QCX 50W Amplifier Efficiency

Efficiency

First, what is efficiency as it pertains to electronic devices? Normally measured in percent, here is a simple equation for efficiency:

$$\text{Efficiency} = (\text{Useful power output} / \text{Total power input}) \times 100\%$$

When measuring the efficiency of an amplifier, usually only the power input to the amplifying devices (transistors or tubes/valves) is used for total input power. In other words, the efficiency of the power supply, the circuit driving the amplifying devices, and any circuit associated with the amplifier is ignored. Thus, an attempt is made to measure the DC voltage and current applied directly to the transistors when the amplifier is operating.

The output of an RF amplifier during an efficiency measurement is usually a constant sine wave into a purely resistive load of 50 or 75 ohms. For this analysis, the load is 50 ohms. The output power can be measured with an accurate power meter or by measuring the peak voltage with an oscilloscope or voltmeter. The equation for power when voltage and resistance are known is:

$$P = V^2/R$$

For true power, the voltage is the RMS (root mean square) voltage of the sine wave. The RMS value of a function is defined as:

$$f_{\mathrm{RMS}} = \lim_{T\to\infty} \sqrt{\frac{1}{T}\int_0^T [f(t)]^2\,dt}.$$

For a sine wave, this becomes: $V_{RMS} = V_{PK}/\sqrt{2}$

R for our analysis is 50 ohms. So, our equation for output power becomes:

$$P_{OUT} = V_{RMS}^2/50 = (V_{PK}/\sqrt{2})^2/50 = V_{PK}^2/100$$

Therefore, using the peak voltage of the output sine wave, our equation for efficiency is:

$$\text{Efficiency} = ((V_{PK}^2/100) / (V_{IN} \times I_{IN})) \times 100\%$$

Amplifier Classes

In the early days of RF amplifiers, amplifiers were divided into four classes: A, B, AB, and C (see Power-Amplifiers-Part-1). In recent years, a number of classes have been added, such as D, E, and F (see Power-Amplifiers-Part-2), which use switch-mode technology to improve efficiency. This analysis will focus on classes B and C.

The class of amplifier refers to the conduction angle over a cycle of the sine wave that the transistor is amplifying. The transistor in a class A amplifier conducts 360 degrees, class B amplifier about 180 degrees, class AB between 180 and 360 degrees, and class C less than 180 degrees. Class B amplifiers are usually used in a push-pull configuration, so the total conduction angle is about 360 degrees.

Traditionally, class C amplifiers were single-ended (single tube/valve) amplifiers that included a parallel resonant circuit, tuned to the transmit frequency.

The Circuit

The QRP Labs 50W Amp for the QCX incorporates two IRF510 FETs in a push-pull configuration with transformer coupling of the input and output stages. The output stage is a seven-element low-pass filter. A single DC voltage applies a positive bias to the gates of both transistors through a center-tapped transformer. The adjustment instruction states: "turn the R5 [gate bias adjustment] trimmer potentiometer very slightly clockwise … until you see the [amplifier] current consumption just rise … then turn it a tiny bit anticlockwise again to just put it back at" the original current.

Adjusting the bias at the point where the transistors are just off will cause the transistors to conduct alternately at or near 180 degrees, the definition of a class B amplifier. The theoretical maximum efficiency of a class B amplifier can be shown mathematically to be $\pi/4$ or 78.5%. However, there will likely be some dead time, when neither transistor will conduct. This small period of non-conductance is likely why the QCX 50W Amp is referred to as a class C amplifier. Nevertheless, even a class C amplifier conducting at 120 degrees has a maximum efficiency of about 80%. So, given the topology and bias of the QCX 50W Amp, we cannot expect to measure efficiencies greater than 80%.

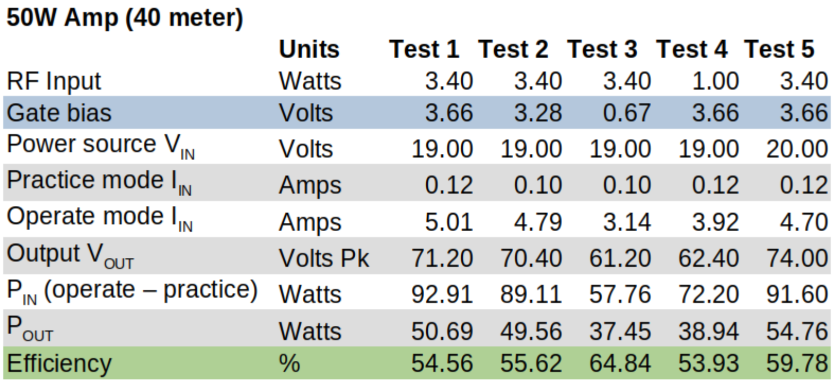
Efficiency Measurements

Although the maximum efficiency only increases 1.5% (78.5% to 80%) by reducing the conduction from 180 degrees to 120 degrees, it seems worth trying to increase the efficiency of the QCX 50W Amp by reducing the transistor bias. What follows are efficiency measurements under various conditions for the two 50W Amps that I have built, one for the 40 meter band and one for the 20 meter band, which work with my two QCX transceivers for the same bands.

