GaN基AC/DC电源高效高密方案探索
---元胞化技术

Exploring the Ceiling of Efficiency and Density of GaN Based AC/DC Power Supply-Cellular Circuit Technology

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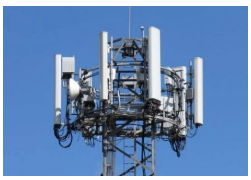
Applications of High Density & High Efficiency Two stage AC/DC Conversions

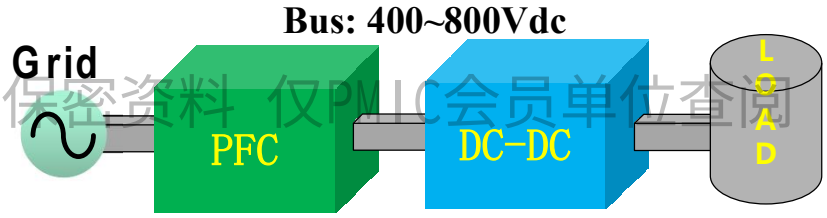
PEV

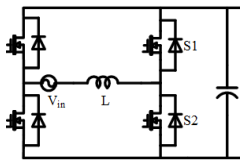


5G Base Station

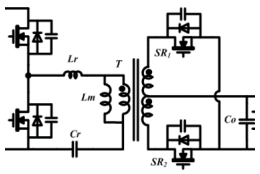
IDC Racks

Full Electric Aircrafts





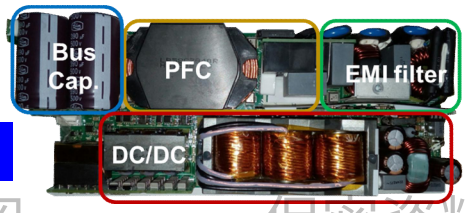
Bridgeless Totem PFC



ZVS Resonant DC/DC

Power Density Limitation of Commercial AC/DC Server Power Supply with Si Devices

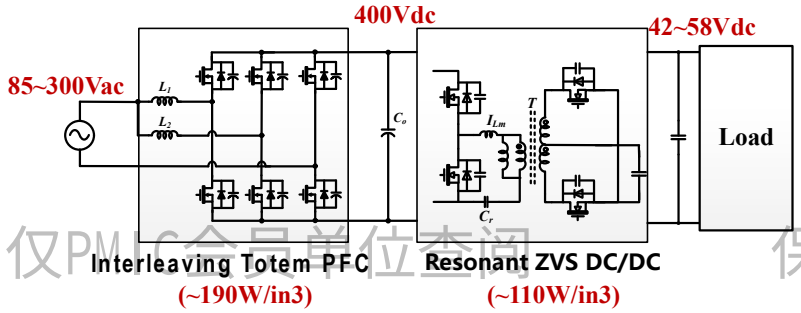
Commercial 3kW 48V AC/DC module



Si

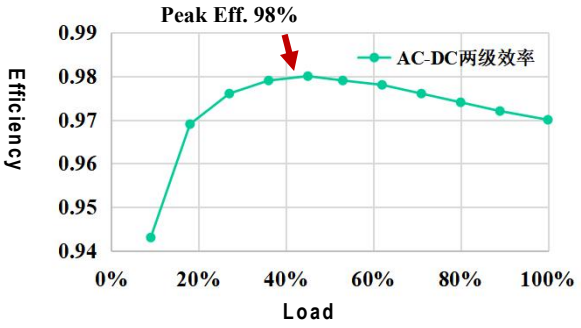
fs: <100kHz

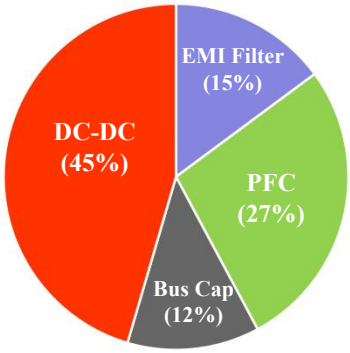
功率密度（两级） ~50W/in³



Interleaving Totem PFC (~190W/in3)

Resonant ZVS DC/DC (~110W/in3)

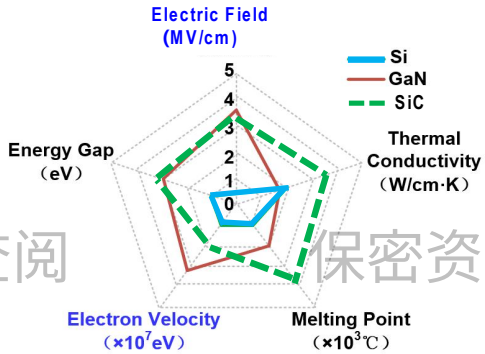


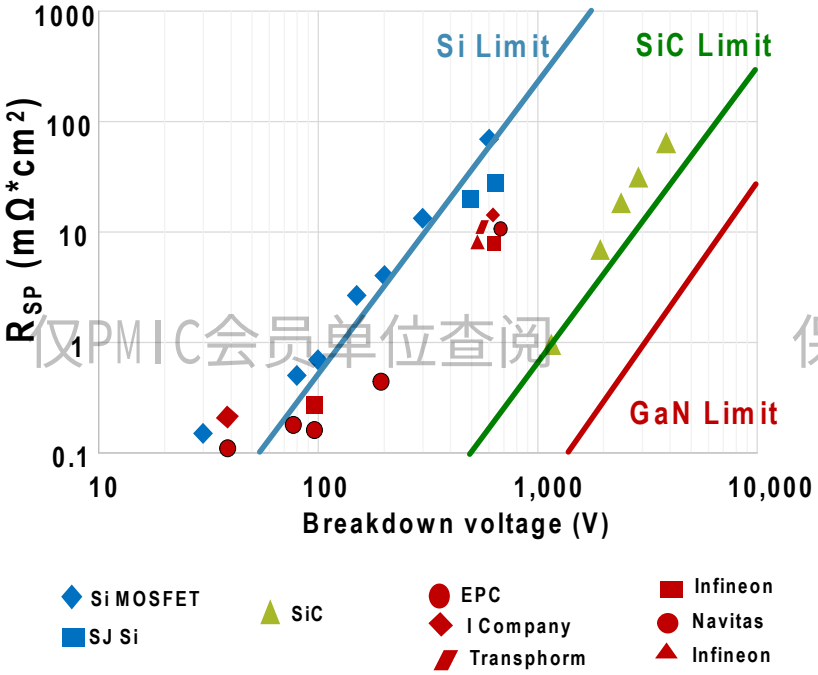


Volume breakdown

3

GaN has Larger Potential Improvements





Ref: [1] N. Ikeda et.al. ISPSD 2008 p.289; [2] IR, APEC2012;

