Application of the Genetic Algorithm in Modeling RF On-Chip Inductors

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***Abstract*—The genetic algorithm (GA) with parameter confinement has been introduced into the extraction of model parameters for RF on-chip inductors. The details of applying the GA in extracting the model's parameters are discussed. For a set of inductors, the meaningfulness of extracted parameters is considered in the procedure of extraction. The S-parameter, inductance, and Q value can be set as the fitting targets simultaneously in this study. The values of model parameters are extracted by a fully automatic programmed GA procedure, which show excellent goodness of fit when compared with the measured data.**

***Index Terms*—Genetic algorithms (GAs), modeling, parameter extraction, RF inductors.**

I. Introduction

As THE exponential growth in wireless communication continues, more and more accurate device models are demanded in RF integrated circuit (IC) on-chip design; not only models of active devices, but also that of passive components, e.g., inductors. It is well known that part of setting up a model is developing a fitting procedure of extracting values of lumped elements in an equivalent circuit, which can be used to express the electric function of the modeled device.

To automatically extract the model's parameters, some algorithms for modeling have been introduced, e.g., to name just a few, gradient optimization, exponential gradient updating algorithm, or the Levenberg–Marquardt (LM) algorithm [3], [5], [9]–[12]. Conventional algorithms contribute to the modeling of inductors to some extent in a computer-aided automatic solution, e.g., GEMCAP, APLAC, Sonnet, EESof's Libra [3], [5], [9]–[12], or IC-CAP; especially IC-CAP, which is widely used in inductor modeling. Conventional algorithms, however, have some shortcomings that need to be overcome, which are as follows.

1) An initial guess is normally required, followed by an iterative method to approach an extremum. It is difficult to find a quick path approaching the global extremum without confusion by local extrema [3], especially when the process should be suitable for general needs, independent from any individual case.
2) Conventional algorithms, in addition to always requiring an initial guess [3], [5], are useful over a relatively narrow value probability range.
3) Due to 2), researchers must frequently have some initial estimate, in advance, which is to say, empirical input is also required.

For example, when IC-CAP is applied, it is not so effective at obtaining a sufficient goodness of fit (GOF) in a wide frequency range, thus, some designers use IC-CAP to do modeling within a narrow frequency band to meet certain design requirements in order to increase the fitting accuracy. However, the fitting in a wide frequency band must be conducted when second- or third-order harmonics are considered in design. Of course, an initial guess is required, which means the accuracy depends on the operator's experience rather than on a fully automatic extraction procedure. Another problem shown in previous modeling is that S-parameters and Q values of an inductor cannot be fitted well simultaneously. Based on our experience, below a certain error criterion, the better the S-parameters' fitting is, the worse the Q values' fitting is. In that case, the problem becomes a multicriterion optimization with conflicting objectives.

The genetic algorithm (GA) has become a powerful tool in solving various optimization problems since Koza introduced his "genetic programming" in 1992. The GA was firstly applied in device modeling by Werner *et al.* in 1998 [6]. They utilized the S-parameters generated from electromagnetic (EM) simulation by software, i.e., Ensemble and EESOF, instead of using real measured ones. The GA was then used to extract the component parameters of the equivalent circuit by fitting the S-parameters both from EM simulation and equivalent-circuit simulation. Their results proved that the GA could be used and was fast convergent for tracking back circuit components calculated by computer-aided programming. In 1999, Yun and Mary compared the data extracted from the GA and HSPICE optimizer [3], which was based on the LM algorithm, and found that the data extracted from the LM algorithm was strongly affected by the initial inputs and might be trapped by local extrema. However, the authors did not discuss the data meaningfulness, even though the discrepancy between those from the GA and the LM algorithm had been found.

To our knowledge, there have been only few papers published to date on GA extraction for IC devices or elements. In our initial study of trying to apply the GA to extract model parameters for RF inductors, it was found that the GA works efficiently and could be a robust tool for fully automatic extraction. However, like other conventional algorithms, the results given by the GA also face the problem of meaningfulness or, in other words, physical meaning.

