A High Efficiency Switchmode RF Amplifier using a MRF101AN LDMOS Device for a CubeSat Plasma Thruster

2019 NXP Homebrew RF Design Challenge

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1 Introduction

As space launch costs continue to decrease, standardized satellite platforms such as the "CubeSat"[1] are going to become more common. Standardized satellite platforms allow for the reuse of assemblies and component design, reducing cost and increasing accessibility to both research and commercial organizations. One important satellite component is a thruster, which allows control of orbit and orientation. However, the CubeSat platform is relatively small (10cm x 10cm x 10cm) and many thruster technologies do not scale down well in size. One promising technology for small satellite thrusters is the inductively coupled plasma thruster, which generates thrust from a jet of plasma created by inductively exciting a gas propellant as it passes through a plasma cavity. Development of the inductively coupled Pocket Rocket plasma thruster is ongoing as part of the Pocket Rocket project at the Space Plasma and Plasma Propulsion Laboratory at Australian National University with the RF amplifier being designed by members of the Stanford University Power Electronics Research Lab. Figure 1 shows an earlier capacitively coupled plasma thruster being tested in a vacuum chamber as part of the Pocket Rocket Project. This page documents the design of the RF amplifier for the thruster system, which uses the MRF101AN LDMOS device in a high efficiency switchmode amplifier, and constitutes our entry to the NXP Homebrew RF Design Challenge. Design and simulation files for this project are available at `https://github.com/westonb/Plasma-Driver`.

2 Design Requirements

A RF amplifier is required to drive the plasma cavity for the thruster. The current design of the plasma cavity requires a power of 30W to 40W at a frequency of 40.68MHz. During operation the exact power level is controlled by varying the supply voltage to the RF amplifier. Due to the limited power budget on cube satellites and the difficulty in dissipating large amounts of heat in the vacuum of space, it is advantageous that the RF amplifier be highly efficient. To meet this requirement we chose a switchmode topology, Class E, which operates the active device in saturation and has higher efficiency than topologies such as Class A or Class C which operate the switch in the linear region.

Due to the high cost of satellite launch and inability to repair systems in orbit the amplifier needs to be highly robust, both thermally and electrically. However, the plasma cavity presents a significant impedance mismatch in the short period between when power is excited and the plasma ignites, which can cause damaging electrical transients and

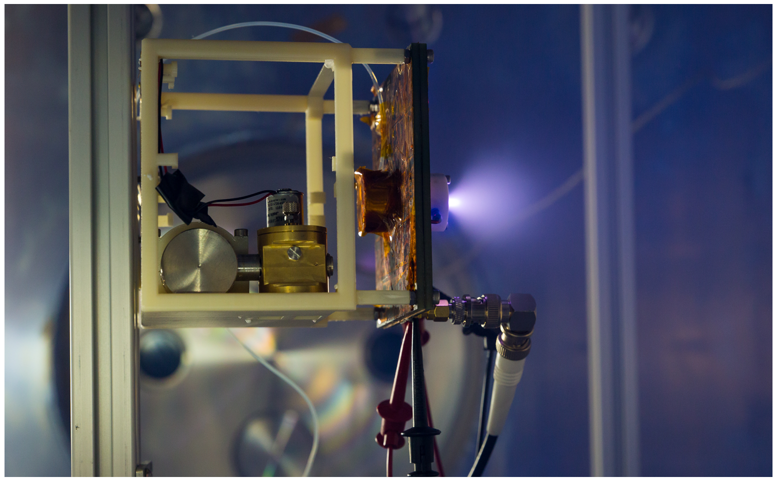


Fig. 1: Capacitively coupled version of the Pocket Rocket plasma thruster being tested at the Australian National University Wombat space simulation chamber[2]

excessive power dissipation. This complicates the design because switch-mode power amplifiers, such as Class E, are especially vulnerable to mismatch conditions because of their nominally high efficiency and the sensitivity of the tuning of load network to changes in load impedance.

