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Switch-Mode MOSFETs for Class A Radio Frequency Amplification

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Abstract

Vertical double diffused MOSFETs ("VDMOSFETs") developed for switching power supplies were successfully used in high voltage, high frequency linear amplifier circuits. These high voltage power switches are surprisingly useful for linear RF power amplifiers and transmitters. In most of their intended applications such as in switching power supplies or switched digital amplifiers, VDMOSFETs are pulsed by a high voltage and the pulsed output is heavily filtered. This avoids the linear region of the VDMOSFET, which normally limits the efficiency to a theoretical maximum of 25%. However, in a search of MOSFETs for high voltage linear amplification using Class A bias without heavy use of filtering, these low-cost switching MOSFETs were found to work best, if limited to radio frequencies above 1.5 MHz. Conditions, and in particular, very low impedance driving of the MOSFET gate, were discovered that gave efficiencies of 70%, rivaling that of non-linear pulse techniques such as Class C or Class D operation. The beneficial effect of linear operation combined with high efficiency at a high voltage is suggested to arise from Miller capacitance. This was only seen at radio frequencies and with the larger current, higher gate capacitance devices. Switching MOSFETs as described here should be considered alongside dedicated RF MOSFETs such as the more expensive LD (lateral diffused) MOSFET when working with RF power.

Keywords: MOSFET's, radio frequency, transmitter, capacitance, photons.

INTRODUCTION

In studying single photon pulse radio signals, a resonance-free transmitter was developed that lacked tuning circuits as described previously [1]. This transmitter employed a high voltage MOSFET transistor biased for class A operation driving either a 2000 ohm (without balun) tilted terminated folded dipole antenna (commercial grade from Comet), [2] or alternately a 500 ohm beverage antenna [3]. Such a transmitter needs to create a clear signal to meet the maximum spurious emission requirements set forth by the FCC in CFR Title 47, section 97.307, which states: "the mean power of any spurious emission from a station transmitter or external RF power amplifier transmitting on a frequency below 30 MHz must be at least 43 dB below the mean power of the fundamental emission." The biggest spurious signal culprits from a transmitter output to an antenna are the 2nd and 3rd harmonics of the signal being amplified [2]. Accordingly, this study was undertaken to see how close a circuit could get to meeting the FCC clean signal requirements before resorting to a bandpass or lowpass filter to clean up the output signal. The circuit was optimized by studying alternative MOSFETs while measuring not only output power of a test sine wave

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signal, but also the 2nd and 3rd harmonics of that signal. Optimization included tuning for minimum harmonics and comparing the effects of detuning the amplifier to sacrifice a little gain in return for a cleaner signal. In the course of this work, a surprising property of switched mode MOSFETs designed for switching power supplies was discovered, which allows unusually higher than the expected 25% efficiency when biased for class A linear operation. For comparison, linear DMOS transistors that are designed for high power linear amplification of radio frequencies were also used. But partly due to the higher (75–275 Volt) drive requirements a regular IRF710 switch mode MOSFET intended for switching power supplies gave much better results. Accordingly, some widely available high voltage switching MOSFETs in the IRF series were evaluated for output and harmonic quality for use in HF power amplifiers. These MOSFETs have a high input (gate to source) capacitance because thousands of smaller MOSFET units are simply connected in parallel to handle higher source to drain current in the power MOSFET, using a matrix of gate electrodes that are spaced off the source material with a thin insulator. And, to withstand higher voltages, these devices use a much thicker epitaxial layer between a vertically arranged source and drain. For these and other reasons, the input gate to source capacitances of these devices are very high, often 1 or 2 nanofarads, which can greatly complicate driving them with a high frequency signal because this capacitance creates a low impedance. Surprisingly, while operating these in a class A configuration, conditions were discovered that yielded unexpected high efficiency performance above audio frequencies. These results may be useful generally for those who build simple, high voltage RF power devices such as transmitters for radio communication [4–7].

SwitchingMOSFETsCompared

The legacy IRF devices used, were originally made by International Rectifier but are now widely available at low cost from many sources. Their relevant characteristics are listed in Table 1. MOSFET datasheets report device capacitances based on a particular drain voltage and gate to source voltage. For convenience each MOSFET input capacitance (between gate and source pins) was measured using a simple capacitance meter, being careful to take a reading within 1 second of applying the probes and taking an average with reversed polarities. Such simple ballpark capacitance measurements were useful, because most of the MOSFETs purchased from ebay, Alibaba, and Amazon turned out to be low current, low capacitance counterfeit parts [8]. Fake MOSFETs seem to be prolific in the marketplace but were detected by their very low (typically 5X or lower) measured capacitances compared to that of a genuine device.

Table 1. Characteristics of some legacy IRF MOSFETS designed for power switches.

Type	Maximum Drain-Gate voltage	Maximum current Amps	Rise Time ns	pF gate to source capacitance	pF measured
IRF520	100	10	50	330	850
IRF540	100	30	60	2600	3400
IRF610	200	3.3	17	135	273
IRF620	200	6	70	460	620
IRF630	200	9	15	540	1450
IRF710	400	2	9.9	170	290
IRF720	400	3.3	14	410	730
IRF730	400	5.5	7.5	700	1283
IRF740	400	10	10	1400	1860
IRF820	800	2.5	8	360	740

These MOSFETs were tested in a class A amplifier circuit with a low signal input level of 0.3 volts peak-to-peak ("p-p") applied to the gate and gate bias optimized for best gain. And then again with a high signal input level of 1 volt p-p applied to the gate, with optimized gate bias for best power output and separately, best purity signal output [9]. It was difficult to get 1 V p-p at 21 MHz so 14.15 MHz was used instead for the higher signal evaluation. Gate bias voltages applied to each transistor were adjusted for maximum power and then adjusted for minimum harmonics generation. Oftentimes the gate bias voltage was increased by about 0.1 volt to obtain minimum harmonics. In the latter case, the power output would drop by about 5–10% [10–12].

METHODS AND RESULTS

The tests were done without any resonance devices in the circuit such as a frequency filter and without impedance matching in order to discover the true effects of the transistor. The MOSFET was DC biased through a 6.7 kilo-ohm resistor bridge to a 5-volt supply and was otherwise floating. The RF signal at the MOSFET input was at a low 51 ohm impedance. The amplified RF signal from the MOSFET drain similarly was shunted with a 50 ohm dummy load to ground. A direct current ("DC") supply of 75 V was provided to the drain through a 47-ohm carbon resistor. Input and output signals were analyzed by a 200 MHz SIGLENT Model 1202-X-E oscilloscope using a 200 MHz probe. Output signal distortion was determined by measuring the second and third harmonics in the output signal using the math function of the oscilloscope and reading the values off the display. Because the input and outputs were loaded by constant resistance of 50–51 ohms the voltage measurements in decibels are equivalent to power decibels. In other words, a measured -20db in voltage difference reported from the oscilloscope of a harmonic represents a 100-fold decrease in power level, with respect to the fundamental signal input to the same resistance. Transistor gate-source capacitances in the last column of Table I were measured with a model UA6013L meter. A FeelTech brand signal generator Model FY3200S was used to supply a sine wave to a two stage emitter follower current amplifier powered by 12 volts and connected to an final output MOSFET as shown in Figure 1.

