Stability and Neutralization of the SNS RF Output Amplifier

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Introduction

An amplifier is stable if its response from an equilibrium state to any and all transient disturbances is a decreasing exponential, returning to its original state. If the amplifier's response is an increasing exponential or growing wave resulting in a stable limit cycle (sinusoidal or relaxation oscillations) or a new state, then the amplifier is unstable. Transient disturbances include thermal noise, shot noise, and power supply switching. The disturbances can be either conductively coupled or induced into the amplifier.

An excited amplifier, can display instability over its entire cycle or over a portion of the exciting cycle. The response of an unstable amplifier can include frequency terms that are not either harmonics of the exciting signal or sum and differences of the frequency components of the input signal.

Instability is the result of feedback, or transmission of power from the amplifier output terminals to its input terminals. In the absence of feedback an amplifier is unconditionally stable. Feedback can be either by design, resulting from controlled circuit components; or parasitic, resulting from properties of the active components.

An amplifier is stabilized in either one of two modalites, shielding or neutralization. Shielding requires a change in physical layout of the circuit to interrupt the feedback path. Neutralization requires the addition of a second feedback path phased with respect to the original feedback path, such that the addition of the two feedback currents cancel.

Parasitic Feedback

Vacuum tubes have two major sources of parasitics feedback. Capacitance between control grid and plate C_{GP}, resulting in voltage feedback; and cathode lead inductance L_K, resulting in current feedback.

For tuned amplifiers parasitic voltage feedback is simultaneously positive (regenerative and possibly unstable) and negative (degenerative and stable). For frequencies that are less than the resonant frequency of the plate load the feedback is positive; and for frequencies that are greater than the resonant frequency, the feedback is negative. Though a tuned amplifier may be stable, the negative and positive feedback skews both the amplitude and phase response. Practical amplifiers must limit the value of the feedback capacitance C_{GP} to a value that is considerably less than the value resulting is an unstable response Cosc.

Parasitic current feedback is negative and stable. It manifests itself as a decrease in the value of the amplifiers input resistance, as seen between grid and cathode. For very high currents (300A) and high gm (1A/volt) tubes such as the TH558, the input resistance can readily fall below 1000 ohms depending on lead dress in the low Mhz frequency region.

Voltage Feedback

A simplified circuit schematic of the power amplifier is shown in Figure 1. A functional equivalent circuit is given in Figure 2. The load resistance R_L includes both ferrite losses and the tube output resistance r_p. The voltage gain from grid to plate A_v is given by

$$A_v = \frac{-g_m R_L}{1+jx}$$

Where x is the normalized detuning of the resonant circuit

$$x = 2Q_o \frac{F-Fo}{Fo}$$

Where F_o is the resonant frequency of the plate load and Q_o is the quality factor. The voltage across the feedback capacitor is

$$V_g \left[\begin{matrix} \\ 1+jx \end{matrix}\right]$$

And the feedback current I_F is

$$j\omega C_{GP} V_g \left[1+\frac{g_m R_L}{1+jx}\right]$$

Which reduces to

$$\omega C_{GP}\, g_m R_L V_g \frac{x}{1+x^2} + j\omega C_{GP} V_g \left(1+\frac{g_m R_L}{1+x^2}\right)$$

The source current I_g is the above expression plus

$$\frac{V_g}{R_g}$$

Stability requires that the

$$\operatorname{Re} Y_{in} > o;\ Y_{in} = \frac{I_g}{}$$

This inequality guarantees that the transient response is a decreasing exponential.

$$\operatorname{Re} Y_{in} = G_{in} = \omega C_{GP}\, g_m R_L \frac{x}{1+x^2} + \frac{1}{R_g}$$

The frequency response of the input conductance G_{in} is in the factor

$$\frac{x}{1+x^2}$$

The inequality is evaluated at the mathematical minimum which is at x = -1, with a minimum value of -1/2. Thus

$$\frac{1}{-} - \frac{\omega C_{GP}\, g_m R_L}{2} > o$$

The value of C_{GP} satisfying the inequality is called Cosc, and is the separatrix between stable and unstable operation. For stability

$$C_{GP} < Cosc = \frac{2}{\omega\, g_m R_L R_g}$$

Evaluation of Stability

The value of Cosc has been evaluated for the proposed SNS RF output amplifier. Cosc is a function of beam loading and has been evaluated for zero and maximum beam loading. The required tube parameters are taken from the tube characteristics, Figure 3. The operating load locus is plotted on the tube characteristics, figures 3A and 3B.

