



HOKKAIDO UNIVERSITY

Title	Topology optimization of wideband array antenna for microwave energy harvester
Author(s)	Mori, Takuya; Igarashi, Hajime
Citation	International journal of applied electromagnetics and mechanics, 52(1-2), 631-639 https://doi.org/10.3233/JAE-162057
Issue Date	2016
Doc URL	https://hdl.handle.net/2115/64700
Rights	The final publication is available at IOS Press through http://dx.doi.org/10.3233/JAE-162057
Type	journal article
File Information	ISEM2015_Full_tmori_ver4.pdf



Topology Optimization of Wideband Array Antenna for Microwave Energy Harvester

Takuya Mori and Hajime Igarashi

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

Abstract. This paper presents optimal shape design of planar array antennas for microwave energy harvesters. The topology optimization of the C_4 -symmetric array antenna is conducted to maximize their isotropic gain and minimize the return losses in a frequency band ranging from 1.5 to 3.5 GHz. Then, we design the rectifier by varying the circuit parameter based on measurement results to realize the impedance matching between the optimized antenna and rectifier. It is shown by experiment that the harvester composed of the optimized array antenna and rectifier has higher receiving voltage in comparison with the single one. Moreover, the resultant harvester is found to start operating when the arrival electric field is greater than 0.1 V/m.

Keywords: Microwave energy harvester, wideband antenna, topology optimization, array antenna

1. Introduction

In recent years, wireless sensors have attained great attentions for monitoring health and safety conditions of infrastructures such as bridge, tunnel and rail ways. When wireless sensors have batteries as their power supply, it is laborious and expensive to replace huge number of the batteries in the sensors distributed in environment. Therefore, wireless sensors which can operate autonomously are required.

The microwave energy harvesting devices which absorb energy from ambient microwaves are promising for the energy sources of the wireless sensors [1-3]. The microwave energy harvester is composed of a receiving antenna and rectifier. Arrival microwave is received by the antenna and the rectifier converts the received microwaves into DC power. To develop the high-efficiency microwave energy harvester, the antenna shape and circuit parameters are optimally designed.

For efficient power generation, the authors have developed the spiral antenna as well as C_4 -symmetric antenna whose shapes are determined by parameter and topology optimizations, respectively [4]. It has been found that the C_4 -symmetric antenna has better characteristics. We expect that the performance would be further improved by arraying C_4 -symmetric antennas.

In this study, we develop a microwave harvester which includes an array antenna composed of four identical C_4 -symmetric antennas. The shape of the C_4 -symmetric antenna is determined by topology optimization using the micro genetic algorithm (μ GA) [5] to realize high-gain and wideband characteristics. The performance of the antenna is computed by FDTD method [6]. For comparison, a single C_4 -symmetric antenna is also developed by topology optimization. We here focus on energy harvesting from microwaves generated by a wireless router using the optimized antenna, whose frequency is assumed to be 2.45GHz. We determine the size of the rectifier and stub length so that it is matched to the antenna at 2.45GHz by varying the circuit parameter based on measurement results. We test the performance of the developed microwave harvester by experiments.

2. Antenna analysis for array antenna

The frequency characteristics of antennas are computed using FDTD method [6] in this study, which allows us to effectively compute the frequency characteristics in a wide band. 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 $\mathbf{E}$, $\mathbf{H}$, $\mathbf{J}$, μ and ε are electric field, magnetic field, current density, permeability and permittivity, respectively. Equation (1) is discretized with the FDTD method where time and space derivatives are approximated by central finite differences.

In this study, the antenna is printed on a dielectric substrate whose relative permittivity and thickness are set to 4.4 and 2.0mm, respectively. The Gaussian pulse is fed at the feeding port of the antenna and its input impedance is computed from the Fourier transform of the input voltage and current as follows:

$$Z_{in}(f) = \frac{F[V_{in}(t)]}{F[I_{in}(t)]} \quad (2)$$

where $V_{in}(t)$ and $I_{in}(t)$ are the feeding voltage and current obtained by the FDTD analysis. For analysis of the array antenna, Gaussian pulses are fed simultaneously at the feeding points of each antenna to consider the interference each other. The other conditions in FDTD analysis are summarized in Table I.

