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EXPERIMENTAL RESEARCH AND DEVELOPMENT ON NOISE REDUCTION OF 2.45GHZ CW MAGNETRONS

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ABSTRACT

The objective of the present study is an experimental research and development on noise reduction of current commercial magnetrons, which will be applied to a SPS. We have found out that turning off the filament current of a magnetron worked exceedingly well for reducing the levels of spurious noises as well as narrowing the oscillation bandwidth when a magnetron was driven by DC stabilized power supply. We have experimentally verified that these improvements are produced by the smoothing effect of anode current, the reduction of thermal effects, and the decline in the number of thermal electrons in the vicinity of both filament ends. Next, we found out that spurious noises were reduced when the rated anode voltage was decreased or the anode-cathode distance was increased. Then, we evaluated effects on SPS transmitters through experimental results.

1. INTRODUCTION

A magnetron is well-known as a microwave source of a microwave oven. Besides, it is one of the candidates for a microwave source of a SPS transmitter, because its DC-RF conversion efficiency is higher, it costs less, and it has lower weight/power ratio than solid state devices. A lot of researches and experiments on microwave power transmission (MPT) and SPS have been conducted at our research institute, and MPT equipments which use magnetrons as DC-RF converters have established there [1][2]. However, a magnetron has a wide bandwidth of the fundamental frequency and spurious noises in various frequencies. The wide bandwidth of the fundamental frequency represents a critical problem that a microwave beam from a SPS is unable to be focused stably to a receiving site. Spurious noises in various frequencies are difficult to prevision, and their radiation from a SPS will severely interfere in the other communication systems. Besides, with regard to a microwave oven, EMC problems are lead to along with the popularization of information technologies. Therefore, it is indispensable to employ measures against the noise generation from a magnetron. The objective of the present study is an experimental research on noise reduction of current commercial magnetrons and a development on low-noise magnetrons.

2. EFFECTIVENESS OF TURNING OFF FILAMENT CURRENT

2.1 Improvements of the bandwidth of the fundamental frequency

It is an effective technique to turn off the filament current of a magnetron during its oscillation when it is driven by a DC stabilized power supply, in order to improve the bandwidth of the fundamental frequency. Brown mentioned that reducing or turning off the filament current improved the spurious noise levels in the vicinity of the oscillation of a microwave oven magnetron [3]. Also, turning off or cutting back the filament current has been a well-known beneficial way to give a long life to the cathode of a magnetron, since these techniques contribute to the reduction of excessive back bombardment energy which overheats the cathode and shortens its lifetime [4]. However, a mechanism of these improvements has not been mentioned. We have experimentally verified that turning off the filament current narrowed the bandwidth of the fundamental frequency. Also, we found out the improvement mostly originated from the smoothing effect of anode current [5].

Fig. 1 shows fundamental frequency spectra of a magnetron (Matsushita Electronic Instruments Corp. 2M210M1F1) at 250mA of the anode current. The thin line and the thick line in Fig. 1 show the spectrum when the filament current is 10A (the rated value) or it is turned on, and when it is 0A or it is turned off, respectively.

The bandwidth of the fundamental frequency improves extremely narrower when the filament current is turned off than when it is turned on, as shown in Fig.1. The Q value of the spectrum was also improved from 8.0 times 10^2 at 10A of the filament current to 1.1 times 10^5 at 0A.

The main factor of the improvement is the smoothing effect of the anode current when the filament current is turned off. Fig. 2 shows anode current waveforms of a magnetron.

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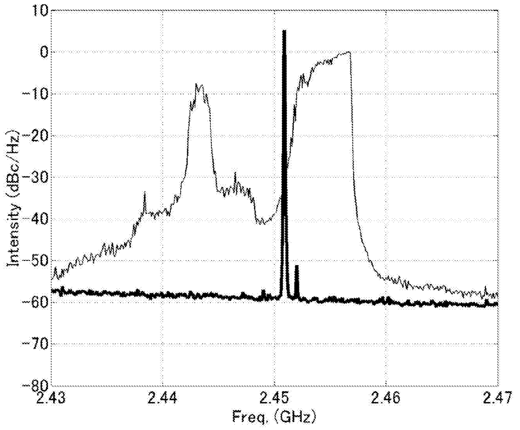

