Optimization of Meander Line Antenna Considering Coupling between Non-Linear Circuit and Electromagnetic Waves for UHF-band RFID

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This paper presents optimization of meander line antennas (MLA) for passive IC tags which contain non-linear circuits. In the present analysis, the tag antenna loaded by the Cockcroft-Walton circuit is analyzed by solving coupling equations for electromagnetic waves and non-linear circuit with FDTD method. The antenna shape is optimized so that the output voltage of the Cockcroft-Walton circuit is maximized using the micro genetic algorithm (μ GA). The computational burden in the optimization processes is effectively suppressed by truncating the transient computations. A criterion is introduced to evaluate the errors caused by the truncation. The present method yields the optimal MLA which has the greater output voltage in comparison with the dipole antenna.

***Index Terms*—Cockcroft-Walton circuit, FDTD, IC tag, RFID**

I. Introduction

The passive UHF-band Radio Frequency Identification (RFID) composed of an RFID reader and IC tag has widely been studied due to its promising applications in, for example, rechargeable contactless and security systems [1] and medication [2]. The RFID reader sends power and data to the IC tag by electromagnetic waves. By receiving them, the IC chip starts operating to make a response by reflecting the backscatter waves modulated by the semiconductor switch. It is desired in various applications to increase communication distance between the RFID reader and IC tag. For this purpose, optimization of the IC tag antenna and IC chip is indispensable [3], [4]. When the IC tag consists of linear circuits and an IC tag antenna, the Thevenin equivalent circuit is effectively used for its analysis [5], [6]. However, in real situations, the IC tag antennas are loaded by non-linear circuits such as Cockcroft-Walton (CW) circuit for voltage amplification [7], [8]. Hence the field analysis must be carried out taking coupling effect between electromagnetic fields and non-linear circuits into account. However, such numerical analysis for IC tags has not been reported yet.

In this work, considering the nonlinearity, the IC tags are analyzed by the hybridization of finite-difference time-domain (FDTD) method and modified nodal analysis (MNA) [9], [10]. Moreover, on the basis of this coupled analysis, the shapes of the meander line antenna (MLA) loaded by the CW circuit are optimized by micro genetic algorithm (μ GA) [11]. The coupled computations with the FDTD and MNA require quite a long computation time when the time constant of the circuit is much longer than the period of electromagnetic waves. To overcome this difficulty, the transient FDTD iterations are truncated when a stopping criterion is fulfilled, which estimates the errors caused by the truncation. The present reduced computation would be useful for other stochastic optimizations in which the fitness is evaluated by the time-consuming transient field computations.

This paper will be organized as follows: in Section II, the coupled method with the FDTD and MNA will be formulated. In Section III, the μ GA based on the truncation of transient field computations will be described, and in Section IV, the optimization problem for the shape of IC tag antenna will be defined, and the results for the optimization of MLA loaded by the CW circuit will be presented.

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II. Hybridization of FDTD method and MNA

A. Formulation

The coupling of FDTD and MNA [6] will briefly be described in the followings. The Maxwell equations are given by

$$\varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \boldsymbol{J}(\boldsymbol{E}) = \nabla \times \boldsymbol{H}\,, \tag{1a}$$

$$\mu \frac{\partial \boldsymbol{H}}{\partial t} = \nabla \times \boldsymbol{E} \tag{1b}$$

where the conduction current density $\boldsymbol{J}$ is determined from the voltage-current characteristics of the non-linear circuit. Let us consider the line antenna, shown in Fig. 1, parallel to z-axis. The spatial size of the non-linear circuit is assumed to be sufficiently smaller than that of the antenna. By integrating (1a) on the surface S of an FDTD cell, we obtain

$$C_0 \frac{\partial V_L}{\partial t} + I_L(V_L) = I\,, \tag{2}$$

where $V_L = E_z \Delta z$ is the voltage imposed to the circuit, $C_0 = \varepsilon \Delta x \Delta y / \Delta z$ is the space capacitance, $\Delta x \Delta y$ is the area of S, and Δz is the height of the FDTD cell, I_L is current flowing into the circuit and I is the total current given by $I = \int_{\partial S} \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{s}$. The equivalent circuit corresponding to (2) is shown in Fig. 2.

In the FDTD process, I is computed from the magnetic field $\boldsymbol{H}^{m-1/2}$, where m denotes the time step, and I is substituted to (2), which is then solved by, in our computation, the MNA for V_L. The resultant electric field $E_z^m = V_L / \Delta z$ is substituted

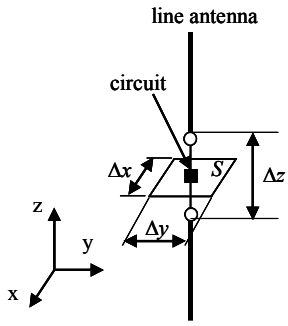

Fig. 1. Line antenna loaded by non-linear circuit.