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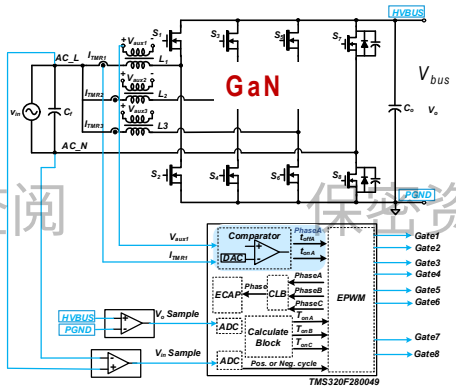
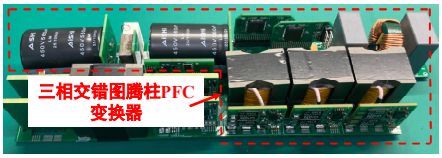
Density and Efficiency Compromise for Interleaving ZVS Totem-pole PFC

PMIC Power Management Innovation Consortium

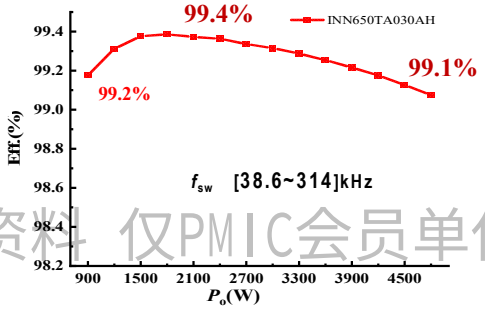
➢ Control Strategy of Interleaving CRM Totem-pole PFC



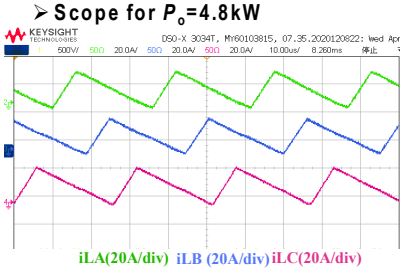
4.8kW/48Voutput ~190W in³



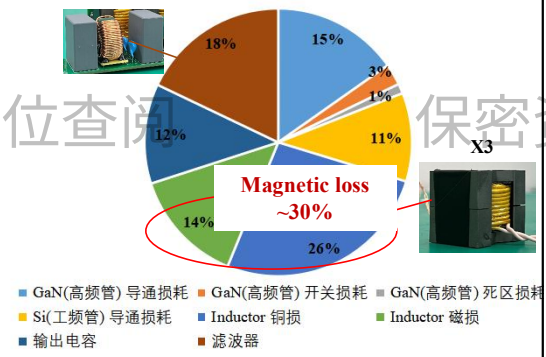
➢ Measured Eff. (w/o auxiliary power)



➢ Scope for P_o=4.8kW

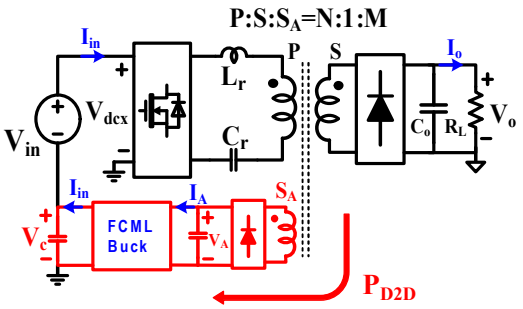


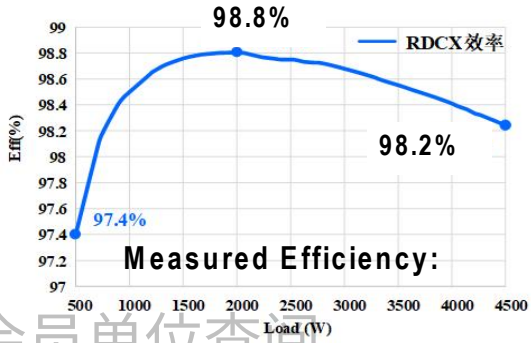
➢ Loss Breakdown @4.8kW



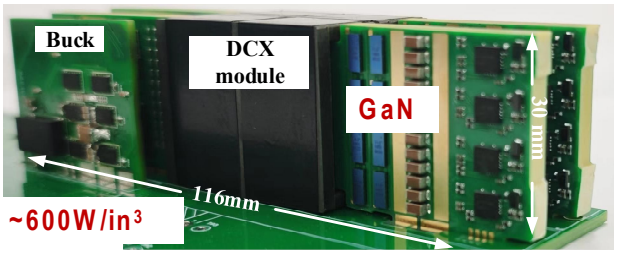
Efficient 2nd-Stage RDCX with all GaNs and Fixed Frequency Resonant DC/DC

PMIC Power Management Innovation Consortium

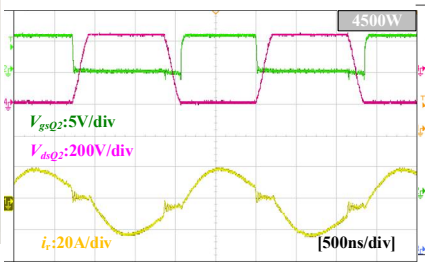




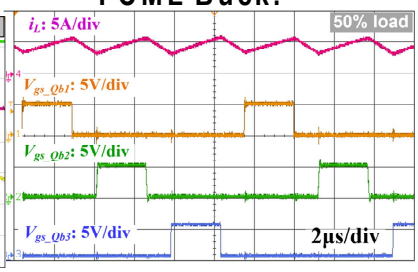
4.5kW DC-DC stage Prototype:



500kHz DCX

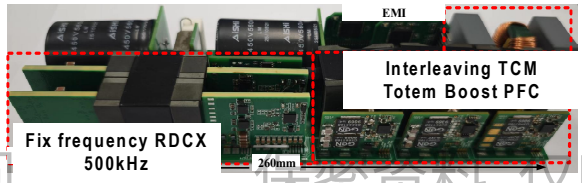


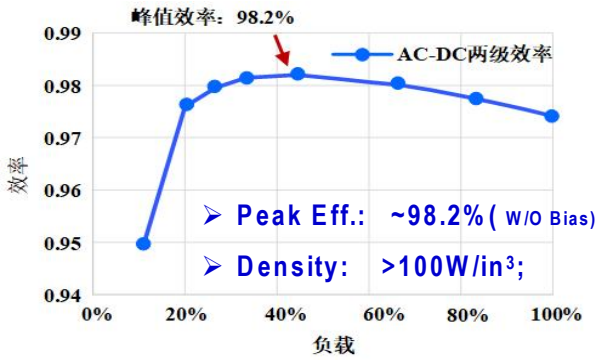
FCML Buck:



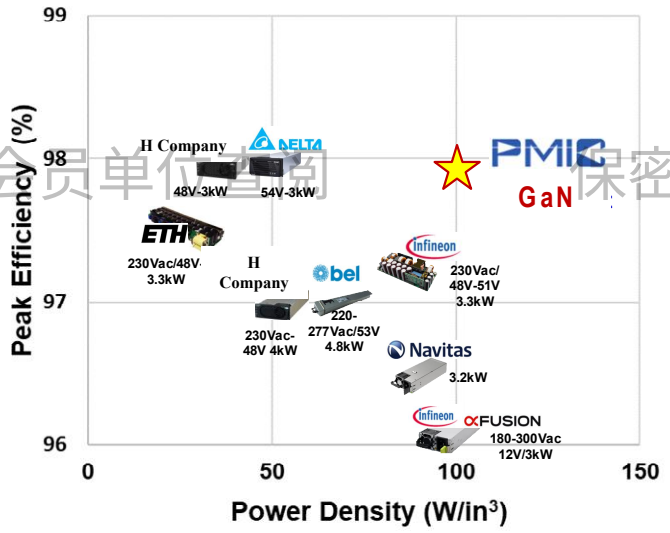
48V Efficient Server AC/DC Power Supply with 650V GaNs

