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June 22, 1966

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Summary

Microwave planar triodes are investigated as low-noise devices for preamplifiers of high-resolution nuclear magnetic resonance spectrometers in the frequency band from 10 to 100 MHz. Noise sources, noise figures, and a preamplifier circuit for planar triodes are considered. Planar triode noise performance is realistically evaluated by measurements under actual operating conditions. Comparisons with other competitive low-noise devices in the frequency band from 10 to 100 MHz are given. A microwave planar triode preamplifier with high amplification stability has been designed; when operated with the optimum value of source conductance, it has a minimum noise figure of 0.35 db at 24.3 MHz.

1. Introduction

Although the instrumentation in nuclear magnetic spectroscopy has made significant progress in recent years, the need for improvement in the sensitivity remains for many applications in chemistry and other fields. There are numerous methods for increasing sensitivity; for example, the sensitivity can be increased considerably by increasing the achievable signal-to-noise ratio by employing higher magnetic fields, lower temperatures, larger samples, or optimum filtering of the signal output of the spectrometer. The sensitivity enhancement can be performed quite effectively under certain conditions by using the method of time averaging¹⁻³⁾, and the application of Fourier transform techniques⁴⁾. These approaches to the problem of sensitivity enhancement and the related improvement in signal-to-noise ratio have been exploited to good advantage in spectrometer design, and the practical and theoretical limitations of it are well understood in most cases.

Since the noise performance of the spectrometer input stage is the basic limiting factor in the sensitivity of a spectrometer, one promising approach to the problem of the sensitivity improvement is the optimization of the probe assembly for a particular experiment and utilization of a very-low-noise high-frequency preamplifier. In the past the application of a very-low-noise preamplifier to the design of spectrometer was made difficult due to the unavailability of convenient electronic tubes or semiconductor components with appreciable gain in the frequency band from 10 to 100 MHz and with noise figures below 1 db. Recently, however, microwave space-charge planar tubes with very-low-noise properties and other favorable electrical characteristics have

become available, and appear to be suitable for inclusion in preamplifiers.

The use of microwave space-charge planar tubes as large-signal amplifiers were designed and described by Morton and Ryder⁵⁾ in 1950. Their small signal performance for broadband use over a wide range of frequencies was investigated and described by VanOhlsen⁶⁾ in 1954. Primas, Arndt, and Ernst⁷⁾ described in 1960 the first application of an older type of planar tube in a preamplifier of a high-resolution spectrometer. They achieved a noise figure less than 2 db. More recently there have been considerable efforts in the development of this device with respect to high-frequency very-low-noise applications; the result has been a great number of commercially available types.

Application of presently available semiconductor components in low-noise high-frequency preamplifiers is limited only to special cases because of their inferior noise performance compared with planar high-transconductance electron tubes, and because of the increasing complexity in preamplifier design for achieving a high amplification stability needed in high-resolution spectrometers.

From a relatively large number of presently available types of microwave planar tubes, planar triodes are chosen for consideration, since they have better noise performance than any multigrid tube. Multigrid tubes, which have two or more electrodes at positive potential, are basically noisier than any triode structure because of the presence of partition noise.

The purpose of this paper is to investigate the low-noise planar triode with respect to its application in very-low-noise preamplifiers for high-resolution nuclear magnetic resonance spectrometers.

Although microwave planar triodes were originally designed for large-signal application for frequencies up to 5 GHz, there has been considerable interest in their application as small-signal low-noise amplifiers over a range of lower frequencies from 10 to 100 MHz. The preamplifier circuit developed is based on a cascode amplifier circuit proposed by Wallman, Macnee, and Gadsden⁸⁾. Of the nine possible ways of cascading two tubes this arrangement has been shown theoretically and experimentally to be the best one with respect to noise figure, stability, and gain. The cascode preamplifier configuration provides stability and gain of pentode, and low-noise figure of the first triode.

2. Noise in microwave planar triode

The basic noise sources of importance in the design of very-low-noise high-frequency preamplifiers using space-charge planar triodes are shot noise and induced grid noise. Shot noise is the fluctuating component of plate current caused by random variations in the cathode emission rate. It can be presented, in the case of space-charge-limited plate current, as a current noise generator in parallel with the plate⁸⁾;

$$\overline{i_p^2} = \frac{\theta}{\sigma} 4KT_c g_m \Delta f, \quad (1)$$

where θ is a factor which in most practical cases is nearly equal to its asymptotic value of 0.655; σ is related to the amplification factor, electrode spacing, and depends slightly on electrode potentials, and generally has a value between 0.5 and 1.0; K is Boltzmann's constant, $K = 1.37 \times 10^{-23}$ joule per °K; T_c is cathode temperature in °K; g_m is transconductance of the tube in mho; and Δf is bandwidth in cycles per second. It is common in noise-figure analysis to express shot noise in

the plate circuit as an equivalent noise resistance (at room temperature T) in series with the grid. From Eq. (1) it follows directly that

$$\overline{i_p^2} = 4KTR_{eq} g_m^2 \Delta f \quad (2)$$

and

$$R = \frac{\theta T_c}{\sigma T g_m} \quad (3)$$

For planar triodes with oxide-coated cathode, operating approximately with $T_c = 1000^\circ\text{K}$, Eq. (3) yields

$$R_{eq} \approx \frac{B}{g_m}, \quad (4)$$

where factor B varies from 2 to 3.5 depending on the geometric configuration and dimensions of the tube electrodes.

Equation (5) indicates that equivalent noise resistance can be reduced by increasing transconductance. For modern planar triodes the transconductance is between 15 000 and 60 000 μmhos , and accordingly the equivalent noise resistance can be as small as 40 ohms.

