Received 21 August 2014; revised 30 September 2014 and 16 October 2014; accepted 17 October 2014. Date of publication 22 October 2014; date of current version 17 December 2014. The review of this paper was arranged by Editor M. Anwar.

Digital Object Identifier 10.1109/JEDS.2014.2364307

A 3-phase AC–AC Matrix Converter GaN Chipset With Drive-by-Microwave Technology

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ABSTRACT This paper describes an ultracompact GaN 3 × 3 matrix power converter with drive-by-microwave (DBM) technology, which comprises a radio frequency (RF)-triggered GaN-gate injection transistor (GIT) bidirectional power switches integration chip with co-integrated RF rectifiers, novel isolated dividing couplers in a printed circuit board to reduce complicated gate lines, and low-consumption GaN/Si DBM gate driver on a chip that controls nine bi-directional power switches. The proposed 4.0-kW GaN 3 × 3 matrix power converter is extremely compact, measuring only 18 × 25 mm due to the use of GaN-GIT power device integration technology and DBM technology that provides isolated gate signals by microwave wireless power transmission and eliminates the need for photo-couplers and isolated power supplies. The GaN/Si DBM driver realizes low power consumption of only 2.0 W as a result of gate power sharing with three RF oscillators. The sequential switching operation by the fabricated GaN 3 × 3 matrix converter was successfully achieved.

INDEX TERMS Gallium nitride, driver circuits, power integrated circuits, power semiconductor switches, matrix power converter, microwave circuits.

I. INTRODUCTION

In order to efficiently run an electric motor with variable speed and torque, inverter systems that generate AC power at the intended frequency and amplitude from a DC power source are commonly adopted in motor drive systems. The Three-phase AC-to-AC power conversion technology is of particular importance, as 3-phase AC motor systems with 3-phase power sources are widespread in industrial applications such as heating, ventilation and air conditioning (HVAC) systems. An inverter-based 3-phase AC-to-AC conversion system [1] with a DC-link can provide the desired AC power via an inverter circuit after the AC power has been converted to DC power using a rectifier circuit with a large electrolytic capacitor and a power factor correction circuit. However, inverter-based systems have several disadvantages, including low power conversion efficiency and the impossibility of power regeneration from a generator to a battery power source due to its multistep conversion process with large numbers of components. AC-AC converters without a DC link [2] have been reported that eliminate the electrolytic capacitor, which has a limited life-time.

On contrast to this inverter-based system, a 3-phase AC matrix convertor system with only 3x3 bi-directional switches is great interest as an ultimate power converter system because it has many advantages [3], [4] such as a high power conversion efficiency, long lifetime, and a regeneration due to its direct AC-to-AC conversion with the simple scheme shown in Fig. 1. However, it has not been practically applied due to the following drawbacks that result from the abundant components it includes. First of all, there is no compact bi-directional power switch in existence that can handle large currents in both directions between two ports. Second, any bi-directional switch with two gate ports would also require two isolated gate drivers because the voltage level between the two ports in the bi-directional switch flips back and forth. In consequence, 18 isolated voltage sources and 18 photo-couplers in all would be needed as isolated gate drivers for a 3x3 matrix converter and would consume a great

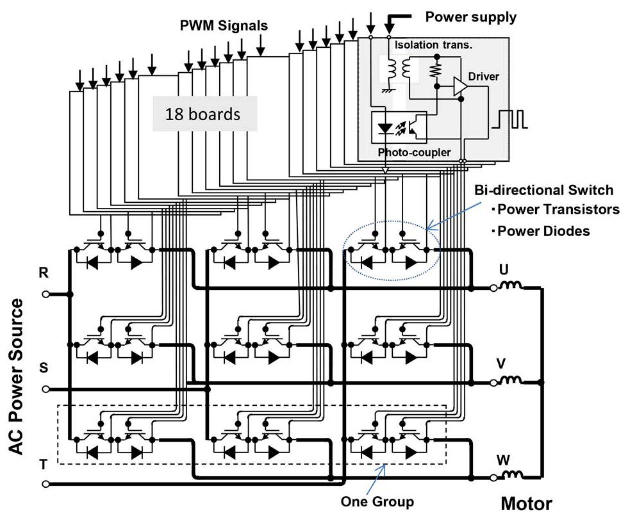

FIGURE 1. System block of the conventional 3-phase ac–ac matrix converter with discrete components.

deal of power. For these reasons, the conventional matrix converter with discrete components suffers the disadvantages of being a complicated and large-scale system.

