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Efficiency improvement of a DC/DC converter using LTCC substrate

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We propose a substrate with high thermal conductivity, manufactured by the low-temperature co-fired ceramic (LTCC) multilayer circuit process technology, as a new DC/DC converter platform for power electronics applications. We compare the reliability and power conversion efficiency of a converter using the LTCC substrate with the one using a conventional printed circuit board (PCB) substrate, to demonstrate the superior characteristics of the LTCC substrates. The power conversion efficiencies of the LTCC- and PCB-based synchronous buck converters are 95.5% and 94.5%, respectively, while those of nonsynchronous buck converters are 92.5% and 91.3%, respectively, at an output power of 100 W. To verify the reliability of the LTCC-based converter, two types of tests were conducted. Storage temperature tests were conducted at −20 °C and 85 °C for 100 h each. The variation in efficiency after the tests was less than 0.3%. A working temperature test was conducted for 60 min, and the temperature of the converter was saturated at 58.2 °C without a decrease in efficiency. These results demonstrate the applicability of LTCC as a substrate for power conversion systems.

KEYWORDS
DC/DC converter, efficiency, low-temperature co-fired ceramic, reliability test, thermal conductivity

1 | INTRODUCTION

There has been growing interest in the development of better technologies to improve the heat dissipation, thermal reliability, and efficiency of switching-mode power electronic products. Thermal issues have become critical in the design of power conversion systems. With increases in temperature, the on-resistance of a MOSFET ($R_{ds,on}$), and the resistance and leakage current of a diode increase. High temperature also degrades the performance of passive devices such as inductors, capacitors, and resistors. Conventional systems using a printed circuit board (PCB) require additional cooling elements for heat dissipation, thereby increasing the overall size of the system.

The thermal conductivity of low-temperature co-fired ceramic (LTCC) is more than 10 times higher than that of an FR-4 PCB in power electronics applications. Notably, through-hole vias in a conventional PCB are electroplated with copper, while embedded vias used in LTCC are filled with silver. This enables an improvement in the power efficiency and optimizes the system volume. LTCC multilayer technology can further reduce the size of a system through three-dimensional high integration, embedding both active and passive devices. Table 1 compares the properties of a traditional PCB and the proposed LTCC substrate material.

Our group has studied discrete power device packages with an embedded cavity in multilayer LTCC to reduce the parasitic

TABLE 1 Comparison of substrate material properties

		PCB	LTCC
Thermal Conductivity (W/mK)		0.2–0.4	4–5
Coefficient of thermal expansion (ppm/°C)		13–17	5–7
Heat dissipation		Low	High
Circuit	Layer	Cu foil	Ag paste
	Thermal Conductivity (W/mK)	385	419
	Electrical Resistivity (μΩ-cm)	1.7	1.55
Substrate layer		FR-4	Ceramics
Cost		Low	Medium

inductance caused by wire bonding [1,2]. Virginia's Polytechnic Institute and State University has studied planar inductors using magnetic tape and a multilayer LTCC manufacturing process to implement small-size non-isolated point-of-load (POL) converters [3–6]. However, their maximum output power achieved is below 50 W, and the maximum output efficiency is 92.5% at an output power of approximately 6 W [3].

The 48-V system including a 48-to-12 V converter is applied in various fields, such as vehicles, servers, industrial power supplies, telecom, etc. In automotive applications, a 48-V system can achieve high efficiency and reduces wiring and component weight. Meanwhile, a 48-to-12 V converter is required for providing power to different types of electrical loads [7–9] for example, servers in data centers require 48-to-12 V converters with high efficiency and power density [10–12].

This paper discusses the applicability of a substrate with high thermal conductivity fabricated with LTCC process technology as a new DC/DC converter platform in power electronics applications. It also details the design of a 48-to-12 V converter, provides an efficiency comparison to four other converters, and describes the results of a reliability test of the proposed LTCC-based nonsynchronous buck converter. The following four types of converters are designed and discussed in this paper:

1. (Type I) synchronous buck converter on LTCC
2. (Type II) synchronous buck converter on PCB
3. (Type III) nonsynchronous buck converter on LTCC
4. (Type IV) nonsynchronous buck converter on PCB

Section 2 of this paper discusses the design of a 48-to-12 V synchronous buck converter and compares the efficiencies of the proposed LTCC- and conventional PCB-based converters. Section 3 discusses the design of a 48-to-12 V nonsynchronous buck converter and compares the efficiencies of the proposed LTCC- and conventional PCB-based converters in a higher heat generation scenario. Finally, we report the reliability tests of the proposed LTCC-based converter.

