RF Power Amplifier (RFPA)
Designing a 'Output Tank Circuit'

By Larry E. Gugle K4RFE, RF Design, Manufacture, Test & Service Engineer (Retired)

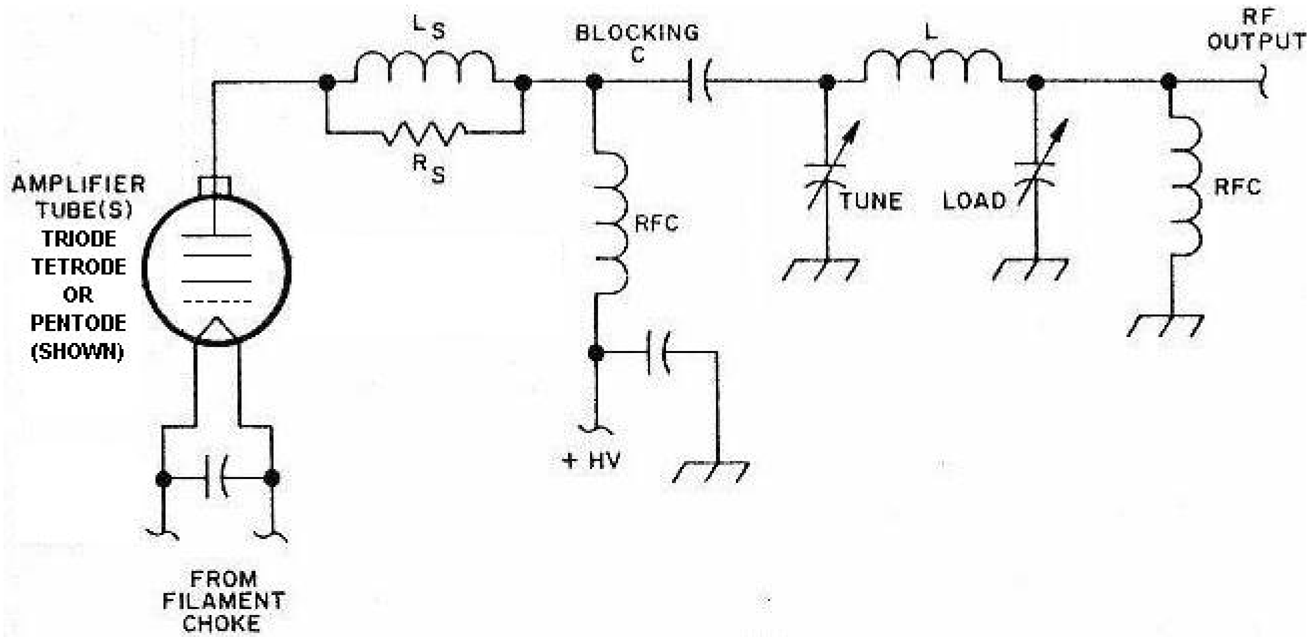

Figure-1 Output 'Tank' Circuit Network in Low-Pass Filter (LPF) 'Pi' Configuration

INTRODUCTION

1. When Alternating Current (AC) Signal Voltage is fed from the output of a Electron Tube RF Power Amplifier (RFPA), AC Impedance (electronic symbol 'Z') measured in Ohms (electronic symbol 'Ω') is the primary Characteristic, not the DC Resistance (electronic symbol 'R'), measured in Ohms (electronic symbol 'Ω) with a Volt/Ohm meter.
2. Alternating Current (AC) Impedance (Z), is made up of a combination of different Characteristic Values caused by the AC and all of the circuit Components which include:
    a. The Capacitive Reactance (electronic symbol 'Xc') of Capacitors ('C').
    b. The Inductive Reactance (electronic symbol 'X_L') of Inductors ('L').
    c. The Resistance (electronic symbol 'R') of Resistors ('R').
    d. The Frequency (electronic symbol 'F') of the Alternating Current (AC).

