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# The RF Separator Amplifier



## *Introduction*

This note summarizes the design methodology and measurements for the rf separator rf amplifier. An idealized analysis ignoring stray components is performed to establish the initial parameter space. The idealized parameters and known stray parameters are then entered in "WAC" ,a computer program, to determine the expected parameter values. The system is then mechanically designed and assembled and measurements are made to determine the actual parameter values. Once a successful system and tuning strategy is arrived at, power is applied and high power tests begin. High power tests consist of first operating into a water cooled load across the tuning range and then into the narrow band cavity. Assuming everything goes well, we can claim victory – otherwise we learn from our mistakes and iterate.

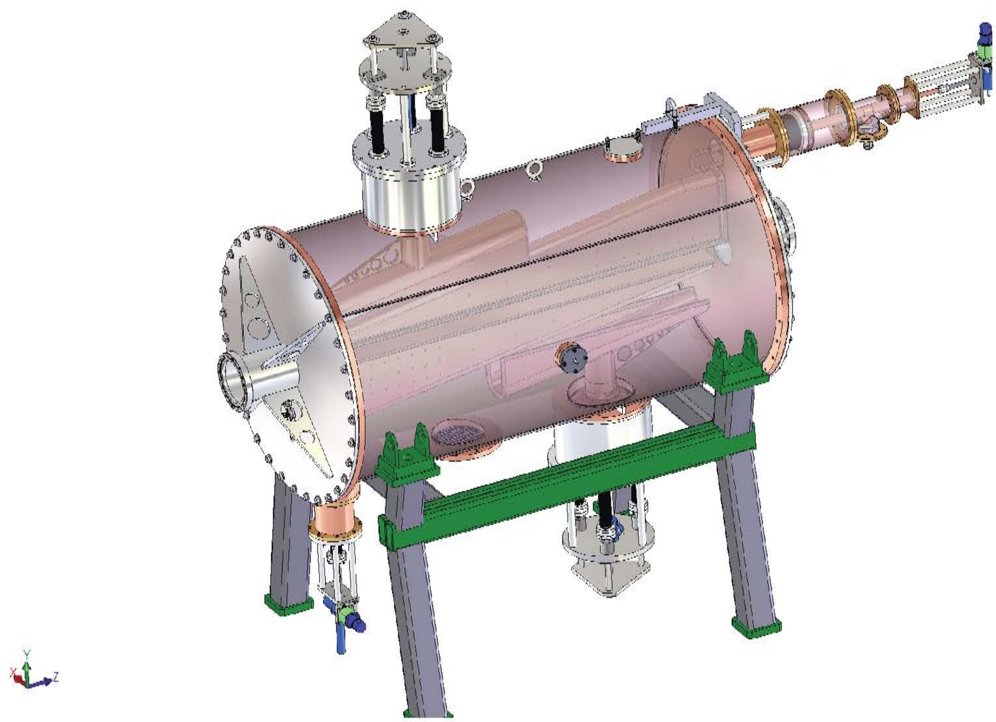


Figure 1
The RF Separator

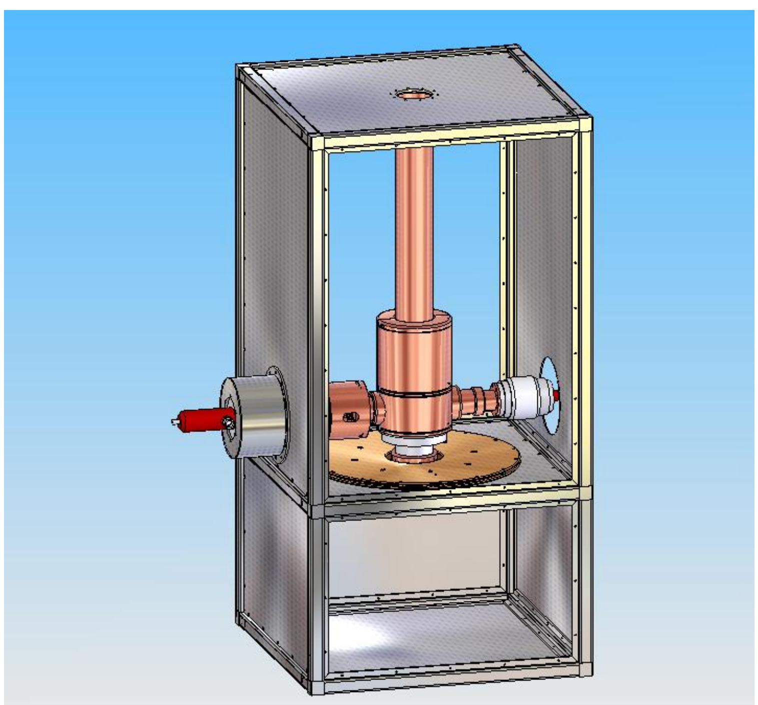
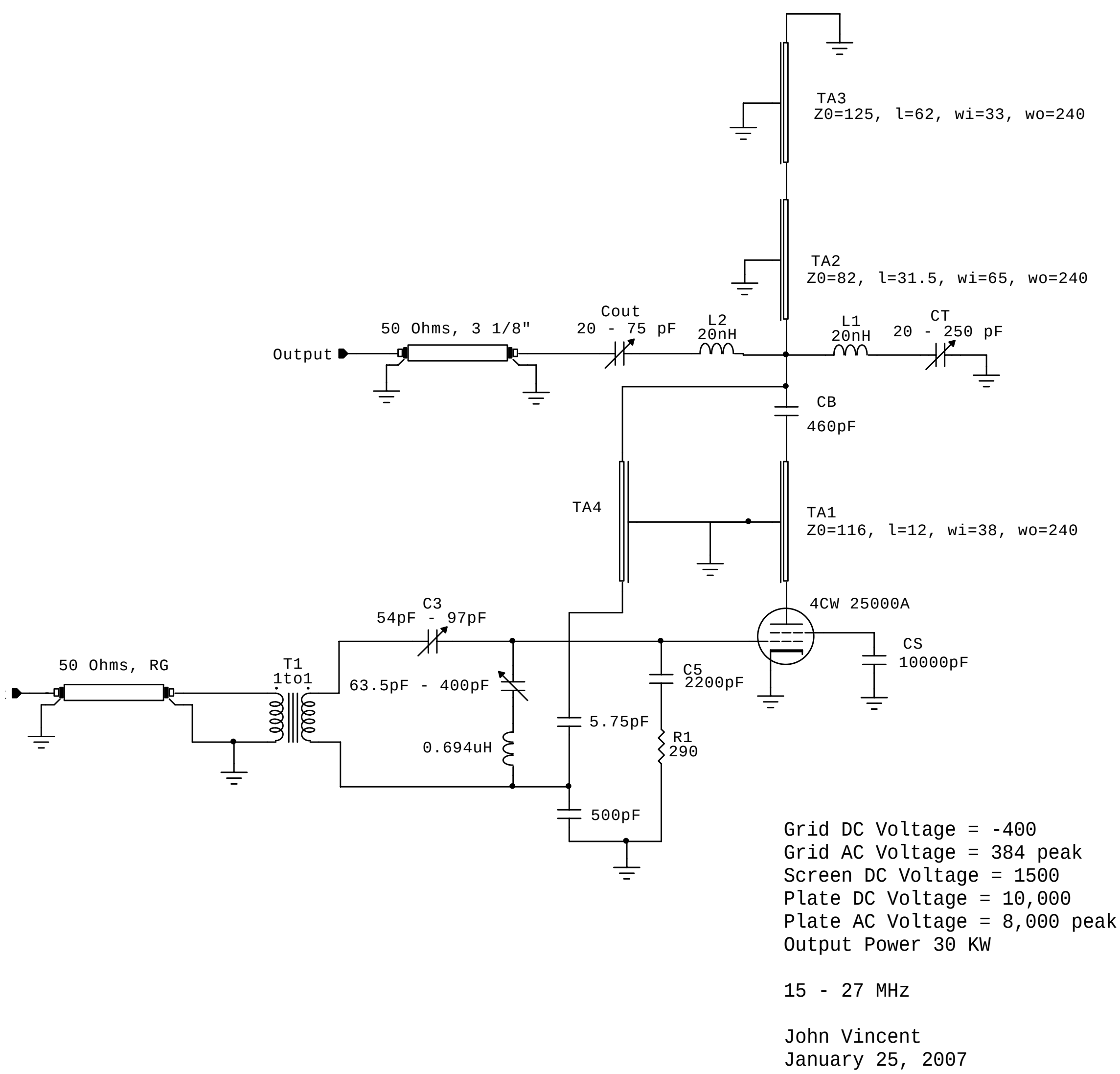