A previous iteration of the RF power amplifier used a GaN HEMT commercially available for use in switch-mode power supplies but the design had challenges with thermal and electrically reliability. GaN HEMT devices do not avalanche in response to over-voltage conditions, unlike silicon LDMOS devices such as the MRF101AN, and thus are more easily damaged due to electrical transients arising from impedance mismatches. Additionally, the GaN HEMT was in a small package that had a relatively high thermal impedance and was not robust against periods of high power dissipation during impedance mismatch. The MRF101AN LDMOS device addresses the issues that were experienced with the previous GaN HEMT version due to the electrical robustness of the LDMOS process and TO-220 case which allows for greater power dissipation. When compared to other LDMOS devices the MRF101AN has an extended gate voltage range which allows for a high RF drive level to ensure that the device operates in saturation, which is important for Class E operation.

3 Design

The Class E amplifier utilizes the active device as a switch, operating in only cutoff (off) and saturated (on) conditions. This minimizes the overlap of voltage and current, reducing losses in the active device. To further reduce loss the Class E amplifier utilizes an inductively tuned resonant network to achieve zero voltage switching, bringing the voltage across the switch to zero before turn on, eliminating energy stored in the output capacitance of the active device that would otherwise be dissipated. This is achieved with an inductively tuned series resonant output filter. The design equations for the Class E amplifier can be found in [3], which determine the magnitude of the inductive loading required and the value of the drain source capacitance, part of which is provided by the switching device itself.

In the Class E amplifier losses are almost entirely determined by the current conducted by the active device so a high drain impedance is desired to maximize efficiency. The drain impedance is ultimately limited by the voltage rating of the switch. For our desired output power of 40W and the maximum voltage rating of 133V for the MRF101AN this impedance is still less than 50 ohms, so a L match circuit is used to match the drain impedance to 50 ohms. The load network in our design provides a drain impedance of 15.4+12.8j.

As the MRF101AN will operate in saturation a high drive level is desired. To eliminate the need for a preamplifier and allow for digital control, we use a high speed gate drive chip typically used in switch-mode power supplies, LMG1020, to drive the MRF101AN instead of a RF preamplifier. A resonant network is used to provide voltage gain at the fundamental and third harmonic, providing a quasi-square wave on the gate which helps insure the device remains in saturation. A design procedure for this resonant gate drive scheme is detailed in [4].

As only S-parameters intended for use in linear amplifier design are publicly available for the MRF101AN, a SPICE model was created using the plots and values provided in the datasheet. This allowed for the initially calculated component values to be verified in simulation before fine tuning on the prototype amplifier. The parameters of the SPICE model are provided below:

```
.model MRF101AN VDMOS(Rg=4 Rd=1 Rs=0.1 Vto=2.2 Kp=7.1 Lambda=0 mtriode=0.692 subthres=1.07m
Cgdmax=5p Cgdmin=1p Cgs=130p Cjo=130p M=0.4 Vj=2.3 BV=140 tt=1n)
```

A simplified schematic diagram of our design is provided in Figure 2 with component information provided in Table 1.

