Miniaturization of built-in antenna loaded with magnetic materials for handset by using topology optimization

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1. INTRODUCTION

With the recent rapid progress in handsets, the downsizing of their antennas is acquiring great importance. The downsizing of these antennas is kept pace with the downsizing of the handset units. In particular, built-in antennas are required. These antennas have been downsized by changing a configuration of the antenna or utilizing materials such as dielectric materials and magnetic materials. In our previous study, a downsizing technique of antennas for handsets by utilizing a magnetic material has been investigated [1]. It was found that a magnetic material has an effect on lowering resonance frequency of a planar inverted-F antenna (PIFA) instead of changing the radiation characteristics at both 900MHz and 2GHz bands. In addition, effective configuration and arrangement of the magnetic materials was investigated on the basis of current distribution of PIFA.
The topology optimization approach is applied for a structure design problem of dielectric materials, which has already been reported [2]. This approach is considered as an effective approach to obtain optimum configuration and arrangement of magnetic materials. In this study, we apply the topology optimization approach to optimize the configuration and arrangement of magnetic materials, which is inserted in the PIFA. In this optimization method, the Adjoint Variable Method (AVM) [3] and the Finite Difference Time Domain (FDTD) method are used. In this paper, we confirm the validity of using the topology optimization approach for designing the configuration and arrangement of magnetic materials.

2. TOPOLOGY OPTIMIZATION

A. Design variables

Topology optimization approach has been developed in the field of structural engineering. The application of this approach has significantly expanded to many optimization problems. In the application of topology optimization to design the configuration and arrangement of magnetic materials, the design domain is divided into small cells. The electric constants of each cell are the design perturbed simultaneously and updated to reach for the optimal design structure. In other words, the structure optimization of materials can be considered as optimization of the material distribution in the design domain. In this study, the permeability and the permittivity of each cell are taken as the design variable.

B. Problem formulation

In this study, the goal by topology optimization is to lower resonance frequency without changing the volume of PIFA. Then, reflection coefficient (S11) can be considered as the object function. Reflection coefficient is obtained by the FDTD simulation. The FDTD method is used as an electromagnetic field solver because electromagnetic problems by FDTD method can be analyzed directly in time domain for a broad band of frequencies by only one calculation. Therefore, formulated problem can be expressed as

$$\underset{(\rho(\mathbf{x})\in\Re)}{\text{Minimize}} \quad f_{freq} = \left|S_{11}\right|_{freq}$$
$$\text{Subject to} \quad \boldsymbol{G}(\mu_r, \varepsilon_r) \tag{1}$$

where
freq = frequency bandwidth of an incident wave

The FDTD method is based on Maxwell's partial differential equations. Then, the constraint in this problem can be considered a wave equation, which is shown as

$$\boldsymbol{G} = \nabla \times \mu^{-1} \nabla \times \boldsymbol{E} + \varepsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2} + \sigma \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{J}}{\partial t} = 0 \tag{2}$$

C. Sensitivity analysis

The optimization process involves obtaining the object function sensitivities, which is the gradient of object function by the perturbation of the design variables. A general approach for the analysis of the sensitivities is to evaluate through finite difference method. When this approach is used, the calculation is at least N+1 in the case where number of the design cell is N. Recently, AVM has been proposed for efficient estimation of design sensitivity [3]. In order to estimate the gradient of the object function, regardless of the number of parameters, AVM computation is only two times calculations of the electromagnetic field and the adjoint solution with respect to all design cells. The flow chart of our program is shown in Fig. 1.

