

Low-Noise, High-Efficiency and High-Quality Magnetron for Microwave Oven

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Introduction

Nowadays, the considerations of energy-efficiency performance in microwave ovens are also required due to environmental concerns. However, stricter restrictions on electromagnetic noise are also promoted all over the world. Therefore, we have been required to develop a magnetron which properly meets the CISPR standard (dictated by the Comité International Spécial des Perturbations Radio-électriques) and yet operates at high efficiency.

However, the magnetron’s efficiency and noise parameters have a trade-off relation, which makes it difficult to satisfy the condition of low noise and high efficiency. We solved the problem using Panasonic industrial magnetron technology, and also succeeded in achieving high-quality devices.

Methodology

1. Theory of magnetron efficiency

The magnetron’s efficiency η is given by:

$$\eta = \eta_c \left(1 - \frac{mv^2}{2eV} \right) \cong \eta_c \left(1 - \frac{r_a + r_c}{r_a - r_c} \frac{\omega}{neB/m - \omega} \right), \quad (1)$$

where η_c is the circuit’s efficiency, e , m and v are the electron charge, mass, and velocity, respectively, V is the anode voltage; r_a and r_c are the anode and cathode radii, respectively, ω is the angular frequency, n is the number of resonators, and B is the magnetic field.

It is necessary to reduce the electron velocity v in order to raise the magnetron efficiency (1). In this trend, the action space size is narrowed, the magnetic field is intensified, and the number of anode resonators is increased.

2. Noise generation factor of magnetron

The magnetron is a cylindrical structure with coaxial cathode and anode (Fig. 1). The electrons perform a rotational motion due to the radial electric field and the axial magnetic field. This rotation is termed the

ExB drift motion. The gyration of the electrons resonates to a number of resonators at the anode. A bunching effect occurs hence the microwave field is amplified by the rotating electron pole, which leads to oscillations.

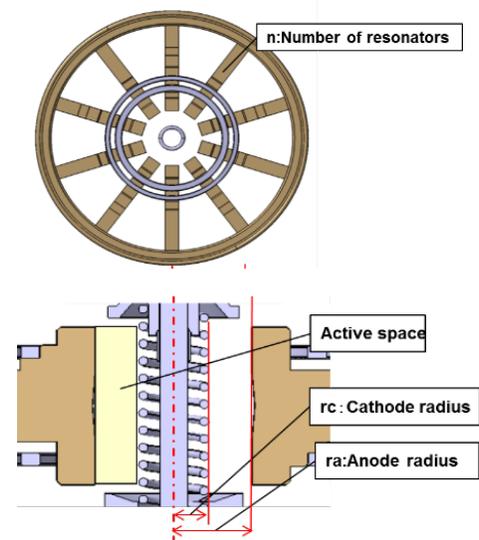


Figure 1: The action space of magnetron

The noise generation factors that have been reported in the past are as follows:

- Noise synchronized with the surrounding electron.
- Noise by ion plasma vibration.
- Noise by ion relaxation vibration.
- Noise by intermodulation.

The noise is divided roughly into three bands (Fig. 2):

- Fundamental wave at 2.45 GHz.
- Line noise and radiation noise.
- High harmonic noise.

The methods of noise control studied earlier are:

- Electronic motion control at both axial ends.
- Axial magnetic field uniformity.
- Electrical discharge suppression.
- Oscillation frequency band narrowing.
- Space charge layer width decrease.
- The $\pi-1$ oscillation mode separation and control (increase the resonance Q value).

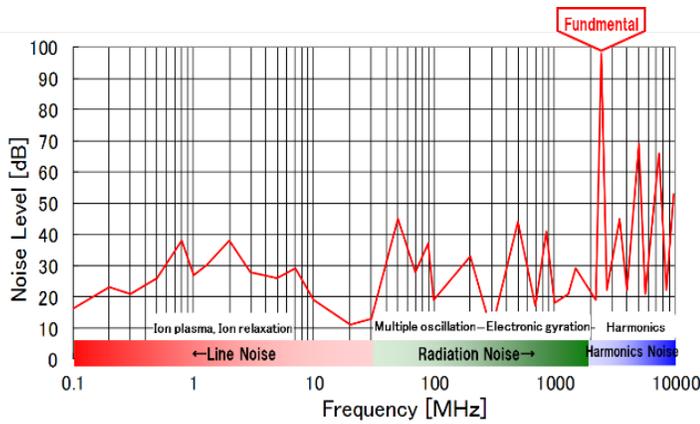


Figure 2: Magnetron's noise bands.

