Efficient Design Approach of RF-DC Conversion Circuit Including Undesirable Radiation

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Abstract

A rectenna is one of the most important components for a wireless power transmission. For an efficient system, a rectenna must be designed with high radio frequency to direct current conversion efficiency. For optimizing the rectenna site for the SSPS or the RFID system, the radiation and the other output power from the circuit must be investigated. With the extended FDTD method, it is possible to investigate the radiation power of the circuit into the space as well as the RF-DC conversion efficiency. In addition, the consumption power at the diode and the reflection and the harmonics power causing the re-radiation and the spurious from the antenna are considered with this method.

1. INTRODUCTION

The microwave transmission technology has been developed for Space Solar Power System (SSPS), which realizes to transmit the power generated in space to the ground with microwaves [1][2]. Recently, this technology is applied to the radio frequency identification (RFID) system and electric vehicles etc. A rectenna consisting of the radio frequency to the direct current (RF-DC) conversion circuits and receiving antennas is one of the most important components to realize this system. For an efficient system, a rectenna must be designed with high RF-DC conversion efficiency.

Various kinds of rectennas had been investigated [3]-[5]. In past reports about the rectenna, characteristics of the antenna or the filter for the rectenna are investigated. Also, the experimental results of the RF-DC conversion efficiency of the rectenna or simulated results based on the theoretical calculation have been reported. However, it is impossible to investigate for the radiation into the space with the approach based on the circuit theory. In addition, the consumption power at the diode used for the rectification device should be considered for designing the rectenna with high RF-DC conversion efficiency.

On the other hand, the extended FDTD method combined with the equivalent circuit simulation had been proposed [6]. It is not only able to simulate 3 dimensional field distributions obtained by the primitive FDTD method but also a state variable of the mounted device on the circuit with this method. In this paper, we propose a RF-DC conversion circuit for mW-class rentenna, and investigate its efficiency by using the extended FDTD method. We also discuss other output powers, such as the reflection of the fundamental frequency, harmonics produced by the nonlinearity of the diode, the consumption power at the diode and the undesirable radiation power, analytically.

2. THE COMPOSITION OF A RF-DC CONVERSION CIRCUIT AND ITS OPERATION PRINCIPLE

The RF-DC conversion circuit designed for 5.8GHz composed of microstrip lines is illustrated in Fig.1.

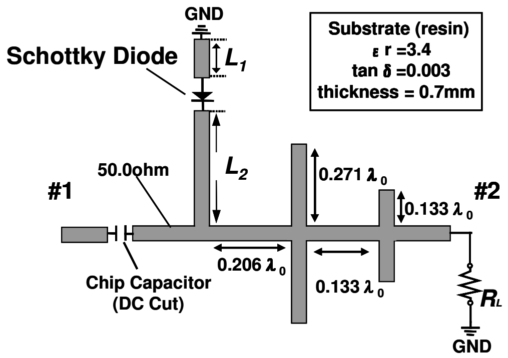

Fig. 1: RF-DC Conversion Circuit for Rectenna designed for 5.8GHz

A resin substrate is used, and its thickness, dielectric constant and tanδ are 0.7mm, 3.4 and 0.003, respectively. The characteristic impedance of all lines is 50ohm at 5.8GHz as the fundamental frequency. There is an output filter for obtaining only the direct current at output port (#2). This filter is designed to block effectively the higher order harmonics produced by the nonlinearity of the diode as well as the input microwave. A line (L_2) is connected to a proper position between the input port (#1) and this output filter. The diode is mounted between L_2 and a line (L_1) connected to ground. A 1.5pF chip capacitor isolates the direct current from #1. Inputting a microwave signal, positive electric charges are stored on the line between #1 and #2, and the direct current goes to the load resistance (R_L) through the output filter. To achieve the rectenna with high efficiency, it is also important to choose the diode that has a low built-in voltage to operate at a low input power. Then, we chose M/A-COM MA4E2054-1141T Schottky Barrier Diode (SBD) for the rectifying device. In addition, RF-DC conversion efficiency is represented as a follow.

$$\eta[\%] = \frac{V_{DC} / R_L}{P_{RF}} \times 100 \qquad (1)$$

where V_{DC} and P_{RF} are the output voltage of the direct current and the input microwave power, respectively.