In this paper, the GA with parameter confinement has been proposed to overcome the shortcomings mentioned above, the details are discussed, and a reasonable and fast fully automatic extraction for RF inductor models is provided.

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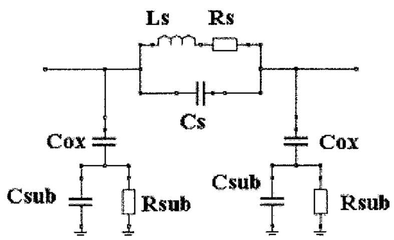

Fig. 1. Schematic equivalent-circuit model for an on-chip inductor.

II. Parameter Confinement

A simple Π-model, as shown in Fig. 1, is the most popular model that has been widely used in RF IC design. In this model, L_s, R_s, and C_s are series inductance, resistance, and capacitance, respectively. $C_{\rm ox}$ can be treated as effective capacitance between the spiral and substrate. $C_{\rm sub}$ and $R_{\rm sub}$ represent substrate parasitic capacitance and resistance, respectively. The fitting procedure is to fit the S-parameters and deduced inductance and Q values obtained from RF measurement with those obtained from the equivalent-circuit calculation. However, the extracted parameters of lumped elements in Fig. 1 may yield unreasonable values. Sometimes, unreasonable final values may appear at some parameters, which are insensitive to the target function, such as $R_{\rm sub}$, $C_{\rm sub}$, and $C_{\rm ox}$. For example, $R_{\rm sub}$ in Fig. 1 will not always descend consistently when spiral turns of inductors increase because this is physically improbable, although mathematically optimum.

To make the extracted results meaningful, the extracting procedure should be reasonably "guided" in a certain direction.

In applications, a set of inductors is normally designed in such a way that only the number of spiral turns, i.e., N, varies and other parameters, i.e., strip width and space and the size of the central hole, remain the same. Therefore, we may suppose the parameters of the lumped elements in Fig. 1 are each a function of one variable $f(N)$ for a set of inductors with a constant strip width, space, and central hole. The inductance for a spiral inductor can be commonly expressed as a second-order polynomial. Hence, the inductance L_s in Fig. 1 can be expressed as

$$L'_s = a_1 + b_1 \times N + c_1 \times N^2. \tag{1}$$

For other parameters, R'_s, C'_s, $C'_{\rm ox}$, $C'_{\rm sub}$ and $R'_{\rm sub}$, a monomial function can be used to express them [7], [8] as follows:

$$R'_s = a_2 + b_2 \times (N+\delta)^{C_2} \tag{2}$$

$$C'_s = a_3 + b_3 \times (N+\delta)^{C_3} \tag{3}$$

$$C'_{\rm ox} = a_4 + b_4 \times (N+\delta)^{C_4} \tag{4}$$

$$C'_{\rm sub} = a_5 + b_5 \times (N+\delta)^{C_5} \tag{5}$$

$$R'_{\rm sub} = a_6 + b_6 \times (N+\delta)^{C_6} \tag{6}$$

where a_i, b_i, c_i ($i = 1, 2, \ldots, 6$), δ are constant coefficients that will be determined in the modeling procedure, in which a_i ($i = 1, 2, \ldots, 6$), δ can be treated as adjustment coefficients to make up for the error between the monomial and real situation. Formulas (1)–(6) set up "guidelines" for the parameters' extraction, which means that the final values of extracted optimal parameters will not deviate far from the traces determined by the formulas.

The procedure of the extraction will have the following two phases.

- To determine the coefficients in (1)–(6) by fitting S-parameters and $L_{\rm eff}$ and Q between the results from the measurement and from calculation of Fig. 1 for a set of inductors, e.g., turns from 2 to 8. The fitting is conducted with GA programming;
- To extract accurate final parameters for an inductor by fitting S-parameters and $L_{\rm eff}$ and Q once again using another GA programming. In the procedure of the GA, the value possible range of the parameters is decided by the values from (1)–(6).