To overcome this issue, the GaN-GIT (GIT: gate injection transistor) power switching device [5], [6] is very attractive in terms of power device integration due to its lateral structure. Isolated gate drivers using drive-by-microwave technology [7]–[9] are potentially ideal for a compact matrix converter, because they are very compact and do not require any isolated voltage source.

In this paper, we describe an ultracompact GaN 3x3 matrix converter [10] that employs GaN-GIT bi-directional power switch [11] integration technology and Drive-by-Microwave (DBM) technology which together realize a compact isolated gate driver employing microwave wireless power transmission. The GaN 3x3 matrix converter is composed of a GaN bi-directional switches integration chip, a GaN DBM gate drive transmitter chip, and isolated dividing couplers in a printed circuit board (PCB).

In Section II, we describe the new power conversion system framework with the Drive-by-Microwave technology for a 3x3 matrix converter. In section III, a novel isolated dividing coupler is proposed to markedly reduce the gate lines. The GaN DBM gate drive transmitter chip and a GaN bi-directional switches integration chip are described in sections IV and section V, respectively. Finally, the conclusion in section VII follows the evaluation and discussion of the fabricated GaN 3x3 matrix converter in section VI.

II. DRIVE-BY-MICROWAVE TECHNOLOGY

The key strategy for a compact matrix converter is to realize a compact isolated gate driver that is essential in a matrix converter because numerous isolated gate drivers with isolated transformers and photo-couplers are conventionally used. Although several advanced digital isolators have been developed [12], it needs an additional isolated power supply

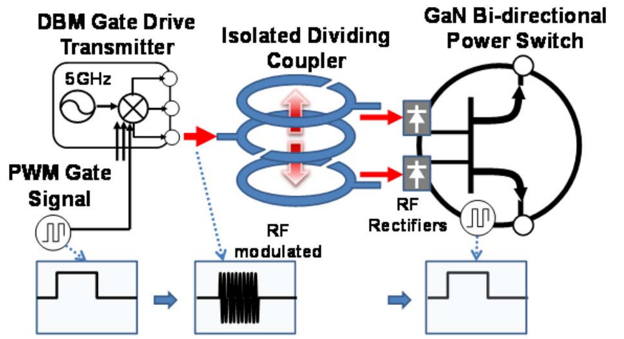

FIGURE 2. Block diagram of the drive-by-microwave technology for a GaN bi-directional switch in a GaN 3 × 3 matrix converter.

to drive a power device with a large gate power. We therefore applied Drive-by-Microwave technology in our compact driving system for the GaN 3x3 matrix converter, since a DBM isolated gate driver provides isolated gate power and an isolated gate signal in combination, without the need for isolated voltage sources. Fig. 2 is a block diagram of Drive-by-Microwave technology for a bi-directional switch's drive in the proposed matrix converter. In the proposed system, the original PWM (Pulse Width Modulation) gate signal is first converted to a 5.0-GHz envelop-modulated signal by an oscillator and a mixer in the DBM gate drive transmitter. After the modulated signal passes through an isolated dividing coupler based on an electro-magnetic resonant coupling [10], [13], [14] for reference ground isolation, the isolated gate signals are generated by being rectified in RF rectifier circuits. Eventually, the isolated gate signals are provided to control the ON and OFF state of the GaN bi-directional power switches. This wireless power transmission with electro-magnetic resonant coupling realizes a very high DC isolation voltage between the primary and secondary side of the coupler in accordance with its large distance with very low insertion loss [15].

III. ISOLATED DIVIDING COUPLER

Since a bi-directional power switch in a matrix convertor requires two isolated gate signals, the mass of gate lines makes the system so complicated. In the proposed system, however, the newly-developed novel isolated dividing coupler that is based on an electro-magnetic resonant coupling reduces the numerous gate lines by duplicating the gate signal with separate grounds from an original gate signal. In other words, it is able to control the operation of the bi-directional switch by only one original gate signal because it provides two isolated gate signals with a separate ground by dividing the single gate signal from the DBM gate drive transmitter. This reduction of gate line is very useful for a compact matrix converter, since an isolated gate line occupies a large footprint with a large creep age distance for large voltage isolation.

The internal structure and a cross-section of the new isolated dividing coupler for 5.0 GHz are shown in Fig. 3.

