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Power Control Electronics for Cryogenic Instrumentation

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POWER CONTROL ELECTRONICS FOR CRYOGENIC INSTRUMENTATION

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ABSTRACT

In order to achieve a high-efficiency high-density cryogenic instrumentation system, the power processing electronics should be placed in the cold environment along with the sensors and signal-processing electronics. The typical instrumentation system requires low voltage dc usually obtained from processing line frequency ac power. Switch-mode power conversion topologies such as forward, flyback, push-pull and half-bridge are used for high-efficiency power processing using pulse-width modulation (PWM) or resonant control. This paper presents several PWM and multi-resonant power control circuits, implemented using commercially available CMOS and BiCMOS integrated circuits, and their performance at liquid-nitrogen temperature (77°K) as compared to their room temperature (300°K) performance. The operation of integrated circuits at cryogenic temperatures results in an improved performance in terms of increased speed, reduced latch-up susceptibility, reduced leakage current, and reduced thermal noise. However, the switching noise increased at 77°K compared to 300°K. The power control circuits tested in the laboratory did successfully restart at 77°K.

INTRODUCTION

An important application of low-temperature electronics is cryogenic instrumentation. The three subsystems of any instrumentation system are sensors, signal processing electronics, and power processing electronics. For cryogenic instrumentation, the signal and power processing electronics should be placed in the cold environment near the sensors in order to achieve a high-density and high-performance system. The objective of this paper is to address the feasibility of placing the power processing electronics in the cold environment. Typically, the instrumentation electronics requires low voltage dc power (e.g., 5 V, ±12 V, ±15 V), obtained from processing single-phase or three-phase line frequency ac voltage. The ac-to-dc power converter will have a front end high-voltage rectifier bridge followed by a dc-to-dc converter with a transformer for electrical isolation and voltage reduction. The

[1] This work was performed while the first author held a National Research Council-NASA Lewis Research Associateship, on leave from the University of Puerto Rico-Mayaguez Campus.

power, voltage, and current required by the instrumentation system are controlled through the dc-to-dc converter.

The dc-to-dc power conversion is achieved primarily using pulse-width modulation (PWM) topology [1]. Single-ended non-isolated PWM converters such as buck, buck-boost, boost, and Cuk are shown in Fig. 1. Also shown in Fig. 1 are typical double ended PWM power converters with transformer isolation such as push-pull and half-bridge. The PWM topology provides efficient power conversion for switching frequencies up to about 100 kHz. For switching frequencies beyond 200 kHz [2], the converter parasitics such as leakage inductance of transformer and junction capacitance of power MOSFET and diode rectifier become important and the converter performance detoriates in terms of efficiency, switch voltage, current stress, and noise. Therefore, for high density and high-efficiency power conversion, some form of soft-switching technique is used instead of the hard-switching used in PWM topology. One such soft-switching technique, known as multi-resonant zero-voltage switching [2], used in a buck converter, is shown in Fig. 2. In a multi-resonant zero-voltage switching converter, both switches turn-on and turn-off under zero-voltage condition and the converter absorbs all major circuit parasitics such as leakage inductance of the transformer and junction capacitances of all semiconductor devices, thus providing a topology suitable for high-density and high-efficiency power conversion.

Operation of several PWM and resonant power converters at liquid-nitrogen (LN_2) temperature has been reported in the literature [3,4]. However, in all these cases, only the power circuits of the dc-to-dc converters were tested at LN_2 temperature, while the control circuits needed to regulate the converters against line and load variations were kept at room temperature. The focus of this paper is on a complete cryogenic power converter that will operate in cold environments, both the control and power circuits. Specifically, the liquid-nitrogen temperature (77°K) operations of several power control circuits designed with commercially available components are compared with room-temperature operations. The designed control circuits can be used for single-ended and double-ended PWM converters as well as resonant converters. The details of the circuits and experimental results supporting the proposed concepts are presented in this paper.