Fig. of Prototype: **GaN** 4.5kW





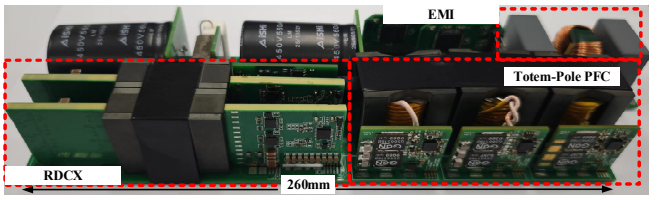
State-of-the-Art:



[2] DPR 3000E Energe, Delta
[3] M., Kasper, et al., Design of a Highly Efficient (97.7%) and Very Compact (2.2 kW/dm³) Isolated AC–DC. IEEE TPE, 2017
[4] PAC3000S12, Huawei

Magnetic Components Dominating the Volume of PFC and DC/DC

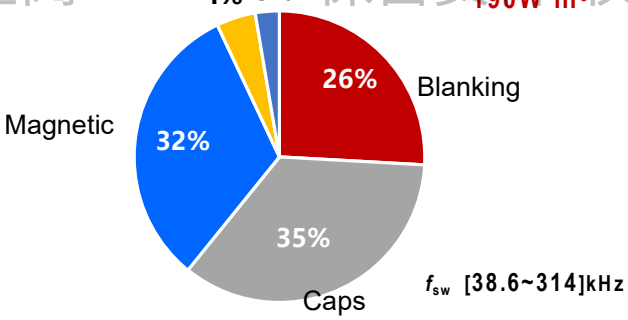
GaN 4.5kW



Two stage AC/DC
Power Density:
>100W in³

Totem PFC Volume breakdown

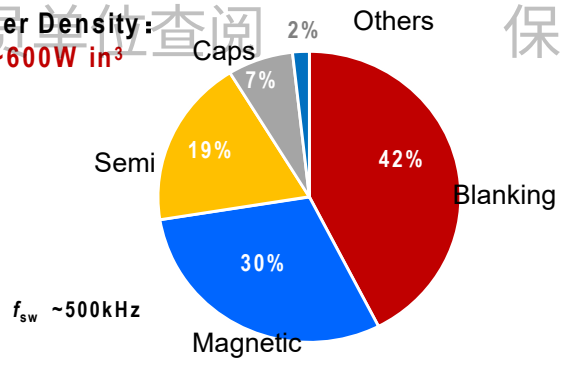
Power Density:
~190W in³



f_{sw} [38.6~314]kHz

DC/DC Volume breakdown

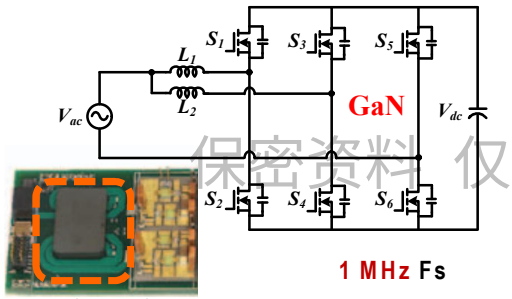
Power Density:
~600W in³



f_{sw} ~500kHz

MHz Frequency Reduce the Inductance for Interleaving Totem Pole PFC with GaN Devices

Two phase interleaving Totem PFC



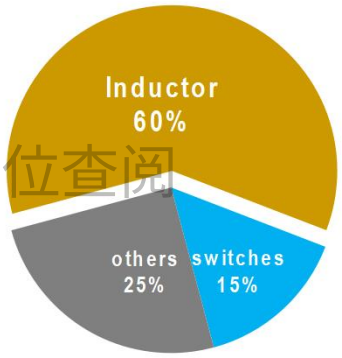
4.32cm*3.72cm*1.74cm

1 MHz Fs

Density：~550 W/in³
（W/O Cap）
Eff: ~98.7

Magnetic Volume Shrinking (>70%)

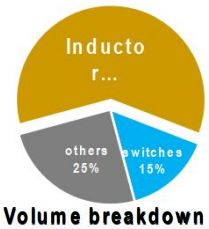
Volume Breakdown



Volume is still determined by Magnetic

F. C. Lee, "Application of GaN devices for 1 kW server power supply with integrated magnetics," in CPSS Transactions on Power Electronics and Applications, vol. 1, no. 1, pp. 3-12, Dec. 2016.

Multilevel Topology Reduce the Inductance Significantly



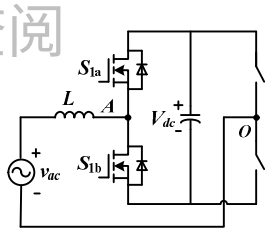
Volume breakdown

Inductance：

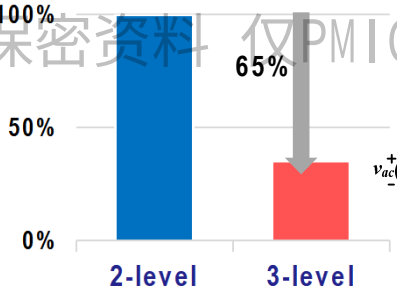
$$L = \frac{1}{f_s}\frac{V_{dc}}{(N_{level}-1)^2}\frac{1}{4\Delta i_{L\_\max}}$$

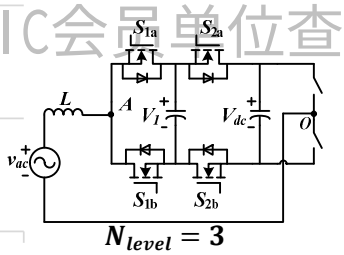
Second Volt.

$$Volume \approx k_L\left(\frac{I_p I_{RMS}}{k_w J B_m}\right)^{3/4} L^{3/4}$$



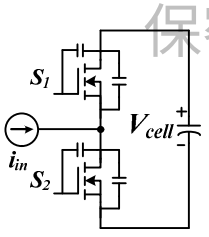
$N_{level} = 2$





$N_{level} = 3$

Device Loss ?