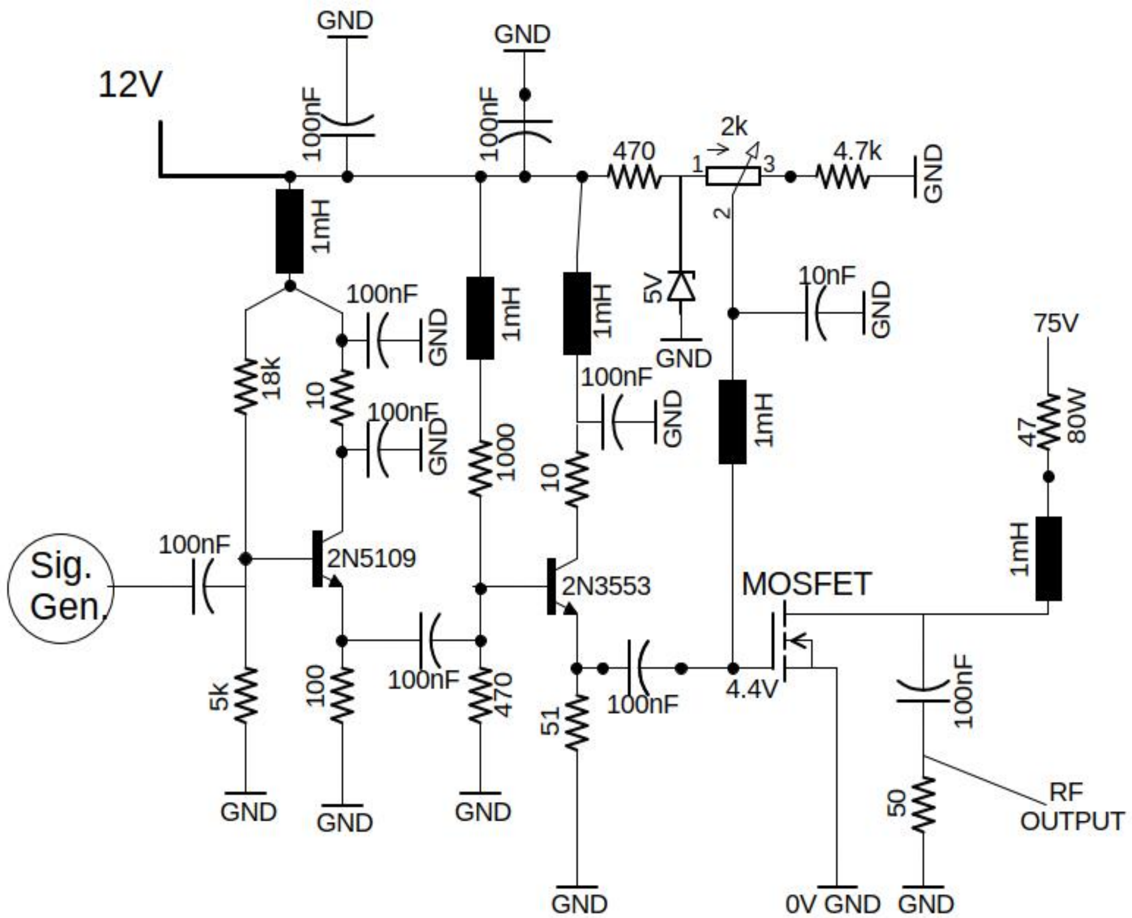

Figure 1. Circuit of the RF test amplifier.

It is unusual to combine two voltage follower bipolar transistor amplifiers (2N5109 and 2N3553 in Figure 1) in series. Initial experiments were done with just one bipolar transistor stage of current amplification directly feeding the MOSFET but did not produce a strong enough signal to the highly capacitive gates of the MOSFETs. This showed up as waveform decomposition of the signal measured at the gate upon applying progressively higher voltages to the MOSFET drain. The second stage of current amplification overcame this problem by providing higher current to the 51 ohm load on the bipolar current amplifier, which feeds the highly capacitive, low impedance MOSFET gate circuit.

MOSFET Performances at 0.3V Signal Input Conditions

In a first study, a 0.3 volt peak-to-peak signal from the signal generator was fed to the input of the bipolar current amplifier at 2 MHz, 5 MHz, 10 MHz and at 21 MHz. The MOSFET gate bias was adjusted at each condition for maximum power output. The voltage applied to the MOSFET was 75 volts and the load was 47 ohms. Figure 2 shows the power output and power efficiency results with different MOSFETs. Power output was taken as peak-to-peak Rf voltage from a 50-ohm resistive load and power efficiency was calculated as Rf power output divided by power consumed in the MOSFET stage.

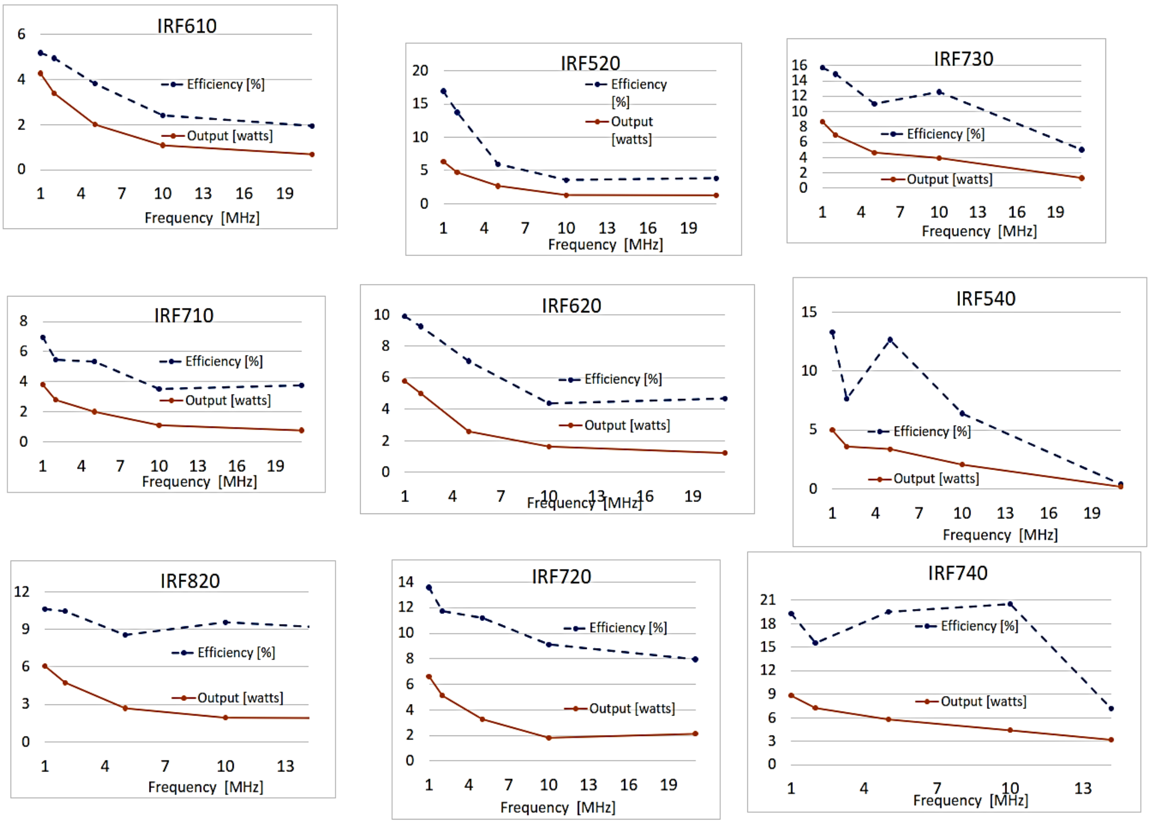

Figure 2. Outputs from 9 MOSFETS driven by a 0.3 V gate signal.