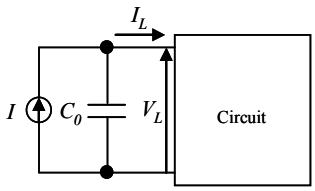

Fig. 2. Equivalent circuit for FDTD method of antenna loaded by non-linear circuit.

to (1b), which is solved by FDTD method for $\boldsymbol{H}^{m+1/2}$. The perfect matched layer is employed to enforce the free space conditions on the domain boundary.

The MNA determines the voltage $\boldsymbol{v}$ between nodes in the electrical circuit in terms of the Kirchhoff's current law. The system of equations is given by

$$\dot{\boldsymbol{v}} = \boldsymbol{f}(\boldsymbol{v}, \boldsymbol{i}), \tag{3}$$

where $\boldsymbol{i}$ is current source of the electrical circuit, and $\boldsymbol{f}$ is a function which includes non-linear terms relevant to effects of active devices. In this work, (3) is solved by the backward Euler method with the Newton-Raphson method.

III. Optimization of Antenna Design

A. Micro Genetic Algorithm

The micro genetic algorithm (μ GA) [10] uses very small population, which typically consists of 5 individuals, in comparison with the conventional GA. The μ GA performs global search by re-initialization and local search by saving elite individual and crossover. The μ GA can avoid the excessive fitness evaluation, because the number of individual is very limited.

The algorithm of μ GA is described in the followings.

1. The initial population of size N_{pop} is generated.
2. The fitness of each individual is calculated from the coupled analysis with FDTD and MNA.
3. The individual having the highest fitness is saved as an elite individual.
4. The two parent individuals are selected by performing tournament selection.
5. A child is produced by applying uniform BLX-α crossover to parents.
6. $N_{pop}-1$ children are produced by repeating steps 4. and 5.
7. If the population converges, that is, the population falls into local optimum, it is reinitialized.
8. Steps 2 to 7 are repeated until the iteration number reaches to maximum.

Here, the optimization parameters are set as follows: N_{pop}=5, α=0.5 for the BLX-α crossover, and the maximum number of iteration step is 500.

B. Problem Definition

The IC tag antenna loaded by the CW circuit shown in Fig.3 is optimized, for which the above mentioned μ GA is employed. The antenna shape is represented by real coded genes. The aim of our optimization is that the output voltage v_{out} is maximized when plane waves are incident on the IC tag antenna. The optimization problem is defined by

$$v_{out} \rightarrow \max . \tag{4}$$

The optimization setting for the MLA is described in the followings. The design variables are shown in Fig. 4.

1. A base line is divided into small line segments, whose number is, in this work, set to five.
2. The antenna is generated from the genes expressing the width and height of segments, which range from 0mm to 15mm and from -20mm to 20mm, respectively.
3. Both ends of each segment are connected to adjacent segments.
4. The other half of MLA is similarly formed, assuming the right left symmetry.

C. Reduced field computation

In the present optimization, the coupled analyses with the FDTD and MNA are carried out for different antenna shapes. As will be shown in IV, the circuit quantities including the v_{out} have tremendously long time constants in comparison with the time step in the FDTD which must be shorter than the threshold given by the Courant condition. As a result, the required number of the time steps is so huge that the

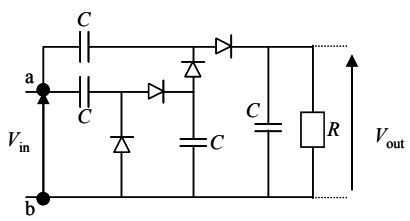

Fig. 3. Cockcroft-Walton circuit. Capacitance is set to 10 pF and V-I characteristic of diode is assumed to be $I = 10^{-11}[\exp(40V)-1]$ (A) .

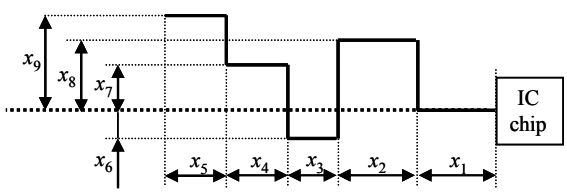

Fig. 4. Genotype and phenotype for μ GA

computational time is unacceptable for practical applications.