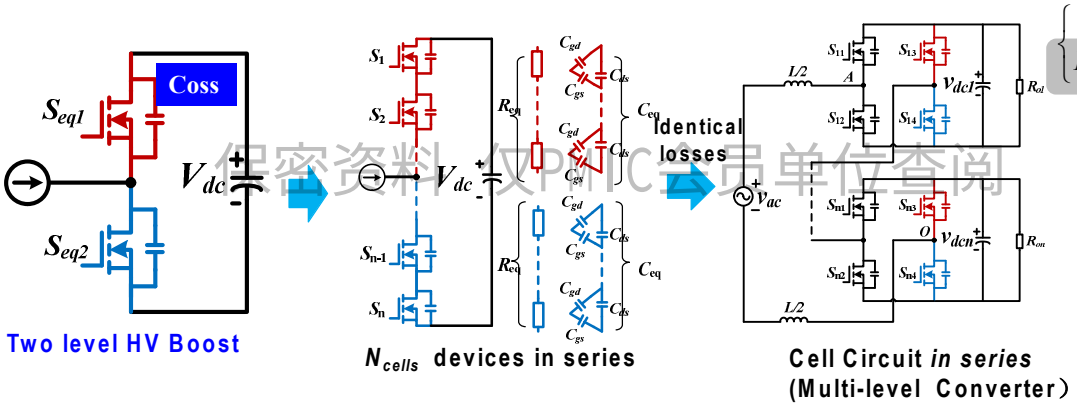


Boost Circuit

W. G. Hurley, “Transformers and inductors for power electronics :theory, design and applications,"
Y. Lei *et al.*, "A 2-kW Single-Phase Seven-Level Flying Capacitor Multilevel Inverter With an Active Energy Buffer," TPEL, Nov. 2017.
Y. Lei, W. Liu and R. C. N. Pilawa-Podgurski, "An Analytical Method to Evaluate …," IEEE TPEL, March 2018.

Unified Cell Circuit Min. Loss Model with $NFoM_{oss}$ (R_{dson}X C_{oss})

$$P_{GaN\_\min} = 4V_{dc}I_{in}\sqrt{k_{temp}k_{dyn}(k_g I_{in}(1+k_{g2d})C_{gd(tr)}R_{ds\_on} + C_{oss(er)}R_{ds\_on})f_s}$$



$$\begin{cases} NFoM_{sw} = C_{gd(tr)}R_{ds\_on} \\ NFoM_{oss} = C_{oss(er)}R_{ds\_on} \end{cases}$$

$$C_{eq} \times R_{eq}\,|_{C_{gs} \gg C_{gd}} = \frac{C_{oss(er)}}{N_{cells}} \times N_{cells}R_{ds\_on} = C_{oss(er)}R_{ds\_on} = NFoM_{oss}$$

Min. Loss depends on individual device's $NFoM_{oss}$

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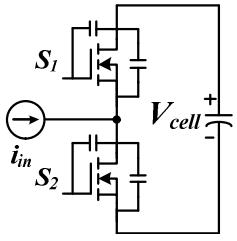
Multi-level Conerter with Low Voltage GaN has Much Room for Efficiency Improvement

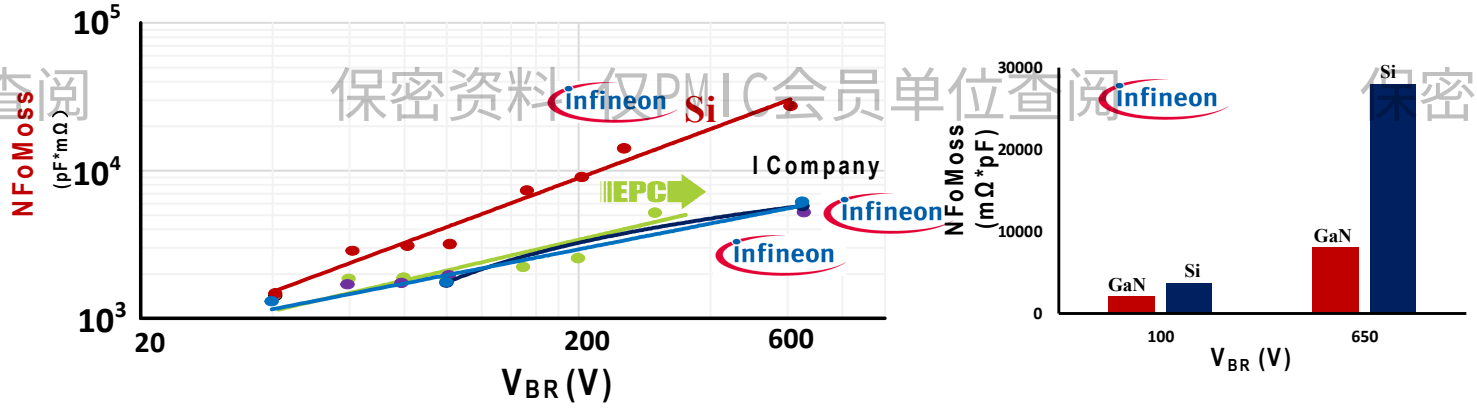


Boost Circuit

$$P_{GaN\_\min} = 4V_{dc}I_{in}\sqrt{k_{temp}k_{dyn}(k_{sw}I_{in}NFoM_{sw} + NFoM_{oss})f_s}$$

Unified loss model

Define: $\begin{cases} NFoM_{sw} = C_{gd(tr)}R_{ds\_on} \\ NFoM_{oss} = C_{oss(er)}R_{ds\_on} \end{cases}$



J Wu, X. Wu. "A unified switch loss model and design considerations for multilevel boost PFC with GaN devices" CPSS TPEA 2021,

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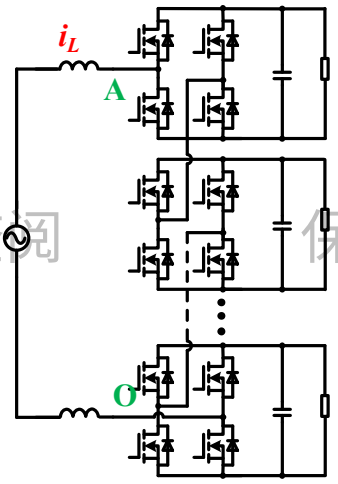
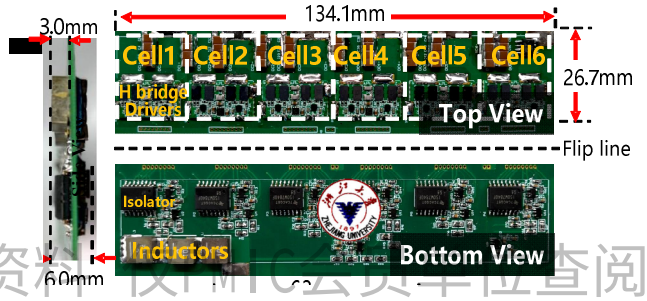
An Example: Cellular Circuit （CHB Multi-level） PFC Converter

