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Abstract- **Planetary exploration missions and deep space probes require electronics capable of low temperature operation. Such electronics will not only improve circuit performance and reliability, but also increase system efficiency, and reduce development and launch costs. DC/DC converters are an essential part of most aerospace power management distribution systems (PMAD). Therefore, DC/DC converters that can operate at cryogenic temperatures are crucial for space missions where low temperatures are encountered. An important component of a DC/DC converter is the pulse width modulation (PWM) chip that provides the control to the converter main switches.**

In the process of designing low temperature DC/DC converters, experimental investigations were performed to evaluate the performance of a number of high-speed PWM chips as a function of temperature in the range of 25 °C to –190 °C. These integrated circuit (IC) chips ranged in their electrical characteristics, modes of control, packaging options, and applications. This paper presents and discusses the experimental procedures along with the experimental data obtained on the investigated chips.

1. INTRODUCTION

Future space missions, such as outer planetary exploration and deep space probes, require electrical power management systems that operate reliably and efficiently in very low temperature environments. For example, inter-planetary probe launched to explore the rings of Saturn would experience an average temperature of about –183 °C.

Presently, spacecraft operating in the cold environment of deep space carry a large number of radioisotope heating units (RHU) to maintain temperature for the on-board electronics at approximately 20 °C [1]. This is not an ideal solution because the RHUs are always producing heat, even when the spacecraft is already too hot, thus requiring an active thermal control system for the spacecraft. In addition, they are very expensive and require elaborate containment structures. Electronics capable of operation at cryogenic temperatures will not only tolerate the hostile environment of deep space but also reduce system size and weight by eliminating radioisotope heating units and associated structures; thereby reducing system development and launch costs, improving reliability and increasing energy densities.

2. POWER ELECTRONICS AT CRYOGENIC TEMPERATURES

Power electronic circuits designed for operation at low temperature are expected to result in more efficient systems than those at room temperature. This improvement results from better electronic, electrical, and thermal properties of materials at low temperatures [2,3]. In particular, the performance of certain semiconductor devices improves with decreasing temperature down to liquid nitrogen temperature (–196°C) [3,4]. At low temperatures, majority carrier devices demonstrate reduced leakage current and reduced latch-up susceptibility. In addition, these devices show higher speed resulting from increased carrier mobility and saturation velocity [3-5]. An example is the power MOSFET that has lower conduction losses at low temperature due to the reduction in the drain-to-source resistance $R_{DS(on)}$ resulting from increased carrier mobility [4,6,7].

The Low Temperature Electronics Program at the NASA Glenn Research Center focuses on research and development of electrical components and systems suitable for applications in deep space missions [8]. Research is being conducted on devices and systems for use down to cryogenic temperatures. Some of the components that are being characterized include semiconductor switching devices, resistors, magnetics, and capacitors [9-11]. A number of commercial-off-the-shelf modular, low power DC/DC converters, with specifications that might fit the requirements of specific future space missions, have been tested. These converters, which ranged in electrical power from 8 W to 13 W and output voltage from 3.3 V to 12 V, were characterized in terms of their performance as a function of temperature in the range of 20 °C to –190 °C [12-14].

Efforts are in progress to build modular DC/DC converters with low temperature capabilities. The converters will be designed or modified to operate from room temperature to –196 °C using commercially available or newly developed components such as CMOS-type devices and MOSFET switches. PWM IC chips will be used to implement the closed-loop control of the converters.

In this work, a preliminary evaluation of the performance of four high-speed PWM chips has been conducted as a function of temperature in the range of 25 °C to –190 °C. These chips ranged in their electrical characteristics, modes of control, packaging options, and applications. The experimental procedures along with the experimental data obtained on the investigated chips are presented and discussed.

3. SPACE POWER AND ADVANCES IN DC/DC CONVERTERS

Most aerospace power management systems are DC-based and thus require DC/DC power converters that will operate over a wide input voltage range to produce an output voltage between 1.5 V to 15 V at various power levels.

