第29卷 第1期 电子科技大学学报 Vol.29 No.1
2000年2月 Journal of UEST of China Feb. 2000

Design of Circuit Analog Absorber Using Genetic Algorithm*

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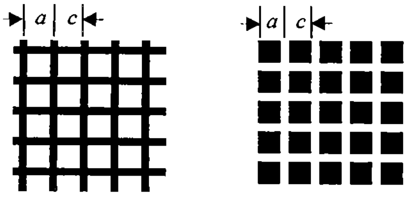
Abstract This paper presents a new method for designing circuit analog (CA) multi-layer absorbers using modern genetic algorithm (GA). The GA automatically synthesizes the EM parameters and thickness of each layer and the parameters of the metal circuit screen provide several design schemes simultaneously. But when using the GA in designing extraordinary wide band absorbers, its iterative process will go to fluctuation and give some bad results within the band. For overcoming these drawbacks, two techniques are introduced to GA program, and the operating performance is improved obviously. The new method shows that it is of high design efficiency and of easy use. The design examples also show that in the absorber without metal base cases, the characteristics of CA absorbers are much superior than ordinary designs, which give low reflection within very wide band with a thinner thickness and less materials used.

Key words circuit analog; absorber; reflection coefficient; genetic algorithm

Circuit analog absorber is constructed by inserting a metal screen into certain layer of a multi-layer absorber. The metal screen is either of a thin metal net or of a thin patches as shown in Fig.1. The screen is equivalent to a lumped susceptance, the metal net is of inductive in nature, and the metal patch is of capactive in nature. It will change the input impedance at the left side of *ab*,when insert the screen into the material at the plan *ab* (Fig.2). For example, if the screen is an inductive one, and if the input impedance at *ab* is also inductive, the resultant impedance will be decreased; if the input impedance at *ab* is capacitive, the resultant input impedance may either be increased or decreased, depending on the relative magnitudes of the input capacitive susceptibility and the screen susceptibility. The design goal of a multilayer absorber is to search an optimized combination of layers which makes the surface input impedance approach the wave impedance of air as well as possible in the operating frequency band. It can be achieved by means of increasing number of layers to compensate the difference of variation of input impedance at high and low frequencies. The CA absorber, when well designed, can achieve the same characteristics with a smaller number of layers and in turn, a less quantity of material to be used. This, of course, appears highly attractive to the users and designers, but owing to the complicated input impedance, and the strongly dispersive character of the screen, its design is difficult. Ref. [1~3] show that the good performances of their CA absorber design examples were obtained by extensive amount of fine tuning of parameters of material and screen, without an efficient design method preventing the CA absorber from being widely used in practice.



(a) Inductive screen (b) Capacitive screen

Fig.1 Inductive screen and capacitive screen

This paper presents a design method using the modern genetic algorithm for the synthesis of material, thickness and screen constants, but the classic genetic algorithm is not adequate for very wide band cases,

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Received October 18, 1999

* The project supported by National Defense Research Foundation

so that we propose two modifications to improve its performance. The new method shows that it is powerful in designing very wide band absorber with large quantity of variables. The design examples give the results superior than ordinary design methods.

1 Equivalent Circuit of CA Absorber

Fig.2 shows a 5-layers CA absorber (in which material 3 is cuted to two layers by the metal screen) and its equivalent circuit. Each layer is denoted by a 2-ports network, and the screen can also be denoted by a 2-ports network, thus the absorber has six 2-port networks in cascade. For i th network, the income and outcome electric fields at the input port are A_{i-1}, B_{i-1} respectively, and the income and outcome electric fields at the output port are A_i and B_i respectively. The input and output quantities are related by a transmission matrix as follows[4]

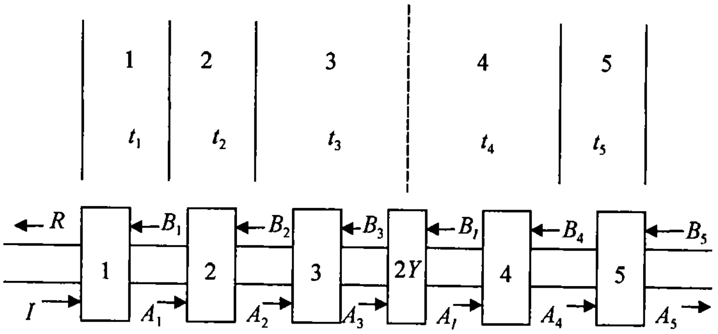

Fig.2 The 4-layers absorber and its equivalent circuit

$$\begin{bmatrix} B_{i-1} \\ A_{i-1} \end{bmatrix} = \frac{1}{1+R_{(i-1)i}} \begin{bmatrix} e^{-jg_i t_i} & R_{(i-1)i} e^{jg_i t_i} \\ R_{(i-1)i} e^{-jg_i t_i} & e^{jg_i t_i} \end{bmatrix} \tag{1}$$

