MODE COOPERATION IN A SUBMILLIMETER WAVE FU SERIES GYROTRON

T. Idehara,¹ S. Mitsuda,¹ M. Pereyaslavets,² Y. Shimizu,² and I. Ogawa³

¹Research Center for Development of Far-Infrared Region
Fukui University
Bunkyo 3-9-1, Fukui 910-8507, Japan
²Department of Applied Physics
Faculty of Engineering
Fukui University
Bunkyo 3-9-1, Fukui 910-8507, Japan
³Cryogenic Laboratory
Faculty of Engineering
Fukui University
Bunkyo 3-9-1, Fukui 910-8507, Japan

Abstract

At certain gyrotron operating conditions, mode cooperation instead of mode competition takes place between a fundamental and a second harmonic mode. This means the phase bunching of a gyrating electron beam under the second harmonic operation reduces the starting current for the fundamental operation and increases total output power as well as beam efficiency. Such mode cooperation is observed in experiments and confirmed by computer simulations for submillimeter wave Gyrotron FU II.

Keywords: Gyrotron, Mode cooperation, Mode competition, Submillimeter Wave

I. INTRODUCTION

Gyrotrons are important sources of medium power submillimeter wave radiation [1] - [3].
Mode competition is a serious problem in high-power gyrotrons, since when it occurs the power from the electron beam goes not into a single operating mode. Furthermore, many gyrotrons, especially in submillimeter wave range, operate at a harmonic of the electron cyclotron frequency to achieve higher frequency for restricted magnetic field intensity. However, due to mode competition, the higher-power operation at the fundamental may suppress the second harmonic, so that higher frequencies cannot be reached. For those reasons, such a phenomenon has been intensively studied both in gyrotron oscillators [1], [4] - [33] and in other electron beam devices [34]-[36].

Experimental observations with gyrotron oscillators were reported for mode competition, e.g. in [17], [18] as well as for mode cooperation [5]. Various approaches have been proposed to eliminate undesirable mode competition, for example specially designed cavities [7] - [9], [37], [38] and careful choice of gyrotron operating conditions [39].

On the other hand, in some circumstances one mode helps to establish another one, i.e., mode cooperation occurs instead of mode competition [5]. Phase bunching of the electron beam by the second harmonic acts as pre-bunching enhancing operation at the fundamental. In such a way, the starting current of the fundamental operation is reduced, whereas total output power as well as beam efficiency is increased.

This paper is devoted to study of some examples of mode cooperation and competition in a submillimeter wave gyrotron named Gyrotron FU II, which was designed for operation at the second harmonic of the electron cyclotron frequency [39],[40].

II. NUMERICAL SIMULATION METHOD

Following [4], let us consider the energy gained by the microwave field in a resonant cavity due to interaction with a gyrating electron traveling along the length of the cavity:

\[ W = -\int_{\text{along cavity}} -eE \cdot \mathbf{v} \, dt; \]  \hspace{1cm} (1)

where \( E \) is the microwave electric field, \(-e\) is electron electric charge, and \( \mathbf{v} \) is the electron velocity. The electron velocity is obtained by solving so-called 'slow equations of motion' [4],[10]. The method [4] was employed to calculate the output power. The energy \( W \) transferred to the
field by a single electron is calculated for a given field amplitude $A$ of the $TE_{120}$ mode by solving the slow equations of motion to obtain $v$ and by performing the integral in (1) thereafter. An average $\langle \mathcal{W} \rangle$ is taken over all the initial electron phase angles and all azimuthal angles describing centers of electron orbits. Steady gyrotron operation at frequency $\omega$ occurs when the power lost by the field $P_{\text{lost}}$ is balanced by the power gained $P_{\text{gained}}$, this means:

$$P_{\text{lost}} = \frac{\omega U}{Q_{\text{total}}},$$

(2)

$$P_{\text{gained}} = \langle \mathcal{W} \rangle \frac{I_b}{e};$$

(3)

and the output power is:

$$P_{\text{out}} = \frac{Q_{\text{cond}}}{Q_{\text{df}}}, P_{\text{lost}}.$$  

(4)

Here $I_b$ is the beam current, $U$ is the microwave energy stored in the cavity, and $Q_{\text{cond}}$, $Q_{\text{df}}$ are the total and diffraction quality factors, respectively.

If two microwave fields at different frequencies are present in the cavity, $E$ is one of the microwave electric fields and $v$ is the motion under combination of the two microwave fields and the main magnetic field, then eq. (1) gives the energy gained by the first field. Let us designate the fundamental mode and the second harmonic by the subscripts 1 and 2, respectively.

The method [4] starts with ranges of values of the amplitudes $A_1$ and $A_2$, calculates the energies $\langle \mathcal{W}_1 \rangle$ and $\langle \mathcal{W}_2 \rangle$ gained by the two fields along with the beam currents $I_{b1}$ and $I_{b2}$ for steady gyrotron operations. If steady gyrotron operation occurs in two modes simultaneously, two conditions must be satisfied at the same time, this means lost and gained powers are balanced for both fields 1 and 2. In other words, the two calculated beam currents $I_{b1}$ and $I_{b2}$ must be equal for steady operation.