Table I
FDTD conditions in the optimization

NX×NY×NZ	150×60×150
($\Delta X, \Delta Y, \Delta Z$)	(1.0, 1.0, 1.0) [mm]
Δt	1.9×10^{-12} [sec]
Number of time steps	3000
Boundary condition	Perfect Matched Layer (10 layers)

3. Topology optimization method of wideband array antenna using NGnet

For the topology optimization, we represent the antenna shape with a linear combination of the normalized Gaussian functions given by [8]

$$y(\mathbf{x}) = \sum_{i=1}^N w_i b_i(\mathbf{x}) \quad (3)$$

$$b_i(\mathbf{x}) = G_i(\mathbf{x}) / \sum_{k=1}^N G_k(\mathbf{x}) \quad (4)$$

where $G_k(\mathbf{x})$ and w_i denote the Gaussian function and weighting coefficient, respectively (see Fig. 1). To express the C_4 -symmetric shapes, we introduce the unit region, symbolized by “ F ”, and the centers of 81 Gaussian functions are uniformly deployed so that the domain is covered by the support of the Gaussians as shown in Fig. 2(a). The antenna shape in the unit region is determined by optimizing the weighting coefficients w_i in (3) using μ GA. The edge length of the FDTD cubic cell is set to 1mm. The antenna is modeled as a perfect conductor in the FDTD computation. The state s_e of each FDTD-cell at its center $\mathbf{x}_e$ is determined from y as follows:

$$s_e = \begin{cases} \text{conductor} & y(\mathbf{x}_e) \geq 0 \\ \text{air} & y(\mathbf{x}_e) < 0 \end{cases} \quad (5)$$

A C_4 -symmetric antenna is modeled by introducing point symmetry around the feeding point surrounded by four unit regions as shown in Fig. 2(b) and (c). The array antenna is composed of four C_4 -symmetric antennas. For comparison, the single C_4 -symmetric antenna is also considered as shown in Fig.2(c). The standard deviations of G_i are set to 24/16 mm and 50/16mm for the topology optimization of the array and single antenna, respectively.

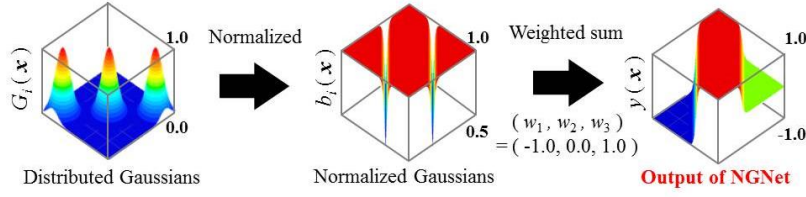
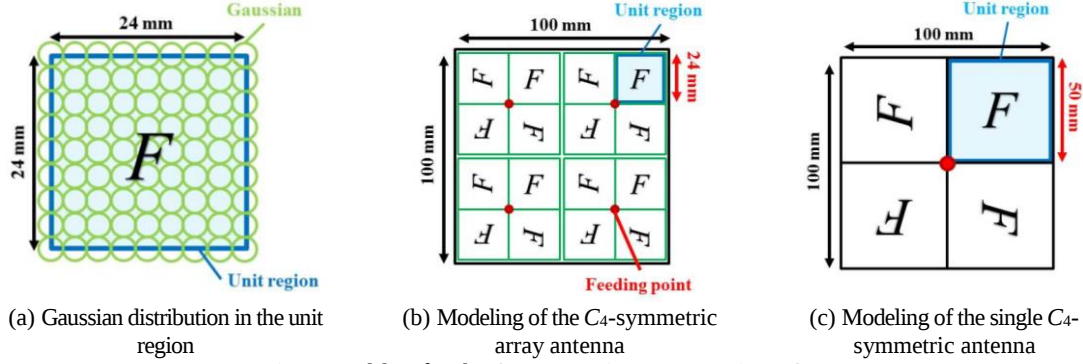


Fig. 1. The output of NGnet.

Fig. 2. Modeling for the C_4 -symmetric antennas using NGnet.