Recently, there has been a tremendous progress in the design of high power density DC/DC converters. Converters that operate at power densities of 50% or higher than the available standard conventional converter designs have been developed. This increase in power density is achieved using new designs, advanced devices and components, and packaging techniques. For example, the newly developed synchronous rectifier-based DC/DC converter modules with multi-layer thick-film hybrid packaging provide, without the use of a heat sink, more usable output power than the conventional, schottky diode based converters with a heat sink and thick-film single layer packaging. As the demand to achieve high power density of DC/DC converters increases, there is a need to provide more integration and, therefore, the role of highly functional PWM control chips will increase.

4. INTEGRATED CIRCUITS PWM CONTROLLERS

Electronic control of DC/DC converter power circuits is achieved by modulating the duty ratio (D) of the controlled switch, defined as the ratio of its ON-time to the switching period. Typically, the intent is to keep the output voltage constant, as determined by a DC reference signal , in the presence of time-varying sources and loads. The technique of modulating the duration (or width) of the ON-time (or pulses) that is applied to the drive circuit of the controlled switch is called "Pulse Width Modulation" (PWM).

Fig. 1 shows a simple PWM controller circuit that controls the switch operation in a DC/DC converter. A sawtooth signal with a fixed frequency and a fixed amplitude (V_R) is applied to the PWM comparator whose second input is fed from the output of an error amplifier (V_e) that compares a reference voltage to the output voltage (V_{OUT}). The output of the latch gives the required PWM signal. This control technique is known as the "voltage-mode" PWM control because only the voltage information is used [15].

It is shown that the utilization of both voltage and current feedback adds significant advantage to the stability of closed-loop PWM controllers. One way of adding the current information is to use the switching analog current waveform in place of the sawtooth generator. The analog voltage of the switching current waveform is usually provided with a small current-sense resistor placed in series with the switch. This control technique is called "current-mode" control and is shown in Fig. 2 [15].

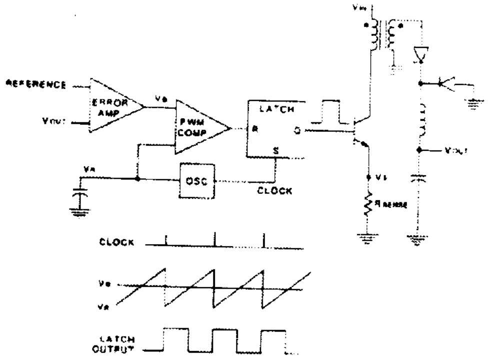


Fig. 1 Voltage-mode PWM control technique

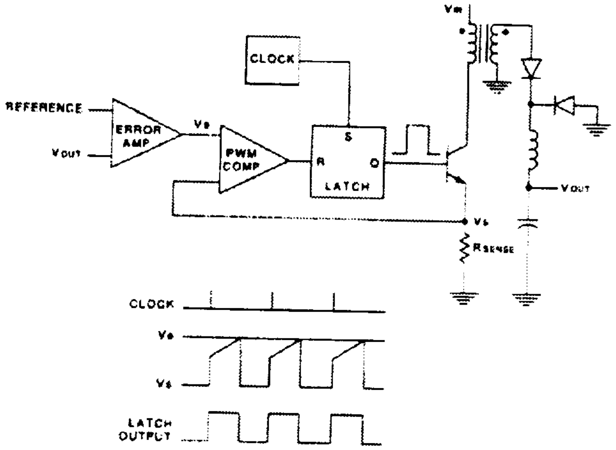
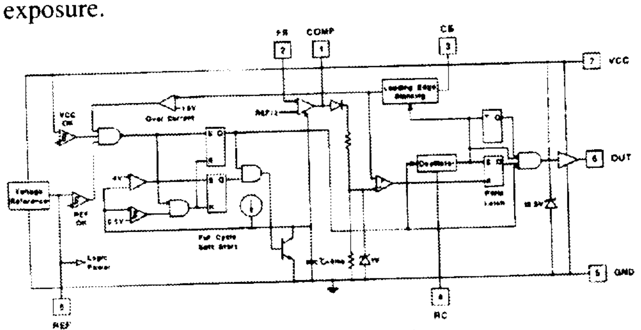