where $g_i = k_0\sqrt{\tilde{\mu}_{ri}\tilde{e}_{ri}}$, $k_0 = 2\pi f / c$, c is the speed of light, and $\tilde{\mu}_{ri} = \mu'_{ri} - j\mu''_{ri}$, $\tilde{\varepsilon}_{ri} = \varepsilon'_{ri} - j\varepsilon''_{ri}$.

$$R_{(i-1)i} = \frac{\tilde{\mu}_{ri} g_{(i-1)} - \tilde{\mu}_{r(i-1)} g_i}{\tilde{\mu}_{ri} g_{(i-1)} + \tilde{\mu}_{r(i-1)} g_i} \tag{2}$$

is the reflection coefficient on the boundary between two media (i–1) and i.

Let the admittance of the screen is $2Y_l$, its matrix equation is

$$\begin{bmatrix} B_3 \\ A_3 \end{bmatrix} = \begin{bmatrix} 1 - Y_l / Y_{e3} & -Y_l / Y_{c3} \\ Y_l / Y_{c3} & 1 + Y_l / Y_{e3} \end{bmatrix} \begin{bmatrix} B_4 \\ A_4 \end{bmatrix} \tag{3}$$

where $Y_l = -jb_L$ or $=jb_c$; $Y_{c3} = \sqrt{\tilde{\mu}_{r3} / \tilde{\varepsilon}_{r3}}$ is the wave impedance of medium 3. It is important to point out that Y_l depends upon the frequency and the medium surrounding it, and the value of Y_l can be determined only when the EM-parameters of medium 3 are known.

Cascade the networks, we have a matrix equation of the absorber

$$\begin{bmatrix} R \\ 1 \end{bmatrix} = \frac{1}{1+R_{0,1}} \begin{bmatrix} e^{-jg_1 t_1} & R_{0,1} e^{jg_1 t_1} \\ R_{0,1} e^{-jg_1 t_1} & e^{jg_1 t_1} \end{bmatrix} \frac{1}{1+R_{1,2}} \begin{bmatrix} e^{-jg_2 t_2} & R_{1,2} e^{jg_2 t_2} \\ R_{1,2} e^{-jg_2 t_2} & e^{jg_2 t_2} \end{bmatrix} \frac{1}{1+R_{2,3}} \begin{bmatrix} e^{-jg_3 t_3} & R_{2,3} e^{jg_3 t_3} \\ R_{2,3} e^{-jg_3 t_3} & e^{jg_3 t_3} \end{bmatrix} \times$$
$$\begin{bmatrix} 1 - Y_l / Y_{e3} & -Y_l / Y_{c3} \\ Y_l / Y_{c3} & 1 + Y_l / Y_{e3} \end{bmatrix} \begin{bmatrix} e^{-jg_3 t_4} & 0 \\ 0 & e^{jg_3 t_4} \end{bmatrix} \frac{1}{1+R_{3,5}} \begin{bmatrix} e^{-jg_5 t_5} & R_{3,5} e^{jg_5 t_5} \\ R_{3,5} e^{-jg_5 t_5} & e^{jg_5 t_5} \end{bmatrix} \begin{bmatrix} B_5 \\ A_5 \end{bmatrix} \tag{4}$$

that is

$$\begin{bmatrix} R \\ 1 \end{bmatrix} = C \begin{bmatrix} U_{11} & U_{12} \\ U_{21} & U_{22} \end{bmatrix} \begin{bmatrix} B_5 \\ A_5 \end{bmatrix} \tag{5}$$

When the absorber has a metal base, the reflection coefficient at it is -1, and $B_5 = -A_5$, then

$$R = \frac{-U_{11} + U_{12}}{-U_{21} + U_{22}} \tag{6}$$

when the absorber is backed by air, B_5 may be written as $B_5 = R_{5,0}A_5$, then

$$R = \frac{R_{5,0}U_{11} + U_{12}}{R_{5,0}U_{21} + U_{22}} \tag{7}$$

with

$$R_{5,0} = \frac{g_4 - \tilde{\mu}_{r4}k_0}{g_4 + \tilde{\mu}_{r4}k_0} \tag{8}$$

Thus, we can evaluate the surface reflection coefficient at any frequency specified, either the absorber is backed with a metal base or backed by air.