3. Approach to high efficiency and low noise

We used the theory mentioned above and CAE to achieve both low noise and a high efficiency. The details are described below.

We analyzed the magnetron operation using CST Particle Studio (hereafter, CST PS), which is a solver module of CST STUDIO SUITE. This simulator can analyze grain motion in three dimensions by using Maxwell's and motion equations of charged particles (hereafter, particles). We modeled and simulated two magnetron shapes (QV and J versions, for a high-efficiency and low-noise specifications, respectively) for actual microwave ovens. The two models are shown in Figs. 3a, b. First, we simulated each model in a uniformed magnetic field distribution. The particle distributions are shown in Fig. 4, and the output voltage changes in timeline are shown in Fig. 5.

Figures 4a, b show that the kinetic energy of the particles reaching the anode in J-version is higher than that of QV-version, and also more particles reach the anode vane. In addition, Fig. 5 shows that the time in which the voltage amplitude increases and stabilizes is shorter in QV-version. Consequently, as shown in Table 1, we succeeded to reproduce the feature that QV-version is more efficient than J-version.

However, the difference between the theoretical efficiency value and that calculated was about 2-6%. It causes that the electron efficiency loss is reduced due to the radial component of the velocity of the particles, accelerated in the cavity resonator. This effect is not included in the theoretical efficiency.

Figure 6 shows the result of the frequency spectra obtained by applying a Fast Fourier Transform

(FFT) to the output voltage time variation. We could not find the spectrum for frequencies below 1 GHz. The reasons are because we could not reproduce the limitation of time resolution in the simulation, and the filament temperature change due to secondary electron emission and back bombardment.

The next simulation was carried out using actual magnetic field distribution as shown in Fig. 7. As a result, the calculated efficiency of both QV-version and J-version decreased about 10% in the actual magnetic field compared with a uniform magnetic field as shown in Table 1. We presumed that it was because the particles in the central portion in the axial direction were likely to be pulled out to the anode portion, and because the number of particles entering into the cavity resonator was increased and the kinetic energy increased more than in the case of the uniform magnetic field. Regarding the noise performance, the frequency spectrum other than the fundamental wave (around 2.45 GHz) became higher in the actual magnetic field than in the uniform magnetic field.

Thus, in order to achieve high efficiency, while ensuring low noise, it is best to make the actual magnetic field close to the uniform magnetic field, after reducing the electron motion space (the anode inner radius; r_a and the cathode outer radius; r_c).

In order to be close to the uniform magnetic field, we focused on the ratio (hereafter 'the current ratio') by separating the anode into three parts at equal intervals in the axial direction, and calculating the anode current of each portion. For that we define three separated parts the anode A side, the anode central part, and the anode K side from the anode vane on the output end side. As a result of obtaining an optimal solution that makes the current ratio as uniform as possible, as shown in Table 2, we successfully established a U-version that improves the efficiency by 5% while the current ratio is equivalent to J-version.

4. Approach to high quality

Regarding the factors that cause variations in the production process, we again checked the influence of the frequency spectrum by simulation and some experiments. As shown in Fig. 8, we found that the most adverse effect took place when the coaxial displacement of the electron motion in space occurred, that is, in the active space between the anode inner radius r_a and the cathode outer radius r_c .

