

# Miniature High-Voltage DC-DC Power Converters for Space and Micro-Robotic Applications

Sanghyeon Park, Aaron Goldin, and Juan Rivas-Davila  
 Department of Electrical Engineering  
 Stanford University  
 Stanford, CA 94305  
 Email: spark15@stanford.edu

**Abstract**—We develop a small and lightweight high-voltage high-gain power converter for applications where weight and size are premium. By driving a Dickson and Cockcroft-Walton voltage multiplier with a megahertz-frequency class-E inverter, we implement two converters, one that achieves 40 V-to-2 kV conversion with 16 cm<sup>3</sup> box volume and the other that achieves 3.7 V-to-2.9 kV conversion with 0.2 cm<sup>3</sup> box volume and 0.49 g weight. Presented converters achieve comparable or better power density and specific power to those of commercial high-voltage power supplies.

## I. INTRODUCTION

High-voltage power converter ranging a few kilovolts is often necessary in many applications where weight and size are premium. Such applications include propulsion systems for small-sized satellites and actuators for micro-scale robots. Since the system weight hugely influences the cost of a space mission or the maneuverability of the micro robots, a power system with a high power density and light weight is desirable.

This paper discusses design and implementation of high-frequency high-voltage power converters for powering a small satellites and micro-scale robots. Section II describes the 40 V-to-2 kV cubic-inch converter for satellite applications. Section III describes the 3.7 V-to-2.9 kV, 0.2 cm<sup>3</sup>, 0.49 g converter for micro-robotic applications motivated by DARPA SHRIMP program [1]. Section IV concludes the document.

## II. CUBIC-INCH CONVERTER

### A. Planar design implementation

Fig. 1 depicts the electrical model of the dc-dc converter. A class-E inverter generates a high-frequency ac voltage which is subsequently filtered by the intermediate LC filter and delivered to the charge pump. For the input inductance  $L_1$  of the inverter, either a regular dc-choke (infinitely large) inductance or a finite inductance can be used [2], [3]. For this project, the finite inductance design scheme is used since smaller inductance often leads to smaller size and lighter weight of the circuit.

The charge pump (rectifier) part in Fig. 1b can be replaced with an RC equivalent circuit to yield the equivalent dc-dc converter model in Fig. 1b. Since the circuit of Fig. 1b

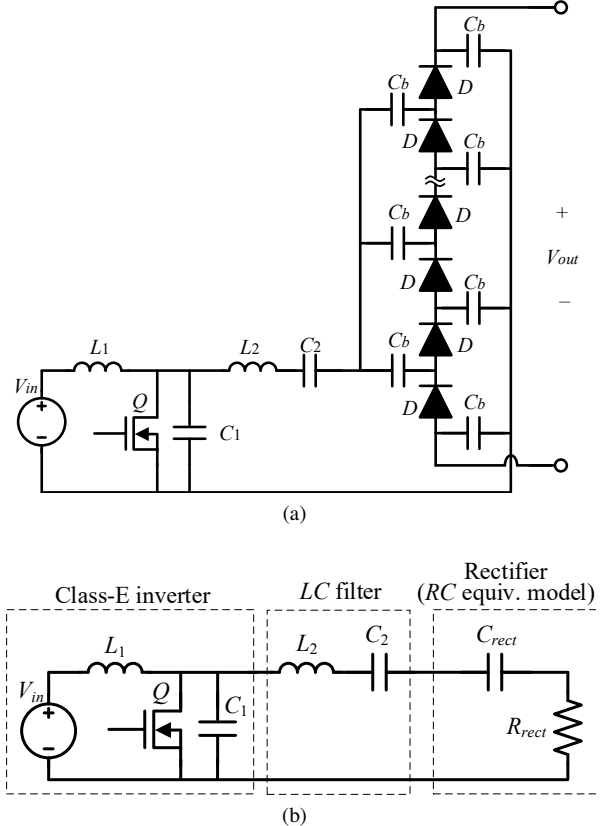


Fig. 1. Electrical model of the developed dc-dc converter. (a) The schematic of the high-voltage dc-dc converter. (b) The equivalent circuit of the dc-dc converter.

matches the conventional class-E power amplifier structure, one can readily use design equations for class-E inverters from existing publications (e.g., [4]) to determine inductances and capacitances.

Based on the well-known analysis and design steps for Dickson charge pumps and class-E inverters, we determine circuit parameters and select parts as shown in Table I. Names of variables and parts in Table I are in reference to the schematic in Fig. 1a.

Fig. 2 shows the implemented 40 V-to-2 kV dc-dc power converter. The developed power converter measures 63.5 mm × 50 mm in terms of the board area, which is about three

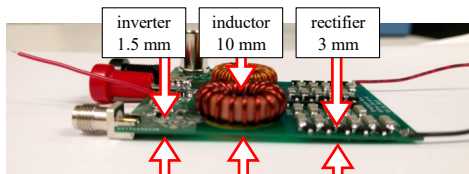
This material is based upon work supported by the National Science Foundation under Grant No. 1808489, and by the National Aeronautics and Space Administration under Phase I SBIR Proposal No. 18-1-S3.03-8502.

TABLE I  
CIRCUIT PARAMETERS AND PARTS USED FOR THE 40 V-TO-2 kV POWER CONVERTER IMPLEMENTATION. VARIABLE AND PART NAMES ARE IN REFERENCE TO THE SCHEMATIC IN FIG. 1A.

