THE STUDY OF REFLEX KLYSTRON

by

C. C. Huang (黄 俊 哲)
Instructor of the Electronic Institute, Chiao Tung University

Although the mathematical analysis of reflex klystron is somewhat complete, there are many assumptions for simplifying the analysis. It is interesting to compare the experimental results and the results predicted from theories.

It is known that the transit time of electrons in the space between the resonator and the repeller may be written as

$$T=\frac{2S}{V_a+V_r}\sqrt{\frac{2MV_a}{q}}\sqrt{1+K\frac{V_g}{V_a}\sin wt_1} \tag{1}$$

where S :distance between resonator and repeller.

V_a:beam voltage.

Vr:repeller voltage.

K :beam coupling cofficient.

V_g:r f signal voltage between the gaps of resonator.

t_1 :the time when the electrons leaving the resonator.

let

$$t_o=\frac{2S}{V_a+V_r}\sqrt{\frac{2MV_a}{q}} \tag{2}$$

$$N=ft_o=\frac{wt_o}{2\pi} \tag{3}$$

The bunching parameter

$$X=\pi NK\frac{V_g}{V_a}$$

If $V_g \ll V_a$

$$T=t_o(1+\frac{X}{2\pi N}\sin wt_1)=\frac{2\pi N}{w}+\frac{X}{w}\sin wt_1$$

$$t_2=t_1+T=t_1+\frac{2\pi N}{w}+\frac{X}{w}\sin wt_1$$

The fundamental component of current induced from the reentrance beam is

$$I_{b1}=2KI_oJ_1(X)\ e^{j(\frac{\pi}{2}-wt_o)} \tag{4}$$

The equivalent circuit of reflex klystron oscillator mav be considered as shown in Appendix.

The power dilivered to the load

$$P_L=\frac{-G_L}{G_s+G_L}V_g\mathrm{Re}I_{b1}$$

$$=\frac{-G_L}{G_s+G_L}V_aI_o\ XJ_1(X)\frac{\sin 2\pi N}{\pi N} \tag{5}$$

$$\eta_L=\frac{P_L}{V_aI_o}=-\frac{G_L}{G_s+G_L}XJ_1(X)\frac{\sin 2\pi N}{\pi N} \tag{6}$$

For max. efficiency $-\sin 2\pi N_m=1$

$$N_m=m-\frac{1}{4}$$

max. value of $XJ_1(X)$ is 1.25 when $X=2.4$

$$\max.\eta_L=\frac{0.4}{N_m}\cdot\frac{G_K}{G_s+G_L} \tag{7}$$

The beam admittance

$$Y_1=\frac{I_{b1}}{V_g}=\frac{2KI_oJ_1(X)}{V_g}(\sin wt_o+j\cos wt_o) \tag{8}$$

let $wt_o=2\pi N=2\pi N_m+\phi$

$$Y_1=\frac{2KI_oJ_1(X)}{V_g}(-\cos\phi+j\sin\phi) \tag{9}$$

when oscillation just start $V_g=0$ $X=0$

the real part

$$G_s+G_L-\frac{2KI_oJ_1(X)}{V_g}\cos\phi=0$$

$$\cos\phi=\frac{(G_S+G_L)\frac{V_a}{I_o}}{K^2\pi N} \tag{10}$$

the imaginary part

$$wc-\frac{1}{wL}+\frac{2KI_oJ_1(X)}{V_g}\sin\phi=0$$

$$\frac{\triangle f}{f_o}=\frac{1}{2Q_L}\tan\phi$$

Where

$$Q_L=\frac{w_o c}{G_s+G_L}$$

At first itis necessary to identiy the mode. It was shown that when $t_o=(m-\frac{1}{4})\ T_o$ the output power is maximum. Where T_o is the period of the signal. Compare two neighboring modes

$$\frac{t_{01}}{t_{02}}=\frac{m_1-\frac{1}{4}}{m_2-\frac{1}{4}}=\frac{V_{a2}+V_{r2}}{V_{a1}+V_{r1}}\sqrt{\frac{V_{a1}}{V_{a2}}} \tag{12}$$

From this eq. two mothods may be used to identify the modes.

