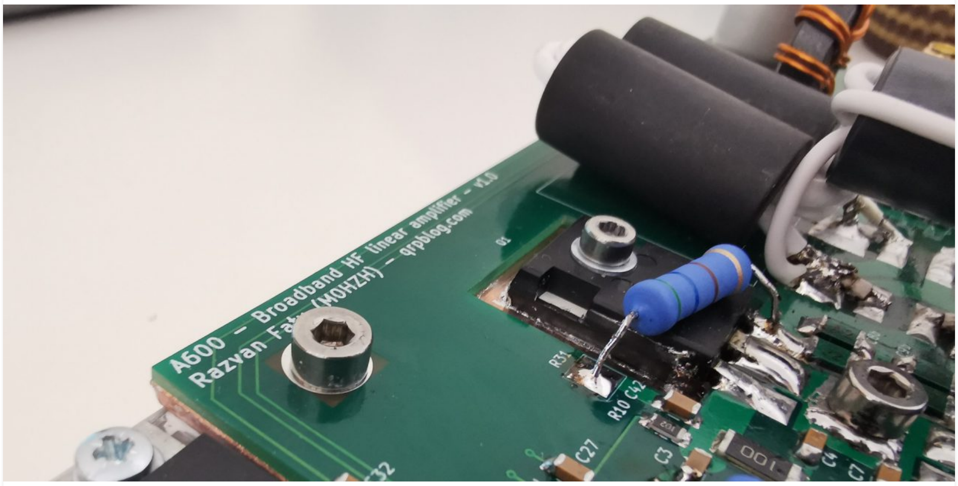
QRPblog

A 600W BROADBAND HF AMPLIFIER USING AFFORDABLE LDMOS DEVICES

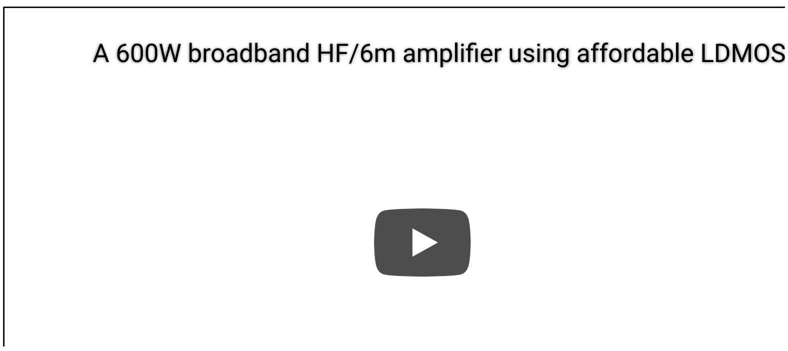
Posted by Razvan | Oct 27, 2019 | In the shack | 84 | ★★★★★



Update: this project is evolving. See this page for the latest version. Kits are available in the shop area.

The announcement of the MRF300 and MRF101 transistors by NXP in 2018 has generated quite a spark of interest in the amateur radio community and as soon as I learned about them I wanted to get some on my workbench.

And of course they're interesting: you get the latest LDMOS technology, they're designed for medium-high power levels (where the offer is not as rich) and are being offered in affordable plastic packages. It almost hits the impossible "quick, easy and cheap" trifecta … if only there would be a design out there that amateur radio enthusiats could use as a starting point for their projects. Well, with the article below we're hopefully a step closer to that point.



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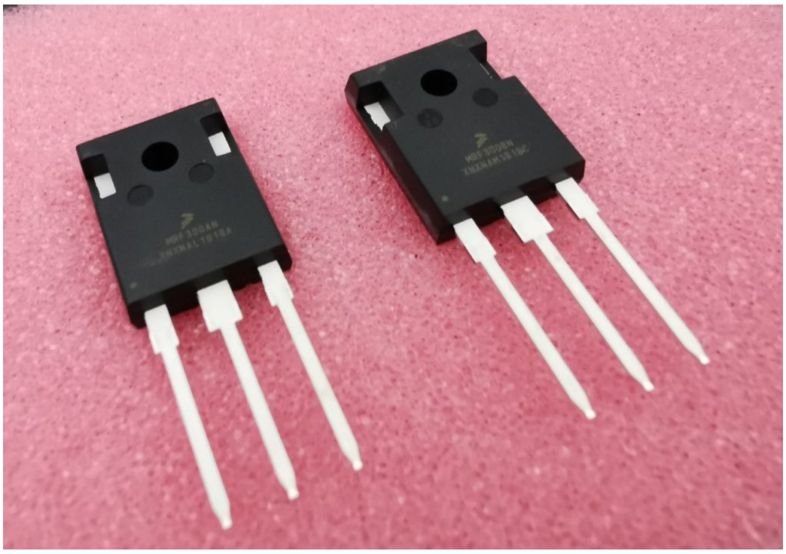
This project is meant to demonstrate the capabilities of the MRF300 transistors as linear broadband devices in the 2-50MHz range and to be used by radio amateurs as a starting point for a medium-high power amplifier. This is also my entry to the NXP Homebrew RF Design Challenge 2019.



