Development of a Radiation-Hardened POL DC/DC Converter for Space Applications

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Abstract

The operating voltages of space grade MPUs and FPGAs are getting lower. Therefore, the operating voltage drop caused by interconnection resistance hinders the stable operation of these kinds of components. To solve this problem, the necessity of a POL (Point of Load) DC/DC converter, a power supply installed adjacent to the MPU or FPGA, is increasing more than ever. This paper reports on the development overview of the POL DC/DC converter and on the results of reliability and environmental testing.

Keywords

POL, DC/DC converter, multi-chip structure, high reliability
radiation- hardened, planar inductor

1. Introduction

Recently use of high-speed MPUs (Micro-Processing Units) and large-scale FPGAs (Field-Programmable Gate Arrays) have increased as space missions became more and more sophisticated. In Japan, the Japan Aerospace Exploration Agency (JAXA) has already developed a space grade MPU and is currently developing a space grade FPGA and ASIC (Application-Specific Integrated Circuit) using SOI (Silicon on Insulator) technology. As core voltages of these devices are getting lower, a low supply voltage, such as 1.8 or 1.5 V, is required for them. This means that, if these devices are powered by a conventional concentration power distribution system that supplies power from a power supply installed at a distance from the circuit board, the interconnection resistance of the long wiring from the power supply to the devices would cause a drop in voltage and hinder the stable operation of the devices. To avoid this problem, it is necessary to adopt a divided power distribution system in which a power supply is installed adjacent to the MPU and FPGA to reduce interconnection resistance through reduced wiring distance. In such a design, the POL (Point of Load) DC/DC converter is a power supply device installed adjacent to the load. Its necessity is increasing more than ever as the operating voltages are getting lower.

We have developed a radiation-hardened POL with high performance and small size that are one of the world's best for space applications under the auspices of JAXA. This paper reports on the development overview and on the results of reliability and environmental testing.

2. Development Goals and Target Specifications

First, we set its development goals and target specifications as described in the following sections. We performed structural design, circuit design and part selection so as to achieve these targets, and we performed reliability and environmental testing to confirm that it has met the targeted specifications.

2.1 Development Goals

Since the POL is installed adjacent to the MPU or FPGA, it is required to be compact, lightweight and low profile which is equal to or less than that of the devices around it. It is also required to have a high power conversion efficiency in order to utilize limited power effectively and to minimize self-heating. It is also necessary to meet all of the requirements for high reliability, environmental tolerance and radiation tolerance. We set the POL's development goals as shown in **Table 1** .

2.2 Target Specifications

Table 2 shows the target specifications of the POL in terms of both electrical characteristics and environmental tolerance. The standard input voltage is 5 V and the maximum input voltage is 16 V. Five output voltages are specified, as shown in Table 2. The target efficiency of the POL is set to 90% or more (at 5 V input, 3.3 V output and 25°C), which is equivalent to that of consumer products and is one of the world's highest level

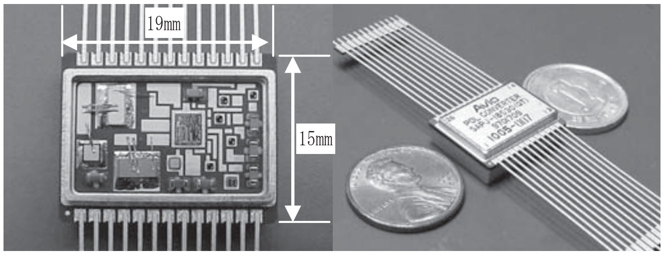
Table 1 POL development goals.

Item	Goals
Size	≤ 20 × 20 mm
Thickness	≤ 6 mm
Weight	≤ 10 grams
Efficiency	≥ 90% (@ 3.3 V output)
Reliability	Reliability required for space applications (JAXA-qualified)
Radiation tolerance	Tolerance required for space applications (see Table 2)

Table 2 Target specifications.

Item	Target Performance
Input voltage range	4.5 to 16 V (Standard: 5 V)
Output voltage/current (ratings)	1.2 V/3 A, 1.5 V/3 A, 1.8 V/3 A, 2.5 V/2.6 A, 3.3 V/2 A
Output voltage regulation	±2% (25°C), ±4% (125°C, -55°C)
Efficiency	≥ 90% (@ 5 V input, 3.3 V output, 25°C)
Switching frequency	250 kHz
Applicable standard	Integrated Circuits, Hybrid, High Reliability, General Specification for (JAXA-QTS-2020B)
Operating temperature range	-55°C to +125°C
Vibration	20 G sine wave
Shock	1,500 G half sine wave
Temperature cycling	-65°C ⇔ +150°C, 100 cycles
Steady-state life	125°C, 1,000 hours
Radiation tolerance – TID[1]	1 kGy (Si)
Radiation tolerance – SEE[2]	> 64 MeV/(mg/cm²)

1) Total Ionizing Dose 2) Single Event Effect



(a)Internal view (b)External view

Photo Internal view (top side) and external view of the POL.