Each tube drives two gaps. The cavity structure is single-ended and is described in Table I.

Ferrite Type	4M2
OD	50 cm
ID	25 cm
Width	2.7 cm
Rings per gap	21
Gap Voltage	10 KV
Frequency	1.19 MHZ
Dissipation	22 KW/gap 44 KW/amplifies

Table I
Cavity Characteristics

With zero beam loading the tube drives a resonant load and is operated class AB with a conduction angle of 234°. The load locus is linear, Figure 3A. The maximum beam intensity is $2.08.10^{14}$ protons and is in quadrature with the gap voltage. The load power is constant with the tube current increasing in direct proportion to the number of injected protons. The load locus is a rotated ellipse, Figure 3B. The tube operates class AB with a conduction angle of 190°.

An evaluation of Cosc, at the extremes of injection is given in Table II, with C_{GP} of 6.3 $\mu\mu$F and an additional 2 to 3 $\mu\mu$F due to stray wiring. The circuit requires neutralization. If the 50 Ω source drives the TH558 directly, the value of Cosc would vary from 46 to 44 $\mu\mu$F and the amplifier need not be neutralized.

Parameter	**Zero Beam Tube, Ferrite Loss**	**Maximum Beam**
Peak Current	98A	270A
Conduction Angle	234°	190°
g_m	0.6 A/V	1 A/V
r_p	250Ω	150Ω
R_L	205Ω	132Ω
Rg	200Ω	200Ω
Cosc	10.9 $\mu\mu$F	10.1 $\mu\mu$F

Cavity Voltage	10KV/gap
Cavity Dissipation	22KW/gap 44KW/amplifier
C_{GP}	6.3 $\mu\mu$F
C feedback	9.0 $\mu\mu$F

Table II

Calculation of Critical Capacitance, Cosc

Neutralization

Neutralization of the feedback current produced by the grid-plate capacitance (C_{GP}) requires a second feedback path to generate a neutralization current. Thus current balance the effects of the feedback current on the input admittance. The input impedance (admittance) of a neutralized amplifier is independent of the plate load.

An amplifier driving a push-pull cavity is neutralized by adding a capacitor of value equal to C_{GP} between the grid and cavity as shown in Fig. 4A. With a balanced or push-pull voltage across the gap (V_{GAP}) the currents I_F and I_N are nominally equal and cancel. Thus the grid drive Ig is independent of the plate load and is a function of the input parameters of the tube.

For single-ended cavities a push-pull input transformer can be employed to balance or cancel the feedback current I_F as shown in Figure 4B. The currents I_F and I_N are each derived from the plate of the tube. They produce equal but opposite sense MMF's in the drive transformer. Thus the grid drive current Ig is independent of the plate load. The magnetic coupling between the two halves of the secondary should be tight. The secondary should be bifilar wound. In addition, the transformer can be wound as a step-up transformer, increasing the drive voltage.

Design of Input Transformer

The input transformer is designed to meet the following specifications:

1. A 1:2 voltage step-up
2. A push-pull secondary
3. Resonate with the tube input capacitance (1200 $\mu\mu$F) at 1.18 MHz
4. With sufficiently low Q as not to require tuning after installation
5. To terminate the input drive cable with 50 ohms.
6. Linear operation with a 500 watt power source.
7. Monotonic frequency response to at least 6 MHz requiring a coefficient of magnetic coupling greater that 0.98

The transformer is built around a 4L2 ferrite core of four rings.

