**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 \( \eta \) is given by:

\[
\eta = \eta_c \left( 1 - \frac{mv^2}{2eV} \right) \approx \eta_c \left( 1 - \frac{r_a + r_c}{r_a - r_c} \frac{\omega}{n eB/m - \omega} \right),
\]

where \( \eta_c \) 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 radiiuses, respectively, \( \omega \) 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 gyrations of the electrons resonate 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*
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

Figure 4: Particle distribution

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

<table>
<thead>
<tr>
<th>Magnetron Type</th>
<th>Current High-efficiency</th>
<th>Current Low-Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>QV-version</td>
<td>J-version</td>
</tr>
<tr>
<td>Theory calculation value Equation (1)</td>
<td>77.6%</td>
<td>74.9%</td>
</tr>
<tr>
<td>CAE results Uniform magnetic field</td>
<td>76.4%</td>
<td>68.4%</td>
</tr>
<tr>
<td>CAE results Actual magnetic field</td>
<td>66.6%</td>
<td>56.9%</td>
</tr>
</tbody>
</table>
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](image)

**Table 2. Comparison of efficiencies**

<table>
<thead>
<tr>
<th>Magnetron Type</th>
<th>QV-version</th>
<th>J-version</th>
<th>New U-version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total anode current</td>
<td>1.88 A</td>
<td>1.98 A</td>
<td>1.92 A</td>
</tr>
<tr>
<td>A-side</td>
<td>8.2 %</td>
<td>23.5 %</td>
<td>24.6 %</td>
</tr>
<tr>
<td>Center</td>
<td>67.0 %</td>
<td>43.7 %</td>
<td>41.3 %</td>
</tr>
<tr>
<td>K-side</td>
<td>24.8 %</td>
<td>32.8 %</td>
<td>34.1 %</td>
</tr>
<tr>
<td>CAE results, efficiency</td>
<td>66.6 %</td>
<td>56.9%</td>
<td>62.0 %</td>
</tr>
</tbody>
</table>

**Table 3. Comparison of specifications to the present Panasonic magnetrons**

<table>
<thead>
<tr>
<th>Magnetron Type</th>
<th>Current High-efficiency QV-version</th>
<th>Current Low-Noise J-version</th>
<th>New U-version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>75 %</td>
<td>72 %</td>
<td>74 %</td>
</tr>
<tr>
<td>For CISPR11</td>
<td>Not so Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Stability to load</td>
<td>Not so Good</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>

![Figure 10: Noise performance in microwave oven](image)
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:

About the Authors

Nagisa Kuwahara received the B.E. degrees in electronic engineering from Utsunomiya University, Tochigi, Japan, in 1989. She has joined Panasonic Corporation in 1989. From 2005, she has been manager of the magnetron design section. She has been engaged in the development and design of magnetrons. She is member of the Japan Society of Electromagnetic-Wave Energy Applications (JEMEA).

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Naoki Shinohara received the B.E. degree in electronic engineering, the M.E. and Ph.D (Eng.) degrees in electrical engineering from Kyoto University, Japan, in 1991, 1993 and 1996, respectively. He was a research associate in Kyoto University from 1996. From 2010, he has been a professor in Kyoto University. He has been engaged in research on Solar Power Station/Satellite and Microwave Power Transmission systems. He is the IEEE MTT-S Technical Committee 26 (Wireless Power Transfer and Conversion) vice chair, IEEE MTT-S Kansai Chapter TPC member, IEEE Wireless Power Transfer Conference advisory committee member, URSI Commission D vice chair, international journal of Wireless Power Transfer (Cambridge Press) executive editor, technical committee on IEICE Wireless Power Transfer, communications society member, Japan Society of Electromagnetic-Wave Energy Applications vice president, Space Solar Power Systems Society board member, Wireless Power Transfer Consortium for Practical Applications (WiPoT) chair, and Wireless Power Management Consortium (WPMc) chair.