SEMICONDUCTORS AT 77°K

Performance of semiconductor devices down to LN_2 temperatures improves with decreasing temperature due to improved thermal, electrical, and electronic properties of materials. Specifically, the field-effect semiconductor devices at low temperatures down to LN_2 have some important advantages over room temperature operation [5-9] such as:

- higher operational speed due to increased carrier mobility and saturation velocity;
- lower power dissipation due to reduced voltage supplies because of improved turn-on and turn-off characteristics;
- shorter signal transmission time because of reduced interconnect resistance and also because of the possibility of using superconducting thin-film as interconnections;
- improved reliability due to reduced electromigration and other thermally activated degradation mechanisms, and also reduced susceptibility to latch-up;
- increased integration density because of the higher semiconductor substrate and metal thermal conductivities; and

- improved digital and analog circuit performance such as noise margins, gain-bandwidth products or slew rates.

Most semiconductor devices exhibit improved speed at temperatures down to LN_2 temperature because of increased carrier mobility due to reduced carrier scattering, increased saturation velocity, reduced junction capacitance and reduced line resistance. For the experimental work reported in this paper, only the enhancement mode CMOS integrated circuits are used because they are expected to give the best overall performance in high speed/high density electronic systems and because their performance improves with decreasing temperatures. The signal delay (τ_D) in going from the input of one device to that of the next is composed of the internal device switching delay (τ_{sw}), the time it takes to charge and discharge (τ_L) the total load capacitance (C_L) including the wiring capacitance, and the time it takes to charge and discharge (τ_J) the parasitic junction capacitances (C_J). Thus,

$$\tau_D = \tau_{sw} + \tau_L + \tau_J \tag{1}$$

where,

$$\tau_L + \tau_J = V_{CC}(C_L + C_J)/I_{D,sat} \tag{2}$$

$$\tau_{sw} = L^2 / \mu V_D \quad \text{for} \quad E \le E_{sat} \qquad \text{or} \qquad \tau_{sw} = L / v_{sat} \quad \text{for} \quad E \ge E_{sat} \tag{3}$$

In the above equations, V_{CC} and V_D are the supply and drain voltages, $I_{D,sat}$, E_{sat}, and v_{sat} are the saturation drain current, saturation channel electric field, and saturation channel carrier velocity, and L and μ are the channel length and channel carrier mobility, respectively.

In terms of reliability, many degrading mechanisms are thermally activated and they obey an Arrhenius-like equation for the mean-time-before-failure (MTBF) or lifetime given by,

$$MTBF \propto e^{E_A/kT} \tag{4}$$

where E_A is an activation energy for electromigration, interdiffusion, chemical reaction, or corrosion and is in the 0.4 to 1 eV range for these processes, k is Boltzmann's constant, and T is temperature in °K. Therefore, as the temperature is reduced, there should be an exponential increase in lifetime. However, this theoretical prediction is not yet supported by any experimental work. Thermal cycling is another important unexplored area.

CONTROL CIRCUITS

Three control circuits were built and tested using CMOS and BiCMOS ICs from Texas Instruments (TLC555CP), Telcom Semiconductor (TC38C25CPE, TC4427ACPA), Harris (HIP5500), and International Rectifier (IR2113). The first control circuit, shown in Fig. 3, uses two TLC555CP to achieve PWM control and the TC4427ACPA as a low-side ground-referenced power MOSFET driver. The first 555 IC is used as an oscillator while the second 555 IC is used in a monostable mode. The duty-ratio control is achieved by using a 20 KΩ pot as a variable resistor for adjusting the width of the monostable output. The load in this case is a 1000 pF capacitor. This circuit can be used for low-side single-switch based topologies such as Boost, Cuk, Flyback, and Forward converters.