It should be noted that the fitting in phase 1 is for the whole set of inductors, while the fitting in phase 2 is for an individual inductor with a certain number of turns. The final parameters extracted from phase 2 may be different from those obtained in phase 1, but we can expect only a slight deviation.

III. GA Extraction

The basic principles of the GA can be found in [1] and [2]. Here, some of the fundamental GA elements are highlighted in coordination with this research.

Population is a group of randomly initialized individuals (represented by chromosomes). Each individual consists of the genes. In this study, the genes are a_i, b_i, c_i ($i = 1, 2, \ldots, 6$), δ in the phase 1 GA procedure, and L_s, R_s, $C_{\rm ox}$, $C_{\rm sub} R_{\rm sub}$ in the phase 2 GA procedure, as mentioned in Section II. Population size is very sensitive to the speed of approaching the global extremum, which, in our study, is 60 in phase 1 and 20 in phase 2.

Evaluation function evaluates an individual's GOF. In curve fitting, the evaluation functions are always directly related to the error functions. Relative mean error of S-parameters is typically used as the error function. In this study, S-parameter, $L_{\rm eff}$, and Q values are considered as the fitting targets. $L_{\rm eff}$ and Q can be expressed by $Z_{\rm eff}$ as follows:

$$L_{\rm eff} = \frac{{\rm image}(Z_{\rm eff})}{\omega} \tag{7}$$

$$Q = \frac{{\rm real}(Z_{\rm eff})}{{\rm image}(Z_{\rm eff})}. \tag{8}$$

$Z_{\rm eff}$ equals the inverse of Y_{11}, $1/Y_{11}$, which can be deduced from the S-parameters.

The error function of S-parameters is

$$E^S_{ij} = (1/n) \sum_1^n \left| (S_{ij,\,{\rm sim}} - S_{ij,\,{\rm mea}})/S_{ij,\,{\rm mea}} \right| \tag{9}$$

$$E^S = (1/4) \sum_{i,\,j=1}^{2} E^S_{ij}. \tag{10}$$

The error function of $Z_{\rm eff}$ is

$$E^Z = (1/n) \sum_1^n \left| (Z_{\rm eff,\,sim} - Z_{\rm eff,\,mea})/Z_{\rm eff,\,mea} \right|. \tag{11}$$

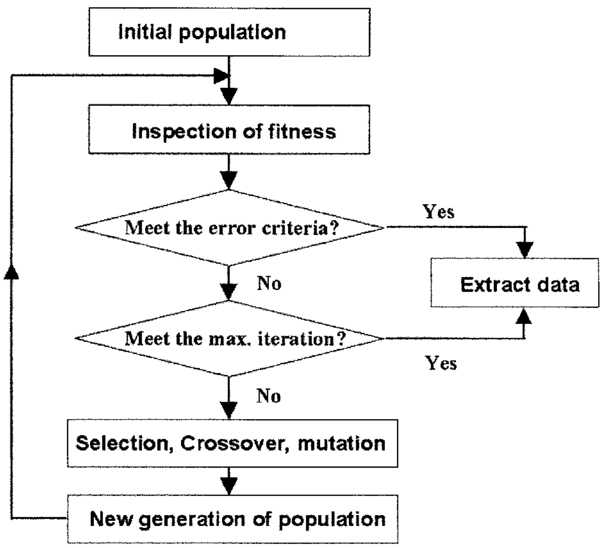

Fig. 2. Schematic flowchart of the GA.

In (9)–(11), n is the number of frequency points measured. $S_{ij,\,\mathrm{sim}}$ are the simulated S-parameters, while $S_{ij,\,\mathrm{mea}}$ are the measured ones.

The evaluating function E can be written as

$$E = m \times E^S + (1-m) \times E^Z \tag{12}$$

where m is the weight from 0 to 1, which shows the fitting accuracy tradeoff between S-parameters and L_{eff} and Q. The weighting parameter m is differently decided by researchers with different considerations.