Fig. 2 Current-mode PWM control technique

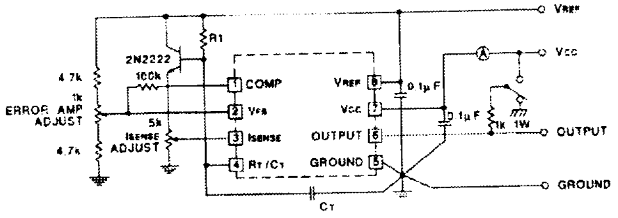
The fundamental challenge of DC/DC converter design is to simultaneously realize, two difficult objectives: good electrical performance and low cost. A large number of fully integrated PWM circuits, available from a number of manufacturers are designed to meet these objectives. In particular, fixed frequency PWM controllers are by far the devices that are widely used. There have been many ways of implementing fixed frequency PWM control. The basic ingredients of all PWM integrated circuit controllers contain an adjustable clock for setting the oscillator frequency, an output voltage error amplifier, a voltage reference, a signal generator for providing a sawtooth waveform synchronized with the clock, and a comparator to compare the error amplifier output signal with the sawtooth signal. The output signal from the comparator is used to drive the controlled switch directly or through a discrete or integrated drive circuit. There has been a large number of PWM integrated circuit manufacturers using different technologies such as all bipolar, BiCMOS or all CMOS which provide all the necessary features to implement fixed frequency control with a minimal external parts count. Moreover, these control chips contain features such as current limiting, over-voltage protection, input under-voltage protection plus primary and auxiliary functions that may improve the performance of the controller. An example of a typical PWM chip is shown in Fig. 3a. Fig. 3b shows the circuit configuration used in testing the performance of the chip. The operating frequency of these chips range from a few kHz to a few MHz [15].

5. LOW TEMPERATURE EXPERIMENTAL SETUP

A preliminary evaluation of the performance of a number of high-speed PWM control ICs with different packages and ratings, acquired from various manufacturers, was conducted as a function of temperature from 20 °C to –190 °C. At a given temperature, the internal voltage reference, and the oscillator and the device modulated outputs were observed. The tests were performed in a Sun Systems environmental chamber utilizing liquid nitrogen as the coolant. A temperature rate of change of 10 °C/min was used throughout this work. At every test temperature, the device under test was allowed to soak at that temperature for a period of 30 minutes before any measurements were made. After the last measurement was taken at the lowest temperature, the chips were allowed to stabilize to room temperature and then the measurements were repeated at room temperature to determine the residual effect of the low temperature exposure.



(a) Circuit schematic



(b) Laboratory test circuit

Fig. 3 PWM current-mode control chip

6. RESULTS AND DISCUSSIONS

Four PWM chips were evaluated under various test parameters. Only selected data, which best represents the performance of the devices at low temperature, is presented in this paper. Table 1 gives a comparative list outlining the main features of each of the chips tested. The functionality of each chip at low temperature is evaluated by observing the waveforms of its internal voltage reference, the oscillator frequency and the PWM output. In order to evaluate the chip functionality, a number of external components were required. In the case of chips 1, 2 and 3, the tests were performed with only the chip inside the chamber and the rest of the components outside the chamber. Chip 4, on the other hand, was located on a surface mount evaluation-board, which made separating the components difficult. As a result, the evaluation-board containing chip 4, as a whole, was tested inside the chamber.

Table 2 shows the variation of the operating frequency for each chip as a function of temperature. It can be seen that chip 1 frequency stayed fairly constant initially but changed considerably as the temperature was lowered below –80 °C. This chip failed to operate for temperatures below –140 °C. Chip 2 maintained fairly constant frequency down to its lowest operating temperature of –180 °C. Similarly, chip 3 maintained fairly constant frequency down to its lowest operating temperature of –100 °C. The evaluation-board containing chip 4, on the other hand, displayed considerable change in frequency as the temperature was lowered down to its lowest at –140 °C. The reason for this could be deviation of some of the external components connected around the chip.