The 40 meter test configuration consisted of a QCX-40 with 3.4W RF output operating at 7.020MHz driving a QCX 50W Amp constructed for 40 meters operating from a variable power supply adjusted at $19V_{DC}$. $19V_{DC}$ was required to obtain a 50W output. For Test 1, the bias of the 50W Amp was adjusted per the instructions (described above) in Rev-f of the manual. The input current was measured during the bias adjustment, while the QCX was keyed in practice-mode (no RF input to the 50W Amp). Then, the input current and output peak voltage were measured while the QCX was keyed in normal-mode. The current measured in practice-mode was current not used by the amplifying devices. Therefore, in the efficiency calculations, the current measured in practice-mode was subtracted from the current measured in normal-mode to approximate the current used by the two transistors.

Two methods for measuring the output power were compared. First, the output was connected to a QRP Labs 20W dummy load, and the peak voltage was measured with a Klein Tools MM200 DMM. Second, the output was connected to an MFJ-260C 300W dummy load, and the peak voltage was measured with a SIGLENT SDS 1052DL Digital Storage Scope. Both measurements were within 1% of each other. However, the peak voltage began to drop immediately after keying the QCX, which made consistent measurements difficult.

For Test 2, the bias was reduced by about 10%, and for Test 3, the bias was reduced to under 1V. For Test 4, the RF input was reduced to 1W. Test 5 was a test I performed several months prior to the other tests. The supply voltage was adjusted at $20V_{DC}$, which increased the output power above 50W. The results of these test can be found in the following spreadsheet, along with calculations for the efficiency. The bias voltage is highlighted in blue and the calculated efficiency in green.



50W Amp (40 meter)

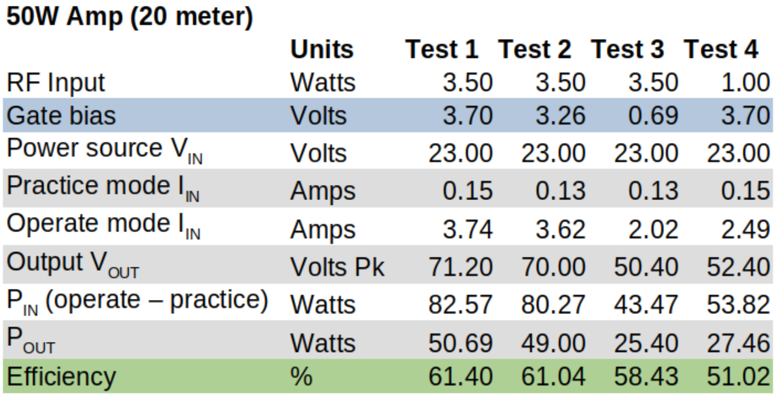
	Units	Test 1	Test 2	Test 3	Test 4	Test 5
RF Input	Watts	3.40	3.40	3.40	1.00	3.40
Gate bias	Volts	3.66	3.28	0.67	3.66	3.66
Power source V_{IN}	Volts	19.00	19.00	19.00	19.00	20.00
Practice mode I_{IN}	Amps	0.12	0.10	0.10	0.12	0.12
Operate mode I_{IN}	Amps	5.01	4.79	3.14	3.92	4.70
Output V_{OUT}	Volts Pk	71.20	70.40	61.20	62.40	74.00
P_{IN} (operate – practice)	Watts	92.91	89.11	57.76	72.20	91.60
P_{OUT}	Watts	50.69	49.56	37.45	38.94	54.76
Efficiency	%	54.56	55.62	64.84	53.93	59.78

Results of the 40 meter 50W Amp tests:

- Decreasing the bias (Tests 2 and 3) decreased the output power.
- Decreasing the bias (Tests 2 and 3) increased the efficiency.
- Decreasing the RF input (Test 4) decreased the efficiency.
- Increasing the supply voltage (Test 5) increased the efficiency.

Interestingly, with a bias of 0.67V (Test 3), the efficiency increased about 10% with a 13W drop in output power. In Test 4, the output power did not decrease proportional to the decrease in RF input, indicating that 3.4W RF input is more drive than necessary for 50W output. However, the efficiency decreased slightly, suggesting that over-driving the amplifier does not reduce the efficiency.

