High Efficiency MW-Band Rectenna Using a Coaxial Dielectric Resonator and Distributed Capacitors

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***Abstract*— This paper presents experimental studies on the improvement of RF-DC conversion efficiency of the rectenna using a high Q λ/4-coaxial dielectric resonator and distributed capacitors at 850 MHz. The conventional rectenna using an LC resonator has ohmic and dielectric losses due to a shunt capacitor. In order to eliminate these losses, it is effective to disperse current by using distributed capacitors, such as a film capacitor. To achieve an ultimate efficiency, we have constructed a rectenna using both a coaxial dielectric resonator and a film capacitor. Using the developed rectenna, charge-up experiments to supply power to a super-capacitor at an input power of –10 dBm were performed and its ability to achieve a long-life operation of an LCD clock device was confirmed.**

***Index Terms*— Rectenna, Dielectric resonator, Quality factor, Distributed capacitor**

I. Introduction

For wearable wireless communication systems and RF-ID applications, there has been a great interest in wireless power transmission (WPT). The rectifying circuit, denoted as “rectenna” in this paper, comprised of the radio frequency to direct current conversion circuit is one of the most important components to realize these systems.

To realize a high efficiency rectenna for long distance transmission, it is effective to increase the amplitude of high frequency signals applied to the diode. A high sensitivity rectenna with the RF-DC conversion efficiency more than 50 % under weak power operation (0 dBm) has been developed using an LC resonator [1]. An LC resonator has an advantage such that it can make a variety of resonant frequencies by choosing the optimum combinations of L and C values. Since Q-factor of the LC resonator is limited to about 200 with the best combinations of L and C values, we cannot expect to obtain Q-factor higher than this value using an LC resonator.

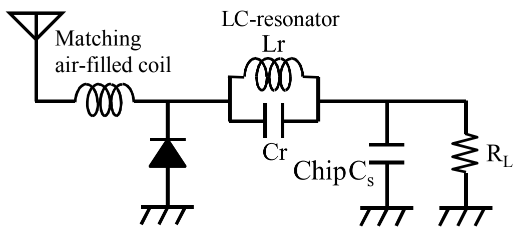
This paper presents experimental studies on the improvement of RF-DC conversion efficiency of the rectenna using a high Q λ/4-coaxial dielectric resonator (denoted as “DR rectenna” hereafter) at 850 MHz. The conventional rectenna using an LC resonator has ohmic and dielectric losses due to a shunt capacitor. In order to eliminate these losses, it is effective to disperse current by using distributed capacitors, such as a film capacitor. To achieve an ultimate efficiency, we have constructed a rectenna using both a coaxial dielectric resonator and a film capacitor. Using the developed rectenna, charge-up experiments to supply power to a super-capacitor at an input power of –10 dBm were performed and its ability to achieve a long-life operation of an LCD clock device was confirmed.

II. Structure Of Rectenna

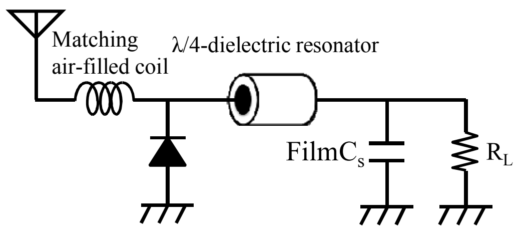
Fig. 1(a) shows the structure of the rectenna using an LC resonator [1]. A shunt capacitor Cs, connected at the end of the LC resonator, has a sufficiently small reactance, and thus the LC resonator can be considered to be short-circuited to the ground. Hence, the junction point of a diode and an LC resonator becomes an open-circuited condition, and consequently RF signals applied to a diode are anticipated to have large amplitude. Impedance matching between the antenna and the diode circuit is achieved by an air-filled coil that is connected at the input terminal.

Fig. 1(b) shows the structure of the proposed rectenna using a λ/4-coaxial dielectric resonator and a film capacitor. The LC resonator in Fig. 1(a) is replaced by a λ/4-dielectric resonator in parallel configuration. The dielectric resonator has a high Q factor compared with the LC resonator. Hence, the amplitude of signals applied to the diode is anticipated to increase, and therefore we can expect a high conversion efficiency of rectenna.

In Fig. 1(b), the chip capacitor Cs is replaced by the dielectric film capacitor. Since current flowing through the Cs is distributed the loss of the capacitor will decrease.