2 Genetic Algorithm

Genetic algorithm, which imitates the principles of natural evolution from parameter optimization problems, is used here for searching the optimized combination of material and screen to fit the special requirement. The use of it in researches in electronics and microwave engineering were largely reported in recent decade. Ref. [5~7] proved it to be a powerful tool for the task mentioned above.

The classic GA, applied in this paper, uses binary string to code the parameters and operates directly the bits. For example, if we have 8 kinds of material, then use a 3-bit binary string to code the serial number of materials, such as , [1 0 1] is for material #5, etc[1]. If the required precision of thickness (in mm) is 1/100, and if maximum allowable thickness of a layer is 4, this thickness should be divided at least into 400 equal size, ranging from $2^8 < 400 < 2^9$,then a 9-bit string should be used. A binary string [1 1 1 1 1 1 1 1 1] gives the real length 4 according to the relation, $x = \frac{4}{2^9 - 1}(2^8 + 2^7 + 2^6 + 2^5 + 2^4 + 2^3 + 2^2 + 2^1 + 2^0) = 4$. Similarly, if the allowable thickness is between 1.5~2.5, the domain of variation of length is 1, then a 7-bit string should be used. A string [1 0 0 1 1 0 1] gives the real length $x = 1.5 + \frac{1}{2^7 - 1}(2^6 + 2^3 + 2^2 + 2^0) = 2.0163$.

If there are several kinds of metal screen for use, the serial number of the screen is coded like the serial number of material, for example, a 3-bit binary string is used for 8 kinds of screen.

Combine the bits for material and the bits for thickness to form a string for the layer, then combine strings of all layers and the string of the metal screen, a binary string for the absorber is obtained, called a “chromosome” or an “individual” in terms of GA terminology, thus each bit is a gene. The genes of a chromosome record all the messages of variables of the absorber.

Let the allowable maximum thickness t_1, t_2 and t_5 are 4, and the thickness t_3, t_4 are within 1.5~2.5, there are (3+9)+(3+9)+(3+7)+3+7+(3+9)=56 bits for the absorber.

The GA optimizes not an individual chromosome, but a population of them. A large polulation can avoid the individual chromosome from prematurely reaching a local optimum point. Let the population size be 20. At the beginning, produces randomly 20 sets of binary string, 56 bits each. For the whole system, there are 56×20=1 120 bits to be optimized. The initial population is the first generation, after genetic

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[1] 3-bit is for 8 kinds, 4-bit is for 16 kinds, if the number of materials is neither 8 nor 16, may give several kinds of material each two serial number to make the total number to be 8 or 16.

operation, the 2nd, 3rd ··· generation will be generated. At the beginning of each generation, decodes the bits of individual chromosome, thus returns the real material used and thickness of layers. Now the EM-parameters of layer 3 are known, and Y_l can be calculated. Then, the reflection coefficient of chromosome can be evaluated at any desired frequency by Eq.(6) or Eq.(7).

The design requires function $\frac{1}{N}\sum_{n=1}^{N}|R_{fn}|$ to be a minimum; f_n represents the samplying frequency (n=1,2,···,N). To minimize the above function is equivalent to maximize a function

$$f = 1 - \frac{1}{N}\sum_{n=1}^{N}|R_{fn}| \tag{9}$$

This is the assumed objective function, which will take positive value to its domain. f is called the "fitness" of chromosome.

Follows are the operations with three operators: "selection", "crossover" and "mutation". We briefly describe these processes.

2.1 Selection

After decoding the chromosomes and evaluating the fitness of each chromosome as stated above, we sum up the 20 fitness, and obtain the total fitness of the population (pop)

$$F = \sum_{1}^{20} f_i \tag{10}$$

Take the ratio of fitness of each chromosome to the total fitness, gives

$$p_i = f_i / F \tag{11}$$

called the probability of selection. Calculate

$$q_i = \sum_{j=1}^{i} p_j \tag{12}$$

this is cumulative probability, where $q_1 = p_1$, $q_2 = p_1 + p_2$, $q_3 = p_1 + p_2 + p_3$, ··· .

Generate 20 random numbers r_j from the range [0,1], called roulette wheel. Spin the roulette wheel twenty times on q_i . Firstly, use r_1 to spin on q_i, through q_1, q_2,···, until q_i, say, i=9, $q_9 > r_1$, select chromosome #9 as the first member of the new combination; then use r_2 to spin on q_i , through q_1, q_2,···, until, say, $q_4 > r_2$, select chromosome #4 as the second member, and so on. Obviously, the larger the fitness f_i of a chromosome is, the larger the ($q_i - q_{i-1}$) will be, which has more opportunity to be selected. As the results, some chromosomes with large fitness may be selected twice or even more times, and some chromosomes with small fitness will disappear in the new combination.