2 | PROPOSED LTCC-BASED SYNCHRONOUS BUCK CONVERTER

We designed a synchronous converter and manufactured two converters, one using LTCC (Type I) and the other using a conventional PCB (Type II) for the substrates. Figure 1

TABLE 2 Major design parameters of the synchronous buck converter

	Model/parameters
FET	GS61008P ($R_{ds,on}$ = 10 mΩ)
L	10 μH (27 mΩ)
C_{out}	594.11 μF
C_{in}	23.6 μF
Controller	LM5116

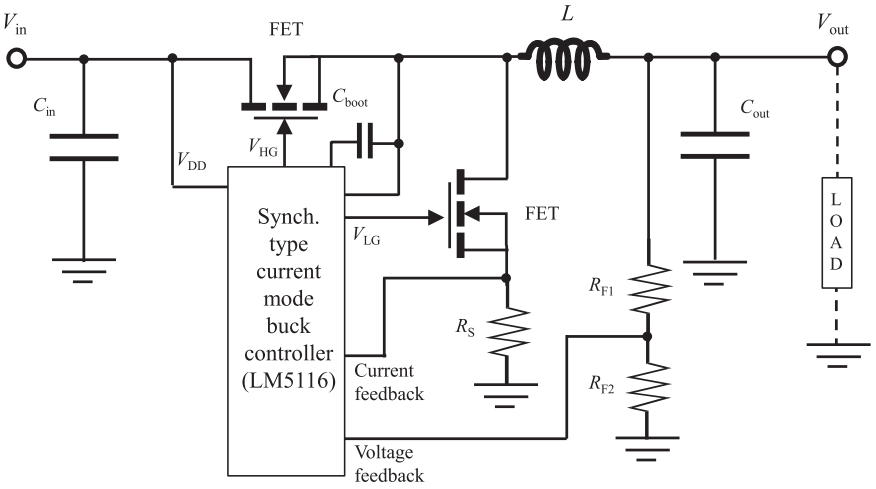

FIGURE 1 Simplified circuit diagram of the 48-to-12 V synchronous buck converter

shows a simplified circuit diagram of the 48-to-12 V synchronous buck converter.

We used gallium nitride (GaN) FETs as the power switches. The fast switching speed, and low switching and conduction losses of a GaN-based power semiconductor enable small-size, highly efficient power conversion systems to be implemented [13–18]. Several research groups have reported highly efficient and small-size power conversion systems such as buck converters, boost converters, and inverters using GaN switching power devices [6,12,19–21]. In our design, an LM5116 was used as a pulse width modulation (PWM) controller to drive the high- and low-side power switches simultaneously.

Table 2 summarizes the major design parameters used in the synchronous buck converter, where L, C_{in}, and C_{out} are selected using (1)−(3). Here, ΔI is an inductor ripple current, f_{sw} is the switching frequency, and ΔV is the maximum output voltage overshoot.

$$L=\left(V_{\text{in, max}}-V_{\text{out}}\right)\times\frac{V_{\text{out}}}{V_{\text{in, max}}}\times\frac{1}{f_{\text{sw}}}\times\frac{1}{\Delta I}, \tag{1}$$

$$C_{\text{out}}=\frac{L\times\left(I_{\text{out,max}}+\frac{\Delta I}{2}\right)^2}{\left(\Delta V+V_{\text{out}}\right)^2-V_{\text{out}}^2}, \tag{2}$$

$$C_{\text{in}}=I_{\text{out,max}}\times\frac{\sqrt{V_{\text{out}}\times\left(V_{\text{in}}-V_{\text{out}}\right)}}{V_{\text{in}}}. \tag{3}$$

Figure 2 shows the breakdown of the power losses calculated by (4)−(8) in the synchronous buck converter. The expected efficiency of the 48-to-12 V synchronous buck converter is 95.44% at a maximum output power of 120 W.