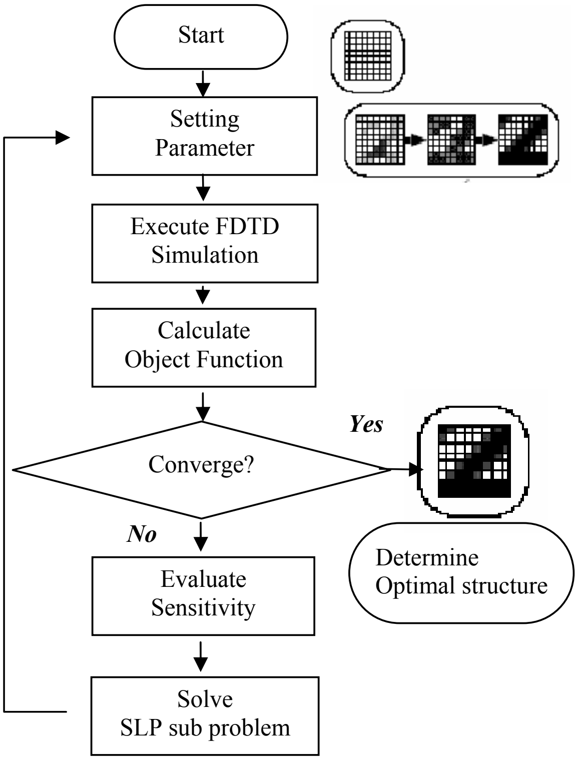


Fig. 1: Program flowchart

3. CONFORMATION OF CALCULATION ACCURACY

A. The analytical model and methods of analysis

Calculation accuracy of the AVM is a key point to solve optimization problem. In order to confirm this approach accuracy, sensitivity calculation result is compared between the finite difference method and AVM. The analytical model is shown in Fig. 2. The PIFA is placed on the infinite ground plane. The PIFA is designed to be operated at 2.4GHz. The analytical domain is surrounded with the perfectly matched layer absorbing boundary conditions (PML). The design domain is set under the antenna element. The coaxial cable is used in the antenna feed model, where the incident wave is a Gaussian pulse modulated by a sine function at 1.0GHz, bandwidth 500MHz. This analytical model is modeled with a resolution of $1\times1\times1$ mm. The FDTD simulation iterates 100 times, every calculation, the relative permittivity or the relative permeability in the design domain is updated in each calculation. The permittivity and the permeability value are increased by the uniform rate 0.1 from the value of the free space. This calculation has 2 cases, where the permittivity value is changed with a constant permeability, or the permeability value is changed with a constant permittivity.

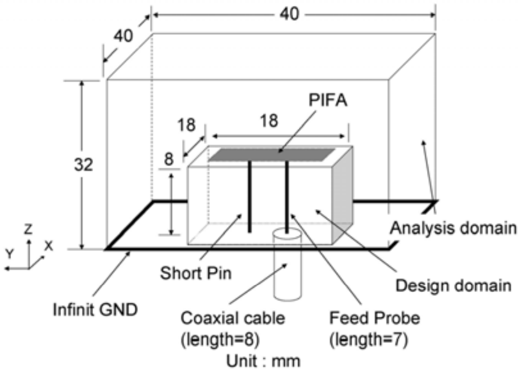
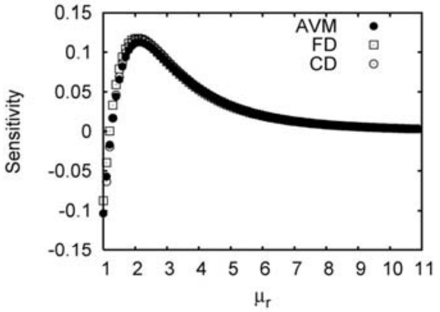


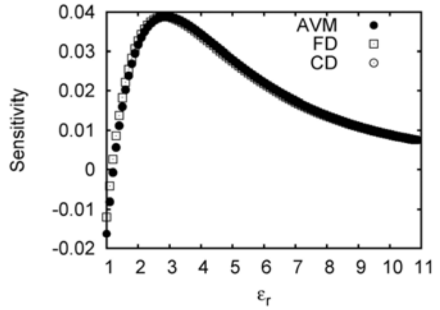
Fig. 2: The analytical model
(The PIFA is designed to be operated at 2.4GHz.)

B. Calculated results

The comparison between the results of the finite difference method and the AVM is shown in Fig. 3. The finite deference method results are given by Forward Difference (FD) and Centered Difference (CD). As a result, it is conformed that the results of AVM are in good agreement with the results of the finite difference method.



