Transformer Topologies for mmW Integrated Circuits

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***Abstract*—Layout topologies for millimeter-wave transformers are presented. Transformers whose windings present different shapes and relative position are compared in terms of inductance, quality-factors, coupling coefficient and minimum insertion loss. We present measurement results of transformers implemented in a 65 nm CMOS technology. It is observed that octagonal transformers present better Q-factors than square transformers, and that transformers whose primary is rotated by 180 degrees present a partial resonance.**

I. INTRODUCTION

The recent improvement silicon-based technologies have experienced on their frequency performance led to the development of some important applications in millimeter-wave bands. Some relevant examples are the high data rate WPAN exploiting the unlicensed band in the vicinity of 60 GHz, and the automobile radar at 77 and 79 GHz.

Integrated transformers are extensively used in RF circuits. They are employed in several transceiver blocks, such as PAs, LNAs [1], VCOs [2], and mixers [3], and their most common applications are impedance matching and single-ended to differential conversion (balun).

Despite the different constraints that mmW design presents, transformers have also been shown to be very useful at these frequencies [4],[5]. If correctly designed, they allow an expressive area reduction comparing to purely transmission line-based circuits [6] at the same time they provide DC decoupling.

In this paper, we introduce the fundamental topologies for mmW transformers. Section II details the different configurations for the transformers layout and Section III presents the measurement results of the fabricated transformers as well as their analysis.

II. TRANSFORMER TOPOLOGIES

Integrated transformers can present several different topologies. The most conventional distinction is between interleaved (Fig. 1a) and stacked transformers (Fig. 1b). Interleaved transformers present the primary and the secondary on the same metal level. This allows both windings to be perfectly symmetric with regard to inductive and parasitic characteristics. The interleaved topology is traditionally preferred for process technologies that contain only one thick metal layer. Stacked transformers, on the other hand, present the primary and the secondary on different levels, which permits a stronger magnetic coupling and a considerable area reduction. For this structure, though, the parasitics are necessarily asymmetric, since the distances between the windings and the substrate are not the same.

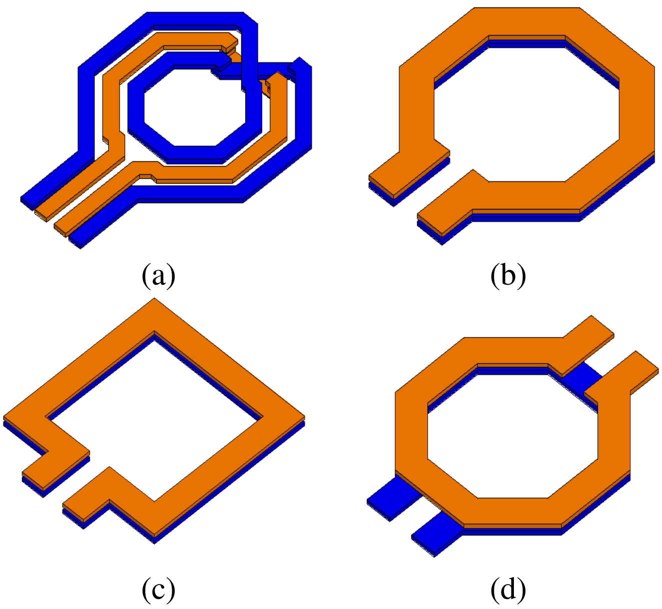

Fig. 1 (a) Octagonal non-flipped interleaved transformer. (b) Octagonal non-flipped stacked transformer. (c) Square non-flipped stacked transformer. (d) Octagonal flipped stacked transformer.

Another distinction concerning transformer topologies refers to the shape of the windings. Square, polygonal and circular spirals have been reported to constitute inductors and transformers [7]. Nevertheless, circular topologies cannot always be employed. CAD and technological limitations may restrain the angles that can be realized. In our case, they were limited to 45 degrees and comparison was hence limited to octagonal (Fig. 1b) and square transformers (Fig. 1c).

Finally, the relative position between primary and secondary is considered. One approach is to have the primary completely covering the secondary, so that their access lines

overlap (Fig. 1b). Another possibility (flipped transformer) consists in a 180 degrees rotation of one of the windings (Fig. 1d). This configuration will result in an uncovered zone of the coils, which will tend to weaken their coupling. The choice between these structures will be made not only in function of their performance but also considering which one is better suited to the layout of a specific circuit.

III. RESULTS AND DISCUSSION

A set of transformers was realized in a 65 nm CMOS technology from STMicroelectronics in order to evaluate the different topologies discussed in this paper. Open and short structures were also implemented so that the effect of pads and interconnects could be de-embedded. All of the transformers were implemented in a 2-port configuration, as shown in Fig.2.

