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The performance of a 42/28 V, 175 W, 50 kHz pulse-width modulated buck dc/dc switching power converter at liquid nitrogen temperature (LNT) is compared with room temperature operation. The power circuit as well as the control circuit of the converter, designed with commercially available components, were operated at LNT and resulted in a slight improvement in converter efficiency. The improvement in power MOSFET operation was offset by deteriorating performance of the output diode rectifier at LNT. Performance of the converter could be further improved at low temperatures by using only power MOSFETs as switches. The use of a resonant topology will further improve the circuit performance by reducing the switching noise and loss.

INTRODUCTION

Recent advances in high-temperature ceramic superconductors have generated great interest in low-temperature power electronics that will find applications in systems such as deep-space exploration, cryogenic instrumentation, medical diagnostics, superconductive magnetic energy storage, high power generators and motor drives, and switching power converters. Low-temperature electronics will provide the interface between the superconducting electronics and room-temperature electronics. The operation of power electronics at low temperatures is expected to result in a more efficient, dense, and reliable system compared to room temperature operation due to better thermal, electrical, and electronic properties of materials at low temperatures (1,2).

In this study, the performance of a 42/28 V, 175 W, 50 kHz pulse-width modulated (PWM) buck dc/dc switching power converter at liquid nitrogen temperature is compared to the room temperature performance. The operation of active and passive power components as well as the overall performance of the converter are discussed along with supporting experimental results. The operation of the control circuit is also investigated at

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liquid nitrogen temperature in terms of rise and fall times, delay times, and switching frequency variation.

PWM BUCK DC/DC CONVERTER

The 42 V±20%/28 V, 175 W, 50 kHz PWM buck dc/dc converter was operated both at room temperature (RT) as well as at liquid nitrogen temperature (LNT). The power circuit for the converter is shown in Fig. 1, and was designed for a minimum output power of 35 W and a maximum output voltage ripple of 0.5%. The output voltage of the converter was regulated against the input voltage and load current variations by controlling the converter duty-ratio in an open-loop fashion.

Based on the steady-state analysis for continuous conduction mode of operation (3), the following design equations are used for the power circuit design:

$$L_f \geq \frac{V_o(1-D_{\min})T_s}{2I_{o,\min}} \qquad [1]$$

$$C_f \geq \frac{(1-D_{\min})V_o}{8f_s^2\Delta V_o} \qquad [2]$$

where, D_{min} = minimum duty-ratio = $V_o/V_{in,max}$, $I_{o,min}$ = minimum output (load) current for continuous conduction mode of operation, f_s = switching frequency = $1/T_s$, and ΔV_o = peak-to-peak output ripple voltage.

Based on equation [1], the required output filter inductor of 100 μH was designed using a molypermalloy powder (MPP) core. The silver-plated copper wire with teflon resin tape insulation suitable for wide-temperature operation was used for winding the inductor. The MPP core was expected to operate at LNT with a somewhat increased loss (4,5). An output filter capacitance of 60 μF was used instead of the calculated value of 45 μF from equation [2], to provide a design margin for the output ripple voltage against the drop in capacitance value at low temperatures. Standard low ESR metalized polypropylene film capacitors were used because of their superior low-temperature characteristics.

<u>*Power semiconductor selection:*</u> For low temperatures, the primary semiconductor material is Si, although GaAs also has considerable potential and the primary device is the field-effect transistor in various forms (1,2). Reduced temperature operation offers improvements in performance through improvement of materials-based properties such as electronic carrier mobility, thermal conductivity, and electrical conductivity. Substantial improvements in reliability are also expected since many degradation mechanisms are

thermally activated. Therefore, LNT operation of Si-based power semiconductors is of great interest for achieving high efficiency power conversion.

For this work, an IRFP 250 power MOSFET (33 A, 200 V, 85 mΩ, 650 pF device) is used as the primary switch and a MUR 3020PT ultrafast diode (2*15 A, 200V) as the output rectifier. Both devices have a TO-3P plastic package. Because of inherent switching noise and ringing associated with any PWM type power converter, an R-C snubber across the power MOSFET is used to reduce this problem. The snubber consisted of a 50 Ω wire-wound resistor in series with a 0.002 μF polypropylene film capacitor.