Ring size is; OD = 5 ½"
ID = 2 ½"
Thickness = 2.7 cm

The primary is one turn, constructed from a 1/64" copper foil 2" wide. The secondary is 2 bifilar turns (total of 4 turns) of #16 AWG copper wire, insulated for at least 2000 volts. The secondary is wound directly over the copper foil as shown in figure 5A. The test set up is shown in Figure 5B. Transformer parameters and the test results are given in Table III. The frequency sweep of the input resistance is given in Fig. 6. From Figure 6 and the equivalent circuit of the transformer the coefficient of magnetic coupling, k, can be calculated. The value of k is in the ratio of the frequencies of the first parallel and first series resonance.

$$\frac{F_{series}}{F_{parallel}} = \sqrt{\frac{1}{1-k2}}$$

Parameters	Value
Primary Inductance	4.08 μH
Coefficient of Magnetic Coupling	0.991
Turns Ratio	1:4 CT
Maximum Flux Density	112 Gauss
Core Loss	9.86 Watts
Copper Loss	0.1 Watt
Thermal Coefficient of Inductance	0.49%/°C
Loaded Q	1.78

Table III

Transformer Parameters and Test Results

A voltage step up transformer is employed to increase the grid drive voltage while maintaining the drive power at a constant value of 500 watts. Thermal drift will detune the circuit and reduce the maximum drive voltage to the tube. Circuits that are tuned with capacitors, normally employ negative temperature coefficient capacitors to compensate for the positive temperature coefficient of the inductor. For this application the inductor is tuned with the tube input capacitance. To minimize the circuit Q-factor and thermal drift of voltage, no additional capacitance is added to the grid circuit. The effect of thermal drift on maximum grid drive voltage is given by Table IV. The thermal coefficient of inductance is primarily due to the properties of the ferrite.

Drift $\Delta\theta$ (°C)	Maximum Grid Drive Volts - Peak
0	448
10	446
20	441
30	433
40	422

Table IV

Maximum Grid Drive Voltage Variation With Temperature

Self heating of the inductor is negligible. Drift is dependent on the ambient temperature and packaging of the transformer and major heat generating components within the amplifier enclosure. A maximum thermal drift of 20° to 25°C is reasonable and tolerable. Following initialization of the transformer at resonance, the circuit can operate open loop.

