Folded dipole antenna with class-F load function for rectenna of microwave power transfer

Takase Oshima\textsuperscript{1} and Hiroshi Hirayama\textsuperscript{1, a)}

\textsuperscript{1} Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, Aichi 466–8555, Japan
\textsuperscript{a)} hirayama_hiroshi@m.ieice.org

Abstract: A folded dipole antenna with a class-F load, acting as a receiving antenna for microwave wireless power transfer, is proposed. Conventionally, a class-F load circuit and matching circuit are connected to a rectifier circuit. A capacitor is used to adjust the impedance for harmonic waves. The proposed antenna involves both the class-F load and matching circuit functions to decrease loss in the circuit and reduce space usage. The antenna design was optimized and demonstrated to verify the class-F function.

Keywords: microwave power transfer, class-F load, folded dipole antenna

Classification: Antennas and Propagation

References

[1] K. Hatano, N. Shinohara, T. Mitani, T. Seki, and M. Kawashima, “Development of improved 24GHz-band class-F load rectenna,” \textit{IEEE Trans. Microw. Theory Techn.}, pp. 163–166, June 2012. DOI: 10.1109/imws.2012.6215776

[2] C. Trask, “Class-F amplifier loading networks a unified design approach,” IEEE MTT-S International Microwave Symposium Digest, pp. 351–354, June 1999. DOI: 10.1109/mwsym.1999.779491

[3] P. Colantonio, F. Giannini, G. Leuzzi, and E. Limiti, “On the class-F power amplifier design,” \textit{RF and Microwave Computer-Aided Engineering}, vol. 9, no. 2, pp. 129–149, March 1999. DOI: 10.1002/(SICI)1099-047X (199903)9:2<129::AID-MMCE7>3.0.CO;2-U

[4] E. Aggrawal, K. Rawat, and P. Roblin, “Investigating continuous class-F power amplifier using nonlinear embedding model,” \textit{IEEE Microw. Wireless Compon.}, vol. 27, no. 6, pp. 593–595, June 2017. DOI: 10.1109/lmwc.2017.2701316

[5] R.A. Beltran, “Class-F and inverse class-F power amplifier lading networks design based upon transmission zeros,” IEEE MTT-S International Microwave Symposium, pp. 1–4, June 2014. DOI: 10.1109/mwsym.2014.6848269

[6] G.A. Elis and S. Liw, “Active planar inverted-F antennas for wireless applications,” \textit{IEEE Trans. Antennas Propag.}, vol. 51, no. 10, pp. 2899–2906, Oct. 2003. DOI: 10.1109/tap.2003.818007

[7] T. Nishio, K. Noguchi, K. Itoh, and J. Ida, “A high impedance folded dipole antenna with three conductors for energy harvesting applications,” IEEE ISAP 2017, pp. 1–2, Oct. 30–Nov. 2 2017. DOI: 10.1109/isapn.2017.8228929

[8] H. Hirayama, M. Ando, and T. Sonobe, “Suppression of common-mode radiation using folded-spiral antenna for wireless power transfer,” Proc. APEMC 2017, p. 86, June 2017.
1 Introduction

To increase the power transmission efficiency of microwave wireless power transfer (MWPT), a class-F load is commonly used for amplifier and rectifier circuits to reduce loss [1, 2, 3]. The class-F load is realized by an external circuit using a distributed element circuit [4] or a lammed element circuit [5]. Additionally, an impedance matching circuit for the fundamental frequency is necessary.

Some applications, for example, MWPT for flying drones, have the primary requirement of reducing the weight of the receiving rectenna. Therefore, it is useful to integrate class-F function into an antenna. Liw et al. proposed novel inverted-F antenna with inverse class-F load function [6]. This antenna consists of a three-layered structure: feeding layer, ground layer and antenna layer. Considering the application for a flying drone, a single layered structure is desirable for weight saving. Additionally, the inverted-F antenna requires unbalanced feeding. To take an advantage of the full-bridge rectifier, which has a capability of suppressing even-order harmonics, balanced feeding structure antenna is desirable.

In this study, we propose a novel antenna structure as a receiving antenna for MWPT that has a class-F load function for the harmonic frequency and an impedance matching function for the fundamental frequency. The proposed antenna is based on a folded dipole antenna, which has the ability to adjust impedance for the fundamental frequency by optimizing the ratio of two elements [7, 8, 9, 10]. Furthermore, capacitors are added on the folded element to control the impedance for the harmonic frequency.