III. EXPERIMENTAL AND CALCULATION RESULTS

To understand mode interaction in the cavity of Gyrotron FU II, one should compute starting currents (more exactly the currents required to
Fig. 1 Simulation of the beam current $I_b$ required to sustain 1 kW output power vs. the magnetic field intensity. $TE_{nm}$ indicates the operating cavity mode, and $N$ the harmonic number. Cathode voltage $V_k = 40$ kV, pitch factor $\alpha = 1.5$, and the e-beam injection point $R_{inj} = 1.25$ mm.
sustain 1 kW output power) versus magnetic field for various modes at fundamental, second and third harmonics. The values of the pitch factor $\alpha = 1.5$ and the injection point of the beam $R_{inj} = 1.25 \text{ mm}$ were optimized using simulation of the electron gun. Those results [40] are presented in Fig. 1. As it follows from Fig. 1, the mostly interesting mode interactions occur between the $TE_{26}$ mode (second harmonic, 384 GHz) and the $TE_{23}$ mode (fundamental, 197 GHz), as well as between $TE_{33}$ mode (second harmonic, 405 GHz) and the $TE_{25}$ mode (fundamental, 207 GHz). As predicted by the simulation, the operation at the second harmonic $TE_{26}$ mode occurs in a narrow region of $B_0$ centered at 7.36 T.

The corresponding experimental results [40] are shown in Fig. 2 and Fig. 3.

As it was pointed out in [4], there is some kind of hysteresis of the output power versus magnetic field at a given mode depending on whether magnetic field is raised or lowered. An example of such a hysteresis for the fundamental $TE_{23}$ mode is shown in Fig. 4 [4] for the fixed values of $V_k = 40 \text{ kV}$ and $I_b = 1 \text{ A}$. Another example of output power hysteresis versus beam current calculated for the fundamental $TE_{22}$ and second harmonic $TE_{35}$ modes is shown in Fig. 5 for the fixed values of the main magnetic field $B_0 = 7.69 \text{ T}$ and $V_k = 40 \text{ kV}$.

The experimentally measured output power [5] versus the beam current $I_b$ for the simultaneous excitation of the fundamental $TE_{23}$ mode and the second harmonic $TE_{26}$ mode with the magnetic field intensity $B_0$ as the parameter is shown in Fig. 6. As it is predicted by the Fig. 1, the second harmonic appears first and grows with the increasing beam current. The fundamental is excited and grows rapidly at higher currents. Eventually the second harmonic is suppressed by the fundamental, and finally it completely disappears. Equipower contours for second-harmonic $TE_{26}$ mode and fundamental $TE_{23}$ mode operation in the parameter space $I_b - B_0$ are shown in Fig. 7 [6]. The hatched region corresponds to the single $TE_{26}$ mode at the second harmonic. The computer simulation results [6] are shown in Fig. 8 for the same conditions as in Fig. 6. The simulation was carried out employing the method of Section II. The appearance of the second harmonic and the fundamental and the suppression of the second harmonic as the beam
Fig. 2. Experimentally measured dependence of the output power on the main magnetic field intensity $B_0$ in the cavity region for the $TE_{261}$ mode operation.
Fig. 3 Dependence of the output power on the auxiliary field $B_1$ in the gun region for the $TE_{26}$ mode operation.
Fig. 4 Output power versus magnetic field $B_0$ for the fundamental $TE_{231}$ mode. Magnetic field increasing (solid curve) and decreasing (broken curve); $V_k = 40\, kV$, $I_s = 1\, A$. 
Fig. 5 Output power versus beam current for the fundamental \( TE_{31} \) and second harmonic \( TE_{55} \) modes. Beam current increasing (solid curve) and decreasing (broken curve); the main magnetic field \( B_0 = 7.69 \ T \) and \( V_k = 40 \ kV \).
current increases, closely matches the experimental results. The experimental values of the magnetic field are slightly higher than the calculated ones. This difference can be accounted for by the fact that the accuracy of our gaussmeter is no better than 3%. The suppression of the second harmonic is a clear illustration of mode competition between the fundamental and second harmonic.

As is was pointed out in [5], mode cooperation occurs in the initial stage, that is, at lower beam currents. The comparison of computer simulation with experiment [6] is shown in Fig. 9. The values of beam current $I_b$ necessary to sustain 1 kW output power versus magnetic field intensity $B_0$ are computed in Fig. 9 assuming a simple single mode operation for the second-harmonic $TE_{211}$ mode and fundamental $TE_{201}$ mode. The comparison with the experimental results gives some qualitative insights for understanding competition and cooperation.