$$P_{\text{loss},C_{\text{in}}}=I_{\text{ripple,in}}^2\times\text{ESR}_{C_{\text{in}}}, \tag{4}$$

$$\begin{aligned}P_{\text{loss,H-FET}}=&\left[I_{\text{load}}^2\times R_{\text{ds,on}}\times\frac{V_{\text{out}}}{V_{\text{in}}}\right]\\&+\left[\left(V_{\text{in}}-V_{\text{out}}\right)\times\frac{I_{\text{load}}}{2}\times\left(t_{\text{r}}+t_{\text{f}}\right)\times f_{\text{sw}}\right],\\&+\left[C_{\text{oss}}\times\left(V_{\text{in}}-V_{\text{out}}\right)^2\times f_{\text{sw}}\right]\end{aligned} \tag{5}$$

$$P_{\text{loss,Inductor}}=I_{\text{load}}^2\times\text{DCR}_{\text{Inductor}}, \tag{6}$$

$$P_{\text{loss},C_{\text{out}}}=I_{\text{ripple,out}}^2\times\text{ESR}_{C_{\text{out}}}, \tag{7}$$

$$P_{\text{loss,L-FET}}=I_{\text{load}}^2\times R_{\text{ds,on}}\times\left(1-\frac{V_{\text{out}}}{V_{\text{in}}}\right). \tag{8}$$

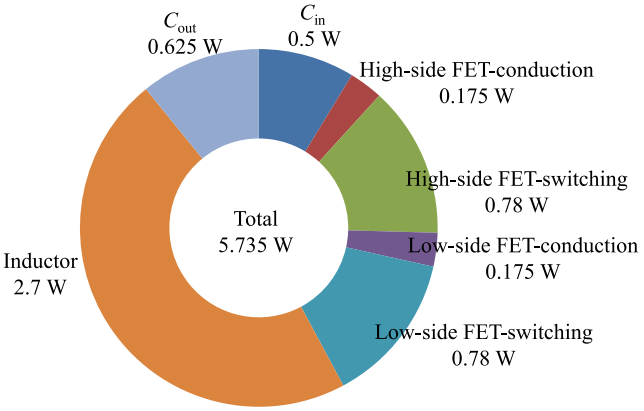

FIGURE 2 Breakdown of the calculated power losses in the synchronous buck converter

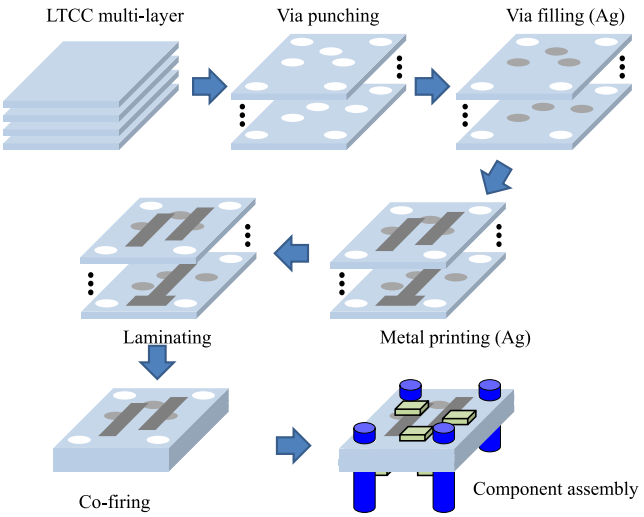

FIGURE 3 Simplified manufacturing process of the proposed LTCC-based converter

Figure 3 shows the simplified manufacturing process of the proposed LTCC-based converter. Unlike the through-hole vias used in a conventional PCB process, which are electroplated with copper, vias used in the LTCC process are filled with silver. This reduces the parasitic inductance and improves the electrical and thermal conductivities. Because the standard thickness of LTCC tape is 100 μm, and many layers are used in power electronics applications, a substantial amount of substrate noise reduction and high design flexibility of the control block, power, and ground planes can be achieved.

Figure 4 shows top and bottom views of the manufactured synchronous converter using an LTCC substrate. The size of the nonsynchronous converter is 55 mm × 40 mm and the thickness of the LTCC substrate is 1000 μm.