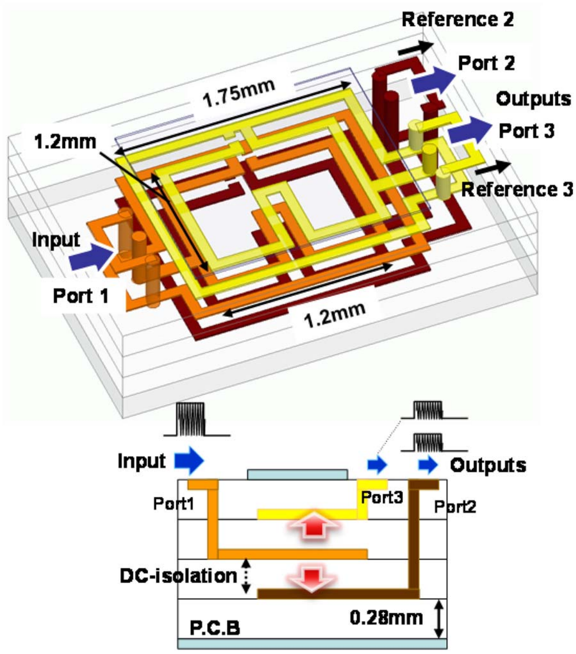

FIGURE 3. Internal and cross sectional structure of the isolated dividing coupler.

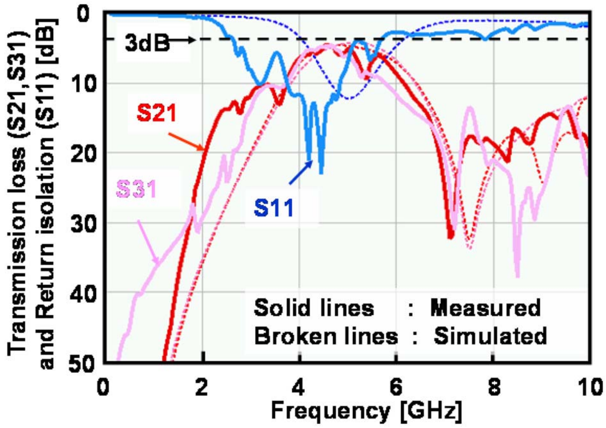

FIGURE 4. Small signal S-parameter of the fabricated isolated dividing coupler in a printed circuit board.

DC isolation measurements showed this fabricated coupler to achieve a DC-isolation voltage exceeding 3.0 kV, with a leak current of less than 4 nA. From the measured results for the breakdown voltage of a variety of PCB thicknesses, we estimate that our fabricated coupler of 0.28 mm layer thickness has a breakdown voltage of 16 kV-DC and 10.0 kV-AC.

This coupler consists of three vertically-stacked resonators with the outer ground lines, which works as a open- and short-edged quarter-wavelength resonator. Because the middle resonator is coupled with the upper and the lower resonators by an electromagnetic resonance coupling, the input signal is divided to two output signals at the two output ports, resulting a low insertion loss and a very high DC-isolation voltage. Since the coupler size is very compact (1.2 x 1.2 mm^2 for the internal resonator and a footprint of 1.75mm x 1.75mm^2), the total footprint of the couplers for a 3x3 matrix converter is small in spite of having nine couplers. Although the coupler size can be reduced for higher frequencies, the conversion efficiency of the DBM Gate transmitter and the RF rectifier circuit might fall in as a result. A 5.0-GHz system is therefore employed in this matrix convertor.

The small signal S-parameter of the fabricated isolated dividing coupler in a printed circuit board is shown in Fig. 4, where the relative permittivity and dielectric loss tangent of the PCB (Risholite CS3396, Risho Kogyo Co., Ltd.) at 1.0GHz are around 10 and 0.003, respectively. The isolated dividing couplers in the PCB result in a low-cost matrix converter. The transmission and return loss of the fabricated isolated dividing coupler in the PCB are respectively around 4.1 dB and 12.0 dB at 5.0 GHz. The insertion loss for a 3-dB power divider is very low, at 1.1 dB, even though it includes the loss of the input and output lines. The wide bandwidth around 1.0 GHz in the fabricated coupler contributes to realizing a very fast data transmission rate of ver 300Mb/s. These properties are very useful for an emerging GaN power switching device that realizes very fast switching.