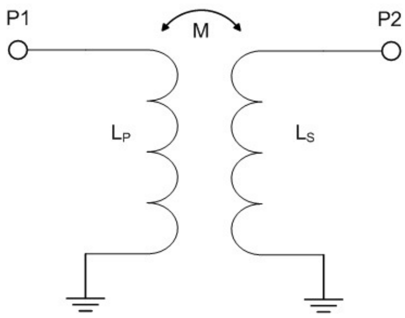

Fig. 2 Transformer in 2-port configuration.

A. Parameters Extraction

The primary and secondary effective inductances L_P and L_S are extracted from the measured impedance parameters using (1) and (2). The quality-factors of the windings (Q_P and Q_S) — defined as the ratio between the net magnetic energy stored in the device and its associated loss [8] — are obtained by (3) and (4). The extracted coupling coefficient k_{im} defined in (6) equals at low frequencies the magnetic coupling coefficient k defined in (5), where M represents the mutual inductance of the transformer. Finally, in order to compare the performance of the different transformers, we adopt the minimum insertion loss (IL_m) as a figure of merit. It is defined as the inverse of the maximum available gain of a 2-port system and takes into account both the quality factors and coupling coefficients of the component [9].

$$L_P = \frac{\mathrm{Im}(Z_{11})}{\omega} \tag{1}$$

$$L_S = \frac{\mathrm{Im}(Z_{22})}{\omega} \tag{2}$$

$$Q_P = \frac{\mathrm{Im}(Z_{11})}{\mathrm{Re}(Z_{11})} \tag{3}$$

$$Q_S = \frac{\mathrm{Im}(Z_{22})}{\mathrm{Re}(Z_{22})} \tag{4}$$

$$k = \frac{M}{\sqrt{L_P \cdot L_S}} \tag{5}$$

$$k_{im} = \sqrt{\frac{\mathrm{Im}(Z_{12}) \cdot \mathrm{Im}(Z_{21})}{\mathrm{Im}(Z_{11}) \cdot \mathrm{Im}(Z_{22})}} \tag{6}$$

$$k_{re} = \sqrt{\frac{\mathrm{Re}(Z_{12}) \cdot \mathrm{Re}(Z_{21})}{\mathrm{Re}(Z_{11}) \cdot \mathrm{Re}(Z_{22})}} \tag{7}$$

$$IL_m = -10 \cdot \log\left[1 + 2 \cdot \left(x - \sqrt{x^2 + x}\right)\right] \tag{8}$$

$$x = \frac{1 - k_{re}{}^2}{k_{im}{}^2 \cdot Q_P \cdot Q_S + k_{re}{}^2}\,. \tag{9}$$

B. Square and Octagonal Transformers

Two transformers were designed to evaluate the influence of the shape of the windings on the performance of the device. They present a stacked and non-flipped topology, with the primary and the secondary implemented on the two top thick metal layers. The windings of both transformers present a single turn with an average diameter of 50 µm and a conductor width of 8 µm.

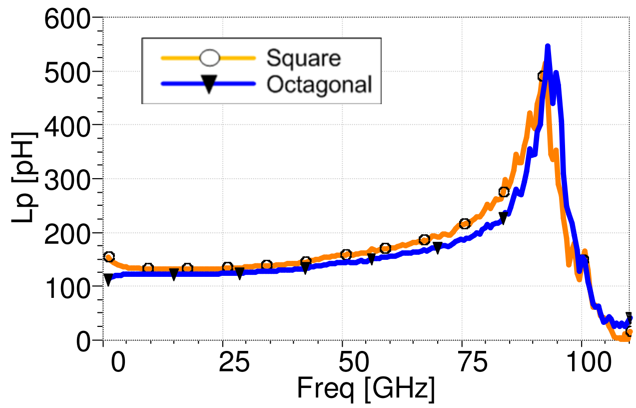

Fig. 3 Measured primary inductance of square and octagonal transformers.

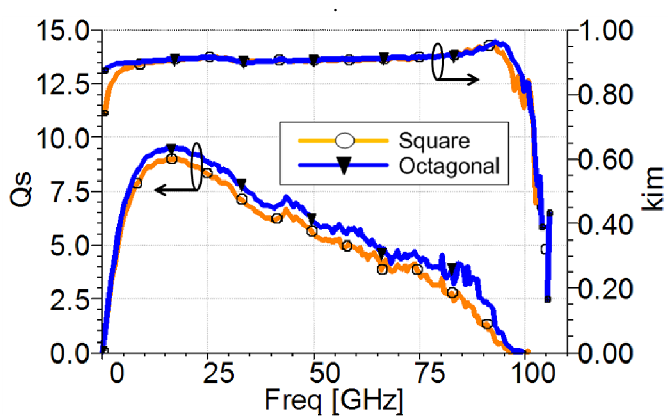

Fig. 4 Measured secondary quality-factor and coupling coefficient of square and octagonal transformers.