2.2 Crossover

GA uses the crossover and mutation to generate new chromosomes. Let the probability of crossover p_c=0.25, so we expect (on average) 25% of chromosomes undergo crossover. For each chromosome in the current (after selection) pop, generate a random number r from the range [0,1], and take those chromosomes whose r<0.25 for crossover. If four such chromosomes are obtained (even number is needed for crossover, when larger or smaller than 4, may remove one or add one extra), mate them into two pairs. Generate randomly two integers, called "pos", from the range [1,56], and indicate the positions of crossing points of these two pairs. Assume the two pos. are 20 and 9, then the first pair should exchange their bits after #20, and the second pair should exchange their bits after #9. Thus two new chromosomes are generated.

2.3 Mutation

The mutation operator is performed bits by bits. Let the mutation probability is p_m=0.01, so we expect 0.01×1 120=11 bits undergo mutation. For each bit in the pop, generate a random number r from the range [0,1], and take those bits whose r<0.01 for mutation, that is, a bit of 1 is changed to 0, and a bit of 0 is changed to 1. After mutation process, another 11 new chromosomes are generated.

Thus we complete one iteration (generation), the total fitness of the new pop and the maximum fitness in the pop may be higher than the previous pop. Repeat the above run several hundreds times or more, until the total fitness of the pop no longer increases, stop the GA, a combination of high fitness chromosomes is got, each representing an optimum design scheme. But when designing a 2~18 GHz absorber by the above process, some unexpected phenomena come forth. The pop fitness grows firstly, but after one or two hundred runs, it fluctuates around a moderate pop fitness value. On the other hand, the reflection curve always has some high reflection points, which means these results are useless in practice.

The pop fitness fluctuation is caused by crossover. Because the crossover exchanges all the bits behind the crossover point "pos", thus when a chromosome has a large number of variables (in our case, up 8 to 10), the number of variables to be exchanged is large in general, which may largely alter its fitness: a previous high fitness may probably turn to a low one, and a previous low fitness may probabely turn to a high one. As the results, the pop fitness begins to fluctuate.

The existence of high reflection points in the operating band is due to the fact that the GA program concerns only the sum of reflection coefficients at all sampling points and does not pay attention to individual point. If some points have high reflection, but the remaining points have low enough reflection, the sum of them will still maintain a low reflection level, and the GA can not detect and eliminate these high reflection points.

Here, introduce two modifications to improve the GA program;

1) Two points crossover The crossover is accomplished within a layer, between the randomly created pos. and the last bit of the same layer, so that only the variables within the layer are exchanged when undergo crossover. This makes the process more stable than the previous.

2) Use penalty function Multiply the fitness of the individual which has high reflection point by a penalty function p<1 to lower its fitness. This individual will have less survival opportunity when undergo the next selection.

3 Design Examples

Use the above method to design CA structural absorbers. 8 kinds of structural material are given. The circuit screen also has 8 kinds. Y_l of the circuit screens shown in Fig.1 may be calculated by using empirical formula in Ref.[8] as follows

$$Y_l=-\mathrm{j}b_L \qquad Y_l=\mathrm{j}b_c \qquad b_L=(\beta-\beta^{-1})\frac{\dfrac{a}{c}+0.5\left(\dfrac{a}{\lambda}\right)^2}{\ln\csc\left(0.5\pi\dfrac{\delta}{a}\right)} \qquad b_c=\frac{\ln\csc\left(0.5\pi\dfrac{\delta}{a}\right)}{(\beta-\beta^{-1})\left[\dfrac{a}{c}+0.5\left(\dfrac{a}{\lambda}\right)^2\right]} \tag{13}$$

$$\delta=\frac{a-c}{2} \qquad \delta=\left(1-0.41\frac{\delta}{a}\right)\Big/\left(\frac{a}{\lambda}\right)$$

where λ is the wavelength in material surrounding the screen. At given frequency, λ varies with material, so that Y_l can not be given prior and may be determined only if the material is known. The formula can be used only at $a<\lambda$, c>0.7a, $(\beta-\beta^{-1})>0$. It means that a should be less than the wavelength at the highest frequency used. So that we choice a fixed length a=2 mm, it will be less than λ in all cases. Also, choice a fixed c=1.5. On the other hand, the screen may be a whole one, or a half, or a quarter of it ,which corresponds Y_l, $Y_l/2$ and $Y_l/4$ respectively. The screens used in the designs are: $-b_L$, $-b_L/2$, $-b_L/4$, b_c, $b_c/2$, $b_c/4$, $-b_L/2+b_c/4$, $-b_L/4+b_c/2$.