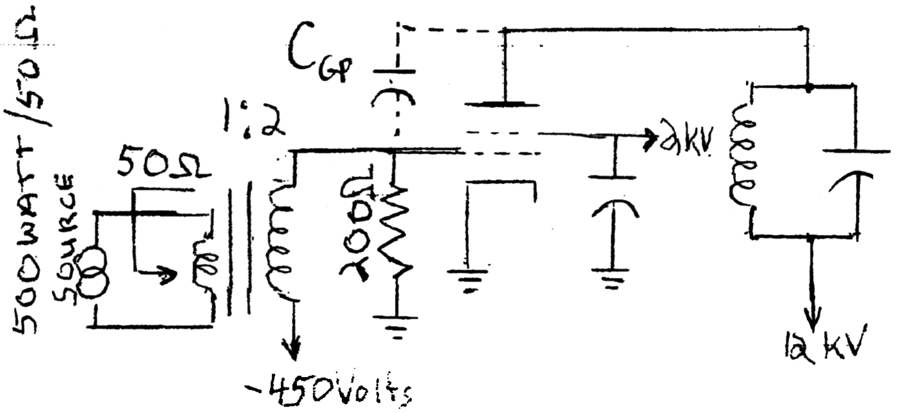


Figure 1
Simplified Circuit Schematic of Power Amplifier

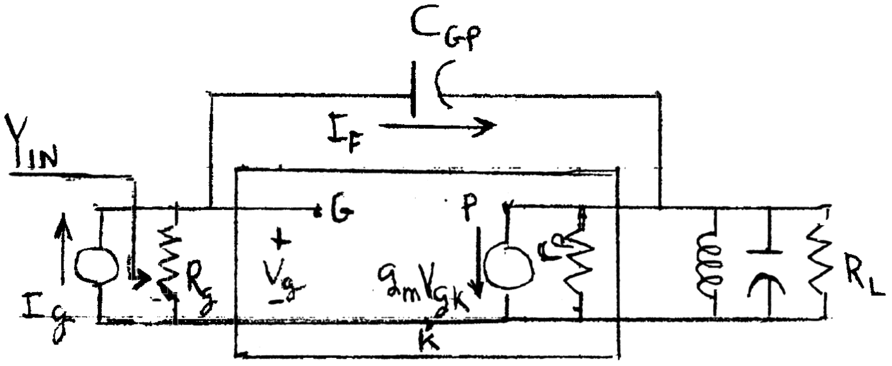


Figure 2
Equivalent Circuit of Power Amplifier

$$Y_{in} = \frac{I_g}{V_g}$$

CONSTANT CURRENT CHARACTERISTICS