Select function simulates the mechanism of natural selection by which the gene with better GOF will have more chance to be inherited by offspring, i.e., the new chromosomes of the next generation. There are many kinds of select functions. Roulette wheel selection [1] is used most frequently, but when the fitting error of different individuals varies widely, the optimization efficiency will be affected by roulette wheel selection. Therefore, rank selection was applied, which was proven to be both suitable and effective.

Crossover operator simulates chromosomes' exchanging genes to create a new offspring. The new offspring will inherit advantages from the parents, the chromosomes in the last generation, in order to obtain better GOF.

Mutation operator simulates the chromosomes' mutation in order to introduce new characteristics that do not exist in the parents in order to increase the offspring's variance.

Fig. 2 illustrates the programming procedure for the GA in this study.

- Step 1) A group of individuals, i.e., the first generation, is randomly initialized.
- Step 2) Their GOF are calculated and ranked.
- Step 3) If the error of the individual with the smallest fitting error in the current generation is below the designed error criteria, that individual will be treated as the final result and, thus, will be extracted.
- Step 4) Otherwise, it will be judged whether the time of iteration has met the maximal limitation. If it is so, the individual with the smallest fitting error among the current generation will be extracted.
- Step 5) If the time has not met the maximal limitation, the select function will be conducted. Generally speaking, the better the GOF of the population is, the more likely it is to be chosen. Rank selection was used in our study.
- Step 6) The selected populations are treated with crossover operations with a certain crossover possibility, which is 0.9 in this study.
- Step 7) The mutation operation is followed with a certain mutation probability, typically 0.005–0.01.
- Step 8) The current generation is defined as a new generation and sent back to step 2) to repeat the calculation of the GOF.

In our study, the whole extraction process is programmed for automatic operation, which includes the phase 1 and 2 procedures mentioned in Section II.

TABLE I
EXTRACTED LUMPED COMPONENTS

N	L_s (nH)	R_s (Ω)	C_s (fF)	C_{ox} (fF)	C_{sub} (fF)	R_{sub} (Ω)
2	1.083	2.337	0.001	30.23	8.990	608.0
3	1.923	3.079	0.100	45.88	17.40	605.0
4	3.076	3.833	2.120	67.46	35.55	600.0
5	4.562	4.698	5.300	85.19	48.66	553.0
6	6.404	5.519	7.130	96.54	60.22	449.0
7	8.622	6.468	10.24	101.2	65.54	346.0
8	11.23	7.617	12.59	110.5	69.25	276.0

IV. RESULTS AND DISCUSSION

A set of spiral on-chip inductors, with turns from 2 to 8, were fabricated. We then used an HP8510C network analyzer to measure the S-parameters used in this study. The S-parameters would be the input of the programmed extraction procedure. After phase 1, the formulas for L'_s, R'_s, C'_s, C'_{ox}, C'_{sub}, and R'_{sub} were extracted as follows:

$$L'_s = 0.4293 - 0.0083 \times N + 0.1678 \times N^2 \tag{13}$$

$$R'_s = 2.2739 + 0.7204 \times (N - 1.8633)^{1.0787} \tag{14}$$

$$C'_s = 0.0001 + 0.5871 \times (N - 1.8633)^{1.8035} \tag{15}$$

$$C'_{\mathrm{ox}} = 26.130 + 20.200 \times (N - 1.8633)^{0.8019} \tag{16}$$

$$C'_{\mathrm{sub}} = 7.7600 + 11.010 \times (N - 1.8633)^{1.0998} \tag{17}$$

$$R'_{\mathrm{sub}} = 893.00 - 171.00 \times (N - 1.8633)^{0.7100}. \tag{18}$$

The final accurate parameters L_s, R_s, C_{ox}, C_{sub}, and R_{sub} (see Table I) for individual inductors were consequently extracted by the GA of phase 2 by inputting the results from the phase 1 GA.

The deviations of the final parameters in Table I from the values given by (13)–(18) are shown in Fig. 3.