(a) Rectenna using an LC-resonator



(b) Rectenna using a λ/4-dielectric resonator

Fig. 1 Structure of the rectenna

III. CHARACTERIZATION OF THE DIELECTRIC RESONATOR

Fig. 2 exhibits a photograph of a dielectric resonator fabricated on an SMA connector to investigate the impedance characteristics using a network analyser. In Fig. 2, a dielectric resonator and a chip capacitor for capacitive coupling can be seen. The dielectric resonator is Ube YCZ150B (9 mm×5.9 mm × 5.9 mm, 2.1 mm in inner-diameter, and dielectric constant ε_r of 92.5).

Fig. 2 shows the measured impedance characteristics of the dielectric resonator using a small coupling capacitor of 0.3 pF. It can be seen from Fig. 2 that the resonant frequency f_r is measured to be 850 MHz. An unloaded Q factor (Q_u) of the resonator is calculated from the following equation.

$$Q_u = \frac{f_r}{f_h - f_l} \qquad (1)$$

where f_h and f_l are the two frequencies indicated by the two markers drawn on eye-shaped curves in the smith chart, as shown in Fig. 2. From Eq. (1), Q_u of the dielectric resonator is found to be 523.

For comparison purposes, an unloaded Q factor of an LC resonator was also measured using the same technique mentioned above, and Q_u of the LC resonator was found to be 242 at 850 MHz. Hence, it is clarified that the dielectric resonator has a Q factor two times larger than the LC resonator.

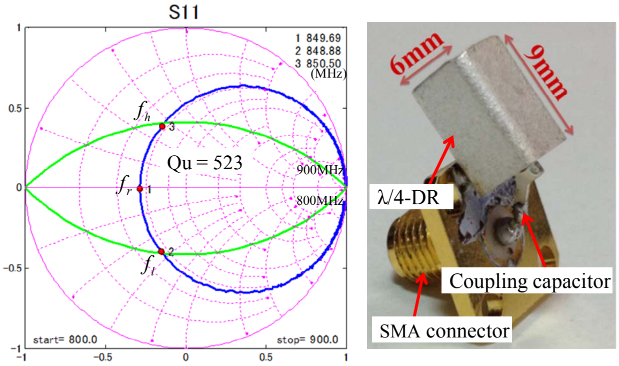


Fig. 2 Impedance characteristics of the dielectric resonator

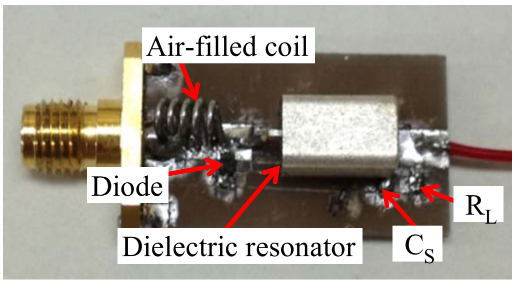


Fig. 3 Rectenna using a λ/4-coaxial dielectric resonator

In order to confirm the effectiveness of the dielectric resonator, we have made experiments on a rectenna using a dielectric resonator fabricated on a glass epoxy substrate (FR4) with a thickness of 1.6 mm, as shown in Fig. 3. The diode is Toshiba 1SS315. The frequency for the experiments is 850 MHz for the LC resonator rectenna and 864 MHz for the DR rectenna. The microstripline has a characteristic impedance of 50 Ω. The shunt capacitor is Cs = 820 pF.

Fig. 4 shows the RF-DC conversion efficiency as a function of the input power (-10 dBm – 10 dBm) for the LC and DR rectennas. The RF-DC conversion efficiency of the resonator is calculated from the following equation.

$$\eta = \frac{V_{DC}^{\ 2} / R_L}{P_{in}} \qquad (2)$$

where P_{in} is the power of a high-frequency signal applied to the rectenna, V_{DC} is the DC voltage generated across the load resistor R_L.