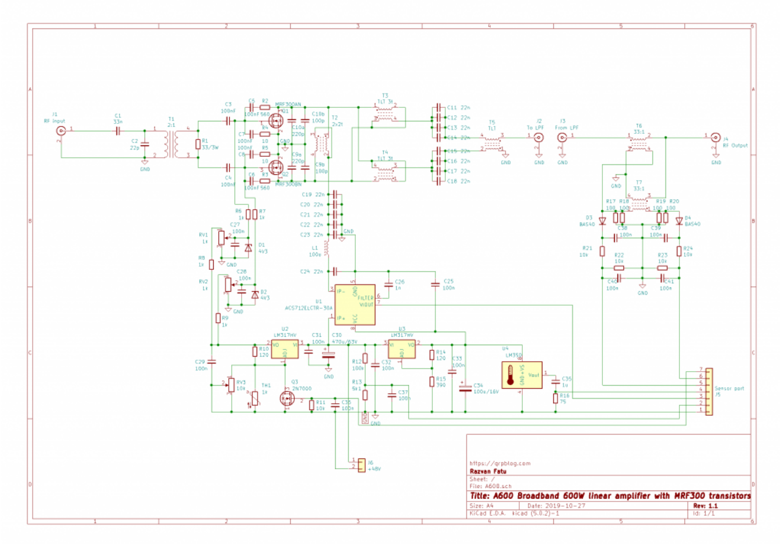
To achieve the target of 600W output while also minimizing the level of even-number harmonics, a "push-pull" configuration of two transistors is used. Luckily, the manufacturer made it easy to design the PCB layout for such a thing by offering two versions (the MRF300AN & MRF300BN) that have mirrored pinout. The common TO-247 package is used, with the source connected to the tab.

Each individual MRF300 LDMOS transistor is specified at 330W output over a 1.8-250MHz working frequency range, a maximum 28dB of gain and over 70% efficiency. The recommended supply range is 30-50Vdc. By studying the specifications, it looks like with correct broadband matching and some operational safety margin we can get close to 600W output at a voltage of around 45V across a resonably large bandwidth; the aim is to cover 1.8 to 54MHz.

Main challenges when designing this amplifier are related to achieving good input and output matching over the entire frequency range as well as maintaining high and flat gain. Good linearity and a low level of harmonic products are mandatory. As the TO-247 is not a package specifically designed for high-power RF, there are some challenges with thermal design and PCB layout as well.

CIRCUIT DESCRIPTION

The circuit schematic can be seen below. For input a 4:1 transformer is used, along with a 33ohm resistor (R1) that partially dampens the reactive response and improves input matching.



Circuit schematic – click to enlarge

The idle current for the MRF300 LDMOS transistors is set at 300mA each, with a bias gate voltage of around 2.7V. To achieve this value, a LM317HV high voltage linear regulator takes the supply voltage and adjusts it down to a value around 8-10V, which is further divided down to the exact value via individual adjustable multi-turn potentiometers. A negative-coefficient thermistor is present in the regulator's feedback loop so when the heatsink temperature increases the MRF300 gate bias voltage decreases slightly in order to maintain the same idle current. An external signal can cut off this voltage in order to reduce power consumption when the amplifier is not used.

The 560 ohm resistors (R2 and R3) provide negative feedback, making the amplifier more predictible in response and improving IMD performance. For a small increase in overall gain, it is worth investigating increasing their value.