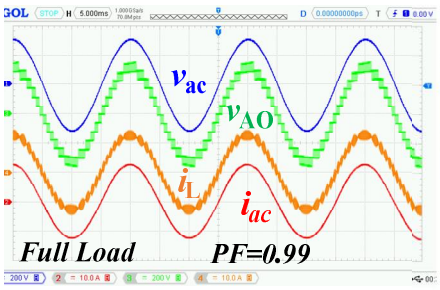
With commercial GaN



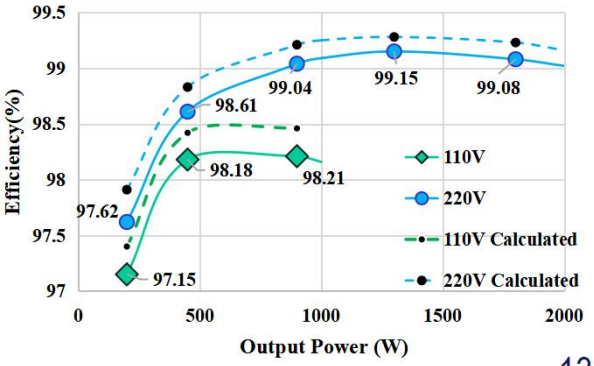
6-Cell CHB PFC



1.3 kW/in³@ 2kW (w/o Bus Cap)



peak efficiency:>99.1%



J. Wu and X. Wu, "FoM Based Optimal Frequency and Voltage Level Design for High efficiency High density Multilevel PFC with GaN Device,"*2020APEC*, pp. 1911-1915.

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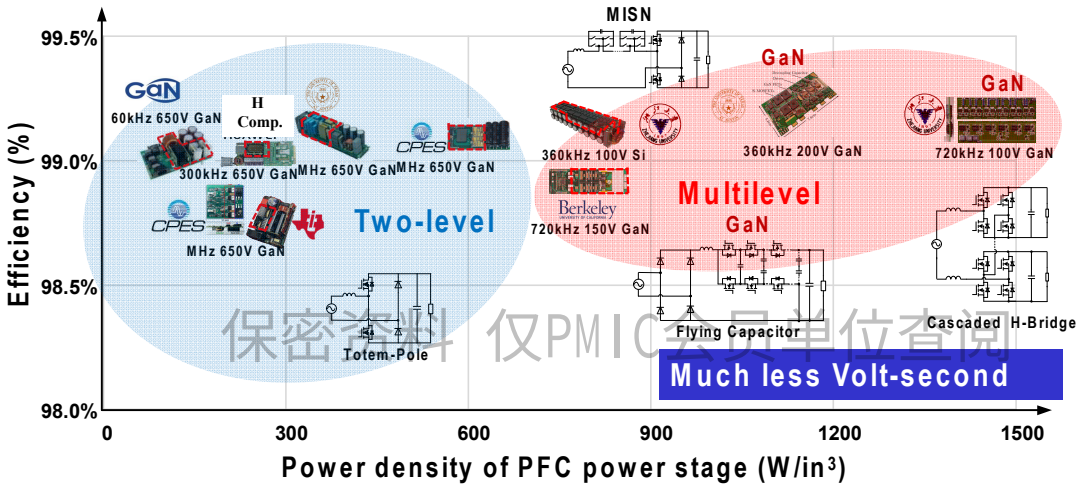
State-of-the-art High Power Density Single Phase PFC



[1] GaN Systems. High Efficiency CCM Bridgeless Totem Pole PFC Design using GaN E-HEMT
[2] Z. Liu, F. C. Lee, Q. Li, and Y. Yang, "Design of GaN-based Mhz totem-pole PFC rectifier," JESTPE2016.
[3] https://training.ti.com/1mhz-987-efficient-interleaved-16-kw-crm-gan-pfc
[4] A. Q. Huang, "Review of GaN totem-pole bridgeless PFC," STPEA2017
[5] Lee, Fred C., et al. "Application of GaN devices for 1 kW server power supply with integrated magnetics," TPEL2016
[6] D. Chou, R. C. N. Pilawa-Podgurski, "An Interleaved 6-Level GaN Bidirectional Converter for Level II Electric Vehicle Charging," APEC 2019
[7] Q. Huang, Q. Ma, P. Liu, A. Q. Huang and M. A. de Rooij, "99% Efficient 2.5-kW Four-Level Flying Capacitor Multilevel GaN Totem-Pole PFC," JESTPE2021
[8] J. Wu, et al, "FoM Based Optimal Frequency and Voltage Level Design for High efficiency High density Multilevel PFC with GaN Device," APEC2020
[9] https://www.clearesult.com/80plus/node/12300
[10] T. Huang, et al, "Single Phase High Power Density MISN PFC Converter, " ECCE 2022

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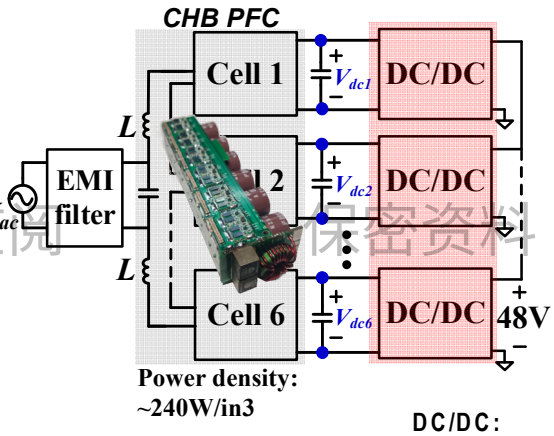
CHB Cellular PFC Needs Multiple Isolated DC-DC stages

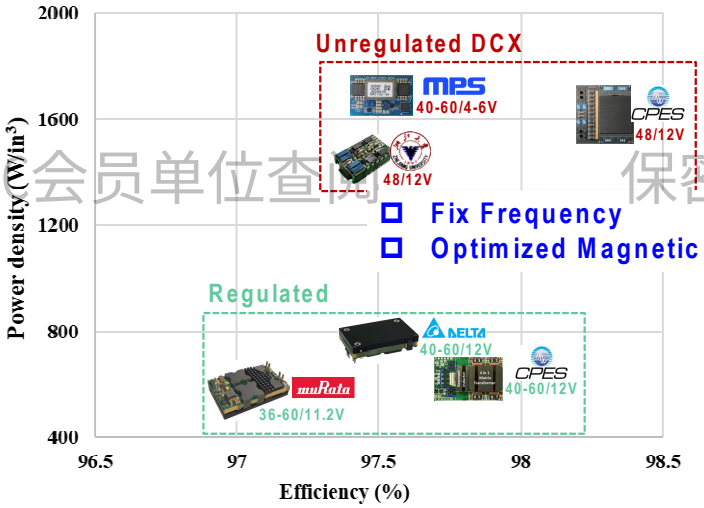


Power density: ~240W/in3

DC/DC:

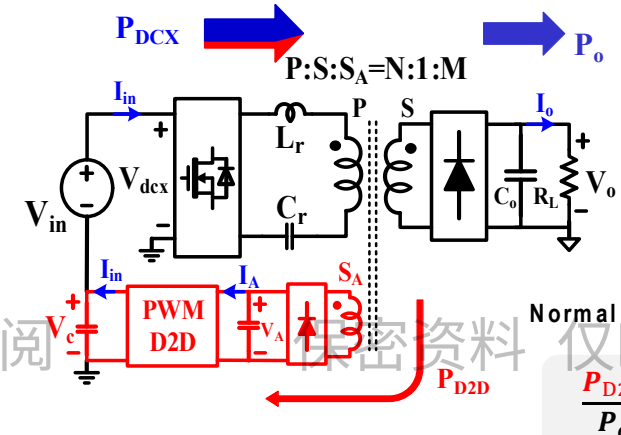
- ➢60V-level input
- ➢Tight regulated and isolation
- ➢High efficiency and high density