TABLE 1

SUMMARY OF PWM IC FEATURES

Chip	1	2	3	4
Technology	Bipolar	BiCMOS	Bipolar	BiCMOS
Packaging	Dip	Dip	Dip	SOIC
Lowest Temperature	0 °C	-55 °C	-40 °C	0 °C
Maximum Frequency	500 kHz	1 MHz	500 kHz	5 MHz
Duty Cycle Range	0 - 100%	0 - 100%	0 - 50%	0 - 100%
PWM Outputs	One	One	Two	Two
Control Mode	Current	Current	Voltage	Voltage

TABLE 2

VARIATION OF CHIP FREQUENCY WITH TEMPERATURE

Temp.	Chip 1	Chip 2	Chip 3	Chip 4
25 °C	87 kHz	67 kHz	95 kHz	40 kHz
0 °C	89 kHz	67 kHz	97 kHz	39 kHz
-20 °C	91 kHz	67 kHz	98 kHz	41 kHz
-40 °C	93 kHz	68 kHz	98 kHz	43 kHz
-60 °C	94 kHz	68 kHz	95 kHz	47 kHz
-80 °C	94 kHz	68 kHz	97 kHz	50 kHz
-100 °C	57 kHz	69 kHz	98 kHz	51 kHz
-120 °C	54 kHz	68 kHz	---------	77 kHz
-140 °C	51 kHz	69 kHz	---------	108 kHz
-160 °C	--------	69 kHz	-----------	-------
-180 °C	--------	70 kHz	----------	--------

Figures 4 through 7 show the waveforms of the four chips. Figure 4 shows the waveforms for chip 1 at room temperature (25 °C) and at the lowest operating temperature (−140°C). It can be seen that the reference voltage maintained its value of 5 V throughout the low temperature test. The frequency of the oscillator and the PWM output dropped significantly at the lower temperatures. Also, multiple switching occurred in the PWM output at the lowest operating temperature.

Figure 5 shows the performance of chip 2 at room temperature and at −180 °C (the lowest temperature). This chip is a modification of chip 1 by incorporating BiCMOS technology and a wider temperature operating range, as seen in Table 1. The frequency and duty cycle maintained their values over the temperature range. However, in the PWM output some pulses skipped at the lowest temperature. Comparing the two traces of the PWM output in Figure 5b, the top trace is similar to that at room temperature but some pulses were skipped in the bottom trace.

Figure 6 shows the reference voltage, the two PWM outputs and the oscillator waveform for chip 3. Figure 6a shows the performance at room temperature and Figure 6b shows the performance at the lower temperature of −100 °C. Compared to room temperature, the performance at −100 °C shows multiple switching in output B and also a very noticeable change in the dead time for switching between the two outputs A and B. Except for a few spikes, the reference voltage maintained its value between the two temperature extremes.

The performance of chip 4 at room temperature and at −140 °C is shown in Figures 7a and 7b, respectively. It can be clearly seen that the reference voltage remained relatively stable but the operating frequency and duty ratio changed considerably. The dead time, however, did not exhibit much change with temperature.

7. CONCLUSIONS

An experimental investigation has been performed to evaluate the performance of four high-speed pulse width modulation chips as a function of temperature in the range of 25 °C to −190 °C. The chips ranged in their electrical characteristics, modes of control, packaging options, and applications. In general, all of the chips exceeded their manufacturer's low temperature limit. The degree of operational stability of the chips with temperature varied from one device to another. Long term testing at cryogenic temperatures, however, is needed to fully characterize these and other devices for potential use in low temperature applications.