The measurement results for those two transformers are shown in Figs. 3 – 5 and summarized in Table I. We observe

that, for the same occupied surface, square coils present a higher inductance value. This difference is mostly due to the greater total length the square device presents. We can also note that octagonal transformers have better quality-factors, which means that the reduction this topology brings to the resistance of the windings is proportionally more substantial than the reduction on the inductance. As a result of this Q-factor improvement, octagonal transformers present a better minimum insertion loss, since the coupling coefficient is the same for both structures.

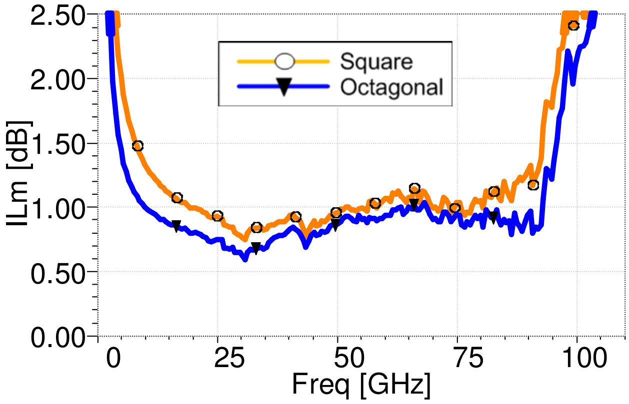

Fig. 5 Measured minimum insertion loss of square and octagonal transformers.

TABLE I
MEASUREMENT RESULTS FOR SQUARE AND OCTAGONAL TRANSFORMERS

		Square	Octagonal
L_P	@ 60 GHz	170 pH	155 pH
L_S	@ 60 GHz	167 pH	151 pH
Q_P	Max.	8.5 (30 GHz)	10.2 (17 GHz)
Q_P	@ 60 GHz	5.5	6.2
Q_S	Max.	9 (17 GHz)	9.5 (17 GHz)
Q_S	@ 60 GHz	4.8	5.6
k		0.91	0.91
k_{im}	@ 60 GHz	0.90	0.91
IL_m	Opt.	0.74 dB (31 GHz)	0.59 dB (31 GHz)
IL_m	@ 60 GHz	1.07 dB	0.94 dB

C. *Flipped and Non-Flipped Transformers*

The comparison between flipped and non-flipped topologies was performed using two other transformers. Primaries and secondaries are stacked and implemented on the two top metal layers. Each winding is constituted by a single octagonal turn, whose average diameter is 60 µm and trace width is 8 µm.

The measurement results are shown in Fig. 6 – 9 and Table II. These curves exhibit a significant reduction on the resonance frequency of the transformer when the flipped topology is adopted. Since low-frequency self-inductances remain unchanged and magnetic coupling is weakened, this reduction results mostly from the augmented oxide and substrate capacitance that this topology presents. It is also observed that the flipped transformer shows a lower minimum insertion loss for frequencies greater than 50 GHz, whereas the non-flipped transformer presents an acceptable performance for a wider band.

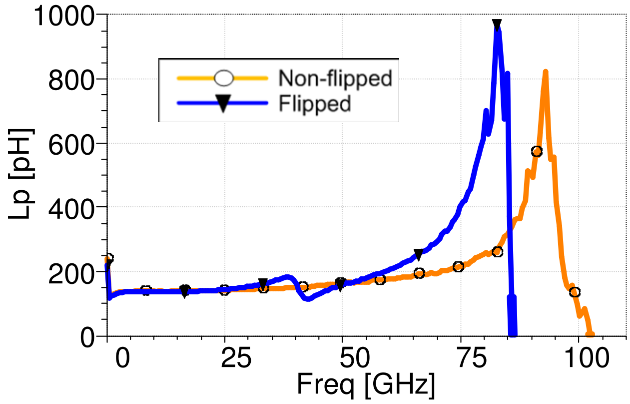

Fig. 6 Measured primary inductance of flipped and non-flipped transformers.