Induced grid noise is generated by fluctuations in the number of current pulses induced in the grid circuit by the passage of electrons between grid wires. At the higher operating frequencies induced grid noise is the limiting factor in very-low-noise preamplifier design. According to the North and Ferris theory⁸⁾ it can be approximately represented by a current noise generator in parallel with the grid

$$\overline{i_\tau^2} \approx 4KT\beta G_\tau \Delta f. \quad (5)$$

The value of quantity β is a function of the cathode temperature as well as certain geometrical factors, and it is usually taken as 5. The

quantity G_T is the input conductance due to transit-time effect. At higher frequencies it is usually simpler to measure the induced noise directly than to measure the input conductance, thus the factor β is associated with the input conductance, defining the quantity βG_T as the equivalent grid-noise conductance of the tube. For modern microwave planar triodes the equivalent noise conductance is between 10 and 50 μmhos at 30 MHz. By comparison, the equivalent noise conductance of the best modern miniature tubes is approximately equal to 50 μmhos ⁹⁾.

Other sources of noise in microwave space-charge planar triodes, such as flicker noise, total-emission noise, secondary-emission noise, and anomalous sources of noise due to improper function of the tube, are generally smaller in comparison with the shot noise and induced grid noise at properly chosen tube operating conditions, and can be excluded from further consideration. Concerning the most favorable operating conditions for low-noise applications, the planar triode should be operated under conditions which provide a maximum ratio of transconductance to plate current, the smallest grid current possible, and sufficiently high gain to reduce second-stage noise effects. These conditions for most cases of application of planar triodes with low plate-voltage ratings are maximum rated dissipation, rated heater voltage, and bias voltage between 0.5 and 1 V. An additional advantage of using planar triodes in low-noise preamplifiers is that the tube planar structure is far less sensitive to mechanical vibration of any kind than any other conventional tube structure. Consequently, amplitude and frequency-modulation effects in nuclear magnetic resonance preamplifiers due to

microphonics have been considerably reduced.

3. Noise figure of preamplifier

The equivalent noise representation of the cascode preamplifier is given in Fig. 1. The overall noise figure of the amplifier is given by

$$F_{12} = F_1 + (F_2 - 1)/A_1, \quad (6)$$

where F_1 and A_1 are the noise figure and available power gain of the first stage, respectively, and F_2 the noise figure of the second stage. The noise figure of the first stage is given by the relation⁸⁾

$$F_1 = 1 + \frac{G_1}{G_s} + \frac{\beta G_{\tau 1}}{G_s} + \frac{R_{eq1}}{G_s} [(G_1 + G_s + G_{\tau 1})^2 + Y_1^2], \quad (7)$$

where G_1 represents the input network and ohmic losses across the input of the tube, G_s is the source conductance, $G_{\tau 1}$ is the input conductance due to transit-time effects, R_{eq1} is the equivalent noise resistance of the first tube, β has a value of approximately 5 for tubes with an oxide-coated cathode and space-charge-limited plate current, and Y_1 is the susceptance of the total input admittance $Y_s = G_s + G_1 + jY_1$ presented by the input network of the tube. The available power gain, A_1 , of the first stage is

$$A_1 = \frac{g_{m1}^2 G_s r_{p1}}{(G_s + G_1 + G_{\tau 1})^2 + Y_1^2}, \quad (8)$$

where r_{p1} is plate resistance of the tube. The noise figure of the second stage is given by

$$F_2 = 1 + \frac{G_2}{G_s} + \frac{\beta G_{\tau 2}}{G_s} + \frac{R_{eq2}}{G_s} \frac{\mu^2}{(\mu+1)^2} [(G_2 + G_s + G_{\tau 2})^2 + Y_2^2], \quad (9)$$

where G_2 , $G_{\tau 2}$, R_{eq2} and Y_2 are input losses, input conductance due to transit-time effect, equivalent noise resistance, and input susceptance respectively, for the second tube.

On the assumption that the output conductance of the grounded-cathode tube is $1/r_{p1}$ and that $\mu \gg 1$, Eq. (9) can be written in the form

$$F_2 = 1 + (G_2 + \beta G_{\tau 2}) r_{p1} + R_{eq2} r_{p1} \left[\left(G_s + G_{\tau 2} + \frac{1}{r_{p1}} \right)^2 + Y_2^2 \right]. \quad (10)$$

If relations (7), (8), and (10) are used, Eq. (6) gives, for the combined noise figure,

$$F_{12} = 1 + \frac{G_1 + \beta G_{\tau 1}}{G_s} + \frac{(G_1 + G_s + G_{\tau 1})^2 + Y_1^2}{G_s} \times \left\{ R_{eq1} + \frac{G_2 \beta G_{\tau 2}}{g_{m1}^2} + \frac{R_{eq2}}{g_{m1}^2} \left[\left(G_2 + G_{\tau 2} + \frac{1}{r_{p1}} \right)^2 + Y_2^2 \right] \right\}. \quad (11)$$

For planar triodes, factors $G_2 + \beta G_{\tau 2} / g_{m1}^2$ and $R_{eq2} / g_{m1}^2 (G_2 + G_{\tau 2} + \frac{1}{r_{p1}})^2$ are generally much smaller than R_{eq1} , and the second-stage thermal noise, shot noise, and induced grid noise can be neglected. The shot noise of the second tube becomes important only when the frequency is so different from midband of the second tuned circuit that Y_2^2 / g_{m1}^2 is comparable to unity. Thus, quite apart from bandpass requirements, it is desirable to have the second-stage circuit resonant at midband frequency. Furthermore, if the first stage also resonates at the midband frequency, the overall noise figure is given by

$$F_{12} = 1 + \frac{G_1 + \beta G_{\tau 1}}{G_s} + \frac{R_{eq1}}{G_s} (G_1 + G_s + G_{\tau 1})^2, \quad (12)$$

where $G_{\tau 1} = G_{\tau}$ and $R_{eq1} = R_{eq}$.