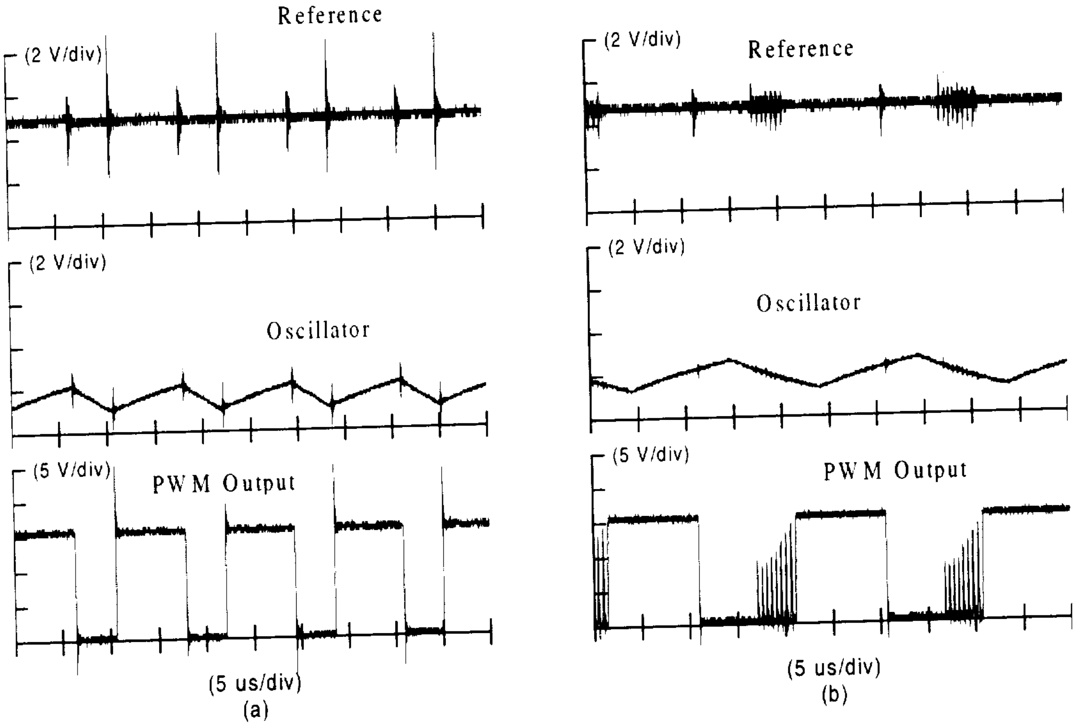


Fig. 4 Performance of chip 1: (a) at room temperature (b) at low temperature of −140 °C.