4. Optimization problem

The antenna shape is optimized to maximize the isotropic gain G_{iso} in consideration of mismatch losses between the antenna and circuit over the frequency band ranging from f_0 to f_1 . For this purpose, we introduce the actual gain G_{actual} to define the optimization problem as follows:

$$\begin{aligned} \langle G_{actual} \rangle &= \frac{\int_{f_0}^{f_1} G_{actual}(f) df}{f_1 - f_0} \rightarrow \max \\ G_{actual}(f) &= G_{iso}(f) \left(1 - \left| \frac{Z_{in}(f) - Z_0}{Z_{in}(f) + Z_0} \right|^2 \right) \end{aligned} \quad (6)$$

where $Z_{in}(f)$ is the input impedance of the antenna. In the optimization, f_0 , f_1 and Z_0 are set to 1.5GHz, 3.5GHz and 50Ω , respectively. The gain and input impedance are computed by the FDTD method. We use μ GA [5] to solve the optimization problem (6), in which the number of individuals is set to 8 and the optimization processes are continued for 100 generations. In this setting it takes about 4 days to obtain the final results using the *Intel Xeon CPU* (2.4GHz, 8cores).

5. Optimization results for wideband antenna

The resultant shapes of the optimization are shown in Fig. 3 and the return losses between the optimized antenna and 50Ω resistance are shown in Fig. 4 where the numbers from 1 to 4 represent the position of antennas in the array antenna. Their actual gains are also plotted against frequency in Fig. 5. It is indicated in Fig. 4 that the return losses of the array antenna are less than -10dB over the target frequency range while the single antenna has larger mismatch losses. It is found from Fig. 5 that the actual gain of the optimized C_4 -symmetric array antenna is higher than that of the single antenna, and the former is more than 5dBi over the target frequency range.

We evaluate the power received by the array antenna illuminated by plane waves using FDTD analysis. In the analysis, the frequency of the plane wave and electric field intensity are set to 2.45GHz and 10V/m, respectively. To consider the effect of the impedance matching between the antenna and circuit, the feeding port is loaded with resistance of 50Ω .

The voltages induced at the load resistances are shown in Fig. 6 where the received voltage of the array antenna is the linear sum of the voltages induced by four C_4 -symmetric antennas. We find that the amplitude of received voltage of the array antenna is about 1.7 times higher than that of the single one. Accordingly, the received power is increased by about 3.0 times by using the array antenna.

6. Measurement results

6.1. The frequency characteristics of the optimized antennas

The computed and measured frequency characteristics of the input impedances Z_{in} of the array and single antennas are plotted in Fig. 7. They are printed on the dielectric substrate made of FR-4 and we used E5061B Network Analyzer for measurement. From these figures, we find that there are some discrepancies between the computed and measured profiles. These discrepancies would mainly be attributed to the manufacturing error and unexpected losses of the dielectric substrate. Then, we design the rectifier considering impedance matching to the optimized antennas at 2.45GHz based on these measurement results.

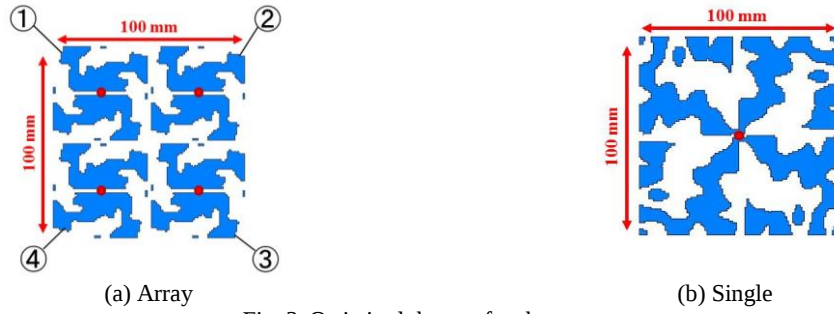


Fig. 3. Optimized shapes of each antenna.

