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RF Spiral Planar Inductor Designs - Preliminary Results

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Abstract- The inductor is a basic component and very vital in designing radio frequency (RF) matching networks, load circuits of voltage controlled oscillators, filters, mixers and many other RF circuits. It is a fundamental device that can be found in almost any RF circuit. Inductors that can be integrated on a silicon chip have been reported in the literature. This has lead to the development of silicon RF integrated circuits (RFICs) where previously discrete component inductors had to be used. Now the size of circuits can be greatly reduced with the integration of RF circuits or even complete systems on a silicon chip. This has raised enormous interest in the study of the on-chip inductor. This paper presents a comparison of various inductor expressions available in the literature. Error trends are highlighted and discussed in the 1 to 10 nH inductance region. The focus of the design is the square spiral inductor. The details of the "new-physic" closed-form expression is found to be the most accurate expression and its implication to inductor synthesis is discussed.

1. Introduction

The demand of consumer products with wireless applications, such as the mobile phones, personal digital assistants (PDA) or mobile computers with built in wireless features have seen tremendous growth recently. This has caused a strong demand for low cost, low power consumption, high volume implementation of radio functions in the electronic components.

Most of the current radio frequency integrated circuits (RFIC's) are implemented in the mature GaAs technology. However, the complementary metal-oxide-silicon (CMOS) process is currently in high volume production for digital signal processors, and is also emerging as an option for RFICs [1]. The latest research and development in CMOS technology has seen an increasing effort to migrate the radio frequency applications onto the silicon process, mainly due to cost. Following this trend, higher integration of RF, analog and digital circuit using the conventional or innovative options in CMOS process is expected to happen in the near future [2].

2. Motivation

The inductors that can be realised on a silicon chip have been reported in the literature [3]. Figure 1 shows a 4.5 turns square spiral inductor.

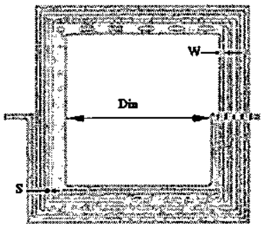

Figure 1: 4.5 turns square spiral inductor

Inductor models that are able to predict the behaviour of inductor over a broad range of frequencies are important for circuit simulation and layout optimisation [4-5]. However, It has always been very difficult to design accurately the low inductance inductor, especially for L less than 5nH. The simulations usually show quite large error percentage compared to the measured inductance. This has been explained in [3], probably due to parasitic inductance inherent in the measurement setup and possibility of inaccurate de-embedding. This work is an attempt to find the most accurate expression for the inductance in the 1 to 10 nH region. In section 3, a comparison of the different inductance expressions for square inductors in the range of 1 to 10 nH are discussed. The error trends are highlighted. In section 4, the influence of the inductance accuracy are addressed. Finally, conclusions and recommendations are given in section 5.

3. Comparison of Inductance Expressions

According to Ampere's Law, the current going through a conductor creates a magnetic field in the orthogonal direction to the electric field:

$$L = \frac{\Phi}{I} \tag{1}$$

where L, Φ, and I are the inductance in Henries (H), magnetic flux in Webers (Wb) and current in amperes

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(A), respectively. The ratio of the magnetic flux to current is defined as the inductance. The inductor stores energy from the applied voltage in magnetic form. When there are two or more loops of conductor carrying current, there will be a mutual inductance effect, either positive mutual or negative mutual. Total inductance is computed by combining these effects.