(1) If beam voltages heep const. and $m_2=m_1+1$

$$\text{then}\ \frac{m_1-\frac{1}{4}}{m_1+\frac{3}{4}}=\frac{V_a+V_{r2}}{V_a+V_{r1}} \tag{13}$$

From Fig. (1) When $V_a=300$ volts the power output is maximum when

$V_r=35.5$ 64 110 volts

Compare the modes of $V_r=64$ and 110

$$\frac{m_1-\frac{1}{4}}{m_1+1-\frac{1}{4}}=\frac{300+64}{300+110}=0.888$$

$m_1=8.18=8$

Compare the modes of $V_r=35.5$ and 64

$$\frac{m_2-\frac{1}{4}}{m_2+1-\frac{1}{4}}=\frac{300+35.5}{300+64}=0.92$$

$m_2=11.75\div12$

But the difference between m_1 and m_2 should be 1

We see that this method is difficult to identify the mode.

(2) If we let $V_a=CV_r$

$$\text{then}\ \frac{m_1-\frac{1}{4}}{m_1+1-\frac{1}{4}}=\sqrt{\frac{V_{a2}}{V_{a1}}} \tag{14}$$

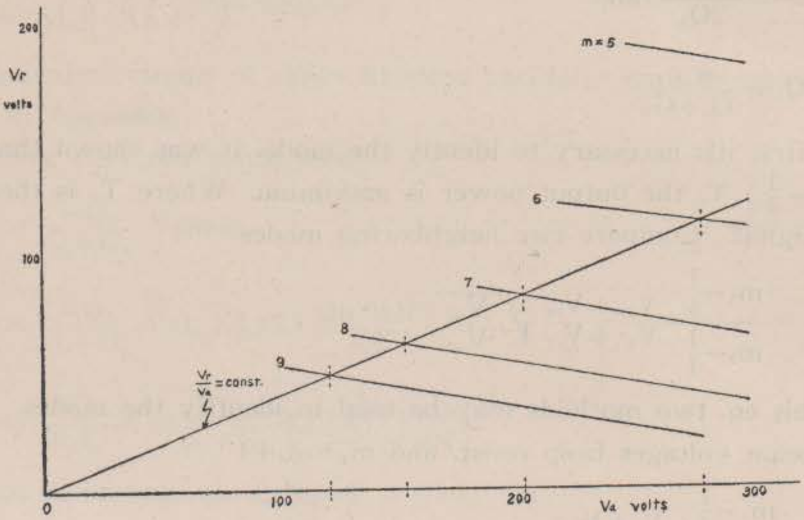


Fig. 1 Vr Vs Va for max. power

Here V_{a1}, V_{a2},……is the beam voltages of each mode on the line $V_a = CV_r$. By measuring the repeller voltage when the power output is max. for several beam voltage the curves in Fig. (1) are obtained. On the line V_a/V_r=Const. for each mode

$$V_a = 280 \quad 204 \quad 154 \quad 122$$

$$m = m_1 \quad m_2 \quad m_3 \quad m_4$$

$$\sqrt{\frac{280}{V_a}} = 1 \quad 1.17 \quad 1.35 \quad 1.514$$

If $m_1=5$ then $m_2=5.85$ $m_3=6.75$ $m_4=7.58$

$m_1=6$ $m_2=7.02$ $m_3=8.1$ $m_4=9.1$

$m_1=7$ $m_2=8.2$ $m_3=9.45$ $m_4=10.06$

Compare the results obviously we see that $m_1=6$

The reason why method I is fail is because $V_r \ll V_a$ and V_r is difficult to be measured very accurate