The optimum source conductance, G_{sopt} , which gives the minimum noise figure, is obtained from Eq. (12) by the relation

$$G_{\text{sopt}} = \left[\frac{G_1 + \beta G_\tau}{R_{\text{eq}}} + (G_1 + G_\tau)^2 \right]^{1/2}. \quad (13)$$

The optimum source conductance of the planar tube itself, neglecting the ohmic losses across the input of the tube, is

$$G_{\text{sopt}} = \left[\frac{\beta G_\tau}{R_{\text{eq}}} + G_\tau^2 \right]^{1/2}. \quad (14)$$

Since for planar tubes in the most practical cases $\frac{\beta G_\tau}{R_{\text{eq}}} \gg G_\tau^2$, the optimum source conductance at the midband will be approximately given by

$$G_{\text{sopt}} \approx \left(\frac{\beta G_\tau}{R_{\text{eq}}} \right)^{1/2}. \quad (15)$$

The corresponding value for the optimum midband-noise figure, for the case $G_1 = 0$ and $\left(\frac{\beta G_\tau}{R_{\text{eq}}} \right)^{1/2} \gg G_\tau$, is approximately

$$F_{12} \approx 1 + 2 (\beta G_\tau R_{\text{eq}})^{1/2}. \quad (16)$$

From Eq. (16) it is seen that in the first approximation, the theoretical minimum noise figure will be smaller for tubes which have a smaller product of the equivalent noise conductance and the equivalent noise resistance. This is one of the main advantages of using a planar triode in low-noise preamplifiers in comparison with miniature tubes of conventional construction. For example, for the best low-noise planar triodes, the term $\beta G_\tau R_{\text{eq}}$ is of the order of 2×10^{-3} at a frequency of 30 MHz. For the best low-noise tube with conventional tube structure the term $\beta G_\tau R_{\text{eq}}$ is of the order of 20×10^{-3} at the same frequency.

Application of the approximation equations (15) and (16) is limited by the given assumptions, and can give only an appraisal about the noise characteristics of a particular planar tube. The minimum absolute noise figure of presently available planar triodes themselves is so small that the noise characteristics of the associated circuitry becomes important in the evaluation of the overall noise figure of a very-low-noise preamplifier. For most applications of nuclear magnetic resonance a parallel-resonant circuit is employed to detect the resonance. The sample is placed in the inductor and an electromotive force is induced by the precessing nuclear moments. The parallel circuit is the input circuit of the very-low-noise preamplifier. The input tuned circuit has to be coupled to the first tube in such a way that its conductance at resonance is transformed to a value that gives the optimum noise figure. To obtain satisfactory amplification stability a neutralization circuit associated with the input tube should be generally used; however it introduces a neutralizing coil loss. Both losses affect the noise figure of a preamplifier, contributing to a term G_1/G_s in expression (12) for noise figure. They have to be taken into account both in the theoretical considerations and in the actual measurement of preamplifier noise figure. From Eq. (16) it can be seen that to the first approximation a minimum noise figure is a function of the product of the equivalent noise resistance and the equivalent grid-noise conductance of a particular tube. The value of optimum source conductance varies as a square root of the ratio of equivalent noise conductance and equivalent noise resistance. Recently there have been made available two main groups of planar triodes suitable for very-low-noise preamplifiers.

with respect to their equivalent noise resistance and equivalent grid-noise conductance. The planar triodes with relatively large plate-current capabilities (e. g., types 7768 and 7588) provide higher amounts of transconductance and lower values of equivalent noise resistance. These triodes have higher values of input conductance due to transit-time effect, and consequently higher equivalent noise conductance. Typical noise parameters for such triodes are approximately 40 ohms for the equivalent noise resistance, and 500 μ mhos for the equivalent noise conductance at 90 MHz and plate current of 25 mA. The second group of planar triodes (e. g., types 7079 and 8082) with comparatively small plate current capabilities with respect to the first group, have lower values of transconductance, higher values of equivalent noise resistance, but relatively smaller values of equivalent noise conductance. Typical noise parameters for these triodes are approximately 300 ohms for the equivalent noise resistance, and 100 μ mhos for the equivalent noise conductance at 90 MHz and plate currents of order of magnitude of 6 mA. For planar tubes the amount of equivalent noise resistance is practically independent of frequency, in the frequency region from 10 to 100 MHz, because of the low value of electron transit time. The equivalent noise conductance varies directly with frequency to the second power. Accordingly in the lower part of the frequency spectrum, planar triodes with larger transconductance and equivalent input noise conductance will give smaller noise figures than triodes with relatively lower transconductance and equivalent grid-noise conductance. On the contrary, in the higher part of the frequency spectrum, planar triodes with smaller transconductance and equivalent input noise conductance will give the lower noise figures.

Although with respect to the minimum noise figure the choice of the second tube is noncritical, the second tube should have a relatively higher transconductance. The stability of the first stage results from input conductance of the second stage, which is approximately equal to g_{m2} . This is especially important in application of planar triodes in cascode preamplifiers, which can cause serious instability of the preamplifier due to fairly high transconductance of the planar tube in the first stage. The amplification of the first grounded-cathode stage is g_{m1}/g_{m2} . If the same type of planar tube is used for the second stage as for the first, the amplification of the first tube is approximately equal to unity and the grounded-cathode stage is very stable. The voltage amplification of the cascode is approximately equal to $g_{m2} R_0$, and R_0 is the load resistance of the second tube. The available power gain A_{12} of the cascode circuit, taking load resistance as a part of it, is⁷⁾

$$A_{12} = \frac{g_{m1}^2 R_0}{G_{\text{sopt}}} \quad (17)$$

Variation of the theoretical minimum noise figure with non-optimum source conductance for various values of the product $G_{\tau} R_{\text{eq}}$ is calculated for $G_1 = 0$ by means of Eq. (12) and (13), and results in normalized form are shown in Fig. 2. The variation of noise figure with nonoptimum source conductance is small when source conductance is in the vicinity of its optimum value. For the low-noise planar triodes the quantity $G_{\tau} R_{\text{eq}}$ is between 5×10^{-5} and 5×10^{-3} for the 10- to 100-MHz frequency band, depending upon the midband frequency.