The second control circuit, shown in Fig. 4, uses a HIP5500 designed for half-bridge circuits. This IC includes the PWM control as well as drivers for low-side and high-side switches. The duty-ratio control is achieved through the soft-start pin (#8) by adjusting the voltage at this pin from $V_{cc}/3$ to $2V_{cc}/3$. The load used for both low-side and high-side outputs is 1000 pF capacitor. This circuit can also be used for push-pull and full-bridge converters. The third and final circuit, shown in Fig. 5, is designed for driving zero-voltage switching multi-resonant circuits such as the buck converter shown in Fig. 2. In this case, two independent control signals are generated for the high and low side switches. The control of the power converter is achieved by adjusting the time interval between the turn-off times of the power MOSFETs. Two TC38C25CPE voltage-mode PWM ICs are used in synchronization and their outputs go through a IR2113 driver IC before feeding the 1000 pF loads. IR2113 is a power MOSFET driver with independent high and low-side referenced output channels. The duty ratios are controlled independently through two 10 KΩ pots as shown in Fig. 5.

EXPERIMENTAL RESULTS

All three circuits were tested at room temperature (300°K) as well as at liquid-nitrogen temperature (77°K). Data were recorded, as shown in Table 1, to compare the rise and fall times and propagation delay. The complete circuitry was dipped in liquid-nitrogen, except the components in dashed box as shown in Figs. 3, 4, and 5, needed for the duty-ratio control. The circuits operated at temperature for one hour before recording any data both at 300°K and 77°K. The control circuits designed with commercially available components worked at 77°K, and their overall performances did improve when operated at liquid-nitrogen temperature compared to room-temperature operation as can be seen from Table I. Recorded waveforms for the output control signals are shown in Figs. 6-8, for the three circuits discussed here. The peak switching noise did increase at 77°K as can be seen from the recorded waveforms. All three circuits successfully restarted at 77°K.

Table I Recorded data at 300°K and 77°K
(* H: high-side switch; L: low-side switch)

Control Circuit	Temperature (°K)	Switching frequency (kHz)	Time period (µS)	On-time (µS)	Off-time (µS)	Rise time (nS)	Fall time (nS)	Duty ratio	Rise delay time (nS)	Fall delay time (nS)	Cold restart
Low-side single-switch	300	50.7	19.73	14.88	4.88	46	41	0.75	56	45	yes
	77	50.9	19.65	14.88	4.88	37	32	0.75	21	17	
Half-bridge	300	24.94	40.1	15.2	25.2	38^{H*} 53^{L*}	42^{H} 40^{L}	0.38	N/A	N/A	yes
	77	22.62	44.2	15.7	28.7	40^{H} 49^{L}	39^{H} 26^{L}	0.35			
Multi-resonant	300	49.5	20.2	15.2^{H} 7.65^{L}	4.85^{H} 12.7^{L}	30^{H} 39^{L}	29^{H} 40^{L}	0.75^{H} 0.38^{L}	166^{H} 185^{L}	190^{H} 182^{L}	yes
	77	50.2	19.93	15.2^{H} 7.65^{L}	5.15^{H} 12.7^{L}	35^{H} 32^{L}	26^{H} 35^{L}	0.75^{H} 0.37^{L}	91^{H} 170^{L}	145^{H} 173^{L}	

The switching frequencies of the circuits increased by 0.4% for the low-side single-switch circuit, decreased by 9.3% for the half-bridge circuit, and increased by 1.4 % for the multi-resonant circuit. 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. For the half-bridge circuit, the decreased switching frequency may be attributed at least partly to the bipolar driver section of the BiCMOS HIP5500. The rise and fall times in general decreased as expected. The rise and fall delay times improved significantly for the high-side switch of IR2113, whereas for the low-side switch, the improvement was not as great. However, for the TC4427ACPA driver, the rise and fall delay times decreased significantly by a factor of 2.7.

CONCLUSIONS

It is possible to successfully operate power control electronics at temperatures down to liquid-nitrogen temperature which were designed with commercially available room-temperature components. The switching speed and delay times improve with decreasing temperatures down to liquid-nitrogen temperature. Carrier freezeout is not a problem at or above liquid-nitrogen temperatures for enhancement-mode silicon MOSFETs. All three control circuits tested were able to restart at 77°K. The reliability of the control circuits is also expected to improve with decreasing temperature down to 77°K.