Amplification of the 0.3 V signal decreased with decreasing frequency for all tested MOSFETS as shown in Figure 2. The distortion measurements for these same conditions are shown in Figure 3. Distortion was higher at the lowest frequencies tested (1 MHz and 2 MHz) but was clearly lower at 5 and 10 MHz However, when signal input level increased, often the output level increased more than linearly, the efficiency increased, but the 2nd and 3rd harmonics increased. Figure 4 exemplifies this relationship as seen with data from MOSFET IRF710. For each condition, the gate bias was optimized for maximum power output. As the signal to the gate increased above 0.3 volts, the device departed from regular class A amplifier performance, presumably due to a change in gate bias that moves the response curve of the MOSFET to the left edge of the saturation region.

MOSFET Performances at 1 V Signal Input Conditions

In a second study, a 1-volt peak-to-peak signal from the signal generator was output to the bipolar current amplifier at 2 MHz, 5 MHz, 10 MHz and 14.15 MHz. Some of the MOSFET inputs did not handle high frequencies well and the output to the MOSFET gate at 21 MHz could not get up to 1 V, even with the highest signal generator output setting. For this reason, 14.15 MHz (20 M band frequency) was used instead of 21 MHz. For each MOSFET and frequency tested at 1V p-p input to the MOSFET gate, the gate bias was adjusted for maximum output power. The output power and harmonic distortion (2nd and 3rd harmonics compared to the fundamental frequency) were recorded. Then the gate bias was adjusted for minimum harmonics and the output (and harmonics) again recorded. The power output and output MOSFET stage efficiencies are shown in graphical form in Figure 5. Figure 6 shows harmonic distortion for the data points of Figure 5. The high efficiencies reported in Figure 5 are due to departure from strict class A performance and are associated with higher 2nd and 3rd harmonic distortion figures and particularly the second harmonic plots shown in Figure 6.

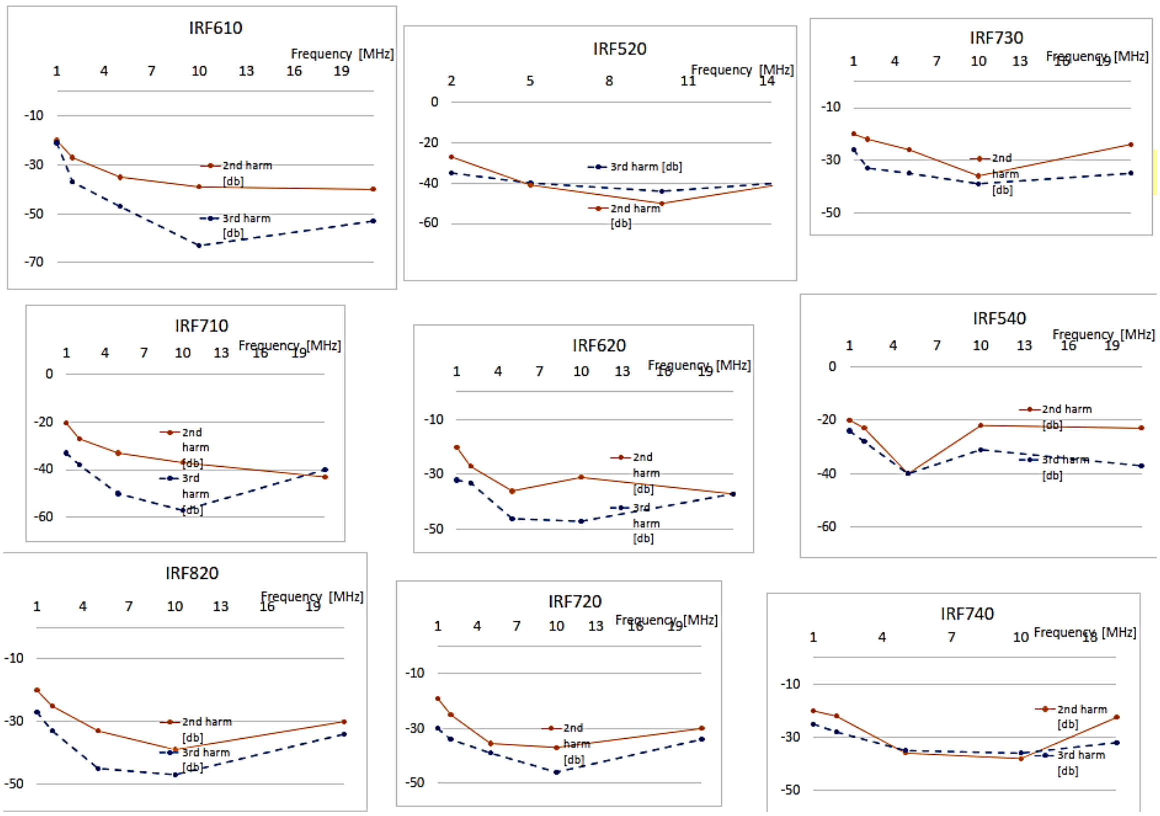

Figure 3. Harmonics from 9 MOSFETS driven by a .3 V gate signal.

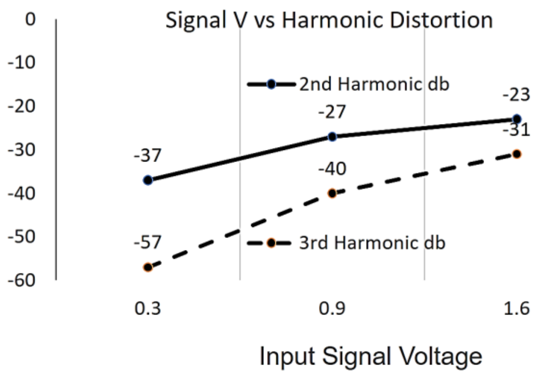

Figure 4. Effect of signal voltage on harmonic distortion.