IV. GAN/Si DBM GATE DRIVE TRANSMITTER

In a 3x3 matrix converter, there is an exclusive operational relationship among these bi-directional switches. In the group of the three bi-directional switches that are connected to the same output port (one of U, V, and W ports) as shown in Fig. 1, only one of the three bi-directional switches is ON and others are OFF. By taking advantage of this algorithm for a 3x3 matrix converter, the gate signal power for gate driving can be shared and saved if the isolated gate power is delivered with a time-division. Therefore, a low-power consumption DBM gate drive transmitter is newly developed, which outputs 5.0 GHz modulated signals from a shared oscillator by switching three output ports in response to the PWM signal input. The circuit of the DBM gate drive transmitter using GaN HFETs (hetero junction field-effect transistors) with a gate length of 800 nm on a Si substrate, shown in Fig. 5, is designed to drive the GaN-GIT bi-directional power switch. GaN-GIT bi-directional power switches are best suited to the DBM driver, as it is readily controlled due to its small gate capacitance and low forward voltage. This GaN HFETs process contains WSi resistances, MIM (metal-insulator-metal) capacitances and Schottky barrier diodes (SBD). This GaN HFET is a depletion-type transistor (normally ON) and has a -2.5V threshold voltage (Vth). Since the fabricated single GaN transistor with a gate length of 800 nm exhibits a Ft of 15 GHz and Fmax of 55GHz, respectively, sufficient signal output power can be obtained at 5.0 GHz using a single-stage amplifier.

To be able to control all the bi-directional switches in a 3x3 matrix converter using one chip, the DBM gate drive

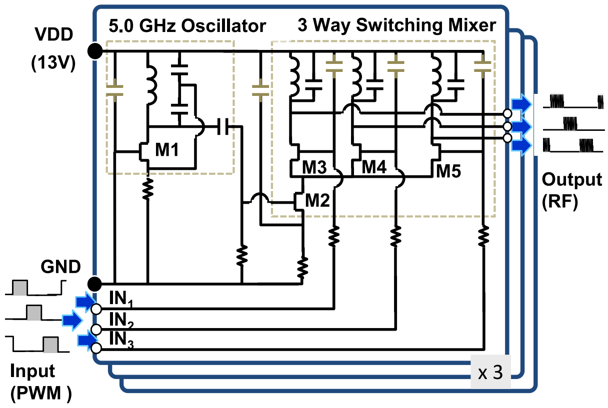

FIGURE 5. Designed schematic of the GaN DBM gate drive transmitter.

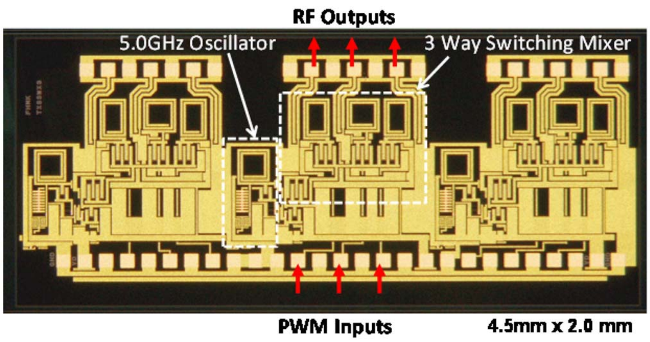

FIGURE 6. Chip photo of the fabricated GaN DBM gate drive transmitter chip.

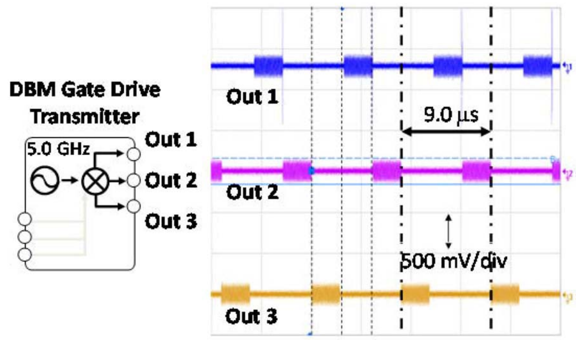

FIGURE 7. Output signal waveforms from the fabricated GaN DBM gate drive transmitter chip.