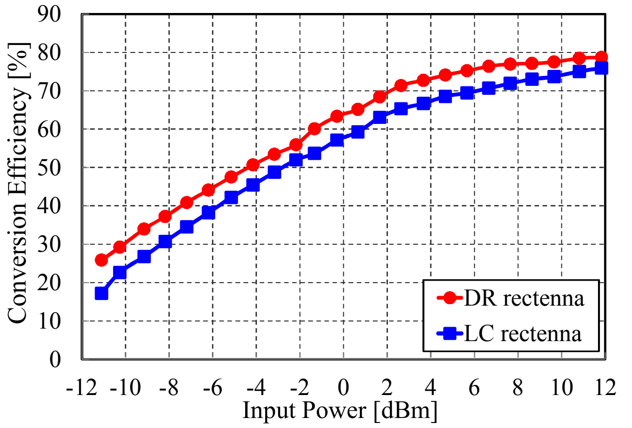


Fig. 4 Conversion efficiency vs. input power

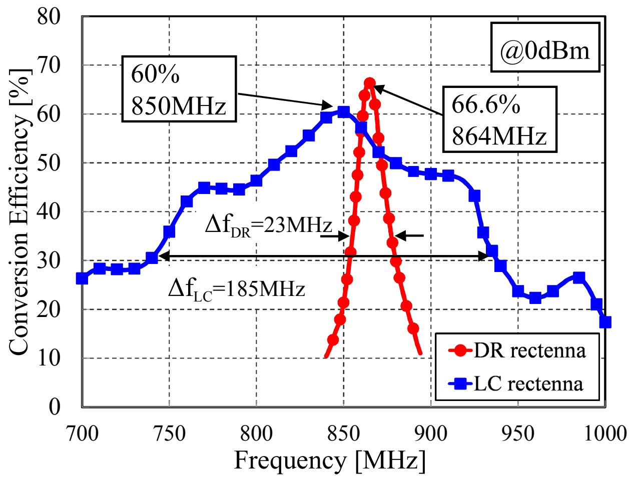


Fig. 5 Conversion efficiency vs. resonant frequency

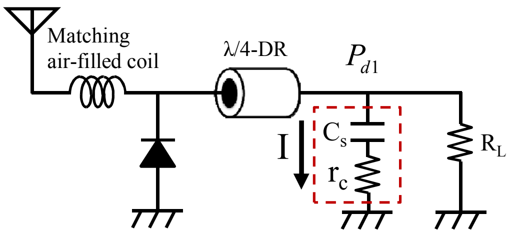
The input impedance was adjusted by an air-filled coil connected at the input of the diode and VSWR of less than 2 was achieved at the resonant frequency. The LC resonator rectenna (■) was measured at 850 MHz and the DR rectenna (●) was measured at 864 MHz. For the DR rectenna, an efficiency of 29.4 % was achieved at an input power of -10 dBm (0.1 mW) with the improvement of 7.1 % from the LC resonator rectenna. At an input power of 10 dBm (10 mW), an efficiency of 77.6 % was achieved with the improvement of 4.3 % from the LC resonator rectenna. This fact indicates that the resonance phenomenon caused by the dielectric resonator allows the input terminal of the diode to be an open-circuited condition, and consequently high conversion efficiency can be achieved due to a large amplitude of RF signals resulted from a high Q factor of the resonator.

Fig. 5 shows the conversion efficiency as a function of the frequency at an input power of 0 dBm (1 mW). It can be seen from Fig. 5 that for the LC resonator rectenna (■) the conversion efficiency shows the maximum value of 60 % at 850 MHz. For the DR rectenna (●), the maximum efficiency of 66.6 % is attained at 864 MHz. The half power width Δf is found to be Δf_{DR} = 23 MHz for the DR rectenna, whereas in the case of the LC resonator rectenna the half power width Δf is found to be Δf_{LC} = 185 MHz. Comparing these two cases, it can be seen that the DR rectenna has a very narrow bandwidth due to a high Q factor of the resonator. This result shows that there is a trade-off relationship between the conversion efficiency and the bandwidth.

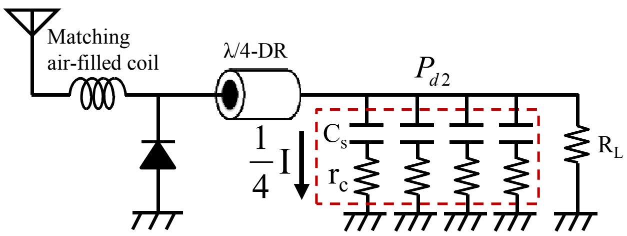
IV. Rectenna Using Distributed Capacitors

Fig. 6 shows the equivalent circuit of a rectenna in which the loss resistances of shunt capacitors are taken into consideration. As shown in Fig. 6 (a), the power, P_{d1}, dissipated in the loss resistance is calculated from Eq. (3) in the case of a single shunt capacitor. The power, P_{d2}, dissipated in the four shunt capacitors shown in Fig. 6 (b) is given by Eq. (4). It can be understood from Eq. (4) that the power, P_{d2}, is a quarter of the power, P_{d1}.

We can see from this fact that the power dissipated in the shunt capacitors can be reduced with increasing the number of capacitors because current flowing through the capacitors is distributed. Therefore, when we assume the case where the number of the capacitor is sufficiently large, the dissipated power could decrease considerably. To realize this situation, we have attempted to construct a rectenna using a thin dielectric film that is located between the bottom of the dielectric resonator and the ground plane. This structure enables infinitely small capacitors to be distributed in the entire surface of the bottom of the dielectric resonator.