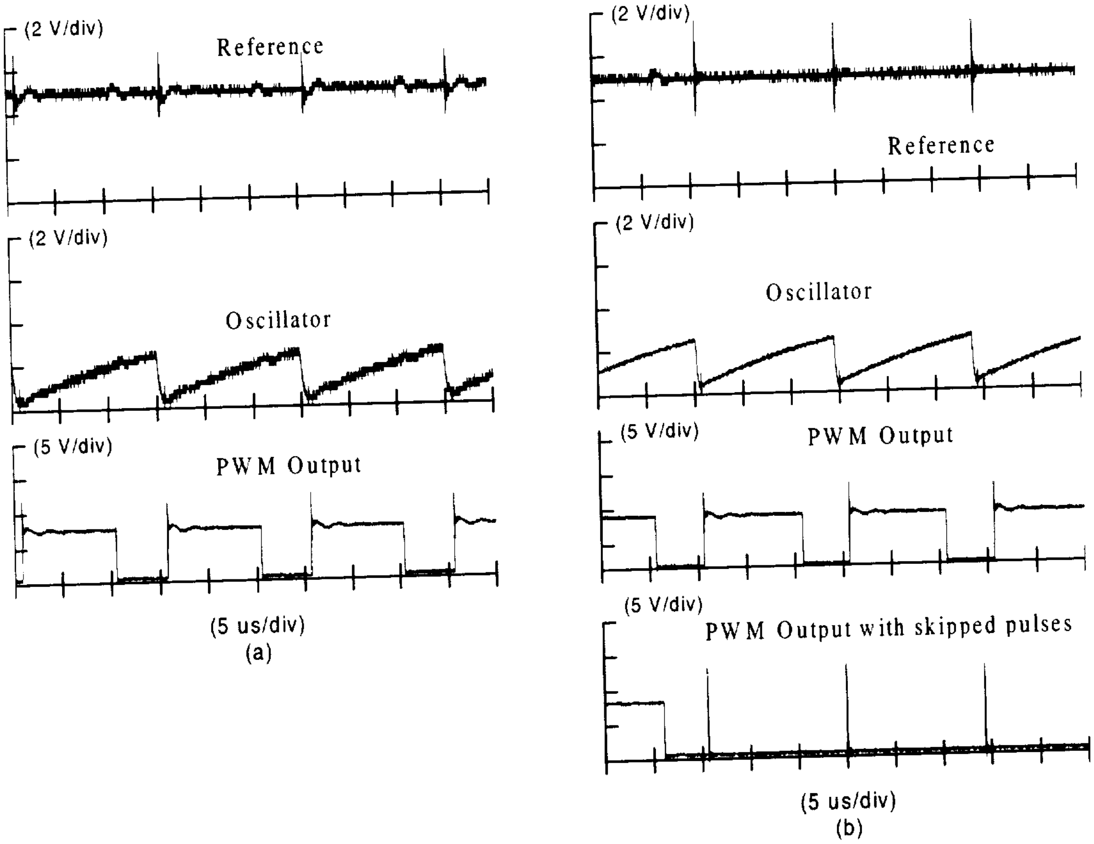
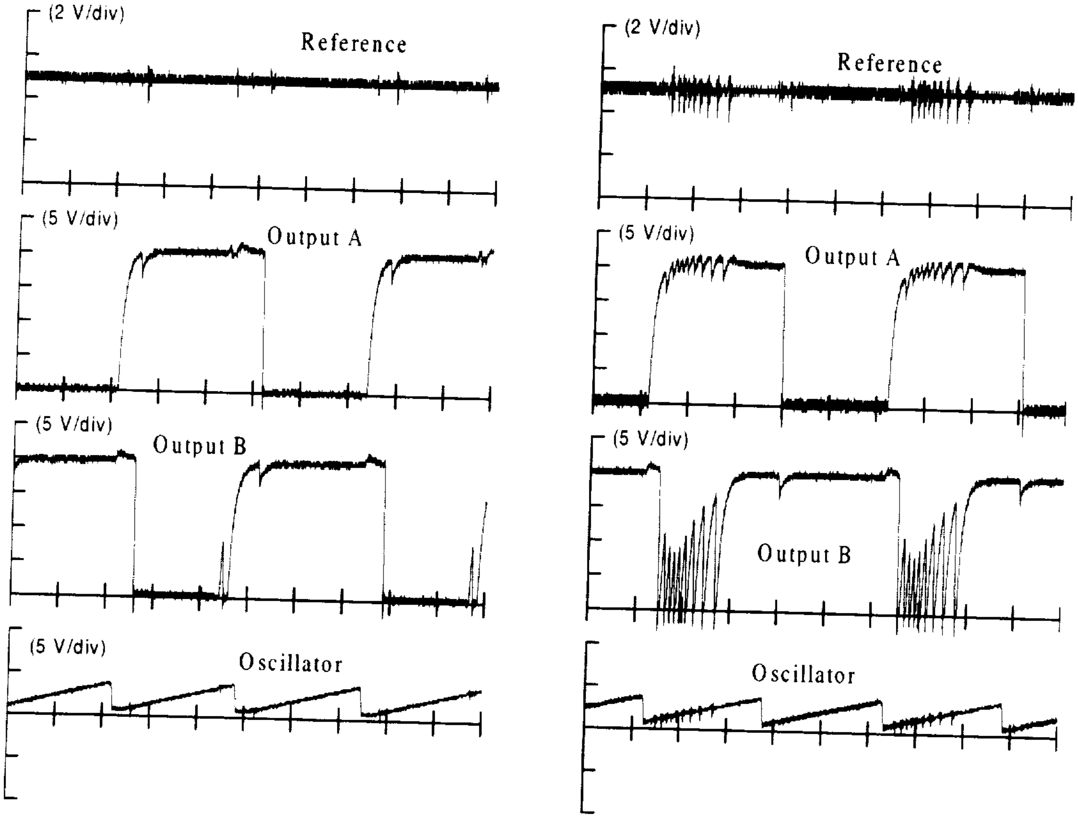