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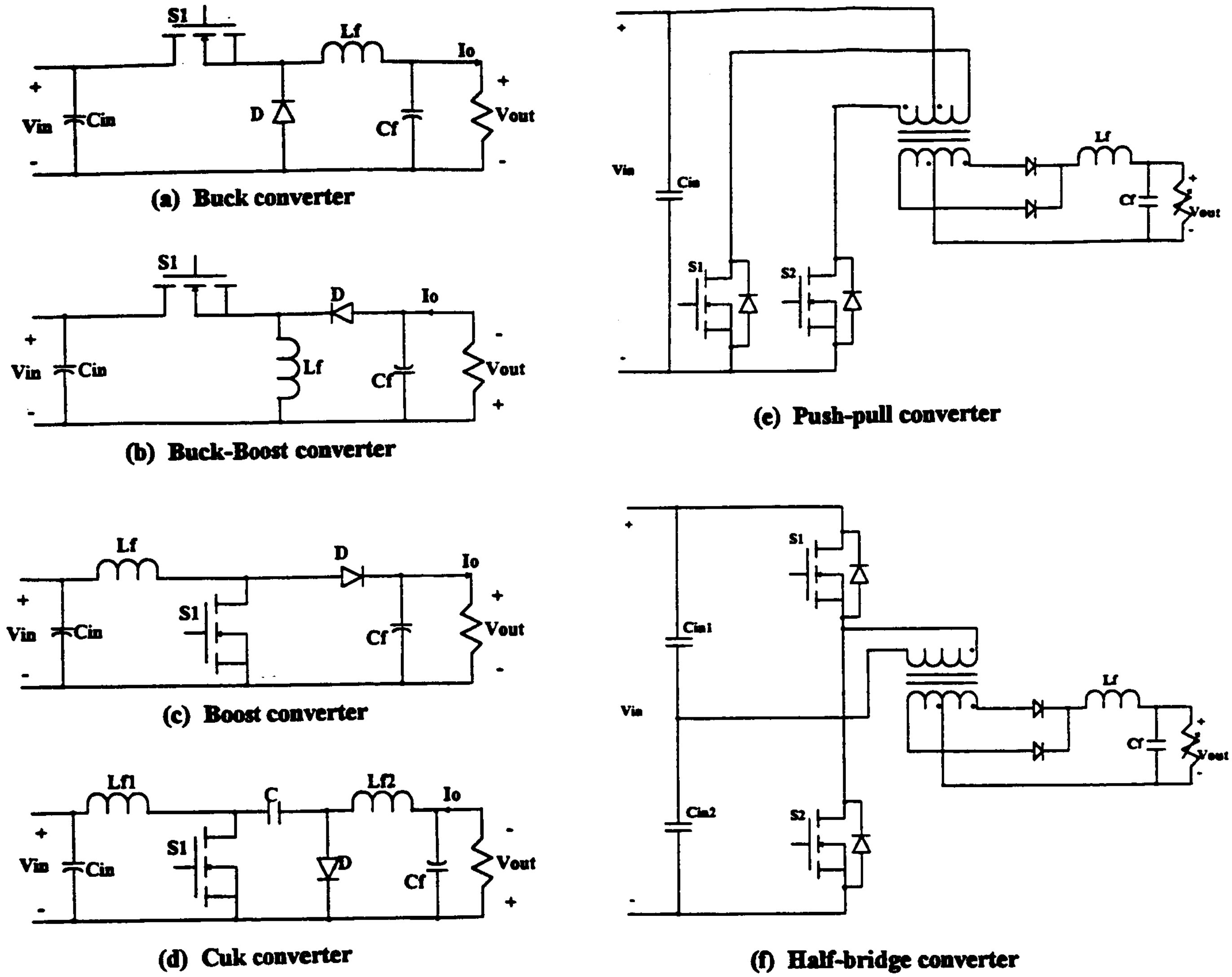


Fig. 1 PWM dc-to-dc power converters.

