USING EM PLANAR SIMULATORS FOR ESTIMATING THE Q OF SPIRAL INDUCTORS

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Abstract

Electromagnetic (EM) simulators have been widely used to model spiral inductors in silicon and gallium arsenide chips. The quality factor, commonly referred as Q is the most important figure of merit for such a device. However, estimating the Q can be quite a challenging task for an EM simulator since the calculation of resistive losses in the conductor is required. Planar EM simulators rely on impedance boundary condition (IBC), which suffers from inaccuracy at edges and corners of the conductors. Besides, for an accurate estimation, the mesh on the conductors must be very fine thus leading to a large computational problem. Three dimensional EM simulators suffer from similar problems since the interior part of the metal must be meshed very finely for an accurate calculation of the resistive losses.

In this paper we present an innovative and fast method for an accurate Q calculation. First a planar EM simulator with normal mesh size is used; then a cross sectional solver (available at low cost) is used to estimate the losses in coupled transmission lines. The result of the second simulation is used to correct the estimation of the planar simulator. Comparisons with measurements have proven the accuracy of the proposed technique.

Introduction

Spiral inductors can be found in every manufacturing technology used today: integrated circuits in silicon, RF and microwave integrated circuit (MMIC) technologies of various kinds, multilayer modules in ceramic, and, of course, printed circuit boards. They are used for a variety of applications, such as filtering, biasing, and signal shaping purposes. The designer would like to use the best possible inductor, and the Q factor is commonly used as a quick indicator on how well the inductor will perform at the frequencies of interest. The higher the Q, the better is the inductor's performance. Q is defined in a variety of ways, all of which are consistent with each other. The most fundamental physical definition of Q for a time harmonically varying system is [1]:

$$Q = \omega \, \frac{average\ energy\ stored}{average\ power\ dissipated}$$

where ω is the angular frequency. Note that Q is dimensionless, and it is the ratio between energy stored and dissipated power multiplied for the angular frequency. For an inductor we can say that Q is the ratio between the inductance and the resistance (mainly due to resistive losses in the conductors) of the device, and therefore is desirable to have a Q as high as possible.

In some other cases, Q is calculated as the ratio between bandwidth of the device and central frequency, or in some other cases is defined based on network theory. For example, for a one port device (port two is shorted):

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

Naively, one would think that calculating the Q of a spiral inductor with an EM simulator is a straightforward process. Having simulated the structure and extracted the S-parameters, they can be converted into admittance and the Q can be easily calculated. However, Q is a very sensitive measurement and we will show that a relatively large error is introduced by adopting the described method.

There are three causes of inaccuracy; calculating the conductors' resistances; understanding the ground return issues; and making sure the ports used are properly calibrated (the latter two are beyond the scope of this paper). Some other, technology dependant issues can arise, e.g. in the case of spiral inductors in silicon, the losses in the substrate must also be accounted for.

In principle, 3D EM simulators could predict the losses in the conductors accurately. However, by default they usually do not mesh the conductors internally, and they predict losses using the IBC approach as with planar simulators. For an accurate Q calculation however, the internal part of the conductors should be meshed finely enough to capture the exponential decay of the current inside the conductors, thus increasing the number of mesh cells. In addition to that, even higher accuracy is required to cope with corners and edges, and the problem becomes too large.

Planar simulators do not require the entire space to be meshed, but only the surface of conductors. They solve the current on the surface of metals and do not need to mesh the dielectric region, and for this reason they can cope with much larger structures than 3D simulators. The drawback is that, for calculating losses in metals, they rely on Impedance boundary conditions and hence they are not suitable for calculating the Q of a spiral inductor.

The technique proposed in this paper provides a fast and accurate Q calculation without the need of meshing the internal part of the conductors. The Q of the spiral is first calculated with a planar EM solver using IBC (there is no need for a very fine mesh). As explained before, such estimation is not accurate and must be corrected. To do that, initially a canonical problem is studied, namely five straight coupled transmission lines (sharing the same cross section as the lines of the spiral). The losses in the canonical problem are then calculated with a planar EM solver, and more accurately with a cross sectional EM solver [2] able to account for the distribution of the currents inside the metal. The ratio between the two values accounts for the inaccuracy of the planar EM simulator, and it is used to correct the Q of the spiral inductor.