Fig. 1. Fundamental frequency spectra at 250mA of the anode current. (filament current: 0A [thick line], 10A [thin line], resolution bandwidth: 10kHz)

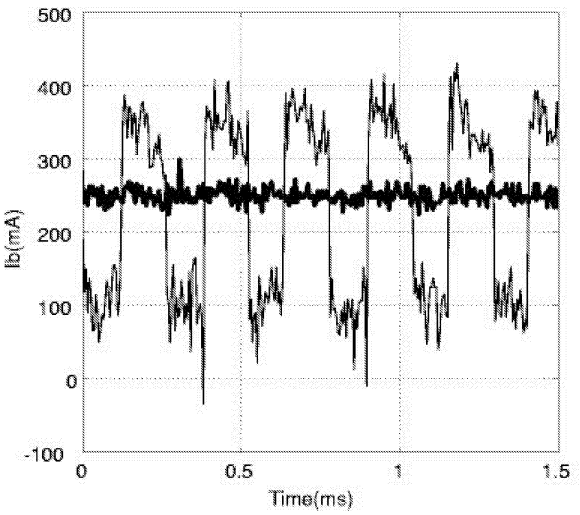

Fig. 2. Anode current waveforms at 250mA of the anode current (Ib). (filament current: 0A [thick line], 10A [thin line])

We found out that the anode current is fluctuated in a certain range of the anode current when the filament current is turned on, even though the magnetron is driven by a DC stabilized power supply, as shown in the thin line in Fig.2. This seemingly inexplicable fluctuation of the anode current is attributable to an anode current vs. anode voltage curve of a magnetron, as shown in Fig. 3. The curve we measured had the almost constant region of the anode voltage in the 100mA to 350mA range of the anode current when the filament current is turned on. Because the feedback system of the DC stabilized power supply is unable to control the anode current normally, the anode current is fluctuated in this range. When the filament current is turned off, on the other hand, the anode current is normally regulated, as shown in the thick line in Fig.2, since the anode current vs. anode voltage curve in Fig.3 has no constant region of the anode voltage.

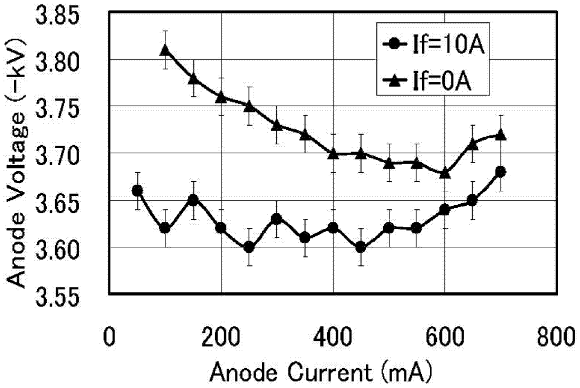

Fig. 3. Anode current vs. anode voltage curve (If: filament current).

It is known that the oscillation frequency of a magnetron is a nearly linear function of its anode current, so called a frequency pushing effect [4]. Then the fluctuation of anode current directly influences the oscillation bandwidth of a magnetron. Therefore, the oscillation at 0A of the filament current provides the narrower bandwidth of the fundamental frequency since the variation of the anode current is much smaller than at 10A of the filament current.

2.2 Improvements of spurious noises

We also experimentally verified that turning off the filament current reduced levels of spurious noises generated from a magnetron [6].

Fig. 4 and Fig. 5 show high frequency spectra of the radiation noises and relative low frequency spectra of the line noise of the magnetron at 250mA of the anode current, respectively. The thin line and the thick line in Fig. 4 and Fig. 5 show the same as those in Fig. 1. Spurious noises are also improved drastically by turning off the filament current.

Besides, we verified that some low frequency spurious noises were related to some high frequency spurious noises. For examples, the discrete noise at 660MHz is observed, as shown in the thick line in Fig. 5, while the discrete noises at 4.9GHz (the second harmonics of the magnetron) plus or minus 660MHz are also observed, as shown in the thick line in Fig. 4. This relationship is probably the intermodulation effect between the low frequency spurious noises and the second harmonic although we are now researching mechanisms of the generation of spurious noises.

