High efficiency mw-band
dielectric resonator rectenna
using 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. In order to
achieve an ultimate efficiency, we have constructed a rectenna using both
a coaxial dielectric resonator and a film capacitor. The measured results show
that the developed rectenna has an RF-DC conversion efficiency of 76.2%
and 44.1% at a low input power of 1 mW and 0.1 mW that achieves the 20%-
efficiency improvement compared with the rectenna with an LC resonator.

Keywords: rectenna, dielectric resonator, quality factor, distributed

capacitor

Classification: Transmission Systems and Transmission Equipment for
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1 Introduction
For wearable wireless communication systems and RF-ID applications, there has been a great interest in wireless power transmission (WPT) [1, 2, 3, 4]. 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, 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 [5]. 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 $\frac{\lambda}{4}$-coaxial dielectric resonator (denoted as “DR rectenna” hereafter) at 850 MHz [6, 7]. 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. The measured results indicate that the developed rectenna has a high efficiency performance compared with a conventional rectenna with an LC resonator.

2 Structure of rectenna
Fig. 1(a) shows the structure of the conventional rectenna using an LC resonator [5]. A shunt capacitor $C_s$, 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 $\frac{\lambda}{4}$-coaxial dielectric resonator and a film capacitor. The LC resonator in Fig. 1(a) is replaced by a $\frac{\lambda}{4}$-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. Moreover, the chip capacitor $C_s$ in Fig. 1(a) is replaced by the dielectric film capacitor. Since current flowing through the $C_s$ is distributed, the loss of the capacitor will decrease.
3 Characterization of the dielectric resonator

Fig. 2(a-1) exhibits the configuration of a dielectric resonator fabricated on an SMA connector to investigate the impedance characteristics using a network analyzer. In Fig. 2(a-1), a dielectric resonator and a chip capacitor for capacitive coupling can be seen. The dielectric resonator is Ube YCZ150B (9 mm × 6 mm × 6 mm, 2.1 mm in inner-diameter, and dielectric constant εr of 92.5).

Fig. 2(a-2) shows the measured impedance characteristic of the dielectric resonator using a small coupling capacitor of 0.3 pF. It can be seen from Fig. 2(a-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.

\[
Q_u = \frac{f_r}{f_h - f_l}
\]

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(a-2). From Eq. (1), \( Q_u \) of the dielectric resonator is found to be 523. For comparison purposes, in Fig. 2(b-1), an unloaded Q factor of an LC resonator was also measured using the same technique mentioned above, and \( Q_u \) of the LC resonator (\( L = 69 \, \text{nH} \) and \( C = 0.5 \, \text{pF} \)) was found to be 242 at 850 MHz, as shown in Fig. 2(b-2). Hence, it is clarified that the dielectric resonator has a Q factor two times larger than the LC resonator.

4 Rectenna using distributed capacitors

In this section, the distributed capacitor is used in order to disperse the current to obtain the further improved efficiency. Fig. 3(a) shows the equivalent circuit of a rectenna in which the loss resistances of shunt capacitors are taken into consideration. As shown in Fig. 3(a), the power \( P_{d1} \), dissipated in the loss resistance is calculated from Eq. (2) in the case of a single shunt capacitor. The power \( P_{d2} \),
dissipated in the four shunt capacitors shown in Fig. 3(b) is given by Eq. (3). It can be understood from Eq. (3) that the power $P_{d2}$ is a quarter of the power $P_{d1}$.

$$P_{d1} = I^2 r_c$$

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

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. Thus, 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.

Fig. 3(c-1) shows the configuration of the DR rectenna using a dielectric film capacitor based on the structure shown in Fig. 3(b). A thin dielectric film is sandwiched between the ground plane made by a copper plate and the dielectric resonator. The copper plate is soldered to an SMA connector directly. Fig. 3(c-2) shows a photograph of the proposed DR rectenna. In Fig. 3(c-2), it is shown that 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 $t$ of 10 µm. The capacitance of the dielectric film $C_f$, is calculated from the following equation.
where $ab$ is the area of the bottom of the dielectric resonator, $9 \text{ mm} \times 6 \text{ mm} = 54 \text{ mm}^2$, as shown in Fig. 2(a-1).

From Eq. (4), $C_f$ is calculated to be 211 pF, which is equivalent to the reactance of 0.9 $\Omega$ at 850 MHz. Here, a good matching condition of VSWR of 1.08 was obtained at 867 MHz using an air-filled coil $L_m$ [7], as shown in Fig. 3(c). The bandwidth corresponding to VSWR of less than 2 is about 10 MHz.
Fig. 3(d) shows the RF-DC conversion efficiency as a function of the input power for the four different types of rectennas: the DR rectenna with a dielectric film; shunt capacitor × 4; shunt capacitor × 1; and the rectenna with an LC resonator. The RF-DC conversion efficiency of the resonator $\eta$ is calculated from the following equation.

$$\eta = \frac{V_{DC}^2}{P_{in} R_L}$$

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 $R_L$.

In Fig. 3(d), it is shown that the conversion efficiency is improved with increasing the number of shunt capacitors, as shown by the black and green curves. Further, the DR rectenna using a film capacitor shows higher conversion efficiency as compared with the DR rectenna using chip capacitors and the rectenna with an LC resonator. Fig. 3(d) also shows that the conversion efficiency of 89.1% is obtained at an input power of 10 mW for the DR rectenna using a dielectric film capacitor, as shown by the red curve. 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. We conclude from this fact that the 20%-efficiency improvement can be attained compared with the conventional rectenna with an LC resonator.

5 Conclusion

Experimental studies on the improvement of RF-DC conversion efficiency of a rectenna using a high Q $\lambda/4$-dielectric resonator and a dielectric film capacitor at 850 MHz have been presented. The measured results show that the developed rectenna has an RF-DC conversion efficiency of 76.2% and 44.1% at a low input power of 1 mW and 0.1 mW that can be used in MW-band WPT applications.