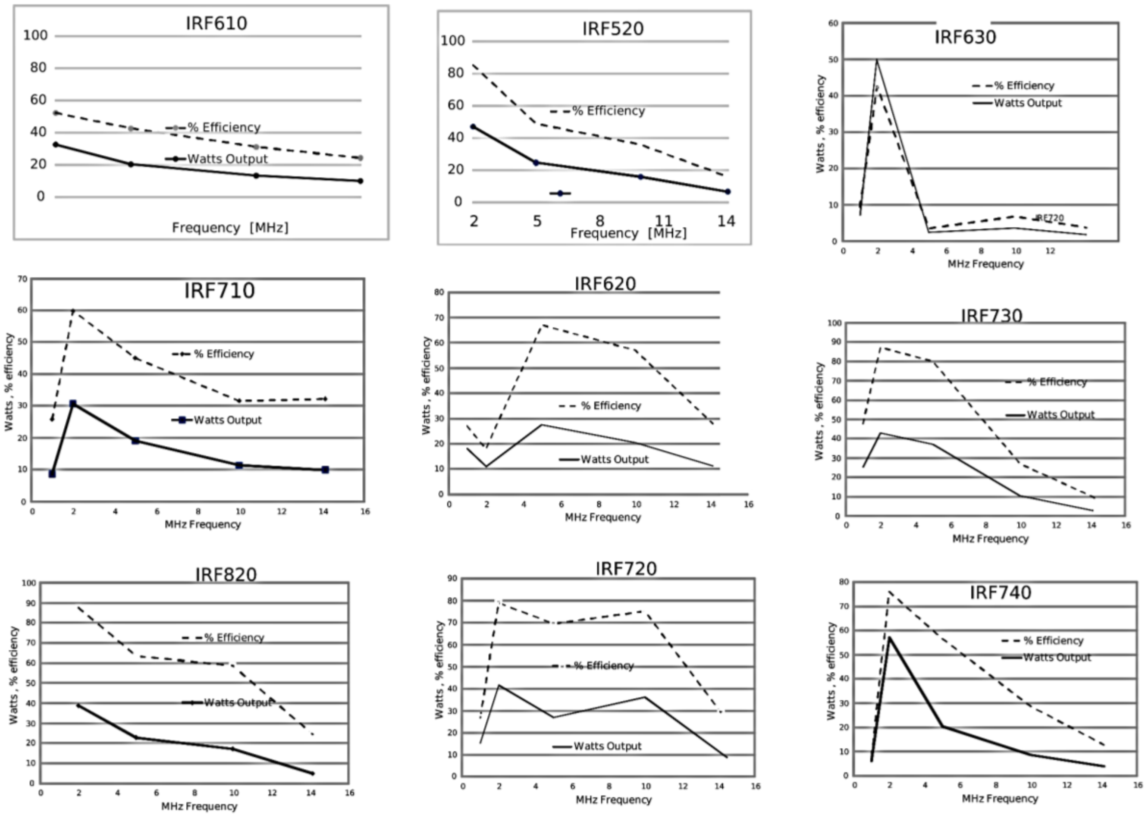

Figure 5. Outputs from 9 MOSFETS driven by a 1V gate signal.

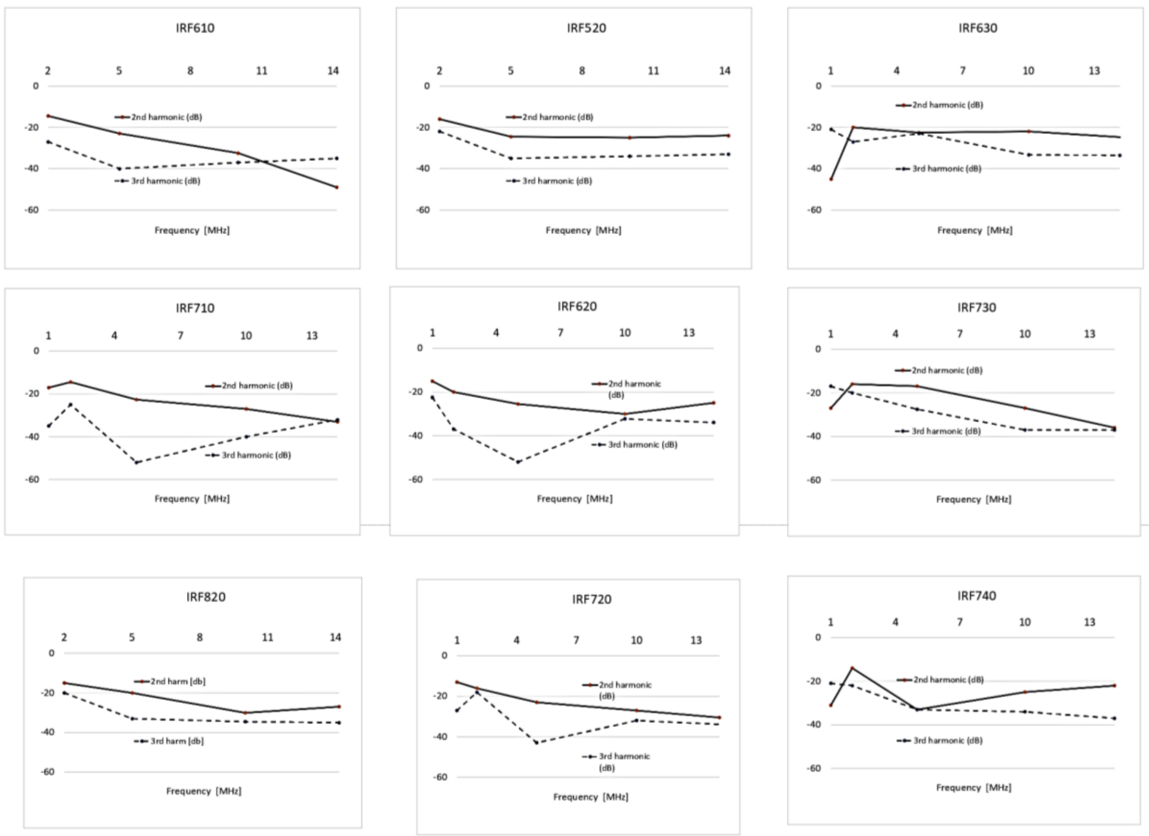

Figure 6. Harmonics from 9 MOSFETS driven by a 1 V gate signal.

Effect of Input Capacitance, Signal Strength, and Frequency on High Efficiency Operation

Surprisingly, it was found that at high frequencies in larger capacitance devices, the efficiencies of the devices went well above the 25% theoretical maximum for class A amplifier performance. A possible explanation of this result is that the high frequency signal feedback from the drain output to the input via the Miller Effect [4] causes an increase in gate bias. This effect would be enhanced when higher frequencies were applied to higher power devices having increased gate capacitance/Miller Effect. This explanation is not very satisfying because the Miller Effect is famous for inhibiting high frequency performance of transistors and thus these results are counterintuitive. For each amplification test, the applied DC gate voltage was optimized for peak power output. Then the signal generator was disconnected to remove signal to the gate, and also signal feedback from the drain to gate (via miller capacitance). When the current was measured at zero signal input at 75 V power, the idle current was clearly proportional to the measured input capacitance of the MOSFET type as shown in Figure 7. This figure compares the input capacitances of the MOSFETs studied (X-axis) versus zero signal current consumption for each MOSFET after the MOSFET gate is biased for optimum (maximum output) operation. The data were obtained at two frequencies, 5 MHz and 10 MHz and show that as the MOSFET gets bigger (has increased gate capacitance) the no-signal current consumption dropped off, contributing to an enhanced efficiency.

