The Handiman's Guide to
MOSFET "Switched Mode" Amplifiers

Part 1
Introduction to Class C,D,E and F

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Part 1 is a tutorial for using switching MOSFET's for QRP power amplifiers. Beginning with the standard Class C power amplifier, special emphasis is given to the Class D, E and F high efficiency modes.

Meet the MOSFET

MOSFET's have been used for years in QRP transmitters, but with an apparent level of mysticism as to how they really work. There are two main types of mosfet's: the linear RF mosfets, such as Motorola's "RF Line," and the more common switching mosfets. The **RF mosfets** are excellent, reliable devices for up to 30MHz, and some VHF versions. However, they cost $25–35 each or more, and beyond the budgets of most amateurs. **Switching mosfets** are far more common, such as the IRF510, available at hobby vendors and Radio Shack for about $1. These cheap switching mosfet's are the ones used in most home brew QRP transmitters, and the ones upon which this article focuses.

As the name implies, this family of mosfet's are designed to be *switches* -- that is, to primarily turn current on or off, just like a switch or relay. They are not perfect. Between the OFF and ON states, there is a linear region. Compared to standard bipolar transistors, mosfets have a narrower linear region. IRF510s, used for QRP Class C PA's, attempt to bias for this more restrictive linear region. However, if the device is accidentally driven into saturation, it causes excessive drain current and heating of the mosfet – and often failure. If you haven't blown up an IRF510 yet – you just haven't worked very hard at it !

The IRF series of switching mosfets were developed by International Rectifier. They make the "dies" for these mosfet's, marketing them under their own name (logo "I-R"), or selling the dies to other manufacturer's, such as Motorola and Harris, who merely adds the TO-220 packaging. Thus, no matter where you get your IRF510, you are getting the same device and can be assured of consistent operation.

The exception to this are some IRF510s sold by Radio Shack. Some are manufactured in Haiti that may or may not meet specs for maximum drain current, or at what gate voltage the device turns on and reaches saturation. To avoid legal problems with I-R, Radio Shack packages these mosfet "clones" under the part number IFR510 (not IRF510). An unrecognizable logo indicates a device manufactured off-shore.

Most power mosfets are made by stacking several dies in parallel to handle higher currents. The disadvantage is the capacitances add in parallel, which is why power mosfets have large input and output capacitances over single die devices. Mosfets made by vertically stacking the dies are called VMOS, TMOS, HexFets and other such names.

According to the I-R applications engineer, the IRF510 is their most widely sold mosfet. This is because it was developed by I-R in the 1970's for the automotive industry as turn-signal blinkers and headlight dimmers to replace the expensive electro-mechanical switches and relays. The good news is, this implies they will not be going away any time soon. In talking to International Rectifier, they were floored to find out QRPers were using them at 7MHz or higher. I faxed them some QRP circuits to prove it. Quite a difference compared to the 1Hz blink of a turn signal, or the 50kHz rate of a switching power supply!

BJT's vs. MOSFET's

Bipolar junction transistors (BJT) are forward biased with a base voltage about 0.7v (0.6v on most power transistors). Below 0.7v, the transistor is in *cut-off*: no collector current is flowing. Above 0.7v, collector current begins to flow. As you increase the base voltage (which is actually increasing base current), it produces an increase in collector current. This is the *linear region* – converting a small change on the base to a much larger change on the collector. This defines amplification. As you continue to increase the base voltage further, a point will be reached where no further increase in collector current will occur. This is the point of *saturation*, and the point of maximum collector current. The base voltage required to saturate the transistor varies from device to device, but typically falls in the 8v range for most power transistors used for QRP PA's. This is, actually, a fairly large dynamic range. A graph showing these regions is called the "transfer characteristics" of a device, as illustrated in **Fig. 1A**, showing a sample Class C input and output signal. Self-biasing is assumed, that is, the input signal is capacitively coupled to the base with no external (0v) bias.

MOSFETs work in a very similar manner, except the gate voltages that defines cut-off, the linear region, and saturation are different than BJT's. While it takes about 0.7v to turn on a BJT, it takes about 4v to turn on an IRF510 mosfet. The voltage required to cause drain current to start flowing is
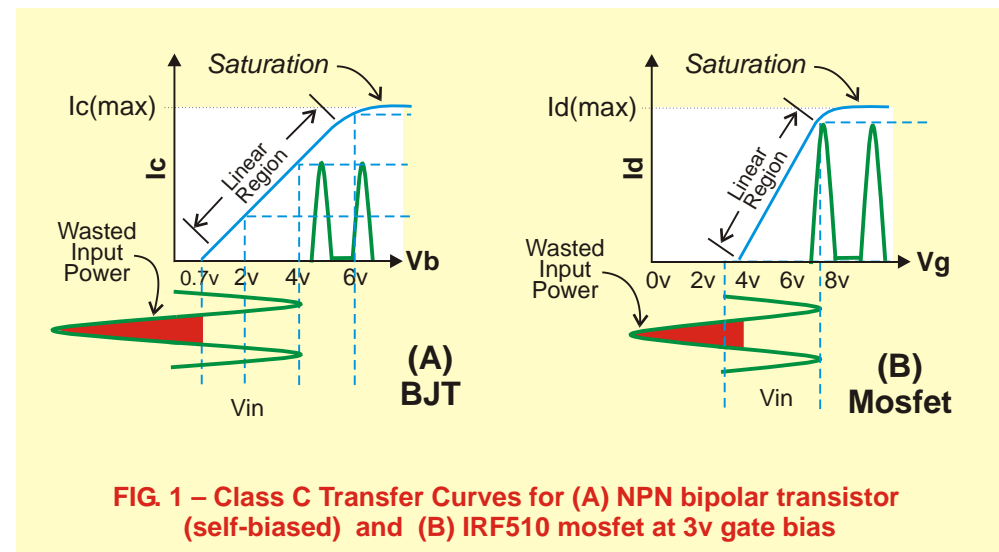