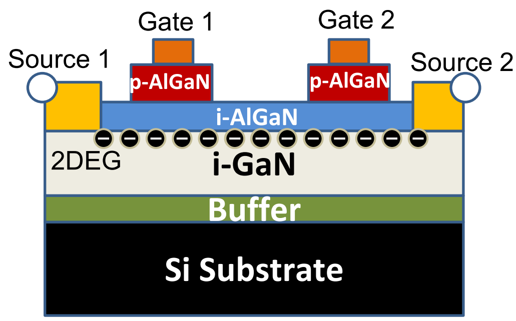

FIGURE 8. Cross-sectional structure of the GaN-GIT bi-directional power switch with dual gates.

transmitter chip for 9 signal output is implemented with 3 sets of 5.0 GHz-oscillators and a 3-way switching mixer, as shown in Fig. 6. This fabricated 4.5 mm x 2.0 mm DBM gate drive transmitter chip can drive 9 bi-directional switches without any isolated voltage source, in contrast to the 18 isolated drivers with 18 isolated voltage sources and 18 photo-couplers needed in conventional setups.

Over 20 dBm output was obtained at 4.9 GHz from the fabricated GaN DBM gate drive transmitter chip, which is sufficient power to generate the gate voltage at the RF rectifier circuit in the GaN-GIT bi-directional switches integration chip and switch it ON. As seen from Fig. 7, the fabricated DBM gate drive transmitter chip successfully outputs the PWM modulated 5.0-GHz signals from the three output ports in sequence. Because this DBM gate drive transmitter shares the source of 5.0 GHz signal, the power consumption is far lower, at 1.95 W (13 V, 150 mA) than a conventional system with 18 separate full-time drivers. The fact that GaN-GIT can be controlled using low gate signal power contributes to this low power consumption.

V. GAN BI-DIRECTIONAL POWER SWITCH INTEGRATION CHIP

Bi-directional switching is typically realized by the two power transistors and two power diodes in the conventional matrix converter shown in Fig. 1. A conventional bi-directional switch has a large insertion loss because the current passes through two devices. Although a reverse blocking insulated-gate bipolar transistor [16]–[18] has been developed that achieves bi-directional operation using two transistors, it is composed of discrete components and cannot be integrated onto a single chip. In this paper, the GaN-GIT bi-directional power switch is employed for the proposed compact 3x3 matrix converter, since these switches can be integrated onto a single chip due to its lateral structure, shown in Fig. 8. The switching operation of the GaN-GIT bi-directional switch is controlled by the equipped dual gates. This switch has inherently very high conductance because there is a high-mobility 2–D electron gas (2DEG) at the interface between the GaN layer and the AlGaN layers in the structure. This GaN-GIT exhibits normally-off operation, since the p-type AlGaN gate raises the potential underneath the gate and partially eliminates the 2DEG. If the gate voltages are applied at the gate ports against each source ports, the GaN-GIT exhibits its very high conductivity with no potential barrier, where the barrier is disappeared by hole injection. Because the GaN-GIT switch with the dual gate structure realizes bi-directional switching with one device with no recovery diode for bi-directional operation, it has a low ON state resistance (Ron) as well as the benefit of compactness. On the other hand, the GaN-GIT bidirectional switch works in diode mode if the only one gate of the dual gates is ON. In the proposed 3x3 matrix converter, the GaN-GIT bi-directional switches are controlled with both gates ON or both gates OFF in order to reduce their gate signal lines. The GaN-GIT bi-directional switch is designed to have

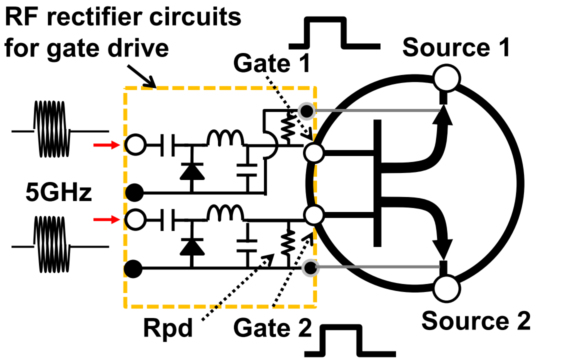

FIGURE 9. Schematic of the RF rectifier circuits for the gate drive in the RF-triggered GaN-GIT bi-directional switch.