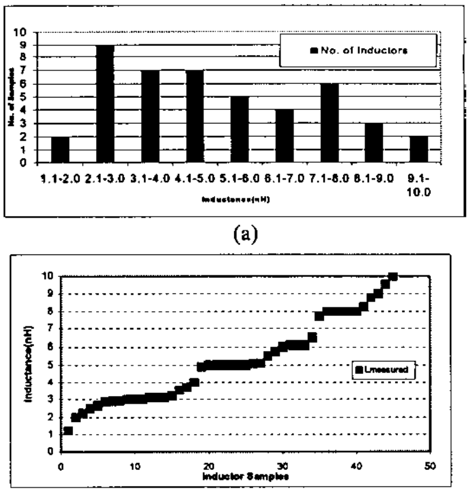
Grover [6] has summarised the formulas and tables for inductance calculation. Later, using the basic inductance computation from Grover, Greenhouse demonstrated spiral inductor inductance calculation in his work [7]. Then, C. P. Yue *et al.* [4] has applied it in the physical model to estimate the series inductance, LGMD2 in the physical model. Recently, several researchers have also published compact closed form equations to estimate the series inductance. For example, S.S. Mohan *et al.* [8] have published three simple expressions for the planar spiral inductor, namely the current sheet inductance approximation, Lgmd, the modified wheeler, Lmwhe and monomial data fit inductance expression, Lmon. S.Jenei *et al.*[9] have published the closed form inductance expression, Lphysics. Similar to S.Jenei *et al.*, S.Asgaran [10] has disclosed a new accurate physics based inductance expression, Lnewphysics. Table 1 summarised all the mentioned expressions.

Table 1: Summary of Various Expressions

Expressions	Equations	Equation
L_{GMD2} [17]	$L_{GMD2} = L_{self} + M^{+} - M^{-}$ $L_{self} = 0.002l[\ln(\frac{2l}{a+b}) + 0.50049 + \frac{a+b}{3l}]$; a,b are the rectangular dimensions, l is the inductor length. For both mutual inductances, M^{+},M^{-} is determined similarly using: $M = 2lQ$; where $Q = \ln[\frac{l}{GMD} + \sqrt{1 + (\frac{l}{GMD})^2}] - \sqrt{1 - (\frac{GMD}{l})^2} + \frac{GMD}{l}$ and GMD is approximated with $\ln GMD = \ln d - [\frac{1}{12(\frac{d}{w})^2} + \frac{1}{60(\frac{d}{w})^4} + \frac{1}{168(\frac{d}{w})^6} + \frac{1}{360(\frac{d}{w})^8} + \frac{1}{660(\frac{d}{w})^{10}} + \ldots]$ where d is the center to the center between separations of conductor, w is the width of the conductor. Note: This formulation is unable to calculate quarter turns (0.25/0.75), hence it is rounded to the nearest integer.	(2) (3) (4) (5)
L_{mwhe} [8]	$L_{mwhe} = K_1 \mu_0 \frac{n^2 d_{avg}}{1 + K_2 \rho}$; where K_1 and K_2 are the layout dependant coefficients. In a square inductor, K_1=2.34 ; K_2=2.75 where *n:number of turns;* average diameter, $d_{avg}=0.5(d_{in}+d_{out})$ and fill ratio, $\rho = (d_{out}-d_{in})/(d_{out}+d_{in})$	(6) (7) (8)
L_{gmd}[8]	$L_{gmd} = \frac{\mu n^2 d_{avg} C_1}{2}(\ln(\frac{C_2}{\rho}) + C_3\rho + C_4\rho^2)$; C_i is the layout independent coefficient. $C_1=1.27$;$C_2=2.07$;$C_3=0.18$;$C_4=0.14$	(9)
L_{mon} [8]	$L_{mon} = \beta d_{out}^{\alpha 1} w^{\alpha 2} d_{avg}^{\alpha 3} n^{\alpha 4} s^{\alpha 5}$; $\beta=1.62\text{x}10^{-3}$; $\alpha1=-1.21$; $\alpha2=-0.147$; $\alpha3=2.40$; $\alpha4=1.78$; $\alpha5=-0.030$.	(10)