$V_{in}$	$V_{out}$	output power	$L_1$	$C_1$
40 V	2 kV	16 W	300 nH	174 pF
$L_2$	$C_2$	$C_b$	$D$	$Q$
450 nH	472 pF	33 pF	BAT240 Infineon	GS66502B GaN Systems



(a)



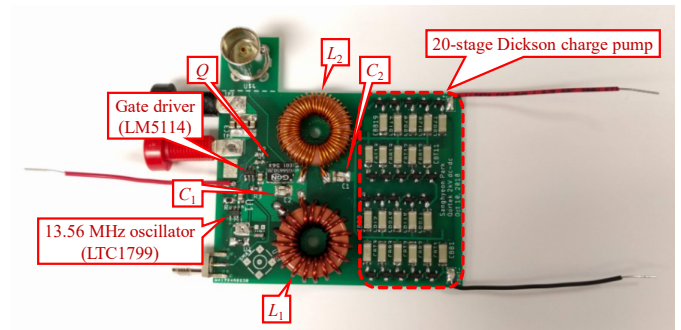
(b)

Fig. 2. Photographs of the planar 40 V-to-2 kV dc-dc converter. (a) Top view. The circuit measures 5 cm  $\times$  6 cm, and is shown next to a business card for size comparison. (b) Side view. The thickness of the developed power converter (including the 0.6 mm-thick circuit board) is: 1.5 mm for the inverter side, 10 mm for inductors, and 3 mm for the rectifier side.

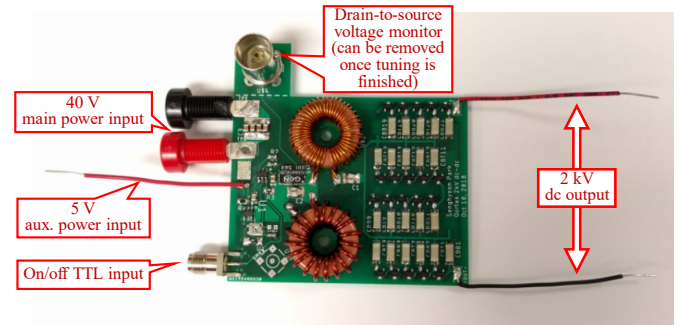
quarters the size of a typical business card or a credit card (Fig. 2a). In terms of the thickness, the inverter is 1.5 mm-thick, the inductor 10 mm-thick, and the rectifier 3 mm-thick, all including the thickness of the 0.6 mm-thick FR4 circuit board (Fig. 2b).

Fig. 3 describes the placements of electrical components (Fig. 3a) and input / output external connectors (Fig. 3b). As indicated in Fig. 3b, the converter requires a 40 V main power supply, a 5 V auxiliary power supply, and a 5 V TTL signal to turn on or off the circuit.

The weight of the circuit is measured 17.3 g, not including the input and output connectors (two banana connectors, one SMA connector, and one BNC connector). They are installed only for the test purpose and can be removed when this circuit is integrated into the full system. When the weight of connectors is taken into account, the converter weight is measured 24.2 g.



(a)



(b)

Fig. 3. Parts placements. (a) Electronic components. (b) Input, output ports and connectors. The BNC connector at the top is installed to monitor the drain-to-source voltage of the transistor, and can be cut off along the white dotted line without affecting the power converter operation.

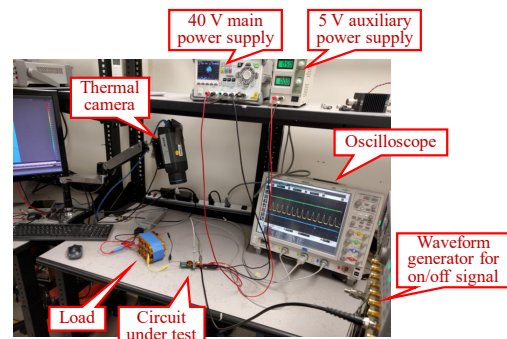


Fig. 4. Experimental setup to test the performance.

### B. Planar design test results

Fig. 4 shows the experimental setup to measure the electrical performance of the power converter. Four variables are constantly monitored and recorded, namely, the transistor drain-to-source voltage  $v_{ds}$ , the output dc voltage  $V_{out}$ , the on/off signal TTL input, and the temperature of the circuit.

Fig. 5a shows measured waveforms of  $v_{ds}$  and  $V_{out}$  at the steady state. The on-chip oscillator drives the transistor at 13.56 MHz switching frequency. The transistor voltage stress is 174 V. This value is higher than typical value for a class-E inverter which is 3.6 times the input voltage, because the duty ratio of this transistor is slightly over 50 %. The waveform of  $v_{ds}$  clearly shows zero-voltage switching, which assures

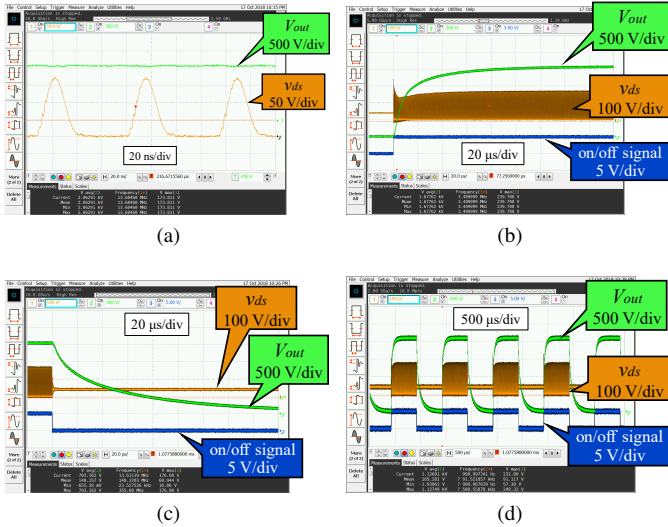


Fig. 5. Measured waveforms of the planar power converter. (a) The transistor drain-to-source voltage  $v_{ds}$  and the output voltage  $V_{out}$  at the steady state. The  $v_{ds}$  waveform clearly indicates zero-voltage switching that eliminates switching loss. (b) Waveforms at the turn-on moment, where the rise time is measured 40  $\mu$ s. (c) Waveforms at the turn-off moment, where the fall time is measured 120  $\mu$ s. (d) Demonstration of a 1 kHz rate, 50 % duty ratio, 0-to-2 kV pulsing operation.

