Millimeter-wave CMOS transformers for power amplifier impedance matching

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***Abstract*—The aim of this work is to characterize 3 different millimeter-wave 130 nm CMOS transformer topologies, designed for high-power applications, applied as variable inductances through switching structures, to be used in a power amplifier output matching circuit. The tested metrics were the different inductances and quality factors that each topology can achieve and the self-resonating frequency of each configuration of each transformer. The first transformer presents a minimum and maximum inductance at 26 GHz of 90.63 pH and 337.8 pH with a maximum quality factor of 14.6. The second transformer presents a minimum and maximum inductance at 26 GHz of 73.7 pH and 572.0 pH and a maximum quality factor 21.5. The third transformer presents a minimum and maximum inductance at 26 GHz of 38.5 pH and 340.3 pH a maximum quality factor of 14.7. All of the transformers occupy individually a chip area of 0.01 mm².**

***Index Terms*—Transformer, Radiofrequency, CMOS, power amplifier**

I. INTRODUCTION

Transformers are components used in all sorts of electrical engineering applications, from high voltage applications to radio frequency (RF) circuits. In RF applications, transformers have a wide range of different and very useful applications, such as power splitting and combining, baluns and impedance matching. Circuit design at high frequencies present several hurdles if compared to other transformer applications, since the parasitic components of the circuits create a significant difference in behavior. At millimeter-waves the application of lumped transformers in place of transmission lines can provide a significant area reduction. For example, a quarter-wave transformer in silicon dioxide at 60 GHz occupies approximately 630 μm [1]. Besides, with the evolution of CMOS technologies, it is simpler to create multilayered circuits that provide an area reduction, and transformers can greatly benefit from these types of technologies.

The power amplifier (PA) is one of the most important circuits used in front end RF communication devices. It is used in transmission circuits with the objective of adding power to a signal to be transmitted by the antenna, without adding excessive distortions to the signal. Besides the linearity, it is important that the PA has a high-power gain and high efficiency, since it's the circuit which draws the most direct current (DC) power in the transmitter front end. [2]

The advantage of utilizing structures similar to those described in [3] with transformers is to create several different values of inductance from a single transformer which occupies a small area within the circuit. This transformer will then serve as a variable inductance that can be used to create a variable output matching circuit (OMC). This advantage can be paired with circuits such as [4] - [6], which present multimode PAs with a single OMC, tuned to the highest power mode. To create a circuit that can match all the different modes from these PAs, and maintain PA efficiency, gain and linearity to a wider range of input power. Also, as seen in [7], it is possible to improve linearity metrics such as error vector magnitude and adjacent channel power ratio, which are regularly used in respect to IEEE and 3GPP standards.

This paper details the design and simulation of 3 different topologies of integrated transformers in a 130 nm CMOS technology for mm-wave applications. The transformers were designed considering they are intended to be used in output impedance matching circuits for PAs.

The objective of this paper was to determine, from S-parameter simulations, 4 inductances that can be obtained by each of the 3 transformer topologies designed, as well as the quality factor if each if the inductances. Also, the self-resonance frequency (SRF) of each of the configurations. The results were presented in graphs in function of the frequency of the input signals, from 1 GHz to 100 GHz, and some points of interest were highlighted.

II. VARIABLE INDUCTANCES

The solution to create variable inductances by occupying the smallest area possible proposed in [3] is to utilize a single transformer to create up to 8 different inductances controlled externally by 3 CMOS switches. It does so by connecting each of the windings in a different manner, and utilizing the mutual inductance between the coils to differentiate even more the inductances provided by each configuration. This paper has utilized 4 different connection structures, without the switches, to verify how these configurations behave in higher frequency regimes and with the transformer topologies designed.

Fig. 1 shows the 4 different configurations that were studied, NC, SC, Series and Parallel. The considerations on how to

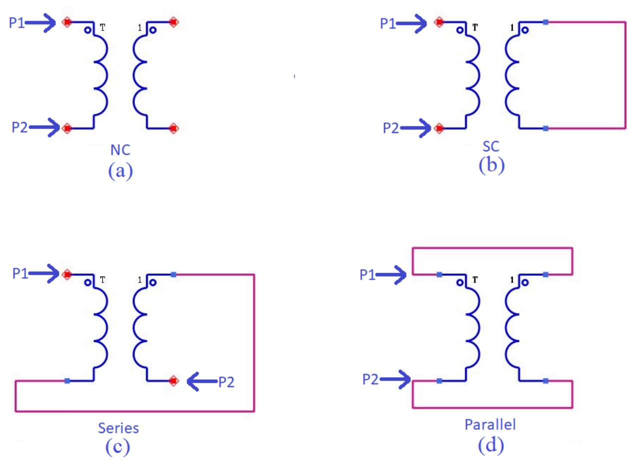

Fig. 1. Wiring topologies for different inductances: NC, (a) SC, (b) Series (c) and Parallel. (d)

calculate the metrics described from the S-parameter matrix of each topology is discussed further.

