of the slow waves, and the relation $(d_{12})_2L=\pi/2\sqrt{2}$ applies (15), where $(d_{12})_2$ is the coupling coefficient between the backward circuit wave and one of the slow waves at the start of oscillation. If there is only a single beam, the condition of start oscillation[7] is $(d_{12})_1L=\pi/2$, where $(d_{12})_1$ is the coupling coefficient between the backward circuit wave and the slow wave. Thus the necessary value of the coupling coefficient for the start of oscillation is smaller if both beams are present. Keeping the beam voltage constant, the ratio of the starting currents is as follows:

$$\frac{I_2}{I_1}=\left[\frac{(d_{12})_2}{(d_{12})_1}\right]^4=\tfrac{1}{4}. \tag{28}$$

Thus the beam current in a double-beam backward-wave oscillator drops by a factor 4, and the total current is still only half of that which is necessary in the single beam device.

If the beam voltages are slightly different, the coupling coefficients can still be regarded as identical because they are slowly varying functions of the beam voltage. Thus, applying the formulas of Section IV, the propagation coefficient of the backward circuit wave is the arithmetical mean of the propagation coefficients of the slow waves.

It may be seen from (17) that for finite voltage differences the starting current increases, which agrees qualitatively with the experimental results.[11] If

$$r^2 > 2d_{12}^2,$$

the amplitude of the backward circuit wave cannot be made zero. Thus, beyond a certain voltage difference, no oscillation can be obtained, however long the circuit.

ACKNOWLEDGMENT

The author wishes to thank Dr. E. A. Ash for many interesting discussions. Thanks are also due to Standard Telecommunication Laboratories Ltd., for permission to publish the paper.

Noise Figures of Reflex Klystron Amplifiers*

KORYU ISHII†

Summary—**The noise figure of the 2K25 reflex klystron amplifier was investigated. The noise figure of the reflex klystron amplifier depends on operating frequency, electronic impedance, circuit impedance, and operating electronic mode. Experimental results show that a noise figure of 5 db is possible under particularly carefully adjusted conditions. In order to obtain the low-noise figure, careful electronic tuning and the impedance adjustments are particularly important. Generally, relatively low noise figures were obtained when the electronic tuning was good. Noise figures of cascaded reflex klystron amplifiers were also investigated experimentally. Noise figures of the cascaded amplifier were generally higher than that of the single stage amplifier, but still low enough to use this reflex klystron amplifiers as a preamplifier of a microwave receiver to increase the sensitivity of the receiving system.**

INTRODUCTION

THE use, as regenerative or negative conductance amplifiers, of reflex klystrons originally designed for use in oscillators, would offer several advantages to microwave receiver design. Ordinary, small-power reflex klystrons are relatively inexpensive, and require neither the high voltages used in TW tubes nor the great magnetic force necessary in magnetrons.

There is some controversy about such an application for reflex klystrons. In the first place, it is questioned whether employment of the reflex klystron amplifier really does increase the sensitivity of a microwave receiver. To increase the receiver's sensitivity, the reflex klystron would have to provide a good gain and at the same time have a low noise figure.

Several papers have been published describing the gain achieved with reflex klystron amplifiers. Okabe[1] obtained a gain of over 20 db at 3000 mc with a 707B reflex klystron. Ishii[2,3] obtained a gain of more than 16 db at 9760 mc with a 723A/B reflex klystron. Quate, Kompfner and Chisholm[4] reported a gain of more than 30 db at 11,000 mc with a WE445A reflex klystron. These papers demonstrate that a substantial gain improvement is possible, but no useful data on noise figures was obtained. For example, Okabe reported a noise figure of less than 7 db but Quate reported 40 db. Clearly, a study of the noise figure itself was required if the value of the reflex klystron amplifier was to be verified or denied.

* Manuscript received by the PGMTT, September 4, 1959; revised manuscript received, November 9, 1959.
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The noise level of the reflex klystron amplifier is dependent on the conditions of the tube and circuit. In order to study one reflex klystron amplifier under various conditions, the circuit shown in Fig. 1 was used. This amplifier used a 2K25 (723A/B) and operated in the X band. The reflex klystron, as shown in the figure, is mounted in the middle of the waveguide, and the output impedance to the reflex klystron is adjusted with six screw tuners and one coaxial shorting plunger to obtain suitable regenerative feedback. Input signals are fed into the left opening of the waveguide and output power is taken from the right end.