3. When any one of these Characteristic Values change, the value of the AC Impedance (Z) will also change.
4. Plate Tune and Load Coupling Networks, either in a ‘Pi’ or ‘Pi-L’ configuration, are designed so that a RF Power Amplifier (RFPA) provides Optimum Output Power with a minimum of Odd-Order Harmonic, Intermodulation Distortion (IMD) content.
5. To obtain high efficient operation from an Electron Tube RF Power Amplifier (RFPA), the RF Amplifying Device, either a Power Triode, Tetrode or Pentode, is normally operated in it’s Linear Region of Conduction Angle (Class ‘AB1’, 'AB2' or ‘B’) for Single Side Band Suppressed Carrier - Amplitude Modulation (SSBSC-AM) Telephony Signals and operated in it’s Non-Linear Region of Conduction Angle (Class ‘C’) for Interrupted Continuous Wave (CW) ‘On’ and ‘Off’ Keying Telegraphy, Frequency Modulation (FM) Telephony and Phase Modulation (PM) Telephony Signals.
6. In coupling a Electron Tube RF Power Amplifier (RFPA) to an Active Load (Active Antenna) or a Dummy Load (Dummy Antenna), presented at it’s output connection, by a 50 Ohm Characterisitc Impedance Coaxial Cable RF Feed Line, two requirements must be satisfied:

    a. First - **the correct Load Resistance (‘R_L‘) must be presented to the RF Power Amplifier (RFPA) output to enable it to deliver its rated output power.**
    b. Second - **the loaded Quality (‘Q’) factor must be carefully selected.**
    c. Plate Current does not conduct for the complete cycle period of the input RF Alternating Current (RFAC) Waveform and it is maintained by the inertia of the tuned coupling circuit. **The different Plate current (‘I_{An}’) conduction angles in degrees are:**
        i. **Linear Region** Conduction Angle
            1. Class ‘A’ (360 degrees)
            2. Class ‘B’ (180 degrees)
            3. Class ‘AB’ [greater than (>) 180 but less than (<) 360 degrees]
        ii. **Non-Linear Region** Conduction Angle
            1. Class ‘C’ [less than (<) 180 degrees]
        iii. Class ‘A’, ‘B’, ‘AB’, and ‘C’ is determined by the magnitude of Negative Control Grid Bias.
        iv. Too low a loaded ‘Q’ causes waveform distortion and increased generation of harmonics. As loaded ‘Q’ is increased, circulating current in the tank circuit is

also increased and if it is made too high, it will cause excessive ($I^2 \times R$) power loss in the circuit.

v. A loaded 'Q' of approximately '12' is considered optimum, although values between 4 and 20 might have to be tolerated over the tuning range of a multiband amplifier.

LOAD RESISTANCE ('R_L')

1. For an Electron Tube RF Power Amplifier (RFPA) operating at power levels suitable for use in the Amateur Radio Service, Load Resistances (R_L) in the region of 1000 to 7000 Ohms are typical. The required Load Resistance (R_L) is normally much higher than the Coaxial Cable Transmission Line Characteristic Impedance ('Z_O'), which is typically 50 Ohms.
2. The 'Pi' Output Coupling Network shown in Figure 1 is an ideal and suitable coupling system. To examine this network, we divide the network into two sections, shown in Figure 2, splitting the band inductor (L) into two parts, L1 and L2.

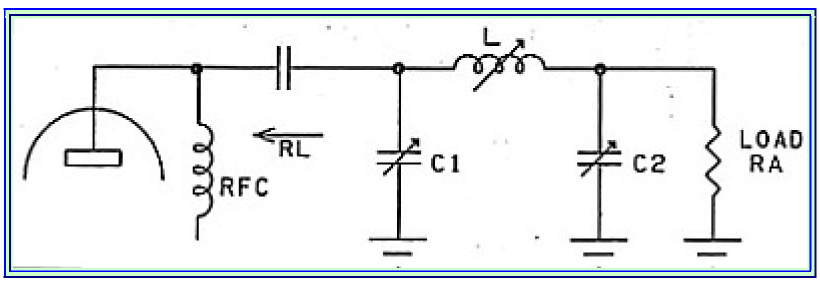

Figure 1: 'Pi' Output Coupling Network.