Vg2 = 2000 V

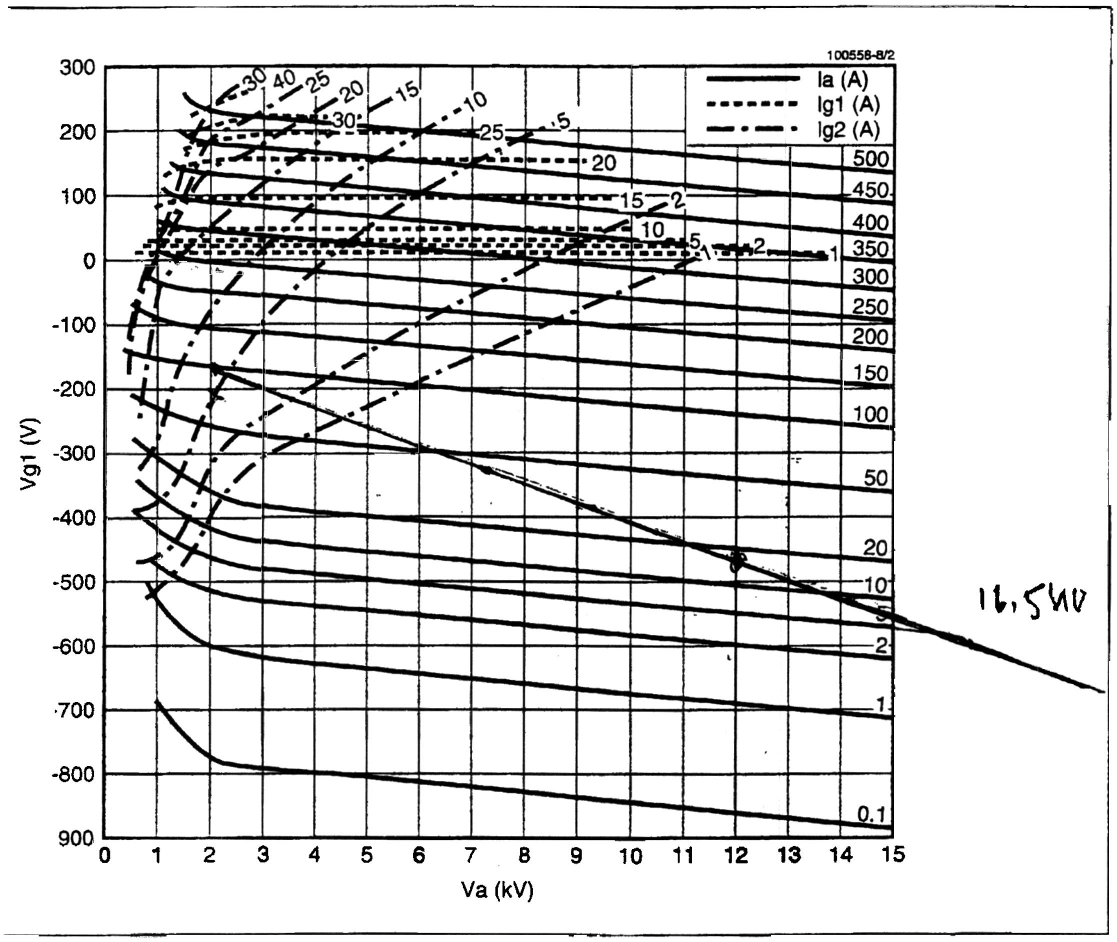


Figure 3A

Load Locus For Zero Beam

CONSTANT CURRENT CHARACTERISTICS
Vg2 = 2000 V

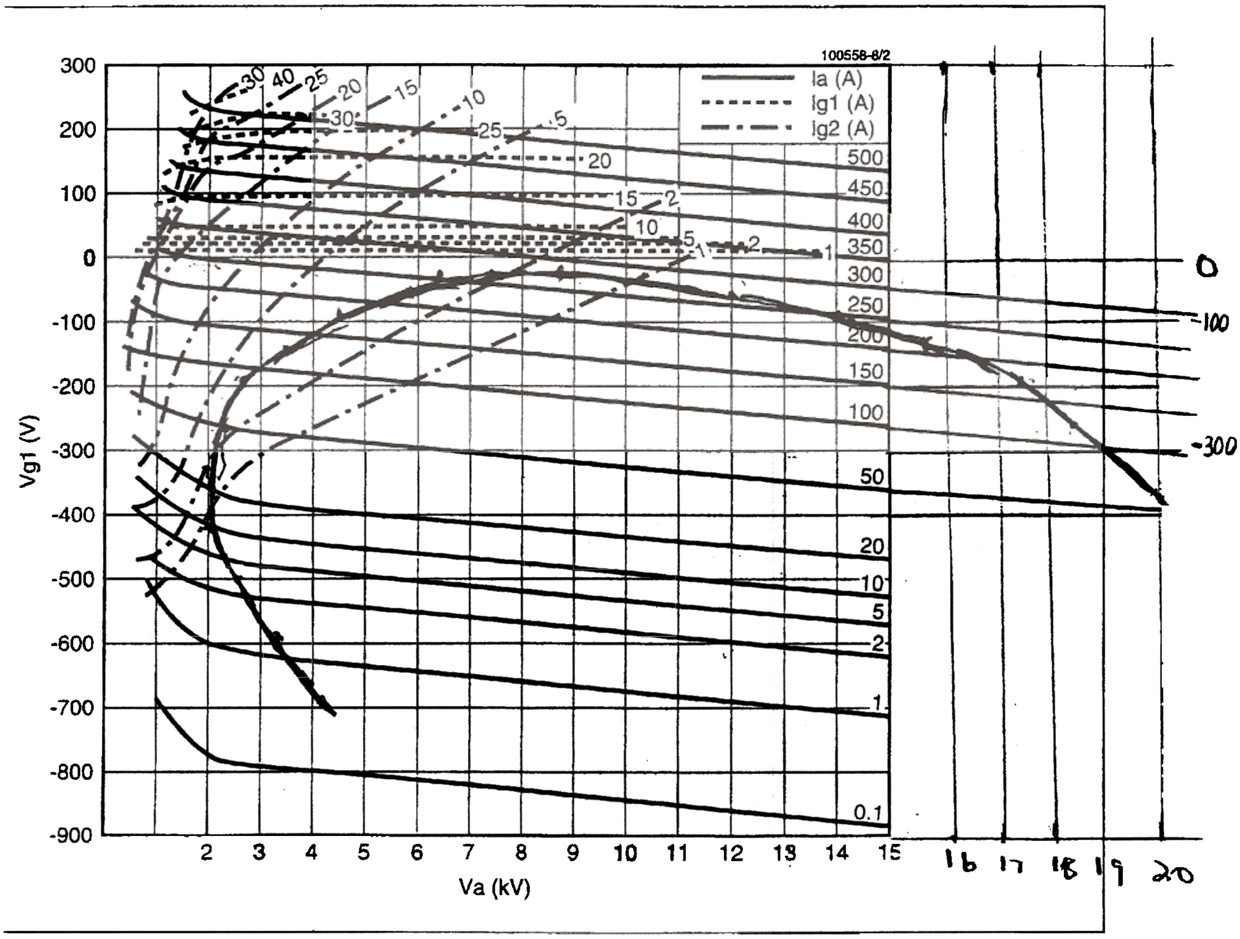


Figure 3B

Load Locus For Maximum Beam Loading