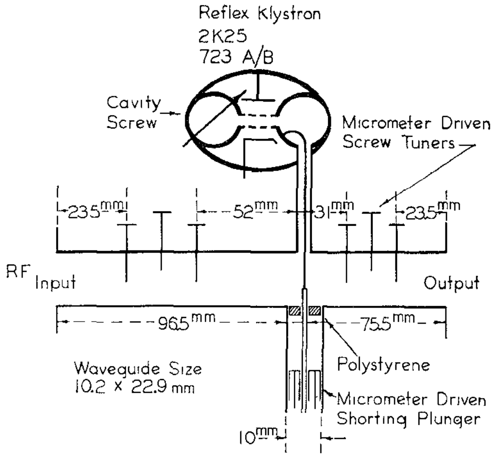

Fig. 1—Schematic diagram of the 2K25 reflex klystron amplifier circuit.

Noise Figure Measurement

Two methods were used to measure noise, one of which was primarily for checking results. The first was the noise generator method, as shown in Fig. 2. The alternate procedure, used for vertification of the other, was the small signal method, shown in Fig. 3.

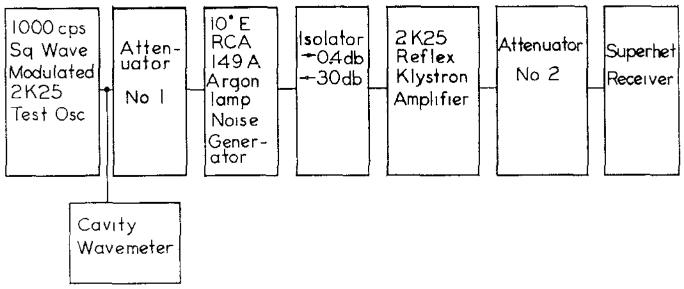

Fig. 2—Noise measurement setup for reflex klystron amplifier.

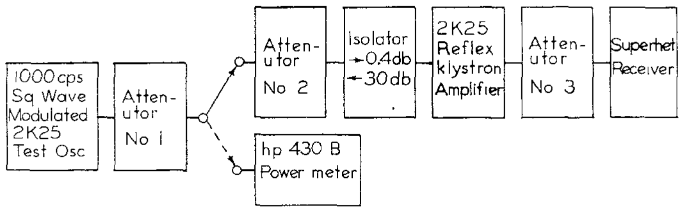

Fig. 3—Small signal method.

The regenerative properties of the reflex klystron make it necessary that the same conditions of amplification be maintained for all noise measurements. The external circuits and tube supply voltages have a great effect on the noise figure of the reflex klystron amplifier.

Therefore, extreme precautions were taken toward supply voltages and the external circuit impedance to keep the same gain of the amplifier during the experiment. Power supply to the reflex klystron anode was electronically stabilized and a battery was used to give stable voltage to the repeller of the reflex klystron. Signal source impedance was carefully examined before the experiment by a standing wave detector. The VSWR was approximately 1.15. In the noise generator method of Fig. 2, due to the isolation effect of the isolator, no detectable change in VSWR on the input waveguide of the amplifier was observed by noise lamp on and off conditions. Similar impedance stabilizing effect of the isolator was observed in the small signal method of Fig. 3. As a matter of fact, the amplifier, carefully adjusted under these conditions, was very stable, and showed very good reproducibility of the same gain after various kinds of circuit manipulations such as noise lamp off and on, or replacing to a reflectionless termination. The amplifier showed very good linearity for small signals. Whenever the equal external impedance was given, the amplifier reproduced the same gain.

Using the noise generator method, an oscillator signal was fed into the amplifier through the attenuator, the argon discharge noise generator, and an isolator. Simultaneously, a noise signal was amplified in the same manner. Then the amplifier was adjusted for optimum gain and the gain was measured with the attenuator. The oscillator was shut off, leaving only the noise signal under amplification. At this time, the amplifier output was read with a thermocouple meter connected to the output of the IF amplifier of the RF head of a USAF APS-3 radar receiver. Though it was not shown in Figs. 2 and 3, the receiver contained an isolator at the input in this case to prevent the local oscillator disturbance to the 2K25 amplifier. This isolator also had an effect to avoid input temperature problem of the receiver. Maintaining the same conditions as above, the noise generator which was isolated by the isolator was replaced by a reflectionless termination and measurements were again taken. The VSWR measurement before the experiment showed there was no detectable change in VSWR after replacing the noise generator by the reflectionless termination. The over-all noise figure of the amplifier and receiver is given by

$$F_{12} = 15 + 10 \log \frac{M}{N - M} \text{ (db)} \qquad (1)$$

where 15 db is the excess noise of the RCA 149 argon lamp with forward isolator insertion loss subtracted, N is the reading of the thermocouple meter when the noise generator was connected, and M is the reading with a reflectionless termination. The isolator helps hold output impedance constant for the reflex klystron.