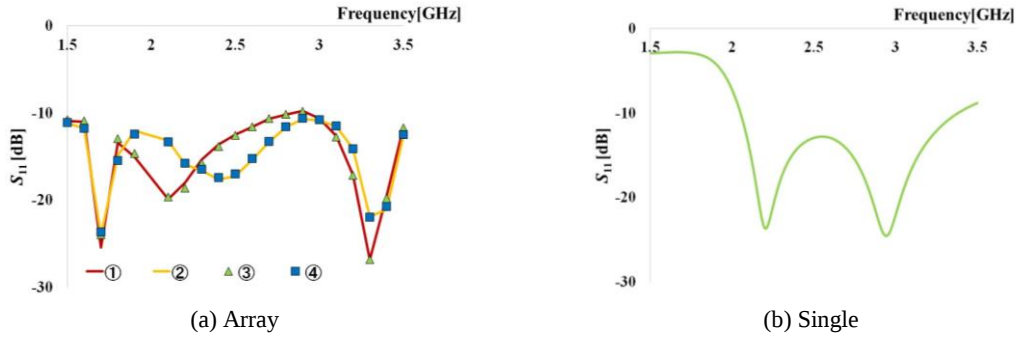


Fig. 4. Computed return losses of each antenna.

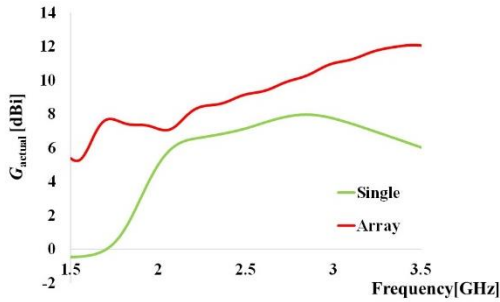


Fig. 5. Computed actual gains of each antenna.

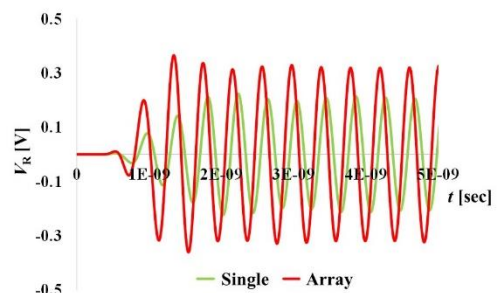


Fig. 6. Computed received voltages.

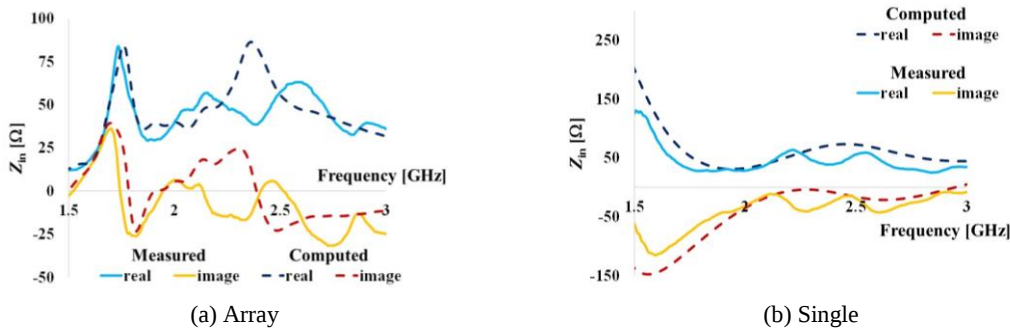
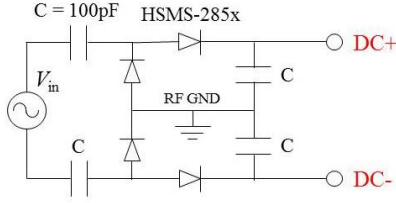


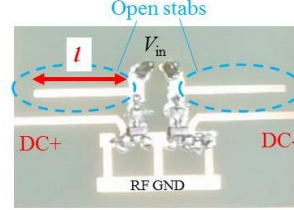
Fig. 7. Measured input impedance of each antenna.

