Two different mode interactions in an electron tube with a Fabry-Perot resonator - The Leadatron

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Two Different Mode Interactions in an Electron Tube with a Fabry–Perot Resonator—The Ledatron[1]

KOJI MIZUNO, SHOICHI ONO, AND YUKIO SHIBATA

***Abstract*—An electron tube with a Fabry–Perot resonator for the generation of millimeter and submillimeter waves, the Ledatron, has been investigated both theoretically and experimentally. Two different mode interactions, Fabry–Perot mode and surface wave mode, were predicted and found to exist. These two modes can be separated by proper selection of the mirror spacing of the Fabry–Perot resonator in the tube.**

These two mode oscillations have different characteristics. In the case of the Fabry–Perot mode, the oscillating frequency is tuned mainly by variation of the mirror spacing, that is, mechanical tuning is predominant. On the other hand, in the case of the surface wave mode, electronic tuning predominates. For gratings of the same physical size, the surface wave mode oscillator needs a larger electron accelerating voltage than the Fabry–Perot mode oscillator in order to obtain the same wavelength. The experimental results are in good agreement with our theory of operation.

I. INTRODUCTION

THIS PAPER deals with theoretical and experimental studies on the electron tube with a Fabry–Perot resonator [1] named "Ledatron." The studies have revealed that two different mode interactions between an electron beam and an electromagnetic wave exist in the tube, and that both of these interactions result in oscillations of the electromagnetic waves.

One of the interactions is a backward wave interaction, that is, an interaction between an electron beam and a backward wave contained in the surface wave guided by the grating. In this paper we call it "surface wave mode" interaction, and so far have observed this mode with an output power of several hundred milliwatts at 300-GHz band.

The other is a "Fabry–Perot mode" interaction, that is, an interaction between an electron beam and a standing wave in the Fabry–Perot resonator. Output power of above 1 W and a continuous frequency tuning range of about 40 percent in the short millimeter waveband have been obtained with our experimental tube, which shows that the tube has excellent characteristics as a bright source of short millimeter and submillimeter waves.

A similar tube configuration called "Orotron" was reported by Rusin and Bogomolov [2]; however, they did not mention the existence of these two different types of oscillations. Our experimental results show that through adjusting the attitude of mirrors composing the Fabry–Perot resonator, a "mode pulling" occurs, and we can select one of the above-mentioned two modes at will.

II. QUALITATIVE EXPLANATION

A. Fabry–Perot Mode Interaction

The fundamental configuration of this electron tube is shown in Fig. 1. A reflecting grating is used as one of the mirrors of the Fabry–Perot resonator. If the spacing between the mirrors is adjusted properly, a resonance will occur for a given electromagnetic wave, and the field distribution just in front of the grating will consist of many space harmonic waves traveling along the surface of the grating. The electron beam interacts with one of these harmonic waves, for which the phase velocity is nearly equal to the electron velocity. We analyzed the interaction according to the kinematic bunching theory in a single-cavity multigap interaction. Under the assumption of small signals, the total electronic admittance is given by the following equation [1], [3]:

$$G_e = \frac{1}{2}\beta_0{}^2\overline{G}_b \sum_{N=2}^{N_0} \sum_{K=1}^{N-1} \frac{K\bar{\theta} V_{N-K} e^{j\phi_{N-K}}}{V_N e^{j\phi_N}} \sin(K\bar{\theta}) = \frac{1}{2}\beta_0{}^2\overline{G}_b g_e(\bar{\theta}, N_0) \tag{1}$$

where β_0 is the beam coupling coefficient on a groove, $\overline{G}_b$ is the dc beam current/dc beam voltage, N_0 is the total number of grooves, $\bar{\theta}$ is the dc transit angle for the pitch of grooves, V_N is the amplitude of the RF voltage on the Nth groove, ϕ_N is the phase delay of the RF electric field on the Nth groove, and g_e is the normalized electronic admittance $(g_{ec}+jg_{es})$.

Applying (1) to an actual grating, the electronic admittance can be numerically calculated. The maximum negative conductance is obtained at

$$\bar{\theta} = \bar{\theta}_{0p} \simeq 2m\pi - \pi/N_0 \quad (\mathrm{TEM}_{00}\ \text{resonance}) \tag{2}$$

and

$$\bar{\theta} = \bar{\theta}_{0p}' \simeq 2m\pi - 2\pi/N_0 \quad (\mathrm{TEM}_{01}\ \text{resonance}) \tag{3}$$

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[1] In Greek mythology, "Leda" was the mother of the twins, Castor and Pollux, who were believed to be the children of Zeus, who visited her in the form of a swan, and "tron" is a familiar ending for electron tubes. The title "Ledatron," therefore, stands for an electron tube having "two" mode oscillations.