The noise figure of the reflex klystron amplifier, then, is

$$F_1 = F_{12} - \frac{F_2 - 1}{G_1} \tag{2}$$

where F_2 is the noise figure of the receiver alone, and G_1 is the gain of the reflex klystron amplifier. In this case, F_2 is measured under the same conditions as F_{12}. To properly assess the noise figure of the klystron amplifier, the contribution of load noise should be subtracted from the experimental value. The load noise contribution was, however, minor because of the isolators, one of which was in front of the amplifier and another in front of the receiver.

The small signal method was used to verify results of the noise generator experiments. The schematic diagram for this method is shown in Fig. 3. The isolator in front of the amplifier, as before, keeps the output impedance of the reflex klystron constant during measurement. The noise figure is given by the equation

$$F_{12} = P_s(\text{dbw}) - \{-204(\text{dbw}) + B_{12}(\text{db})\} \tag{3}$$

where P_s is the available signal input power to the reflex klystron amplifier required in order to double the noise power output, and B_{12} is the over-all noise bandwidth.

It is important to measure P_s carefully, and if residual reflections exist, correction must be made. Image effect is not serious in this case because the reflex klystron bandwidth is very narrow in comparison with the receiver IF frequency. Difficulty in obtaining accurate measure of P_s made this small signal method difficult and, for this reason, the noise generator method was used as the primary means of investigation.

Noise Figure of Reflex Klystron Amplifier

The measurements made of the 2K25, as described above, reveal that circuit impedances and supply voltages for the reflex klystron affect the noise figure significantly. For example, if the operating frequency is changed, output impedance must be adjusted and electronic impedance must follow to maintain optimum gain; as a result, the noise figure changes. Table I shows the relation between the noise figure and the operating frequency. For each frequency, amplifier circuit conditions were adjusted for optimum gain by means of the screw tuners, cavity screw, shorting plunger, and adjustments of anode and repeller voltages. The circuit adjustments were not difficult to make and noise figures ranged from 5.2 db to 23.2 db, depending on operating conditions.

Table II shows noise figures for a fixed frequency level, with the reflex klystron electron transit cycles in a number of operating modes. Noise figures varied from 15.5 db to 24.8 db.

TABLE I
NOISE FIGURE OF 2K25 AMPLIFIER UNDER VARIOUS OPERATING FREQUENCIES

Operating Frequency mc	Frequency Bandwidth mc	Noise Figure db	Optimum Gain db
9310	7.6	15.5	22
9351	6	10.5	21
9362	6.5	5.2	16
9387	11.5	7.2	15
9407	6.2	6.2	17
9429	14	9	20
9452	12	23.2	16
9499	5.2	15	15

TABLE II
NOISE FIGURES OF 723A/B AMPLIFIER UNDER VARIOUS OPERATING MODES AT 9310 MC

Mode, Electron Cycles N	Optimum Gain db	Frequency Bandwidth mc	Noise Figure db
$8\frac{3}{4}$	18	5.4	17.8
$9\frac{3}{4}$	25	22	24.8
$10\frac{3}{4}$	17	34	17.5
$11\frac{3}{4}$	22	7.6	15.5

TABLE III
NOISE FIGURES OF 723A/B AMPLIFIER UNDER VARIOUS CIRCUIT CONDITIONS OPERATED IN $N=8\frac{3}{4}$ MODE AT 9429 MC

Case	Optimum Gain db	Frequency Bandwidth mc	Noise Figure db
A	13	30	12.5
B	22	19.6	11
C	29	10	20

Table III lists noise figures measured with the reflex klystron amplifier operated at one frequency and in one mode, but with varying circuit conditions. Again, noise figures varied. For this experiment, the 2K25 was operated in mode $N=8\frac{3}{4}$ and at frequency 9429 mc. With varying circuit conditions, repeller and anode voltages were adjusted for optimum gain. Cases A, B, and C in the table each represent a different adjustment of the screw tuner, cavity screw, and shorting plunger.

Finally, when the reflex klystron was operated in one mode and at one frequency, circuit conditions were unchanged. However, the repeller voltage, or electronic tuning, was changed, and the noise figure varied, as shown in Fig. 4. With repeller voltage higher than −152 volts, the electronic tuning is relatively poor, gain is low, and noise is high. But with repeller voltage at −153 volts, electronic tuning is fair and the noise figure is minimum. When repeller voltage goes below −154 volts, electronic impedance approaches the self-oscillation region and gain increases, but the noise figure rises, too. Both the noise generator method and the small signal method were used for noise measurements and both produced similar results.