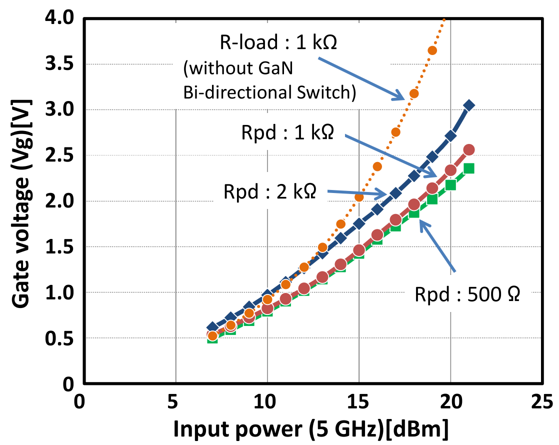

FIGURE 10. RF to dc conversion characteristics of the fabricated GaN RF rectifier circuit for gate drive.

a breakdown voltage of 600 V with the 10 μm gate spacing (Lgg) between the two gates. Because the current collapse is caused by the electron trapping by defects in the GaN layer and the interface between the passivation film and the AlGaN layer, the fabricated GaN-GIT bi-directional switch achieves current-collapse-free operation due to the improved device structure and the processing to eliminate the trapping effects [19]

This GaN-GIT bi-directional switch with the dual gate needs two isolated gate signals against each source ports. Although the two isolated RF signals with separate grounds can be easily provided by the proposed isolated dividing coupler, in Drive-by-Microwave technology, the DC gate voltage needs to be regenerated from the RF signal. This prompted us to develop a novel RF-triggered GaN-GIT bi-directional switch in which the RF rectifier circuits are integrated at the gate ports in the GaN-GIT bi-directional switch to create a gate voltage from the 5.0 GHz signal that is supplied from the DBM gate drive transmitter via the isolated couplers. As a result, the bi-directional switch is switched ON and OFF in response to the microwave signal input. Fig. 9 is a schematic of the RF rectifier circuits. Each comprises a single shunt rectifier [20], [21] with a Schottky barrier diode, a 1/4 wavelength inductance (1.5 nH) and a capacitance. The forward voltage, junction capacitance and on-state resistance of the fabricated GaN SBD are 0.7 V, 0.2 pF and 108 Ω, respectively. This simple topology is normally employed to realize a RF to DC rectifier with high conversion efficiency. In the OFF state with no signal input at the RF rectifier circuit, the GaN-GIT bi-directional switch turns itself off by the pull-down resistances (Rpd: 500Ω) that releases the gate charge at the gate ports. Although this RF rectifier circuit will not turn the GaN-GIT bi-directional switch OFF instantaneously, this simple circuit saves circuit area. The smaller pull-down resistance (Rpd) should be implemented or the fast turn-off circuit should be introduced [7], if Miller turn-on is a problem. However, the simulation implies that the resistance (Rpd) is enough small for a 1 kHz carrier frequency system because the RC time constace is estimated to be 0.15 us from the gate capacitance of 330 pF.

Fig. 10 shows the RF to DC conversion characteristics of the fabricated RF rectifier circuit in the GaN-GIT bi-directional switch as a function of 5.0 GHz input power. The fabricated RF rectifier creates enough gate voltage as signal power of over 15 dBm to swith the GaN power device ON. The fabricated simple RF rectifier generates over 4.0 V with a 1.0kΩ resistance load at 20dB m input signal power.

The GaN-GIT bi-directional switches integration chip for a 3x3 matrix converter are fabricated as shown in Fig. 11, where the 9 GaN-GIT bi-directional switches with the RF rectifiers are integrated. Although power device integration is very challenging due to its high heat density, it is can achieve because the GaN device operates at very high temperatures such as 200 °C due to its wide band-gap. The compact GaN-GIT bi-directional switches integration chip, measuring 3.5 mm x 17 mm, is useful for reducing assembly and wiring costs in addition to its existing advantage of compactness. Because the gate width (Wg) of the single GaN-GIT bi-directional switch is 100 mm, it has a current rating of 10 A. The I-V curve of the fabricated RF- triggered GaN-GIT bi-directional switch is shown in Fig. 12. By increasing the input power of 5.0 GHz at the gate ports, this switch passes a high current in both directions. These results indicate that the fabricated GaN-GIT bi-directional switch exhibits bi-directional operation in response to RF signal input. The ON state resistance of the fabricated GaN-GIT bi-directional switch is excellent at 200 mΩ. As seen in Fig. 13, the fabricated GaN-GIT bi-directional switch has a breakdown voltage over 500 V in both directions.