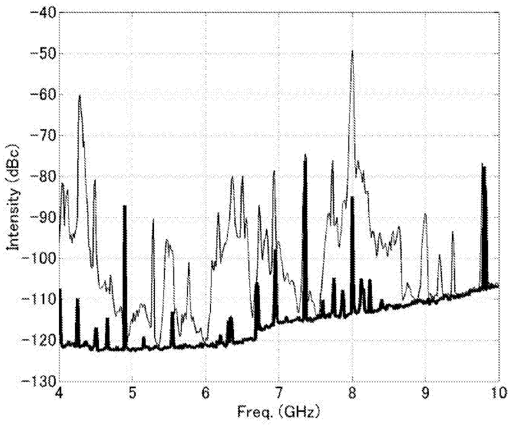

Fig.4. High frequency spurious spectra at 250mA of the anode current. (filament current: 0A [thick line], 10A [thin line], resolution bandwidth: 100kHz)

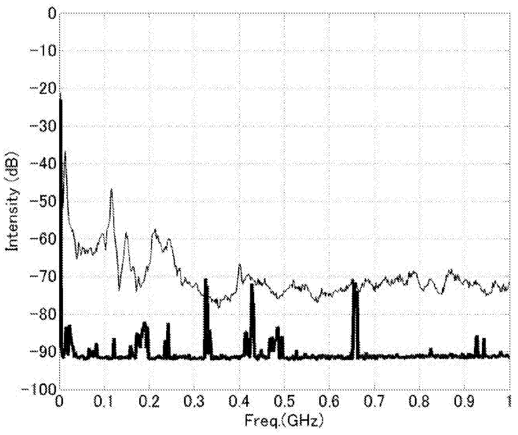

Fig. 5. Relative low frequency spurious spectra at 250mA of the anode current. (filament current: 0A [thick line], 10A [thin line], resolution bandwidth: 100kHz)

The reduction of the spurious noises is provided by the reduction of the thermal effects and the decline in the number of thermal electrons in the vicinity of both filament ends.

Fig. 6 shows a curve of the filament current vs. the filament temperature. The difference of the filament temperature is about 100 degrees between 10A and 0A of the filament current. The lowering of the filament temperature causes the reduction of the number of thermal electrons emitted from the cathode filament. Therefore, thermal effects such as thermal noises may reduce in a magnetron.

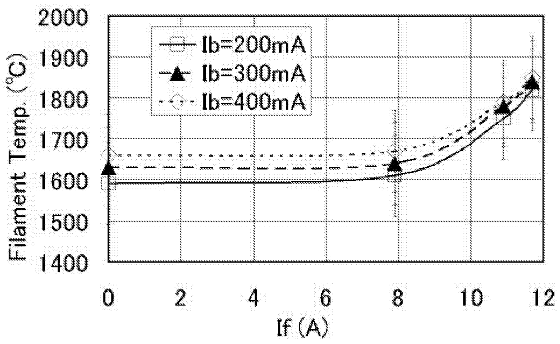

Fig. 6. Filament current (If) vs. filament temperature curve.

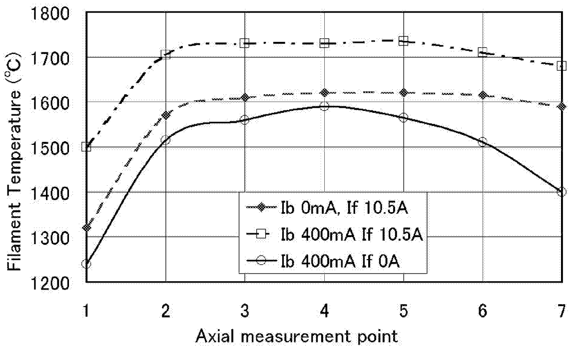

Fig. 7. Filament temperature distribution to the axial direction.

Fig. 7 shows filament temperature distribution to the axial direction. The horizontal axis means axial measurement points. The number 1, 4 and 7 are the point at the filament end of the RF output probe side, at the center of the filament, and at the filament end of the DC input side, respectively. We found out that the filament temperatures of the both filament ends are much lower than that of the center of the filament. Besides, when the filament current is turned off, filament temperatures of both filament ends are relatively so low that thermal electrons are hardly emitted from the cathode. The strong decline in the number of thermal electrons at both filament ends will reduce the thermal effects.