(a) Rectenna using a shunt capacitor



(b) Rectenna using four shunt capacitors

Fig. 6 Equivalent circuit considering the loss resistances of Cs

$$P_{d1} = I^2 r_c \qquad (3)$$

$$P_{d2} = 4\left\{\left(\frac{1}{4}I\right)^2 r_c\right\} = \frac{1}{4}I^2 r_c = \frac{1}{4}P_{d1} \qquad (4)$$

Fig. 7 shows a photograph of the DR rectenna using a dielectric film capacitor. A thin dielectric film is sandwiched between the ground plane made by a copperplate and the dielectric resonator. The copperplate is soldered to an SMA connector directly. A tight pressure is applied on the whole structure using acrylic plates and plastic screws in order to achieve a good contact throughout the surface of the dielectric film. The dielectric film is made of polyvinylidene chloride (wrapping material for food packaging) with a relative permittivity of 4.5 and a thickness of 10 μm. The capacitance of the dielectric film, C_f, is calculated from the following equation.

$$C_f = \frac{\varepsilon_0 \varepsilon_s ab}{t} \qquad (5)$$

where ab is the area of the bottom of the dielectric resonator, 9 mm×6 mm = 54 mm^2. From Eq. (5), C_f is calculated to be 211 pF, equivalent to the reactance of 0.9 Ω at 850 MHz. A good matching condition of VSWR of 1.08 was obtained at 867 MHz using an air-filled coil L_m. The bandwidth corresponding to VSWR of less than 2 is about 10 MHz.

Fig. 8 shows the RF-DC conversion efficiency as a function of the number of shunt capacitors when the input power is set to -10 dBm. The symbol ◆ denotes the measured results when using chip capacitors at 864 MHz as shown in Fig. 6, and the symbol ● represents the measured results when using a dielectric film at 867 MHz. It can be seen from Fig. 8 that the conversion efficiency is improved with increasing the number of capacitors. Furthermore, the rectenna using a film capacitor shows higher conversion efficiency as compared with the rectenna using chip capacitors.

The conversion efficiency of four types of rectennas developed in this study is summarized in Fig. 9. It can be seen that the conversion efficiency of 89.1% is obtained at an input power of 10 mW for the rectenna using a dielectric resonator and a dielectric film capacitor. Furthermore, at a low input power of 1 mW and 0.1 mW, an RF-DC conversion efficiency of 76.2 % and 44.1 % has been achieved.