FIG. 1 – Class C Transfer Curves for (A) NPN bipolar transistor (self-biased) and (B) IRF510 mosfet at 3v gate bias

called the *gate threshold voltage*, or Vgs(th). From the IRF510 data sheet, the Vgs(th) is specified at 3.0v minimum to over 4.0v maximum. This large range is typical of mosfets, whose parameters tend to be quite sloppy compared to BJT's – something to always keep in mind. My experience shows the Vgs(th) of the IRF510 is more in the 3.7-4.0v range and goes into full saturation with about 8v on the gate. This defines a smaller dynamic range (4v–8v) for the linear region than a BJT (0.7v–8v).

The transfer characteristics of a typical IRF510 is shown in **Fig. 1B**. The gate is externally biased at 3v (no-signal) and the input signal is limited to no more than 7v on the peaks to avoid the saturation region. Note that the scaling between the BJT and mosfet transfer curves are different.

Class C PA with a BJT

Figure 2 is a schematic of a typical low power QRP transmitter PA using an NPN power transistor. RF input from the driver stage is stepped-down through T1 to match the very low input impedance of Q1, typically 10W or less.

The low output impedance (12–14W at 5W) is converted to about 50W by the 1:4 step-up transformer T2. This circuit is the common *self-biasing* circuit -- there is no external dc biasing applied to the base, such that the signal voltage alone forward biases the transistor. Referring back to **Fig. 1A**, the shaded area of the input signal shows the power that is wasted in a typical Class C PA using self-biasing. This is power from the driver that *is not being used to produce output power*. This is an inherent short coming of the Class B and C amplifiers.

Class C PA with a MOSFET (IRF510)

The circuit of a typical mosfet **Class C** PA is shown in **Figure 3**. It appears very similar to the BJT circuit in **Fig. 2** in most regards. The RF input signal from the driver stage can be capacitively coupled, as shown, or transformer coupled. Capacitive coupling is easier for applying the external biasing. Since the Vgs(th) of an IRF510 is about 3.5–4.0v, setting of the gate bias, via RV1, should initially be set to about 3v to ensure there is *no drain current with no input signal*. R1 is chosen to simply limit RV1 from accidently exceeding 8v on the gate, which would cause maximum drain current to flow and certain destruction after 10–15 seconds. The input RF applied to the gate (during transmit) should likewise never be allowed to exceed about 7–7.5v, just shy of the saturation region. As illustrated, the input signal is 8Vpp, or –4v to +4v after C1, and after the +3v biasing, from –1v to +7v. *This ensures the IRF510 is operating within it's safe operating area* for a Class C amplifier. Like the BJT Class C PA, the input signal from +4v to –1v is wasted power, not being converted to output power.