TABLE II  
MEASURED INPUT / OUTPUT POWER AND EFFICIENCY.

	At the turn-on moment	After 5 min. of operation
Main power	40 V, 0.485 A	40 V, 0.475 A
Auxiliary power	5 V, 0.040 A	5 V, 0.040 A
Output voltage	2.00 kV	1.95 kV
Load resistance	250 k $\Omega$	250 k $\Omega$
Efficiency	81.6 %	79.2 %

negligible hard switching loss. The average value of  $V_{out}$  is measured 2.06 kV in this waveform. The 10 %-to-90 % rise and fall times are measured to be 40  $\mu$ s and 120  $\mu$ s, as shown in Fig. 5b and 5c. These rise and fall times values allow pulsing operation of up to about 2 kHz rate. Fig. 5d demonstrates a 1 kHz pulsing capability.

Table II summarizes the measured input / output power and relevant parameters to calculate the power conversion efficiency. The efficiency is 81.6 % at the turn-on moment and degrades to 79.2 % after 5 minutes of operation, most likely due to the increased temperature of transistors, inductors, and diodes. The output power changes from 16.0 W to 15.2 W after 5 minutes, which is still above the target power of 15 W.

The power density is 18.9 W/in<sup>3</sup> based on the assumption that the board area occupied by the inverter, two inductors, and the rectifier is in 1 : 1 : 2 ratio, which gives the average thickness of 4.375 mm. If one decides to use a box volume to derive the power density, the inductor thickness of 10 mm should be used to calculate the volume. The resulting box volume power density is 8.258 W/in<sup>3</sup>. The specific power (power processed per unit mass) is 0.923 W/g when the connectors are not taken into account, and 0.660 W/g when

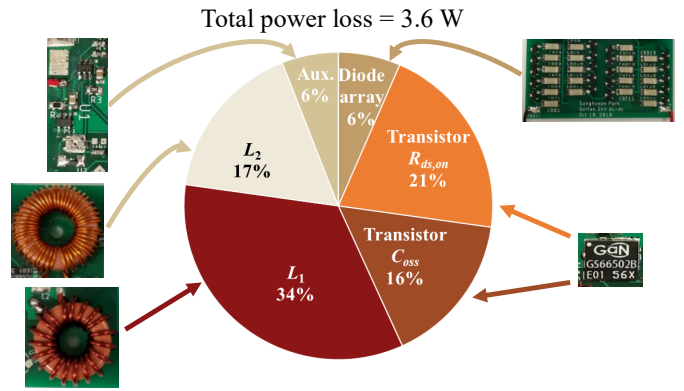


Fig. 6. Power loss breakdown of the planar design.

TABLE III  
PERFORMANCE MEASUREMENTS OF THE CUBIC POWER CONVERTER.

Performance metric	Value
Input voltage and current	40 V, 0.520 A
Output voltage	1.96 kV
Load resistance	250 k $\Omega$
Transistor voltage stress	195 V
Rise time	40 $\mu$ s
Fall time	120 $\mu$ s
Efficiency	73.5 %
Power density	15.3 W/in <sup>3</sup>
Specific power	0.773 W/g

their weight is included. Fig. 6 shows the estimated power loss breakdown.

### C. Cubic design implementation

We redesign the planar power converter so that it has a better form factor. First, we relocate inverter parts so that they occupy less board area, namely, 1 in<sup>2</sup>. Second, we break the Dickson multiplier into two and implement them on two separate 1 in<sup>2</sup> board areas. Then we vertically stack the inverter board, two inductors, and two voltage multiplier boards, all within a one-inch height constraint.

The result is shown in Fig. 7. The entire circuit is contained in a 3D-printed plastic case measuring 1 inch  $\times$  1 inch  $\times$  1 inch. The weight is 19.8 g, although it can be reduced to 14.8 g by removing the SMA connector (1.4 g) and two plastic toroidal cores (Micrometals T68-0, 1.8 g each). The inverter board at the top includes a 40 V-to-5 V buck converter that powers the oscillator and the gate driver.

### D. Cubic design test results

Table III summarizes measured performance of the cubic power converter. The power density and the specific power are 15.3 W/in<sup>3</sup> and 0.773 W/g, respectively, which are comparable to those of commercial high-voltage generators, e.g., FS20-12 from XP Power. The switching frequency of FS20-12 is specified as 25-125 kHz, so we expect that the developed converter has much faster rise and fall times, making it suitable for pulsing operation.

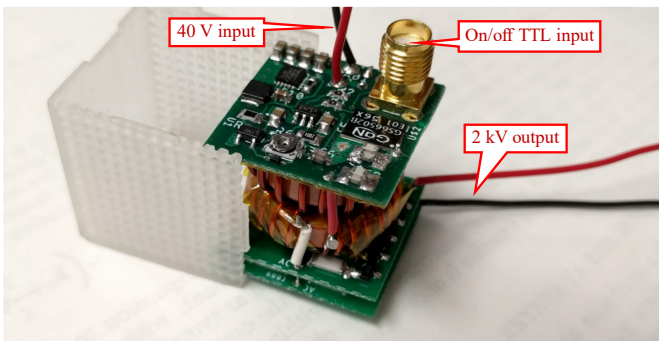
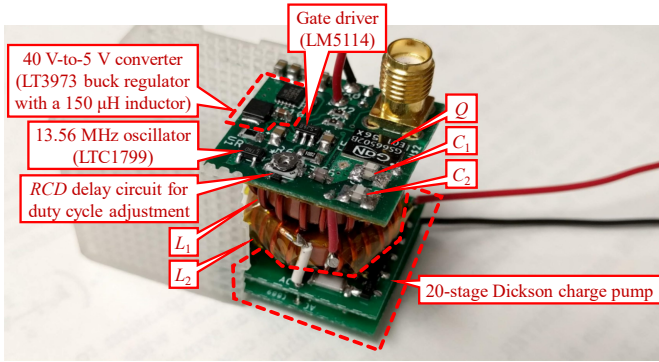
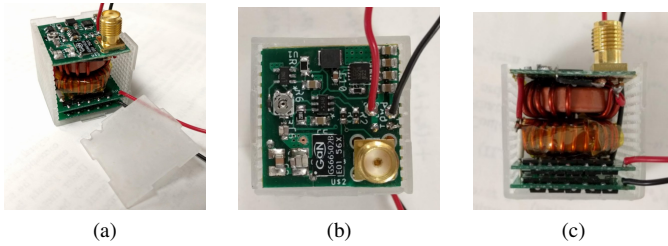