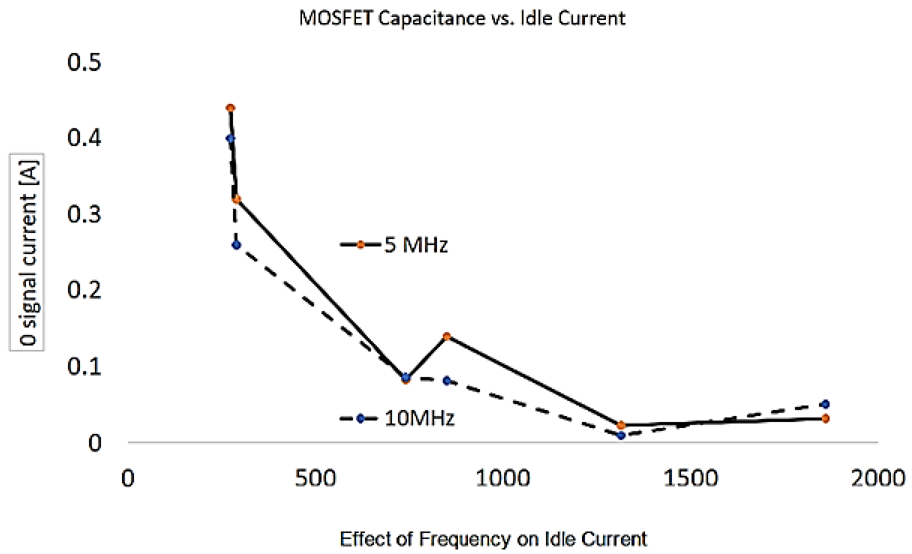

Figure 7. MOSFET rated input capacitance *vs.* standby current for optimized gate bias.

Signal strength also is positively correlated to increased efficiency. By increasing the signal from 0.3 V p-p to 1 V p-p for each transistor, the efficiency increased, as seen by comparing the efficiency plots of Figure 2 (0.3 V signal inputs) with those of Figure 5 (1.0 V signal inputs). Increasing signal frequency also seemed to play a role in increasing the optimized gate bias voltage and increased efficiency. Figure 8 shows the measured gate bias voltage, which decreases with increasing signal frequency.

Thus, both increased signal and increased frequency of the signal caused the optimum gate bias to decrease, while at the same time, efficiency increased above 25%. This indicates departure from expected class A performance, which has a 25% theoretical maximum efficiency. In each experiment the DC bias applied to the gate was adjusted for maximum signal amplification and, after adjustment the zero signal input created almost no background current. In other words, the Miller Effect allowed a lower gate bias so that the MOSFET is dynamically turned on under lower gate bias conditions. Applying a high frequency and high strength signal to the gate is then enough to increase the gate voltage only in response to a signal. This surprising result is not from gate capacitance *per se*. Further evidence that the high efficiency conditions are caused by the Miller Effect comes from the fact that when a cascode MOSFET, which lacks the Miller Effect was used having similarly high input capacitance, and under high voltage, application of a high frequency signal failed to produce the effect. The studied cascode MOSFET, TPH3206PS is specifically designed to lack Miller Effects and also has a high input capacitance of 740pF and high voltage capacity of 600 V. But, when examined at 5 MHz with 1 volt input and optimizing for maximum output in the test circuit, this MOSFET had an efficiency of 8%. Test results at 1, 2 and 10 MHz were no better in increasing efficiency.

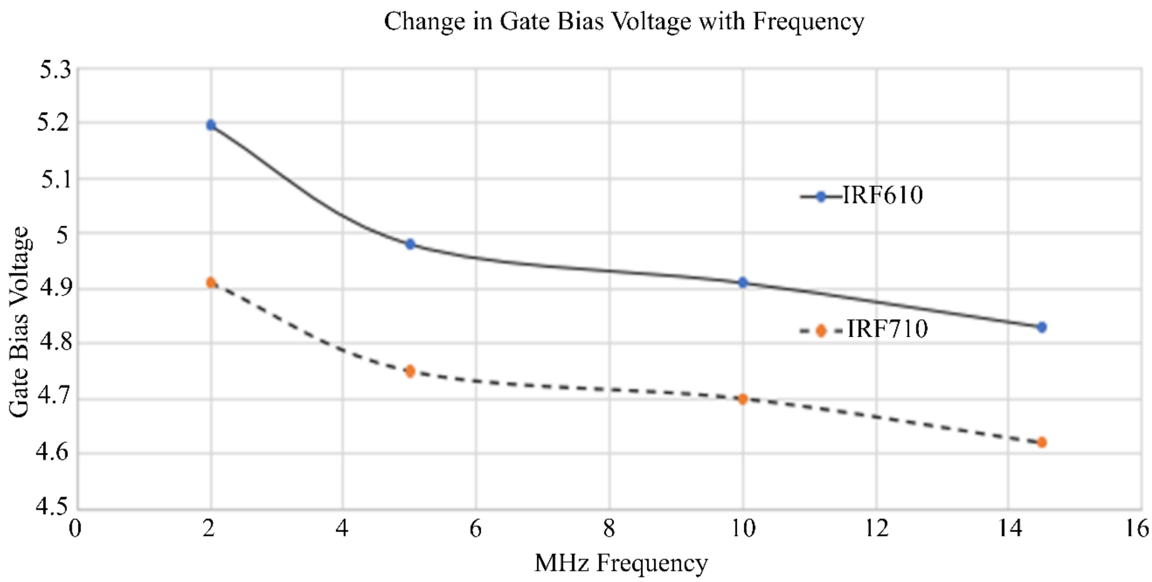

Figure 8. Effect of frequency on optimized gate bias voltage.

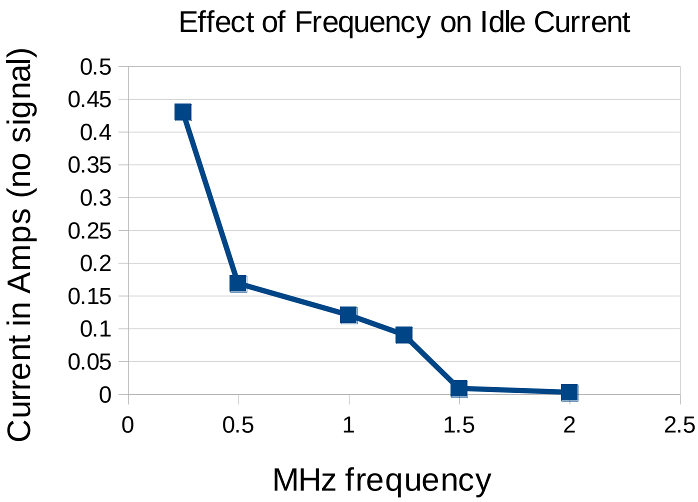

Figure 9. Effect of frequency on 0 signal idle current.

Effect of Frequency

Figure 9 shows that as frequency decreases below about 2 megahertz the enhanced efficiency effect disappears, and normal low efficiency class A operation returns even during conditions of high input capacitance and high input signal. What happened here in practical terms is that the idle current is determined by the gate bias, which is set for maximum amplification. As signal frequency increased, the gate bias had to be decreased, which led to improved efficiency. Measurements of the p-p signal voltage at the gate showed that the actual gate signal voltage was increasing as a result of powering up the device and also increasing the frequency. Because this effect is not present at audio frequencies, the effect reported here would have been overlooked by most workers who use these MOSFETs for class A amplification in their audio applications.