For a typical Class C PA operating at around 50% efficiency, about 850mA of drain current will be required to produce 5W output. It is wise to monitor the drain current to ensure excessive current is not being drawn, indicating the RF input peaks are not approaching the saturation region of the device, or the static gate voltage from RV1 is set too high. This is extremely important to preserve your IRF510 longer than a few moments!
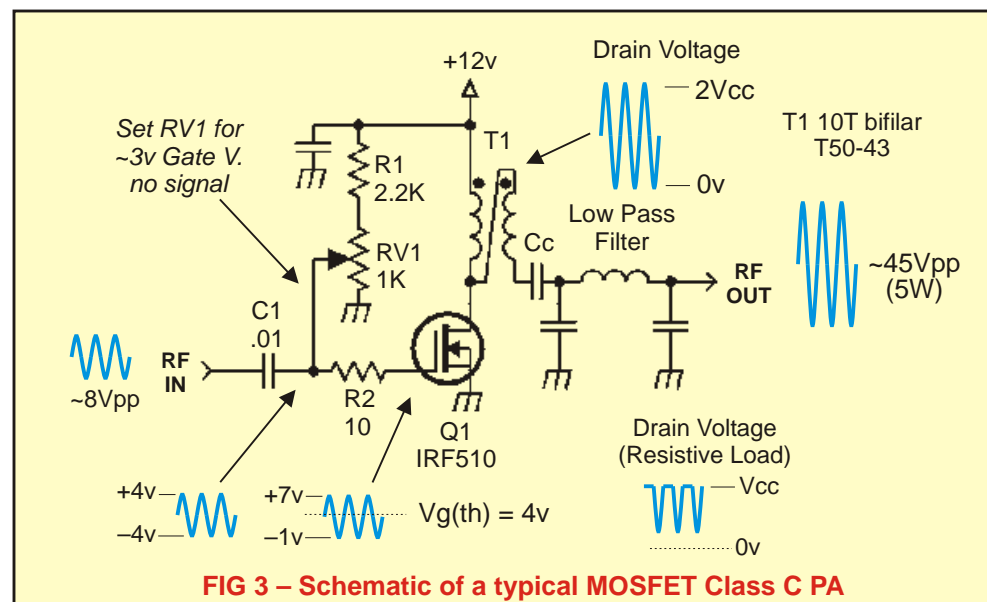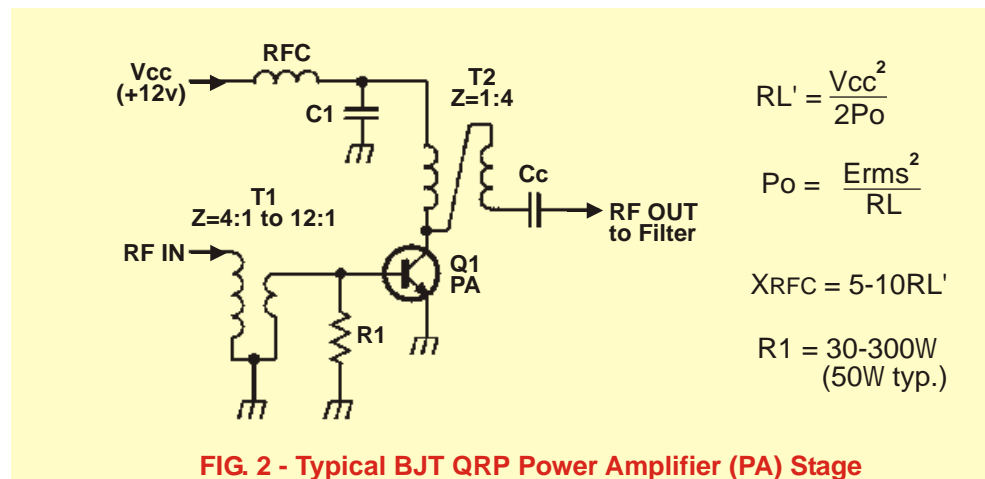
Drain current will only flow when the gate voltage exceeds the Vgs(th) of the device. With a resistive drain load, this translates into +12v of drain voltage when no current is flowing, then dropping towards 0v as drain current flows, as shown in **Fig. 3**. However, with the inductive load of T1, the voltage swing will be 2Vcc (24v) as expected. This is due to the current stored in the inductance of T1 being dumped into the load (low pass filter) when drain current from the IRF510 stops, and is stepped up further, by a factor of two, to about 48Vpp, by the bifilar windings on T1. Some loss through the low pass filter yields about 45Vpp for 5W output.

Once the circuit is working properly, RV1 can be carefully adjusted to produce more power, again carefully monitoring for <1A of current flow. This is much easier to do with an oscilloscope, to ensure that the gate voltage never approaches the 7.5–8v saturation region on the RF peaks, and for a fairly clean sinewave entering the low pass filter.

Evaluating Class C MOSFET Efficiency

A well biased IRF510 PA can be a bit more efficient than a BJT circuit, primarily because it takes less peak-peak input signal to produce 5W, and thus less driver power is needed. Since the slope of the linear region is steeper than a BJT, the IRF510 actually has more potential gain.

$$RL' = \frac{Vcc^2}{2Po}$$

$$Po = \frac{Erms^2}{RL}$$

$$X_{RFC} = 5\text{-}10 RL'$$

R1 = 30-300W
(50W typ.)

FIG. 2 - Typical BJT QRP Power Amplifier (PA) Stage

FIG 3 – Schematic of a typical MOSFET Class C PA

The largest contributors to power losses, and hence poor efficiency with switching mosfets, are the very large values of input and output capacitances compared to a BJT.

Remember how you've always heard the input impedance of a mosfet is very high, in the megohms? Well, forget you ever heard that! That is the *DC input resistance* of the gate with *no drain current flowing*. The AC input impedance is the Xc of Cin (about 120–180pF) or 130W at 40M (7 MHz). This means your driver stage must be able to provide an 8Vpp signal into a 130W load, or about *a half watt of drive*.

On the output side, the large output capacitance, *Cout*, is like having a 120pF capacitor from the drain to ground. This absorbs a fair amount of power being generated by the mosfet. But there is nothing you can do about that (at least in Class C).

The other large contributor to reducing efficiency is the power lost across the drain-source junction. This is true as well across the collector-emitter junction in a BJT. Power is E times I. The power being dissipated across the drain-source junction is the drain voltage (Vd) times the drain current (Id). When no drain current is flowing, there is no power being dissipated across the device, since +12v Vd times zero is zero. But for the rest of the sinewave, you have instantaneous products of Vd times Id. Looking at the mosfet again as a switch, this is known as the *transition loss,* as drain current is transitioning from it's OFF state (Id=0), through the linear region, to the ON state (Vd=0). Of course with Class C, you are in the transition loss region at all times while drain current is flowing. Again, there is little you can do about this loss in Class C amplifiers.