Fig. 7. Photographs of the cubic 40 V-to-2 kV dc-dc converter. The circuit measures 1 inch  $\times$  1 inch  $\times$  1 inch. (a) Angled view. (b) Top view. (c) Side view. (d) Electronic components placement. (e) Input, output ports and connectors.

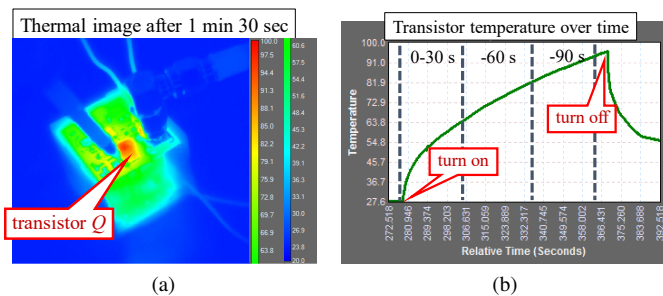


Fig. 8. Thermal performance of the power converter during continuous 2 kV, 15 W power delivery for 1 minute 30 seconds. (a) After 1 minute 30 seconds of continuous operation. (b) Transistor temperature versus time. The transistor was the hottest component of the circuit throughout the run. The temperature reaches 100 °C at the end of the run.

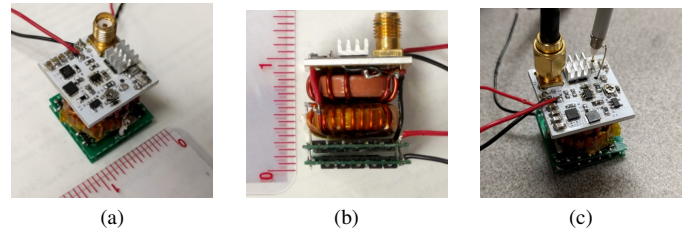


Fig. 9. Photographs of the cubic 40 V-to-2 kV dc-dc converter with an aluminum inverter board and no plastic case. (a) Angled view. (b) Side view. (c) Circuit under test, with an SMA cable and a voltage probe attached.

Fig. 8 shows the thermal performance of the cubic design. The transistor temperature reaches 100 °C after one and a half minutes and keeps rising, unlike the planar design that can run continuously.

### E. Cubic design with an aluminum inverter board

In order to mitigate the thermal issue, we remove the plastic case, replace the inverter board with a 1.6 mm-thick aluminum board, and re-tune the resonant network for better soft switching. Fig. 9 shows the implemented circuit. With this circuit, 40 V-to-1.97 kV conversion, 1.97 kV output voltage, and 77.2 % efficiency are achieved. Unfortunately, the transistor temperature was still an issue, which reached 100 °C after a 5-minute run and kept increasing. We suspect that the cubic shape of the power converter rendered it disadvantageous in terms of heat dissipation compared to the planar design in Section II-A.

## III. SUPER SHRIMP CONVERTER

In this section, we present a small, 200 mW power, and 3.7 V input high-voltage power converter. We name this converter 'Super Shrimp' because its development is motivated by DARPA SHRIMP program [1]. The goal of the program is to develop an insect-sized robot that embeds the energy source, the power converter, and the actuator, and can operate independently without any nearby external system supporting it. Specifically, the requirement to the power converter is that it be powered by a single-cell battery, that is, the input voltage should be 3.7 V or lower. Also, the volume should be 0.188 cm<sup>3</sup> or less, the weight be 0.5 g or less, the longest edge of the circuit be 7 mm or less. The converter should be able to pulse at 40 Hz frequency with 50 % duty cycle. Most importantly, the converter should be able to power the actuator with 3 kV dc, 200 mW peak power (100 mW average power). Table IV summarizes the target performance by DARPA SHRIMP program and compares it with the performance achieved and presented in this work.

### A. Planar design implementation

Fig. 10 is the schematic of the developed Super Shrimp converter. A class-E inverter, powered by a 3.7 V input voltage, creates a 9 V peak-to-peak ac voltage. This ac voltage is stepped up by the transformer to a 100 V peak-to-peak ac voltage, which is then rectified and multiplied by the 55-stage

TABLE IV  
COMPARISON OF THE TARGET PERFORMANCE BY DARPA SHRIMP PROGRAM [1] AND THIS WORK (“SUPER SHRIMP”).