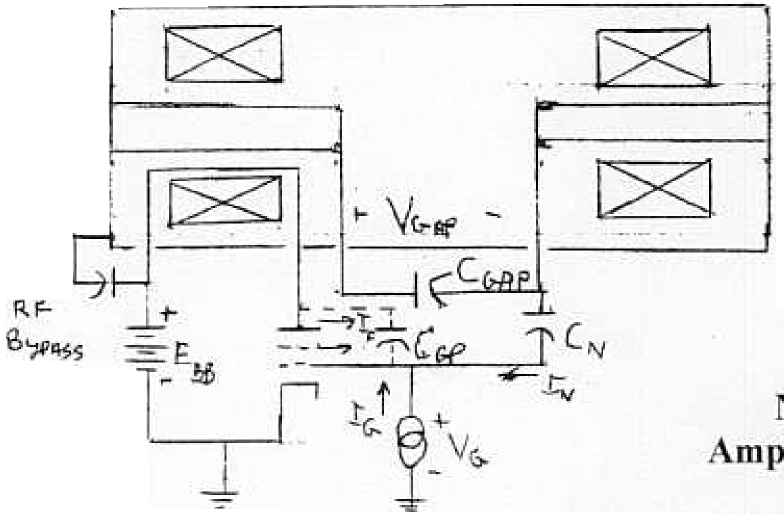


Figure 4A

Neutralization of an Amplifier Link Coupled to a Push Pull Cavity

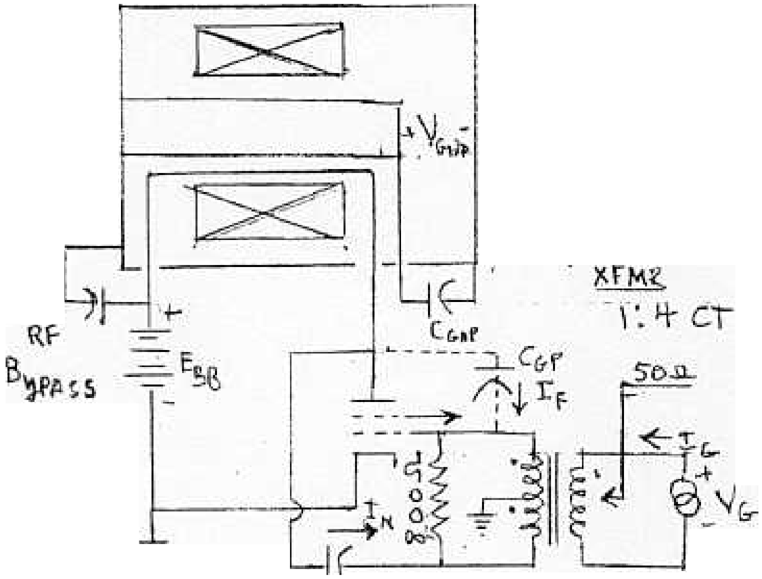


Figure 4B

Neutralization of an Amplifier Link Coupled to a Single Ended Cavity