In Fig. 3, the solid lines present the values from (13)–(18) and the scattered hollow dots give the final accurate parameters L_s, R_s, C_{ox}, C_{sub}, and R_{sub}. It can be found that all of final extracted parameters have some deviations from their

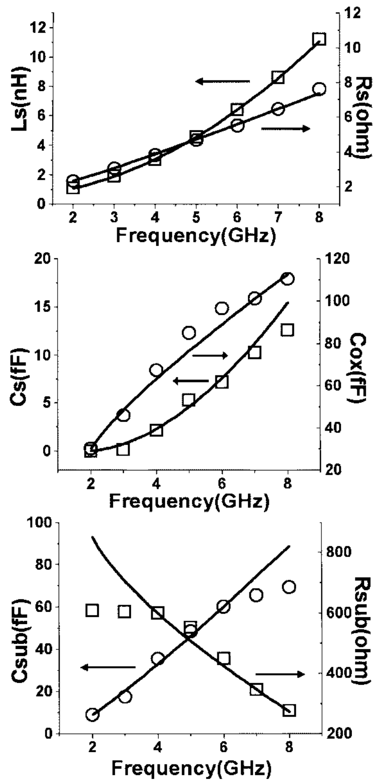

Fig. 3. Comparison of parameters obtained from phase 1 (solid line) and phase 2 (scattered hollow dots). (a) L_s and R_s. (b) C_s and C_{ox}. (c) R_{sub} and C_{sub}.

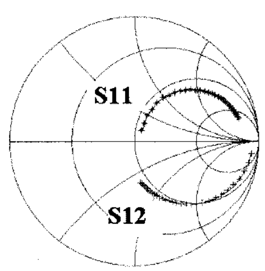

Fig. 4. Comparison of measured (scattered crosses) and simulated (solid line) $S11$ and $S12$.

corresponding values from (13)–(18). L_s and R_{sub} have the smallest and largest deviations, respectively. In our research, it has been found that L_s and R_s can be accurately extracted even if the phase 1 procedure is skipped and only phase 2 is applied. However, both of the two phases have to be involved in the procedure if accurate and meaningful values of C_s, C_{ox}, C_{sub}, and R_{sub} are expected, especially C_{sub} and R_{sub}. It has also been found, in some cases, the variations of C_{sub} and R_{sub} with an increasing number of inductor turns are absurd if phase 1 is skipped, e.g., the value of R_{sub} increases at first and then decreases as the inductor's turns continually rise.

For a validation of the degree of fitting error, an example is taken from the inductor with six turns. Fig. 4 depicts the Smith chart to show excellent fit between the measured and simulated values of S_{11} and S_{12}, and Fig. 5 is for that of the inductance and Q value. In these two figures, the simulated values (solid line) result from the simple model shown in Fig. 1, the parameters of which are extracted by the GA with parameter confinement.

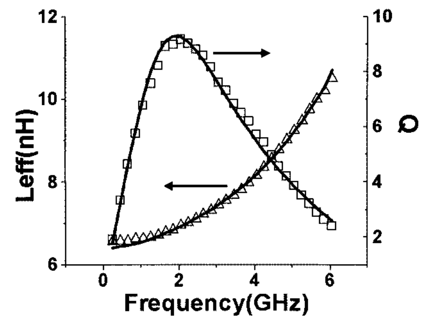

Fig. 5. Comparison of measured (scattered squares and triangles) and simulated (solid line) L_{eff} and Q of a six-turn inductor.