Performance Metric	DARPA Phase I	DARPA Phase II	This work, before folding	This work, box shape	This work, box shape (2)
volume	$< 0.333 \text{ cm}^3$	$< 0.188 \text{ cm}^3$	$0.2 \text{ cm}^3$	$0.2 \text{ cm}^3$	$0.2 \text{ cm}^3$
longest edge	$< 10 \text{ mm}$	$< 7 \text{ mm}$	117 mm	7 mm	7 mm
weight	$< 1 \text{ g}$	$< 0.5 \text{ g}$	0.25 g	0.29 g	0.49 g
peak output power	$> 200 \text{ mW}$	$> 200 \text{ mW}$	248 mW	162 mW	189 mW
output voltage	$> 3 \text{ kV}$	$> 3 \text{ kV}$	3.2 kV	2.7 kV	2.9 kV

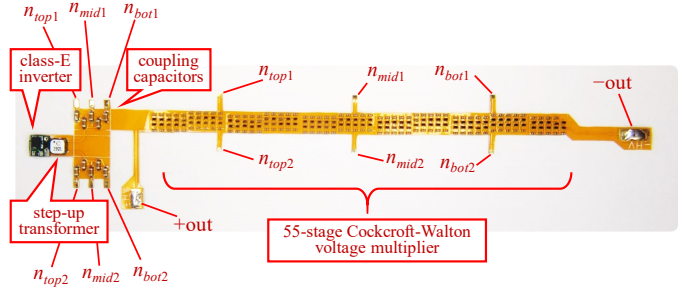
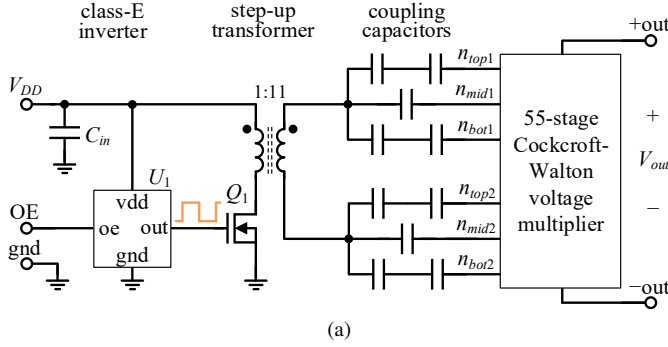


Fig. 11. Implemented Super Shrimp converter before folding.

Fig. 10. Schematic of the Super Shrimp converter. (a) Overall structure. (b) 55-stage voltage multiplier with taps in the middle. (c) Detailed structure of the 9- or 10-stage Cockcroft-Walton multiplier.

Cockcroft-Walton voltage multiplier. Table V lists the parts used for the implementation.

Fig. 11 shows the implemented converter. The circuit is built on a 0.08 mm-thick flexible polyimide PCB. Fig. 12 are close-up photographs of the converter. The grid in the background is at 1-mm spacing to show the dimension of the circuit. It is designed such that when folded, it becomes a 7 mm-thick stack of multiple 7 mm by 4 mm layers. The circuit board spans 117 mm long and weighs 0.25 g in total.

### B. Planar design test results

We connect the output terminals of the developed Super Shrimp converter to a  $40.476 \text{ M}\Omega$  resistive load. The load doubles as a 85-to-1 resistive voltage divider, through which

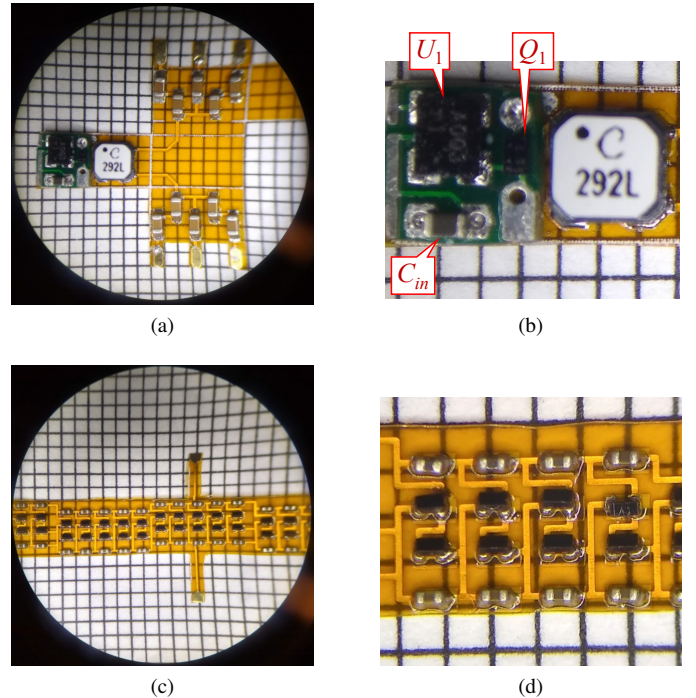


Fig. 12. Close-up photos of the Super Shrimp converter before folding. The grid in the background is at 1-mm spacing. (a) Inverter (left), transformer (middle), and coupling capacitors (right). (b) Inverter (left) and transformer (right), close-up. (c) Cockcroft-Walton voltage multiplier. (d) Voltage multiplier, close-up.

TABLE V  
PARTS LIST FOR THE SUPER SHRIMP POWER CONVERTER. PART NAMES  
ARE IN REFERENCE TO FIG. 10.

Name	Description
$U_1$ , inverter	SIT8924B, 1 MHz oscillator, SiTIME
$C_{in}$ , inverter	4.7 $\mu$ F, X5R, 10 V, 0402 pkg
$Q_1$ , inverter	SSM3K56CT, 20 V 800 mA NMOS, Toshiba
step-up transformer	UA7868-AE, 1:11 coupled inductor, Coilcraft
coupling capacitors	1.5 nF, X7R, 630 V, 0603 pkg
volt. multi. capacitors	10 nF, 50 V, X5R, 0201 pkg
volt. multi. diodes	DLLFSD01LP3-7, 80 V 100 mA, Diodes Inc.