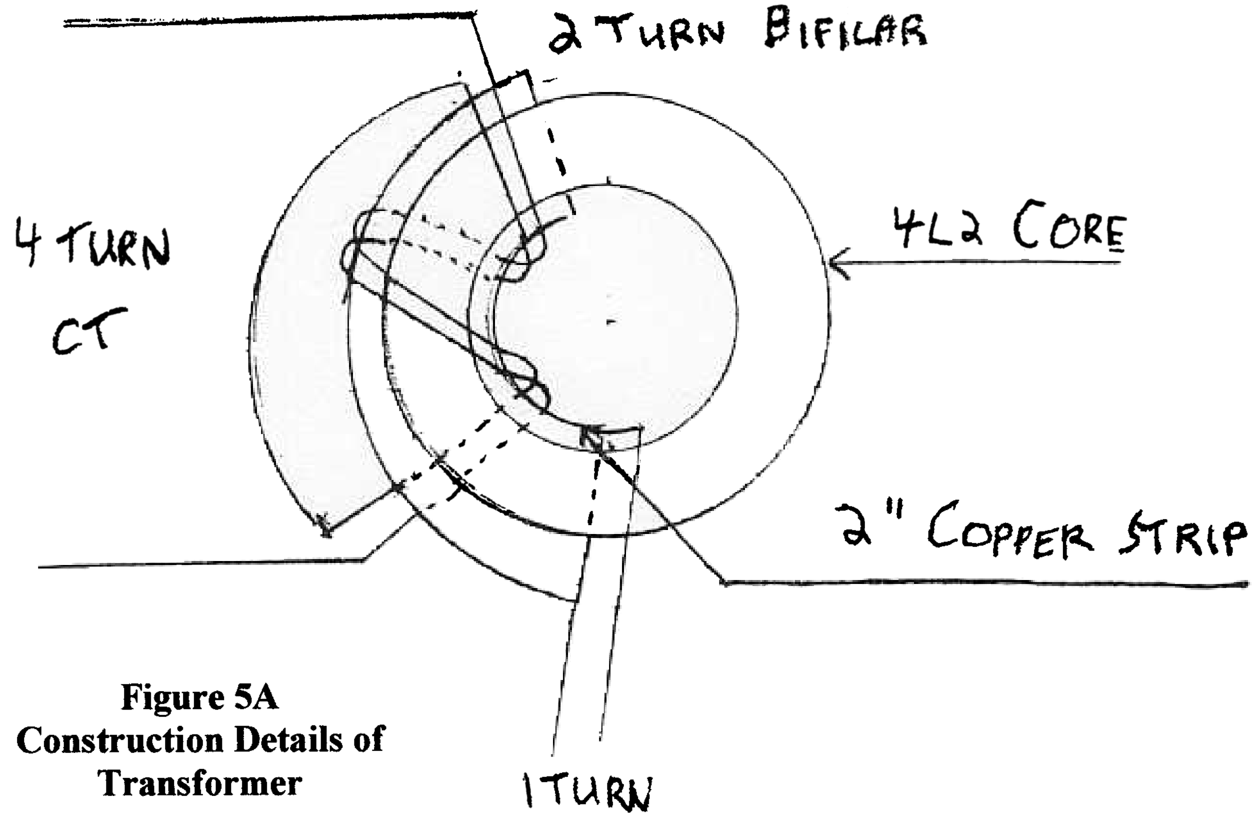


Figure 5A
Construction Details of Transformer

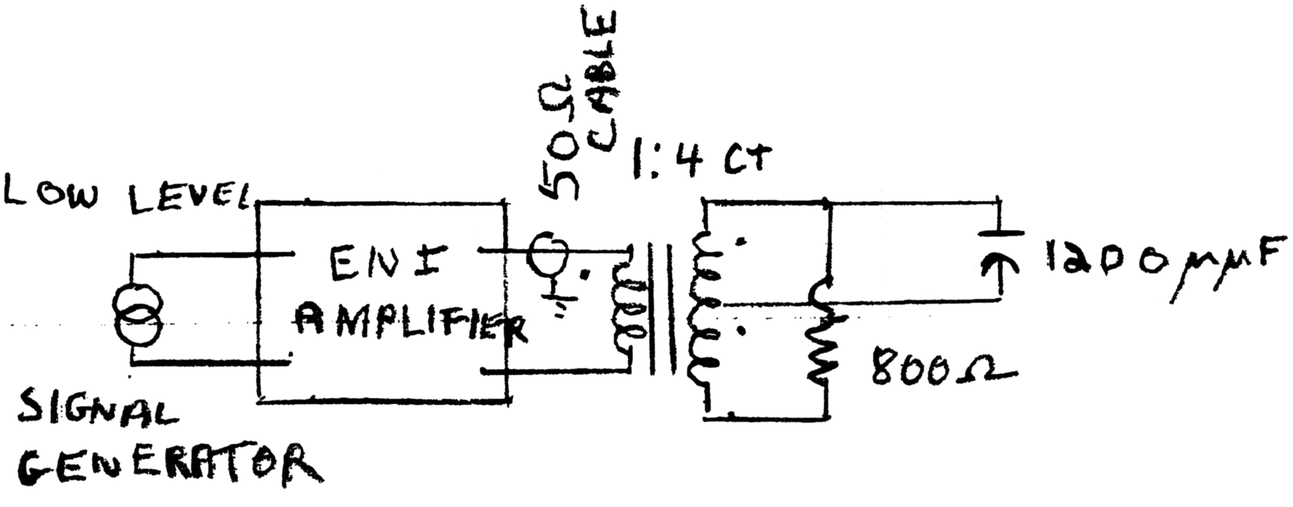
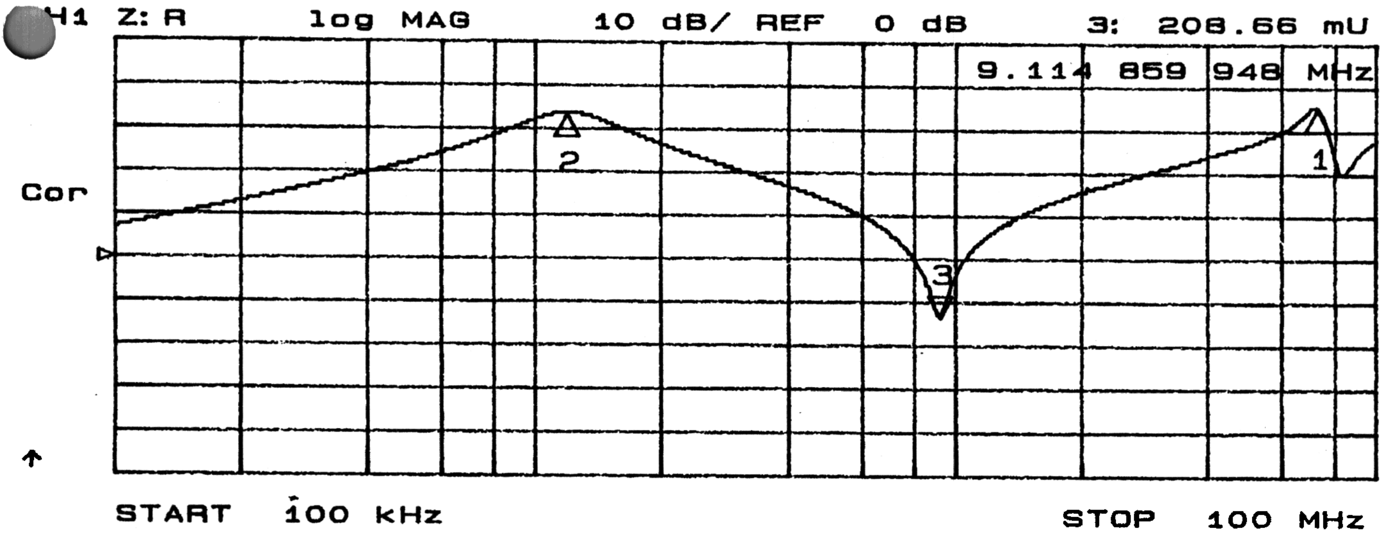


Figure 5B

Test Circuit of Transformer



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N   STIMULUS                 val

1   71.903 494 906 MHz       58.896 U
2   1.175 574 075 MHz        49.02 U
3   9.114 859 948 MHz        208.66 mU
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Figure 6

Frequency Sweep of Input Resistance