(a) Sensitivity when only permeability value is changed



(b) Sensitivity when only permittivity value is changed

Fig. 3: The results of comparison between the finite difference method and the AVM

4. CONSIDERATION OF μ_r AND ε_r

In this section, the degree to which the permeability or permittivity has an influence on lowering the VSWR frequency of PIFA is considered. In our previous study [1], it is found that the variation of permeability is more effective to reduce the lowest VSWR frequency, on the other hands, the variation of permittivity does not have the same effect. It is investigated whether similar result can be obtained by using the topology optimization approach.

A. Methods of the analysis

The analytical model is the same as the one, shown in Fig. 2. The optimization settings are shown in Table 1. This optimization problem is analyzed in 2 cases. As for one case, the relative permittivity is varied from 1 to 10 while the relative permeability is fixed to 1. As for the other case, the relative permeability is varied from 1 to 10 while the relative permittivity is fixed to 1. The other conditions are the same as each other. The results of each calculation results are compared.

TABLE 1: THE OPTIMIZATION SETTINGS

(a) Case 1

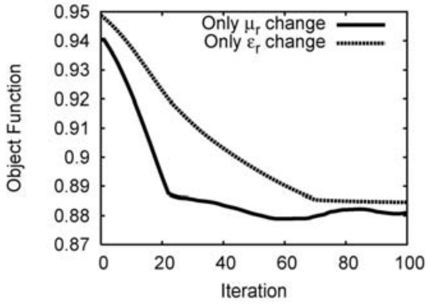
Incident wave	Modulated Gaussian pulse Center frequency = 1.0GHz Bandwidth = 500MHz	
Electric constant	Relative Permeability	Relative permittivity
	1～10	1
Loss	Loss less condition	

(b) Case 2

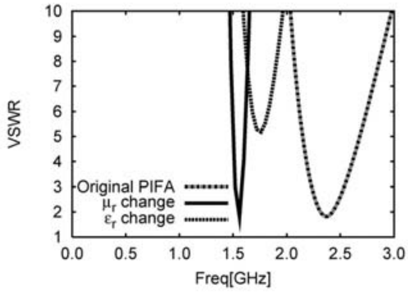
Incident wave	Modulated Gaussian pulse Center frequency = 1.0GHz Bandwidth = 500MHz	
Electric constant	Relative Permeability	Relative permittivity
	1	1～10
Loss	Loss less condition	

B. The results of two calculations

The results of two calculations are shown in Fig. 4. Fig. 4(a) shows the object function convergence locus for 2 calculations. When only the relative permeability is changed, the object functions converge in a small number of iteration. But when only the relative permittivity is changed, the convergence of the object function needs more iteration. In addition, when only the relative permittivity is changed, the convergence value is higher. Fig. 4(b) shows VSWR vs the Frequency at the convergence. For both cases, the resonance frequency lowers from that of the original PIFA. Resonance frequency when only the relative permeability is changed lowers more than that when only the relative permittivity is changed. As a result, it is confirmed that the permeability is more effective to lower resonance frequency compare with the permittivity, and topology optimization approach shows similar results to our previous study.



(a) The object function convergence locus for two calculations



(b) VSWR vs. frequency at convergence

Fig. 4: The results of two calculations

5. NUMERICAL EXAMPLE

On the basis of the results showed above, miniaturization of the PIFA by using topology optimization approach is applied.

A. Methods of the analysis

The analytical model is the same as the one, shown in Fig. 2. The optimization settings are shown in Table 2. The relative permittivity is varied form 1 to 13 while the relative permeability is varied from 1 to 2.5. These values are based on the electric constant of holding the magnetic material actually.