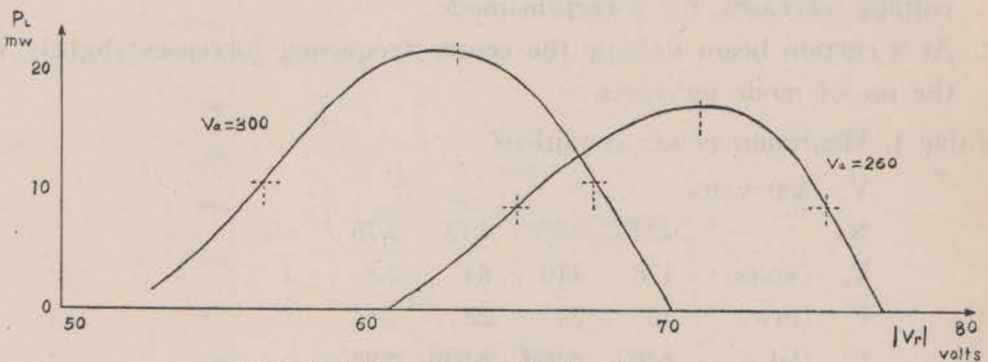
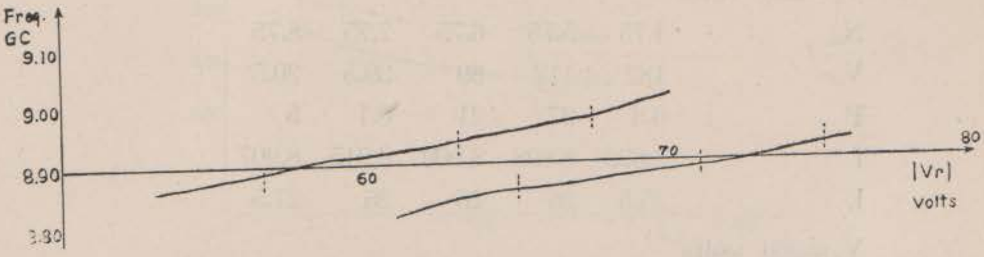


Fig. 2 P_L & Freq. Vs V_r of 7 th. mode



Now consider the 7th mode.

Measure the power output and frequency as function of repeller voltage and is shown in Fig. 2

The max. power from measurement

$P_L = 21.5$ mw

D. C. power $300 \times 30 = 9000$ mw

$$\eta_L = \frac{21.5}{9000} = 0.24\%$$

From eq. (7)

$$\eta_L = \frac{0.4}{7-0.25} \cdot \frac{G_L}{G_s + G_L} = 6.4 \frac{G_L}{G_s + G_L} \%$$

Usually $G_L \gg G_s$ $\quad \therefore \eta_L \doteqdot 6.4\%$

The efficiency of the reflex klystron is greatly different from the theoretical value.

From Table 1 and Fig. 3

1. The center frequency (when output power is max.) decreases if beam

voltage increases. for a certain mode

2. At a certain beam voltage the center frequency increases slightly if the no. of mode increases.

Table 1. Maximum power conditions

V_a=300 volts

N_m	4.75	5.75	6.75	7.75
V_r (volts)	178	110	64	7.8
P (mw)	13	34	22	7.8
f (GC)	8.921	8.927	8.936	8.945
I_c (mA)	29	30	30	30

V_a=280 volts

N_m	4.75	5.75	6.75	7.75	8.75
V_r=	182	112	69	39.5	20.5
P	6.3	27	21	8.1	5
f	8.893	8.898	8.909	8.915	8.907
I_c	25.5	26	26	26	27.5

V_a=260 volts

N_m	4.75	5.75	6.75	7.75	8.75
V_r	185	117	72	42.5	24.2
P	16	21	17	18.2	2
f	8.885	8.891	8.892	8.895	8.897
I_c	27	24	24	24	24

V_a=240 volts

N_m	5.75	6.75	7.75	8.75
V_r	118	75	46	27.2
P	16	15	7.9	1.1
f	8.876	8.878	8.879	8.884
I_c	21	21	21	22