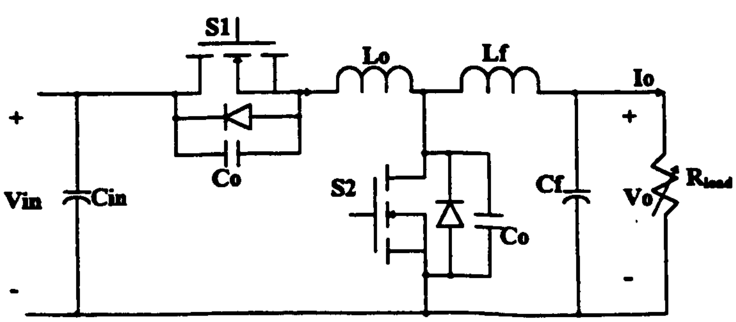


Fig. 2 Multi-resonant zero-voltage switching buck converter.

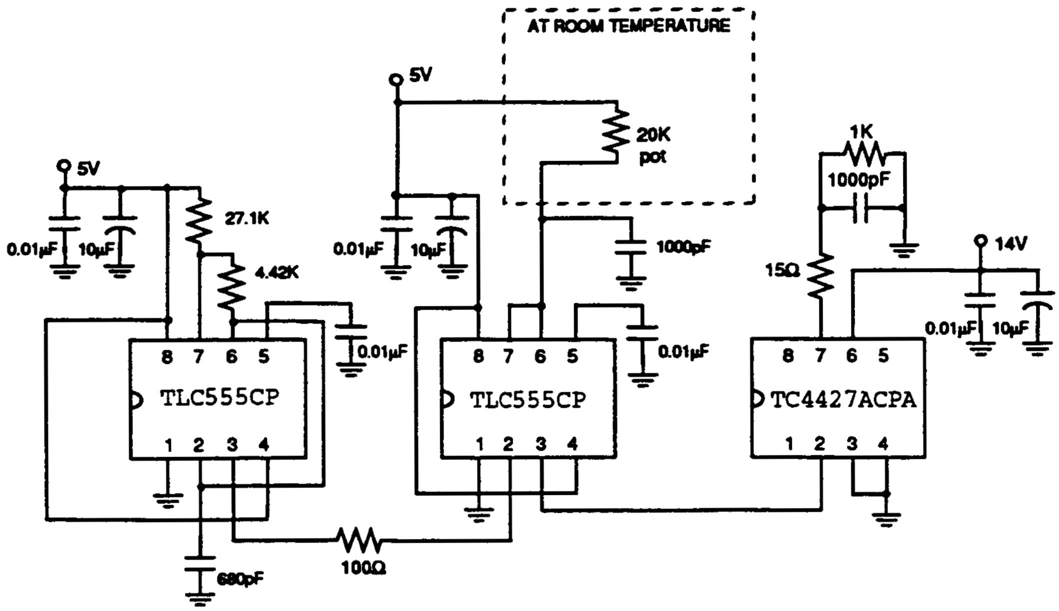


Fig. 3 Low-side single-switch PWM control circuit.