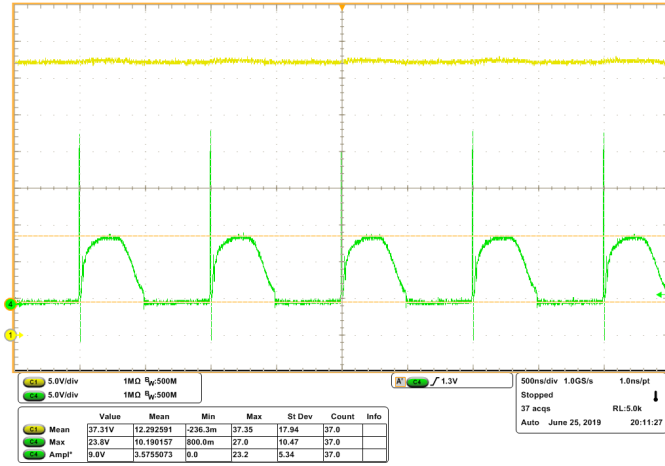


Fig. 13. Measured waveforms of  $Q_1$ 's drain-to-source voltage (green curve; 5 V/div) and the output voltage (yellow curve; 425 V/div) of the Super Shrimp power converter before folding.

we measure the output voltage. Fig. 13 shows measured waveforms of  $Q_1$ 's drain-to-source voltage and the output voltage, when the input voltage of 3.6 V is provided. The average output voltage is 3.171 kV which means the average output power is 248 mW. The total input power is measured 346 mW, which makes the power conversion efficiency 71.7 %.

It is interesting to compare this result with the converter for an autonomous flying micro robot presented in [5]. The power converter of the flying robot weighs 0.09 g and takes 4.8 V dc input to create 400 V peak-to-peak 170 Hz ac voltage that drives the actuator, which consumes 30 mW real power and 50 mW reactive power. Compared to [5], our circuit features 25 % lower input voltage, 7.5 times higher output voltage, 8 times higher output power, meanwhile, is only 3 times heavier.

Fig. 14 is the thermal image of the converter after it reaches the thermal steady state. The transformer temperature reaches 53 °C before stabilizes, while the inverter reaches 36 °C and the voltage multiplier 25 °C. Considering the relatively large thermal mass of the transformer, we suspect that a significant portion of the power loss occurs from the transformer.

### C. Box-shape converter implementation

The planar Super Shrimp converter meets all the DARPA Phase II target performances except for the longest length of 7 mm or shorter. To shorten the longest edge down to 7 mm,

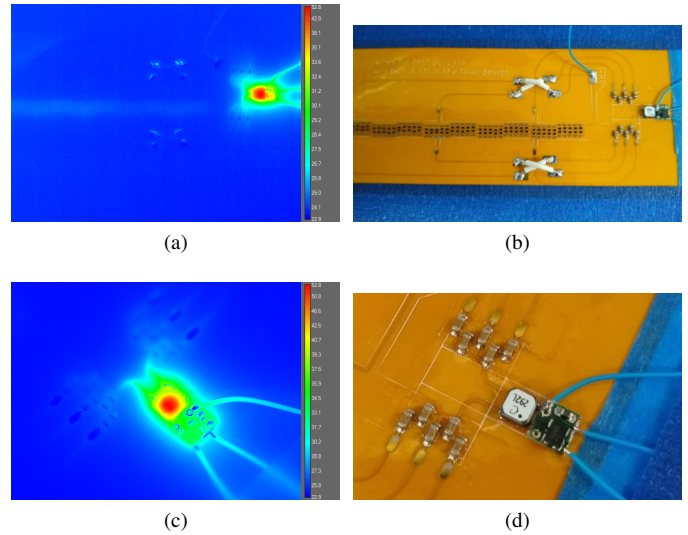


Fig. 14. Thermal images of the Super Shrimp converter at the thermal steady state. (a) Thermal picture. (b) Reference picture for (a). (c) Close-up thermal picture of the inverter and the transformer. (d) Reference picture for (c).

we fold the planar design developed in the previous section into a box shape. Since the circuit is on a flexible PCB, we can easily fold it in an origami-like fashion. Fig. 15 is the instruction on how to fold the circuit in Fig. 11 into a box shape.

Fig. 16 shows the Super Shrimp converter after folding. The dimension is 7 mm  $\times$  7 mm  $\times$  4 mm in a box shape. (Vertical jumper wires and output terminals are not included.)

### D. Box-shape converter test results

Fig. 17 shows measured output voltage waveforms of the Super Shrimp power converter after folding. Waveforms demonstrate that the Super Shrimp can pulse at 40 Hz, which is the required pulsing rate by DARPA SHRIMP program.

Unfortunately, the circuit suffered significant degradation in performance: at 3.7 V input, the output is 2.7 kV and 162 mW, with the efficiency of only 34 %. After investigation, We realized that the conformal coating done to prevent shorts was not sturdy enough in this first prototype. As a result, some of the diodes are suspected to have undergone overvoltage breakdown and ended up acting like a resistor, undermining the voltage multiplier's function while bleeding energy whenever they are charged and discharged. Another issue that affects the performance is that some of the copper traces crack at the crease when the PCB is folded, creating disconnected nodes and rendering the voltage multiplier dysfunctional.