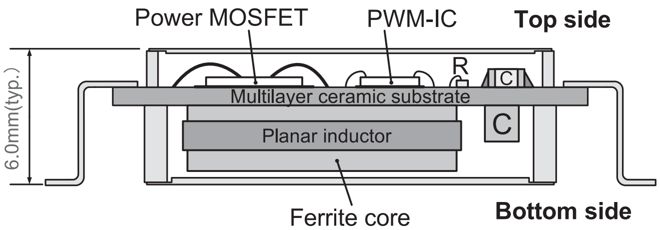


Fig. 1 Cross sectional view of the POL assembly.

for space applications. Reliability, environmental tolerance and radiation tolerance are set to the same class I level as that required for space grade hybrid ICs.

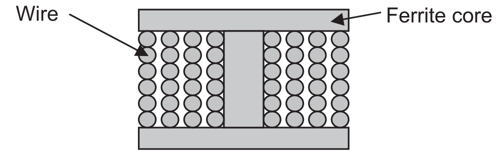
3. Development Overview and Test Results

3.1 Structure

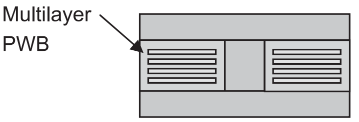
The POL is installed directly onto the side or back of an MPU or FPGA. This means that it should be implemented with a small size and a low profile that allows it to be mounted on both sides of the circuit board. It should also be lightweight so that it can be mounted on the circuit board. Therefore, we studied a structure that can achieve a small size, light weight and low profile.

For our approach to miniaturization, we adopted a multi-chip structure, as shown in the picture on the left of **Photo** . In this structure, devices such as the PWM-IC and power MOSFET (Metal Oxide Semiconductor Field Effect Transistor) are bare chip mounted and hermetically sealed. Since a bare chip is smaller than a packaged discrete device, the use of a bare chip contributes greatly to miniaturization. Additionally, we adopted a both sides mounting and hermetic seal structure for further miniaturization, as shown in **Fig. 1** . This structure has made it possible to implement the POL in a size of 15 × 19 mm, which is one of the world's smallest level for space applications. The picture on the right of Photo shows an external view of the POL.

This both side mounting structure contributes to miniaturization but also tends to increase device thickness. To compensate for this disadvantage by minimizing thickness, low profile parts such as the bare chip and small capacitors are mounted on top side to keep its thickness as low as possible. .Meanwhile, as the inductor, which has a high profile, is mounted on the bottom side, it is necessary to reduce the profile of the inductor in order to reduce thickness on the bottom side of the device. Therefore, we decided not to use a wire-wound inductor, as shown in **Fig. 2** (a), and instead adopted a planar inductor that uses a multilayer PWB, manufactured by ourselves, as shown in Fig. 2 (b). A planar inductor replaces wires with multilayer PWB. This structure is already in frequent use in consumer products and is the mainstream of current on-board power supplies. A planar inductor design contributes to device profile reduction because it can form a thinner inductor than wire-wound inductor. In addition, it can be regarded as the optimum structure for space applications, which are subject to



(a) Conventional wire-wound inductor



(b) Planar inductor adopted by the POL

Fig. 2 Planar inductor schematic.

high reliability requirements, because it can eliminate the reliability-degrading elements accompanying the use of wire-wound inductor (such as disconnection of wire at micro-soldering points, scratches of wire coating, etc.).

In our approach to weight reduction, we adopted a multi-chip structure in which a multilayer ceramic substrate is employed in the package base onto which the electronic parts are mounted. This structure has made possible a weight of 7.2 grams (max.), which is one of the lightest in the world for space applications.

3.2 Electrical Performance

To achieve an efficiency of 90% or more, we selected a step-down switching regulator topology. As there had been no switching regulator PWM-IC applicable to space use in Japan, it was decided that JAXA would develop an exclusive PWM-IC for the POL. This PWM-IC employs a synchronous rectification system, which can contribute to the improvement of POL efficiency. At the same time, JAXA also developed a power MOSFET of the low on-resistance type, assuming combination with the PWM-IC. We were able to achieve an efficiency of 90% or more (at 5 V input, 3.3 V output), one of the highest in the world, by implementing these parts and optimizing the parts layout and pattern layout on a multilayer ceramic substrate.

Fig. 3 is a graph showing the efficiency of the POL with respect to load current. It shows that its efficiency, when load current is 2 A at a temperature of 25°C, is around 93%, and that the target performance of 90% or more has therefore been achieved. It also shows that an efficiency close to 90% is maintained at the high temperatures at which efficiency tends to drop. Efficiency at low temperatures is almost identical to that at room temperature.

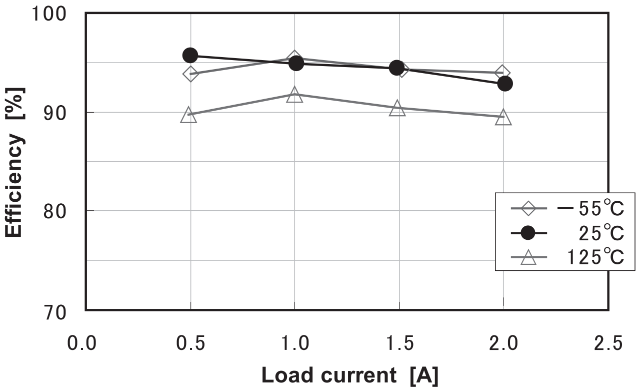


Fig. 3 Efficiency vs. load characteristics (Vin = 5 V, Vout = 3.3 V).

