Topology Optimization of Self-Complementary Antenna for Microwave Energy Harvesters

Takuya Mori and Hajime Igarashi

Graduate School of Information Science and Technology, Hokkaido University, 060-0814, Sapporo, Japan

This paper presents topology optimization of self-complementary antennas (SCA) for microwave energy harvesters for wireless sensors. The antenna shapes are optimized to maximize isotropic gain and reduce return loss in a given frequency band using the micro genetic algorithm and FDTD computation. For the topology optimization, we employ the normalized Gaussian network. The self-complementary antenna is realized by taking its spatial symmetries into account. It is shown that the actual gain of the optimized SCA is more than 5dBi from 2.0GHz to 3.0GHz.

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

I. INTRODUCTION

ENERGY harvesting devices harvest power from ambient mechanical vibration, electromagnetic waves, wind and so on to drive low-power sensors and circuits [1-3]. This technology is especially useful for battery-less sensors used for monitoring health and safety condition of constructions and natural environments. The microwave energy harvester transforms the ambient microwave energy to DC power which is supplied to sensor systems. The microwave energy-harvesting device is composed of a receiving antenna and rectifier which converts the microwaves into DC power. For the efficient power absorption, broadband and high-gain antennas are required. For this purpose, the authors have developed the optimized spiral antenna as well as planar antenna whose shape is optimized by topology optimization [4]. The self-complementary antenna (SCA) [5], which has congruent metal and slot shapes, would be suitable for microwave energy harvesters due to its wide frequency ranges. However, there have been few works where the shape of self-complementary antennas is optimized to realize wideband operations.

In this paper, we present the topology optimization of SCA based on the micro genetic algorithm (μGA) [6] to realize high-gain and wideband antennas for energy harvesters. The return loss is minimized and simultaneously the isotropic gain is maximized in a specified frequency band. The antenna properties are analyzed using FDTD method [7]. We perform topology optimization of SCA using the normalized Gaussian network (NGnet) [8] 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 this topology optimization. The self-complementary topology is realized by taking spatial symmetries into account. We will compare the optimized SCA with other antennas from various points of view.

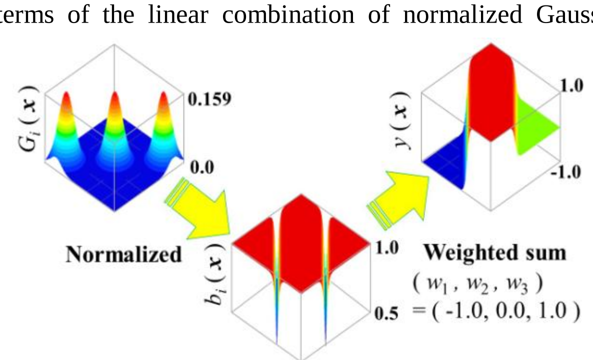


Fig. 1. Gaussians, normalized Gaussians, and output of NGnet.

II. OPTIMIZATION OF SELF-COMPLEMENTARY ANTENNA

For the topology optimization of SCA, we employ the NGnet [8] in which the output is computed from the normalized Gaussian functions as follows:

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

$$b_i(\boldsymbol{x}) = G_i(\boldsymbol{x}) \Big/ \sum_{k=1}^{N} G_k(\boldsymbol{x}) \tag{2}$$

where $G_k(\boldsymbol{x})$ and $\boldsymbol{w}_i$ denote the Gaussian function and weighting coefficient, respectively (see Fig.1). To express the SCA shapes, 81 Gaussians are uniformly located as shown in Fig. 2. The standard deviation in the Gaussian is set to 50/16 mm, while the size of the FDTD cells is set to 1mm. The antenna is modeled as a perfect conductor in the FDTD computation. The material state s_e of each FDTD-cell surface is determined from the output of the NGnet at its center $\boldsymbol{x}_e$ as follows:

$$s_e = \begin{cases} \text{conductor} & y(\boldsymbol{x}_e) \geq 0 \\ \text{air} & y(\boldsymbol{x}_e) < 0 \end{cases} \tag{3}$$

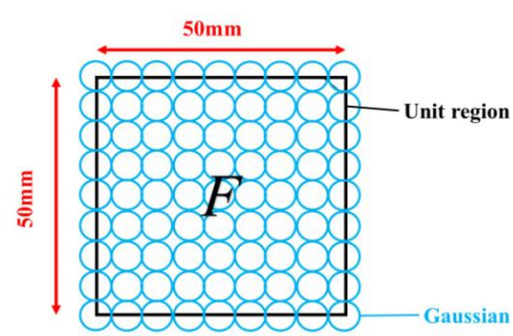


Fig. 2. Gaussians distributed in unit region

The antenna shape in the unit region, symbolized by "*F*" in Fig.3, is determined by optimizing the weighting coefficients w_i in (1) using μGA. The SCA shape is modeled by introducing point symmetry around the feeding point as shown in Fig. 3. The region symbolized with "F^{-1}" represents the complementary domain to *F*; the metallic region in *F* is converted to air, and vice versa.