To compare the performance of the LTCC and PCB, we manufactured two converters, one using LTCC (Type I) and the other using a conventional PCB (Type II), using the

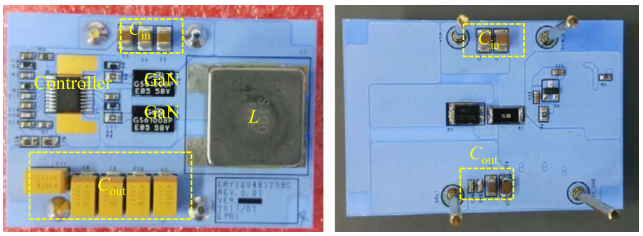

FIGURE 4 (A) Top and (B) bottom views of the manufactured LTCC-based synchronous buck converter

circuit schematic of Figure 1. Figure 5 shows the waveforms of the gate voltage of the high-/low-side FETs, source voltage of the high-side FETs, and inductor current. Because the proposed Type I using the embedded metal planes and vias in the multilayer LTCC substrate has low parasitic inductance and capacitance, the noise and voltage spikes of the Type I are lower than those of the Type II.

Figure 6 shows the measured power conversion efficiency at an input voltage of 48 V. The efficiencies of the LTCC- and PCB-based converters are 95.5% and 94.5%, respectively, at an output power of 100 W. As the output power increases, the difference in their efficiencies increases owing to the increased heat generation in the active elements.

3 | PROPOSED LTCC-BASED NONSYNCHRONOUS BUCK CONVERTER

To compare the efficiency under higher heat generation, we designed a 48-to-12 V nonsynchronous buck converter, as shown in Figure 7.

A GaN-based FET and Schottky barrier rectifier (SBR) are used as the power switch and freewheeling diode, respectively. We used an LM5088 as the PWM controller. The output of the LM5088 is fed to an LM5113 used as a gate driver. A low drop

