Shape Optimization of Wideband Antennas for Microwave Energy Harvesters Using FDTD

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This paper presents parameter and topology optimizations of wideband antennas for microwave energy harvesters based on FDTD computations. The antenna shapes are optimized to reduce return losses in a specific frequency band using micro genetic algorithm. The shape parameters of a two-arm planar spiral antenna (PSA) are optimized. Moreover, topology optimization is performed using normalized Gaussian network, where spatial symmetries are assumed. It is shown that the return losses of the optimized antennas are less than -10dB from 1.0GHz to 2.0GHz in which they have isotropic directivity.

Index Terms—Topology optimization, normalized Gaussian network (NGnet), Group Theory, FDTD method, energy harvesting.

I. INTRODUCTION

In recent years wireless sensors have attained great attentions for monitoring health and safety condition of constructions and natural environments. When wireless sensors have batteries as their power supply, it is laborious and expensive to charge batteries of wireless sensors located in difficult access environments. Energy harvesting allows us to realize wireless sensors which can operate autonomously.

Energy harvesters absorb energy from ambient environment. Many kinds of energy harvesters have been developed so far [1-3] because there are diverse forms of environmental energy such as sunlight, temperature difference and vibration.

The key element of a microwave energy-harvesting system is the rectenna [4] which consists of a receiving antenna and rectifier which converts the microwaves into DC power. For the efficient power absorption, various antenna shapes have been proposed [2] [5-6]. For uniform directivity, point, left- and right-rotational symmetries have been introduced to the antenna [7-9]. There are, however, few works where the shape of antennas for energy harvesters is optimized by metaheuristic approaches to realize wideband operations.

In this paper, we present the parameter and topology optimizations based on micro genetic algorithm (µGA) [10] to realize wideband antennas for energy harvesters. The return loss in a specified frequency band is minimized. The antenna properties are analyzed using FDTD method. The design parameters of a two-arm spiral antenna are optimized. Moreover, we perform topology optimization of the antenna using normalized Gaussian network (NGnet) [11] in which the antenna shape is expressed in terms of the linear combination of normalized Gaussian functions. We do not need design parameters to represent the shapes for the topology optimization. In our optimization, spatial symmetries are assumed for isotropic directivity. We will report the optimization results and compare the simulated properties with measured results of the manufactured antennas.

II. ANTENNA ANALYSIS

In this work, the frequency characteristics of antennas are computed using FDTD method [12] by which the frequency response in a wide frequency band can easily be computed. Let us consider the Maxwell equations

\[ \nabla \times \mathbf{E} + \mu \frac{\partial \mathbf{H}}{\partial t} = 0 \quad (1a) \]

\[ \nabla \times \mathbf{H} - \varepsilon \frac{\partial \mathbf{E}}{\partial t} = \mathbf{J} \quad (1b) \]

where \( \mathbf{E} \), \( \mathbf{H} \), \( \mathbf{J} \), \( \mu \) and \( \varepsilon \) are electric field, magnetic field, current density, permeability and permittivity, respectively. Equation (1) is discretized with FDTD method in which time and space derivatives are approximated by central finite differences to obtain

\[ E^n = \frac{1 - \frac{\sigma \Delta t}{2 \varepsilon}}{1 + \frac{\sigma \Delta t}{2 \varepsilon}} E^{n-1} + \frac{\Delta t}{1 + \frac{\sigma \Delta t}{2 \varepsilon}} \nabla \times H^{n-1/2} \]

\[ H^{n+1/2} = H^{n-1/2} + \frac{\mu}{\Delta t} \nabla \times E^n \]

where \( n \) and \( \sigma \) denote time step and conductivity. In the FDTD method, (2a) and (2b) are calculated alternately. The input impedance of the antennas are computed from the Fourier transform of the input voltage and current as follows:

\[ Z_{in}(f) = \frac{F[V_{in}(t)]}{F[I_{in}(t)]} \quad (3) \]

where \( V_{in}(t) \) and \( I_{in}(t) \) are the feeding voltage and current obtained by the FDTD analysis.