In the light of the relationship between the anode current vs. anode voltage curve and the decline in the number of electrons, there is a possibility that the constant voltage region will be formed by the existence of overabundant electrons when the filament current is turned on. These overabundant electrons will freely move in the interaction space of a magnetron, hence their behavior is considered as one of the causes that spurious noises in various frequencies are generated.

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3. RELATION BETWEEN SPURIOUS NOISES AND SPECIFICATIONS ON MAGNETRON

We have also researched the relation between spurious noises and specifications on a magnetron. We chose the rated anode voltage and the anode-cathode distance in the specifications as parameters.

3.1 Rated anode voltage vs. spurious noises

Fig. 8 shows relative high frequency spurious noises in relation to the rated anode voltage. The thick line and the thin line show the spectrum when the rated anode voltage is 2.6kV and 4.6kV, respectively. The anode-cathode distance is the same as that of Matsushita Electronic Instruments Corp. 2M210 M1F1. The filament current is turned off during these measurements.

We found out that spurious noises are extremely reduced, except for the harmonics, at 2.6kV of the rated value compared to 4.6kV. This improvement is caused by two factors: that the initial potential energy which is supplied to emitted electrons is decreased, and that the magnitude of the RF oscillation which influences motions of electrons is decreased.

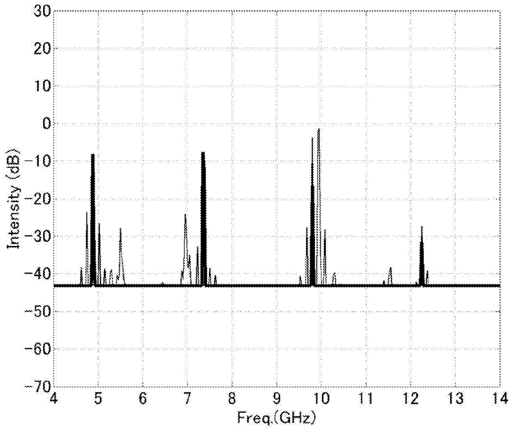

Fig. 8. Relative high frequency spurious noise spectra in relation to the rated anode voltage (2.6kV [thick line], 4.6kV [thin line], filament current: 0A, resolution bandwidth: 1MHz)

3.2 Anode-cathode distance vs. spurious noises

Fig. 9 shows relative high frequency spurious noises in relation to the anode-cathode distance. The thick line and the thin line show the spectrum when the anode-cathode distance is normal and about 0.3mm narrower than the normal one, respectively. The rated anode voltage is 3.6kV; the same as that of Matsushita Electronic Instruments Corp. 2M210M1F1. The filament current is turned off during these measurements.

We found out that the wider the anode-cathode distance is, the lower the levels of spurious noises are. The magnitude of the effect in this case, however, seems to be less than in the case of the rated anode voltage. This improvement is provided by weakening the magnitude of mutual interaction between the RF oscillation near the anode and electron clouds near the cathode.

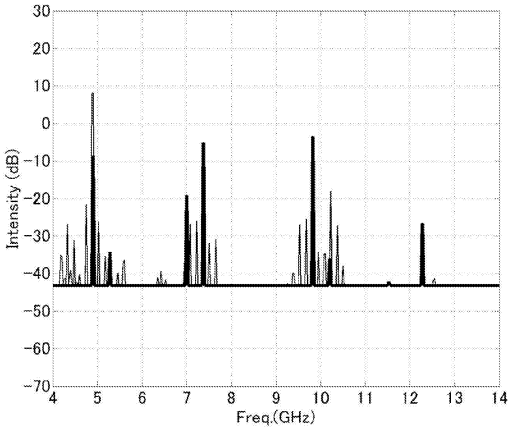

Fig. 9. Relative high frequency spurious noise spectra in relation to the anode-cathode distance (normal distance [thick line], narrower distance [thin line], filament current: 0A, resolution bandwidth: 1MHz)

3.3 Discussion on factors of reduction of spurious noises

Our experiments show that spurious noises from a magnetron are reduced when the rated anode voltage is decreased or the anode-cathode distance is increased. Considering common points between both experimental results, they probably indicate that the generation of spurious noises depends on the electrostatic field intensity to the radial direction.