Fig. 10 shows calculated output power [5] for the second-harmonic $TE_{201}$ mode (solid lines) and the fundamental $TE_{211}$ mode (broken lines) versus beam current for the magnetic field $B_0 = 7.32 \ T$. Thick and thin lines represent the actual simultaneous excitation of fundamental and second harmonic and a hypothetical single mode excitation, respectively. The total power of both excitations is shown by the dotted line. Although other low power branches appear in the simulation for single mode excitations of the fundamental and second harmonic, they are not presented in the figure, because we can treat them as spurious modes. Comparison of the curves in Fig. 10 gives some interesting insights. First, when the second harmonic is present, the starting current for the fundamental falls from point A to B. Second, the total power between these points is greater than it would be if there was second harmonic excitation only. Therefore, when mode cooperation occurs, more power is extracted from the electrons. For example, the total power increases by more than 80% at $I_b = 1.1 \ A$ and $B_0 = 7.32 \ T$.

The range of beam currents for mode cooperation [5] derived from experimental results is shown in Fig. 11 (a), whereas the corresponding calculated results are presented in Fig. 11 (b). In both figures, the curves labeled B correspond to the starting current for the fundamental and the curves labeled A show the current of complete suppression of the second harmonic. Once again, slightly weaker field intensity in experimental results than that in simulation comes from inaccuracy of our gaussmeter.
Fig. 6 Experimentally measured output power versus beam current $I_b$ for the second harmonic $TE_{231}$ mode (solid line) and the fundamental $TE_{231}$ mode (broken line) with the magnetic field intensity $B_0$ as the parameter.
Fig. 7 Equipower lines in the parameter space $I_s - B_0$ for the second-harmonic $TE_{261}$ mode and fundamental $TE_{231}$ mode operation.
Fig. 8 Calculated output power versus beam current $I_b$ for the second harmonic $TE_{261}$ mode (solid lines) and the fundamental $TE_{231}$ mode (broken lines) with the magnetic field intensity $B_0$ as the parameter.
Fig. 9 Computed values of beam current $I_b$ necessary to sustain 1 kW output power versus magnetic field intensity $B_0$ for the second-harmonic $TE_{261}$ mode and fundamental $TE_{231}$ mode. Single mode operation is assumed in computation. The broken lines show experimental results.
Fig. 10 Calculated output power for the second-harmonic $TE_{261}$ mode (solid lines) and the fundamental $TE_{231}$ mode (broken lines) versus beam current for $B_0 = 7.32 \, T$. The actual simultaneous excitation of fundamental and second harmonic (thick lines) and a hypothetical single mode excitation (thin lines); total power of both excitations (dotted line). Mode cooperation occurs between currents denoted as A and B.
Fig. 11 Electron beam current range for mode cooperation versus magnetic field $B_0$.
(a) Experimental results (b) simulation results; $\Delta$ denotes the starting current for the second harmonic $TE_{261}$ mode.
Fig. 12 Angular positions and gyroradii of 100 electrons at each second harmonics periods $\tau$ for the case of mode cooperation; $I_0 = 1.1 A$ and $B_0 = 7.32 T$. (a) $\tau = 20$, (b) $\tau = 40$, (c) $\tau = 60$, (d) $\tau = 80$. 
The phase bunching of the electrons for the case of \( I_a = 1.1 \, \text{A} \) and \( B_0 = 7.32 \, \text{T} \) is illustrated in Fig. 12 [5]. According to a single mode calculation, the fundamental would not occur at those conditions. The illustration starts with a group of 100 electrons entering the cavity. Their initial angular positions are uniformly distributed from 0 to \( 2\pi \). Thereafter electron positions at each second harmonic period are calculated. The bunching is weak in the initial stages, and two weak bunches appear to be almost symmetric. Nevertheless, the symmetry is later disturbed and one bunching develops strongly. This is a typical illustration of mode cooperation, where gyrotron operation at the second cyclotron harmonic provokes excitation of another mode at the fundamental cyclotron resonance, so these two modes may coexist. It seems that prebunching by the second harmonic occurring in the initial stage enhances the operation at the fundamental, which cannot rise without the help of the second harmonic operation. This mechanism results in decrease of the starting current for the fundamental operation.

Another example of similar mode interaction is presented in Fig. 13. Here the calculated output power versus beam current \( I_a \) is presented for the second harmonic \( TE_{25} \) mode (solid lines) and for the fundamental \( TE_{25} \) mode (broken lines) with the magnetic field intensity \( B_0 \) as the parameter.

IV. CONCLUSION

The mode cooperation can reduce the starting current for operation at the fundamental and increase the amount of total power extracted from the electron beam. Those phenomena were demonstrated experimentally in Gyrotron FU II and confirmed by the computer calculations.

Perhaps mode cooperation offers a suitable way to achieve useful output powers from a gyrotron operating at lower voltages and currents, not to mention enhancement of the total beam efficiency.

Acknowledgement

The work is supported in part by a grant-in-aid from the Ministry of Education, Science, Sport and Culture of Japan. Thanks are due to Dr. G.F. Brand from School of Physics, University of Sydney and to Prof. V. Bratman of IAP, Nizhny Novgorod for invaluable discussions.
Fig. 13 Calculated output power versus beam current $I_b$ for the second harmonic $TE_{35}$ mode (solid lines) and the fundamental $TE_{25}$ mode (broken lines) with the magnetic field intensity $B_0$ as the parameter.
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