show good agreement.

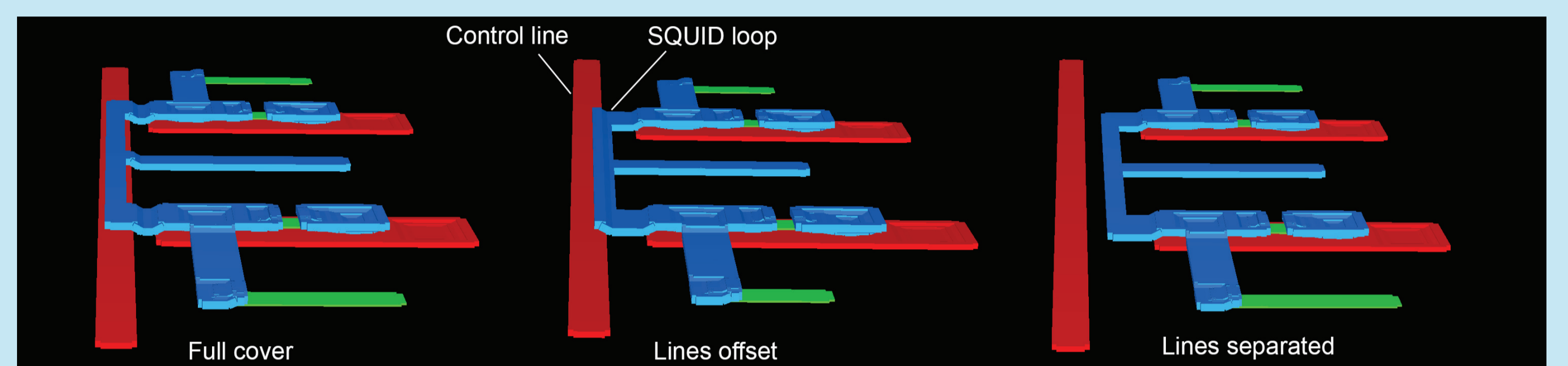


Fig. 3: Inductance calculation models (generated with InductEx) for mutual inductance experiments. From left to right: 0 μm , 3.8 μm and 11.4 μm offsets between line centers. Ground plane omitted for clarity. The SQUID loop inductance is about 19 pH.

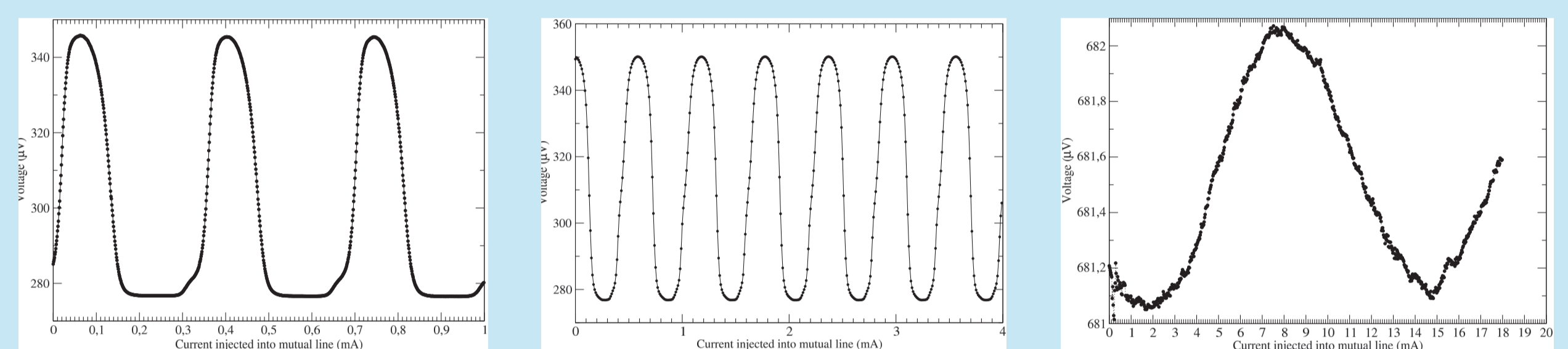


Fig. 4: Measured voltage modulation curves to determine the mutual inductance for each experiment in Fig. 3.

Table I: Calculated and measured mutual inductance M of three microstrip line coupling structures.

Coupling structure	M [pH]	
	Calculated	Measured
Lines fully over each other (0 μm offset)	6.7	6.1
Lines offset (3.8 μm offset)	4.1	3.6
Lines separated by distance (11.4 μm offset)	0.23	0.16

Conclusion

Mutual inductance in circuit layouts, even with ground plane holes or no ground planes, can be calculated. Results compare very well with measurements.

Mutual inductance (including stray coupling) in monolayer circuits with no ground plane is significant. This necessitates careful design and layout, and might render many monolayer layouts non-functional.

Acknowledgment

This work was supported in part by the Région Ile-de-France within the framework of C'Nano IdF, by the Délégation Générale de l'Armement (DGA) through a doctoral grant, by the PEPS-ST21 NANANA (Projet Exploratoire Pluridisciplinaire) of the French Centre National de la Recherche Scientifique (CNRS), and by the South African National Research Foundation, grant number 78789.

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