Figure 2
The RF Separator Amplifier

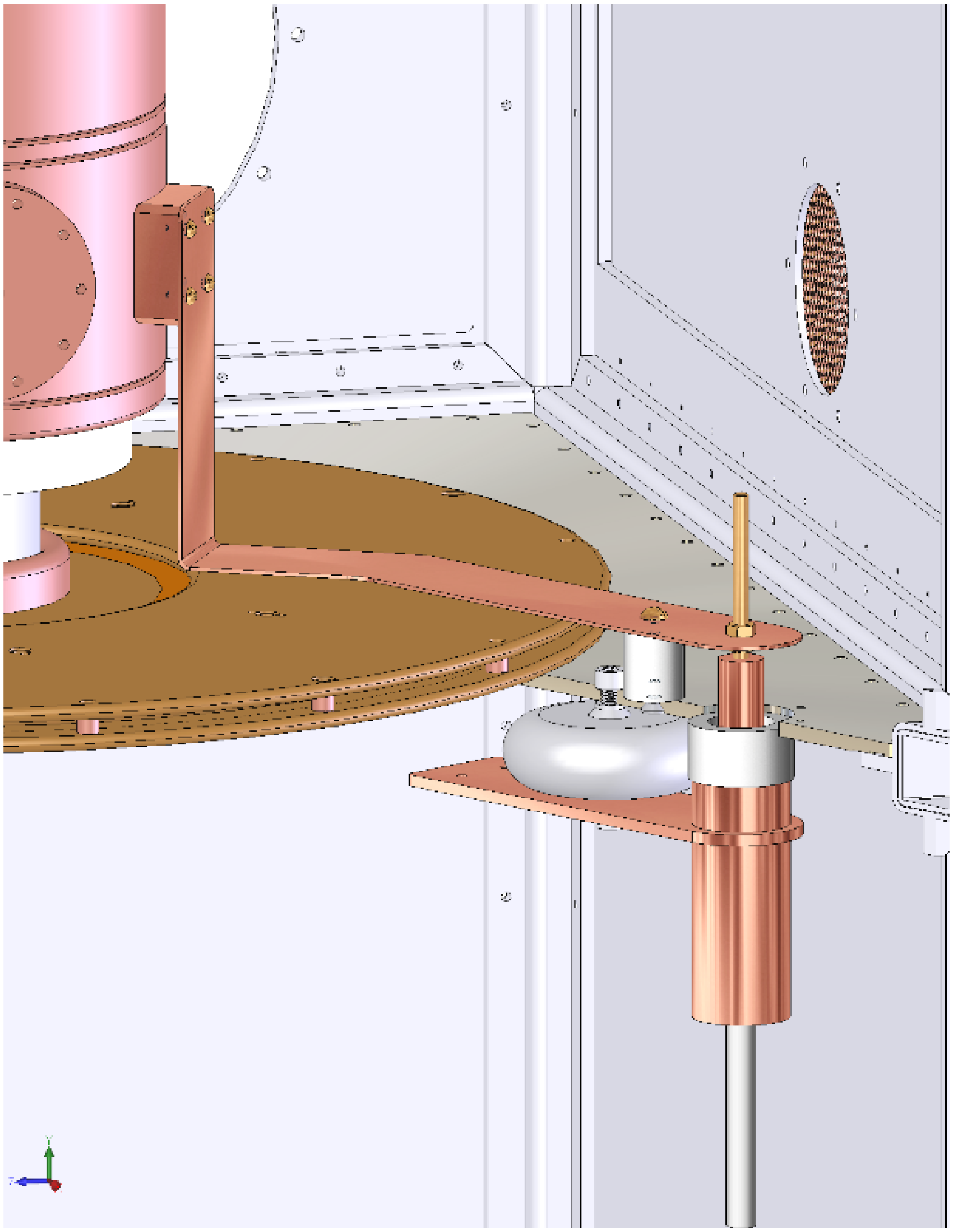
## *Schematic*

**Transmitter RF Schematic** (bias circuits not shown)

- The circuit consists of a tuned plate circuit, a tuned grid circuit, a bridge neutralizer circuit, and variable output coupling capacitance.
- The circuit input is designed to be driven from a 50 Ohm source and the output designed to drive a 50 Ohm load.
- Input power is < 300 Watts and output power is <= 30 KW.
- Tuning range is from 15MHz to 27MHz.




***The Amplifier Schematic***



***The Initial Neutralizing Circuit***

## *Plate Design and Operation*

- The plate resonant circuit consists of transmission line based inductance, a variable tuning capacitance, and a variable output coupling capacitor.
- The circuit is tuned by adjusting the output coupling capacitor to a specified value and then adjusting the variable tuning capacitor to peak the plate rf voltage. Once the control electronics place the system into voltage regulation mode "closed

loop", then the variable tuning capacitance is adjusted to minimize the plate bias current.

- The tuning circuit inductance consists of the anode box modeled as TA1, TA2, and TA3 in the schematic. The output coupling capacitance consists of Cout and its parasitic inductance L2. The tuning capacitor consists of CT and its parasitic inductance L1. CB is the plate dc blocking capacitor. C5 is the screen bypass capacitor. TA4 provides the connection to the neutralizing circuit. (now removed)
- The tuning capacitor is adjustable from 10 to 250pF. The output coupler is adjustable from 10 – 75pF. These elements also have stray capacitance to ground and stray series inductance. Measurements of the tube in socket plate capacitance indicate a net capacitance of 70pF. If the capacitance of the anode to its radial surroundings and the internal tube to screen capacitance is subtracted, the remaining stray capacitance to the socket and its ground place amounts to 34pF. This value (34pF) is added as a lumped element in parallel with the tube anode. The tube to screen capacitance is accounted for in the tube model, and the remaining radial effects are handled by the connecting transmission lines.
- The tube anode is biased at 10KVDC and the screen to 1500 VDC. To prevent significant screen dc current, the plate rf swing needs to be limited to less than 10KV – 1.5KV = 8.5KV peak. The plate circuit will be designed to deliver 30KW with a plate swing of 8KV peak. The effective plate resistance is then:

$$R_p = \frac{V_p^2}{2*P} = \frac{8000^2}{2*30{,}000} \cong 1075 Ohms$$

- The amplifier is design to drive a 50 Ohm load, so the 1075 Ohm plate source must be matched to drive a 50 Ohm load. This will be done via proper adjustment of the output coupling capacitor.