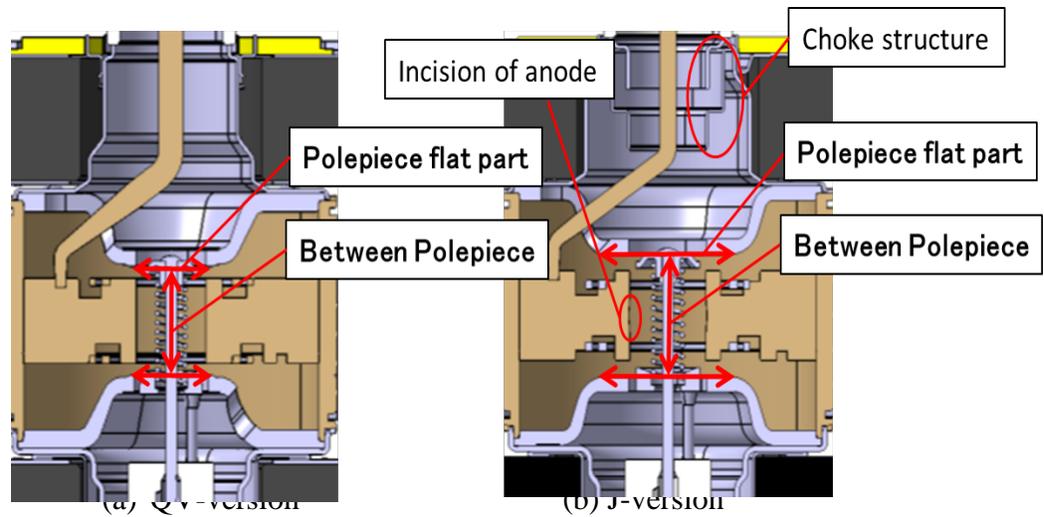
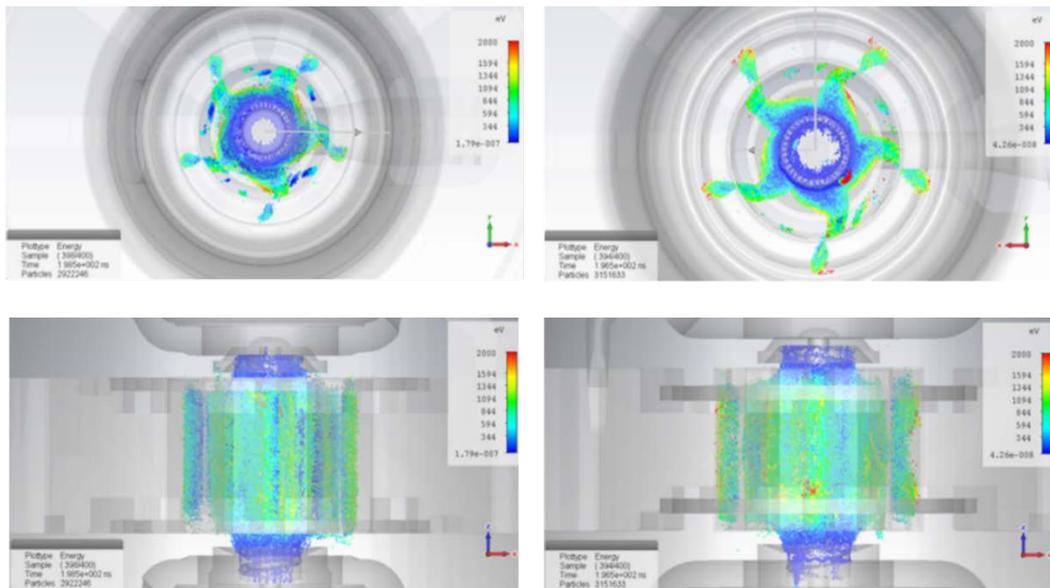