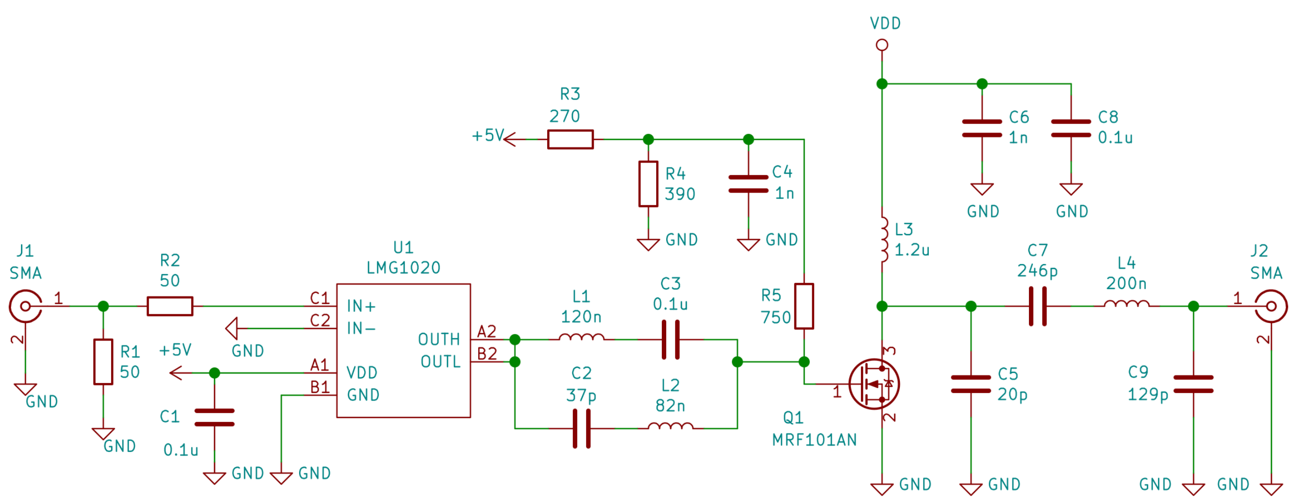


Fig. 2: Simplified schematic diagram of the Class E amplifier

4 Prototype

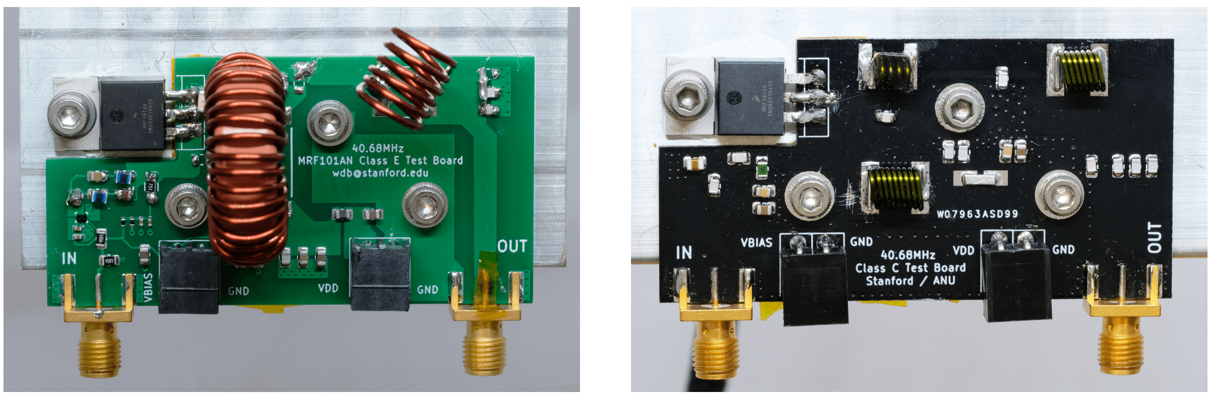
The final plasma thruster system for the CubeSat will have the RF amplifier as part of a larger integrated system with monitoring and a DC/DC converter to control output power by varying the supply voltage. Here we present a first prototype of the amplifier to evaluate the performance of the MRF101AN in Class E operation and for use in preliminary vacuum testing. Additionally, for comparison, an amplifier based on the reference design for 40.68MHz provided in the MRF101AN datasheet was constructed [5]. Kicad PCB files and SPICE simulatin files for the prototype

Table 1: Class E amplifier component details

Component	Implementation
Q1	NXP MRF101AN LDMOS
U1	LMG1020 Gate Dive IC
L1, L2	Coilcraft 805HP
L3	30 turns, T106-0 Core
L4	5 turns, 18AWG, 12mm diameter
C1, C3, C8	X7R SMD Chip
C2, C4, C5, C6,C7,C9	C0G SMD Chip

are hosted at `https://github.com/westonb/Plasma-Driver`.

The prototype occupies a 65mm x 35mm two layer PCB (1.6mm, 1oz copper, FR-4) and the PCB and MRF101AN was mounted on a section of aluminum extrusion heatsink with thermal grease. Figure 3 provides a photograph of the prototype Class E inverter and our implementation of the reference design.