From the curves given in Fig. 2 it can be concluded that the variation in minimum noise figure for the particular ratio of the nonoptimum

source conductance to optimum source conductance will be larger for smaller amounts of the quantity $G_{\tau} R_{eq}$.

4. Noise figure and optimum source conductance of 7768 planar triode

One of the best planar triodes now available as a first stage of a very-low-noise preamplifier, in the region from 10 to 100 MHz, is General Electric Type 7768. This triode, with a cathode area of 0.34 cm^2 , a grid-to-cathode spacing of about 0.05 mm, and a grid-to-plate spacing of about 0.33 mm, has a transconductance of approximately 60 000 μmhos at a plate current of 25 mA, and an equivalent noise conductance of 62 μmhos at a frequency of 10 MHz and 620 μmhos at a frequency of 100 MHz. The measured equivalent noise resistance is approximately equal to 40 ohms, and consequently the constant $B = 2.4$ in Eq. (4). The bias voltage is 0.5 V for the optimum noise performance. The theoretical minimum noise figure and the optimum source conductance as a function of frequency can be calculated from Eqs. (12) and (13) respectively, if the effect of both the input circuit and the neutralization circuit losses are taken into account. By use of Eq. (12) the theoretical minimum noise figure of the 7768 planar triode has been calculated as a function of frequency for various amounts of the input-loss conductance and the equivalent-noise conductance. The minimum noise figure is calculated for the frequency band from 1 to 250 MHz, and results are plotted in Fig. 3. The theoretical absolute minimum noise figure as a function of frequency is calculated and plotted as curve c in Fig. 3 for the input-loss conductance $G_1 = 0$, and the equivalent noise resistance $R_{eq} = 40$ ohms. The theoretical absolute minimum noise figure amounts to 0.13 db at 10 MHz and 1.2 db at 100 MHz.

Supposing a reasonable amount of input-loss conductance $G_1 = 10^{-4}$ mhos, which can be met in a number of practical cases, the theoretical noise figure has been calculated and is represented by curve b in Fig. 3. From direct comparison of curves c and b it can be seen that the input-loss conductance has a larger influence on the minimum noise figure in a low-noise planar triode preamplifier at the lower frequencies of the 10 to 100-MHz frequency spectrum than at the higher frequencies; this is because at the lower frequencies the contribution of the thermal noise of the input circuitry is of far greater importance than the planar triode noise itself. For example, at 10 MHz the increase of the minimum noise figure due to the input-loss conductance is equal to 0.42 db. At a frequency of 100 MHz the increase of minimum noise figure is approximately 0.12 db. Meanwhile the increase of equivalent noise resistance from 40 to 50 ohms has practically the same effect on the minimum noise figure increase at both the lower and the higher frequencies of the 10-to 100-MHz frequency band. The optimum source conductance of a 7768 planar triode as a function of frequency for various amounts of the input-loss conductance are calculated from Eq. (13) and shown in Fig. 4. The optimum source conductance amounts to 0.4 mmho at 10 MHz and 4 mmhos at 100 MHz for input-loss conductance G_1 equal to zero (curve b in Fig. 4). For input-loss conductance of $G_1 = 10^{-4}$ mho the optimum source conductance increases to 1.6 mmhos at 10 MHz and to 4.3 mmhos at 100 MHz. From these data, it can be seen that the input-loss conductance has a larger influence on optimum source conductance at the lower frequencies than at the higher frequencies in the 10-to 100-MHz frequency band.

5. Circuit description

The preamplifier circuit developed with planar triodes and based on a parallel cascode configuration is shown in Fig. 5. This unit was designed to replace the conventional 24.3-MHz preamplifier of a high-resolution nuclear magnetic resonance spectrometer employing a type 5702 cascode input stage. A parallel-resonant circuit with the resonance frequency of 24.3 MHz was employed to detect the resonance.

The General Electric 7768 planar triode was selected as the first tube. This triode has the equivalent grid-noise conductance of approximately 36 μ mhos at frequency of 24.3 MHz.

The 7768 was chosen as the second tube in grounded-grid stage because of its high transconductance and the small sensitivity to mechanical vibrations. The high transconductance of the second stage is important for obtaining as high as possible a stability of the first stage. Planar triode 7768 was originally designed and intended for use in grounded-grid circuits. In grounded-cathode circuits of the cascode first stage it can introduce significant amplification instability due to positive capacitive feedback, particularly with a relatively large input impedance. The first-stage stability results from the loading applied to the first tube plate by the input conductance ($\approx g_m^2$) of the second tube. To improve the first-stage stability, V_1 is neutralized by inductance L_2 , which resonates with the 1.7-pF grid-plate capacitance and the capacitance of C_1 . Since the preamplifier is intended to be located in the fringe magnetic field of the spectrometer magnet, the neutralization circuits are tuned by means of a variable capacitor C_1 . To obtain additional stability a damping 10-ohm resistor is placed in series with the grid. The coils L_1 and L_3 tune the interstage capacitance of about 10 pF.

The bandwidth of the interstage circuit is extremely wide, because of heavy input loading of the grounded-grid stage. For this reason the inductances L_1 and L_3 are not critical.

The usual self-bias supply voltage is not satisfactory for use with the microwave planar tubes because of their high transconductance. To provide additional reduction in the variation of tube performance caused by line-voltage fluctuations and tube aging, relatively large cathode resistors were used; they provide a large amount of the negative feedback for the dc path. This method is the most efficient one for reducing the variation in tube performance but requires an external voltage source to provide the proper tube bias. The cascode circuit is followed by a 7077 planar triode, neutralized, grounded-cathode stage.

This stage provides additional amplification, as well as providing a match to the characteristics impedance of the output cable.

The overall voltage amplification of the preamplifier is 300, with the optimum source conductance of 1.8 mmhos. The preamplifier bandwidth is approximately 1.1 MHz.

