如何为DCDC电源选择合适的开关频率？

Jonny.Jiang 姜彦昊

Field Application Engineer, MPS北中国区

(特别鸣谢 **Jens Hedrich**)

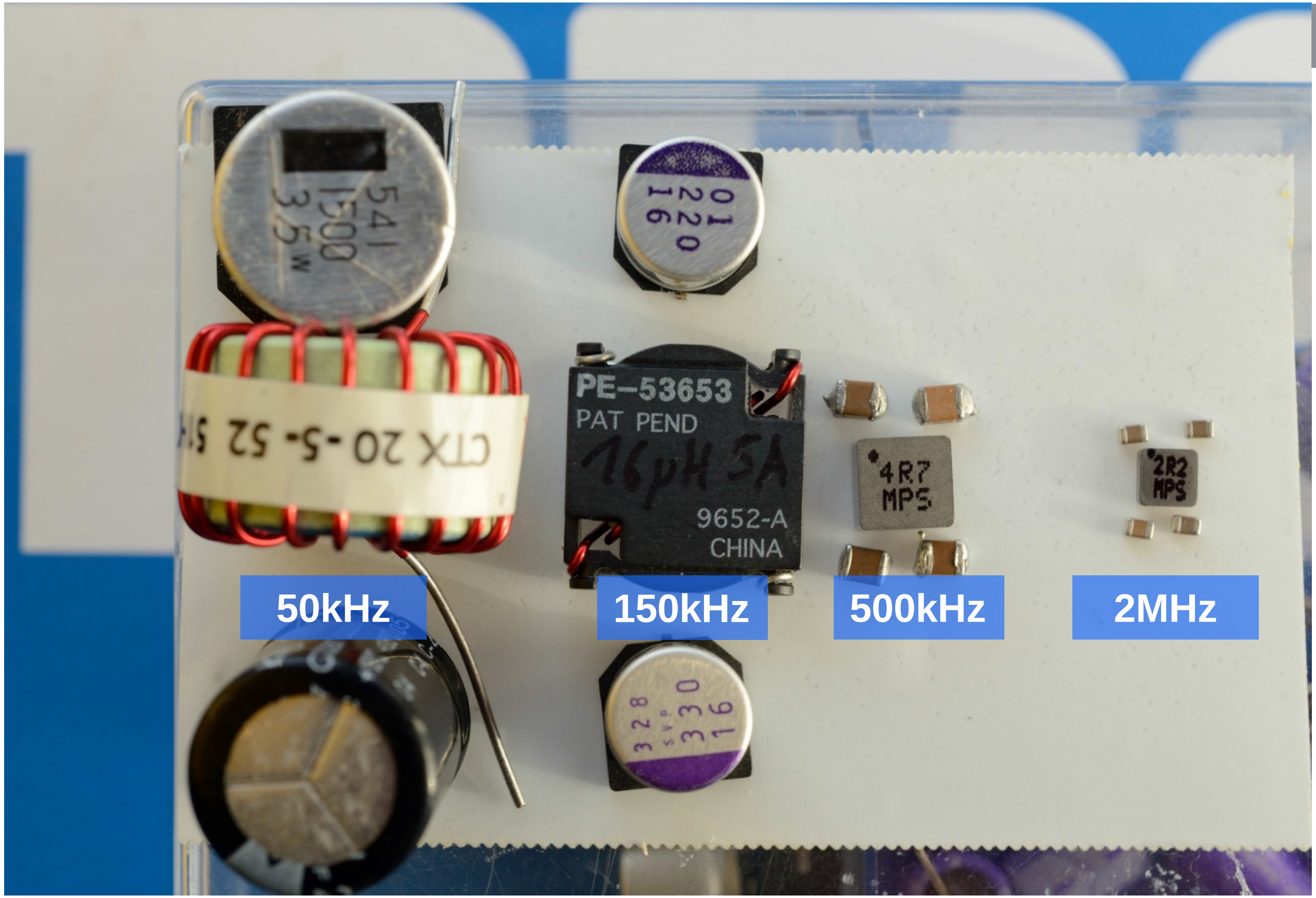
September 2020

概览

- 动机：电源方案尺寸的缩减与成本的降低
- 开关频率对电源参数的影响：设计公式一览
- 开关频率对动态响应性能的影响
- 开关频率对电源效率&损耗的影响
- 开关频率对芯片结温的影响
- 最小导通/关断时间对占空比的限制
- 开关频率对电源EMC/EMI性能的影响