The control circuit for the converter consists of a BiCMOS voltage mode PWM IC (TC38C25CPE) and a CMOS power MOSFET driver IC (IR 2110). The complete converter circuit including the control and power circuits is shown in Fig. 2. The programmed switching frequency is 50 kHz, and the duty-ratio can be controlled through the 10 K potentiometer at room temperature, shown in the dashed box, practically from 0 to 1. The driver IC has independent high and low-side referenced output channels. The high-side floating channel is used to drive the power MOSFET without having to use an opto-coupler or an isolation transformer.

EXPERIMENTAL RESULTS

Even though the complete converter is operated in liquid nitrogen, the necessity to observe various current and voltage waveforms using instrumentation at room temperature resulted in a non-compact circuit layout with long wires. Data were recorded both at room temperature (RT) and liquid-nitrogen temperature (LNT). The converter was run at full-load for one hour before recording any data both at RT and LNT.

The recorded converter switching frequency was 49.8 kHz and 51.4 kHz at RT and LNT, respectively. This indicated an increase in switching frequency by about 3.2% at 77°K compared to 300°K operation. In general, the switching frequency was expected to increase slightly because of higher operating speed of CMOS logic at lower temperatures resulting from an improved carrier mobility and a reduced carrier scattering. Also, the low-temperature effects on discrete as well as monolithic resistors, capacitors, diodes, and transistors contributed to the increase in frequency. However, the duty-ratio remained practically constant at 0.7. The rise and fall times of the drive signal for the power MOSFET improved marginally at LNT. In addition, the rise delay time of the IR2110 high-side driver decreased by a factor of 1.8, and the fall delay time by a factor of 1.3. The contributing factors for these improvements are increased carrier mobility, increased saturation velocity, reduced junction capacitance, and reduced line resistance.

The recorded full-load efficiencies of the converter at RT and LNT were 95.8% and 96.3%, respectively. Thus the converter loss decreased from 7.8 W at RT to 6.9 W at

LNT, only a slight improvement. The power converter was able to restart at LNT successfully. The MOSFET and diode rectifier current, voltage, and power waveforms are shown in Figs. 3 - 8 for RT as well as LNT operation. As can be seen in these figures, the waveforms at RT and LNT look almost identical. However, the important observations are discussed below.

DISCUSSION OF RESULTS

The turn-on loss of MOSFET ($0.5CV^2$) decreased at LNT due to somewhat decreased drain-to-source junction capacitance and slightly increased switching speed. However, the turn-off loss ($0.5LI^2$) remained practically unchanged because it is dependent on the circuit layout inductance. The conduction loss decreased significantly due to reduced drain-to-source on-resistance contributed by increased carrier mobility (6). Overall, the performance of the power MOSFET improved at LNT as can be seen in Figs. 3 and 4.

As per the diode rectifier, its conduction loss increased with decreasing temperature due to increased forward voltage drop as can be seen in Figs. 5 and 6. However, the reverse recovery characteristics improved significantly in terms of peak reverse current, peak voltage, reverse recovery time, and turn-off loss as can be seen in Figs. 7 and 8. The leakage current of diode is supposed to decrease with decreasing temperature (7), however, the experimental waveforms in Figs. 5 - 8 show just the opposite. The reason for this occurrence has not been fully investigated. Thermal cycling might be one factor. Overall, the improvement in low-temperature operation of the power MOSFET is offset by detoriating performance of the diode rectifier.

In terms of passive components, the inductor loss increased a little due to increased hysteresis loss and decreased core resistivity (4,5). The output filter capacitor used is film type, and its value is expected to drop slightly at LNT (4), however, it was not studied in this work. For the converter under test, total loss due to filter inductor and capacitors was not significant compared to power semiconductor loss.

The switching noise is significant in the converter. The switch turn-on noise is due to discharge of the stored energy in junction capacitance of the MOSFET, whereas the switch turn-off noise is due to discharge of the energy stored in the circuit layout inductance. This situation can be improved by having a compact circuit layout that was not possible in this work because the converter was placed in a LN_2 dewar whereas all the measurement equipment were outside.

The best way to attack this problem is to use some form of soft switching technique for all power semiconductor devices such as the zero-voltage switching, instead of the hard switching used in PWM converter (8). Also, the use of synchronous rectification employing power MOSFETs is strongly recommended instead of diode rectification in order to improve the converter performance. The implementation of synchronous rectification in low-temperature power converters is highly attractive since the MOSFET conduction loss decreases with temperature whereas that of its body-diode increases.