State of the art of 48V-level isolated DC/DC:



[1] DRQ-11.4/88-L48NB-C, MuRata
[2] Q54SJ108A2, Delta
[3] MPC1100-54, MPS
[4] M. H. Ahmed, et al., High-efficiency, High-density Isolated/Regulated 48V Bus Converter... APEC 2019.
[5] G. Li, et al. High Power Density 48–12 V DCX With 3-D PCB Winding Transformer. IEEE TPE, 2020
[6] M. H. Ahmed, et al., Two-Stage 48V VRM With Intermediate Bus Voltage Optimization... IEEE JESTPE 2021.

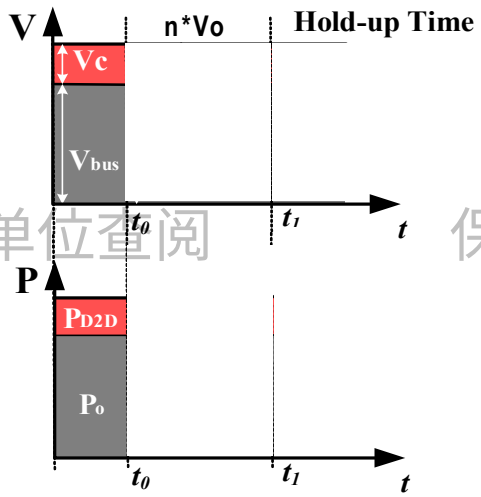
Regulating Principle of Single Transformer RDCX for Cellular D2D stage



Normal Power distribution:

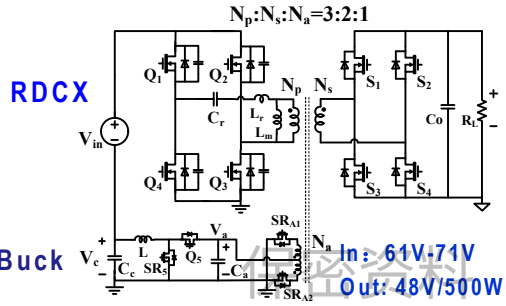
$$\frac{P_{D2D}}{P_o} = \frac{V_c}{V_{bus}} \approx 8\%$$

Vdcx = Vbus + Vc



- ☐ Fixed frequency resonant DCX;
- ☐ Aux. Multi-level Buck for regulation;
- ☐ Low P_{D2D} @normal operation;

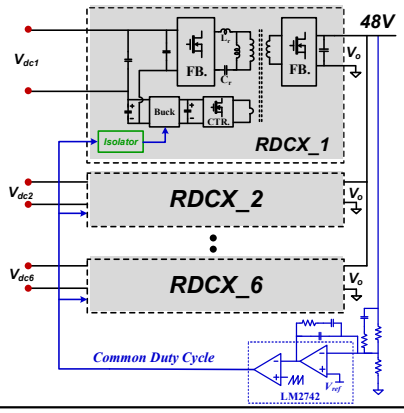
Common Duty-cycle Control for Cellular D2D Stage

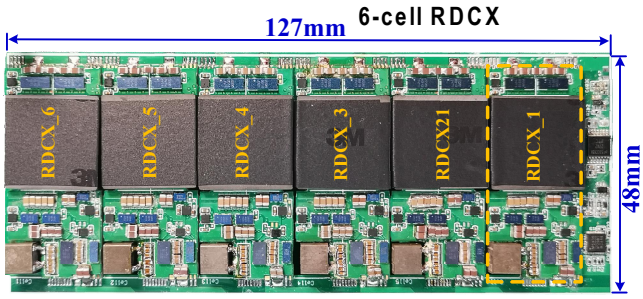


Size: 43.5*19.5*6.5mm³

Density: ~1.5 kW/in³
Eff.: 98.1%

RDCX-cell prototype





Power: 3kW
Density: ~1300W/in3
(with Controller)

Common Duty-cycle Control

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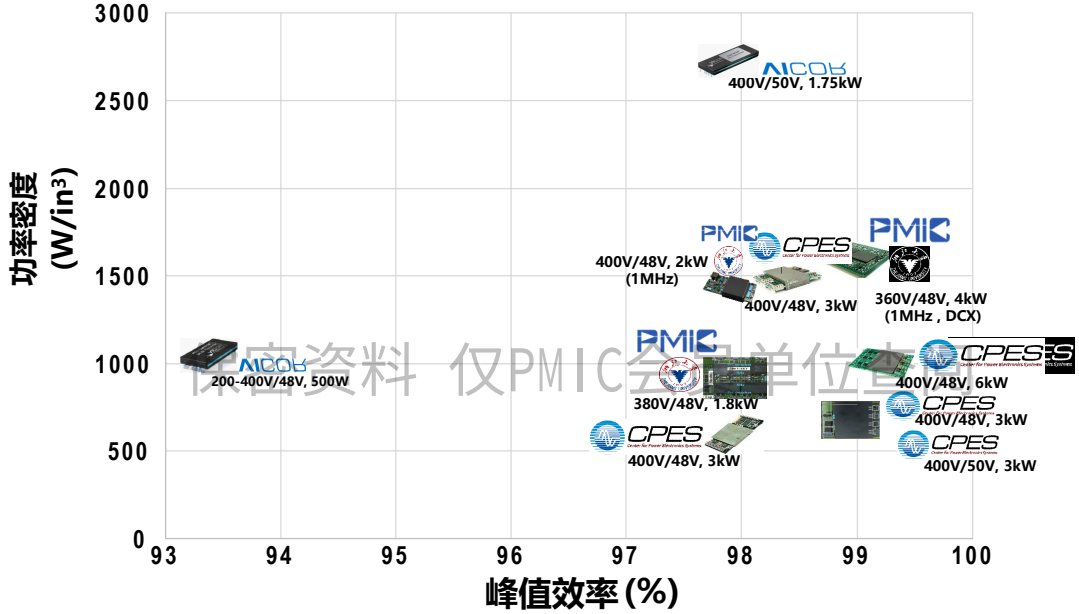
State-of-the-art of 2nd Stage DC/DC for 48V Server Power Supply



