Impedance relationship of operating diode and planar circuit in high-efficiently operated RF-DC conversion circuit

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Abstract: Highly efficient RF-DC conversion circuit is required for wireless power transmission. Since a diode with non-linear characteristics is used for the RF-DC conversion circuit, it is difficult to theoretically design a highly efficient RF-DC conversion circuit. Therefore, we have investigated automatic design by genetic algorithm. As a result of automatic design, it was found that the impedance of the input circuit converges to a certain area when the input power and load are fixed. Furthermore, we constructed a measurement system and found that in a highly efficient RF-DC conversion circuit, there is a canceling relationship between the reactance of the input circuit and the diode.

Keywords: Wireless Power Transmission, RF-DC Conversion Circuit, Rectenna

Classification: Antennas and propagation

References

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1 Introduction

As one solution to the power problem, microwave power transmission such as space solar power generation [1] and energy harvesting are being actively studied. In microwave power transmission, the highly efficient operation of the rectenna, which is the power receiving device, is an important point. The rectenna consists of an antenna and an RF-DC conversion circuit, and the RF-DC conversion circuit is required to have high conversion efficiency, however it is difficult to theoretically design the RF-DC conversion circuit due to its component, diode, which is non-linear element [2]. Therefore, the circuit design method has not been established, and there is no document that clearly describes the design method, so the designer needs to make trial and error each time to make a high-efficiency circuit. If some design method is clarified, it will be easy to design a highly efficient circuit, and the time and effort of designing can be saved. In our previous research, we have been studying the automatic design of circuits by genetic algorithm (GA), and highly efficient circuits have been obtained [3, 4]. This time, a class-F load was used for the output circuit, and as a result of automatically designing only the input circuit, which is a matching circuit, five times, it was found that the impedance of the automatically designed planar circuit seen from the diode converged to a certain region. Furthermore, as a result of measuring the operating impedance of the diode and the impedance of the planar circuit seen from the diode, it was found that the reactances cancel each other out. The above suggests that a highly efficient RF-DC conversion circuit can be designed by measuring only the operating impedance of the diode. In this paper, we report the impedance measurement system and the impedance relationship in a highly efficient RF-DC conversion circuit obtained by actual measurement.

2 Input circuit impedance of GA generated circuit

In automatic circuit design by GA, a highly efficient circuit is generated without being based on human design theory, so an unprecedented design method may be clarified. In the previous research [3, 4], RF-DC conversion circuit with high conversion efficiency were obtained by automatic design of the circuit by GA. In order to simplify the automatic design, we used a class-F load for the output circuit and performed the automatic design with the search area as the input circuit only. Here, the input power is fixed at 20 dBm and the load resistance is 300 Ω, and it is confirmed that the automatic design has converged five times in a row. Fig. 1(a) shows one of the circuits obtained by performing automatic design five times in a row with only the input circuit as the search area, and Fig. 1(b) shows the impedance on the input circuit side as seen from the diode of the five obtained circuits. The efficiency of the obtained circuit was as high as 63-65%. The efficiency was calculated by the following Eq. (1),

\[ \eta[\%] = \frac{V_{DC}^2}{R_L P_{in}} \times 100 \]  

where \( P_{in} \) is the input power, \( V_{DC} \) is the output voltage, and \( R_L \) is the load resistance. As a result of automatic design, it was found that the impedance of the input circuit
seen from the diode of the obtained highly efficient circuit converges in a specific area. Therefore, convergence in a certain area is considered to be a condition when designing a highly efficient circuit.

![Diagram](image1)

**Fig. 1.** GA generated circuit and input circuit impedance

### 3 Measurement of impedances

It is predicted that the convergence of the impedance of the input circuit to a specific area is closely related to the operating impedance of the diode. Therefore, we considered the construction of a measurement system to clarify these relationships. A network analyzer was used for the measurement, however, since the network analyzer cannot handle the high-power input/output, the high-power measurement system shown in Fig. 2(a) was constructed and the measurement was performed.

![Diagram](image2)

**Fig. 2.** Measurement system and measurement board

A signal was output from the signal generator at a frequency of 5.8 GHz, and the input signal was supplied to the diode through an amplifier and attenuator. A part of the input signal was separated by a directional coupler and given to the network analyzer as a reference signal. The reflected signal from the diode was input to the network analyzer through the circulator. The input power $P_{in}$ to the diode and the connected load resistance $R_L$ were set to 20 dBm and 300 Ω, which is the same as the automatic design of GA. The diode was mounted on the measurement board shown in Fig. 2(b). HSMS-282B was used as the diode, and Rogers RO4350B was used as the substrate. In automatic design of GA, a theoretically designed output
circuit was attached, and a high-efficiency circuit was generated by searching for an input circuit. Therefore, in the measurement, the output circuit was attached so that the configuration of the conversion circuit has the same conditions as the automatic design of GA. Although the stub for 5.8 GHz has a different position in Fig. 2(b), the modification is for simplifying the implementation and the output circuit works the same as the one theoretically designed in Fig. 1(a). To operate the diode with the highest efficiency in fixed input power and load resistance, the stub tuner was adjusted so that the output DC voltage was high. The efficiency was obtained by measuring the output DC voltage and calculating using Eq. (2),

\[
\eta[\%] = \frac{V_{DC}^2}{P_{in}} + \frac{(V_{DC})^2}{R_L} \cdot \frac{R_{BT}}{R_L} \times 100
\]

where \(R_{BT}\) is the internal resistance of the bias tee, which is 7.4 \(\Omega\). As a result of measurement in this system, the \(V_{DC}\) was 4.26 V and the maximum efficiency was 73%. In the measurement of diode operating impedance, SSL (Short - offset Short - Load) calibration was performed to be the diode cathode end in Fig. 2(b) is the measurement surface. We also measured the impedance of the input circuit during high-efficiency operation. The stub tuner was fixed with the position of the conversion circuit is most efficient, and the impedance of the input circuit was measured. In the measurement, the input circuit part was taken out and used TRL calibration to be the impedance was as seen from the diode cathode end.

4 Measurement result

Fig. 3 shows the measurement results of the diode operating impedance and the input circuit impedance. From the measurement result, it was found that in the highly efficient RF-DC conversion circuit, the reactances are positioned so as to cancel each other out. Therefore, a highly efficient RF-DC conversion circuit can be designed by making the reactance of the planar circuit cancel the reactance of the operat diode. The resistance does not match in this time. This seems to be due to the input power does not reach the maximum efficiency for the diode. Measuring under the condition that the diode has the maximum efficiency would clarify the real part relationship.
5 Conclusion

From the automatic circuit design by GA, it was found that the planar circuit impedance seen from the diode converges in a certain area in the highly efficient RF-DC conversion circuit. Therefore, it was predicted that there is a close relationship between the diode in high-efficiency operation and the planar circuit seen from the diode. To confirm this relationship, the operating diode impedance and the planar circuit impedance were measured. From the measurement result, it was clarified that the reactance cancels each other out between the operating diode impedance and the planar circuit impedance seen from the diode. Therefore, a highly efficient RF-DC conversion circuit can be designed by making the reactance of the planar circuit cancel the operating diode reactance. This result suggests that a highly efficient RF-DC conversion circuit can be designed by measuring only the operating impedance of the diode and is expected to contribute to future design of RF-DC conversion circuit.