$$Q = \sqrt{\frac{Rp}{Zo} - 1} = \sqrt{\frac{1075}{50} - 1} = 4.53$$

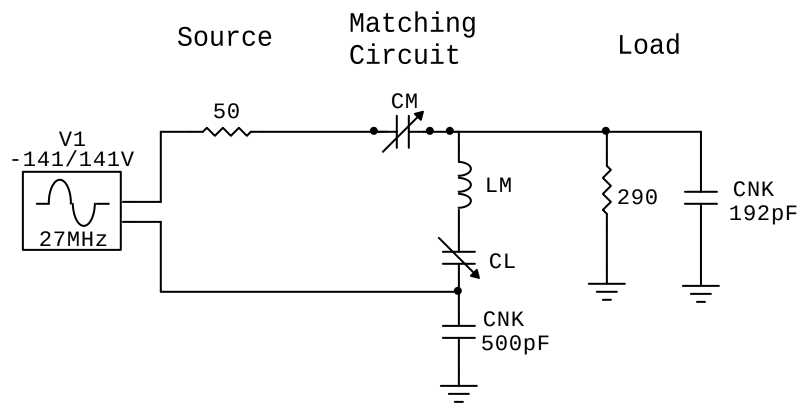
$$Cout = \frac{1}{Zo*Q*\omega} \; , \; Cout(15MHz) = 46.8\,pF \; , \; Cout(27MHz) = 26\,pF$$

- Cout varies from 46.8pF to 26pF as a function of frequency.
- The table of calculated values appears in the measurements section of this note.

## *Grid Design and Operation*

- The grid input power is set to 200 Watts through a combination of grid losses and an applied parallel resistor.
- Data sheet input capacitance is 160pF, we measured ~192pF in the socket.
- The input sees the 192pF capacitance is in series with the 500pF neutralizing capacitor to be described later in this note.

- Calculated peak drive voltage is 384 Volts grid to cathode.
- The smallest parallel resistor (assumes the grid is lossless) to dissipate 200 Watts is 290 Ohms
- Use the "High Pass Matching Circuit" to minimize components




- "LM" is the parallel combination of the needed matching circuit inductance and the inductance needed to resonate out the grid capacitance.
- Determine LM and CM for the high (28MHz) and low (15MHz) tuned frequencies to determine the minimum and maximum element values needed to cover the frequency range.

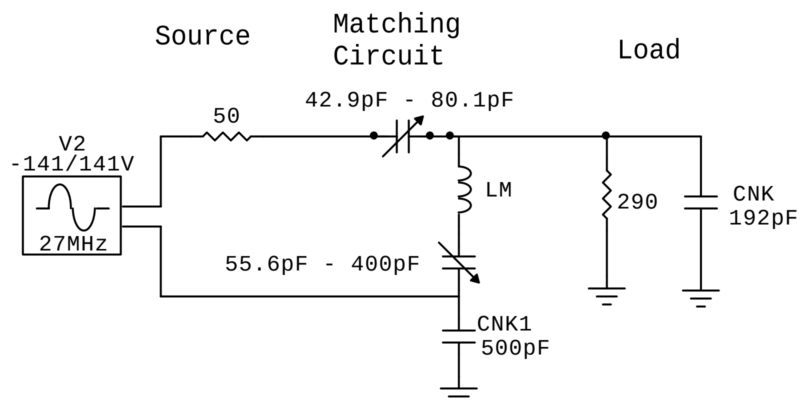
- Determine LM and CM for 28MHz.
  - Resonate-out the input capacitance:
    - $L = \frac{1}{\omega^2 CG} = \frac{1}{\left(2\pi \times 27 \times 10^6\right)^2 \left(139 \times 10^{-12}\right)} = 0.25\mu H$
  - Transform the grid resistance to the input
    - $R_p \cong \left(1 + \frac{CG}{CNK}\right)^2 R = \left(1 + \frac{192}{500}\right)^2 290 = 555$
  - Design the matching circuit:
    - $Q = \sqrt{\frac{R_p}{R_s} - 1} = \sqrt{\frac{555}{50} - 1} = 3.18$
    - $X_p = \frac{R_p}{Q} = \frac{555}{3.18} = 174.5 = \omega L_M^{'} \Rightarrow L_M^{'} = 0.992\mu H$

- $X_s = R_s Q = 50 * 3.18 = \frac{1}{\omega C_M} \Rightarrow C_M = 35.75 pF$
- Combine the resonance and matching functions
- $L_M = L_M^{'} \parallel L = \frac{0.992 * .25}{0.992 + .25} = 0.200 \mu H$