Improving Efficiency (Introduction to Class D/E/F)

From the above, it appears there are three major sources of power loss, leading to poor amplifier efficiency:

1) Transition (switching) losses (Vd x Id products)

2) Large internal gate input capacitance (~120-180pF for the IRF510)

3) Large internal drain-source capacitance (~ 120pF for the IRF510)

If these losses could be largely overcome, then the amplifier's efficiency could be greatly improved.

In class D/E/F, the mosfet is intentionally driven into saturation using a square wave. This drives the mosfet from OFF (Id=0), to fully ON (Vd=0) as quick as possible. The square wave input will have to go to >+8v to ensure saturation.

This purposely avoids the linear region, operating the device only as a switch. For this reason, Class D, E and F amplifiers are often called *switched mode amplifiers*, not linear amplifiers, as in Class A, B or C.

The transfer curves of a Class C vs. Class D/E/F PA with a square wave drive is shown in **Fig. 4**. The gate is biased at 3v in both cases, and Vgs(th) is 4v. The amount of wasted input power is greatly reduced with the square wave drive. The output will have a slope on the rising and falling edges, due to the short time drain current must travel through the linear region. Still, the ON–OFF switching action of these modes is evident.

A square wave is an infinite combination of odd harmonics. The square wave output must be converted back into a sine wave by removing the harmonic energy before being sent to the antenna
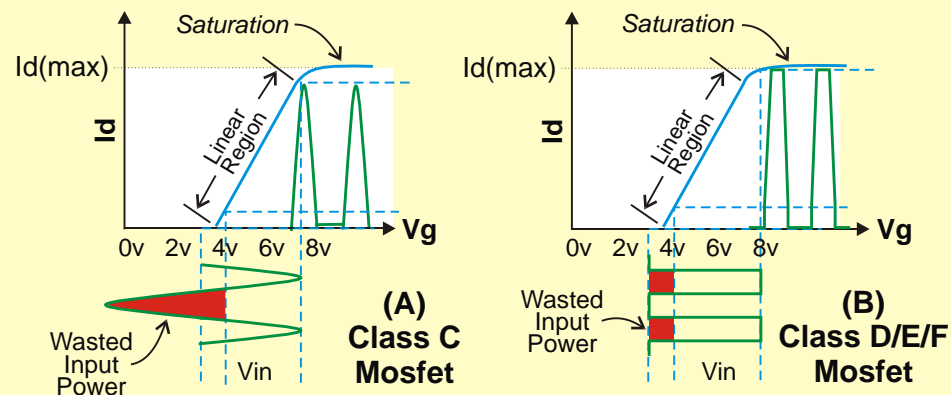

FIG. 4 – IRF510 Transfer Curves for (A) Class C Sine Wave Drive and (B) Class D/E/F Square Wave Drive

for FCC compliance. *The method by which the fundamental frequency is recovered from the square wave output determines whether it is Class D, E or F.* In all cases, it is based on driving the mosfet with a square wave input.

Legally, you can drive a mosfet into saturation with a huge sine wave as well, as many Class D/E circuits on the internet or ham radio publications are based. However, you are in the saturation region for a relatively short period of time (only during the positive input peaks), the rest of the time in the linear region. It is this authors opinion that the first step to increasing efficiency is avoiding the lossy linear region. This is defeated with a sine wave drive.

Therefore, the remaining discussion on Class D, E and F amplifiers are based strictly on a square wave drive.

It is worth mentioning an important distinction between the classes of amplifier operation. With *linear amplifiers*, the class of operation is based on the amount of time that collector or drain current flows: 100% for Class A, >50% for Class B, and

<50% for Class C. However, the amount of time drain current flows in a *switched mode amplifier* has nothing to do with it's class of operation. It is based entirely on how the output power is transfered to the load and how harmonic power is removed.