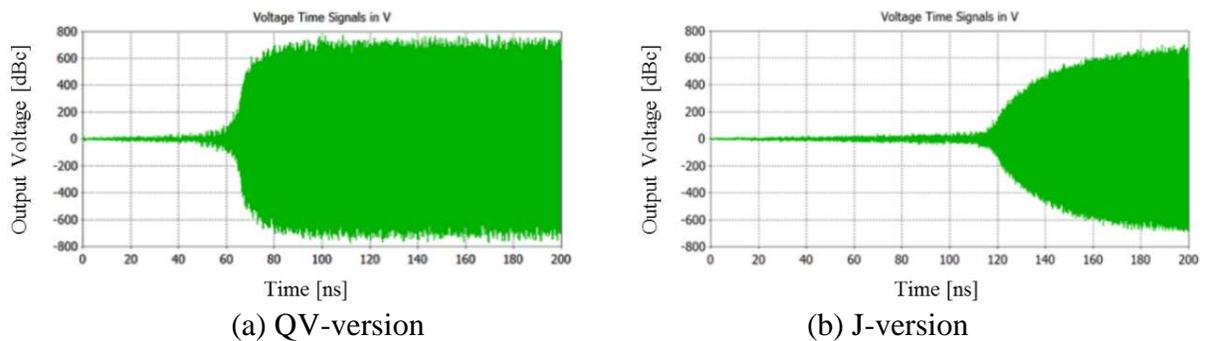
Figure 3: Magnetron model



(a) QV-version

(b) J-version

Figure 4: Particle distribution



(a) QV-version

(b) J-version

Figure 5: Evolution of the output voltage with time

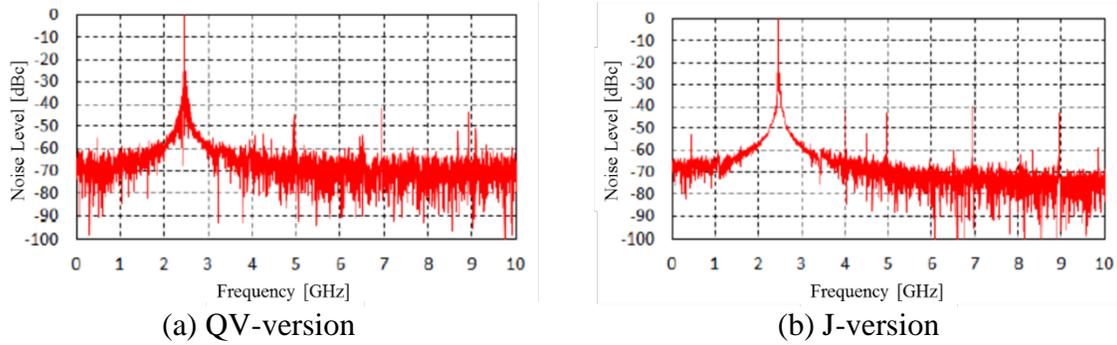


Figure 6: Frequency spectrum from FFT

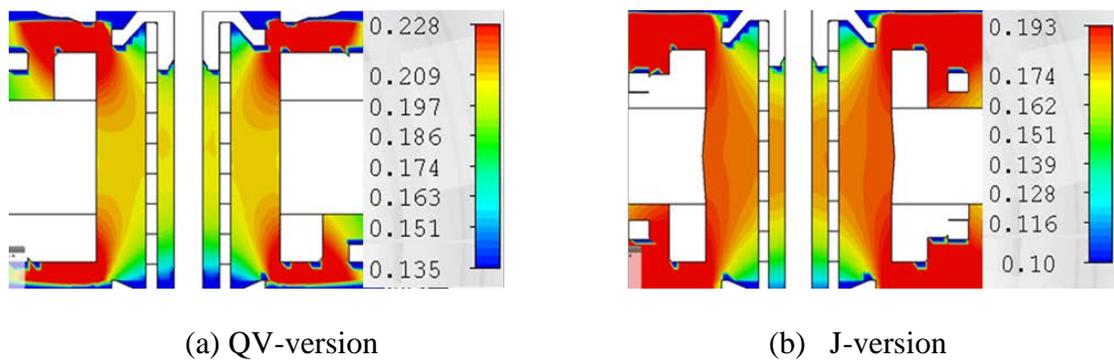


Figure 7: Magnetic field distribution

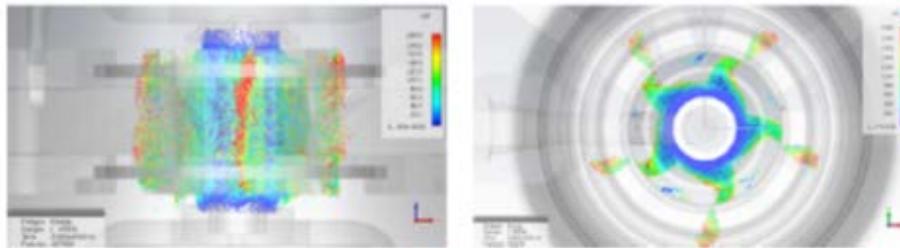


Figure 8: Axial and radial particle distribution (coaxial displacement)

Table 1. Comparison of efficiencies

Magnetron Type	Current High-efficiency QV-version	Current Low-Noise J-version
Theory calculation value Equation (1)	77.6%	74.9%
CAE results Uniform magnetic field	76.4%	68.4%
CAE results Actual magnetic field	66.6%	56.9%

It was also noticed that the frequency change increased due to altering the distance between the cathode and the anode in the axial direction. Therefore, we also incorporated the technologies of industrial magnetrons and reexamined the dimensions, jigs and equipment, for a stabilized quality design.