Sensitivity of Q

To illustrate the problem, a spiral inductor in a microwave integrated circuit (MMIC) process is simulated with AXIEM™. **Error! Reference source not found.** shows a MMIC spiral on gallium arsenide (GaAs). The spiral is typical of MMIC technology. It is placed on top of the GaAs substrate, which is 100 um thick. Gold lines are used. The total thickness of the line is approximately 3 um. The lines are 10 um wide with 6 um gaps. The right side of the figure shows the details of the mesh used by the planar simulator. The size of the mesh is approximately 9500 unknowns. Note that the finite thickness is modelled, and also the sides of the conductors are meshed. The thickness of the conductors must be considered since it is in the same order of the line spacing. Note that there a few mesh cells both across the width of the line, and along the height of conductors.

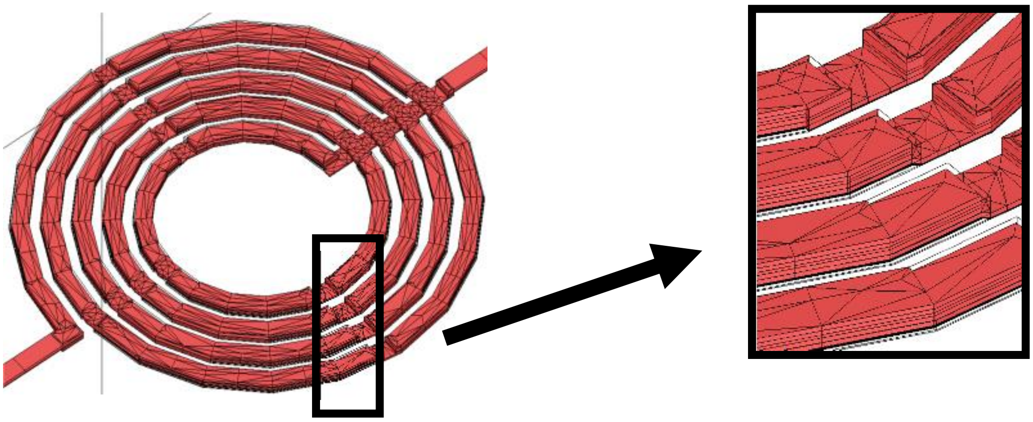

Figure 1 Figure 1 MMIC spiral inductor simulated with a planar EM solver.

Error! Reference source not found. compares S-parameters and Q factor between measurements and simulated data in the frequency range 0.1-10 GHz. At a glance, the S-parameters agree very well, however the derived Q values are not close. In particular, at the centre frequency of 5 GHz the simulated Q is 27% overestimated.

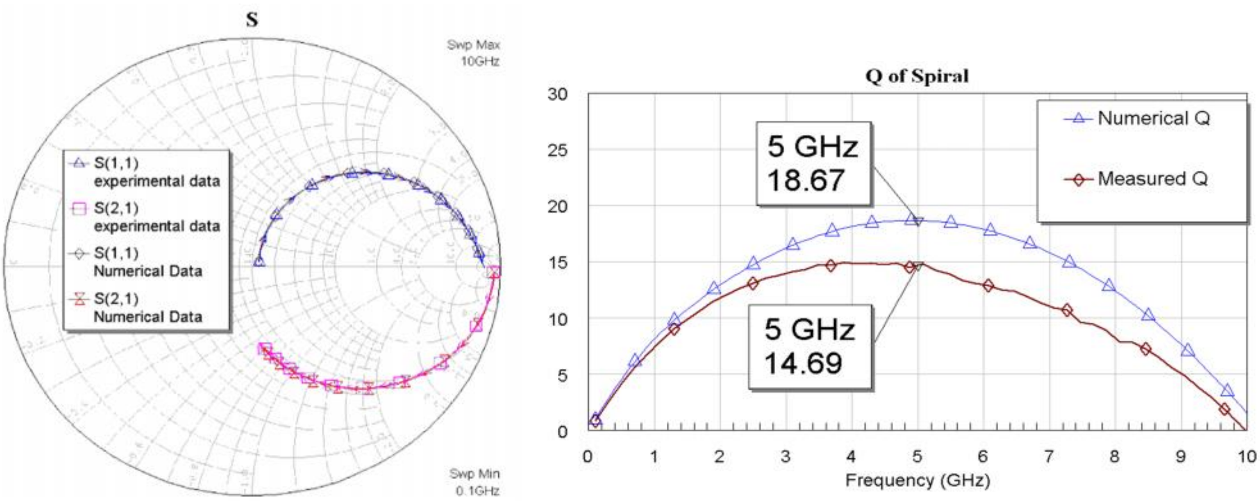

Figure 2 Return loss and Q-factor of the MMIC spiral inductor

At lower frequencies the two values agree quite well, and to understand this we must spend a few words discussing the theory of IBC. This theory is used to simplify the EM simulation; Instead, of meshing inside the conductors, the metal surfaces are replaced by the impedance boundary condition. Maxwell's equations must then be solved in the exterior regions and satisfy the IBC on the conductors. The method is valid if some conditions are met, namely the metal is a good conductor, it is locally flat, and the conductor thickness is at least two or three times the skin depth (δ), which is defined as follows