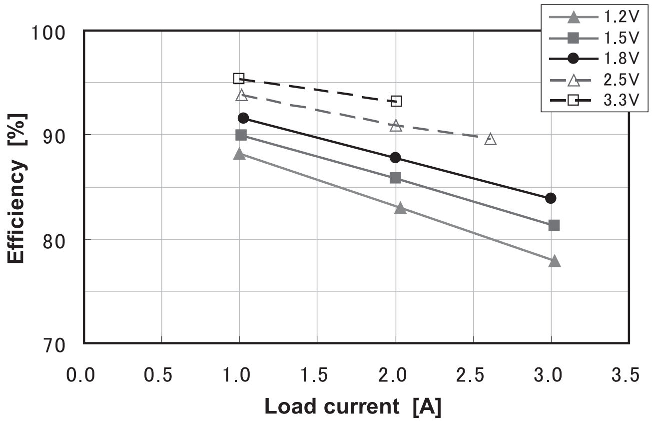


Fig. 4 Efficiency vs. load characteristics by output voltage.

Efficiency is variable depending on output voltage, as shown in the characteristic graph in **Fig. 4** . This graph shows efficiency with respect to load current at 1.2 V, 1.5 V, 1.8 V, 2.5 V and 3.3 V. It indicates that efficiency tends to drop as output voltage decreases.

As output voltage regulation with respect to load current is about 1%, and regulation with respect to temperature is about 2% at maximum, it can be concluded that the target specifications of ±2% (at 25°C) and ±4% (at extreme temperatures) are met sufficiently.

3.3 Reliability and Environmental Tolerance

To confirm that the POL has the reliability and environmental tolerance required for space applications, we performed the

Table 3 Main reliability tests and their results.

Item	Details, Conditions, Samples	Result
Gr. A	Electrical parameter test: 45 samples -55°C, +25°C, +125°C	Good
Gr. B	DPA, etc. : 3 samples Bond strength, die shear, solderability, lead integrity, resistance to solvents, etc.	Good
Gr. C1	Reliability test : 22 samples Steady-state life (125°C, 1,000 hours)	Good
Gr. C2	Environmental test: 5 samples Temperature cycling (-65°C ⇔ +150°C, 100 cycles) Shock(1,500 G, 6 directions) Vibration (20 G, 3 axes), etc.	Good
Gr. D	Environmental test: 5 samples Thermal shock(-55°C ⇔ +125°C, 15 cycles) Shock(1,500 G, 6 directions) Vibration (20 G, 3 axes) Moisture resistance, Salt atmosphere, etc.	Good

Table 4 Additional reliability tests and their results.

Item	Conditions, Samples	Result
Steady-state life	125°C, 3,000 hours: 3 samples	Good
Random vibration	43.92 Grms, 3 axes: 3 samples	Good

reliability test (qualification test) specified in JAXA-QTS-2020B, the General Specification for the High Reliability of Hybrid Integrated Circuits for Space applications. The main details and results of this testing are shown in **Table 3** . All of the results were satisfactory. With these results, we succeeded in acquiring a JAXA QML certification.

In addition to reliability tests, we also conducted more stringent tests, shown in **Table 4** , and obtained favorable results with them as well. Based on the results of these tests, we believe that the developed POL has enough reliability and environmental tolerance for space applications.

3.4 Radiation tolerance

The POL components that are vulnerable to radiation are the PWM-IC and the power MOSFET. Both of these were developed by JAXA and designed to meet the target level of radiation tolerance. Those parts were subjected to the TID and SEE tests at JAXA and were proven to be free of problems.

We performed an additional TID test on the POL for reconfirmation. Total radiation dose was 1 kGy, assuming a geostationary orbit satellite. The radiation source used was cobalt-60 (γ-rays). The test indicated that output voltage decreased by about 1% after irradiation. This result is due to the characteristics of the PWM-IC and should be regarded as reasonable because a similar variation was also observed in the TID test conducted on the PWM-IC as a standalone unit. The results related to other electrical characteristics were favorable and free of problems. Based on the results of these tests, we believe that the developed POL has enough radiation tolerance for space applications.

4. Conclusion

We developed a radiation-hardened POL for MPUs and FPGAs with an efficiency and size in the top class in the world for space applications under the auspices of JAXA. We performed various tests and confirmed that it has the reliability and environmental tolerance required for space applications. In the future, the POL will be used as a JAXA-qualified part in a wide range of spacecraft.

The development of the POL was performed in the framework of the JAXA-committed research entitled “Development of a POL DC/DC Converter for Space Applications.” We would like to express our deep gratitude toward JAXA for their kind guidance and encouragement, as well as for giving us the opportunity for such an interesting development project.

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