V_a=220 volts

N_m	5.75	6.75	7.75	8.75
V_r	120	7.9	80	30.5
P	12	12	7.2	2.6
f	8.866	8.87	8.868	8.877
I_c	18.5	18.5	18.5	19

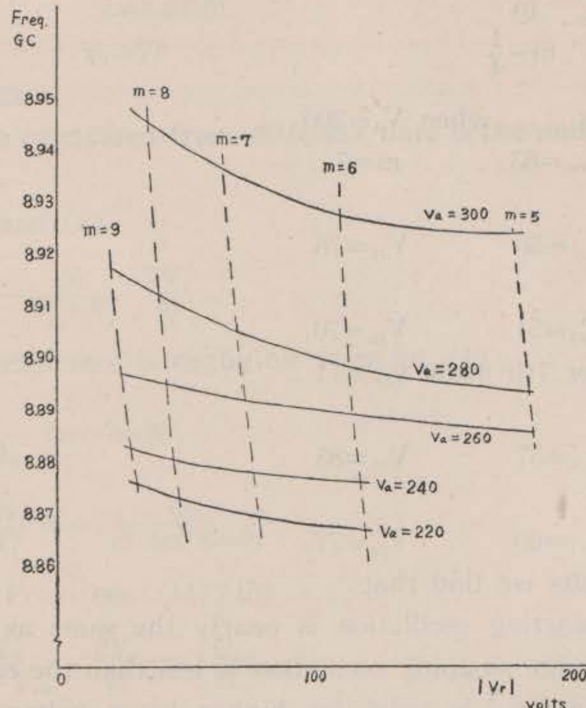


Fig. 3 Center Freq. vs. Vr & Va

we may estimate the range of repeller voltages in which the oscillation may occurs.

From eq. (10) we see that the oscillation starts when

$$\phi=\cos^{-1}\frac{(G_s+G_L)\dfrac{V_a}{I_o}}{K^2\pi N}$$

For simplicity assume $\phi=\frac{\pi}{2}$

let t_{om} represent the transit time for max. output

then $$\frac{t_o}{t_{om}}=\frac{V_a+V_r}{V_a+V_{rm}}=\frac{MT_o}{(m-\frac{1}{4})T_o}$$

$M=m-\frac{1}{2}$ when oscillation start

$M=m$ when oscillation stop

$$\frac{V_a+V_{r1}}{V_a+V_{rm}}=\frac{m-\frac{1}{2}}{m-\frac{1}{4}}$$

$$\frac{V_a+V_{r2}}{V_a+V_{rm}}=\frac{m}{m-\frac{1}{4}}$$

In the experiment when $V_a=300$

For 7th mode $V_{rm}=63$ $m=7$

From calculation

$V_{r1}=50$ $V_{r2}=76$

From experiment

$V_{r1}=51$ $V_{r2}=70$

When $V_a=260$ For 7th mode $v_{rm}=71$

From calculation

$V_{r1}=57$ $V_{r2}=85$

From experiment

$V_{r1}=60$ $V_{r2}=77$

Compare the results we find that

1. The voltage starting oscillation is nearly the same as the estimate value. The voltage stopping oscillation is less than the estimate value.
2. The assumption $\phi=\frac{\pi}{2}$ is valid for higher beam voltage than lower beam voltage, this may be seen from

$$\cos\phi=\frac{(G_{rs}+G_L)}{K^2\pi N}\cdot\frac{V_a}{I_o}$$

we seefrom Table 1 that $\frac{V_a}{I_o}$ increase if V_a decrease

and K^2 decrease if V_a decrease

thus when V_a increase $\frac{1}{K^2}\cdot\frac{V_a}{I_o}$ decrease and the assumption

$\phi=\frac{\pi}{2}$ is approached.