CLASS D QRP PA

One implementation of a **Class D** QRP transmitter is shown in **Figure 5**. Note that there is little difference between the Class D PA, and the Class C mosfet PA shown in **Fig. 3**, other than being driven with a square wave and into saturation. One advantage of a square wave drive is it can be generated or buffered with TTL or CMOS logic components, making a 0v to 5v TTL signal, as shown. RV1 is again set for about 3v, which now corresponds to the 0v portion of the square wave, elevating the ON or HI portion of the square wave to +8v (+5V TTL + 3v bias), the minimum gate voltage to slam the mosfet into saturation. This is verified with an oscilloscope by monitoring the drain voltage, and noting that it falls nearly to 0v. A good IRF510 in saturation should drop to <0.4v.
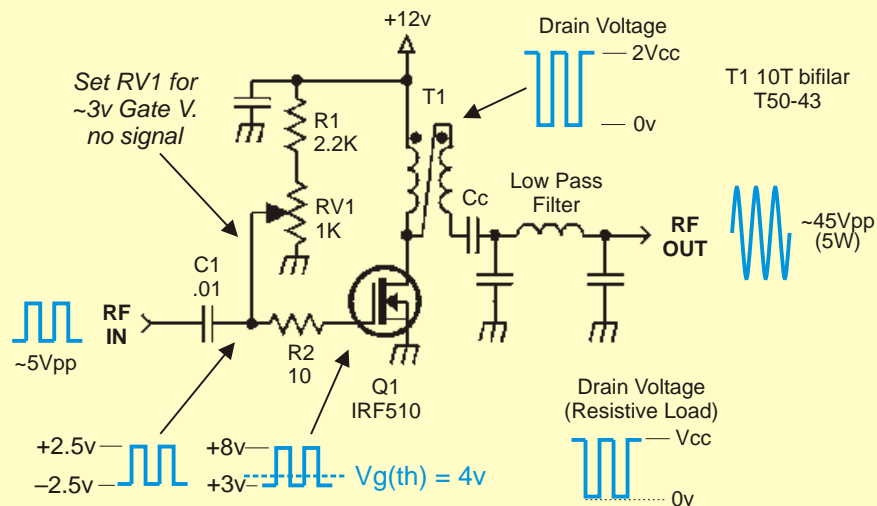
FIG 5 – Schematic of a typical MOSFET Class D PA

FIG 6 – Schematic of a typical MOSFET Class E PA

Cout = Cds drain-source capacitance

FIG. 7 – Class E PA Parallel Equivalent Circuit

Speaking of oscilloscopes, having one is virtually required to properly build and tune Class D, E or F amplifiers. One must be able to see what the waveforms look like, the voltages, and the timing (or phase) relationships to ensure the amplifier is operating properly.

The output circuitry is also identical to the linear Class C amplifier of **Fig. 3**, impedance converted through T1, followed by a traditional reciprocal (50W in – 50W out) low pass filter. Input resistor R2 is a low value resistor, 3.9W to 10W, to dampen the input Q a bit and prevent VHF oscillations. The value is not critical. A ferrite bead could be used as well (but a small value resistor more available).

Controlling the Output Power of the PA

Note that the input signal, as shown in **Fig. 4**, depicts a square wave with a 50% duty cycle. One of the beauties of switched mode amplifiers is the ability to change the output power by changing the duty cycle of the input square wave.

Remember that with an IRF510 in saturation, you are drawing the maximum rated drain current, about 4A. This, of course, is way too much current to draw for any length of time. With the circuit shown, 5W is produced with about a 30% duty cycle, drawing about 800mA of total transmit current (including driver stages) for an overall efficiency of ~70%. You are "pulsing" the 4A ON and OFF to produce an *average* desired current, and hence output power. The shorter period of time the mosfet is ON, the lower the average power.

Final thoughts on Class D

Class D amplifiers were initially developed for hi-fideltity audio amplifiers, converting the audio into pulse width modulation (PWM). Class D really defines an amplifier that uses PWM for generating *varying* output power, such as audio.

The basic fundamentals have been applied to CW RF amplifiers, by simply driving the mosfet PA into saturation. Since these amplifiers do not use a PWM input (since a CW transmitter demands a constant output power), they are not legally Class D. However, it
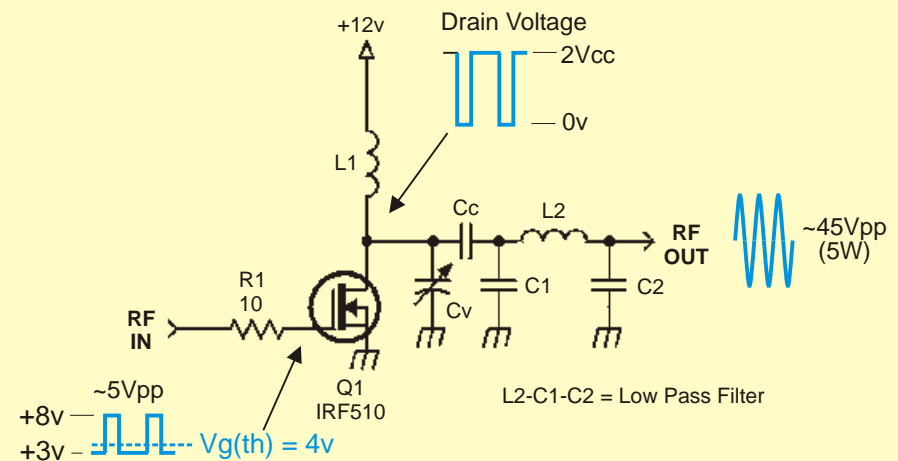
has become accepted to refer to a mosfet PA, being driven into saturation *with standard low pass output filters*, as Class D.

For those wishing to experiment with these hi-efficiency switching amplifiers, start out with a simple Class D to see how they work and note the increase in efficiency. However, I would certainly recommend to any serious builder to graduate to a Class E PA.