- Determine LM and CM for 15MHz.
  - $L = \frac{1}{\omega^2 CG} = \frac{1}{(2\pi \times 15 \times 10^6)^2 (139 \times 10^{-12})} = 0.807 \mu H$
    - $Q = \sqrt{\frac{R_p}{R_s} - 1} = \sqrt{\frac{555}{50} - 1} = 3.18$
    - $X_p = \frac{R_p}{Q} = \frac{555}{3.18} = 174.5 = \omega L_M^{'} \Rightarrow L_M^{'} = 1.85 \mu H$
    - $X_s = R_s Q = 50 * 3.18 = \frac{1}{\omega C_M} \Rightarrow C_M = 66.73 pF$
  - Combine the resonance and matching functions
    - $L_M = L_M^{'} \parallel L = \frac{1.85 * .807}{1.85 + .807} = 0.562 \mu H$
- Variable inductors are difficult to manufacture and are not as reliable as variable capacitors. A variable inductor may be designed as a combination of a variable capacitor in series with a fixed inductor.
- As determined previously, the effective inductance (LM) of the series circuit must vary from 0.200uH to 0.562uH and the variable capacitance (CM) must vary from 35.8pF to 66.7pF.
- The “effective” inductance of the series circuit of a capacitor (C) and an inductor (L) is:
  - $L_e = L - \frac{1}{\omega^2 C}$
  - At 15MHz, Let Le = 0.562uH when C=400pF
  - $L = L_e + \frac{1}{\omega^2 C} = 0.562 \times 10^{-6} + \frac{1}{(2\pi * 15 \times 10^6)^2 (400 \times 10^{-12})} = 0.843 \mu H$

- What is C at 27MHz?
  - $C = \frac{1}{\omega^2 (L - L_e)} = \frac{1}{\left(2\pi \times 27 \times 10^6\right)^2 \left(0.843 - 0.200\right) * 10^{-6}} = 54.0\,pF$
- A 10 to 500pF variable capacitor is available, so the circuit designed fits well within its range. A fixed inductance of 0.843uH in series with a variable capacitor that varies from 54.0pF to 400pF is used to produce the needed inductance of 0.200uH to 0.562uH.

- The electrical design of the input circuit without neutralizing is complete:

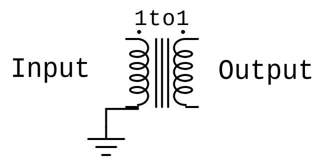



## Neutralizing and Input Transformer

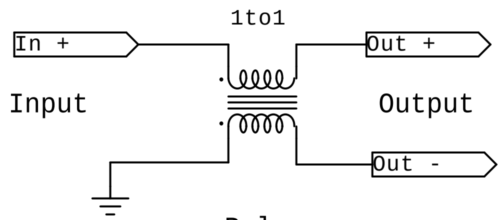
- The transformer design results in a F-240-67 toroidal core form CWS-ByteMark with 7 turns of 16 AWG wire with Teflon insulation. The primary and secondary windings are twisted together to create a low impedance (<120 Ohms) transmission line and minimize leakage inductance. Using two such transmission line windings in parallel on the same core creates a net < 60 Ohm impedance that is much closer to the ideal 50 Ohm impedance sought.
- The tube needs to be "neutralized" from the adverse effect of the internal plate-to-grid feedback capacitance. If the screen is not solidly grounded, then this effect is increased further. This capacitance either causes significantly increased drive power or causes the tube to self-excite at a slightly differently frequency then the driven frequency.
- The effective feedback capacitance is derived:
  - In the following equations, the subscripts stand for s: screen, g: grid, k: cathode, p: plate, and n: neutralize. For example Csg means capacitance between the screen and grid.