6.1. Design of rectifier

For the rectifying circuit, we employ the single-stage full-wave Greinacher rectifier [9] shown in Fig. 8. For the diodes, we employ HSMS285x zero-bias Schottky-barrier diode [10] and the capacitance is set to 100pF. In this study, the open stabs are add to this rectifier (see Fig. 8(b)) and we determine the overall size of the rectifier and the stab length l by trial and error to have impedance matching between the antenna and rectifier at 2.45GHz. It is found that the array and single antenna have the minimum return losses when l is 15mm and 8mm, respectively. The measured return losses between the each antenna and designed rectifier are shown in Fig. 9. From the figure, both return losses at 2.45GHz are lower than -20dB.

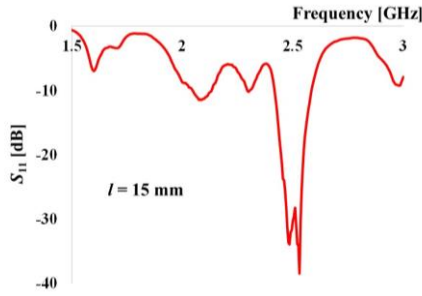


(a) Circuit diagram

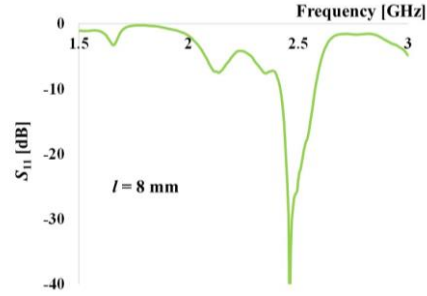


(b) Manufactured rectifier

Fig. 8. Design of the single-stage full-wave Greinacher rectifier.



(a) Array



(b) Single

Fig. 9. Measured return loss S_{11} between the antenna and circuit.

6.2. Radio reception experiment

The manufactured microwave harvester composed of the array antenna and the rectifier circuit printed on the back side is shown in Fig. 10. The harvester which contains the single antenna is also developed. They are printed on the same dielectric substrate (FR-4). The microwave radiated by the horn antenna is received by these harvesters as shown in Fig. 11. The distance between the harvesters and the transmitting horn antenna is set to 50cm and the frequency of microwave is set to 2.45GHz.

The measured output voltages of the rectifier is plotted versus the input electric field evaluated from Friis formula in Fig. 12. It is clearly seen from Fig. 12(a) that the output voltage of the harvester with the array antenna is higher than that with the single one. For example, when the electric field intensity E is 10V/m, the former output voltage is about 1.5 times higher than that of the latter. These results are consistent with the analysis results. From Fig. 12(b), it is found that when the electric field strength is larger than about 0.1 V/m, both harvesters can work. This suggests that these harvesters can get power from the microwaves radiated by usual routers in indoor environment [7].

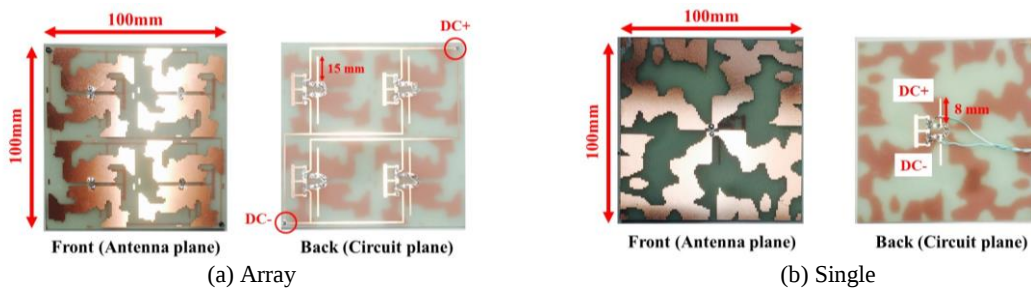


Fig. 10. Manufactured harvesters composed of optimized antennas and rectifiers.