III. OPTIMIZATION METHOD

A. Parameter optimization

We consider the two-arm PSA using µGA because it has broad bandwidth characteristics [6]. In this study, design parameters are defined as shown in Fig. 1 and the optimization
is conducted by changing them using µGA. The two-arm PSA has 2-fold rotational symmetry, namely, that is identical after 360/2 degree rotation. This symmetry is expressed by the point group $C_2$ [13], that is,

$$C_2 = (e, a)$$

where $e$ and $a$ represent the identity operation and counter clockwise rotation of 360/2 degrees around a feeding point, respectively.

**B. Topology optimization**

1) Representation of antenna shape

In the topology optimization, we can flexibly change the antenna shapes. However, the antenna for energy harvesting, in which we cannot assume any polarization in microwaves, should have spatial symmetry to have isotropic directivity. For this reason, we assume $C_2$ and the following symmetries:

$$D_1 = (e, b)$$

$$C_4 = (e, a, a^2, a^3)$$

$$D_2 = (e, a, b, ba)$$

In the groups $C_n$ and $D_n$, $a$ and $b$ denote 360/$n$ degree rotation around the center in the two-dimensional plane, and fold around the central horizontal axis. Fig. 2 depicts the shapes which have the above symmetries. The shape in the unit region, symbolized by “F”, is optimized. There is redundancy in the symmetric assumptions because $C_4$- and $D_2$-symmetric shapes also have $C_2$ and $D_1$ symmetries, respectively.

It is difficult to find the global optimum in the topology optimization which has high DoFs. Even if the global optimum has, for example, $C_4$ symmetry, it would be difficult to find it assuming $C_2$ symmetry. This is the reason why we consider $C_4$ and $D_2$ symmetries.

2) Optimization method

For the topology optimization, we employ the NGnet whose output is given by the linear combination of the normalized Gaussian functions shown in Fig. 3, that is,

$$y(x) = \sum_{i=1}^{N} w_i b_i(x)$$

$$b_i(x) = G_i(x) / \sum_{k=1}^{N} G_k(x)$$

where $G_i(x)$ and $w_i$ denote the Gaussian function and weighting coefficient, respectively. We uniformly deploy 81 Gaussians in the square unit region as shown in Fig. 4. For models in (a) and (b) in Fig. 2, we place two square unit regions. The standard deviation in the Gaussian is set to 50/16 mm. The size of the FDTD cells is set to 1 mm. The perfect conductor condition is imposed to the surface of the FDTD cell corresponding to the antenna. The state $s_e$ of each FDTD-cell surface is determined from the output of the NGnet at its center $x_e$ as follows:

$$s_e = \begin{cases} 
  \text{conductor} & y(x_e) \geq 0 \\
  \text{air} & y(x_e) < 0
\end{cases}$$

The optimization is conducted by changing the value of $w_i$ in (6a) using µGA.
where
\[ S_{11}(f) = 20 \log_{10} \frac{Z_{in}(f) - Z_0}{Z_{in}(f) + Z_0} \] (8b)
and \( Z_{in}(f) \) and \( S_{11}(f) \) are the input impedance and return loss of the antenna. The values of \( Z_0, f_0 \) and \( f_1 \) are set to 50\( \Omega \), 1.0GHz, 2.0 GHz, respectively. In the analysis, the antenna is assumed to have infinitely thin metallic surface which is loaded by a dielectric sheet of 2mm thick and \( \varepsilon_r = 4 \). Moreover, a feeding point is assumed to be at the center of the design region. The computational times for the parameter and topology optimization are almost identical. In \( \mu \)GA, the number of individuals is set to 8 and the optimization is conducted over 100 generations. In this setting it takes about 3 days to obtain final solution using the Intel Xeon CPU (2.4GHz, 4 cores).