$L_{physics}$[9]	The authors defined the length,l as: $l = (4n+1)d_{in} + (4N+1)N(w+s)$ $L_{physics} = Lself + M^{+} - M^{-}$ $L_{self} = \frac{\mu_0 l}{2\pi}\left(\ln\left(\frac{l}{n(w+s)}\right) - 0.2\right)$ $M^{-} = \frac{0.47 l \mu_0 n}{2\pi}$ $M^{+} = \frac{\mu_0}{2\pi} l(n-1)\left(\ln\left(\sqrt{1+\left(\frac{l}{4nd^{+}}\right)^2} + \frac{l}{4nd^{+}}\right) - \sqrt{1+\left(\frac{4nd^{+}}{l}\right)^2} + \frac{4nd^{+}}{l}\right)$ $d^{+} = (w+s)\frac{(3n-2N-1)(N+1)}{3(2n-N-1)}$; N is the integer part of n	(11) (12) (13) (14) (15) (16)
$L_{newphysics}$[10]	$L_{newphysics} = Lstot + M_{tot}^{+} - M_{tot}^{-}$ $L_{stot} = \frac{2\mu_0 n}{\pi}\left(d_{avg}\left(0.5 + \ln\left(\frac{2d_{avg}}{w}\right)\right) + 0.178w\right)$ $M_{tot}^{-} = \frac{2\mu_0 0.47 n^2 d_{avg}}{\pi}$ $M_{tot}^{+} = \frac{2\mu_0}{\pi}\left\{N(2n-N-1)d_s\left(\ln\left(\frac{2d_s}{w+s}\right) - 1\right) - 2d_s\left(\ln(P) + (n-N)\ln(N!)\right) + \right.$ $\left.\left(\frac{\sqrt{2} - \ln\left(1+\sqrt{2}\right)}{3}\right)N(N+1)(3n-2N-1)(w+s)\right\}$ $P = 1!2!\ldots(N-1)!$ $d_s = d_{avg} + \frac{w}{2}$	(17) (18) (19) (20) (21) (22) (23)

Figure 2 shows the distribution of the inductance 1 to 10nH for 45 samples collected from various sources [4-5,8,11-19]. It is interesting to see that Mohan's expressions are very similar in the trend of errors as illustrated in Figure 3. Therefore, taking one of them can represent the other two. In our work, the best from Mohan *et al*'s work, Monomial data fit (Lmon) is used to compare with the other expressions. This best trend is repeatedly compared with the other expressions. For example, a similar error trend is observed for most of the data points comparing Lmon and Lnewphysics as depicted in Figure 4. The same is seen for samples number 1 to 10 and 35 to 45 comparing Lnewphysics and LGMD2 (Figure 5). All these comparisons have shown that the new physic closed form by Saman, Lnewphysics is the most accurate expression for square inductors in the 1 to 10 nH inductance range. It has the smallest overall discrepancy (7.9% absolute error) compared to the others (9-13%) as shown in Table 2.



(a)

(b)

Figure 2: (a) Bar Chart of 45 Inductors
(b) Distribution of 45 inductors ranged 1 to 10 nH

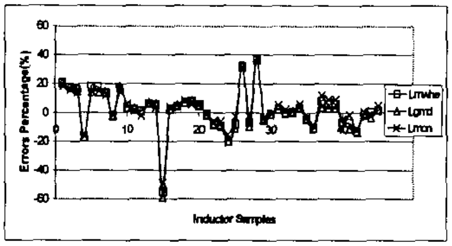


Figure 3: Mohan's expressions error trends

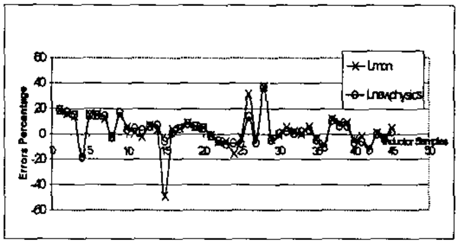


Figure 4: Error trends between Lmon and Lnewphysics

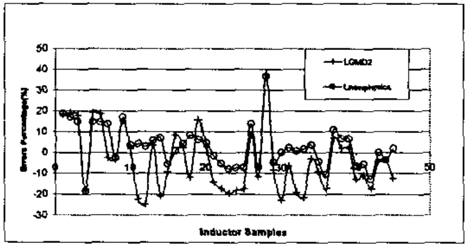


Figure 5: Error trends between the LGMD2 and Lnewphysics

Table 2: Errors comparison of various expressions

Expressions	Average Errors	Average Absolute Errors
L_{GMD2}	-4.0	12.9
L_{mwhe}	1.8	9.8
L_{gmd}	1.5	9.9
L_{mon}	2.9	9.0
L_{physic}	-3.6	9.9
$L_{newphysics}$	3.0	7.9