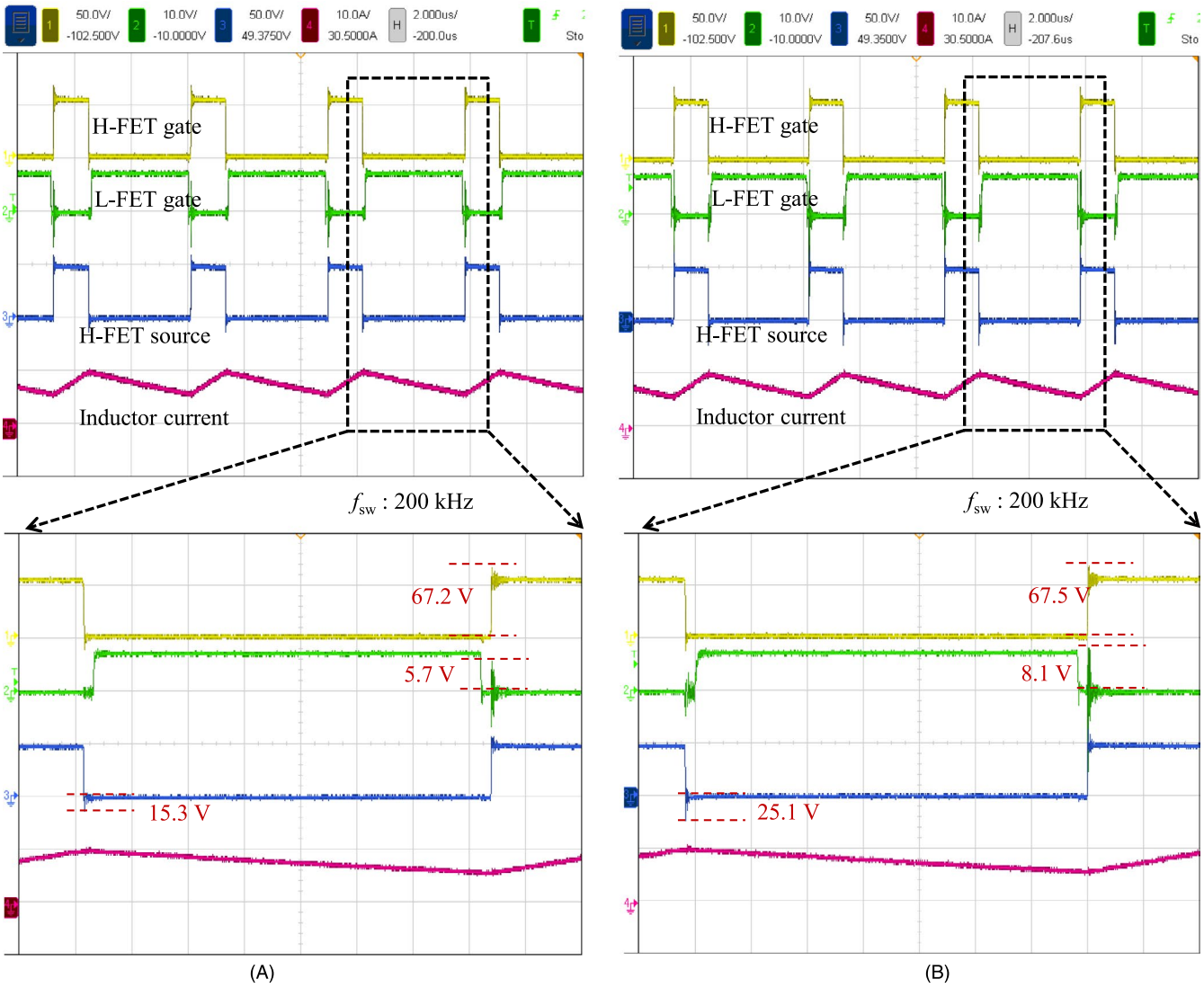

FIGURE 5 Measured voltage and current waveforms of the (A) Type I and (B) Type II systems

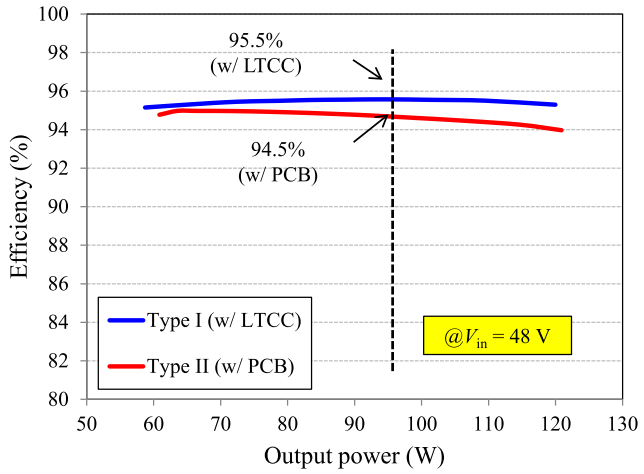

FIGURE 6 Measured efficiency as a function of output power

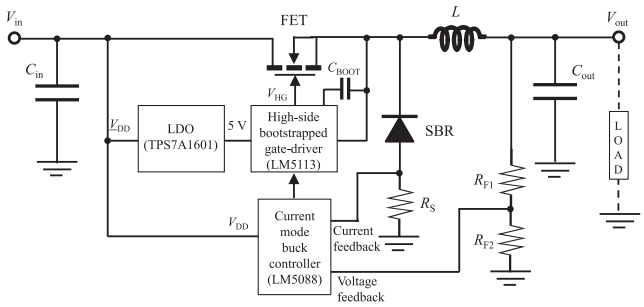

FIGURE 7 Simplified circuit diagram of the 48-to-12 V nonsynchronous buck converter

out (LDO) regulator, TPS7A1601-Q1, is used to supply 5 V to the gate driver. During the on-state, the LM5113 provides 5 V at the gate of the FET. Table 3 summarizes the major design parameters used in the nonsynchronous buck converter.

Figure 8 shows the breakdown of the power losses calculated by (4)–(7) and (9) for the nonsynchronous converter. The expected efficiency of the designed 48-to-12 V nonsynchronous buck converter is 92.82% at a maximum output power of 120 W. Although the diode has a superior forward performance with a low V_t of 0.43 V and a forward current of 10 A at a forward voltage of 0.6 V, the diode power loss of 4.5 W makes up the largest portion of the total power loss of the converter. The inductor power loss is caused by a DC resistance (DCR) of 27 mΩ. This is directly proportional to the inductor size, and is therefore not discussed further.

$$P_{\text{loss,diode}} = \left(1 - \frac{V_{\text{out}}}{V_{\text{in}}}\right) \times I_{\text{load}} \times V_{\text{F}}. \tag{9}$$

Figure 9 shows top and bottom views of the manufactured nonsynchronous converter using LTCC. The size of the converter is 55 mm × 40 mm, and the thickness of the LTCC substrate is 1000 μm.