$$\delta = \frac{2}{\omega\mu\sigma}$$

Where μ is the permeability and σ the metal conductivity. Also, for the conditions to be valid, the metallic surface must be several δ long and wide, and must not possess sharp edges. In simple words, it is valid if the conductor is thick enough and the surface is large and flat. If the conditions are met, the Maxwell's equations at the metal interface must satisfy

$$\boldsymbol{E}_{tan} \approx Z_s \hat{n} \times \boldsymbol{H}_{tan}$$

Where Zs is the surface impedance, defined as $Z_s = (1 + j)/\delta\sigma$. The skin depth of gold is 2.5 um at 1 GHz and 0.79 at 10 GHz, and therefore is in the same order of the line thickness and width. Moreover, the losses at the corners are neglected thus leading to a large error, especially at high frequencies.

Correcting the Q

In the proposed technique, transmission line models that correctly estimate the loss of coupled transmission lines are used to correct the Q-factor. These models can be simulated quickly, are very accurate and are available in commercial simulation packages (such as Microwave Office™). The current distribution in the conductors mainly depends on the cross sectional geometry of the conductor itself, and therefore coupled lines represent a good first order approximation of the problem.

The proposed technique works as follows:

1. The spiral is simulated using the planar EM simulator with normal meshing and surface impedance boundary conditions.
2. A coupled line model (with same cross sectional geometry) is used to approximate the spiral. The overall length of the coupled lines is found by tuning the length until the low frequency resistance matches well at the lowest frequencies of interest (see Figure 3).
3. The planar EM simulator is used to calculate the Q of the coupled line model described above. The mesh settings should be the same as used in the original spiral simulation.
4. The conductor loss is now compared for the coupled line model and the EM simulation of that model. Typically, the simulator will give a lower value of loss. The ratio of the two predictions is used to correct the Q of the spiral simulated with the planar EM simulator.

The coupled lines have been modelled using the GFMCLIN model of Microwave Office 2010. The model consists of five identical coupled lines with same cross-sectional geometry as the spiral (width of 10 microns, gap of 6 microns). The total length of the coupled lines is 800 microns, and it is found by tuning to match the low frequency resistance of the EM spiral simulation (see the right side of Figure 3)

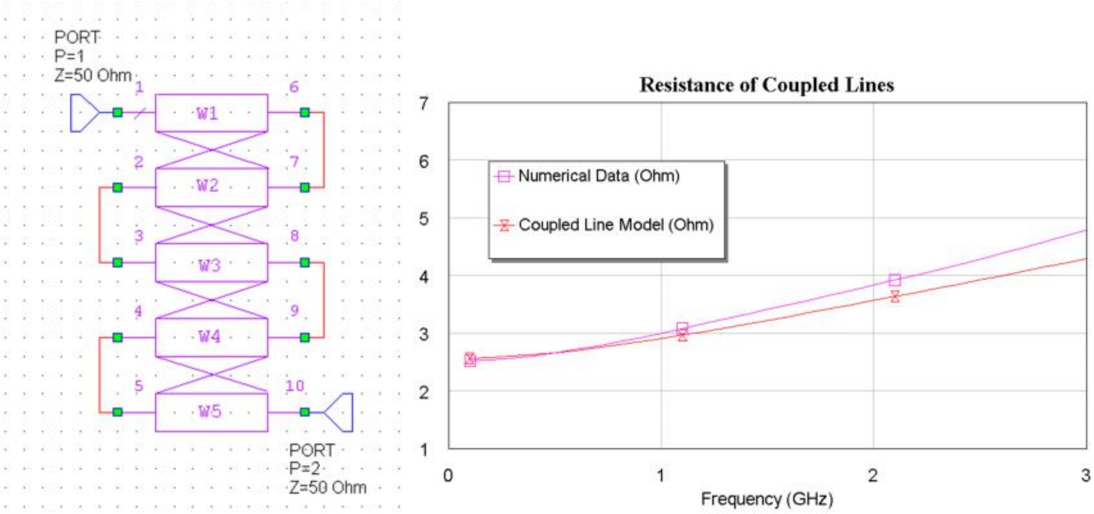

Figure 3 GFMCLIN model in Microwave Office 2010 (left); resistance of the coupled line model compared with the planar EM simulation of the spiral (right). The length of the coupled line model has been tuned to match the resistance value at low frequency.