Matching the output to 50ohm is where the real challenge is. For maximum efficiency across a large bandwidth, transmission line transformers (TLT) are the best option and the closest transformation ratios possible are 1:4 or 1:9. With 50V supply and a 1:4 transformer, the maximum output power that can be obtained is around 400W as the theoretical load impedance for each transistor is too high. With a 1:9 transformer higher power can be achieved but the matching becomes more critical; the supply voltage can be reduced below 50V in order to improve efficiency, but current needs to be actively monitored and kept in the safe area (below 20A in total).

The two sides of a broadband 1:9 TLT transformer

For minimal losses, the coaxial cable used in the TLT has to have a characteristic impedance that is the geometric mean of the input and output impedances. As this is a

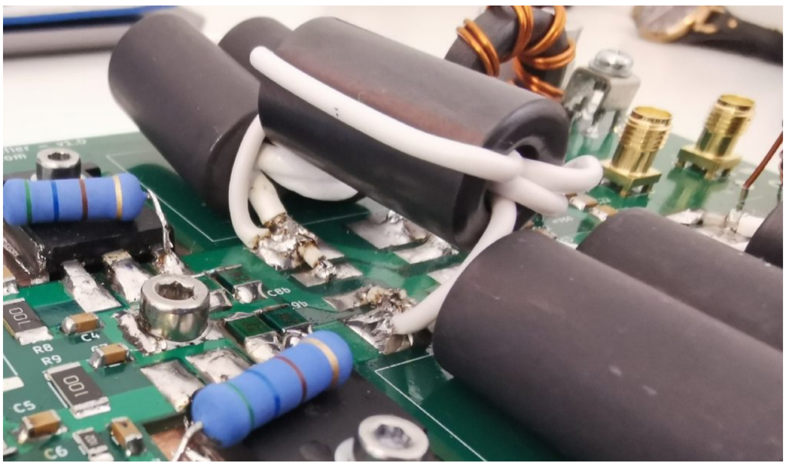
1:9 transformer and the output has to be 50ohm, the input impendance works out as 50/9 = 5.56ohm and the coax characteristic impedance is sqrt(50*5.56) = 16.67ohm. I chose TC-18 coaxial cable specifically designed for this purpose, that has 17ohm impedance and uses high quality materials so it can handle high power and temperature. 3 lengths of RG-316 in paralel can be used as well in order to achieve the 17ohm impedance, but RG-316 is harder to work with and it might be a challenge to fit it 9 times within usual ferrite cores.

The length of coaxial is best kept short in order to maintain efficiency at high frequencies, ideally below 1/10 of a wavelength at the maximum frequency. 30cm is enough for 3 turns through the popular 26xx540002 bead ferrite cores from Fair-Rite and taking the ~0.7 velocity factor into account, it stays below that.

Choosing the ferrite core for the output transformer is key to achieve the best performance. The first prototype used Fair-Rite 2667540002 ferrite beads (material 67) in an attempt to achieve the widest working range possible with best efficiency; this sacrifices performance in the lower amateur radio bands, as below 10MHz there is a significant drop in efficiency. Laird 28B1020-100 cores have been tested as well, with relatively similar performance to the material 67 Fair-Rite cores.

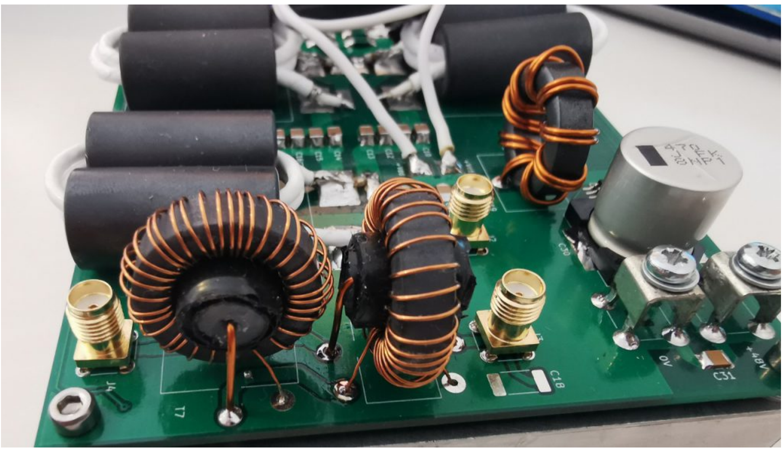
Some of the ferrite cores evaluated for this project

In the second design 2661540002 cores are used. Material 61 has higher permeability than 67 (125 vs 40), providing suffcient choking inductance at 1.8MHz even if it could become slightly lossy at higher frequencies. Material 43 (850ui) is a good candidate as well and should also be investigated.