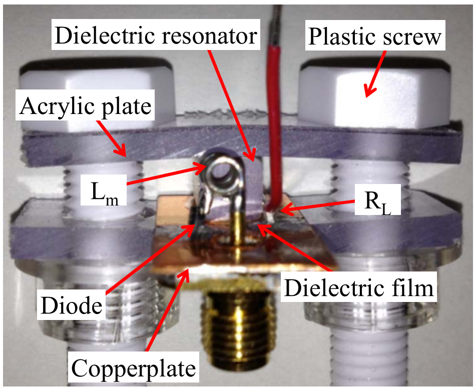


Fig. 7 Rectenna using a dielectric resonator and a film capacitor

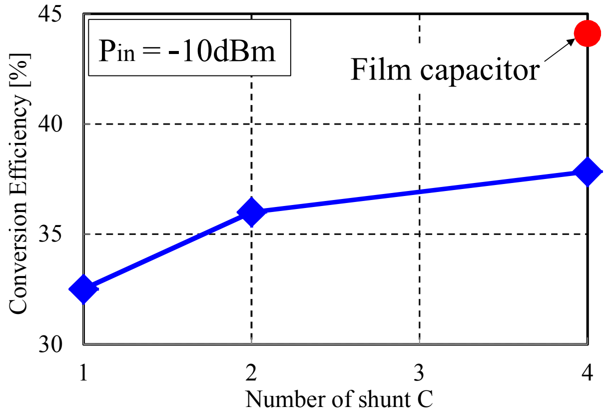


Fig. 8 Conversion efficiency vs. the number of shunt C

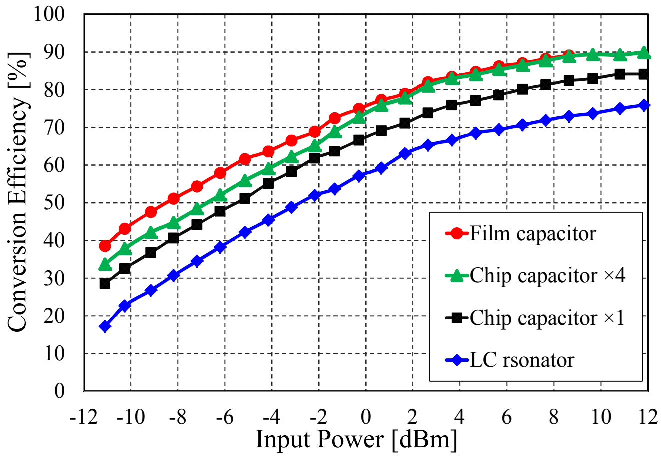


Fig. 9 Conversion efficiency vs. input power

V. Super-Capacitor Charge-Up Experiments

Using the developed rectenna, charge-up experiments to a super-capacitor were performed to supply power to an LCD clock device. Fig. 11 shows the experimental setup. As can be seen in Fig. 10, an output power from a signal generator (SG) is converted to a direct current by the developed rectenna, and DC current is accumulated in a super-capacitor (Panasonic EECF5R5H1 1F). A voltage appearing at the super-capacitor is increased by a DC-DC converter (LINEAR TECHNOLOGY LTC3108) so that the LCD clock can operate suitably (1.5 V and 2.5 µA operation).

Fig. 12 shows the accumulated voltage as a function of the charge-up time when the input power is set to -10 dBm. The symbol ■ denotes the measured results using the LC resonator rectenna. The symbol ● shows the DR rectenna with a dielectric film. We can see in Fig. 12 that the DR rectenna can produce a higher voltage than the LC resonator rectenna at any charge-up time, indicating that a large amount of charge is accumulated in the capacitor.

Table 1 shows the operating time of the LCD clock when the capacitor charging was carried out for 30 minutes at an input power of-10 dBm. It can be seen from Table 1 that using the developed rectenna a 2.5-times of long-life operation of the LCD clock device was confirmed.

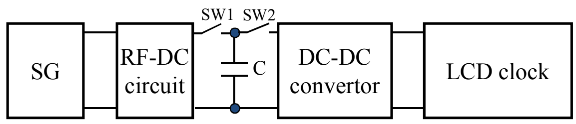


Fig. 10 Block diagram of the charge-up experiment

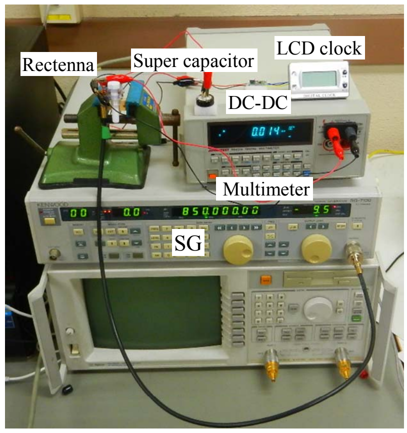


Fig. 11 Experimental setup

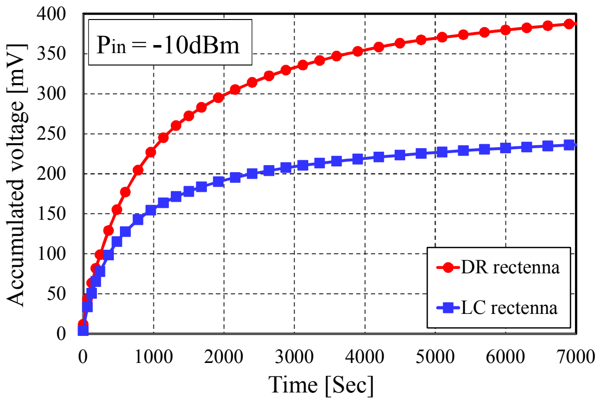


Fig. 12 Accumulated voltage vs. charge-up time

TABLE 1
Operating time of the LCD clock

	DR Rectenna	LC Rectenna
Operating time	32 sec.	13 sec.

VI. Conclusion

Experimental studies on the improvement of RF-DC conversion efficiency of a rectenna using a high Q λ/4-dielectric resonator and a dielectric film capacitor at 850 MHz have been presented. Using the developed rectenna, charge-up experiments to supply power to a super-capacitor at an input power of –10 dBm were performed and its ability to achieve a long-life operation of an LCD clock device was confirmed.

References

[1] K. Ogawa, K. Ozaki, M. Yamada, and K. Honda, "High Efficiency Small-Sized Rectenna Using a High-Q LC Resonator for Long Distance WPT at 950 MHz," IMWS-IWPT2012, Kyoto, FRI-J-1, May 2012.

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