The 20 meter test configuration was the same, except that the RF output of the QCX-20 was slightly higher at 3.5W, the frequency was 14.020MHz, and the supply voltage had to be increased to $23V_{DC}$ for 50W output. The bias for Test 1 was adjusted per the manual, and the other tests were conducted similar to the 40 meter tests. The results can be found below.



50W Amp (20 meter)

	Units	Test 1	Test 2	Test 3	Test 4
RF Input	Watts	3.50	3.50	3.50	1.00
Gate bias	Volts	3.70	3.26	0.69	3.70
Power source V_{IN}	Volts	23.00	23.00	23.00	23.00
Practice mode I_{IN}	Amps	0.15	0.13	0.13	0.15
Operate mode I_{IN}	Amps	3.74	3.62	2.02	2.49
Output V_{OUT}	Volts Pk	71.20	70.00	50.40	52.40
P_{IN} (operate – practice)	Watts	82.57	80.27	43.47	53.82
P_{OUT}	Watts	50.69	49.00	25.40	27.46
Efficiency	%	61.40	61.04	58.43	51.02

Results of the 20 meter 50W Amp tests:

- Decreasing the bias (Tests 2 and 3) decreased the output power.
- Decreasing the bias (Tests 2 and 3) decreased the efficiency.
- Decreasing the RF input (Test 4) decreased the efficiency.

As with the 40 meter amplifier (Test 4), the output power did not decrease proportional to the decrease in RF input, indicating that 3.5W RF input is more drive than necessary for 50W output. Many of the results for the 20 meter 50W Amp are different from the 40 meter 50W Amp. The following is a comparison of the two 50W Amps:

- When adjusted per the manual, the gate bias voltage for both amplifiers was within 1% of each other.
- The efficiency of the 20 meter amplifier was about 7% higher than the 40 meter amplifier at 50W. However, when the 40 meter supply voltage was increased slightly, the efficiencies were within 2% (although the output power also increased).
- The output power of both amplifiers decreased with a decrease of bias voltage.
- The efficiency of the 40 meter amplifier increased as the bias voltage was decreased, while the 20 meter amplifier efficiency decreased.
- The efficiency of both amplifiers decreased with a decrease of RF input.
- Decreasing the bias voltage below 1V on the 20 meter amplifier, decreased the output power nearly twice as much as the 40 meter amplifier.

Conclusions

The efficiency of the 40 meter amplifier did increase with a decrease of the bias voltage. However, the initial efficiency was significantly lower than the 20 meter amplifier, and an increase in supply voltage also increased the efficiency.

It may be possible to optimize the efficiency of these 50W Amps by adjusting the RF input, bias voltage, and supply voltage. However, I did not have a means of continuously adjusting the RF input. I used a fixed 13.8V_{DC} power supply for 3.4W/3.5W RF input and a fixed 8V_{DC} power supply for 1W RF input. My variable power supply was used for the 50W Amp. A second variable power supply for the QCX or an adjustable attenuator would be needed to conduct tests varying the RF input.

Taking into consideration switching, transformer, and low-pass filter losses, it is unlikely that efficiencies greater than 70% can be achieved with this low cost amplifier. However, even at 60% efficiency, the power loss is only 33W or 21W short of the ideal 80% efficiency.

Most of the lost power is dissipated in the transistors. If we assume 60% efficiency and about 90% or 30W of the loss is dissipated in the transistors, each transistor will dissipate 15W when the amplifier is keyed. This is well within the IRF510 rated Maximum Power Dissipation of 43W. Also, the peak voltage and peak current are within the specifications derated per the IBM Component Derating Guidelines. Therefore, the area of greatest concern is the temperature rise and the junction temperature specification, which is 175°C, but should be derated by 50°C.

The thermal resistance from junction to heatsink for the IRF510 is 4°C/W, which will result in the junction temperature rising 60°C above the heatsink with 15W dissipated in the transistor. Therefore, the heatsink should not be allowed to rise above 65°C (175°C – 50°C – 60°C). Actually, the heatsink should be limited to about 95°C because the amplifier is used for CW, which has a duty cycle of about 50%, resulting in a temperature rise of only 30°C (7.5W per transistor). Even at a room temperature of 35°C (95°F), the heatsink can be allowed to rise 60°C (140°F) above the ambient temperature.

One concern with reducing the gate bias is that shortening the conduction angle of the transistors will increases distortion of the sine wave output. Although the low-pass filter in the output reduces the level of harmonics, reducing the conduction angle may increase the harmonics produced by the amplifier to an unacceptable level. Unfortunately, I did not have access to a spectrum analyzer to measure the level of the harmonics at the output of the QCX 50W Amp.