6. Measurement of noise figure

The measurement of noise figure of the 24.3-MHz preamplifier was carried out by a method introduced by Lawson⁹⁾. This method is especially suitable for measurements of very-low-noise figures, since other methods as well as commercially available noise-figure meters are not accurate enough for the measurements of very-low-noise figures. The lower value is usually limited by the instability of the noise generators. Commercial noise-figure meters in the best case have the measurement accuracy of ± 0.5 db.

A noninductive high-stability resistor was used as a noise source. It was placed in a brass cube about 2 in. on a side. A cylindrical hole was provided for insertion of a thermometer. The resistor was connected to the input terminals of the low-noise amplifier; it was the only source of noise apart from that in the amplifier alone. The noise power of the preamplifier output was measured as a function of the temperature of the brass cube by means of a postamplifier and a Hewlett-Packard 431A power meter. The brass cube was large enough to achieve a good approximation to temperature equilibrium. The measurement was carried out at the temperature of liquid nitrogen (77°K) and over a temperature range from 290°K to about 400°K. As indicated on Fig. 6, the points of measurement lay practically on a straight line. The extension of this line to 0°K gives the noise originated in the amplifier alone. The standard noise figure (i. e., at the standard noise-source temperature of 290°K) can be found from

$$F = N_A / N_S, \quad (18)$$

where N_A is the output noise power of the preamplifier at 290°K, and N_S is the output noise power which owes its origin to the thermal noise in the resistor. Now $N_S = N_A - N_O$, where N_O is the preamplifier noise output power given by extrapolation at 0°K, and the standard noise figure is given by

$$F = N_A / (N_A - N_O). \quad (19)$$

For the particular preamplifier with the midband frequency of 24.3 MHz, $N_A = 99 \mu\text{W}$ and $N_O = 16 \mu\text{W}$, which gives the overall measured noise figure of 0.76 db. This noise figure includes losses of the input circuit, neutralization coil, and 10-ohm damping resistor. The

damping resistor was placed in the series with the grid of the input tube to avoid possible amplification instability. When Eq. (12) was used with $G_1 = 10^{-4}$ mhos and $R_{eq} = 50$ ohms the calculated minimum noise figure was 0.704 db; this can be considered to be in a good agreement with the experimental value. The calculated noise figure with $G_1 = 0$ and $R_{eq} = 50$ ohms gave the minimum noise figure of 0.35 db. At 24.3 MHz the input-loss conductance caused an increase in the minimum noise figure of approximately a factor of two over the planar triode minimum noise figure alone. Consequently, the standard noise figure of the pre-amplifier can be further decreased by decreasing the operating temperature of the input circuitry, since the cooled input circuitry minimizes the thermal noise.

6. Conclusions

Microwave planar triodes are particularly suitable for very-low-noise preamplifiers in high-resolution nuclear magnetic resonance spectrometers, because of their excellent low-noise properties and very small sensitivity to mechanical vibrations. The noise performance of planar triodes has been considered, with the purpose of achieving a minimum noise figure along with high amplification stability of preamplifiers at frequencies from 10 to 100 MHz. Planar triodes are superior in noise performance to presently available high-frequency low-noise transistors, because of the lower equivalent noise resistance and better high-frequency noise characteristics. For example, with the high-frequency transistors now available, the best noise performance in the 10 to 100-MHz frequency band is obtained with RCA 2N2857 and TI X3015; they have a calculated theoretical minimum absolute noise figure of 1.8 db.

The field-effect transistors TI XM301 and TI 2N3823 have minimum figures of 1.8 db and 2.5 db respectively. However, it has been found experimentally that the spread in noise characteristics and the discrepancies between the computed and the measured values of the transistor noise figure are larger than the discrepancies between the calculated and the measured planar triode noise figure, especially for very-low-noise units. These differences are very often larger than 0.5 db even if one takes into account all possible measurement corrections. Accordingly, the calculated and often published values of the minimum absolute noise figure are more reliable for planar triodes than for transistors.

Planar triode preamplifiers are inferior in comparison with parametric preamplifiers in the minimum absolute noise figure. However, application of parametric preamplifiers in high-resolution spectrometers is limited by their relatively large amplification instability and design complexity.

With regard to the correlation between the shot noise and the induced grid noise of planar triodes, and possible benefit from it for a further reduction in noise figure, it has been experimentally found that in the 10- to 100-MHz frequency band the correlation is so small that it cannot be detected by the noise-figure measurement methods used here. This is probably due to two factors:

- (a) large input-circuit thermal noise related to the induced grid-noise correlated component, and
- (b) a large uncorrelated component of induced grid noise compared with the total induced-grid noise.

Although literature dealing with correlation problems between the shot

noise and the induced grid noise for conventional tube structure is extensive, there are, to the knowledge of the author, no published data about the planar triode correlation problems.

The planar triode preamplifier can be used in the fringe magnetic fields of a spectrometer magnet, provided that the proper orientation of planar tube structure is observed. It was found experimentally, however, that higher magnetic fields can cause an increase in preamplifier output noise power under particular conditions. This is due to the magnetic field's upsetting the beneficial effects of the space-charge reducing the shot noise.

Because of the small amount of shot noise of planar triodes, they can also be successfully applied in nuclear resonance absorption experiments as an active element in marginal oscillator circuits, where intrinsic noise of the oscillator is often very important in resonance signal detection and observation.

Due to the microwave planar triodes' low narrow-band absolute noise figure, they can be suggested for inclusion in wide-band low-noise preamplifiers, since the wide-band average noise figure will also be small in frequency regions where flicker noise can be neglected.

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Figure Captions

1. Equivalent noise representation of cascode preamplifier.
2. Variation of noise figure with nonoptimum source conductance.
3. Variation of minimum noise figure of planar triode 7768 with frequency.
4. Optimum source conductance of planar triode 7768 as a function of frequency.
5. Schematic diagram of very-low-noise 24.3-MHz preamplifier.
6. Determination of preamplifier noise figure by ratiometer method.