III. Transformers

A. Design considerations

For integrated transformers, the parasitic capacitance resulting from the electric field from the metal traces to the substrate causes it to self-resonate. To lower the capacitive effect, it is necessary to maintain the overall area of the transformer small. This includes lowering both the overall radius of the coils (d) as well as the width of the metal Traces (w). Even though normally in RF integrated circuits (RFIC) design, the width of the traces is usually high, to reduce the resistance, this approach increases capacitance to substrate as well. [1]

Lowering the width of the traces indefinitely is not possible, as there is a minimum width permitted by the technology in regards to the maximum alternating current (AC) and DC current that crosses the metal trace, due to reliability constraints imposed by the foundry. Also, lowering the overall area of the inductor in this case lowers the inductance of both the primary and secondary, and also the magnetic coupling of the transformer, as the length of the trails is much higher than their width.

Considering the current limitations set by the foundry for reliable operation of the uppermost metal levels, AM, LY and MQ, which were the metallization levels used when designing the transformers of this work, the minimum metal trace width was set as 10 μm.

As for the geometric characteristics of the transformers, the form of the coils chosen were octagonal for all topologies as they present a higher overall quality factor than square coils and almost the same coupling factor, resulting in fewer losses [8]. The coupling direction can be either planar, where both coils are at the same metallization level or stacked, where the coils are on different metallization levels. Stacked transformers present a higher magnetic coupling, as there is a higher area of contact between the coils, but also a lower SRF, as the capacitance between the metal levels is more prevalent

B. Simulation and metrics

To determine the metrics of the transformers, electromagnetic simulations were used to determine the S-parameter matrix of each transformer. The software used for the electromagnetic simulations was Pathwave ADS [9] with the finite elements method (FEM).

For a 2-port configuration, using the schematics from Fig. 1, the equivalent inductance is

$$L = \frac{Im(\frac{1}{Y_{11}})}{\omega}. \tag{1}$$

It is possible to calculate the primary and secondary coil inductances, as well as the mutual inductance between them by using a different port configuration from those seen in Fig. 1, by connecting a port in the primary winding and another at the secondary. The coupling factor is a metric to determine the strength of the magnetic coupling achieved by the transformer, it varies from 0 (no coupling) to 1 (perfect coupling), and is function of the 3 main inductances described above. Also, the SRF is determined as the frequency in which the net inductance of the circuit drops to zero.

To calculate the quality factor (Q) of the transformers, the formula:

$$Q = \frac{Im(\frac{1}{Y_{11}})}{Re(\frac{1}{Y_{11}})} \tag{2}$$

is used, where $Im(1/Y_{11})$ is associated to the net magnetic energy stored by the component and $Re(1/Y_{11})$ is associated with the dissipated power due to its resistance.

C. Transformer topologies

The first designed transformer was TP11. Its planar coupling direction is done by inserting one of the coils inside the other, in order to maintain the magnetic coupling higher. In this way, the transformer is not symmetric and its secondary coil will provide a lower inductance than the primary.

The second transformer designed was TS11. This transformer presents a relatively simple topology and is expected to provide a very high SRF, since both its primary and secondary have a single winding. However, since the area of contact between the windings is higher for this topology than TP11, the coupling factor should approximate the unit. This is important since the mutual inductance is supposed to compensate for the lower primary and secondary coils inductance, resulting from the low number of windings. Also, from all of the presented structures, it is the only symmetric transformer, and this is very important for some RF applications.

The third transformer, TS21, was designed to provide a higher transformation ratio by creating different inductances from the primary and the secondary. The coupling factor from this topology should be comparable to TS11. It is expected that the SRF from the primary be lower than that of the secondary, because of the capacitance between the windings.