3. CHARACTERISTICS OF RF-DC CONVERSION CIRCUIT

The end of L_1 is short-connected to ground and the position where L_2 is connected to the line between #1 and #2 is open for a fundamental frequency. Therefore, varying the length of L_1 and L_2, the efficiency will be quite changed. In this section, the RF-DC conversion efficiency is investigated with the extended FDTD method when the length of L_1 and L_2 are varied. In the extended FDTD analysis, the equivalent circuit simulation is applied at the SBD, the chip capacitor and R_L. The nonlinear equivalent circuit of the SBD is shown in Fig.2.

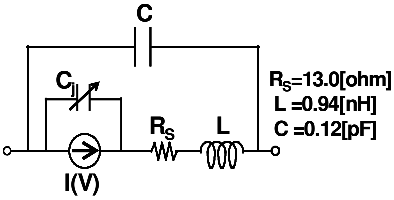

Fig. 2: SBD Equivalent Circuit (M/A –COM MA4E2054-1141T)

The inductance L and the capacitance C as parasitic reactance are 0.94nH and 0.12pF, respectively. The resistance R_S is 13.0ohm. These parameters were obtained from its datasheet or our measurements. Common FDTD analytic parameters are shown in Tab.1.

TABLE 1: FDTD ANALYTIC PARAMETERS

Cell Size	Δx =Δy =0.255mm Δz =0.175mm
Iteration	30000
Absorbing Boundary Condition	Mur
Incident Voltage Signal	5.8GHz CW, 10dBm

At first, the simulated efficiency is shown in Fig.3, varying the length of L_1 and L_2, respectively. At this time, the optimum value of R_L is chosen for obtaining highest efficiency. Fig.4 shows characteristics of optimum R_L corresponding to the Fig.3.

In these Figs., it is confirmed that the efficiency is changed approximately 0~60% varying the length of L_1 and L_2, respectively. The maximum efficiency is obtained when the length of L_1 and L_2 are 4 and 14mm, respectively. The minimum conversion efficiency is 0% when the length of L_1 is 8mm in spite of the length of L_2. According to this result, the efficiency depends on the length of the both lines, then, these are principal parameters to design the RF-DC conversion circuit with high efficiency. In addition, the efficiency is changed by around 16mm equal to a half wavelength at the fundamental frequency in terms of the length of both lines. This is due to the change of the standing wave distribution on these lines.

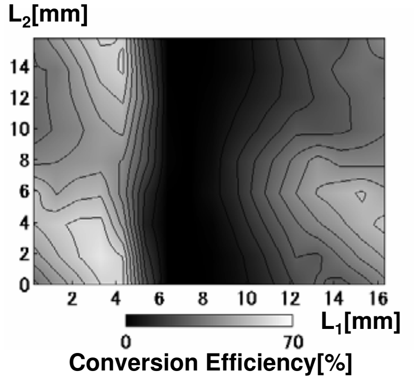

Fig. 3: Conversion Efficiency with the extended FDTD method corresponding to the length of L_1 and the L_2 respectively. The load resistance is optimum.

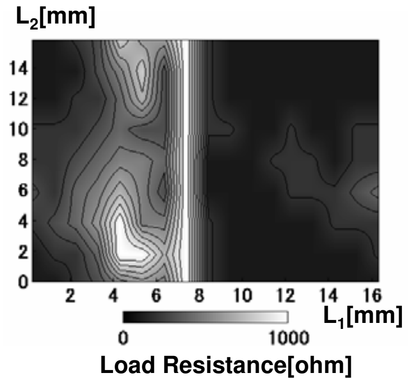

Fig. 4: Optimum value of R_L with the extended FDTD method corresponding to the length oL_1 and the L_2 respectively.

Next, the efficiency is investigated when the R_L and the length of the one line, either L_1 or L_2, are varied. Another line is fixed to optimum length L_1=4mm or L_2=14mm. Simulated results are shown in Figs.5 and 6.