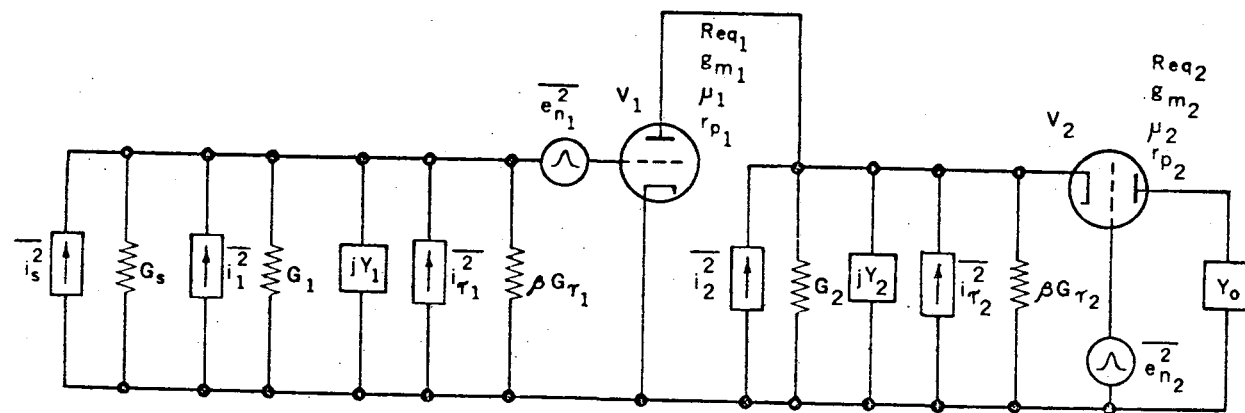


Fig. 1

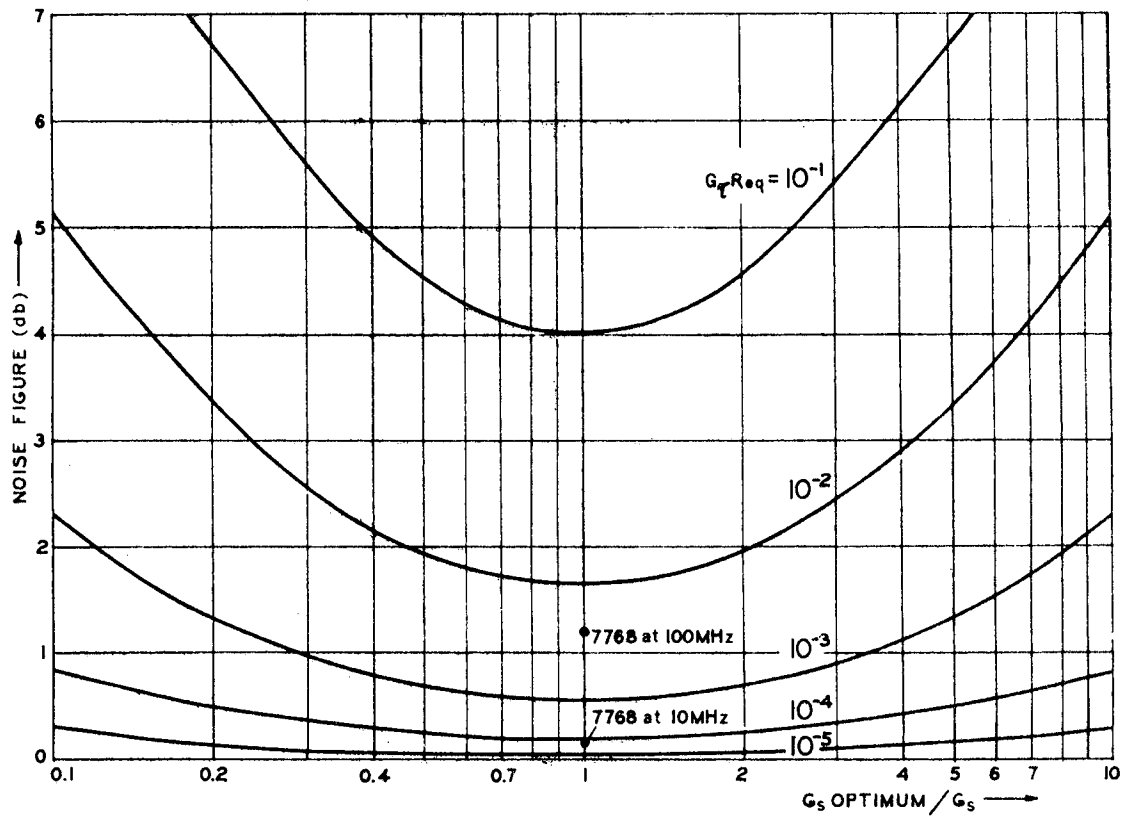


Fig. 2

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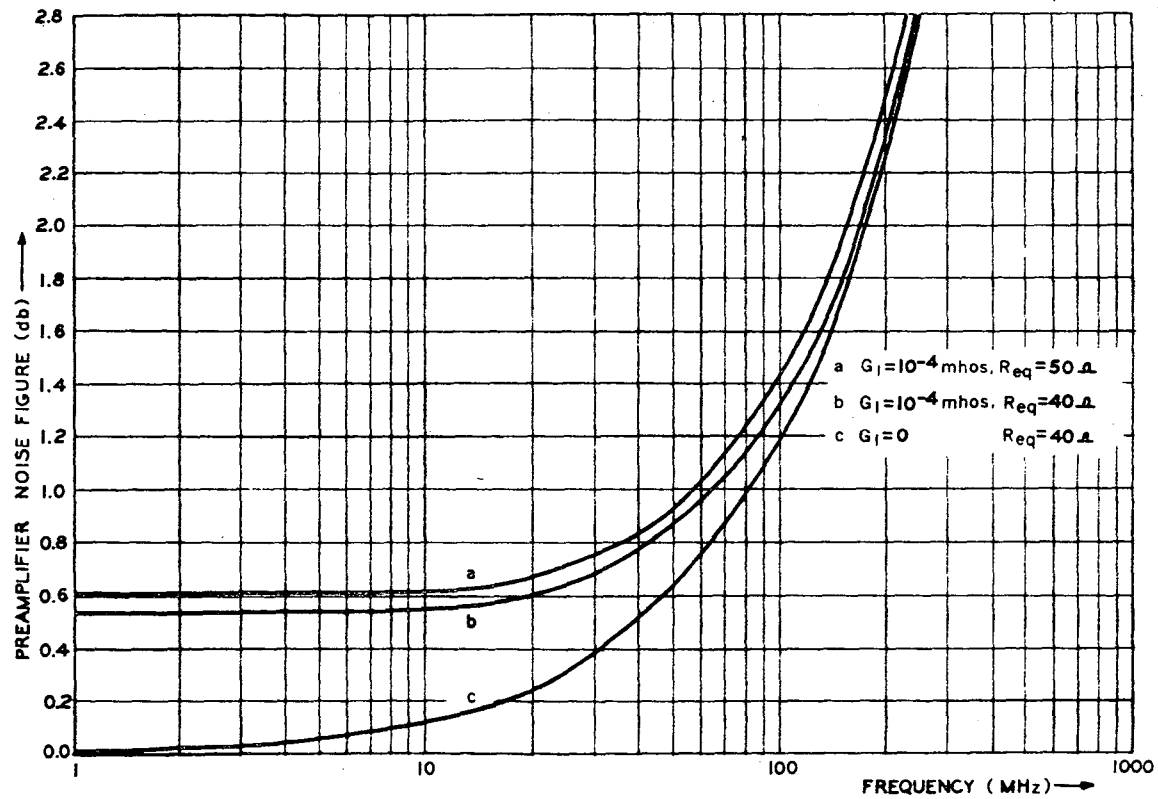