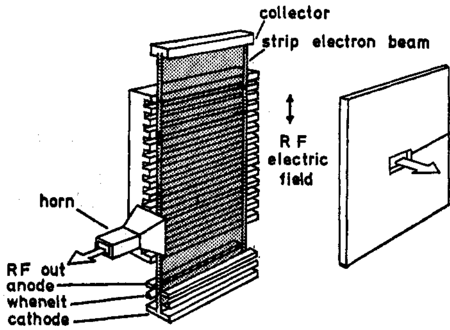

Fig. 1. Perspective view of the fundamental configuration of the tube. Output power in two different ways shown in this figure can be obtained. A microwave horn is put beside the grating.

where $m(1, 2, 3, \cdots)$ is the order of the space harmonic wave with which the electron beam interacts.

B. Surface Wave Mode Interaction

The electromagnetic characteristics of corrugated structures have been studied by many authors. The general theory indicates that the surface will act as a guide for electromagnetic waves, and the guided surface wave consists of an infinite number of space harmonic waves. Therefore, when an electron beam passes near the surface at a velocity close to the phase velocity of one of the backward space harmonics, an effective interaction may take place between the electron and the wave, resulting in backward wave oscillation.

The method of field matching, taken at the surface of the grating, gives the determinantal equation as follows:

$$\sum_n \frac{\sin\frac{\beta_n}{2}d}{\beta_n\sqrt{\beta_n^2-k^2}} = \frac{D}{2k}\cot kt \qquad (4)$$

where d is the groove width, t is the groove depth, D is the groove pitch, $k=\omega/c$, and $\beta_n=\beta_0+2\pi n/D$. The phase velocity of the nth space harmonic is given by $v_{pn}=\omega/\beta_n$.

Since there is some leakage energy along the grating, the oscillating wave can be enhanced by putting a reflector in suitable position, thereby forming a Fabry–Perot resonator together with the grating. Since the leakage energy is small, the reflector does not play an essential role in this interaction. In our experiments, the oscillating wavelength was found to be almost completely determined by the groove dimension of the grating and the electron velocity, and not by the reflector position. Therefore, this interaction is completely different from that of the Fabry–Perot mode, where the oscillating frequency can be tuned by changing the mirror spacing.

III. Mechanical and Electrical Design of the Experimental Tube

We have made gratings for various operating wavelengths (Table I). The dimensions of the grooves were calculated from our theoretical results [1]. The dimensions of the grating surface were 30×30 mm². The accuracy was kept to within 3 μm for all dimensions of the grooves [4].

TABLE I

The Gratings for Various Operating Wavelengths Have Been Made. The Milling Machine Used Has an Optically Indexed Precision Scale and was Permitted to Idle for About 4 h in Order to Expand All Parts Fully Before the Operation was Started. The Milling Cutters are Made of Tungsten Carbide of Extremely Small Grain Size

Grating Number	1	2	3	4	5	6
Dimension of Grooves						
D (pitch)	460 μm	460	460	390	230	150
d (width)	218 μm	218	218	218	91	71
t (depth)	496 μm	496	350	345	220	140
Number	7	8	9	10	11	
D	150	190	460	920	990	
d	50	70	95	218	316	
t	205	290	488	496	990	
Number	12	13	14			
D	664	460	664			
d	318	93	318			
t	690	690	690			

The experiments were performed with a demountable tube. A convergent electron gun produced a ribbon-like electron beam (20×0.3 mm²), and a magnetic field of about 4000 G was necessary for proper beam focusing. The chamber was continuously evacuated to 10^{-7} torr by an ion pump. The experimental tube was operated under pulsed conditions (2 μs, 50 Hz) at a beam voltage of 6–20 kV. The electron beam density used was about 20–30 A/cm².

The RF output is extracted through a coupling port at the smooth mirror. We have also observed that the RF power is radiated from the groove ends along the direction parallel to the grooves (Fig. 1).

IV. Experimental Results

A. Fabry–Perot Mode Interaction

In our experiments the start-oscillation currents of Fabry–Perot mode oscillations were slightly larger than those of surface wave mode oscillations. However, by tuning to the Fabry–Perot mode by adjusting the mirror attitude, mode pulling occurs, and we could get only the Fabry–Perot mode oscillation.

1) Oscillation Mode: We have observed the oscillation due to the TEM_{00} mode in the resonator, and when using the smooth mirror with a large coupling hole at the center, we observed the oscillation due to the TEM_{01} mode. The experimentally obtained transit angles between adjacent grooves are in good agreement with theoretically obtained values described in Section II-A.