CLASS E QRP PA

The first **Class E** QRP transmitter to be considered is shown in **Figure 6**. The input is a 5Vpp square wave at the RF frequency, ranging between +3v and +8v due to the R1-RV1 bias network in **Fig. 5**, or as developed in the driver stage. The real difference, *which defines this circuit as Class E*, is the output side of the mosfet. A single inductor, L1, replaces the common bifilar transformer, and a variable capacitor, Cv, is placed from drain to ground. The output is capacitively coupled through Cc to the low pass filter.
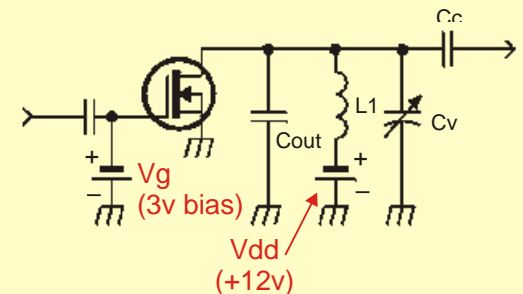
To better understand this circuit, refer to the equivalent schematic in **Figure 7**. The IRF510 output capacitance, *Cout* or *Coss*, is 100-120pF, which would normally be an unwanted low impedance load to the drain circuit. However, in Class E, this output capacitance is used to our advantage by using it as part of a tuned circuit. Representing the +12v drain voltage as a battery, it can be redrawn to show how L1 is in parallel with *Cout*, forming a tuned circuit. Therefore, in Class E, the value of L1 is calculated to resonate with *Cout* at the desired output RF frequency. A fixed or variable capacitor, Cv, is usually added to the L-C circuit to

reach resonance at the transmit frequency. A parallel tuned circuit has very little net loss. Converting the mosfet's *Cout* from a loss element, to a low loss tuned circuit, is what *greatly increases the efficiency of this amplifier.* The current needed to charge Cout in Class E comes from the "flyback" energy of the tuned circuit, *not from the mosfet drain current.* In a properly tuned circuit, current flows through *Cout* only when the mosfet is OFF (no drain current flowing).

The combination of reducing the switching losses by using a square wave input, and reducing the effects of the internal capacitances, is what defines Class E.

Table 1 shows some initial starting values for the HF ham bands. *Cs* is the *total shunt capacitance* to add between the drain and ground – a fixed capacitor in parallel with the variable capacitor, Cv. On 40M, for example, this is a *total* drain-source capacitance of 240pF, including the internal *Cout* of the IRF510. The inductance, and the toroidal inductor to wind, is also shown to form the equivalent tuned circuit. I have built Class E PA's with these approximate values for all bands shown, except 80M, and all yielded an overall efficiency (total keydown current, including receiver and transmit driver currents) of at least 80%. However, these values need to be used with caution, primarily because the IRF510 *Cout* of 120pF, as listed on the data sheet, is for a Vd of +12v, that is, when the IRF510 is OFF. It rises to about 200pF as you approach saturation. The trick is to guestimate what the average IRF510 capacitance will be, depending on the duty cycle of the input square wave. To be truthful, it takes a little piddling around to get it right, but getting another percent or two of efficiency out of the PA is fun. In fact, it can become an obsession! Again, this is

Table 1 – Initial Values

BAND	Cs	L1	WIND L1
80M	270p	5.0uH	10T T50-43
40M	120p	2.1uH	6T T50-43
40M	120p	2.1uH	20T T50-2
30M	120p	1.0uH	14T T50-6
20M	47p	0.8uH	13T T50-6
15M	---	0.5uH	10T T50-6

where an oscilloscope, and a power meter, is a must to tune the Class E PA for maximum efficiency. In practice, the *Cs* capacitance values listed in Table 1 will likely end up being a bit less than shown.

Note the square wave input shown in **Fig. 6** is depicted having a 30% duty cycle, not 50% in the Class D circuit. Output power is determined by varying the duty cycle of the input drive. With Class E, it is my experience that maximum efficiency occurs around 45% duty cycle of the input gate drive (45% ON, 55% OFF).

CLASS E QRP PA
with Series Tuned output

F i g u r e 8 s h o w s a n o t h e r implementation of a Class E amplifier. Instead of using an LPF output filter, a combination of parallel and series tuned resonant circuits are used. As in the first example of the Class E amplifier, L1 forms a parallel tuned circuit with the total shunt capacitance of Cv and the internal drain-source capacitance of *Cout*. Instead of following this with a low pass filter, it is followed by a series tuned resonant circuit, consisting of L2 and C2. The combination of the two tuned circuits is sufficient to ensure FCC compliance for harmonic attenuation.