CONCLUSIONS

The complete power converter designed with commercially available components operated in liquid nitrogen, and its efficiency did improve slightly. The efficiency can be further improved if the output rectifier is replaced by a power MOSFET and the concept of synchronous rectification is used. More compact circuit layout will also contribute to improved converter performance. The change in switching frequency contributed by low-temperature operation of the control circuit is not a significant problem for PWM type converters. However, for resonant type power converter circuits, the change in switching as well as resonant frequency with temperature would pose a significant challenge to the circuit designer in terms of meeting the specified line and load regulation while maintaining soft-switching. Work must continue on low-temperature power electronics to exploit the benefits as well as solving the upcoming challenges in the realm of low temperatures.

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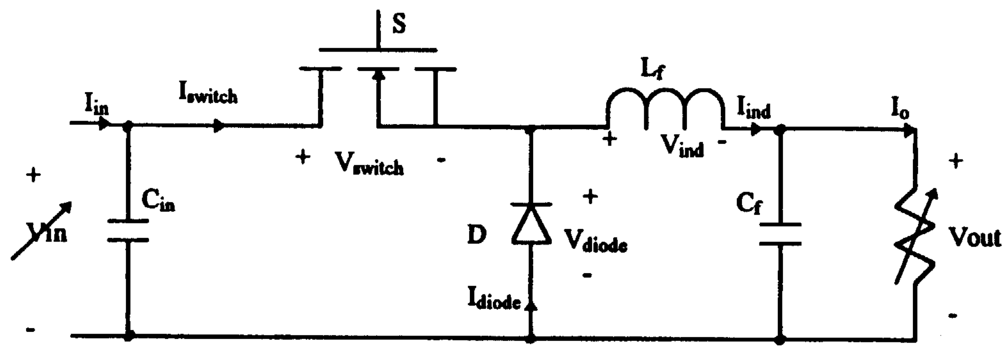