As a rectifier circuit, a full-bridge diode rectifier is assumed, in which even order harmonic waves are cancelled because of its balanced structure. Moreover, the power of the 5th harmonic wave is relatively small compared to the 3rd harmonic wave. Thus, only the 3rd harmonic wave is considered in this paper. In general, the class-F load conditions are: 1) conjugate matching impedance for fundamental frequency; 2) short impedance (i.e. magnitude and angle of reflection coefficient are 0 dB and 180°, respectively) for even order harmonic frequencies; and 3) open impedance (i.e. magnitude and angle of reflection coefficient are 0 dB and 0°, respectively) for the odd order harmonic frequencies. The proposed antenna has a function of conjugate matching for the fundamental frequency and open impedance for the 3rd harmonic frequency.

2 Simulation model

The proposed structure is shown in Fig. 1. A folded structure is employed because of its self-balancing effect to suppress common mode currents. To control the...
impedance of the 3rd harmonic frequency, a capacitor with capacitance $c$ is connected between the folded elements. The dimensions are as follows: $l_1$ and $l_2$ are the length of the inner and outer elements, respectively. $w_1$ and $w_2$ are the width of the inner and outer elements, respectively. $d$ indicates the spacing between the inner and outer elements. $p_1$ and $p_2$ indicate the distance from the center of the antenna to the short pin and capacitor, respectively. $l_3$ is the length of the feeding line.

Because of its balanced circuit topology, the full-bridge rectifier circuit has an advantage of suppressing even-order harmonics. Additionally, it is well-known that the folded-dipole structure has a capability of adjusting an impedance of the fundamental frequency [7]. Moreover, a power of the 5th and the higher order of odd-mode harmonics is much smaller than the 3rd order harmonics. Therefore, we focus on controlling the impedance of 3rd order harmonics to be open and the impedance of fundamental frequency to be $50 \Omega$.

These parameters are optimized through a method-of-moment simulation using the following evaluation function: 1) the gain at the fundamental frequency (2.45 GHz) is maximized; 2) the reflection coefficient at the fundamental frequency is minimized; 3) the reflection coefficient at the 3rd harmonic frequency is maximized; and 4) the angle of the reflection coefficient at the 3rd harmonic frequency is minimized. For numerical simulation, conductivity of copper ($\sigma = 5.8 \times 10^7 \text{ S/m}$) is assumed. Rogers3750B ($\varepsilon_r = 3.66$, $\tan \delta = 0.004$) is assumed as a substrate, whose conductor thickness is 75 $\mu$m and substrate thickness is 0.76 mm.

| Parameters | Search range [mm] | Optimization result | Parameters | Search range [mm] | Optimization result |
|------------|-------------------|---------------------|------------|-------------------|---------------------|
| $l_1$      | 2 ~ 22            | 46.7                | $d$        | 1 ~ 5             | 1.5                 |
| $l_2$      | 2 ~ 22            | 45.5                | $p_1$      | 2 ~ 22            | 2.1                 |
| $l_3$      | 10 ~ 70           | 43.0                | $p_2$      | 2 ~ 22            | 9.0                 |
| $w_1$      | 1 ~ 5             | 4.7                 | Parameter  | Range [pF]        | Result [pF]         |
| $w_2$      | 1 ~ 5             | 2.4                 | $c$        | 0.1 ~ 100         | 0.42                |
As an optimization algorithm, genetic algorithm is employed. Search range of the optimization is listed in Table I.

Fig. 2. Simulation result

(a). Reflection coefficient on Smith chart

(b). Directivity (3D pattern)

(c). Directivity on XZ plane

(d). Directivity on YZ plane

(e). Current distribution (fundamental)

(f). Current distribution (3rd harmonic)
3 Simulation result

The optimized parameters are shown in Table I. The optimized antenna characteristics are shown in Fig. 2.

Figure 2(a) shows the reflection coefficient of the designed antenna. The reflection coefficient was $-24.6$ dB at the fundamental frequency and $-4.7$ dB at the 3rd harmonic frequency. The antenna gains in 3D format as well as in the XZ and YZ planes are shown in Figs. 2(b), (c), and (d), respectively. The maximum gain is 2.52 dBi, which is greater than the gain of dipole antenna, i.e., 2.15 dBi. The current distributions at the fundamental and 3rd harmonic frequency are shown in Figs. 2(e) and (f), respectively. The current flow as a dipole antenna can be confirmed for the fundamental frequency.

4 Conclusion

In this study, a class-F load function is realized in a folded dipole antenna for microwave wireless power transfer reception. The antenna is designed via optimization to minimize the reflection coefficient, maximize antenna gain at the fundamental frequency, and maximize the impedance at the 3rd harmonic frequency. Numerical simulation verified that the designed antenna has a reflection coefficient of $-24.6$ dB and antenna gain of 2.52 dBi at a fundamental frequency of 2.45 GHz, and a reflection coefficient of $-4.7$ dB, $-0.2^\circ$ at the 3rd harmonic frequency.

Acknowledgments

This work was supported by Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), “Energy systems of an Internet of Energy (IoE) society” (Funding agency: JST).