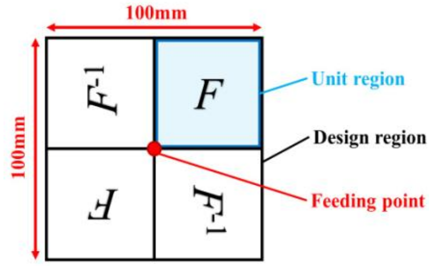


Fig. 3. Modeling of the self-complementary antenna

III. Optimization Problem

The antenna shape is optimized to maximize the isotropic gain G_{iso} of SCA in consideration of mismatch losses between the antenna and Z_0 transmission line over the frequency band from f_0 to f_1 using μGA [6]. For this purpose, we introduce the actual gain G_{actual} to define the optimization problem as follows:

$$
\begin{aligned}
&< G_{\text{actual}} > = \frac{\int_{f_0}^{f_1} G_{\text{actual}}(f)\,\mathrm{d}f}{f_1 - f_0} \to \max \\
&G_{\text{actual}}(f) = G_{\text{iso}}(f)\left(1 - \left|\frac{Z_{\text{in}}(f) - Z_0}{Z_{\text{in}}(f) + Z_0}\right|^2\right)
\end{aligned}
\tag{4}
$$

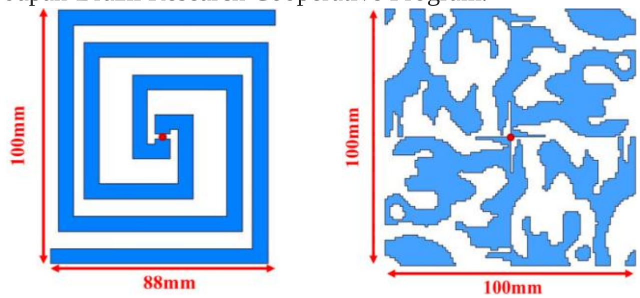
where $Z_{in}(f)$ is the input impedance of the antenna. In optimization, f_0, f_1 and Z_0 are set to 2.0GHz, 3.0GHz and 50Ω, respectively. In the analysis, the antenna is assumed to be on a dielectric sheet of 2mm thick and $\varepsilon_r = 4$. The feeding point is located at the center of the design region. For comparison, the parameter optimization of planar spiral antenna (PSA) [4], which has a point-symmetrical shape, is carried out under (4).

In μGA, the number of individuals is set to 8 and the optimization processes are continued for 200 generations. In this setting it takes about 7 days to obtain the final results using the *Intel Xeon CPU* (2.4GHz, 8cores).

IV. Optimization Results

The optimized SCA shape is shown in Fig.4 and its return losses, actual and isotropic gains are shown in Figs. 5 and 6, respectively. From Fig. 5, it is found that the return losses of both antennas are less than -10dB over the target frequency range. On the other hand, we find in Fig.6 that the actual gain of SCA is higher than that of PSA and the former is more than 5dBi over the target frequency range. In the full paper, we will report the experimental results for the manufactured microwave energy harvester equipped with SCA and PSA to discuss their performance for real uses.

This work was supported in part by JSPS KAKENHI Grant Number 24310117, as well as JSPS and CAPES under the Japan-Brazil Research Cooperative Program.



(a) Optimized PSA (parameter optimization) (b) Optimized SCA (topology optimization)

Fig. 4 Shapes of optimized antennas

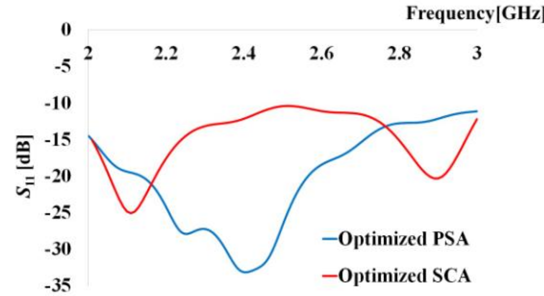


Fig. 5. Return losses

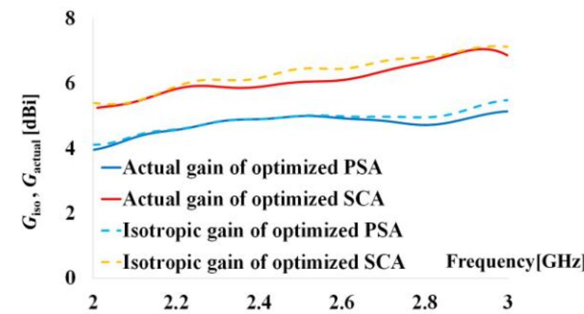


Fig. 6. Actual and isotropic gains

References

[1] L. C. Blystad, et. al, "Piezoelectric MEMS energy harvesting systems driven by harmonic and random vibrations," *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, vol. 57, Apr. 2010, pp. 908-19

[2] D. Bouchouicha, et. al, "Ambient RF Energy Harvesting," *International Conference on Renewable Energies and Power Quality (ICREPQ'10)*, March, 2010

[3] C. Lu, et. al, "Maximum Power Point Considerations in Micro-Scale Solar Energy Harvesting Systems," *ISCAS 2010*, pp. 273-276

[4] T. Mori, et. al, "Shape Optimization of Wideband Antennas for Microwave Energy Harvesters Using FDTD" *IEEE Trans. Magn.*, 2015 (to be published)

[5] A. Kumar, et. al, "Design and Analysis of CPW-fed Quasi-Self-Complementary Pentagonal Antenna for Ultra-wideband Systems," *International Conference on Signal Propagation and Computer Technology*, pp. 754-757, 2014

[6] C. Coello and G. Pulido, "A Micro-Genetic Algorithm for Multiobjective Optimization," Lecture Notes in Computer Science, Volume 1993, pp. 126-140, 2001

[7] A. Taflove. *Computational Electrodynamics: The Finite Difference Time-Domain Method*. Norwood, MA: Artech House, 1996

[8] T. Sato, et. al, "Topology Optimization Considering Multimaterial Distributions Based on Normalized Gaussian Network," *IEEE Trans. Magn.*, 2015 (to be published)