VI. GAN 3 × 3 MATRIX CONVERTER

Fig. 14 shows the fabricated GaN 3x3 matrix converter with Drive-by-Microwave technology, which consists of the fabricated GaN-GIT bi-directional switches integration chip, the fabricated GaN/Si DBM gate drive transmitter chip and the fabricated isolated dividing couplers in the PCB. The extremely compact GaN 3x3 matrix converter, with an effective footprint of 25 mm x 15 mm, can convert 3-phase AC power with the desired frequency and amplitude, and has the potential to control a 4.0-kW motor connected to a

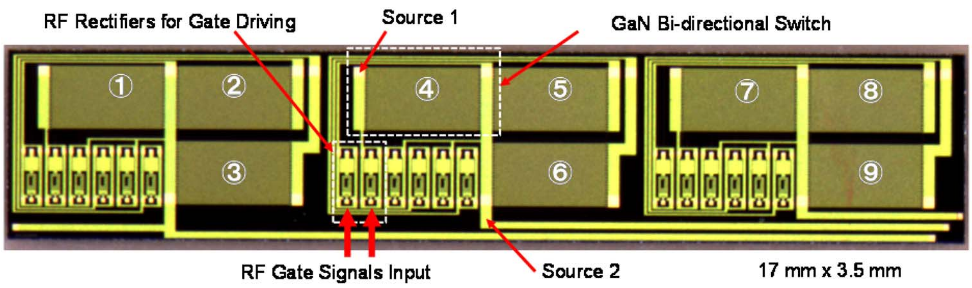

FIGURE 11. Chip photo of the fabricated GaN-GIT bi-directional switches integration chip.

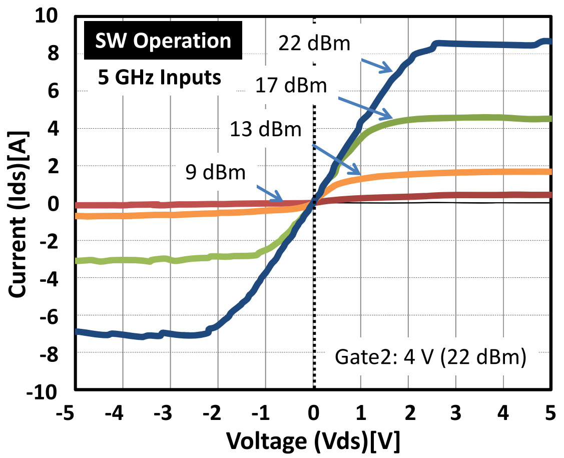

FIGURE 12. I–V curve of the fabricated RF triggered GaN-GIT bi-directional power switch as a function of 5 GHz signal input.

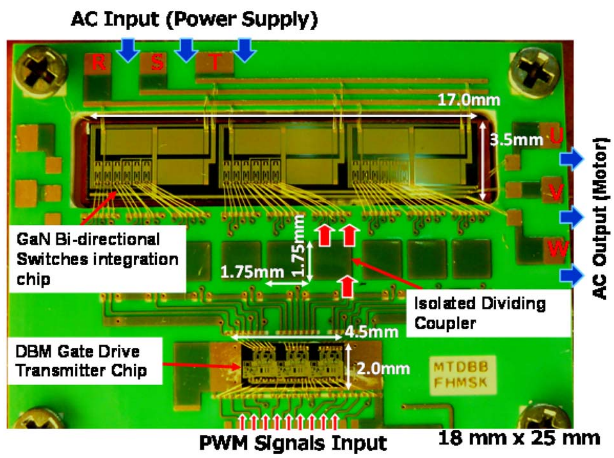

FIGURE 14. Photo of the fabricated GaN 3 × 3 matrix converter for a 4.0-kW motor drive.

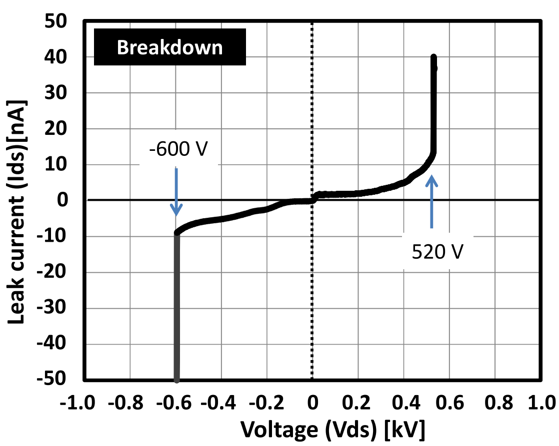

FIGURE 13. OFF state I–V characteristics of the fabricated RF-triggered GaN-GIT bi-directional power switch.