开关频率对外围器件尺寸/成本的影响

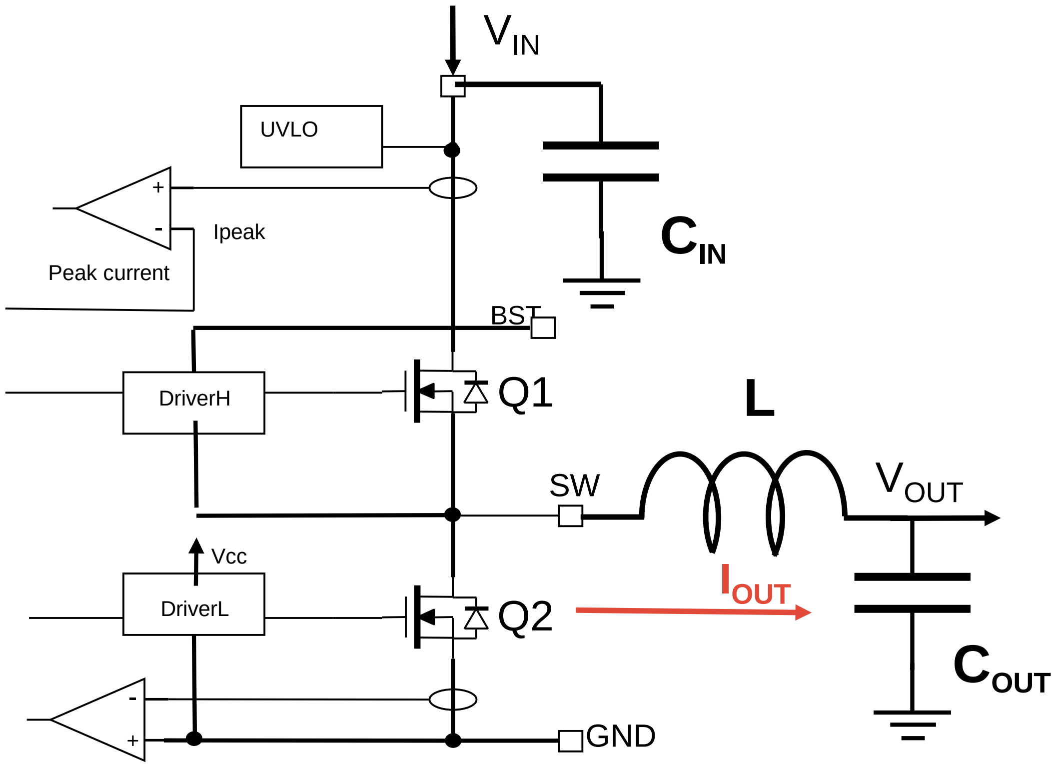
示例: 5A Buck

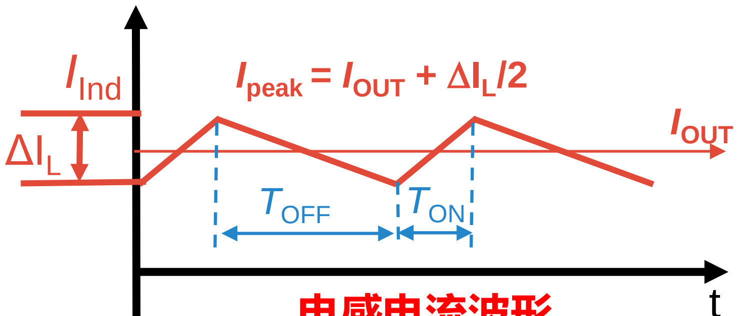


开关频率

电源尺寸

设计所需公式概览(以Buck电路为例)





电感电流波形

关键设计指标:

- I_{OUT}
- ΔI_L
- ΔV_{IN}
- ΔV_{OUT}

$$\text{Q1 Duty Cycle} = \frac{V_{OUT}}{V_{IN}}$$

$$T_{ON} = \frac{D.C.}{F_{SW}}$$

以40%电感电流纹波系数要求为例，可得：

$$L = \frac{(V_{IN} - V_{OUT}) * Ton}{0.4 * I_{OUT}}$$

$$C_{IN} \geq \frac{T_{on} I_{OUT}}{\Delta V_{IN}} \quad \boxed{\Delta V_{IN} < 100mV} \quad ESR < \frac{\Delta V_{IN}}{I_{peak}}$$

$$C_{OUT} \geq \frac{\Delta I_L}{(8 * F_{SW} * \Delta V_{OUT})} \quad \boxed{\Delta V_{OUT} < 10mV}$$