We are now researching the relationship theoretically between electrostatic field intensity and spurious noises by considering two factors: (A) loci of the potential minimum in a magnetron and (B) loci of the boundary between the space charge region and the interaction region.

3.4 Evaluation of effects on SPS transmitters through experimental results

The reduction of spurious noises gives a good impact to

SPS transmitters. Here, we evaluate total effects on SPS transmitters through our experimental results, especially, the results in the case of the rated anode voltage.

We are now considering the following advantages by lowering the rated anode voltage, except for the reduction of spurious noises: (a) an advantage for a high voltage power supply in space, (b) an advantage for a cooling system to a magnetron in space, and (c) reduction of thermal energy losses. The advantage (a) contributes to the reduction of the weight since turns ratio of transformers installed in a high voltage power supply is decreased. In terms of the advantage (b) and (c), thermal energy losses per magnetron are reduced by the reduction of the total energy flow including DC input and RF output. These advantages also contribute to the loss of weight of a SPS transmitter.

However, we are also considering a disadvantage of weight gain of SPS transmitters posed by increase of the number of magnetrons and their power supplies. This disadvantage originates from decrease of output RF power per magnetron. Also, the decrease of the rated anode voltage has a negative effect on DC-RF conversion efficiency. This is expressed by the following equations of the magnetron's operation curve and the magnetron's electron efficiency:

$$V = \frac{\omega(r_a^2 - r_c^2)}{2n}\left(B - \frac{\omega m}{ne}\right) \qquad (1)$$

$$\eta = 1 - \frac{r_a + r_c}{r_a - r_c}\frac{\omega m}{neB - \omega m} \quad , \qquad (2)$$

where V, B, η, e, m, r_a, r_c and n are a anode voltage, an external magnetic field, the electric charge, the electron mass, an anode radius, a cathode radius and a half of the number of anode vanes. When V is decreased, B or the anode-cathode distance $r_a - r_c$ has to be decreased in order to sustain the oscillation as shown in Eq.1. Therefore, the electron efficiency, which related to the DC-RF conversion efficiency, can't help but fall off since both B and $r_a - r_c$ are in the denominator of Eq.2.

The experimental measurements of DC-RF conversion efficiency actually follow this consideration. The DC-RF efficiency when the rated anode voltage is 2.6kV is 52.4%, while it is 69.9% when the rated anode voltage is 4.6kV.

After all, we need to evaluate trade-off between these advantages and disadvantages quantitatively including cost problems of SPS transmitters.

4. SUMMARY

In the present study, we improved both the bandwidth of the fundamental frequency and the spurious noises generated from a magnetron by turning off the filament current when it is driven by a DC stabilized power supply. Also, we found out that spurious noises were also reduced by the decrease of the rated anode voltage and the increase of the anode-cathode distance.

Thanks to the improvement of the oscillation bandwidth, a phase-controlled magnetron (PCM) has been developed, which is achieved by a frequency-locking technique with phase-locked loop (PLL) feedback [1] [2]. The PCM has an active phase control system. Therefore, huge microwave power is able to be focused by an array of PCMs. In order to demonstrate and research the total SPS system, Solar Power Radio Transmission System (SPORTS) has been developed at our research institute [1] [2]. The transmitting system of SPORTS is composed of an active phased array with 12 PCMs, and can concentrate about 4kW of the microwave power on the receiving system.

The current problem in the present study is reduction of discrete spurious noises, which still exist when the filament current is turned off. We have found that one of their origins is the modulation between the harmonics and low frequency noises below 1GHz, although mechanisms of the generation of spurious noises are under investigation. Hence, our future tasks are to reduce such low frequency noises, and finally to develop low-noise magnetrons. Though straightforward changes of the specifications may create a few percent loss of DC-RF conversion efficiency as we described, low-noise magnetrons not only contributes to microwave ovens, but also have a great chance to be installed in SPS transmitters.

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