A 2×2 turn transformer built on a separate 2643540002 (material 43) core is used to supply DC voltage to the LDMOS' drains. This proved a key component as well, as performance below 10MHz is affected by its configuration. The 1:9 output transformer is followed by a 1:1 choke BalUn that makes sure the output is rid of any common mode current.

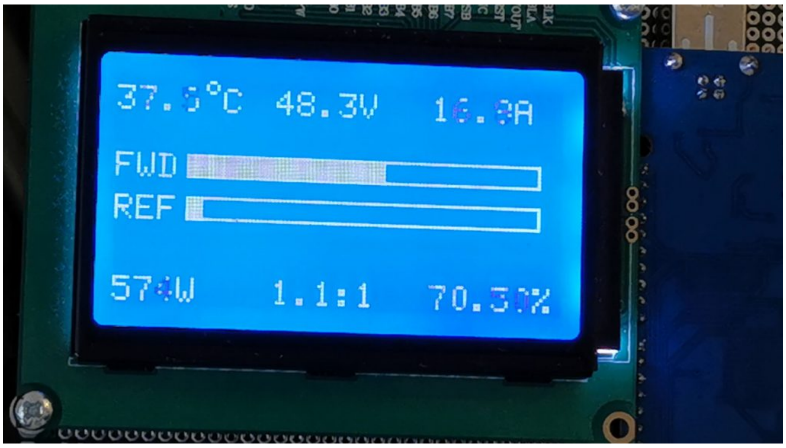
The board is fitted with two SMA connectors where a bank of low-pass filters can be inserted, in order to further diminish the harmonic contents at the output; as this is is not the purpose of this article, a straight jumper cable is installed instead.



The output of the amplifier board includes a tandem coupler designed to measure the output and reflected power. The signals are provided via a 7 pin header connector, that also outputs a fraction of the main supply voltage, a current measurement (achieved with an ACS713 Hall sensor) and a temperature measurement (from a LM35D precision temperature sensor).

48Vdc input with filtering and current sensor IC

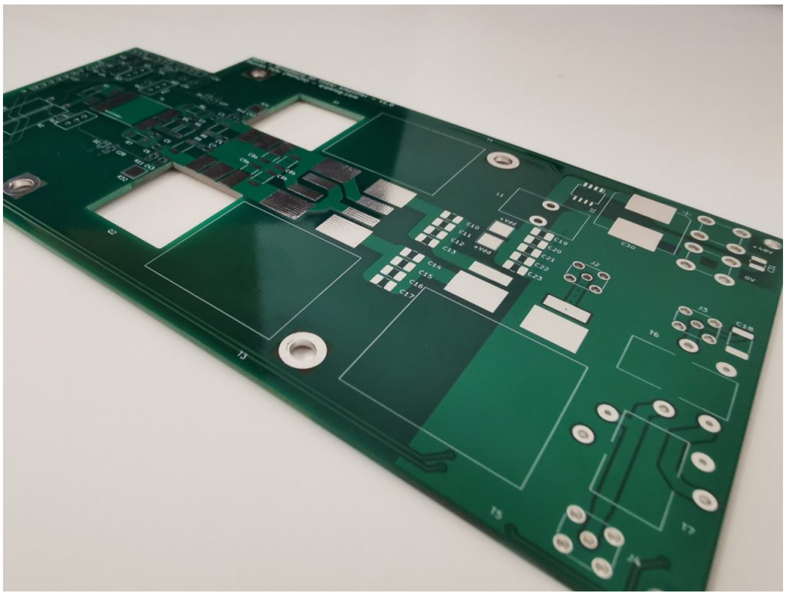
These signals can be used to measure the performance of the amplifier and can also be used to implement fast-acting protection logic for overvoltage, overcurrent, overheating, output mismatch etc with the help of additional circuitry.



Above you can see the Arduino based monitoring tool that offers accurate measurement and has been used during the development of this circuit. Its precision has been verified against multiple industrial equipments and calibrated where necessary.