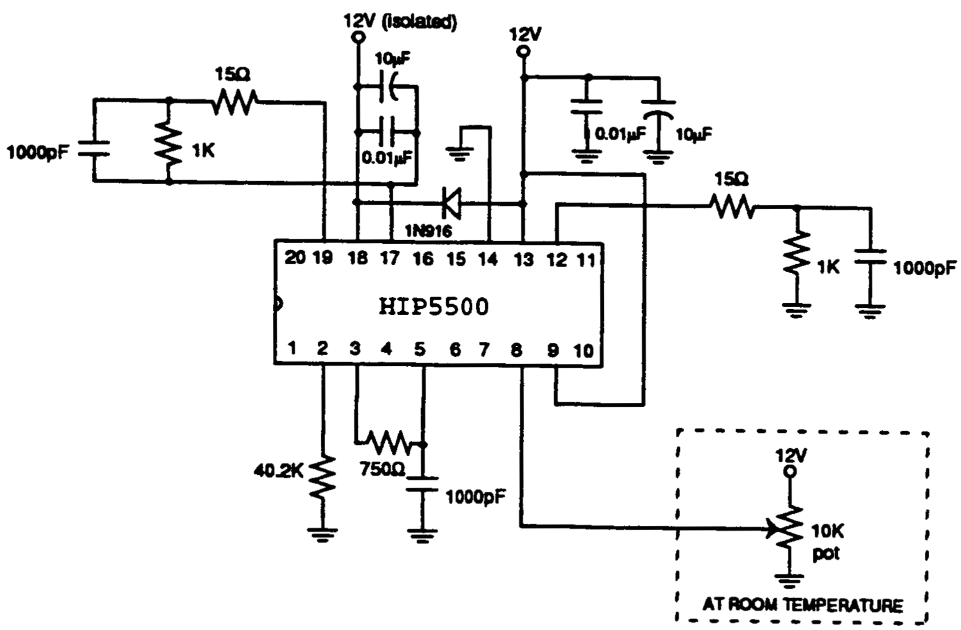


Fig. 4 Half-bridge PWM control circuit.