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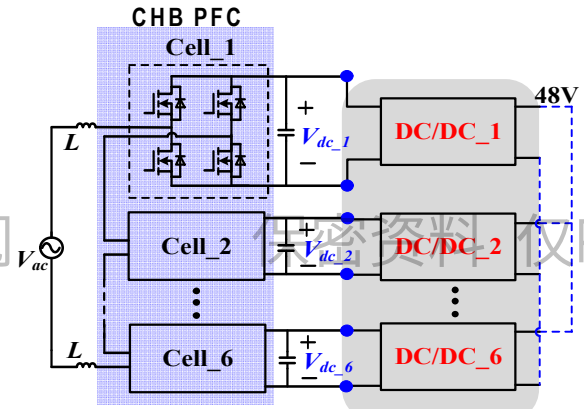
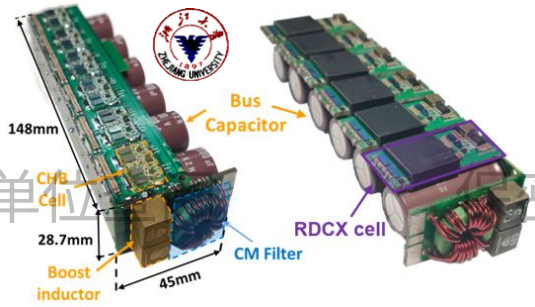
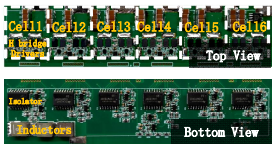
Cellular Two-stage AC/DC Converter with Higher Power Density



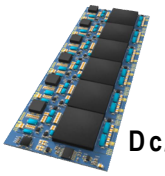
Two stages



Density: ~180 W/in3 (including E-Cap)
Peak Eff.: >97%
Input: 90-290Vac
Output: 48 V/ 3kW

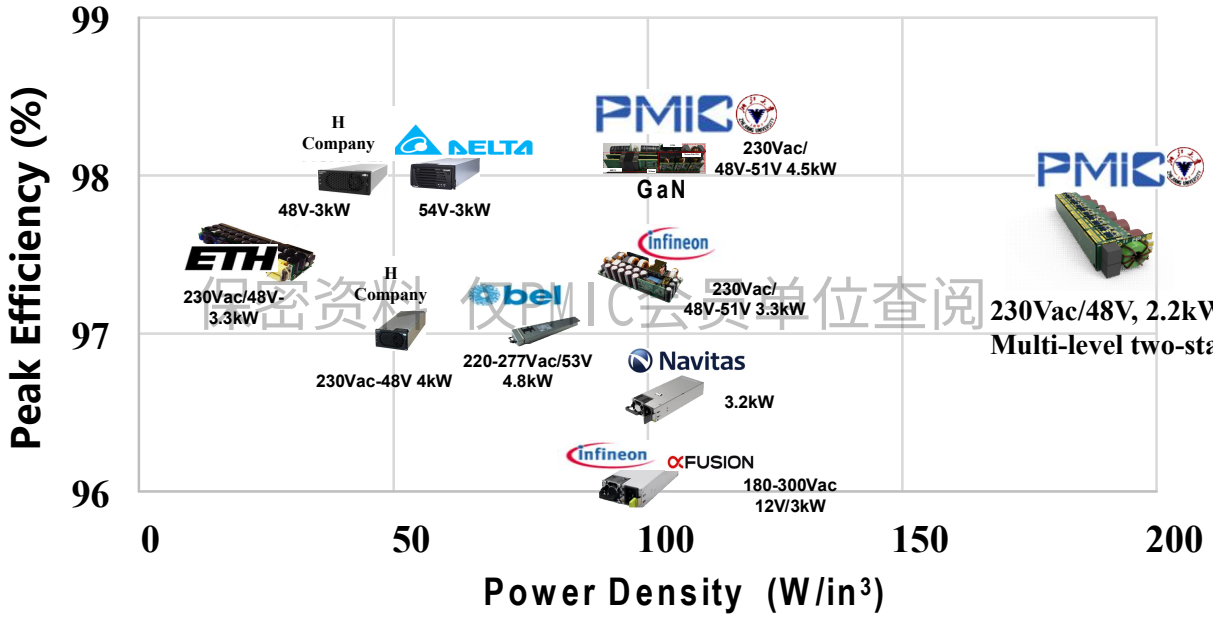


PFC: ~1.3kW/in³
Eff.: >99%(@220Vac)

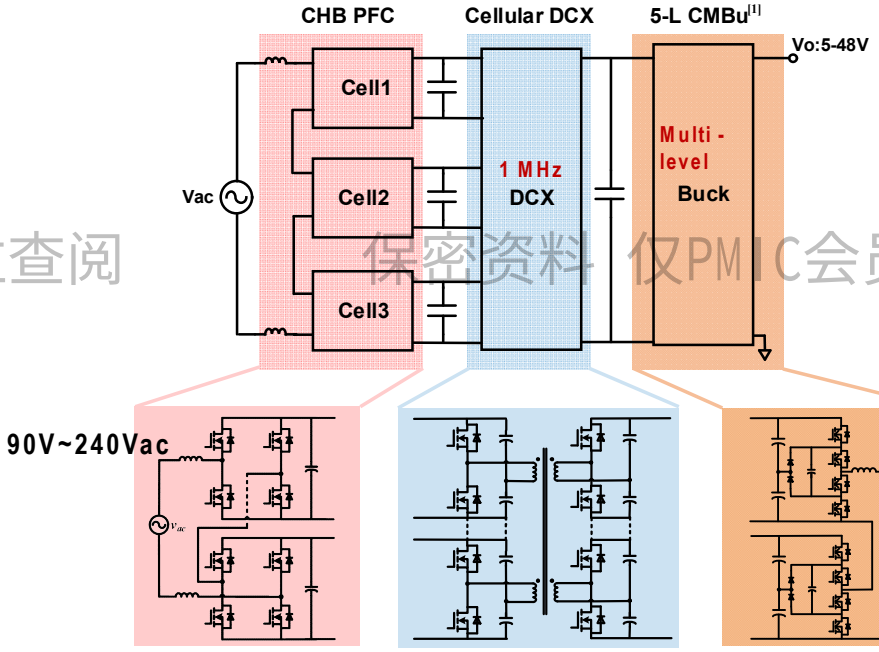


Dc/dc Density: ~1.5 kW/in³
Eff. (@350W): >98% @1MHz

48V Efficient Cellular AC/DC Server Power Supply with All GaNs



Cellular Circuit Topology CCT Achieving Ultra-High Efficiency and Power Density for 240W PD Power Supply



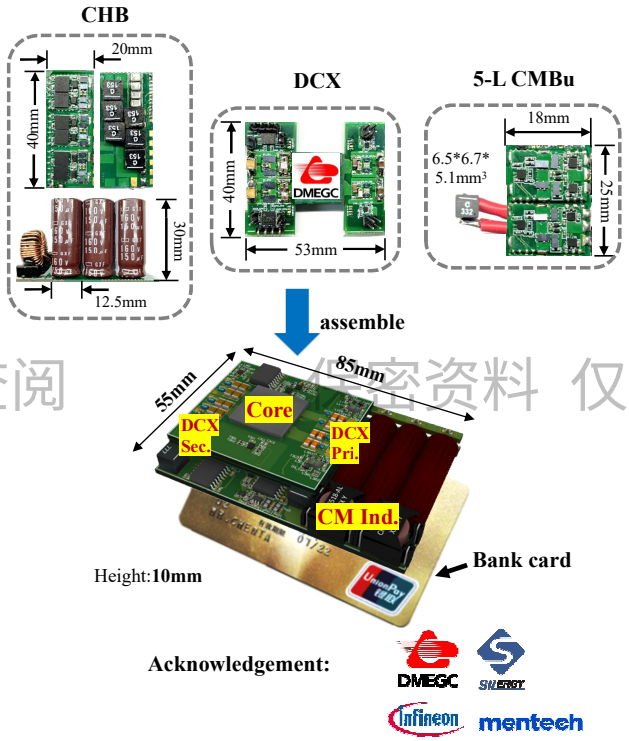
Features:

- CCM PFC improve efficiency @90Vac
- 1 MHz-DCX achieves high efficiency
- High efficiency among wide output range
- Voltage range 5V to 48V(PD3.1)
- High power density & efficiency

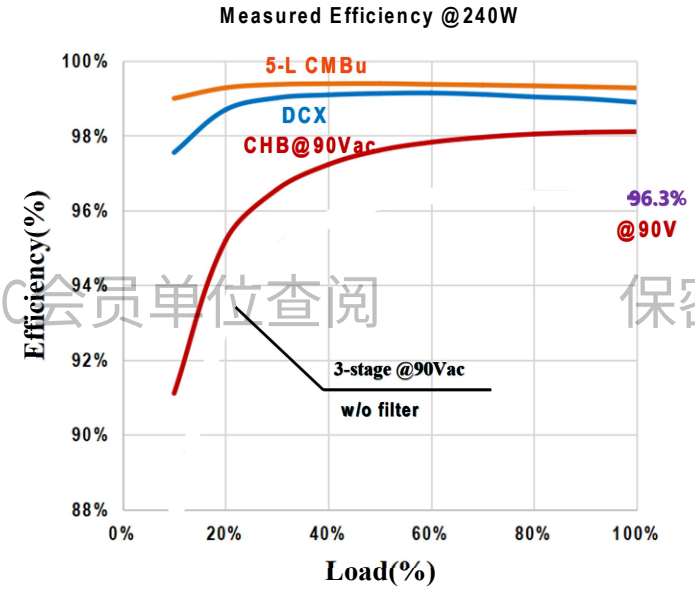
[1] Cascaded Multi-level Buck (CMBu)

[2] Detailed design based on NFoM loss model refers to PMIC presentation in 2022.04

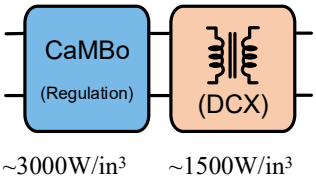
Full-load Efficiency Achieves 96.3%@90Vac



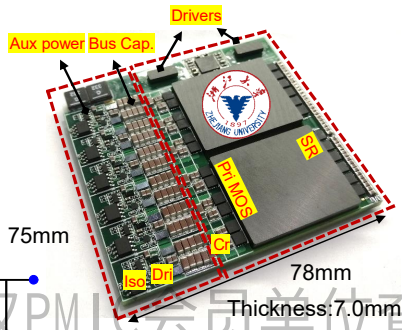
Acknowledgement:
DMEGC
Infineon
mentech



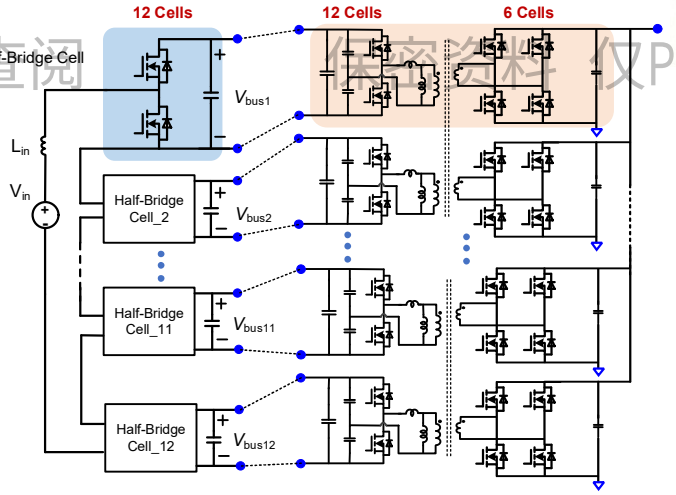
CCT Applied in Wide Voltage Range General Brick DC/DC Module



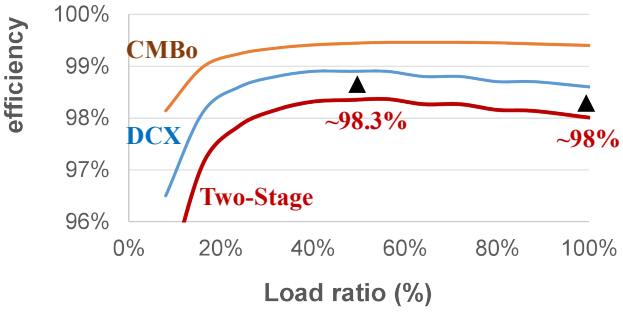
~3000W/in³ ~1500W/in³



Vin: **200-400V**
Vo: **17V/120A-34V/60A**
Rated Power: 2.5kW
Efficiency @full load 28V: **~98%**
Power density: **> 1.2 kW/in³**



➢ **Measured Eff.@ 270Vin/28Vo (Rated)**



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装置与系统公司 (26)

英飞源技术 INFY POWER | oppo | DELTA 台達 | 阳光电源 SUNGROW | 杰瑞
AOHAI 奥海科技 | FOX ESS 麦田能源 | mi | 航嘉 Huntkey | ZTE中兴
Great Wall 长城电源 | MEGMEET | HAWUN 皓文电子 | CukTech | Anker Innovations
LUXSHARE-TECH 立讯技术 | ZM | Sevenstar 七星微电子 | 爱科赛博 ACTIONPOWER | JDENERGY 奇点能源
SHINRY 欣锐科技 | EVTECH 富特科技 | 晟星和·SXH | BOCO 铂科电子 | DA FENG

元器件公司 (9)

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DMEGC | poco 铂科新材
Mentech 铭普光磁 | JOULWATT
SOUTHCHIP | SINOMAGS 希磁科技
Si-power

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PMIC 高校主导、行业共建的电源管理技术生态链

器件 → 装置 → 系统

器件	装置		系统
矽力杰半导体	深圳英飞源	阳光电源	OPPO技术
杰华特半导体	杰瑞电子	奥海科技	台达电子
铭普光磁	长城电源	麦田能源	中兴通讯
硅动力	浙江富特科技	酷科电子	小米科技
横店东磁	铂科电子	航嘉	安克创新
希磁科技	皓文电子	振华微	奇点能源
英飞凌科技	麦格米特	欣锐科技	蔚斯博系统
南芯半导体	晟星和	爱科赛博	
铂科新材	七星华创	聚新汽车	
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Thank You

for Your Time

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