The distance between the cavity and repeller can be estimated

Since

$$N=ft_0=\frac{2sf}{V_a+V_r}\sqrt{\frac{2mV_a}{q}}$$

$$=6.74\ 10^{-6}sf\ \frac{\sqrt{V_a}}{V_a+V_r} \qquad \text{s in cm}$$

From experimental value in Fig. 2

(a) $N_m=6.75$ $f=8.935\times10^9$

$V_a=300$ $V_r=63$

then $s=0.235$ cm

(b) $N_m=6.75$ $f=8.8910^9$

$V_a=260$ $V_r=71$

then $s=0.232$

The value of s calculated from different data is the same thus this value maybe correct.

From eq. (2) and (3)

$$\frac{\partial N}{\partial f}=\frac{N}{f}-\frac{N}{V_a+V_r}\frac{\partial V_r}{\partial f} \tag{14}$$

If the load susceptance is negligible from eq. (1)

$$\frac{f}{f_0}=-\frac{1}{2Q_L}\tan 2\pi\triangle N$$

$$\frac{\partial N}{\partial f}=\frac{\partial(\triangle N)}{\partial(\triangle f)}=-\frac{Q_L}{\pi f\ \sec^2 2\pi\triangle N} \tag{15}$$

When $N=N_m$ From eqs. (14),(15)

$$\frac{N_m}{f_o}-\frac{N_m}{V_a+V_{rm}}\cdot\frac{\partial V_r}{\partial f}=-\frac{Q_L}{\pi f_o}$$

$$\left(\frac{\partial f}{\partial V_r}\right)Nm=\frac{\pi N_m f_o}{(V_a+V_{rm})\ (\pi N_m+Q_L)} \tag{16}$$

From Fig. 2

(a) $V_a=300$ $f_o=8.953$ $N_m=6.75$

$V_{rm}=63$ $Q_L=\frac{8.953}{8.98\text{-}8.89}=99.3$

From eq. (16) $\frac{\partial f}{\partial V_r}=4.35$ MC/volt

From Fig. (2) $\frac{\partial f}{\partial V_r}=9$ MC/volt

(b) $V_a=260$ $fo=8.89$ $N_m=6.75$

$V_{rm}=71$ $Q_L=\frac{8.89}{8.925\text{-}8.856}=129$

From eq. (16) $\frac{\partial f}{\partial V_r}=3.8$ MC/volt

From Fig. (2) $\frac{\partial f}{\partial V_r}=6$ MC/volt

The estimate value is nearly one half of the actual value.

Conclusions

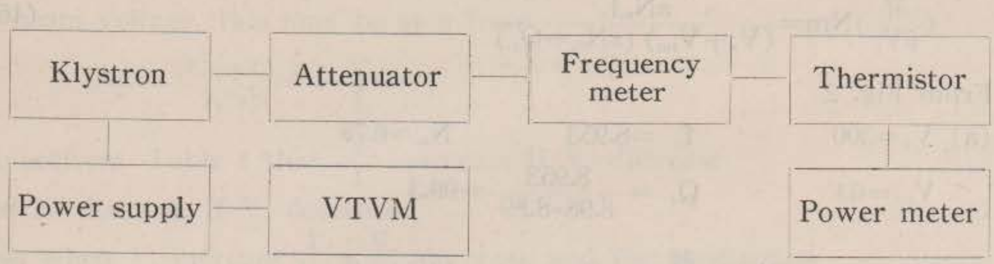
The experimental results are deviated from theroretical discussion to a certain degree. The simplified equations is not good enough to predicate the experimental results satisfactorily, experiment is important in studying the reflex klystron.

Reference:

1. Spangenberg — Vacuum Tubes
2. Hamillton — Refex klystrons
3. Hamilton, Knipp, Kuper — Klystron and Microwave Triode
4. Slater — Microwave Electronics
5. Sucher Fox — Handbook of Microwave Measurement
6. Ginzton — Microwave Measurements

APPENDIX

1. The tube Raytheon 723 A/B is used in the whole experiment.
2. The block diagram is shown as follow



3. The equivalent circuit of reflex klystron