Fig. 1 PWM Buck Converter Power Circuit

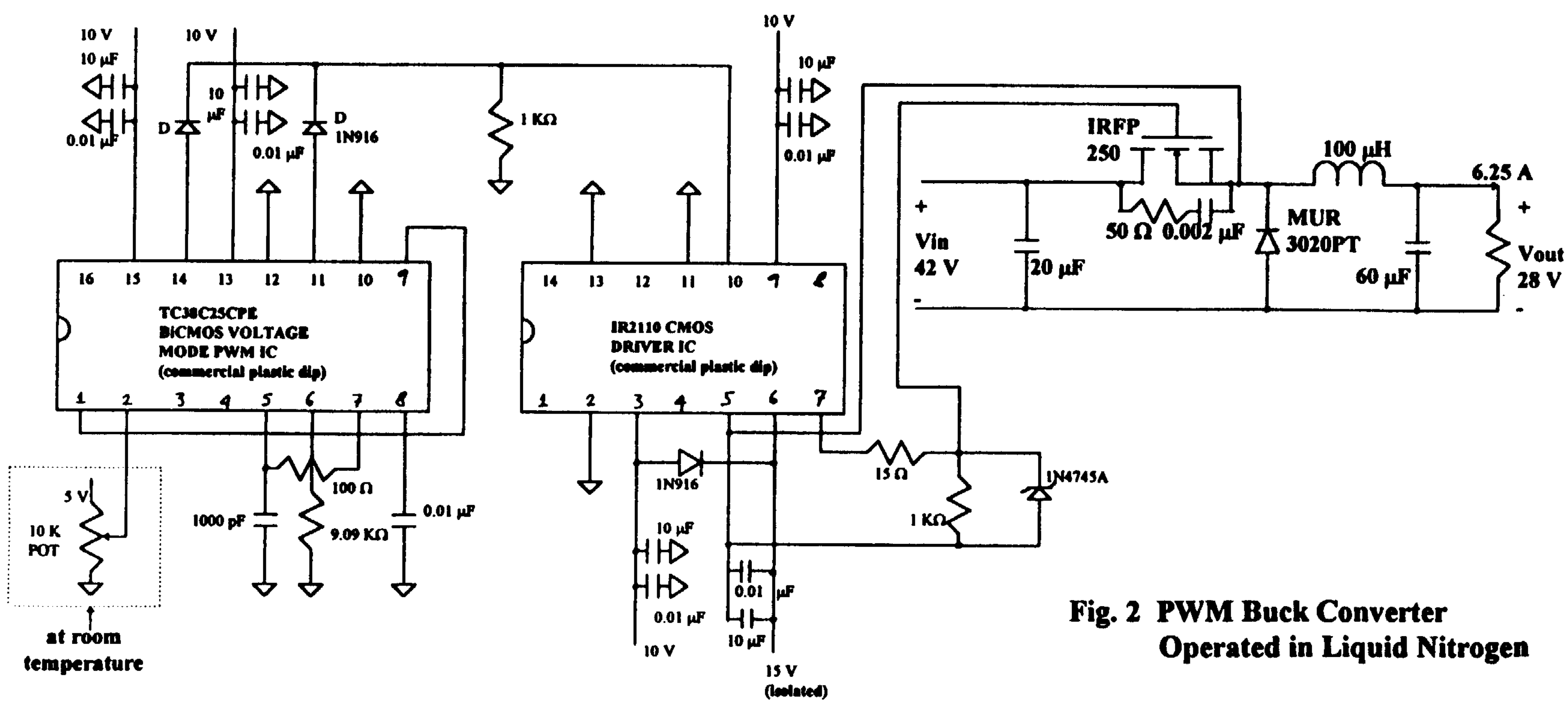

Fig. 2 PWM Buck Converter Operated in Liquid Nitrogen

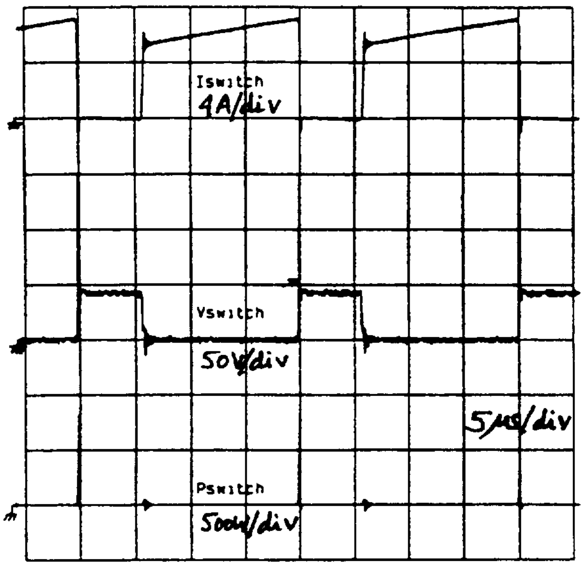

Fig. 3 Power MOSFET Waveforms at Full-load (Room temperature operation)

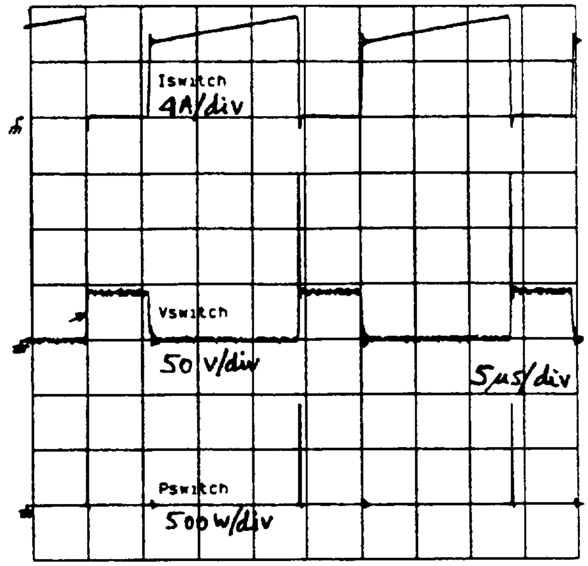

Fig. 4 Power MOSFET Waveforms at Full-load (Liquid nitrogen operation)