At this stage, the five straight coupled lines are simulated with the planar EM simulator, and the resistance value is compared with the one obtained with the cross-sectional solver. As expected, the two values are similar at low frequency but they differ at high frequencies.

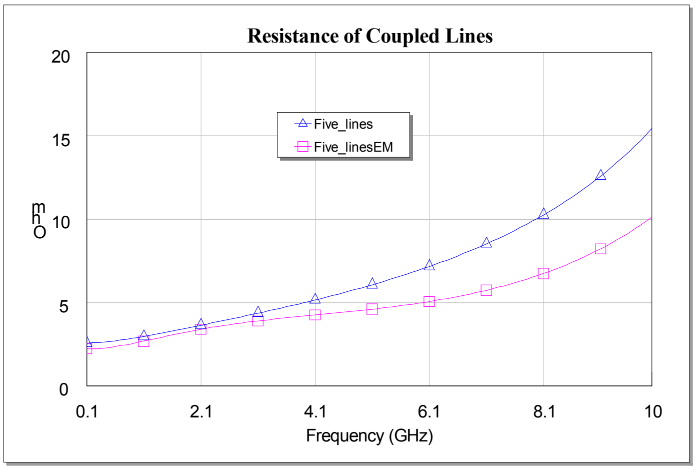

Figure 4 Resistance value of the five coupled lines calculated with the EM solver and the cross-sectional model.

Now it is possible to correct the Q as follows

$$Q_{corrected} = Q\,\frac{Real\ (1/Y_{11\_Lines\_EM})}{Real\ (1/Y_{11\_Lines\_Model})}$$

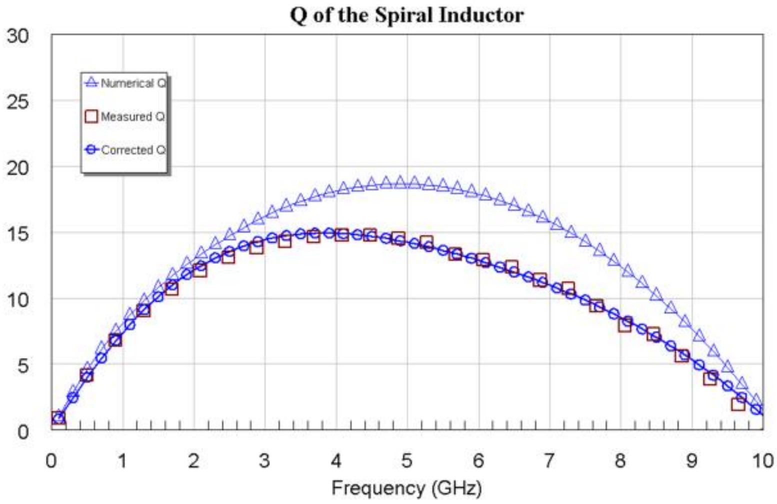

Figure 5 Corrected Q value, the value agrees with the measured one.

As shown in Figure 5, the corrected Q-factor agrees with the measured one.

Conclusions

This paper shows a technique for correcting the inaccuracy of EM simulators in calculating the Q of spiral inductors. The impedance boundary condition, commonly used by EM solvers for conductor loss calculation suffers from inaccuracy at edges and corners. Besides, for an accurate calculation, a very fine mesh should be adopted thus leading to a large problem. In the technique proposed, in addition to the EM simulation of the spiral with normal mesh, a canonical structure is studied. The losses of five straight coupled lines (with the same cross-sectional geometry as the spiral) are calculated with a cross-sectional solver and with the planar EM simulator. The ratio between the two values obtained is used to correct the Q of the spiral calculated with the EM solver. The technique is very fast, and comparison with measurements has proven its accuracy.

References

1. Lee, T. H. (2004). The Design of CMOS Radio-Frequency Integrated Circuits, Second Edition. Cambridge University press.

2. GFMCLIN model in Microwave Office, version 2010, AWR Inc.