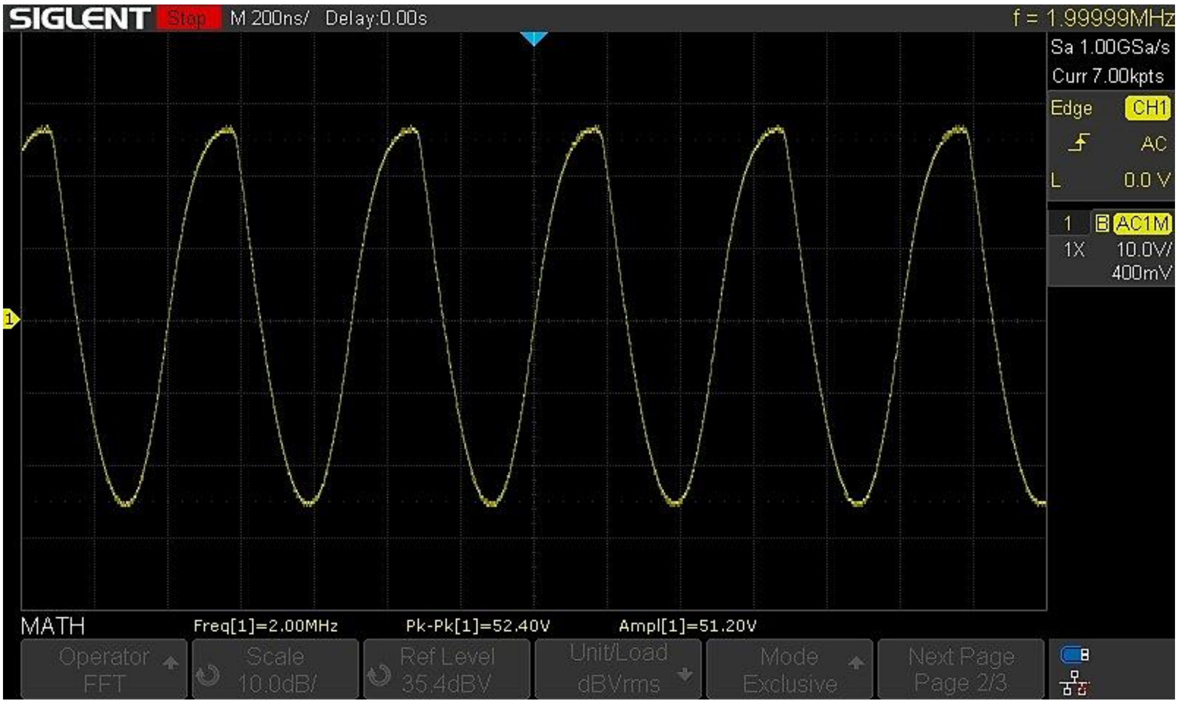

Figure 10. Scope display of 55-watt output at 2 MHz with IRF730.

DISCUSSION

Use Switching MOSFETs for HF Amateur Radio

The plots in Figure 5 and Figure 6 show that high efficiency amplification with reasonable purity (i.e. more than 30db inhibition of 2nd and 3rd harmonics) can be obtained from the higher voltage, higher power MOSFETs in some popular amateur radio bands.

2MHz,160Meters

Power output was highest at the lowest frequencies but needed the most cleanup. At 2 MHz using an IRF730 MOSFET at 75 volts, 55 watts output were obtained. The 2nd and 3rd harmonics in this output were down 33db and 26.5db with respect to the 2 MHz fundamental and the waveform at this high-power level showed the need for filtering. See Figure 10.

5 MHz (near60 meters)

Higher frequencies, particularly 5–10 MHz showed the cleanest signals, having much lower 3rd harmonic energy. Figure 11 shows a much cleaner 5 MHz 27.7-watt output from IRF620, having 2nd and 3rd harmonic contents down by 26db and 52db, respectively. The power efficiency of the MOSFET in this condition was 67%.

10 MHz, 30 Meters

Using 1 volt signal input to the gate, and 75 V applied to the drain of the MOSFET, power continued to drop as frequency increased. Figure 12 is a scope shot of a 10.6 watt output obtained at 10 MHz with the IRF730. The measured efficiency of this IRF730 MOSFET output power was 28%. The 2nd and 3rd harmonics were down by 40db and 36db, respectively. When 100 V was applied to the MOSFET and the input signal decreased slightly to 0.7 V, the DC gate bias was re-optimized lower by 0.27 volts and the output jumped to 29 watts. This new, higher power condition was 69% efficient. The idle high voltage current (with no signal applied) was only .024 amps in the higher power condition due to the lower gate bias. However, the 2nd harmonic increased 17 db (to -23db) and the 3rd harmonic increased 1db (to-35db), with respect to the 10 MHz primary frequency. If one were to use a typical low pass filter for 10M Hz then this 29 watt output could drive an antenna. Figure 13 is a scope display of this higher output signal.

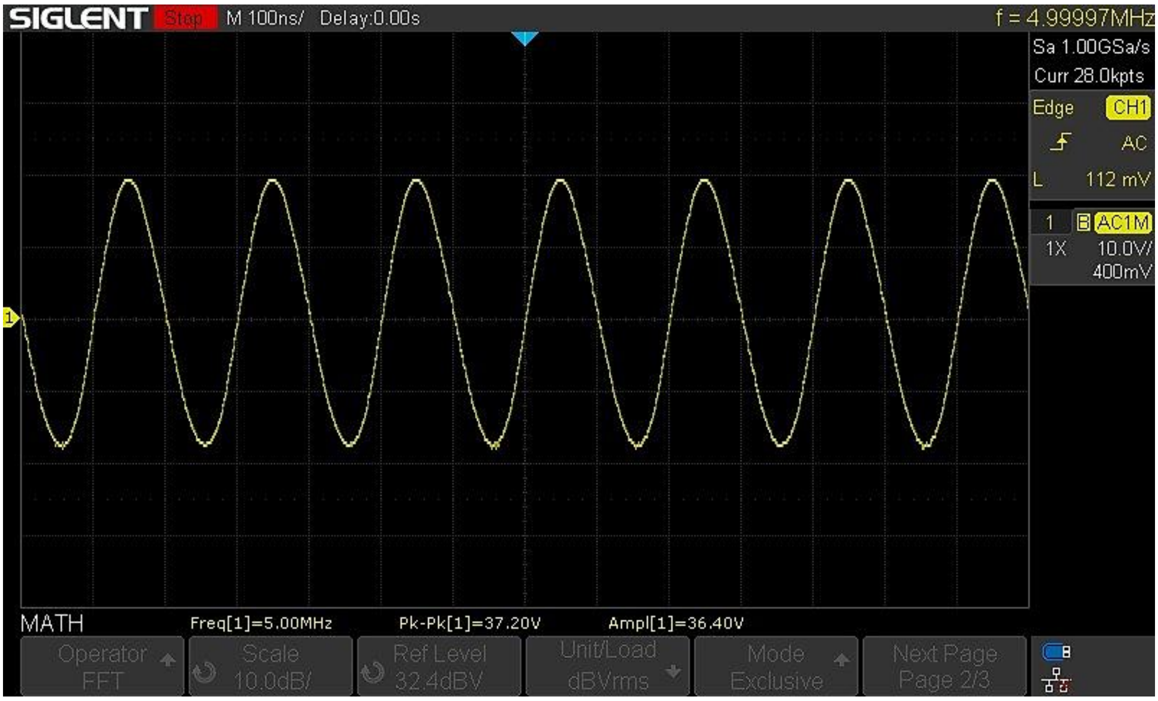

Figure 11. Scope display of 28-watt output at 5 MHz with IRF620.