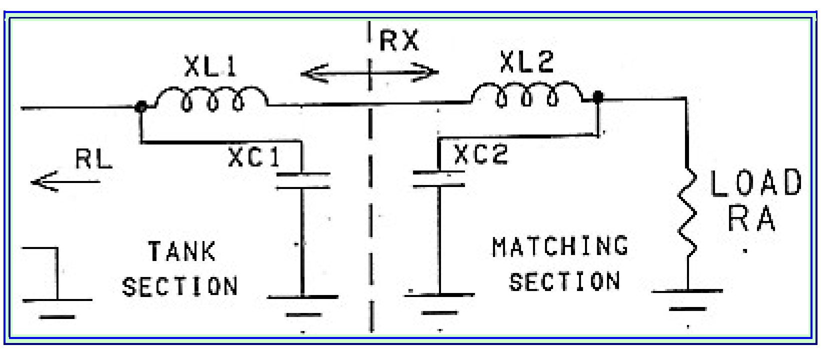

Figure 2: 'Pi' Output Coupling Network split into two sections for analysis.

3. Optimal Plate Load Resistance ('R_L') is equal to (=) the Direct Current (DC) Electro Motive Force ('EMF') of the Power Supply ('Ep') divided by (/) the conduction angle degree constant ('K') determined by class of amplification, times (x) the **average** Plate Current ('Ip') in Amperes. To approximate Plate Load Resistances ('R_L') for a Electron Tube RF Power Amplifier (RFPA), the **ARRL Handbook** and the **Radio Engineers Handbook** give the following formula:

$$R_L = Ep / (K \times Ip)$$

   a. R_L = Load Resistance.
   b. Ep = Direct Current (DC) Electro Motive Force (EMF) in Volts.
   c. K = Number Constant determined according to the conduction angle in degrees of the class of operation of the tube.
      1. **Class A Operation (K = 1.3 ~ 1.4): R_L = Ep / (1.3 ~ 1.4) x Ip**
      2. **Class AB Operation (K = 1.5 ~ 1.7): R_L = Ep / (1.5 ~ 1.7) x Ip**
      3. **Class B Operation (K = 1.8 ~ 1.9): R_L = Ep / (1.8 ~ 1.9) x Ip**
      4. **Class C Operation (K = 2.0): R_L = Ep / 2.0 x Ip**
   d. Ip = Plate Direct Current (DC) in Amperage.

4. The first section is considered to be the LC tank circuit, which sets the correct value of loaded 'Q'. To reflect the correct value of Load Resistance ('R_L') to the amplifier output, a resistance value of ('R_x') must be presented at the tank circuit output. The reactive components ('X_{L1}') and ('X_{C1}') and resistive component ('R_x') in the first section are calculated as follows:

$$X_{L1} = R_L / Q \text{ (using a optimum Q = 12)}$$

$$X_{C1} = X_{L1}$$

$$R_x = R_L / (Q^2 + 1)$$

5. The second section can be considered to be the LC tank circuit, which matches the value of ('R_x') which is normally lower than Coaxial Cable Feed Line 50 Ohm characteristic impedance ('R_a'). The reactive components ('X_{C2}') and ('X_{L2}') in the second section are calculated as follows:

$$X_{C2} = \sqrt{[(R_x \times R_a^2) \div (R_a - R_x)]}$$

$$X_{L2} = (X_{C2} \times R_a^2) \div (R_a^2 + X_{C2}^2)$$

6. Putting the two sections together, a single inductive reactance ('X_L') is formed by the sum is calculated as follows:

$$X_L = X_{L1} + X_{L2}$$

7. The components 'C1' (Plate Capacitor), 'L1' (Band Inductor), and 'C2' (Load Capacitor) are calculated from their reactances. Using the calculated plate load resistance ('R_L') we can figure the values needed for the coupling 'Pi' network C1, L1, and C2.
8. The output coupling Tank Circuit Quality ('Q'), the Capacitive Reactance ('X_{C1}') of the Plate 'Tune' Air Variable Capacitor ('C1') and the optimal Plate Load Resistance (R_L) for the different Electron Tube Operation Classes ('A', 'AB', 'B' or 'C') are interrelated.
9. The output coupling Tank Circuit Quality ('Q') is equal to (=) the Plate Load Resistance ('R_L') divided by (/) the Plate 'Tune' Air Variable Capacitor's ('C1') Capacitive Reactance ('X_{C1}').

$$Q = R_L / X_{C1}$$

10. Calculating the Plate Air Variable Capacitor ('C1'), For 1.8 MHz with a X_{C1} = 228 ohms would Be:
    a. $C1 = 1 / (2 \times Pi \times f \times X_{C1})$ = 1 / (2 x 3.14 x 1.8 MHz x 228 ohms) = 378pF
        1. C1 also includes the output Plate Capacitance ('Ca') of the Electron Tube and this must be subtracted from the total capacitance.
    b. C1 = C1 - Ca = 378pF - 10pF = 368pF
11. Calculating the Plate Air Variable Capacitor ('C1'), For 29.7 MHz with a X_{C1} = 228 ohms would be:
    a. $C1 = 1 / (2 \times Pi \times f \times X_{C1})$ = 1 / (2 x 3.14 x 29.7 MHz x 228 ohms) = 23.5 pF
        1. C1 also includes the output Plate Capacitance ('Ca') of the Electron Tube and this must be subtracted from the total capacitance.
    b. C1 = C1 - Ca = 23.5 pF -10pF = 13.5 pF

12. Calculating the Load Air Variable Capacitor ('C2'), For 1.8 MHz with a X_{C2} = 39 ohms would Be:
    a. $C2 = 1 / (2 \times Pi \times f \times X_{C2})$ = 1 / (2 x 3.14 x 1.8 MHz x 39 ohms) = 2268 pF
13. Calculating the Load Air Variable Capacitor ('C2'), For 29.7 MHz with a X_{C2} = 39 ohms would Be:
    a. $C2 = 1 / (2 \times Pi \times f \times X_{C2})$ = 1 / (2 x 3.14 x 29.7 MHz x 39 ohms) = 138pF
14. Calculating the Inductor ('L1'), For 1.8 MHz with a X_L = 252 ohms would be:
    a. $L1 = X_L / 2 \times Pi \times f$ = 252 / 2 x 3.14 x 1.8 MHz = 22 uH
15. Calculating the Inductor ('L1'), For 29.7 MHz with a X_L = 252 ohms would be:
    a. $L1 = X_L / 2 \times Pi \times f$ = 252 / 2 x 3.14 x 29.7 MHz = 1.35 uH
16. The Transmission RF Feedline Load has been considered as Resistive, however, the three components in the network are normally made adjustable and can be used to correct for reactances.

EFFICIENCY

1. Efficiency is a measure of how much of the DC Input Power from the Source Power Supply is usefully applied to the RF Power Amplifier (RFPA) Output Power. Plate efficiency is the ratio of the 'RF Output Power' to the 'DC Input Power' when the primary DC Input Power has been fed to the Plate of an Electron (Vacuum) Tube. A more efficient RF Power Amplifier (RFPA) runs cooler and often does not need any cooling fans even in a multi-kilowatt design. The reason for this is that the loss of efficiency produces heat as a by-product of the energy lost during the conversion of power.
    a. A Class 'A' RF Power Amplifier (RFPA commonly has a Low Efficiency, in the range of 20–30%, in radio frequency systems, with a maximum efficiency of 25% for direct coupling of the output. Inductive coupling of the output can raise their efficiency to a maximum of 50%.
    b. A Class 'AB' RF Power Amplifier (RFPA commonly has a Medium Efficiency of between 40-60%, in radio frequency systems.
    c. A Class 'B' RF Power Amplifier (RFPA commonly has a High Efficiency of 60-70%, in radio frequency systems, but are impractical for audio work because of high levels of distortion. In practical designs, the result of a tradeoff is the class AB design.