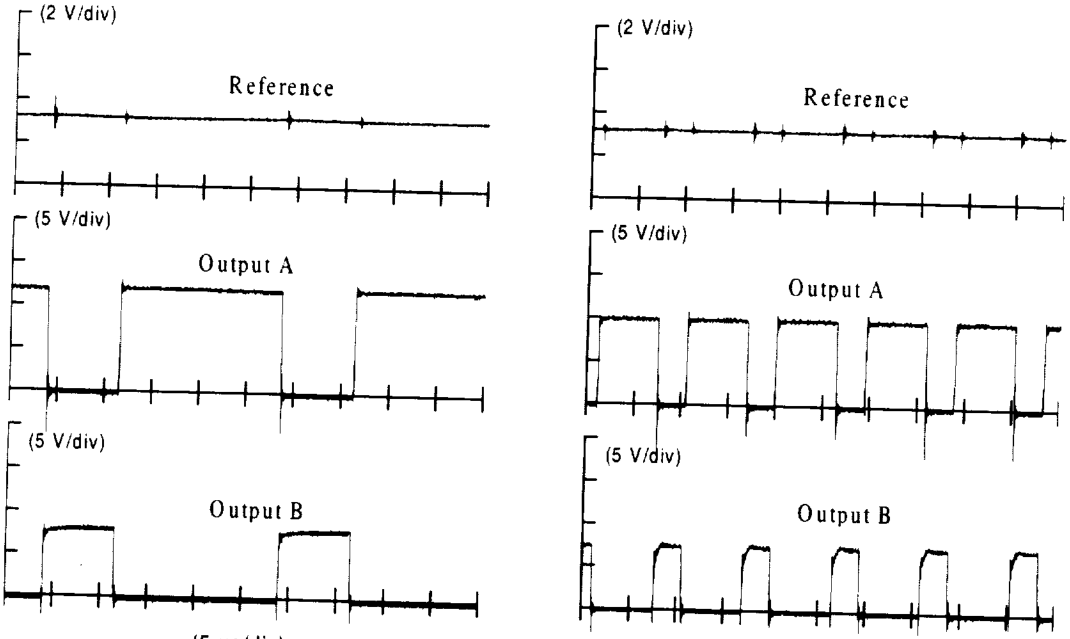
Fig. 5 Performance of chip 2: (a) at room temperature (b) at low temperature of −180 °C.



(2 us/div)
(a)

(2 us/div)
(b)

Fig. 6 Performance of chip 3: (a) at room temperature (b) at low temperature of −100 °C.



(5 us/div)
(a)

(5 us/div)
(b)

Fig. 7 Performance of chip 4: (a) at room temperature (b) at low temperature of −140 °C.

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13. ABSTRACT ***(Maximum 200 words)***

The operation of power electronic systems at cryogenic temperatures is anticipated in many NASA space missions such as planetary exploration and deep space probes. In addition to surviving the space hostile environment, electronics capable of low temperature operation would contribute to improving circuit performance, increasing system efficiency, and reducing development and launch costs. As part of the NASA Glenn Low Temperature Electronics Program, several commercial high-speed Pulse Width Modulation (PWM) chips have been characterized in terms of their performance as a function of temperature in the range of 25 to –196 °C (liquid nitrogen). These chips ranged in their electrical characteristics, modes of control, packaging options, and applications. The experimental procedures along with the experimental data obtained on the investigated chips are presented and discussed.

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