- $V_s \cong V_p \left( \dfrac{1}{1 + \dfrac{Cs}{Csp}} \right)$
- Where Cs is the applied screen to ground capacitor and Csp is the tube internal screen to plate capacitance.
- Using superposition:
- $V_g = \left( \dfrac{1}{1 + \dfrac{Csg + Cgk}{Cpg}} \right) V_p + \left( \dfrac{1}{1 + \dfrac{Cpg + Cgk}{Csg}} \right) V_s$
- Substituting and solving leaves:
- $\dfrac{V_g}{V_p} = \dfrac{Cpg + C_{sg}\left( \dfrac{Csp}{Csp + Cs} \right)}{Cpg + Csg + Cgk} = \dfrac{1.5 + 93\left( \dfrac{24.5}{24.5 + 10{,}000} \right)}{1.5 + 93 + 67} = 0.0107$
- $Cn = \dfrac{\dfrac{V_g}{V_p} Cnk}{1 - \dfrac{V_g}{V_p}} = \dfrac{0.0107 * 500}{1 - 0.0107} = 5.41 pF$

- A broadband bridge-circuit is designed to reduce this effect consisting of 5.41pF capacitor, a 500pF capacitor, and a transformer (T1) as shown in the circuit schematic. The divider circuit consisting of the 5.41pF capacitor feeding the 500pF capacitor to ground results in the same voltage from the plate appearing on the 500pF capacitor as appears on the tube input grid due to the internal feedback capacitance. When the grid resonant drive circuit is placed across the input grid to the 500pF capacitor, then the feedback voltage is cancelled out or "neutralized". The circuit requires the use of a rf transformer either acting as a isolation transformer or balun.




Isolation Transformer




Balun

- The balun is preferred since it tends to be more broadband and easier to match.
- The transformer will be designed to handle 300 Watts into 50 Ohms from 15MHz to 28MHz with a voltage regulation of better than 5%.
- The low frequency end is used to determine the winding inductance while the high frequency end is reduced by the leakage inductance. The winding inductance is calculated for the lowest frequency to be operated.
- Transmission line winding techniques are used to minimize the leakage inductance.
- A core material is chosen suitable for the frequency of operation and the core size to limit the cores loss density to <= 150 mW/cm^3
- A torroidal core was chosen available at CWS-Bytemark with part number F-240-67. This is a 2.4 inch OD, 1.4 inch ID, and 0.5 inch thick core using material 67. AL = 50 nH/(Sq N) for this core.

- MATERIAL 67 properties:
    - A high frequency NiZn ferrite for the design of broadband transformers, antennas, and high Q inductor applications up to 50 MHz.
    - Strong magnetic fields or excessive mechanical stresses may result in irreversible changes in permeability and losses.
    - Initial Permeability: µi = 40 @ B < 10 gauss
    - Flux Density: B = 2300 gauss @ Field Strength H = 20 oersted
    - Residual Flux Density: Br = 800 gauss
    - Coercive Force: Hc = 3.5 oersted
    - Loss Factor: tan δ/µi = 150 x 10-6@ Frequency = 50 MHz
    - Temperature Coefficient of Initial Permeability (20-70°C): 0.05 %/°C
    - Curie Temperature: Tc >475 °C
    - Resistivity: ρ = 1x107 Ω cm

- For good regulation and maximum bandwidth the winding inductance is designed to limit the voltage droop at the low frequency end to < 5% into a 50 Ohm load.

    - $L = \frac{R}{2\pi f}\sqrt{\frac{a}{1-a}}$ where $a = 1 - \frac{\%Z}{100}$

- The lowest frequency of operation is 15MHz, %Z = 5, and R = 50 Ohms.

- $L = \frac{50}{2\pi(15\times10^{6})}\sqrt{\frac{0.95}{1-0.95}} = 2.31\mu H$

- The number of turns needed to achieve this inductance on the chosen core is:
  - $N = \sqrt{\frac{L}{A_L}} = \sqrt{\frac{2310}{50}} \cong 7turns$

- The core loss density is:
  - $Q = \frac{1}{\tan\delta_e} = \frac{1}{40\times150\times10^{-6}} = 167$
  - $R = \frac{\omega L}{Q} = \frac{\left(2\pi\times27\times10^{6}\right)\left(2.31\times10^{-6}\right)}{167} = 2.34Ohms$
  - $W_{core} = W_{RF}\frac{R}{Z_o} = 300\frac{2.34}{50} = 14Watts$
  - $\frac{W_{core}}{cm^3} = \frac{W_{core}}{V} = \frac{W_{core}}{\pi\left(r_o^2 - r_i^2\right)\times H} = \frac{14}{\pi\left(36-12.67\right)\times1.27} = 150\frac{mW}{cm^3}$
  - The loss density indicates the core size is adequate

- The maximum current in the winding is 2.44 Arms for 300 Watts into 50 Ohms.