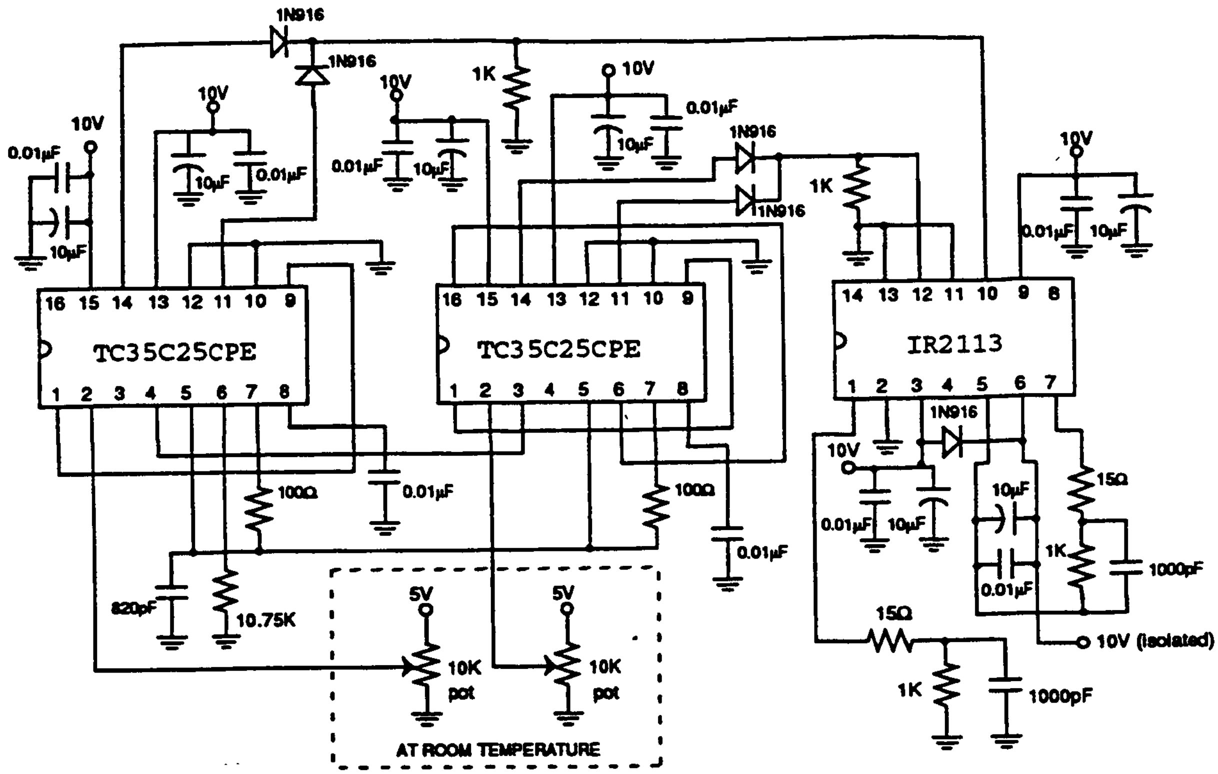
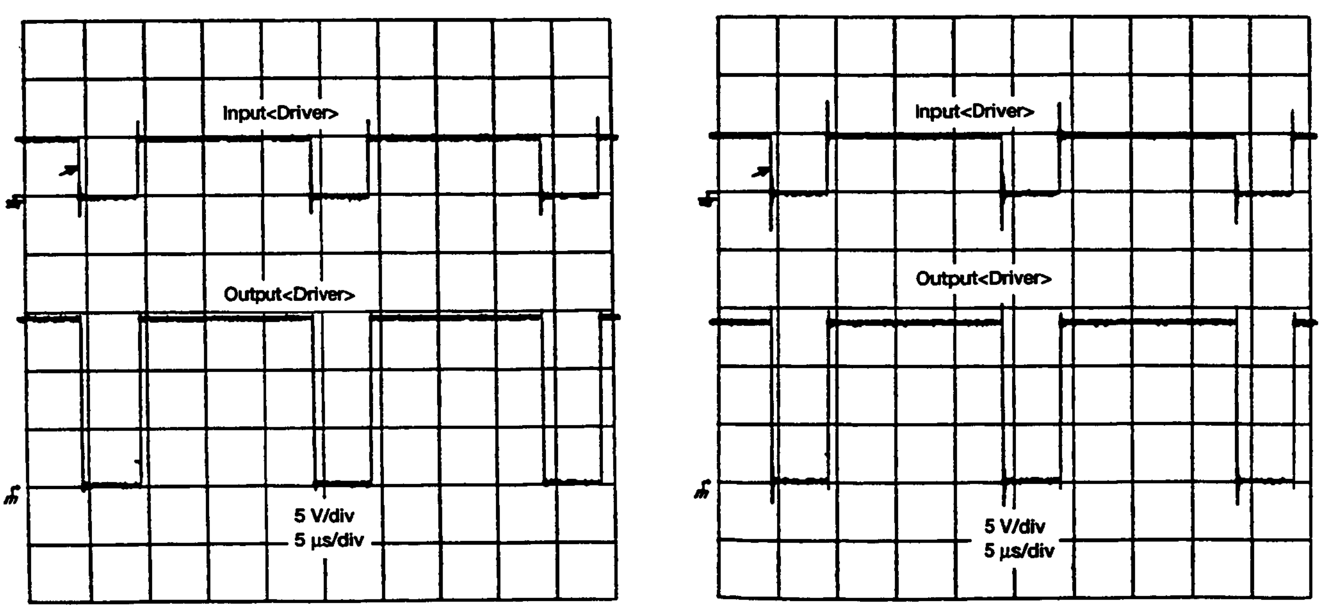
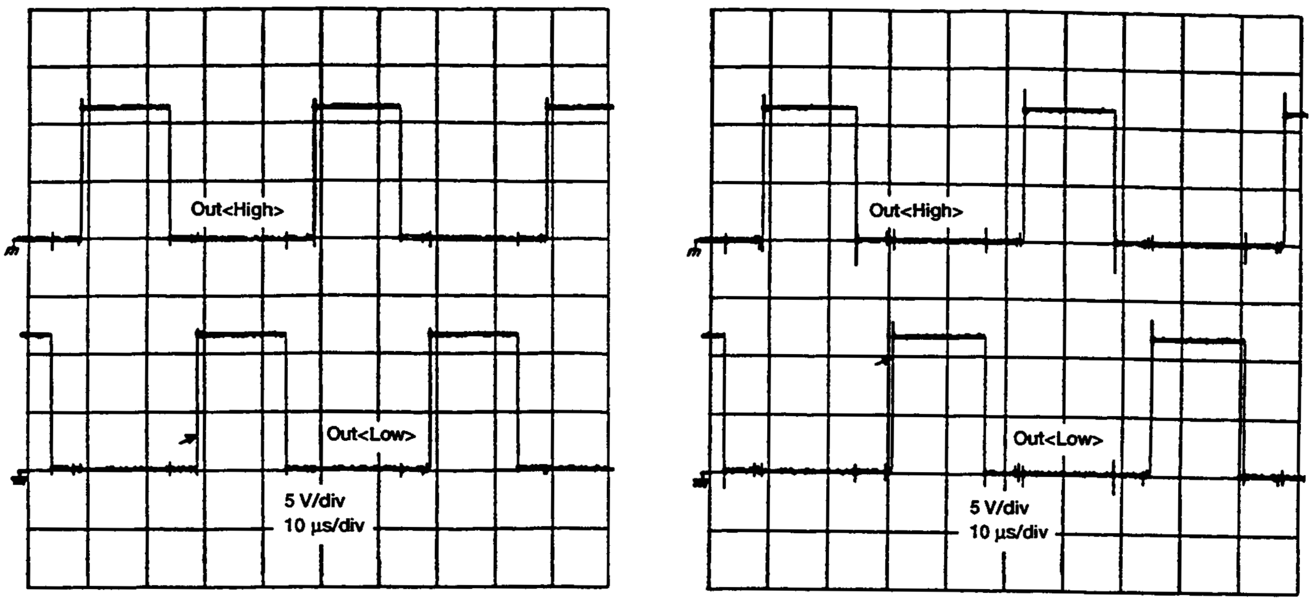