Example 1 Two layer CA absorber with metal base. The optimized 20 lg|R|–f curve is shown in Fig.3. For comparison, a design of three layer absorber without metal screen is shown in Fig.4.

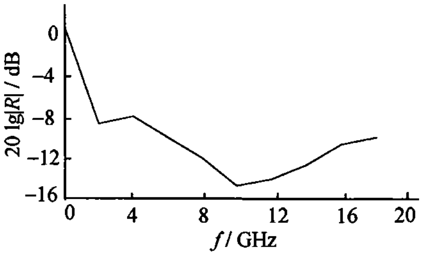

Fig.3 20 lg|R|–f curve of 2-layer CA absorber with metal bases, overall thickness =6.152 mm, Y_l=jb_c

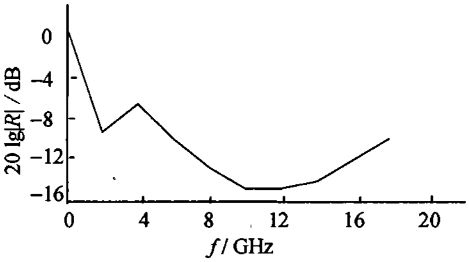

Fig.4 20 lg|R|–f curve of 3-layer absorber with metal base, overall thickness=6.28 mm

Both absorbers have good |R|–f curves, and the CA absorber uses less kinds of material, but the overall thickness of the two designs are equivalent, which shows that the CA has no advantage over the ordinary design in this case.

Example 2 Three layer CA absorber without metal base. The optimized 20 lg|R|–f curve is shown in Fig.5. For comparison, a design of four layer absorber without metal screen is shown in Fig.6.

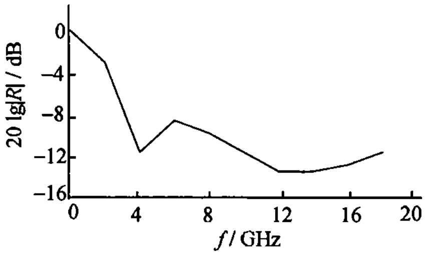

Fig.5 20 lg|R|–f curve of 3-layer CA absorber without metal base, overall thickess= 6.731 mm, Y_l=–jb_L/4

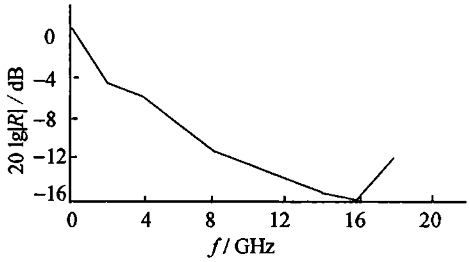

Fig.6 20 lg|R|–f curve of 4-layer CA absorber without metal base, overall thickness= 18.730 mm

In the no metal base case, the differences between CA absorber and ordinary absorber are pronouned. Both the material used and the overall thickness of the CA absorber are less than the ordinary absorber, and most importantly, the CA has much better reflection characteristics compared with the ordinary designs.

4 Conclusions

1) The modified GA is a powerful tool for CA multi-layer absorber design. It gives simultaneously several different design schemes with good performances. It also has the advantages of easy use and high speed operation (less than 10 sec for 1 000 runs).

2) In no metal base case, using CA multi-layer absorber can largely save the material used and obtain much better performance than ordinary absorbers.

3) In these designs, there are still some points which have reflections larger than –10 dB, limited by the parameters of the materials. It is observed that if for the first layer, with permeability slightly larger than 2, permittivity less than 5, the reflection characteristics will be improved obviously.

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电路模拟吸收体的遗传算法设计*

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【摘要】 提出了一个应用遗传算法的电路模拟多层吸收体的新设计、遗传算法自动综合各层的电磁参数和厚度以及金属电路屏的各参数，并同时提供几个设计方案。当应用遗传算法对特宽带吸收体设计时，其迭代过程出现波动和在带内出现不好的结果。为了克服这些缺点，文中引入了两项技术，使其工作特性明显地改善。设计实例表明在无金属基底的吸收体情形，电路模拟吸收体比普通设计优越得多，在厚度更小和用更少材料下能在特宽带内获得低反射。

关 键 词 电路模拟；吸收体；反射系数；遗传算法

中图分类号 TN011

1999年10月18日收稿

* 国防科研基金资助项目

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