TABLE 3 Major design parameters of the nonsynchronous buck converter

	Model/parameters
FET	GS61008P ($R_{ds,on}$ = 10 mΩ)
Diode	MBR12U100L (V_t = 0.43 V)
L	10 μH (DCR = 27 mΩ)
C_{out}	594.11 μF
C_{in}	23.6 μF
Controller	LM5088
Gate driver	LM5113
LDO	TPS7A1601-Q1

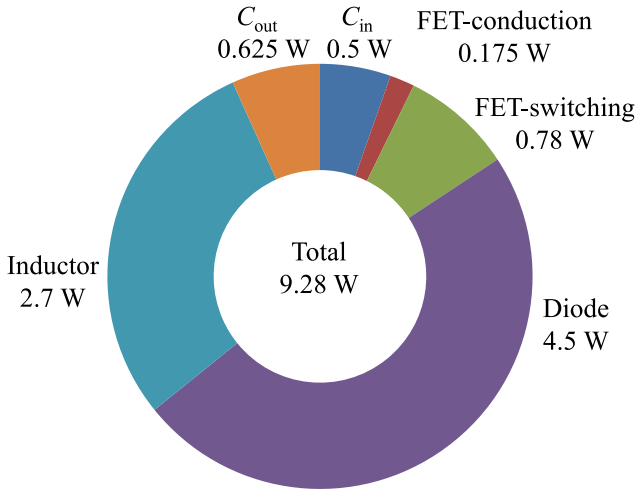

FIGURE 8 Breakdown of the calculated power losses in the nonsynchronous buck converter

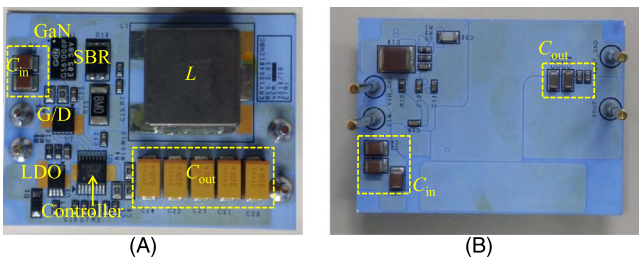

FIGURE 9 (A) Top and (B) bottom views of the manufactured LTCC-based nonsynchronous buck converter

To compare the performances of the LTCC and PCB devices, we manufactured two converters, one using LTCC (Type III) and the other using a conventional PCB (Type IV), using the circuit design of Figure 7. Figure 10 shows the power conversion efficiency at an input voltage of 48 V. The efficiencies of the two converters are 92.5% and 91.3%, respectively, at an output power of 100 W. As

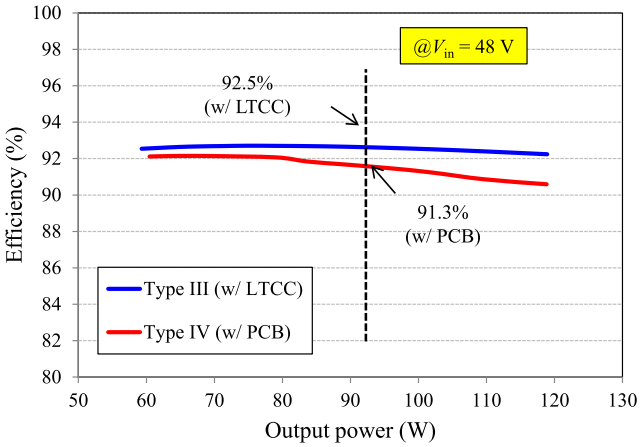

FIGURE 10 Measured efficiency as a function of output power

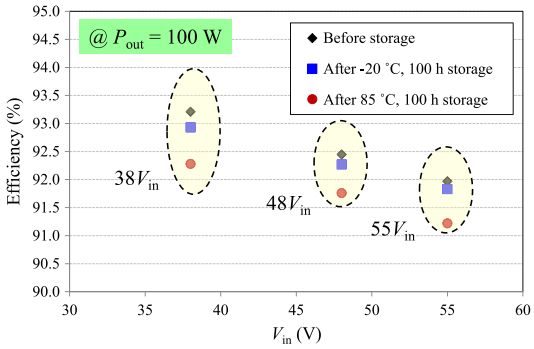

FIGURE 11 Measured storage temperature test results of the proposed LTCC-based converter (Type III)