TABLE II
ERROR TABLE

N	E(S) (%)	E(L_relv) (%)	E(L_abs) (nH)	E(Q_relv) (%)	E(Q_abs)
2	1.4	0.8	0.008	7.5	0.62
3	1.2	0.6	0.011	5.0	0.39
4	1.1	0.5	0.015	3.4	0.27
5	1.4	0.4	0.021	2.4	0.17
6	2.0	0.6	0.040	3.2	0.19
7	3.2	1.1	0.129	4.0	0.19
8	5.1	4.2	0.287	6.9	0.19

Here, it should be noted that S-parameters, Q, and L are accurately fitted synchronously. The weights of accuracy for the S-parameter, Q, and L can be decided as predicted by (12). A more accurate value can be achieved for either the S-parameter or Q and L by adjusting the m value in (12). In this study, where m is 0.5, the relative mean error of the S-parameter is less than 2%, and that of L and Q are 0.6% and 3.2%, respectively, for the inductor with six turns. With respect to all inductors with a number of turns from 2 to 8, Table II gives the detailed error list, where the errors are defined as follows (n is the number of measured frequency points):

S-parameter relative mean error:

$$E(S) = (1/4n) \sum_{1}^{n} \sum_{i=1}^{2} \sum_{j=1}^{2} \left| (S_{ij,\,\mathrm{sim}} - S_{ij,\,\mathrm{mea}})/S_{ij,\,\mathrm{mea}} \right| \tag{19}$$

Inductance relative mean error:

$$E(L\_\mathrm{relv}) = (1/n) \sum_{1}^{n} \left| (L_{\mathrm{sim}} - L_{\mathrm{mea}})/L_{\mathrm{mea}} \right| \tag{20}$$

Inductance absolute mean error:

$$E(L\_\mathrm{abs}) = (1/n) \sum_{1}^{n} \left| L_{\mathrm{sim}} - L_{\mathrm{mea}} \right| \tag{21}$$

Q relative mean error:

$$E(Q\_\mathrm{relv}) = (1/n) \sum_{1}^{n} \left| (Q_{\mathrm{sim}} - Q_{\mathrm{mea}})/Q_{\mathrm{mea}} \right| \tag{22}$$

Q absolute mean error:

$$E(Q\_\mathrm{abs}) = (1/n) \sum_{1}^{n} |Q_{\mathrm{sim}} - Q_{\mathrm{mea}}|. \tag{23}$$

It is noticed that the inductance relative mean error of the eight-turn inductor is dramatically higher than that of the remaining six inductors. It is true that the model accuracy of an eight-turn inductor itself is not as good as that of the other inductors, but the main reason is that the resonant frequency shows up within the frequency range of our modeling. Inductance will be nearly zero at those points near the resonant frequency so the inductance relative errors will be very high there. The Q relative mean error shares the same problem since Q values are typically very low at low frequency and near the resonant frequency. Therefore, the inductance absolute mean error and Q absolute mean error will be more convincing to validate the degree of fitting error of inductance and Q.

The errors mentioned above correspond to the working frequency of an inductor below 6.5 GHz. If the frequency is higher than that value, the errors of the inductors with a large number of turns will expand because the model in Fig. 1 is too simple to achieve highly accurate results in the high-frequency region. A more complicated model is available to be used for larger turn inductors in the high gigahertz region, and a GA with parameter confinement has been successfully applied to extract the accurate parameters for that model in our study.

V. Conclusion

A GA with parameter confinement has been successfully applied in RF inductor modeling. The meaningfulness of extracted parameters has been considered in the procedure of the extraction. A two-phase procedure has been proposed for the extraction of the model's parameters. The results from phase 1 provide a "trace" or confinement for the final extracted parameter in phase 2. The S-parameter, inductance, and Q value can be set as the fitting targets simultaneously and the accuracy can be laid with particular emphasis on one of them by simply adjusting the weighting parameter in the evaluating function. By using the proposed GA with parameter confinement, very good GOF for the S-parameter, inductance, and Q value can be obtained. Meanwhile, the model's parameters are extracted with meaningful values.

The whole procedure of extraction is programmed and can be automatically implemented. It is a fully automatic process since there is no initial estimated parameter as an input for the extraction, but only the measured raw data of the S-parameter. It can be applied on not only a simple model, as discussed in this paper, but also on other complicated models. What one needs to do is only define the relevant contents, i.e., the chromosome representation and evaluation function.

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