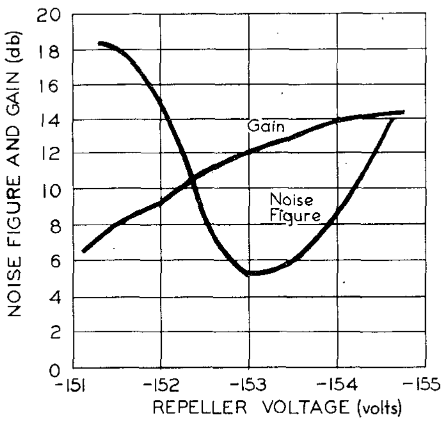

Fig. 4—An example of noise figure, gain and repeller voltage relations of 723A/B amplifier.

If careful adjustment of circuit and electronic impedances can reduce noise figures to 5 db, the use of a reflex klystron amplifier as a preamplifier will increase the sensitivity of a microwave receiver. In this experiment the RF head of a USAF APS-3 aircraft radar receiver was used. It has a sensitivity of -98 dbm and a noise figure of 28 db. A 2K25 amplifier with a 14-db gain and a 5-db noise figure was connected in front of the receiver. The resulting amplifier-receiver could "see" a signal of 9362 mc, 10 db lower than could the APS-3 receiver alone. The sensitivity, then, was improved by -98 dbm to -108 dbm.

Assuming that a reflex klystron amplifier will increase sensitivity, cascading two of them should improve receiver operation even more. In Table IV, results of experiments with a cascaded reflex klystron amplifier are given. In this table, I, P, and T represent methods of combining two reflex klystron amplifiers by means of an isolator (I), a phaseshifter (P), and a transformer (T). P-T and I-P-I represent combinations of these elements. The APS-3 receiver was taken as a reference-sensitivity of a receiving system. The results of the experiment show that receiver sensitivity is increased, and that the noise figure can be reduced enough to make the reflex klystron amplifier acceptable as a preamplifier for ordinary microwave receivers. Generally, over-all noise of the cascaded amplifier is higher than that of a single stage one, but the additional gain is high enough to give a net improvement in sensitivity.

When the 2K25 amplifier, which has an isolator ahead of it, if gain G_1, and noise figure F_1 are connected in front of a receiver of noise figure F_2 by an isolator, the over-all noise figure is given by

$$F_{12} = F_1 + \frac{F_2 - 1}{G_1} \cdot \qquad (4)$$

For example, when the isolator-phase shifter-isolator coupled amplifier is connected in front of the APS-3 receiver which contained an isolator in its input, then

$$F_1 = 16 \text{ db}, \quad F_2 = 28 \text{ db}, \quad \text{and} \quad G_1 = 60 \text{ db};$$

TABLE IV

SENSITIVITIES IMPROVED BY THE USE OF REFLEX KLYSTRON AMPLIFIERS

Reflex Klystron Amplifier	Frequency Bandwidth mc	Noise Figure db	Gain db	Sensitivity Minimum Detectable Signal Below APS-3 Receiver db
APS-3 Receiver	2	28	0	0
	(Reference Standard)			
Single Stage	20	5	14	10
	(Following are two stage amplifiers)			
Direct Coupled	6	28	30	4
Isolator Coupled	4.4	26	28	4
Phase Shifter Coupled	2	16	43	19
I-P Coupled	4.5	8	35	26
P-I Coupled	2	17.5	42	26
P-I-I Coupled	3.25	11	49	26
I-I-P	3.7	13	54	28
I-I	2	5	31	12
I-P-I	2.4	16	60	42
I-I-I	1.6	17	49	16

and

$$F_{12} \doteq F_1 = 16 \text{ db}.$$

Thus, the over-all noise figure is improved from 28 db to 16 db.

CONCLUSIONS

Since the noise figure of the reflex klystron is dependent upon the operating output impedance, the frequency, and the electronic impedance, it is difficult to predict what its value will be. However, measurements of the 2K25 amplifier indicates that a noise figure on the order of 6.5 db can be obtained for an optimum net gain of 24.5 db at 9362 mc. And if the optimum gain required is below 15 db, the noise figure can be decreased to approximately 5 db if circuit conditions are carefully adjusted.

Minimum noise figures are usually obtained when the circuit is adjusted for optimum gain or when good electronic tuning was performed in individual electronic modes. If electronic tuning is poor, or the tube is operated in semioscillation conditions, the noise figure is high.

The 2K25 reflex klystron amplifier has a low enough noise figure to be used as a preamplifier to improve the sensitivity of ordinary microwave receivers.

ACKNOWLEDGMENT

The author wishes to thank Prof. E. H. Scheibe of the University of Wisconsin for his friendly advice in this research and S. Krupnik of Marquette University, and P. Smith of A.C. Spark Plug Co., for help in the preparation of this manuscript.