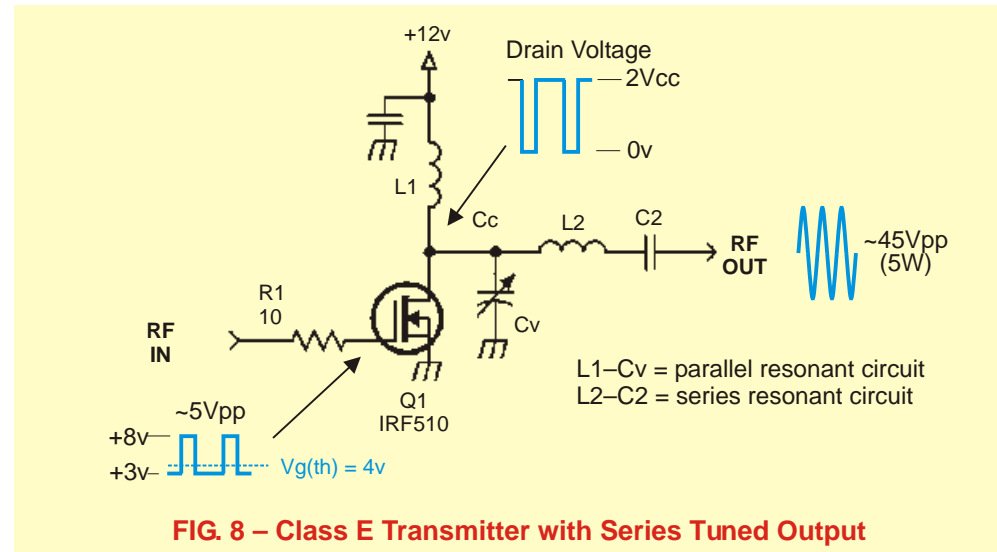From my experience, the difficulty with this approach is selecting the component values to effect a proper

FIG. 8 – Class E Transmitter with Series Tuned Output

impedance match to the 50W load. It can be done with a little math, computer modeling, or experimentation, but again, due to the uncertainty of the actual IRF510 *Cout* value and resulting average output impedance, a fair amount of tweaking is required. Once the output impedance is properly transformed into 50W at the antenna, and L2–C2 tuned for resonance, the efficiency will be about 85%. However, with the L2–C2 series tuned element, it becomes rather narrow banded and efficiency drops when the frequency is moved about 10KHz. A variable capacitor across C2 will allow retuning upon frequency changes, although in practice, this is cumbersome for the way most of us prefer a no-tune QRP transmitter.

There are still other ways to implement the Class E amplifier, such as additional parallel or series tuned circuits on the output, or using impedance transformation schemes. It is an area worthy of further development by hams and QRPers. The main goal is to use the internal drain-source capacitance as part of the parallel tuned output circuit with the drain inductance. This will generally require some additional

capacitance between drain and ground, and some means to tune it to resonance. By doing so, the output capacitances are charged from the "flywheel effect" of the tuned circuit, that is, current from the drain inductor, not from the drain current. The later is wasted energy, which lowers the efficiency.

CLASS F QRP PA

The square wave *drain voltage* is rich in odd harmonics, predominantly the 3rd and 5th harmonics (3fo and 5fo). A sinewave with odd harmonics will be flattened at the peaks (at 90⁰ and 270⁰), lowering the efficiency of the PA. Upon removing the odd harmonics, it will be a proper sinewave. In a typical QRP transmitter, the harmonic power is thrown away by the low pass filter. However, if one were to use this odd harmonic power in proper phase, the power could be added to the fundamental frequency to boost the output power. This would increase the efficiency of the amplifier.

This is the essence of Class F. The output network consists of odd harmonic peaking circuits in addition to

resonant circuits at the desired fundamental frequency. This forms the clean output sine wave, and the odd harmonic peaking adds a bit of power to the fundamental to increase PA efficiency.

Figure 9 shows one approach to accomplishing this. Component values are chosen such that L2–C2 is resonant at the 3rd harmonic, and L1–C1 and L3–C3 resonant at the fundamental frequency.

To analyze the circuit, consider the functions of these networks at different frequencies.

At the 3rd harmonic (3fo), L2–C2 is resonant, their reactances cancel out, offering little resistance to the 3fo voltage, passing the 3fo power to the L3–C3 network. L3–C3 will appear capacitive at 3fo, and will be charged with the 3fo power.

At the fundamental frequency (fo) L3–C3 is resonant, with a slight boost in power due to the voltage added to the network by the 3fo peaking circuit described above. At fo, L2–C2 (fr=3fo) will appear inductive, and the value of

C1 is selected to form a series resonate circuit at the transmit frequency with this inductance. Normally, C1 is a dc blocking capacitor, usually 0.1lF. In Class F, C1 will be a few hundred pF, depending upon the fo.

Obviously, it takes some math to figure out these values for the respective resonances, and to achieve the proper impedance transformation to a 50W load.

I have built several Class F amplifiers, using an impedance network analyzer to verify the impedances, capacitance and inductance of all elements at fo, 2fo and 3fo. Inspite of being properly tuned, I have never been able to reach an efficiency higher than what I've obtained with Class E. It is my opinion that the extreme complexity of Class F is not worth the effort over Class E *at QRP levels*. Class F is used in commercial 50kW AM transmitters, and at even higher powers for shortwave transmitters. Perhaps the extra 1–2% of efficiency is worth it for saving a kilowatt at these power levels, but is scarcely measurable at QRP powers.

None-the-less, Class F is a clever approach to increasing efficiency, and presented here for sake of completeness of the high efficiency modes.