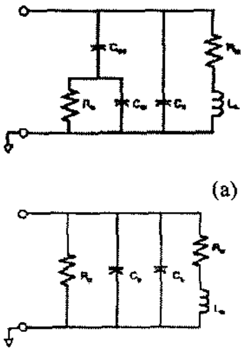
4. Inductance Expression in Inductor Synthesis

For the inductor synthesis, the substrate branch of the model can be simplified to a resistor in parallel to a capacitor as shown in Figure 6. Then, the *L* curve can be plotted using the formulation

$$L=\frac{\mathrm{Im}(Z_{in})}{\omega}=\frac{\mathrm{Im}(\frac{1}{Y_{11}})}{2\pi f} \qquad (24)$$

where

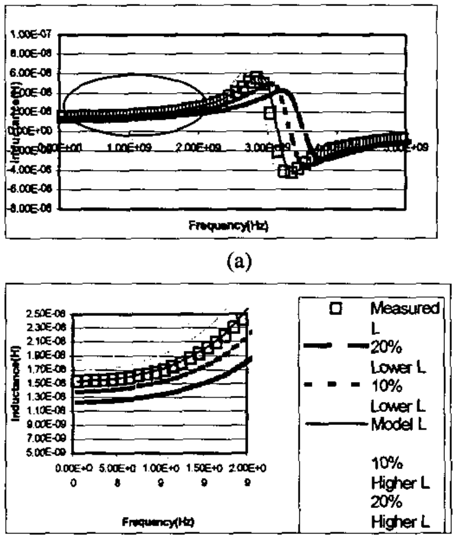
$$Y_{11}=Y_{22}=\frac{1}{Z_s}+\frac{1}{Z_p}=\frac{1}{Rs+j\omega C_s}+j\omega C_s+\frac{1}{R_p}+j\omega C_p \qquad (25)$$



(b)

Figure 6: (a) Single ended Inductor Model, (b) Simplified Single Ended Inductor Model [4]

Using the measured inductance at lowest frequency as the reference, a few different accuracy curves are computed. In Figure 7 we plot the measured L; 20% and 10% lower L; model L; 10% and 20% higher L; respectively. Figure 7(b) shows a zoom-in view of Figure 7(a) at the 0.5 to 2 GHz region. From these graphs, it can be seen that errors in the inductance calculation influence both the horizontal level of the L curves (as in Figure 7(b)), as well as the location of the self-resonant frequency (SRF) as seen in Figure 7a. (The SRF is the frequency where the L curve crosses from positive to negative).



(b)

Figure 7: (a) The influence of Inductance at different error percentage. (b) Zoom in plot of Figure 7(a)

The accuracy of the inductance expression is very important for RF circuit design. For example, in impedance matching, maximum power transfer cannot be achieved if the inductor in the matching network is not designed correctly. For other applications such as the load circuit in voltage controlled oscillator, the accuracy in designing the SRF is vital to ensure the circuit operates in the desired frequency range.

5. Conclusion and Future Work

The most accurate inductance expression is required for the inductor design and layout optimisation. Using the physical model for inductor synthesis is faster, cheaper and easier compared to 3-D electromagnetic simulation. It can be integrated into the design flow of RFIC design to improve time-to-market. This work has found that for inductors in the 1 to 10nH range, the most accurate expression for a square spiral inductor is Saman's new-physic closed-form expression [20]. More accurate prediction of the inductance especially in the lower range, L < 5nH, is to be developed.

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