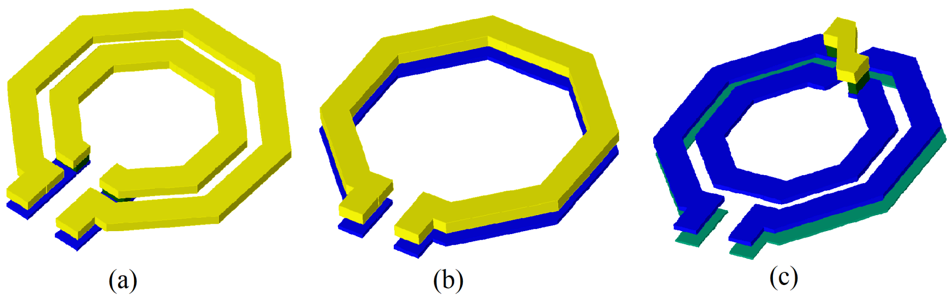

Fig. 2. Integrated transformer topologies designed: TP11, (a) TS11 (b) and TS21. (c)

All of the transformers have a d of 100 μm horizontally and vertically, these values were chosen in order best suit the circuits to the mm-wave regime. They also boast the minimum value of w of 10 μm, determined above for current requirements, for all the traces. And all of their 3D design models can be seen in Fig. 2.

IV. Results and Discussion

All of the results are shown as graphs of the metrics described above, in respect to the frequency, and some key points will be highlighted to compare all of the topologies. The metrics will be highlighted at 26 GHz, which is one of the key mm-wave frequencies for 5G, and the value of the SRF frequency for each inductance will be detailed as well.

Fig. 3 show the inductances and the quality factors of the configurations made with coils of TP11. From the graph it can be seen that this topology only self resonates in a frequency above of the 100 GHz range tested, except for the series configuration which resonates at 61.4 GHz. The inductances presented by these configurations are 113.4 pH, 90.63 pH, 337.8 pH and 70.0 pH, for NC, SC, Series and Parallel configurations at 26 GHz, respectively. This topology presents a relatively high quality factor for all configurations, with the highest one being the Parallel, which were 11.5, 9.7, 12.1 and 14.6 for NC, SC, Series and Parallel configurations, respectively. The inductances provided by this topology do not vary much, with 3 of the for 4 configurations providing inductances with only approximately 20 pH of difference. However, the series configuration provides an inductance 3 times as large as the NC one, with very little variation around the 26 GHz, and also provide a high SRF for this configuration. A slight improvement in the quality factor is verified with the parallel and series configuration at this frequency, in comparison to the NC configuration.

For the TS11 topology, Fig. 4 show the inductances and quality factors provided by this topology. From the curves it can be seen that this transformer also self-resonates in a frequency higher than the range tested, except for the series configuration which resonates at 51.8 GHz. This topology presents similar inductances as TP11, which are 129.3 pH, 73.7 pH, 572.0 pH and 110.3 pH for NC, SC, Series and Parallel configurations at 26 GHz, respectively.

The quality factor for each of these configurations are 17.5, 8.9, 15.9 and 21.5, respectively, at 26 GHz. This topology presents a wider range of different inductances if compared to TP11, but also with little difference in 3 configurations if compared to the Series one. The series configuration provides a very high inductance if compared to the rest. But it varies around 26 GHz more if compared to TP11, which can be detrimental to some applications. Also, at 26 GHz, the only

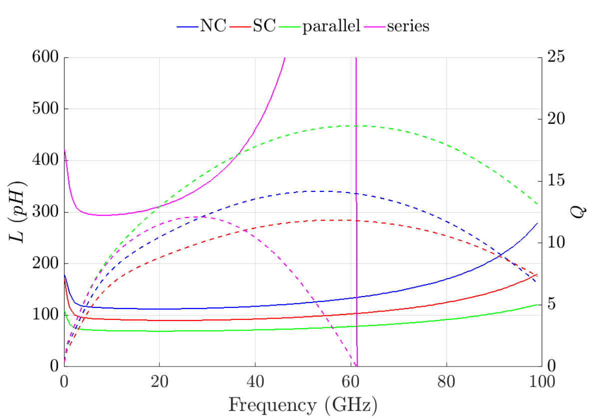

Fig. 3. Simulated equivalent inductance (solid lines) and quality factor (dashed lines) versus frequency for the transformer TP11.