Fig. 3

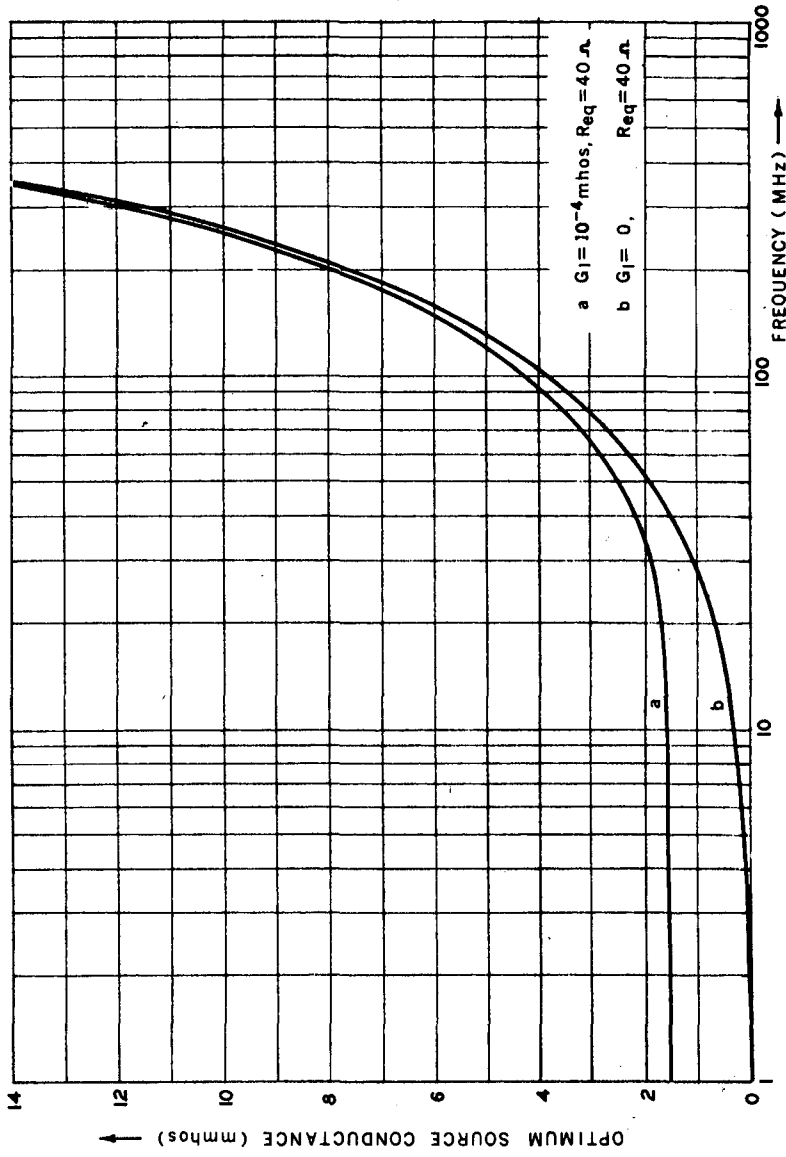


Fig. 4

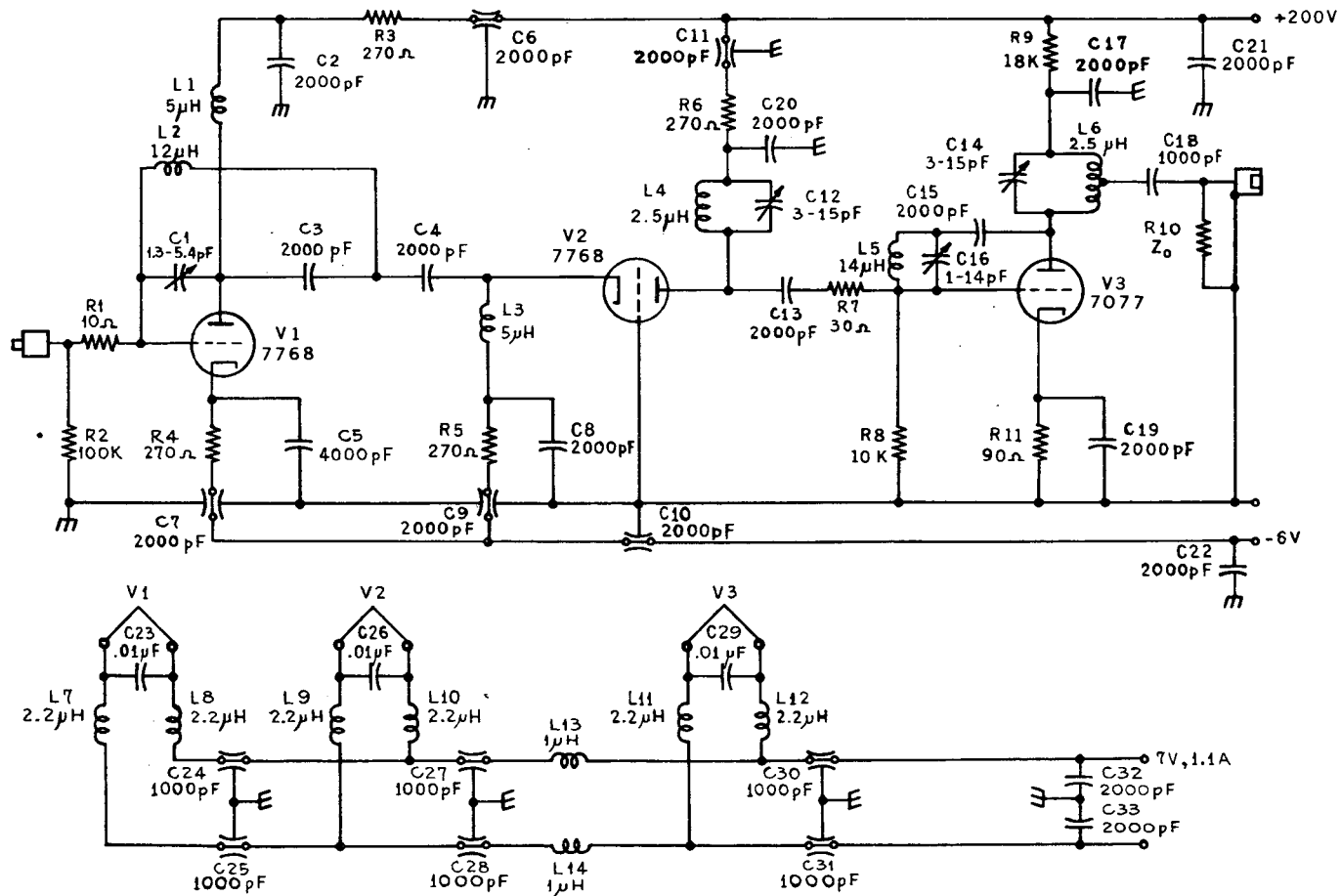


Fig. 5