TABLE 2: THE OPTIMIZATION SETTINGS

Incident wave	Modulated Gaussian pulse Center frequency = 1.5GHz Bandwidth = 500MHz	
Electric constant	Relative Permeability	Relative permittivity
	1～2.5	1～13.0
Loss	Loss less condition	

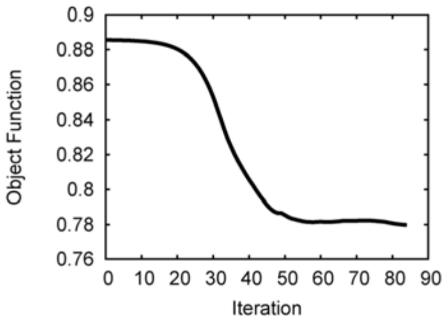


Fig. 5: The convergence locus of the object function

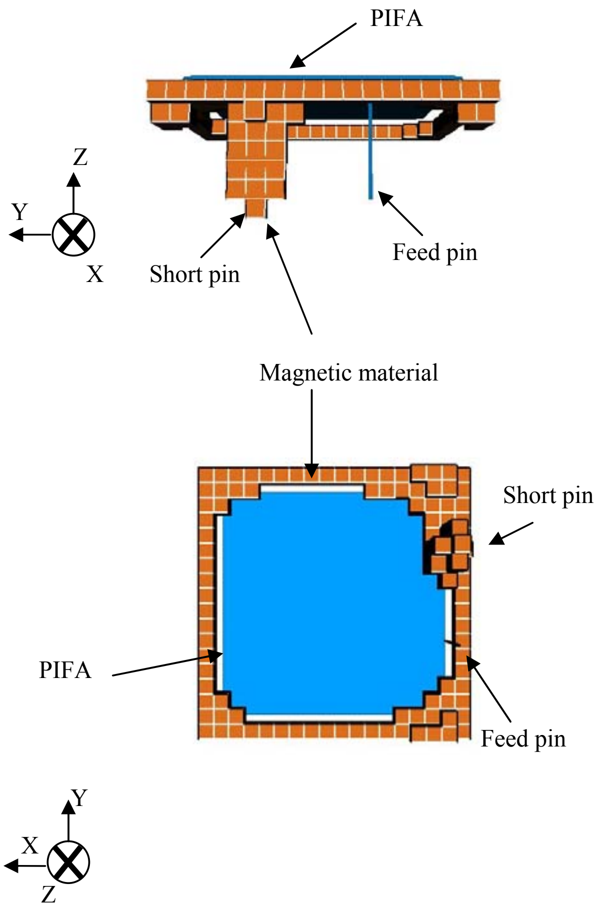


Fig. 6: The structure of the magnetic material at the convergence

B. The results of analysis by topology optimization approach

The convergence locus of the object function is shown in Fig. 5. It is found that the object function converges smoothly. Fig. 6 shows the structure of the magnetic material at the convergence. It is found that the magnetic material at the convergence has some features of the structure, such as wrapping the short pin, and forming a loop. The PIFA has the strong electric current on the feed and short pin and also backside of PIFA. It is considered that the structure of magnetic material is optimized to flow effectively the electric current. Fig. 7 shows VSWR vs. frequency. A decrease of 600MHz for the resonance frequency compared with the original PIFA is found.

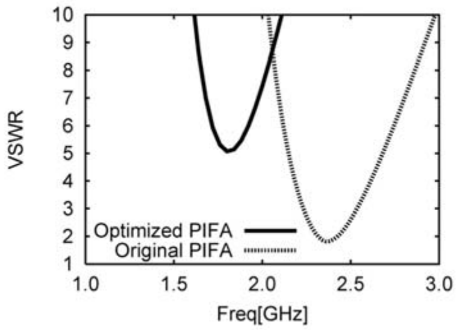


Fig. 7: VSWR vs. frequency at convergence

6. CONCLUSION

The objective of this study is to make sure of using the topology optimization method to design the structure of the magnetic material. As a result, topology optimization approach shows similar results to our previous study, and it is confirmed that the optimal configuration of magnetic materials can be obtained by using topology optimization approach. Therefore, it is found that topology optimization approach can be successfully applied to design the structure of magnetic materials for miniaturization of PIFA.

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