2) Frequency Tuning Characteristics: We have observed that the oscillation of the Fabry–Perot mode could cover continuously a frequency tuning range of about 40 percent ($\lambda=4.2$–6.4 mm, with Grating 11). Such a wide frequency tuning range is obtained by changing both the mirror spacing and the electron ac-

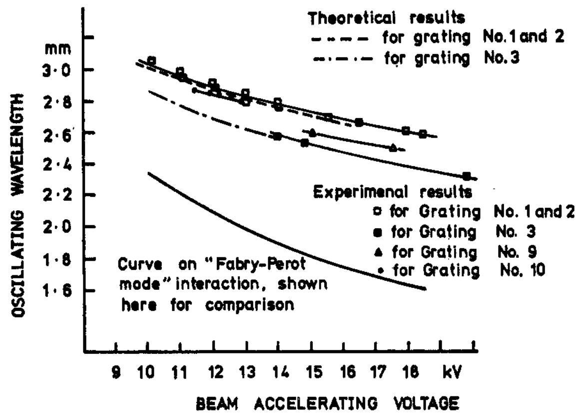

Fig. 2. Electronic tuning characteristics of surface wave mode interaction. The oscillation in the tube with Grating 10 is due to the third harmonic interaction ($n = 2$).

celerating voltage. The feature of wide frequency tuning of this tube offers an excellent spectroscopic source of short millimeter and submillimeter waves.

We did not observe any change of the oscillation frequency when varying the current density. Therefore the effect of electronic susceptance on the resonant frequency turns out to be small.

3) Start-Oscillation Current: In the range of 3-mm wavelength, the starting current was around 800 mA. This is four times larger than the predicted value obtained from our theoretical analysis [1]. Considering the actual RF field distribution, however, we can say that the theory is in reasonable accord with experiment.

B. Surface Wave Mode Interaction

An investigation on the surface wave mode interaction described in Section II-B was carried out. The mirror attitude was adjusted so as not to give oscillation in the Fabry–Perot mode.

1) Oscillating Wavelength: Fig. 2 shows electronic tuning characteristics of the tubes with Gratings 1, 2, 3, 9, and 10. Oscillating wavelengths of the tubes with Gratings 4 and 5 are 2.35 and 1.40 mm, respectively, at the accelerating voltage of 13.0 kV. We used a cavity resonator that can measure a 0.1 percent frequency change, but mechanical tuning was not observed in our experiments. Theoretical tuning characteristics obtained from (4) are also shown in Fig. 2, and we can see that the experimental curves agree well with the theoretical one.

The frequency pushing figure of 2.0–1.5 MHz/mA was observed in the tube with Grating 12.

2) Role of the Smooth Mirror: Putting a reflector, i.e., a smooth mirror, at suitable positions, we could enhance the output power [Fig. 3(a)]. We also found that the start-oscillation current was affected by the mirror position, as shown in Fig. 3(b). Therefore the mirror functions are as expected in Section II-B.

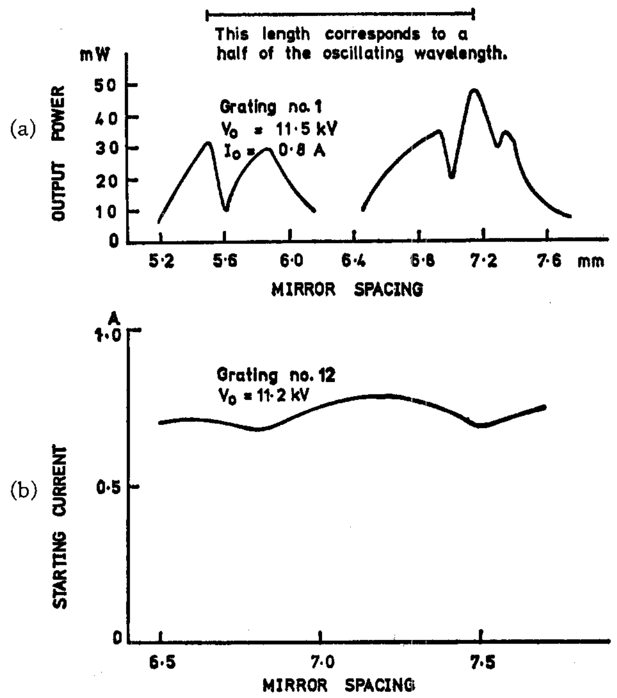

Fig. 3. Effects of the mirror spacing on characteristics of the surface wave mode interaction. (a) Output power versus mirror spacing. (b) Starting current versus mirror spacing.