Fig. 5 Multi-resonant control circuit.



(a) Room temperature operation **(b) Liquid-nitrogen temperature operation**

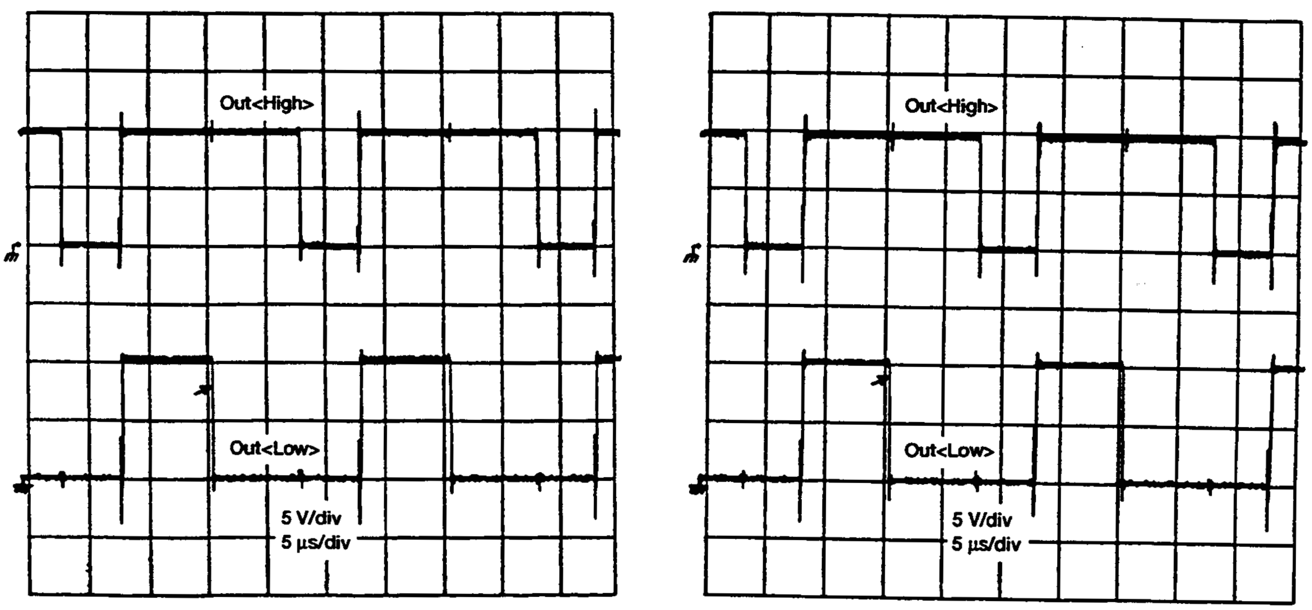
Fig. 6 Input and output control signals of the low-side single-switch driver.



(a) Room temperature operation

(b) Liquid-nitrogen temperature operation

Fig. 7 Output control signals of the half-bridge control circuit.



(a) Room temperature operation

(b) Liquid-nitrogen temperature operation

Fig. 8 Output control signals of the multi-resonant control circuit.

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

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