### E. Box-shape converter, second implementation

In order to address the issues identified in the first prototype, namely, insufficient layer-to-layer insulation and wire crack at the crease, we build the second implementation with two changes: First, for better insulation, mineral oil is seeped in between voltage multiplier board layers. Second, components at the crease were removed and the pads were shorted with a jumper wire in order to prevent disconnection. An unwanted,

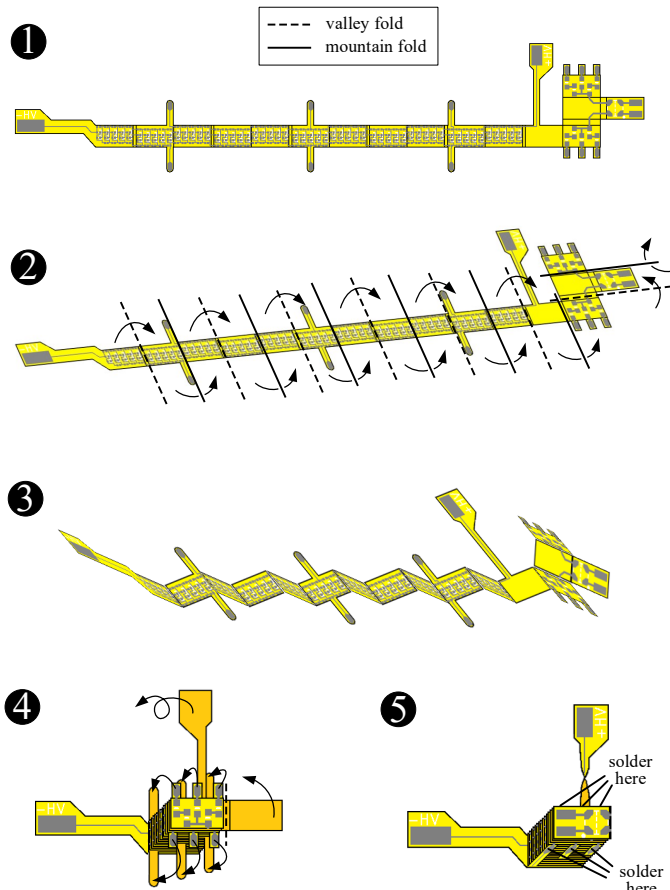


Fig. 15. Origami instructions on how to fold the planar converter into a box shape.

albeit unavoidable, side effect is that the number of voltage multiplier stages was reduced from 55 to 50, which reduces the output voltage by 10 % and the output power by 20 %.

Fig. 18 shows the implemented converter and the measured waveform. At the input of 3.7 V and 0.285 W, the output is measured 2.918 kV and 0.189 W. The efficiency is improved to 66.3 %. The total weight is increased to 0.49 g due to the mineral oil between stacked layers.

#### F. Ways to further improve the converter performance

We discuss four ways to improve the performance of the box-shape converter so that it becomes more suitable for micro-robotic applications and meets the performance requirement by DARPA SHRIMP program. First, use low-viscosity insulating varnish in place of mineral oil for permanent and reliable insulation in the open air. Second, add two or three more voltage multiplier stages so that the output voltage reaches 3 kV and the power reaches 200 mW. Third, use a higher-end PCB assembly service that allows closer spacing between components. Our PCB manufacturer required 0.6 mm minimum pad-to-pad spacing for 0201 package devices, which is clearly not the limit of the current PCB assembly technology. With the specs give in [6]–[8], the volume of the voltage multiplier can be reduced to as much as half, which will reduce

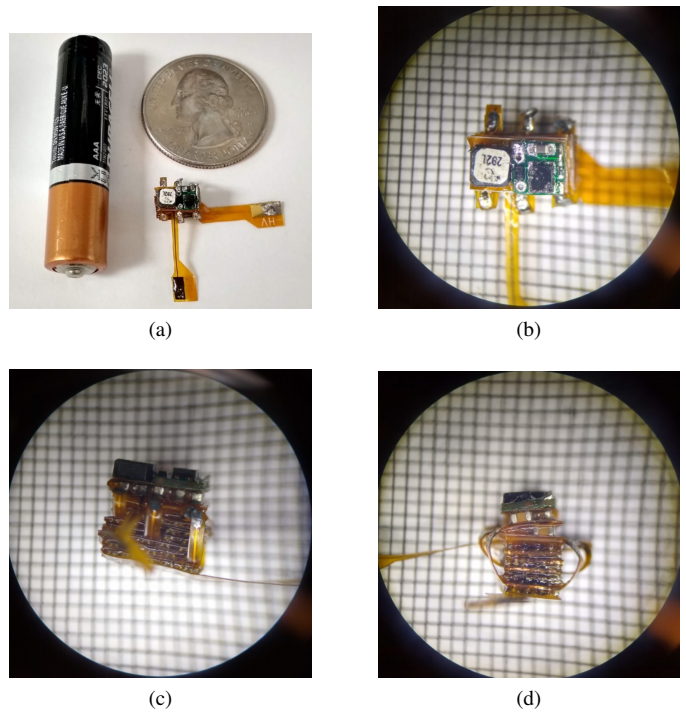


Fig. 16. Close-up photos of the Super Shrimp converter after folding. The grid in the background is at 1-mm spacing. (a) Size comparison with a US quarter coin and a AAA battery. (b) Top view. (c) Side view. (d) Front view.

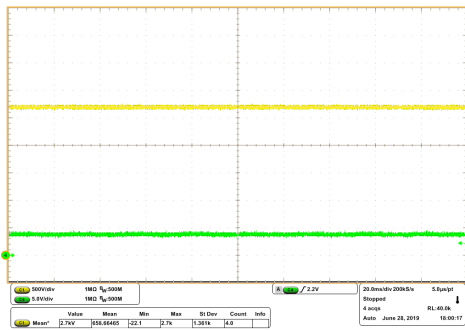
the total converter volume to 2/3 of its current volume. Lastly, re-route PCB traces so that they run parallel to the crease and thereby do not crack at the crease.

#### IV. CONCLUSION

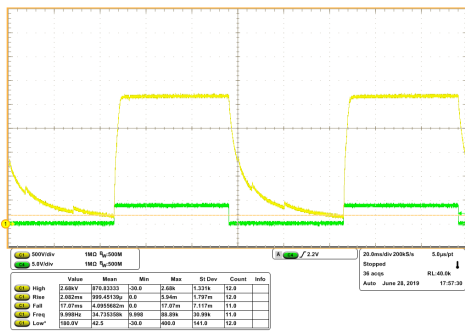
This paper provided implementation details and test results of miniature high-voltage power converters.