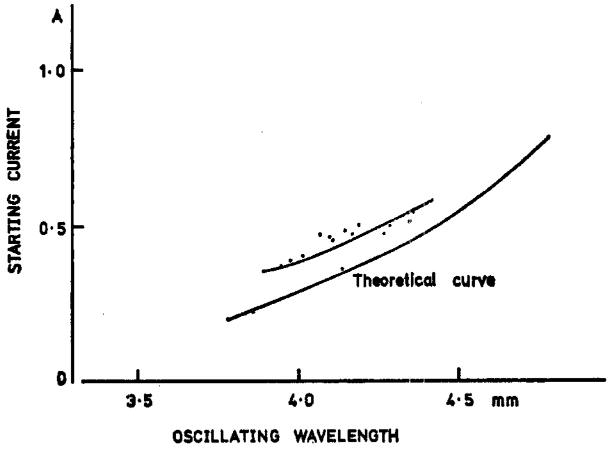

Fig. 4. Starting current versus the oscillating wavelength.

3) Start-Oscillation Current and Output: The starting current of the tube with Grating 12 is shown in Fig. 4 as a function of the oscillating wavelength. The theoretically obtained curve, according to the following equation [5], [6], taking no account of space charge and losses, is also shown.

$$(I_0)_{\text{start}} = \frac{32\pi^3(0.314)^3 V_0}{K(\beta_e L)^3} \tag{5}$$

where V_0 is the dc beam voltage, K is the coupling impedance for the particular space harmonic, β_e is the propagation constant of electrons, and L is the total active length of the circuit.

Output power was found to be almost a linear function of a beam current, as Fig. 5 shows.

VI. CONCLUSION

An electron tube with a reflecting grating and a mirror, the Ledatron, was studied, and two different mode interactions were predicted theoretically and

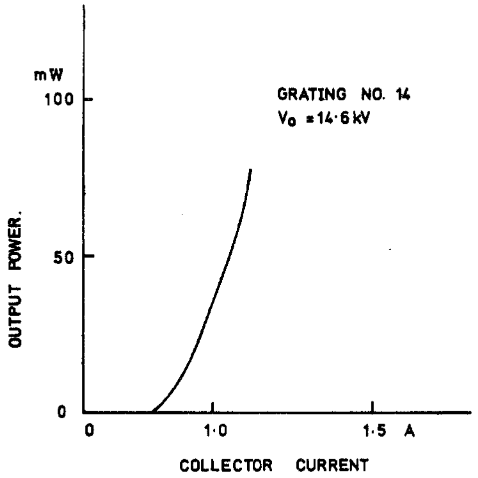

Fig. 5. Variation of the power versus the collector current.

found to exist experimentally. Either of these interactions in the tube can be selected by varying the attitude of the mirror.

It is worth noting that, compared with conventional two's, we need lower beam accelerating voltages in the Fabry–Perot mode when operating at the same wavelengths. Through operation of this electron tube with various grating structures, we expect to cover the spectrum wavelength region extending from a few millimeters to below 0.3 mm with more than several hundred milliwatts of power.

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Intrinsic AM Noise in Singly Tuned IMPATT Diode Oscillators

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***Abstract*—Analytical relationships are derived for the ratio of the intrinsic AM to FM noise, and for the intrinsic AM noise of IMPATT diode oscillators. The theory is confirmed experimentally for a silicon n$^+$-p diode and an n-gallium-arsenide Schottky barrier diode operating at low and intermediate signal levels.**

IMPATT diode oscillator noise originates from the random character of the thermal generation and impact ionization processes. The noise connected with these processes can be described by a related total noise current flowing through the diode [1]–[3]. The high-frequency components of this noise current give rise to the "intrinsic" oscillator noise [2], [4], while the low-frequency components can give rise to "up-converted" oscillator noise [2], [7]. Additional effects which might influence the oscillator noise are the nonlinear interaction of the signal with the total noise current [4]–[6], and "down-conversion" of oscillator noise into low-frequency noise due to rectification effects [8]. In the following the total resistance in the bias circuit is always chosen so high that effects of up-conversion and down-conversion can be neglected [2], [7], [8].

In this paper an analytical expression will be derived for the intrinsic AM oscillator noise by combining the results of the FM noise theory given in [2] and the results of the general theory of oscillator noise given in [8]. The expressions derived will be verified by experiments on a silicon n$^+$-p diode and an n-gallium-arsenide Schottky barrier diode. The theory of [2], which will be used in the following, has been confirmed experimentally for several types of diodes operating at low signal levels

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