Conclusion.

These switched mode PAs are ideal for QRP and the homebrew construction of low power transmitters, in that the higher efficiency directly relates to lower battery drain. It is worthy of further development by QRPers and experimenters, and the reason the theory has been presented in the first part of this article.

In **Part 2** – a more technical approach to Class D/E/F will be presented, along

with details of the gate input drive requirements and suitable driver stages, with actual oscilloscope waveforms. The IRF510 Data Sheet is also included in Part 2. sometimes more!)

For those interested in Class D/E/F, I hope you have found the information in Part 1 of this tutorial informative. For those of you building such circuits, I would be interested in hearing of your success and approach.

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L3–C3 = resonant at fundamental freq. (RL=50W)
L2–C2 = resonant at 3rd harmonic freq.
C1 = resonates with L1–L2 at fundamental freq.

FIG. 9 – Class F Transmitter with Harmonic Peaking

Appendix A – Pulse Width Modulation (PWM) or varying the duty cycle to control output power
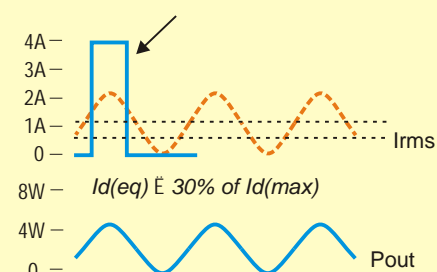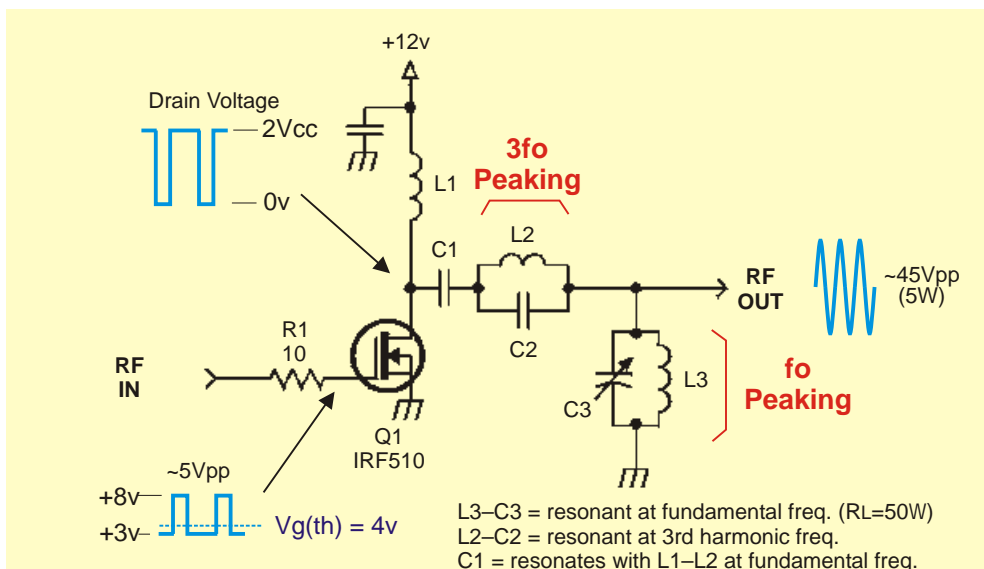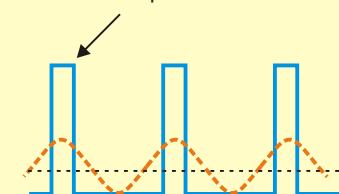
50% Duty Cycle Drive

30% Duty Cycle Drive
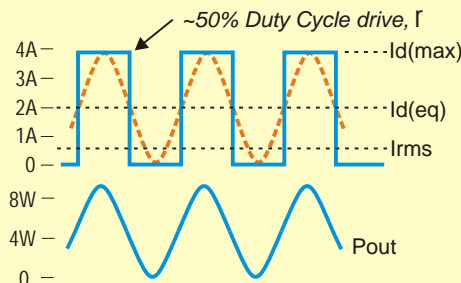
Consider the drain output current above with a 50% duty cycle and the IRF510 Id(max) of 4A. The sinewave equivalent is shown as the dotted wave-form. Id(eq) is effectively converting the peak-to-peak current to peak current (at 50% duty cycle), then converting to Irms to determine output power, as calculated below.
r = duty cycle, g = PA efficiency

Id(eq) = r Id(max) = 50% x 4A = 2A
Id(avg) = .637Id(eq) = .637 x 2A = 1.3A
Irms = .707Id(avg) = .707 x 1.3A = 0.9A
Po = IrmsVddg = 0.9A x 12v x 80% = 8.8W

Id(eq) = rId(max) = 30% x 4A = 1.2A
Id(avg) = .637Id(eq) = .637 x 1.2A = 0.76A
Irms = .707Id(avg) = .707 x 0.76A = 0.54A

Po = IrmsVddg = 0.54A x 12v x 80% = 5.2W

20% Duty Cycle Drive

What is the Output Power at r= 20%?