THE PRINTED CIRCUIT BOARD

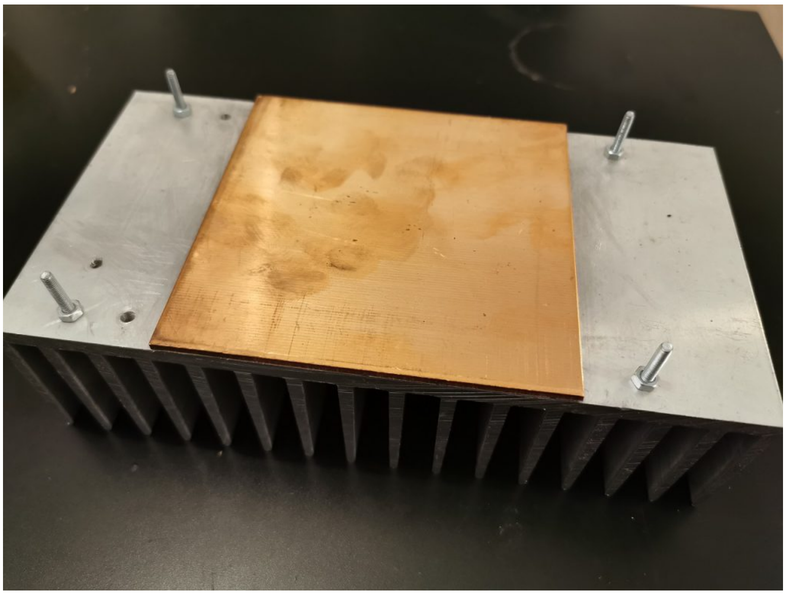
With high-power RF devices, it is always important to have a very good, solid and continuous ground plane. Because the MRF300's Source is connected to the tab, the heatsink will be used as a ground plane and the PCB is designed with that in mind; the bottom PCB layer is also used as a ground plane, as it comes in contact with the heatsink over a large area.
SMD parts are used where possible, in order to minimise stray inductance. The power traces are thick in order to support the high current and the RF traces have been sized for the right trace impedance where possible.



For the schematic and PCB design I've been using KiCAD, which is is good as it gets for free software; the files generated by KiCAD can then be sent to a PCB manufacturer. I have used PCBway for this, the process is as simple as creating an account and uploading your files (they have a quick guide on how to do this if you haven't done it before). They check your files and send them to production and if you choose DHL delivery you could get the finished product in just a few days. Tip: if you manage to keep your PCB under 100x100mm, they only charge US$5 for 10 pieces (!). This is insanely cheap for hobbyists.

THERMAL DESIGN

One of the critical points with high power transistor amplifiers is keeping them cool. The datasheet Mean Time To Failure (MTTF) for the MRF300 is about 70,000 hours for a current of 8.7A and a junction temperature of 175C, so the cooling system needs to keep the transistors below that temperature at all times. As the junction-to-case thermal resistance is 0.55C/W and we expect a maximum thermal dissipation of about 200W per device, this means the case temperature can't go over 65C.



An intermediary 3mm thick copper plate is installed between the transistors and the aluminium heatsink, as copper has better thermal transfer properties and offers a path of lower resistance for the thermal energy from the two tiny (1.7 square centimeters) power transistors to the entire heatsink base.

To make sure we have minimal resistance transferring heat from the transistors to the copper plate, the surfaces have to be perfectly even & clean, enough pressure is applied and a Thermal Interface Material (TIM) is used. Usually the TIM is a silicone-based grease that requires high pressure to be applied and is often electrically insulating; as we are using the heatsink as a ground plane as well, we want the electrical contact to be as good as possible. Alternatively, some transistors can be soldered directly to the copper plate, but this is a rather permanent process, requires a special oven for the best results and doesn't really work with the MRF300's TO-247 packaging.

Liquid metal applied before mounting the transistors on the heatsink

My choice was to use the best of both worlds: metal, but liquid. More precisely, an eutectic alloy of soft metals (tin, gallium and indium) called Galinstan. Depending of the mix ratios, this alloy is liquid at room temperature, naturally adheres to other metals, offers exceptional thermal and electrical conductivity and doesn't require much pressure to achieve best performance. The disadvantage is it is expensive, corrodes aluminium agressively and it's a bit difficult to contain. Luckily, you can find it in a few commercial flavours as a computer cooling TIM that includes the kit necessary to apply it correctly. I chose Thermal Grizzly Conductonaut but I understand Coollaboratory Liquid Metal Pro is just as good. A totally unecessary better option would be pure Indium pads (like the Indium Heat-Spring), but these are much too expensive for this purpose and also quite difficult to source.