We truncate the transient field analysis before reaching at the steady state to overcome this difficulty. The circuit quantities have monotonous time responses although they have small ripples. Hence, the affection caused by this truncation on the fitness evaluation for the tournament selection procedure in the GA could be made sufficiently small when the truncation is appropriately controlled. To evaluate the error caused by this truncation in the fitness evaluation, we here introduce probability of failure defined by

$$\varepsilon = N / N_{\max} , \tag{5}$$

where N is the number of incorrect selections and $N_{\max}$ is the total number of the evaluation, where $N_{\max}$ should be determined such that the confidence interval of ε is smaller than the prescribed value. To determine N, the fitness values of two arbitrary antennas are computed at the truncated time steps n_t, and the antenna with better fitness is selected. If this selection is inconsistent with that determined by non-truncated computation with n steps, the selection is judged to be incorrect. Such trials are carried out for $N_{\max}$ times. The value of ε which depends on n_t is computed before the optimization process to determine the appropriate value of n_t.

IV. Numerical Result

A. Output Voltage of CW Circuit

Although the IC tag contains various non-linear circuits for voltage amplification, regulation and switching and so on, the CW circuit shown in Fig. 3, which is used for voltage multipliers in the IC chip, is considered here as the non-linear circuit for simplicity. In the MNA, the diode included in the CW circuit is assumed to obey V-I characteristic given by $I = 10^{-11}[\exp(40V)-1]$ (A).

In the analysis, assuming that the RFID reader is sufficiently far from the IC tag, it is illuminated by plane waves. The size of FDTD cell, where $\Delta x=\Delta y=\Delta z$, is set to 3mm. The frequency of incident wave is set to 1GHz. The time evolution of resultant output voltage v_{out} for half-wave dipole antenna loaded by the CW circuit is shown Fig. 5. The amplitude of the incoming electric field is assumed to be 20 V/m. It can be observed in Fig. 5 that v_{out} tends to increase monotonously and reach at the steady value although it includes small ripples. If the ripple amplitude becomes too large, the digital circuit, to which v_{out} is supplied, would have malfunctions in its operation. It is found from the computations that the ripple can be reduced by increasing C in Fig.3, whereas the rise time becomes longer with C.

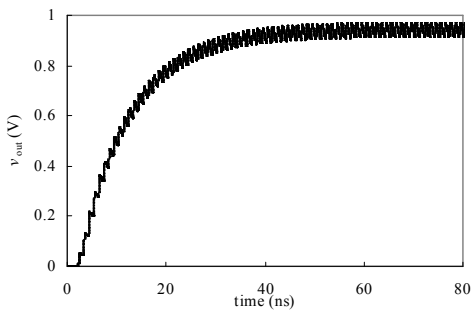

Fig. 5. Output voltage for half-wave dipole antenna loaded by Cockcroft-Walton circuit.

B. Test of Reduced Computation for a Simple Problem

To test the validity of the truncated computation mentioned in III, optimization is carried out for a simple problem

$$g(x_1, x_2, x_3) = x_1 x_2 - x_3 \rightarrow \max , \tag{6}$$

where x_1, x_2 and x_3 range from -10 to 10 which are represented by the real-coded genes. The objective function takes the maximum value $g_{\max}$=110 at (10,10,-10). In the optimization, uniform noises $\sigma g_{\max}$, where $-1 \le \sigma \le 1$, are added to g to mimic the truncation effect. The error ε depending on the noise is shown in Fig. 6, which shows that the error ε given by (6) decreases with $1-|\sigma|$. The root square error E

$$E = \sqrt{\sum_{i}^{n} (g_i(\sigma) - g_{\max})^2 / n} \tag{7}$$

is evaluated for different σ, where $g_i(\sigma)$ is the fitness obtained by the μ GA. It can be seen from Fig. 7 that E and ε have the similar tendencies. This suggests that ε can be used for rough estimation of the fitness evaluation error instead of E which cannot be known *a priori* for the present antenna optimization problem.

Fig. 8 shows the dependence of ε on n_t, where n is set to

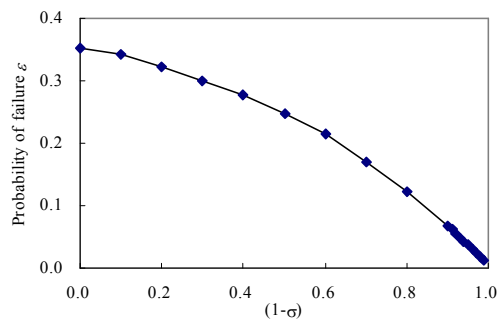

Fig. 6. Probability of failure due to noise added to g in (6).