We built and tested a 40 V-to-2 kV 16 W power converter with a switching frequency of 13.56 MHz. The developed circuit achieves 80 % power conversion efficiency, and is capable of pulsing at kilohertz-range frequency. The power density and the specific power of the planar converter are 18.9 W/in<sup>3</sup> and 0.923 W/g, respectively, which is several times higher than existing works of comparable power and voltage ratings. Those of the cubic converter were 15.3 W/in<sup>3</sup> and 0.773 W/g.

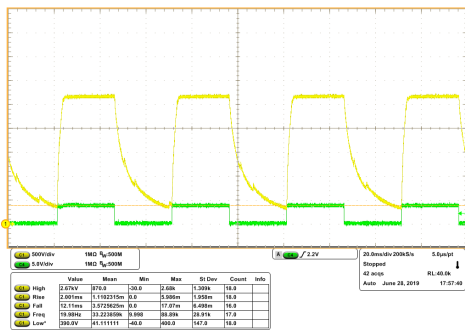
We then developed a power converter with a smaller size, lighter weight, lower input voltage, and higher output voltage. Before being folded to fit in the small box, the developed circuit achieves 3.6 V-to-3.17 kV voltage conversion at 248 mW output power and 71.7 % efficiency. When folded, the circuit fits in a 7 mm × 7 mm × 4 mm box volume and weighs 0.29 g. The circuit is capable of pulsing at 40 Hz, with its pulsing capability mostly limited by the fall time that is related to RC discharge at the turn-off. Unfortunately, several issues were identified regarding wire cracks and shorts that were not completely solved at the time of writing this document. Due to those issues, when folded into the small box volume, the



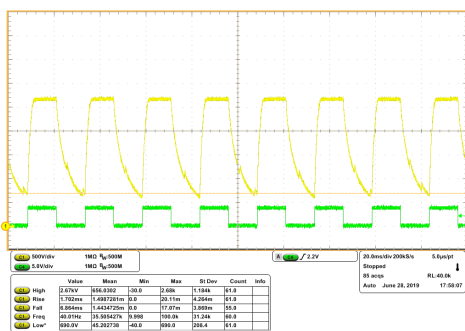
(a)



(b)

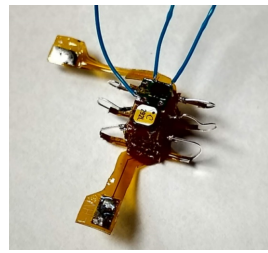


(c)

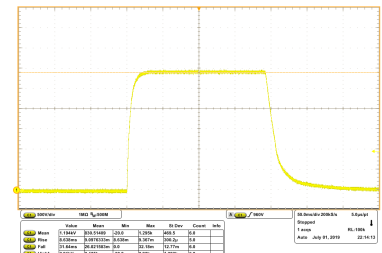


(d)

Fig. 17. Measured waveforms of the output enable (OE) input (green curve; 5 V/div) and the output voltage (yellow curve; 500 V/div) of the Super Shrimp power converter after folding. (a) At dc. (b) 10 Hz pulsing. (c) 20 Hz pulsing. (d) 40 Hz pulsing.



(a)



(b)

Fig. 18. The Super Shrimp converter, second implementation. (a) Close-up photograph of the converter. (b) Turn-on and turn-off transient waveform of the output voltage (vertical scale 500 V/div, horizontal scale 50 ns/div).

converter performance degrades to 3.7 V-to-2.7 kV voltage conversion at 162 mW output power and 34 % efficiency. The second implementation fixes the insulation and mechanical failure issues, and achieves performance that is very close to the phase II target of DARPA SHRIMP program. We discussed ways to improve the performance so that the converter retains the excellent performance of the planar design and thereby better fits intended robotic applications.

#### ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant No. 1808489, and by the National Aeronautics and Space Administration under Phase I SBIR Proposal No. 18-1-S3.03-8502. Authors are grateful to Coilcraft, Inc. for providing free samples of miniature transformers.

#### REFERENCES

- [1] Defense Advanced Research Projects Agency. (2019) SHort-Range Independent Microrobotic Platforms (SHRIMP). [Online]. Available: <https://www.fbo.gov/index?id=26d25ebbec24da3652ced04304fa1296>
- [2] N. O. Sokal and A. D. Sokal, "Class E—A new class of high-efficiency tuned single-ended switching power amplifiers," *IEEE Journal of solid-state circuits*, vol. 10, no. 3, pp. 168–176, 1975.
- [3] R. Zulinski and J. Steadman, "Class E power amplifiers and frequency multipliers with finite DC-feed inductance," *IEEE Transactions on Circuits and Systems*, vol. 34, no. 9, pp. 1074–1087, 1987.
- [4] N. O. Sokal, "Class-E RF power amplifiers," *QEX*, vol. 204, no. 1, pp. 9–20, 2001.
- [5] N. T. Jafferis, E. F. Helbling, M. Karpelson, and R. J. Wood, "Untethered flight of an insect-sized flapping-wing microscale aerial vehicle," *Nature*, vol. 570, no. 7762, pp. 491–495, 2019. [Online]. Available: <https://doi.org/10.1038/s41586-019-1322-0>
- [6] P. Gerits and A. Mandos, "0201 placement - Only with the Right Team and Tools," Assembleon BV, Tech. Rep., 2002.
- [7] G. Westby, J. Adriaance, W. P. von Hessen, J. Schake, and D. Barbini, "0201 Issues and Process Window," Advanced Process Lab, Tech. Rep., 2000.
- [8] "PCB CAD Design Guidelines," Honolulu Development Center, Tech. Rep., 2002.