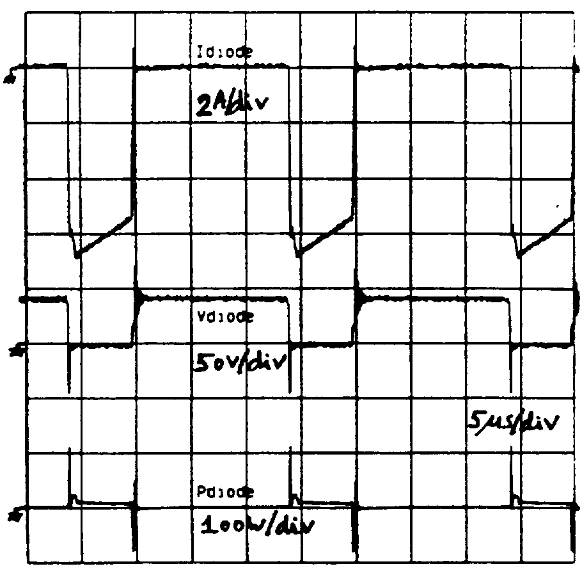

Fig. 5 Output Diode Waveforms at Full-load (Room temperature operation)

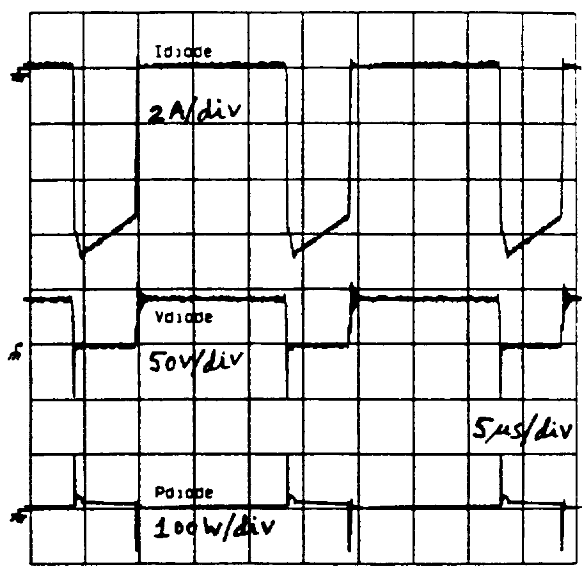

Fig. 6 Output Diode Waveforms at Full-load (Liquid nitrogen operation)

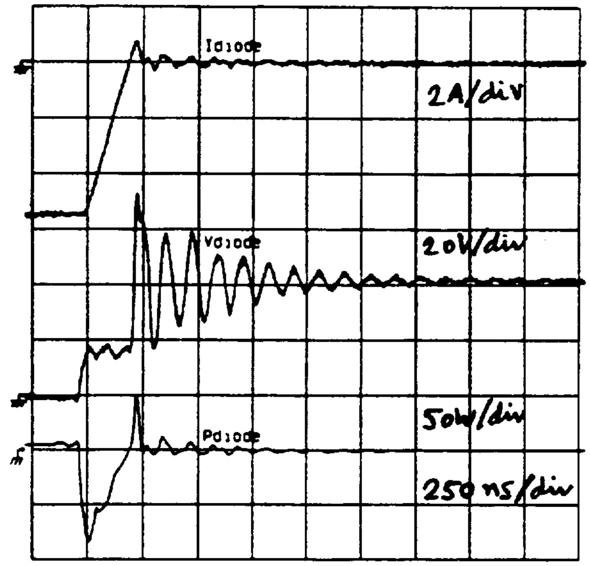

Fig. 7 Diode Reverse Recovery Waveforms at Full-load (Room temperature operation)

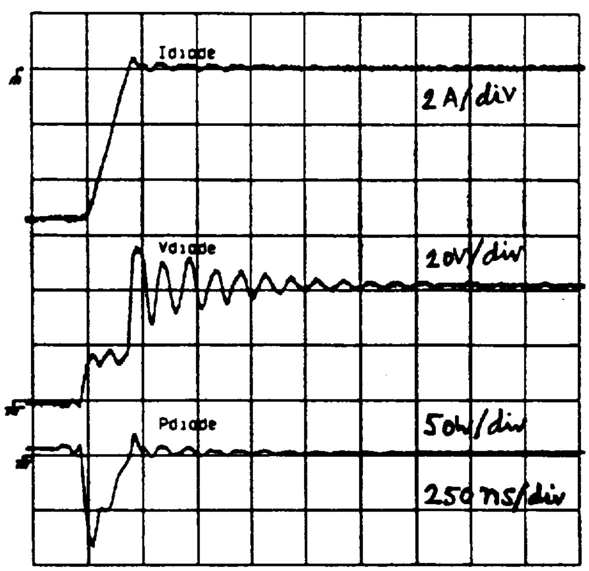

Fig. 8 Diode Reverse Recovery Waveforms at Full-load (Liquid nitrogen operation)

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