Results

The performance of the newly developed magnetron using a waveguide measurement system is shown in Table 3. The noise performance on a microwave oven is shown in Fig. 10. In addition, the durability test results are shown in Fig. 11, which show that the life time has been longer than 5,000 hours (while the magnetron is still working).

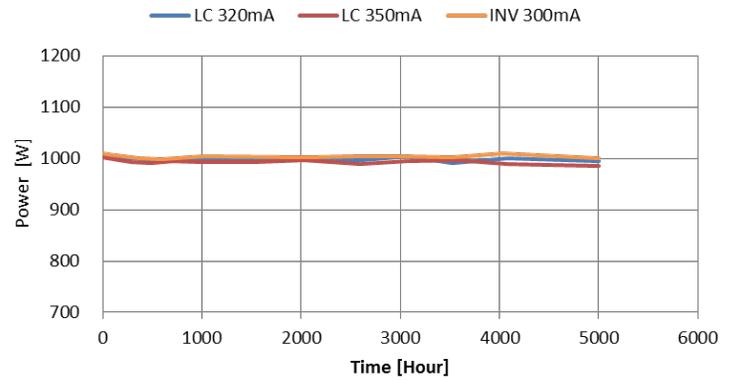


Figure 11: Durability test data

Table 2. Comparison of efficiencies

Magnetron Type	QV-version	J-version	New U-version
Total anode current	1.88 A	1.98 A	1.92 A
A-side	8.2 %	23.5 %	24.6 %
Center	67.0 %	43.7 %	41.3 %
K-side	24.8 %	32.8 %	34.1 %
CAE results, efficiency	66.6 %	56.9%	62.0 %

Table 3. Comparison of specifications to the present Panasonic magnetrons

Magnetron Type	Current High-efficiency QV-version	Current Low-Noise J-version	New U-version
Efficiency	75 %	72 %	74 %
For CISPR11	Not so Good	Good	Good
Stability to load	Not so Good	Good	Good

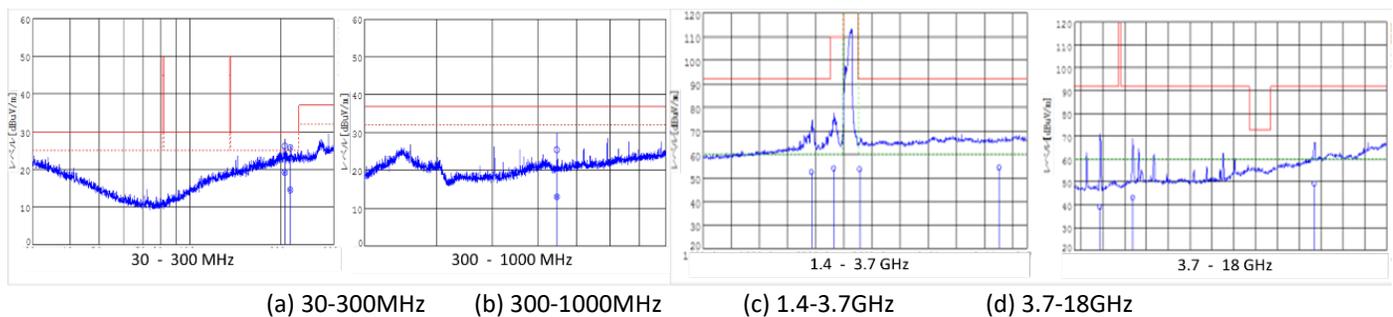


Figure 10: Noise performance in microwave oven

Discussion

The theoretical efficiency is derived assuming an ideal orthogonal electromagnetic field. Therefore, we proved that it was possible to obtain high efficiency and low noise by forming an ideal orthogonal electromagnetic field over the entire axial direction of the active space. Furthermore, by improving the manufacturing precision of the structure and production methods, we also confirmed securing high reliability.

Conclusion

In this study, we have successfully developed a new magnetron U-version with high efficiency, low noise and high quality by optimizing the part shaping, while utilizing electromagnetic field distribution analysis and electron motion analysis. With this achievement, we were able to add new magnetrons in our product list, which should be possible to be deployed all over the world.

For further reading:

1. K. Hirayama, T. Mitani, N. Shinohara, K. Kawata, and N. Kuwahara, "3D Particle-in-cell simulation on efficiency and back-bombardment of an oven magnetron", 17th International Vacuum Electronics Conference (IVEC2016), Monterey, USA, Apr. 2016.

About the Authors



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