(a) (b)

Fig. 3: (a) Class E prototype amplifier and (b) our implementation of the MRF101AN reference design

5 Testing

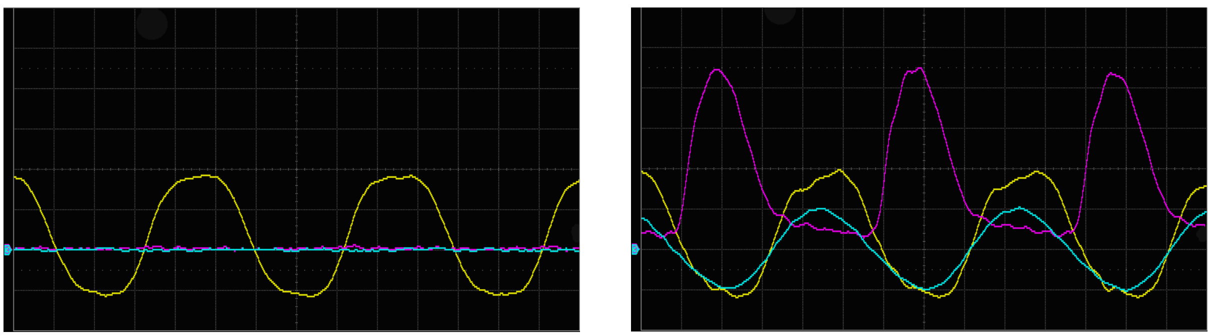
The Class E amplifier prototype and the amplifier reference design were both tested at 30W and 40W. A Agilent N1914A power meter and Werlatone C5827-10 directional coupler were used to measure RF power delivered to a 50 ohm load and input power from a Rigol DP832 supply was measured with a pair of Agilent 34401A multimeters. For both amplifiers supply voltage was used to control output power. The reference design had bias current adjusted to 100mA and was drive power was adjusted until gain saturation was achieved to optimize efficiency. Table 2 provides drain efficiency (RF output power / DC supply power) and conditions for the tests comparing the Class E amplifier with the reference design. The drive power for the Class E design is the DC power for the gate drive IC while it is the RF input power for the linear design. Although the Class E design requires greater drive power this is DC input power and a preamplifier required to provide the RF drive required for the reference design would likely require a higher DC input power.

In Figure 4 we provide gate waveforms before drain voltage is applied and gate, drain, and output waveforms of the Class E amplifier under testing at 30W output. The gate waveform becomes mildly distorted under operation due

Table 2: Test data comparing Class E amplifier with reference design

	Supply Voltage	Output Power	Drive Power	Drain Efficiency
Class E	32.8V	30.1W	0.65W	91.3%
Class E	37.5V	40.0W	0.65W	91.1%
Reference Design	23.8V	30.1W	0.5W	80.3%
Reference Design	27.6V	40.0W	0.5W	80.7%

to coupling through the drain to gate capacitance, but voltage is still enough to maintain operation in the saturated region. Although not critical in this application, it can also be observed that the output waveform has relatively little harmonic distortion. The peak drain voltage for a 30W output is 90V and for a 40W output is 110V. Both of these values are less than the rated maximum of 133V and should provide sufficient margin given the avalanche capability of LDMOS devices.



(a) (b)

Fig. 4: (a) MRF101AN gate waveform before drain voltage is applied (b) Gate, drain, and output waveforms for 30W output power. For both waveforms gate voltage in yellow (10V/div), drain voltage in purple (20V/div) and output voltage in turquoise (50V/div). Timebase is 5ns/div.

6 Conclusion

Our Class E amplifier design using the MRF101AN achieved a 91.1% efficiency at an output power of 40W. This represents a 57.5% decrease in power dissipation compared the linear reference design. We also created a SPICE model of the MRF101AN to aid in the design of switch-mode RF amplifiers using the device.

The high efficiency of the Class E amplifier and the electrical and thermal robustness of the MRF101AN LDMOS when compared to a GaN HEMT makes this design a good fit for the Pocket Rocket inductive plasma thruster where reliability and low power dissipation are important. Vacuum chamber testing of the updated design will happen shortly.

References

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[5] "MRF101AN, MRF100BN 100 W CW, 1.8-250 MHz, 50 V Data Sheet," https://www.nxp.com/docs/en/data-sheet/MRF101AN.pdf.