In Fig.5, the efficiency is approximately changed 0~60% when R_L and the length of L_1 are varied 0~1000ohm and 0~16mm, respectively. The efficiency depends on the length of L_1 significantly. The maximum conversion efficiency is obtained at L_1=4mm and R_L=500ohm. On the other hand, the efficiency is changed 35~60% approximately in Fig.6. From this result, the change of the efficiency is smaller than that one whose length of L_1 is varied. The maximum conversion efficiency is obtained at L_2=14mm and R_L=500ohm.

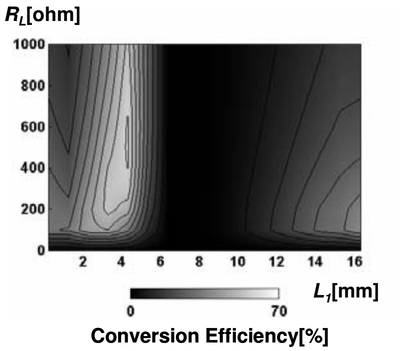

Fig. 5: Conversion Efficiency with the extended FDTD method corresponding to the length of L_1 and R_L respectively. The length of L_2 is optimum.

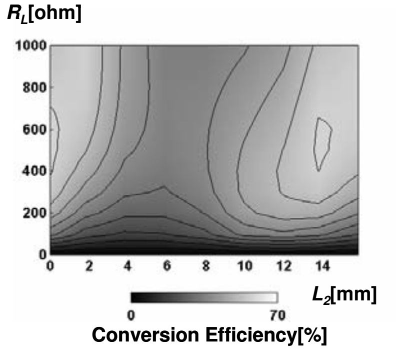

Fig. 6: Conversion Efficiency with the extended FDTD method corresponding to the length of L_2 and R_L respectively. The length of L_1 is optimum.

After all, the circuit parameters of the RF-DC conversion circuit with high efficiency are decided. Here, we compare the simulated efficiency with measurements for estimating simulated results. The measurement system is shown in Fig.7. First, a comparison of the efficiency between simulated results and measurements are shown in Fig.8 when the length of L_1 is varied. At this time, the length of L_2 is fixed to the optimum length and the optimum R_L is connected.

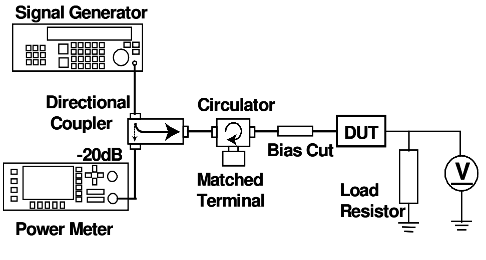

Fig. 7: Measurement series for measuring the conversion efficiency of the RF-DC conversion circuit.

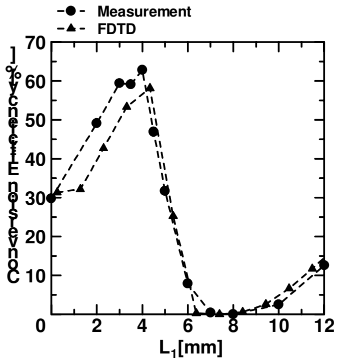

Fig. 8: Conversion Efficiency corresponding to the length of L_1. The length of L_2 is optimum length 14mm and the load resistance is optimum.

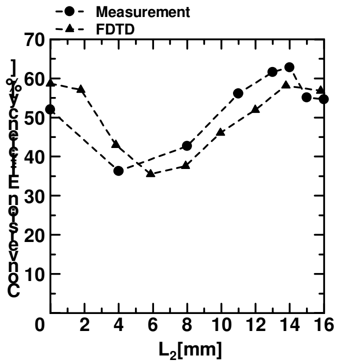

Fig. 9: Conversion Efficiency corresponding to the length of L_2. The length of L_1 is optimum length 4mm and the load resistance is optimum.

In this figure, simulated results agree well with measurements, and the maximum measured conversion efficiency is achieved 62.8% when the length of L_1 is 4mm. Next, a comparison of the efficiency is shown in Fig.9 when the length of L_2 is varied. At this time, the length of L_1 is fixed to the optimum length. In Fig.9, simulated results also agree with measurements though there are slightly errors caused by the dispersion of the FDTD method. The maximum measured conversion efficiency is obtained when the length of L_2 is 14mm.