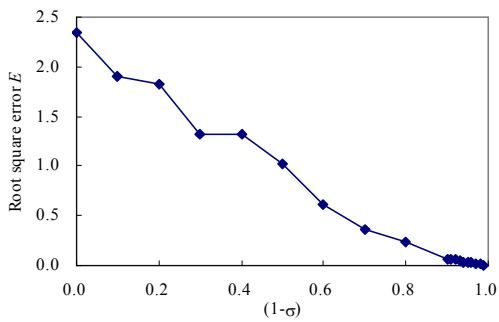

Fig. 7. Root square error evaluated for different σ.

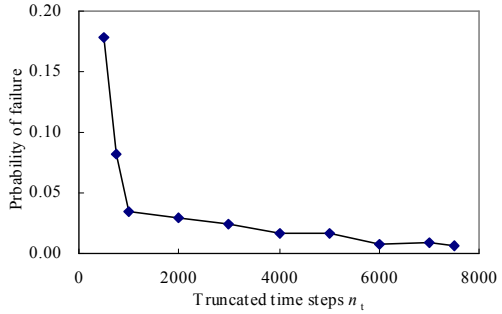

Fig. 8 Truncation error of μ GA adding noise to fitness.

8000. In the evaluation of ε, $N_{\max}$ is set to 1000 where the confidence interval in ε is $[\varepsilon(1-\alpha), \varepsilon(1+\alpha)]$, $\alpha = 0.052$. It can be seen in Fig.8 that ε decreases rapidly, until n_t=1000, and then has a slow reduction. From this result, the truncation time step is set to 4000 in this work. Note that the number of fitness evaluation for the Monte-Carlo method, $N_{\max} = 1000$, is much smaller than that required in the optimization processes. It is ensured that the present method can halve the computational time in the non-truncated optimization.

C. *Optimized Shape of MLA*

The shape of the optimized MLA is shown in Fig. 9. The size of the MLA in the horizontal direction, parallel to polarization of the incident electric field, is 78mm which is nearly a half length of the half-wave dipole antenna, that is, 150mm. It is ensured that the input impedance of optimized antenna computed by FDTD method is in good agreement with that computed by the moment method. When the random seed is changed, the optimized shape of MLA is found to be different, while the output voltages v_{out} of the optimized antennas are almost the same. Hence, the final design of the antenna should be determined from the other factors, e.g., the antenna area, robustness against the parameter changes and so on.

The output voltage v_{out} for the optimized antenna and half-wave dipole antenna loaded by the CW circuit are comparatively shown in Fig. 10. It can be observed in Fig. 10 that the steady value of v_{out} for the optimized antenna is larger than that for the half-wave dipole antenna although the horizontal size of the former is smaller than the length of the latter.

It is found out that the steady value of v_{out} for the optimized antenna remains almost unchanged even if n_t is reduced from 4000 to 2000. This fact is consistent with the result of the pre-process shown in Fig.8. This suggests that the computational time can further be reduced by the truncation of the transient field computations based on the present stopping criterion.

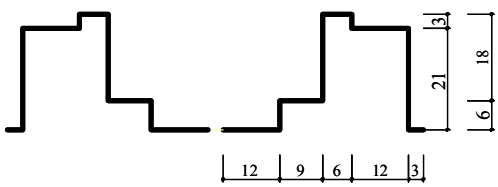

Fig. 9. Optimized shape of MLA.

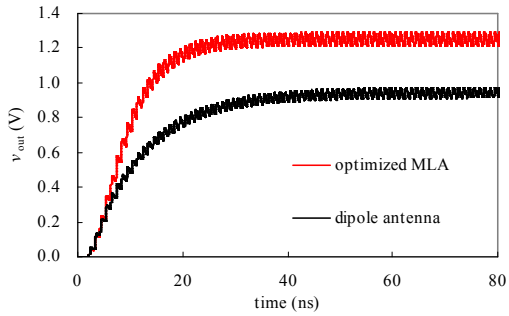

Fig. 10. Output voltage for optimized antenna and falf-wave dipole antenna loaded by CW circuit.

V. Conclusion

In this paper, the output voltage of the Cockcroft-Walton circuit connected to the IC tag antenna is analyzed by FDTD method coupled with MNA. The optimization of MLA using the μ GA considering nonlinearity in the IC chip has been presented. For reduction of computational burden for fitness evaluation, the transient field analysis is truncated before reaching at the steady state. The number of time steps for the truncation is determined from the stopping criterion. The optimized IC tag antenna has higher output voltage of in comparison with the half-wave dipole antenna. The present method can easily be applied to optimization of other antennas such as patch and slot antennas.

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