## *Measurements and tuning*

| Grid Circuit | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Calculated | | | | | | Measured | | | |
| Frequency (MHz) | In C (pF) | In C Turns | In C Dial | Tune C (pF) | Tune C Turns | Tune C Dial | In C Turns | In C (pF) | Tune C Turns | Tune C (pF) |
| 15 | 66.7 | 14.9 | 742.7 | 381.8 | 4.1 | 202.6 | 665 | 67.8 | 227 | 367.6 |
| 17 | 58.9 | 15.1 | 756.2 | 220.5 | 9.6 | 479.1 | 672 | 56.5 | 446 | 239.8 |
| 19 | 52.7 | 15.3 | 766.8 | 147.8 | 12.1 | 603.8 | 675 | 54.5 | 542 | 183.8 |
| 21 | 47.7 | 15.5 | 775.4 | 107.8 | 13.4 | 672.3 | 678 | 52.5 | 596 | 152.3 |
| 23 | 43.5 | 15.7 | 782.5 | 82.7 | 14.3 | 715.4 | 682 | 49.9 | 630 | 132.5 |
| 24 | | | | | | | 684 | 48.6 | 642 | 125.5 |
| 25 | 40.0 | 15.8 | 788.5 | 65.9 | 14.9 | 744.2 | 684 | 48.6 | 653 | 119.0 |
| 27 | | | | | | | 684 | 48.6 | 670 | 57.8 |

| Plate Circuit | | | | | | |
|---|---|---|---|---|---|---|
| | Calculated | | | | Measured | |
| Frequency (MHz) | Out C (pF) | Out C Turns | Out C Dial | Tune C (pF) | Tune C Turns | Tune C Dial |
| | | | | | | |
| 18.1 | 39.0 | 10.0 | 499.5 | 151.0 | 10.6 | 211.0 |
| | | | | | | |
| 19 | 37.0 | 10.6 | 527.8 | 134.6 | 12.3 | 246.0 |
| | | | | | | |
| 21 | 33.5 | 11.5 | 576.4 | 106.5 | 15.3 | 306.0 |
| | | | | | | |
| 23 | 30.6 | 12.3 | 616.7 | 82.1 | 17.9 | 358.0 |
| | | | | | | |
| 25 | 28.1 | 13.0 | 651.3 | 40.0 | 21.1 | 422.0 |
| | | | | | | |
| 27 | 26.0 | 13.6 | 680.2 | 25.0 | 28.4 | 567.0 |

## *Concluding Comments*

The amplifier works as intended, but like most rf circuits, required some minor field modifications. The main stem, denoted as TA3 in the schematic, was shortened by 2” using a manual sliding short to match the required frequency range, and the neutralizer required minor modification to eliminate a high frequency mode. The circuit simulation and testing indicated the neutralizing capacitance value needed was 1/10$^{th}$ of the amount calculated. Since this effect shows up in the simulation it is clearly a calculation problem that is not yet understood. Additionally, during initial testing we found the neutralizing caused a parasitic mode at between 150 – 200 MHz. We removed the neutralizer transmission line as seen in the figure and denoted as “TA4” in the schematic and replaced the neutralizing capacitor with a 4” by 6” plate facing the anode. Since the RF Separator requires brief periods of conditioning due to multipactor resulting in a impedance mismatch, we also placed a load in parallel with the transmission line at the output of the transmitter. This load provides 1) a minimum load to the transmitter, 2) lowers the Q of the transmission line, and 3) a high frequency filter significantly dampening harmonic and other high frequency components. The minimum load circuit consists of a 50pF capacitor in series with a 50 Ohm load. Overall the amplifier is in normal service and is working well.