UCRL-16917

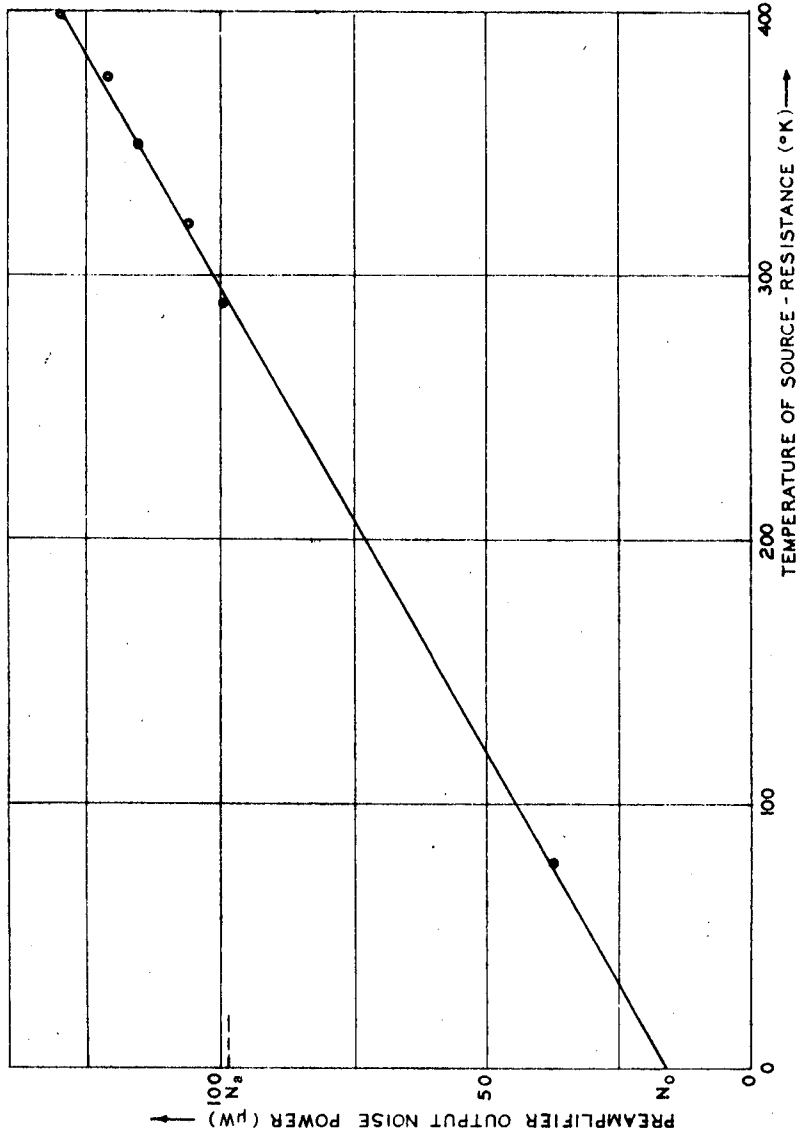


Fig. 6

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