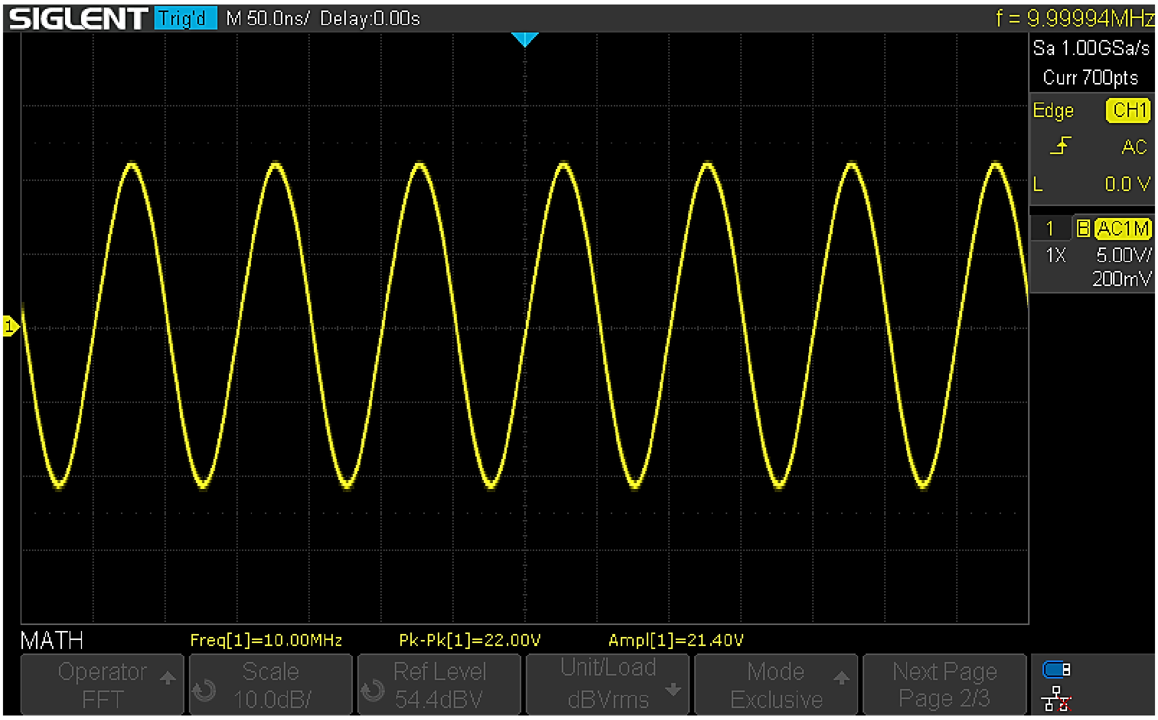

Figure 12. Scope display of 10.6-watt output at 10 MHz with IRF730.

Compared to the 10.6 watt output from the same transistor driven at higher gate voltage further into the linear region of the MOSFET, the peaks of this 29 watt output are a little pudgy due to the presence of the 17db stronger second harmonic. However the higher efficiency (69% vs 28%) and 2.7X output power could be a good tradeoff if a low pass filter or bandpass filter were used to remove the extra harmonic power, which comprised as much as about 0.5% of the total power output. These data show that push-pull class B efficiency and performance can be achieved with just one MOSFET power transistor wired in a simple configuration.

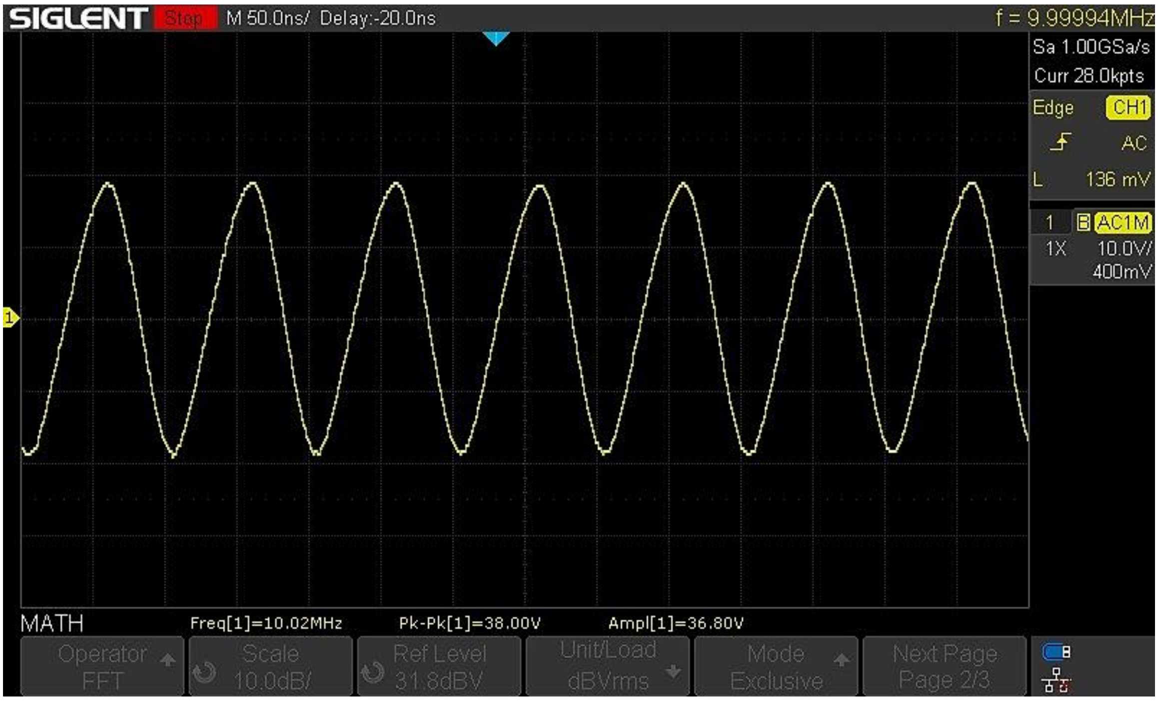

Figure 13. Scope display of 29-watt output at 10MHz.

14.15 MHz, 20 Meters

The clearest signal outputs seemed to come from the highest frequencies. Figure 14 is a scope shot of a 14.15 MHz (20 M band) 10.0 watt output from an IRF610 transistor powered by 75 volts. The 2nd and 3rd harmonics in this signal were -49db and -35db with respect to the fundamental 14.15 MHz signal. This purity is close to the requirement for amateur radio of -43db for harmonics of the transmitted signal frequency. This output could be used for transmission with just a small amount of filtering, such as a 2-element low pass filter to remove much of the higher harmonics. Simply attaching this output to a resonant antenna such as a 20-meter dipole antenna possibly could provide enough resonance filtering of the residual higher harmonics and allow construction of a transmitter without any filter circuit.