d. A Class 'C' RF Power Amplifier (RFPA commonly has a Very High Efficiency of 65-85%, in radio frequency systems.

e. Example design:

   i. When using 'one' (1) Electron Tube in single ended configuration, running in Class 'AB' conduction operation, the Plate will be required to dissipate approximately 20-40 percent (%) of the power consumed in the process of amplification.

      1. To the total power input (Pin) to the tube, use the following formula:

         a. Pin = Plate dissipation in watts / (40 / 100).

      2. To find the Plate amperage (Ip), use the following formula:

         a. Ip = Pin / E_{supply}

   ii. When using 'two' (2) Electron Tubes in parallel configuration, running in Class 'AB' conduction operation, the Plates will be required to dissipate approximately 20-40 percent (%) of the power consumed in the process of amplification.

      1. To find the total Power Input (Pin) to the tube, use the following formula:

         a. Pin = (Plate dissipation in watts / (40 / 100) x 2.

      2. To find the Plate Amperage (Ip), use the following formula:

         a. Ip = Pin / E_{supply}

      3. In virtually every instance, when using Two (2) Electron Tubes in parallel configuration:

         a. Load Resistance (R_L) will be cut in ½ half.

         b. DC Power Input (Pin) will double.

         c. RF Power output (Pout) will double.

         d. Plate idling current (Ip) will double.

A tuning method for 'Pi' Output Coupling Networks is suggested as follows:

1. Set the Inductor ('L1') near its desired value (set for a suitable loaded 'Q').
2. Set the Load Capacitor ('C2') at about two-thirds (2/3) of its' maximum capacitance value (capacitor stator and rotator plates 2/3 meshed, i.e. setting '3' of '0~10').

3. Resonate the Plate Tuning Capacitor (‘C1’) for maximum Output Power by alternatively rotating the capacitor clockwise and counterclockwise until the peak power is obtained.
4. Increase the Load Capacitor (‘C2’) gradually, by decreasing its’ capacitance value (un-mesh the capacitor stator and rotator plates), until the rated Output Power is reached. (For each change of Load Capacitor (‘C2’), reset resonance with Tuning Capacitor (‘C1’).

A Scematic Diagram of a ‘Pi-L’ Output Coupling Network

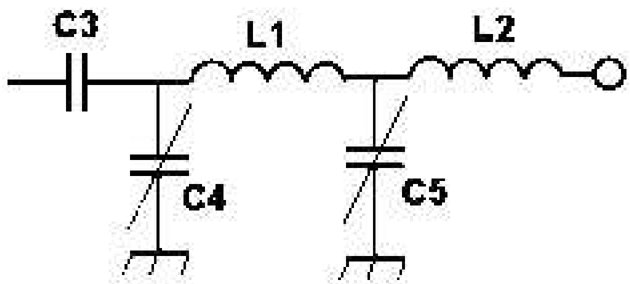

Figure 3, Pi-L Output Coupling Network

1. The advantage of using a Pi-L network output coupling as shown in figure 3 above, is that it has the ability to provide a greater transformation ratio (feed line impedance), and provide better harmonic suppression. Keep in mind; however, the voltage handling capacity of C5 (Load Capacitor) will be somewhat higher with the addition of L2. Consequently, a transmitting type Air Variable or Vacuum Variable Capacitor must be used for C5.