V. OPTIMIZATION RESULTS

The results of the optimization are summarized in Table I. For reference, the result of the topology optimization without assumption of symmetry is included (represented by \( E \)). It is found that the best fitness is obtained for \( D_1 \) symmetry. There are no significant differences in the fitness values for the two-arm PSA and \( C_2^-, \ C_2^+, \ D_2^- \)-symmetric antennas. We find that the \( D_1^- \) and \( D_2^- \)-symmetric solutions have anisotropic directivities. Moreover, we find that \( C_2^- \)-symmetric antenna has rather narrow band. For this reason, we choose PSA and \( C_4^- \)-symmetric antenna for further considerations. Figure 5 shows the shapes of these two antennas, while the shapes with other symmetry are shown in Fig. 6 for reference. The \( C_4^- \)-symmetric antenna has a floating metal which surrounds the four-arm metal connected to the feeding point. We manufacture these antennas on the dielectric substrate (NZ-G31KR) which are shown in Fig.7.

The return losses \( S_{11} \) are plotted as a function of frequency in Fig. 8. The measurement results for the manufactured antennas are also plotted, where they are measured by E5061B Network Analyzer. We find that both return losses are lower than -10dB from 1GHz to 2GHz. There are some discrepancies between the computed and measured profiles. These discrepancies would be attributed to deviation in the permittivity in the substrate and metallic loss. We also find two clear resonances in the profile of the two-arm PSA, whereas \( C_4^- \)-symmetric antenna has rather flat profile.

The radiation patterns obtained by FDTD analysis are shown in Figs. 9 and 10. Both are found to have almost isotropic directivities which are suitable for energy harvesting.

![Fig. 5 Selected optimized antennas](image)

![Fig. 6 Antenna Shapes obtained by topology optimization](image)

![Fig. 7 Manufactured antennas](image)

![Fig. 8 Return losses \( S_{11} \)](image)

<table>
<thead>
<tr>
<th>Symmetries</th>
<th>( &lt;S_{11}&gt; )</th>
<th>Directivity ( (E_{max}/E_{min}) ) (xy-plane, xz-plane) [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E )</td>
<td>-7.68</td>
<td>(-10.5, -8.6)</td>
</tr>
<tr>
<td>( C_2^- )</td>
<td>-13.72</td>
<td>(-12.6, -6.7)</td>
</tr>
<tr>
<td>( D_1^- )</td>
<td>-19.00</td>
<td>(-13.7, -34.2)</td>
</tr>
<tr>
<td>( D_2^- )</td>
<td>-14.39</td>
<td>(-2.6, -38.2)</td>
</tr>
<tr>
<td>two-arm PSA*</td>
<td>-14.49</td>
<td>(-5.0, -13.9)</td>
</tr>
<tr>
<td>( C_4^- )</td>
<td>-14.81</td>
<td>(-5.7, -14.8)</td>
</tr>
</tbody>
</table>

* \( (W_0, W_1, \ldots, W_7) = (8.0, 8.0, 4.0, 6.0, 4.0, 2.0, 3.0, 9.0) \) [mm]
Current density distributions are shown in Figs. 11 and 12 at 1.0 GHz and 2.25GHz. We can see in these figures that there are local currents concentrating near the feeding point at 1GHz while the global currents exist at 2.25GHz. For wide frequency operations, we need sufficiently rich complexity in the antenna shape, which are realized by the topology optimization.

VI. CONCLUSION

In this paper, we have proposed two kinds of antennas for energy harvesters obtained by parameter and topology optimization. The shape parameters of the two-arm PSA are optimized. Moreover, topology optimization is performed assuming spatial symmetries to have isotropic directivity. The measured and computed return losses are lower than -10dB from 1GHz to 2GHz. The optimized two-arm PSA and $C_4$ symmetric antenna have almost the same performance. We plan to develop antennas which have more wide operating range using the present topology optimization.

REFERENCES