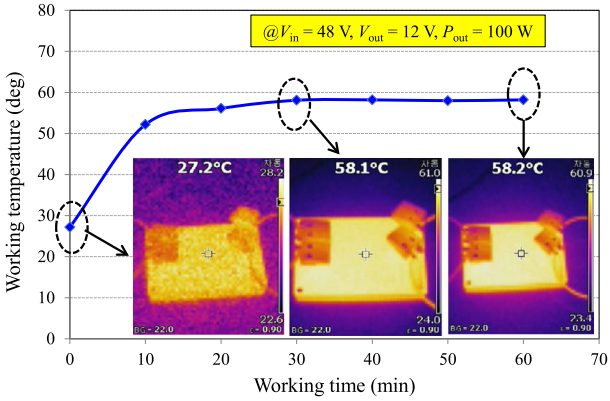

FIGURE 12 Temperature variation of the LTCC-based converter (Type III) as a function of the working time at an input voltage of 48 V, output voltage of 12 V, and output power of 100 W

with the synchronous buck converters, we can see that as the output power increases, the difference in their efficiencies increases owing to the increased heat dissipation.

To verify the reliability of the LTCC based converter, two types of tests were conducted on the Type III converter: two storage temperature tests and a working temperature test. Storage temperature tests were conducted to compare the efficiency under normal operating conditions before and after storage in a chamber at −20 °C and 85 °C, respectively, during a 100-h period. Figure 11 shows the variations in efficiency before and after the two storage tests. The observed variation in efficiency is less than 0.3%, demonstrating that the proposed converter achieves outstanding reliability.

Figure 12 shows the temperature variation of the converter as a function of the working time under an input voltage of 48 V, output voltage of 12 V, and output power of 100 W. The temperature variation was measured for 60 min, and the working temperature was increased from 27.2 °C to 58.2 °C. During the test, the efficiency of the converter remained constant, at approximately 92%.

Table 4 summarizes the performance comparison of previously reported LTCC-based converters with those presented in this work. Although the reported LTCC-based converters used a very high switching frequency of above 1 MHz to achieve a small form factor, their maximum output power is below 50 W, and their maximum output efficiency is 92.5% at an output power of approximately 6 W [3–6,12].

4 | CONCLUSION

We proposed a new platform using multilayer LTCC substrates for power electronics applications. Four types of buck

TABLE 4 Comparison of LTCC-based converters

		V_{in} (V)	V_{out} (V)	Max. P_{out} (W)	f_{sw} (kHz)	Max.η (@P_{out}) (%)[a]
[3]		5	1.2	24	1300	92.5 (@6 W)
[4]		5	1.2	18	1500	89 (@8.4 W)
[5]		5	1.2	48	1500	89 (@24 W)
[6]		12	1.2	18	1000	91 (@9.6 W)
[12]		12	1.8	36	2000	88 (@19.8 W)
This Work	*Type I*	48	12	120	200	95.5 (@100 W)
	Type III	48	12	120	200	92.5 (@100 W)

[a]Expected maximum efficiency based on measured graphs.

converters, operating at 48-to-12 V, were manufactured using the proposed LTCC- and conventional PCB-based substrates to compare their efficiencies at high output power. The efficiencies of the LTCC- and PCB-based synchronous converters (Type I and Type II), and LTCC- and PCB-based nonsynchronous converters (Type III and Type IV) were 95.5% and 94.5%, and 92.5% and 91.3%, respectively, at an output power of 100 W. It was observed that as the output power increases, the difference in efficiency of the proposed LTCC- and conventional PCB-based converters increases owing to the increase in heat generation. Storage temperature and working temperature tests were carried out to evaluate thermal reliability. The LTCC substrate exhibited outstanding thermal reliability, which is approximately 10 times higher than that of a traditional PCB substrate. Based on a performance comparison between the proposed LTCC- and conventional PCB-based converters, we have demonstrated the potential of a multi-layer LTCC substrate for use in power electronics applications.

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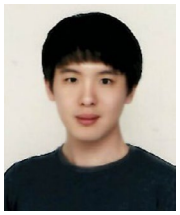

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