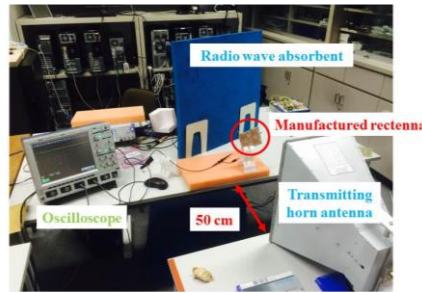
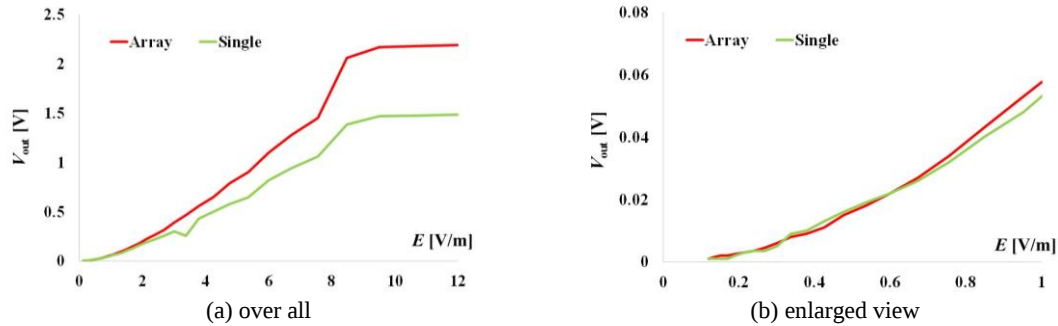


Fig. 11. Experimental setup.

Fig. 12. Measured output voltages V_{out} of each harvester.

7. Conclusions

In this paper, we have presented optimal antenna design for microwave energy harvesters. The shapes of the array and single antenna have been determined so that the actual gain is maximized. Actual gains and return losses from 1.5GHz to 3.5GHz of optimized C_4 -symmetry array antenna are more than 5dBi and less than -10dB, respectively. The rectifier has been designed by trial and error based on measured frequency characteristics of the optimized antenna aiming at impedance matching. The measured receiving voltage of the harvester composed of the array antenna is higher than that of the single one by about 1.5 times. These harvesters start working when the input electric field is stronger than about 0.1V/m. We will implement the power management system in these harvesters and use it as a power source of a wireless sensor.

Acknowledgements

This work was supported in part by JSPS KAKENHI Grant Number 15H02976, as well as JSPS and CAPES under the Japan-Brazil Research Cooperative Program.

References

- [1] D. Bouchouicha, et. al., "Ultra-efficient microwave harvesting system for battery-less micropower microcontroller platform," *IET Microw. Antennas Propag.*, vol. 5, iss. 7, pp. 811-917, 2011.
- [2] K. W. Lui, et. al., "Ambient RF Energy Harvesting," *International Conference on Renewable Energies and Power Quality (ICREPQ'10)*, March, 2010.
- [3] R. Shigeta, et. al., "Ambient RF Energy Harvesting Sensor Device With Capacitor-Lakage-Aware Duty Cycle Control," *IEEE Sensors Journal*, vol.13, no. 8, pp. 2973-2983, August, 2013.
- [4] T. Mori, et. al, "Shape Optimization of Wideband Antennas for Microwave Energy Harvesters Using FDTD" *IEEE Trans. Magn.*, vol. 51, No. 3, March, 2015.
- [5] C. Coello and G. Pulido, "A Micro-Genetic Algorithm for Multiobjective Optimization," *Lecture Notes in Computer Science*, Volume 1993, pp. 126-140, 2001.
- [6] A. Taflove. *Computational Electrodynamics: The Finite Difference Time-Domain Method*. Norwood, MA: Artech House, 1996.
- [7] H. J. Visser, et al., "Ambient RF Energy Scavenging: GSM and WLAN Power Density Measurements", *Proc. The 38th European Microwave Conference*, pp. 721-724, 2008.
- [8] T. Sato, et. al, "Topology Optimization Considering Multimaterial Distributions Based on Normalized Gaussian Network," *IEEE Trans. Magn.*, vol. 51, No. 3, March, 2015.
- [9] U. Olgun, C. -C. Chen, J. L. Volakis, "Design of an efficient ambient WiFi energy harvesting system" *IET Microwaves, Antennas & Propagation*, vol. 6, iss. 11, pp. 1200-1206, 2012.
- [10] Avago Technologies, "HSMS-285x surface mount RF Schottky barrier diodes," <http://www.avagotech.com/docs/AVO02-1377EN>, 2010.