4. Ratio of Output Power and Current Distribution

In this section, output power ratios referred to the input power are investigated. The undesirable radiation power in the space, the consumption power at the SBD, the reflection and the harmonics power observed at #1 are included in output powers. The undesirable radiation power is obtained by calculating the poynting vector. The investigation is performed about 2 types of circuits. Type1 is a circuit with high efficiency (L_1=4mm, L_2=14mm, η=61.1%), another Type2 is a one with low efficiency (L_1=4mm, L_2=6mm, η=36.6%). The each value of R_L is optimum in both circuits. The power ratios of them are listed in Tab.2.

TABLE 2: RATIO OF THE OUTPUT POWER

	Type 1	Type 2
Conversion Efficiency [%]	61.1	36.6
Reflection [%] (Fundamental)	1.8	39.1
Harmonics observed at the input port [%]	3.3	0.9
Consumption at the SBD [%]	17.1	11.6
Radiation Loss [%] (Fundamental & Harmonics)	22.3	11.5
Total	105.6	99.7

Reflections of Type1 and Type2 at the fundamental frequency are 1.8 and 39.1%, respectively. Type1 with high efficiency indicates lower reflection than Type2. This is due to the change of the input impedance at the fundamental frequency by changing the length of L_2. The consumption power at the SBD of Type1 is larger than that one of Type2, since higher voltage would be applied to the SBD when the efficiency is higher. Harmonics power ratios of Type1 and Type2 are 3.3 and 0.9%, respectively. The harmonics power includes 2^{nd}~4^{th} harmonics though their levels are very low compared with the fundamental frequency. Undesirable radiation powers of Type1 and Type2 are 22.3 and 11.5%, respectively. These powers shown in Tab.2 include the fundamental and its 2^{nd} ~4^{th} harmonics frequencies. In these results, it is confirmed that the consumption at the SBD and the undesirable radiation grows when the efficiency is higher. And the total of the all output powers are 105.6 and 99.7%, respectively. Principal factors exceeded 100% are the potential numerical error of the extended FDTD method and the calculation error of the poynting vector.

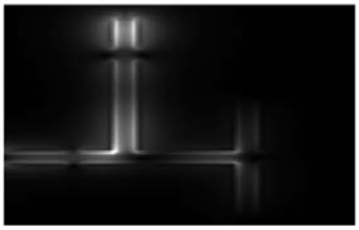

Fig. 10: Current Distribution on the line of the RF-DC conversion circuit Type1

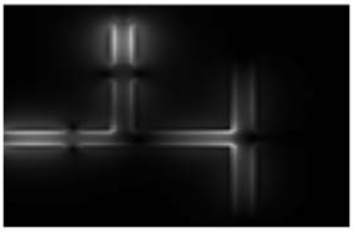

Fig. 11: Current Distribution on the line of the RF-DC conversion circuit Type2

Next, the position where the radiation takes place is investigated by observing the current distribution on the surface of the circuit. Current distributions of Type1 and Type2 at the fundamental frequency are shown in Figs.10 and 11, respectively. Both results are normalized with the same maximum and minimum value.

From these results, both indicate the strong current distribution on L_1. Therefore, it is considered that the undesirable radiation will mainly take place at this part. However, considering the composition of the circuit, it might be difficult to reduce the radiation power because the length of L_1 is most important parameter for obtaining high efficiency. In Fig.10, the current distribution on the output filter of the circuit Type1 is weak. Then, the almost power will flow into the line mounted the SBD, not the output filter. On the contrary, the current distribution on the output filter of Type2 is strong shown in Fig.11. The input power scatters to the branch line mounted the SBD and the output filter. Also, the current distribution on the line near #1 is strong in this figure, because the reflection of Type2 is larger than Type1.

5. CONCLUSION

This paper presented that it is possible to investigate output powers including the undesirable radiation from the circuit, the power consumption at the SBD and so on by the extended FDTD method. Consequently, it is confirmed that simulated results agree well with measurements, and optimum parameters were obtained for the proposed circuit with high efficiency. Moreover, the undesirable radiation into the space is 22.3% to 10dBm input, which has high RF-DC conversion efficiency of 61.1%. It is important to consider characteristics including the radiation for designing the RF-DC conversion circuit.

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