400-V 3-phase power grid, since the fabricated GaN-GIT bi-directional switch can handle 10 A at up to 500 V. It is approximately 1% of the size of a conventional matrix converter with discrete components [21]. The fabricated DBM gate drive transmitter chip is mounted on the PCB that the 9 isolated dividing couplers are made inside. On the other hand, the GaN-GIT bi-directional switches integration chip is mounted on a copper heat sink to permit direct cooling on its back side. The features of the GaN power device—its low ON resistance and high operation junction temperature—are expected to dramatically reduce the size of the heat sink that accounts for most of the size of conventional power converter systems.

This proposed GaN matrix converter does not equip a fly back diode for return current in parallel with the GaN-GIT bi-directional switch, because the GaN-GIT bi-directional switch can handle reverse current with its ON state [11]. In general, commutation control is essential for a matrix converter to protect the fatal damage of the GaN bi-directional switches [23], [24], caused by the large potential that created a return current when all switches are turned off. However, this proposed matrix converter does not require the commutation control since the GaN-GIT bi-directional switch tolerate a return current in a few hundred of watts system. To safely operate an electric motor without a commutation process, the diode operation by the GaN-GIT bi-directional switch [11] should be applied.

The switching characteristics of the fabricated GaN 3x3 matrix converter were evaluated. Up to 200 V was applied at the R, S, and T input ports in the fabricated matrix converter against the U output port via 10 kΩ resistances. As shown in Fig. 15, the fabricated GaN 3x3 matrix converter demonstrated sequential 150V switching at 1.0 kHz. We confirmed a 3.0A switching under 150V, a 8.0A switching is

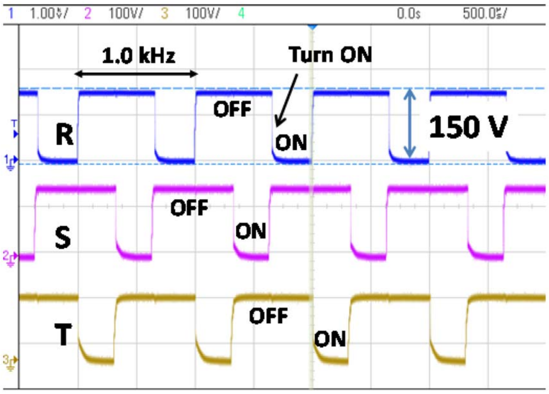

FIGURE 15. Switching waveform of the fabricated GaN 3 × 3 matrix converter.

available as shown in Fig. 12, by an inductive load double pulse test. However, a motor driving without a commutation process by the fabricated module was not tested, since some GaN-GIT bi-directional switches do not completely switch (slow turn-on) the 150 V due to a lack of the gate current at a turn-on from the fabricated gate driver. The slow turn-on switching degrades the conversion efficiency by a large switching loss. Insufficient gate power was provided to some GaN bi-directional switches due to the 5.0 GHz low signal output power from the DBM gate drive transmitter chip, also causing the poor ON-state resistance.

Unfortunately, mutual interference among the lines was also observed as very small spikes in the OFF-state when other switches were turned on, which might be caused by lack of balance between the 3-way switching mixer in the GaN DBM gate drive transmitter chip. The high ON-resistance of the GaN-GIT bi-directional switch and mutual interference need be improved to make this setup practical for 3-phase motor drive using this GaN 3x3 matrix converter.

VII. CONCLUSION

In this paper we describe our development of an extremely compact GaN 3x3 matrix converter with Drive-by-Microwave technology. It is composed of only the GaN DBM gate drive transmitter chip, the GaN-GIT bi-directional switches integration chip, and the isolated dividing couplers in a PCB board. The developed GaN 3x3 matrix converter for a 4.0 kW (10 A in a 3-phase 400 V system) electric motor is significantly more compact, at 18 mm x 25 mm, than conventional types that require numerous power switches, flyback diodes, photo-couplers, isolated power supplies and gate drivers. This more compact GaN 3x3 matrix converter has the potential to contribute significantly to the realization of low-cost power converters and their widespread uptake. On top of its compactness, this Drive-by-Microwave technology is ideally suited for compact and low-power-consumption isolated gate drivers, since it shares and switches isolated gate signal power without requiring an isolated power source.

ACKNOWLEDGMENT

The authors would like to thank M. Nishijima, Y. Kawai, H. Fujiwara, Dr. K. Mizutani, Y. Kudoh, and Dr. H. Ueno with Panasonic for their supports.

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