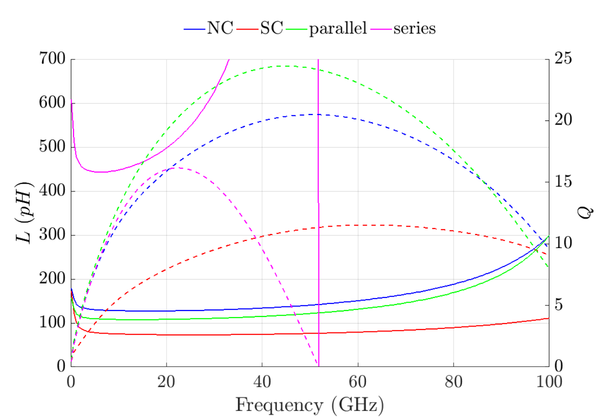

Fig. 4. Simulated equivalent inductance (solid lines) and quality factor (dashed lines) versus frequency for the transformer TS11.

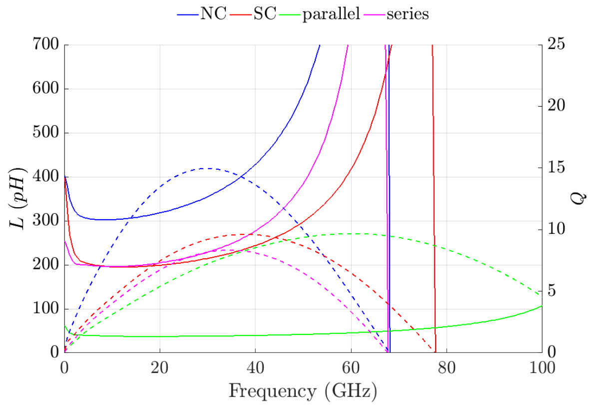

Fig. 5. Simulated equivalent inductance (solid lines) and quality factor (dashed lines) versus frequency for the transformer TS21.

configuration which provides an improvement in Q comparing to NC is the Parallel.

Lastly, for the topology TS21, the graphs can be seen in Fig. 5, showing the inductances of the configurations and the quality factors. Fig. 5 also shows that this configuration resonates for most of the different wiring topologies, but in different frequencies, these are 67.8 GHz, 67.8 GHz and 77.4 GHz for NC, SC and Series, respectively, the parallel configuration shows a resonance at a frequency higher than those tested. This effect is due to the SRF of the primary coil being already lower than the 100 GHz tested. The inductances achieved with this transformer at 26 GHz, were 340.4 pH, 209.0 pH, 219.3 pH and 38.5 pH for the configurations, NC, SC, Series and Parallel, respectively. The quality factors observed for each of these configurations at 26 GHz were 14.7, 8.6, 7.7 and 6.5. This topology presents the highest range of possible inductances presented, this is most likely because of the transformation ratio between the primary and the secondary being the highest, and from the equations show in [3], this makes a big difference. Also, this topology shows the lowest quality factor between all tested, this is because this topology has the highest capacitive parasitic between all tested, since the primary coil has 2 windings. All of the results discussed above, for 26 GHz, as well as the coupling factor of each transformer topology can be seen in Table I.

V. Conclusion

The main purpose of this work was to characterize mm-wave transformers used as variable inductances for high power applications, such as the output impedance matching of a power amplifier. The work presents 3 topologies of integrated transformers with 4 different wiring configurations to achieve several different values of inductances and quality factors, all of them occupying the same chip area.

The presented results show that it is possible to shift the resonance of a variable inductor by using a different wiring topology. This is important because this transformer can be used in a higher frequency than the SRF achieved by only

TABLE I
Summary of results at 26 GHz

Summary of results	Metrics			
Topology	**K**	**Configurations**	**L (pH)**	**Q**
TP11	0.44	NC	113	11,5
		SC	91	9.7
		Series	338	12.1
		Parallel	70	14.6
TS11	0.65	NC	129	17.5
		SC	74	8.9
		Series	572	15.9
		Parallel	110	21.5
TS21	0.69	NC	340	14.7
		SC	209	8.6
		Series	219	7.7
		Parallel	39	6.5

the primary or secondary windings, especially the parallel configuration, which is show to have a very high SRF by reducing the inductance measured at the first port. Also, the quality factor of the inductors can be made higher at a given frequency, this is observed in topologies such as TP11 and TS11, which do not have an inherently high primary winding inductance, and in those topologies the mutual inductance has a big part in making the inductance or the quality factor of the Series and Parallel configuration higher.

This work sets the basis to design a variable inductance based on the configurations discussed, that provides the values of inductance desired to create an optimal output matching circuit for a PA with various modes of operation. This can be achieved by designing the primary inductance, the transformation ratio and the coupling factor of the transformer.

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