Assuming a conservative 0.1C/W thermal resistance from transistor case to the aluminium heatsink and an environmental temperature of 30C, the thermal resistance of the heatsink to air adds up to 0.0775 C/W (for both transistors, 400W dissipation in total). Heatsink manufacturers will provide this figure sometimes as a chart, depending on airflow. With the help of a microcontroller we can design a fan controller that will regulate the fan speed so it follows this chart and only reach 100% when temperature gets close to the limit (calculated here at 61C for the aluminium base). The heatsink's thermal inertia can help keep sudden fan speed variations in check, so a larger copper base might be useful.

Machining the heatsink (and especially the copper plate) is challenging, as copper is soft and will load the drill bit until it gets stuck and breaks. The tricks are to use a cutting fluid and a slow speed; lard seems to be very good for lubrication and it really makes drilling much much easier, the brand I've used is Monument White Tallow Medium. Tapping the screw holes afterwards was easy, all it needs is patience. I had to be careful not to get TIM close to the bolts that hold the transistors down, as those reach the aluminium heatsink base and it would corrode it.

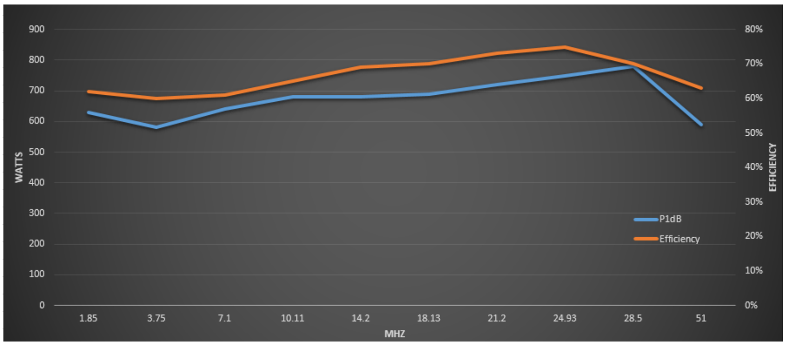
TEST SETUP

This is a homebrew project, so the test setup is pretty typical of a hobbyist's test bench. Most of the equipment is not of lab-grade precision, but still accurate enough for amateur radio.

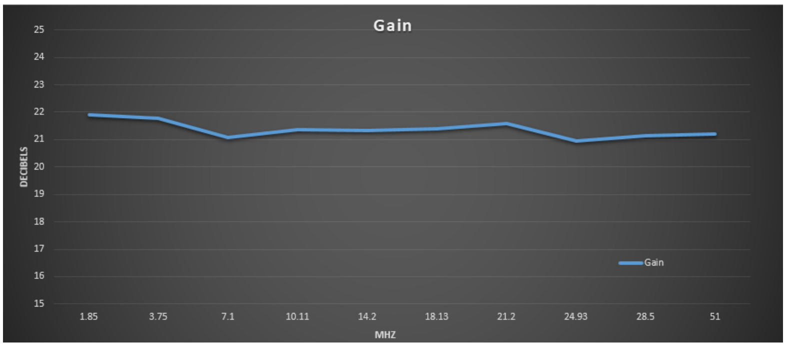
- Power supply: HP ESP120 3kW telecommunications PSU
- PSU for accessories: Daiwa PS-304
- Dummy load: MFJ-264 1.5kW 50ohm with -40dB output port
- Signal source: Xiegu G90 and Xiegu X5105
- Input power & SWR meter: MFJ-929
- Output power & SWR meter: Avair AV-600 (for measurements under 400W)
- Oscilloscope & FFT analyser: Hantek DSO5102P
- Multimeters: Uni-T UT61E, Uni-T UT31C, Amprobe 5XP-A
- VNA: nanoVNA (for testing input & output transformers and matching)

MEASUREMENTS

The results have been compiled into these charts:



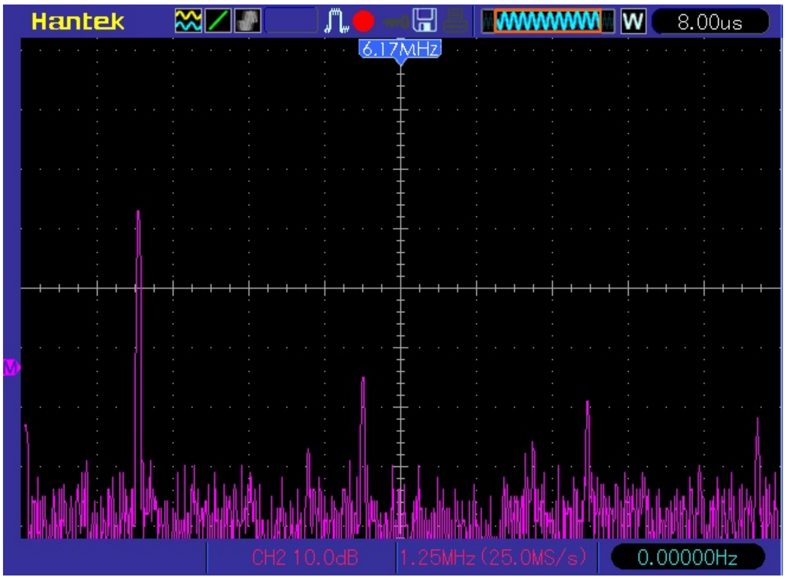
P1dB output power and efficiency



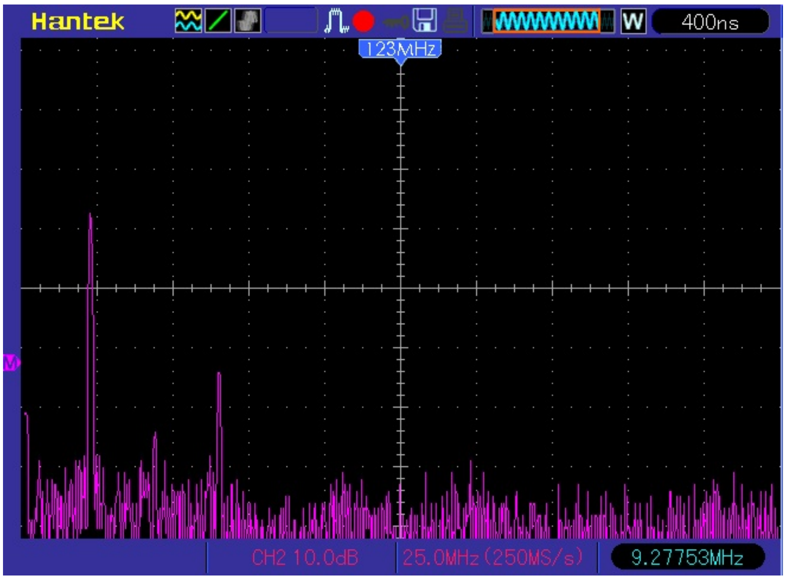
Gain at P1dB

The amplifier is slightly under 600W (about 580W) at 3.7MHz (the 80m band) and works most efficiently in the higher bands. The highest output power I've measured was 840W (!) in the 10m band, but the wave was distorted and the harmonic levels were high. Around 750-780W the output is still clean enough, but it's debatable if that's a safe operating area.

Without pushing it over the limit, the harmonic levels are quite low and close to what the signal source measures. Here are two examples below; keep in mind the measurement is in voltage, so for RF power the vertical scale is double (20dB/div instead of 10dB/div).



Output harmonics at 1.85Mhz



Output harmonics at 21.3MHz

As a conclusion, I think these new devices are excellent. Leaving the performance aside, during the development of this amplifier I've abused this pair of transistors in many ways, including driving them into short and open loads, using them with sub-par cooling and massively exceeding the drain current. They're still alive and well.

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ABOUT THE AUTHOR

Razvan

Interested in computers, electronics, building radio equipment, portable/SOTA operations and SDR. I think amateur radio is all about building, experimenting and testing new stuff. Licensed M0HZH / YO9IRF.

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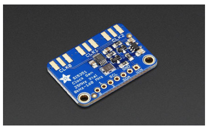

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