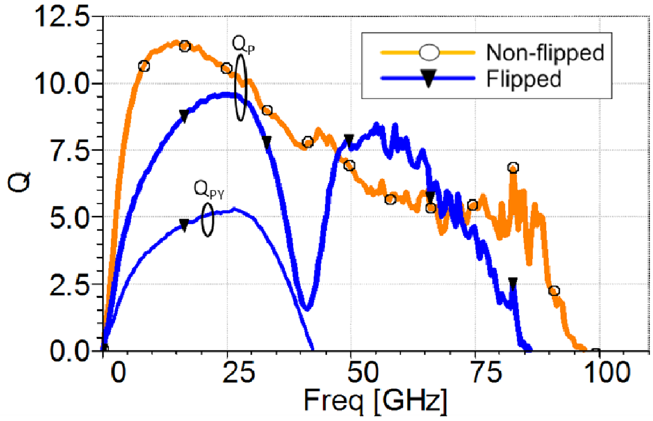

Fig. 7 Measured primary quality-factors of flipped and non-flipped transformers.

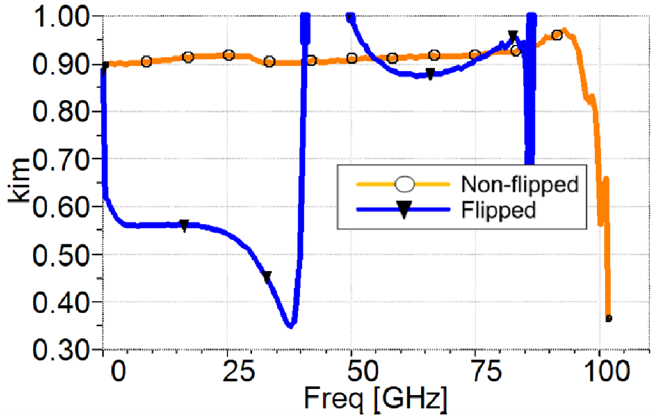

Fig. 8 Measured coupling coefficient of flipped and non-flipped transformers.

Nevertheless, the most notable phenomenon observed for the flipped transformer is its *partial resonance* around 40 GHz.

Even though a comprehensive explanation of such behavior has not yet been provided, it has already been reported in [10] and we have made some observations. We note that this frequency corresponds to the resonance frequency of the primary when the secondary is shorted, as Fig. 7 shows. Indeed, Q_{PY}, defined in (10) represents the quality-factor of the primary when the secondary is shorted. It is also noticed that this frequency is only inferior to the resonance frequency traditionally calculated from the impedance parameters in the case of single-turn flipped transformers.

$$Q_{PY} = \frac{\mathrm{Im}(Z_{11})}{\mathrm{Re}(Z_{11})} \tag{10}$$

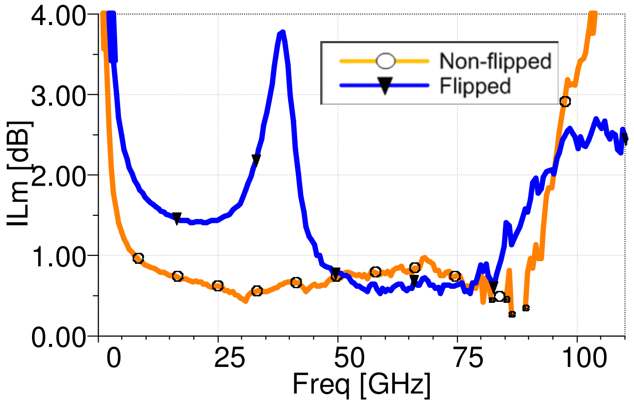

Fig. 9 Measured minimum insertion loss of flipped and non-flipped transformers.

TABLE II
MEASUREMENT RESULTS FOR FLIPPED AND NON-FLIPPED TRANSFORMERS

		Flipped	Non-Flipped
L_P	@ 60 GHz	206 pH	177 pH
L_S	@ 60 GHz	204 pH	182 pH
Q_P	Max.	9.6 (25 GHz)	11.5 (15 GHz)
Q_P	@ 60 GHz	7.8	5.7
Q_S	Max.	10.7 (15 GHz)	9.6 (15 GHz)
Q_S	@ 60 GHz	8.2	5.7
k		0.56	0.91
k_{im}	@ 60 GHz	0.88	0.91
IL_m	Opt.	0.52 dB (71 GHz)	0.43 dB (30 GHz)
IL_m	@ 60 GHz	0.55 dB	0.77 dB

IV. CONCLUSIONS

The use of transformers can be advantageous on the design of integrated circuits in the mmW frequency range. We presented some of the most important topologies adapted to operate at those frequencies. Transformers were fabricated in a 65 nm CMOS technology and measurements of their S-parameters were carried out in order to evaluate their performance. Octagonal transformers were shown to present better quality factors than those with a square format, and flipped transformers exhibited a *partial resonance*, which is not observed when a non-flipped topology is adopted. Further studies must be undertaken in order to explain the source of this resonance.

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