MOSFET Biasing is Critical

The gate bias was adjusted for either maximum power output or minimum harmonic distortion for all measurements. These MOSFETs start to turn on at a gate voltage of about 3 volts, as depicted in Figure 15. But the linear relationship between gate voltage and current output does not start until after 4 volts as seen in this figure. Surprisingly, the voltage measured at the gate increased when power was supplied (plus 75 volts) to the drain connection. This was particularly enhanced at high frequencies. Although not generally reported previously, this seems to be a result of miller capacitance as it was only seen in high voltage MOSFETs having large input capacitance and high Miller Effect capacitance. Generally, if the frequency were above 1 MHz, the signal strong enough, and the MOSFET input capacitance high enough, the gate could be biased below 4 volts, which provided both low power consumption at no signal condition and high efficiency during signal amplification. For example, the 29 watt power output from the MOSFET of Figure 13 was obtained by biasing the gate down to 3.52 volts. Signals from 1 MHz to 21 MHz were tested in different configurations and optimum conditions were found for amplifying sine waves within this range. Power outputs were highest at the lowest frequencies, reaching 47 watts for 2 MHz using the IRF740, and reaching 57 watts when the applied voltage to this transistor was raised from +75 V to +100 V. Power outputs were much lower at 21 MHz but MOSFETs with lower capacitances worked better for this highest frequency tested (my signal generator only went up to 25 MHz). For example, IRF610, having the lowest input capacitance tested, output 3.7 watts from a 0.8 V p-p input at 21 MHz on the 15 M band. This was definitely class A, as the optimum gate bias was 4.65 V, the power efficiency was only 10%, but the signal was clean, with 2nd and 3rd harmonics down by -29db and -37db, respectively. Perhaps lower capacitance devices such as IRF610, IRF510 and IRF710 could amplify higher frequencies such as for the 10 M and 6 M bands (up to 50 MHz) if driven with suitable signals.

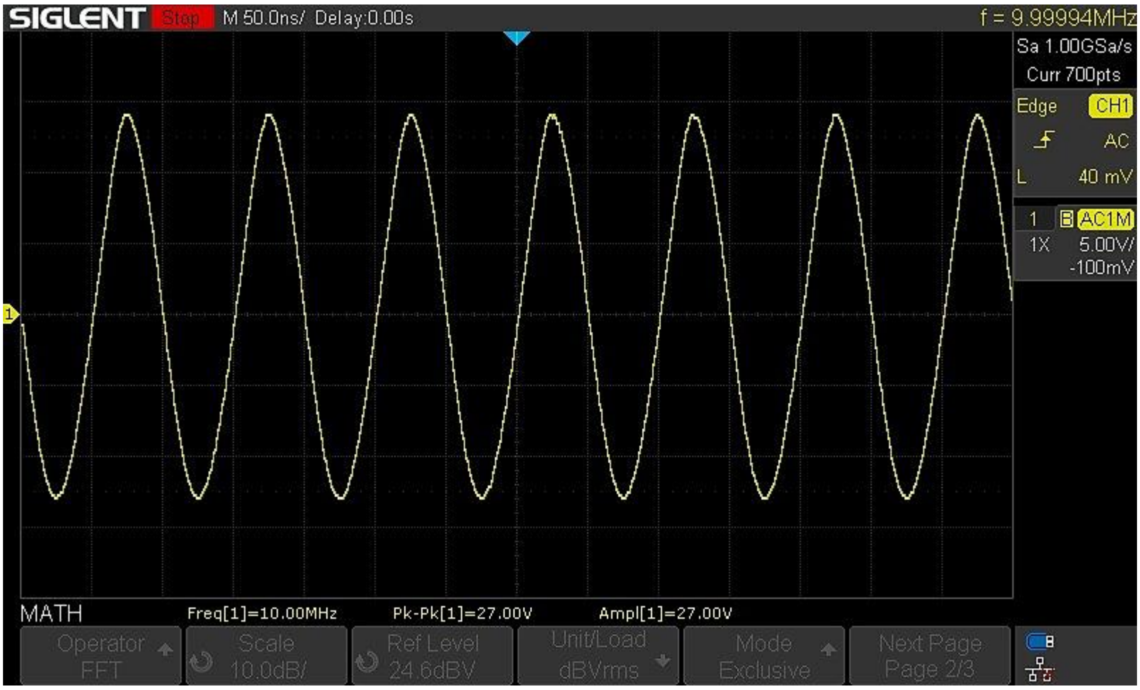

Figure 14. Scope display of 10-watt output at 14.15 MHz with IRF610.

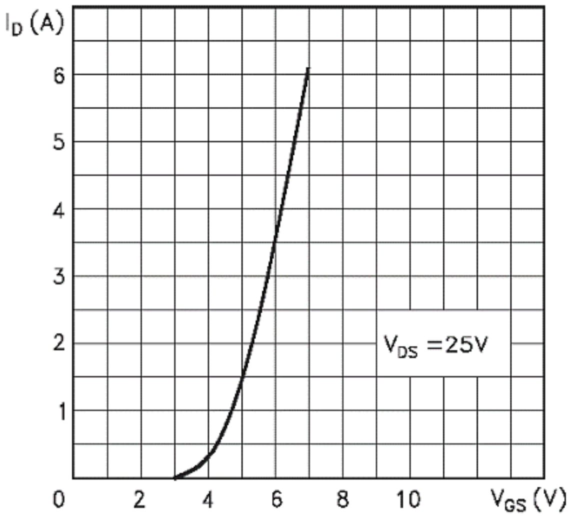

Figure 15. MOSFET drain current versus gate bias voltage.

CONCLUSION

RF power circuits often avoid operating MOSFETs in their linear region to achieve high power efficiency. Instead, switching MOSFETs are driven in Class C, Class D or Class E pulsing mode to minimize the time that a MOSFET spends in its linear region, and then use heavy filtering to smooth out and linearize the output pulses. We conclude from the data however, that a high voltage switching MOSFET, can be configured to carry out linear Class A type amplification by biasing in its linear region with a very low impedance (e.g. 50 ohms) driver stage, to get much higher efficiencies. This can go a long way to minimize filtering of the amplified signal. One advantage of using these switching MOSFETs for RF power is the ability for higher voltage operation when compared with the lower voltage lateral diffused MOSFETs that are normally considered for linear operation. Another advantage is cost because the switching MOSFETs are more plentiful and much lower cost. Yet another advantage, which prompted this study, was the ability to amplify larger RF power at high voltage without heavy filtering to remove the harmonics. Although not often considered, heavy filtering causes transients, signal pulse delays and other non-linearities, which we needed to avoid. The comparative effects on 2nd and 3rd harmonic generation seen in the graphs indicate that a VDMOSFET can be selected with a suitable gate bias voltage to achieve good power efficiency with at least 99% signal purity and in some cases much better than this. We also conclude that higher capacitance (i.e. higher current rated) devices should be used, which reveals higher efficiency when using higher gate capacitance devices. These advantages accrue only at frequencies above audio, starting at about 1.5 MHz. Furthermore, lower applied gate bias is needed at the higher frequencies. Due to signal generator limitations higher frequencies were not evaluated, although good results were obtained at 2 MHz, 5 MHz, 10 MHz and 14.15 MHz.

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