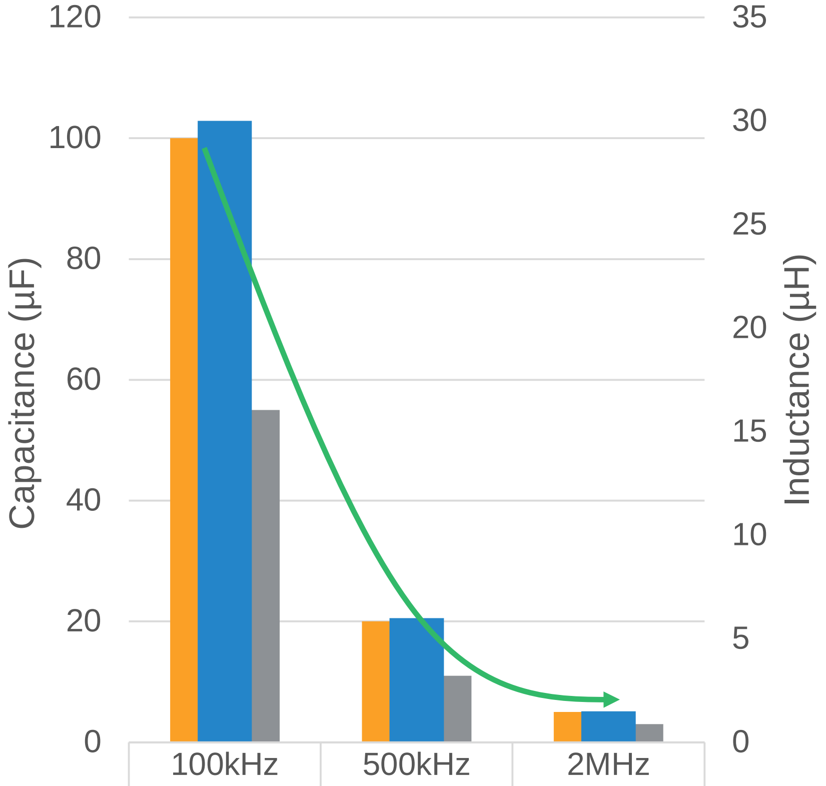
$$ESR < \frac{\Delta V_{OUT}}{\Delta I_L}$$

V_{OUT} ripple:

$$\Delta V_{OUT} \sim \Delta I_L \,(ESR + 1/(8 * F_{SW} * C_{OUT}))$$

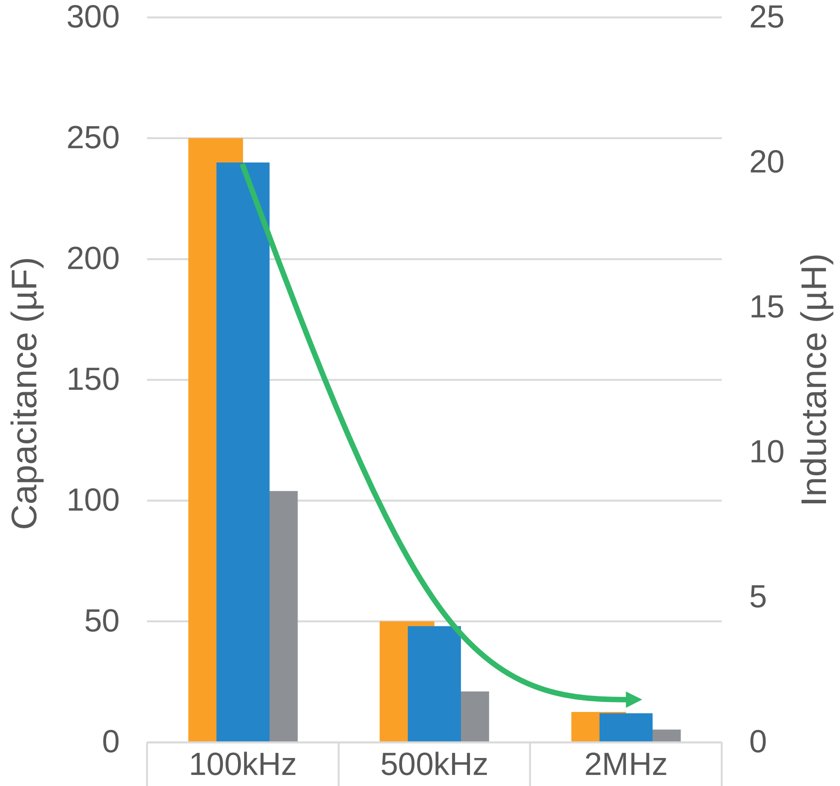
高开关频率带来小尺寸设计

Component Sizing
12V to 3.3V at 2A



	100kHz	500kHz	2MHz
Cout (uF)	100	20	5
Cin (uF)	55	11	3
Lmin (uH)	30	6	1.5

Component Sizing
24V to 5V at 5A

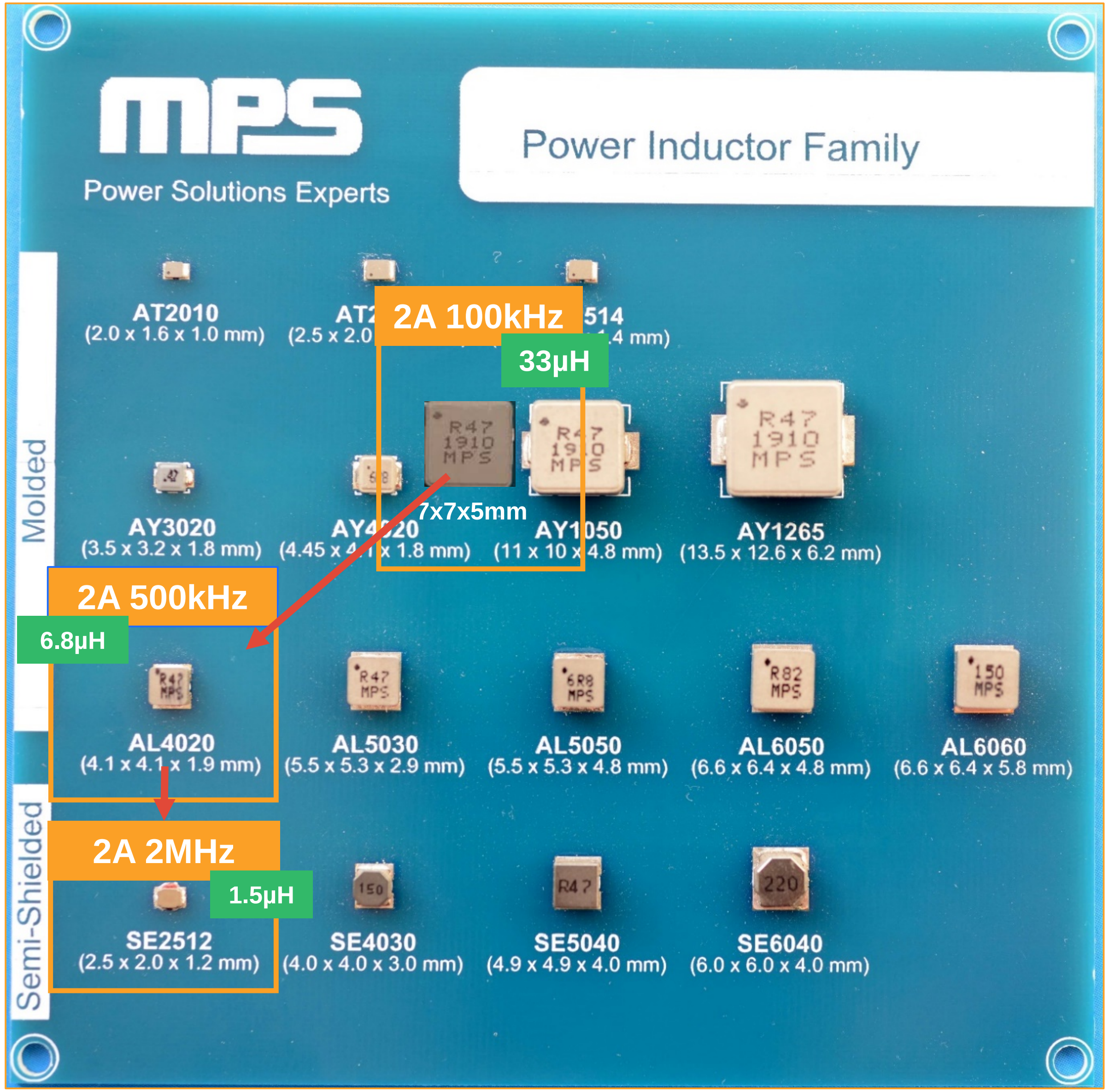


	100kHz	500kHz	2MHz
Cout (uF)	250	50	12.5
Cin (uF)	104	21	5.2
Lmin (uH)	20	4	1

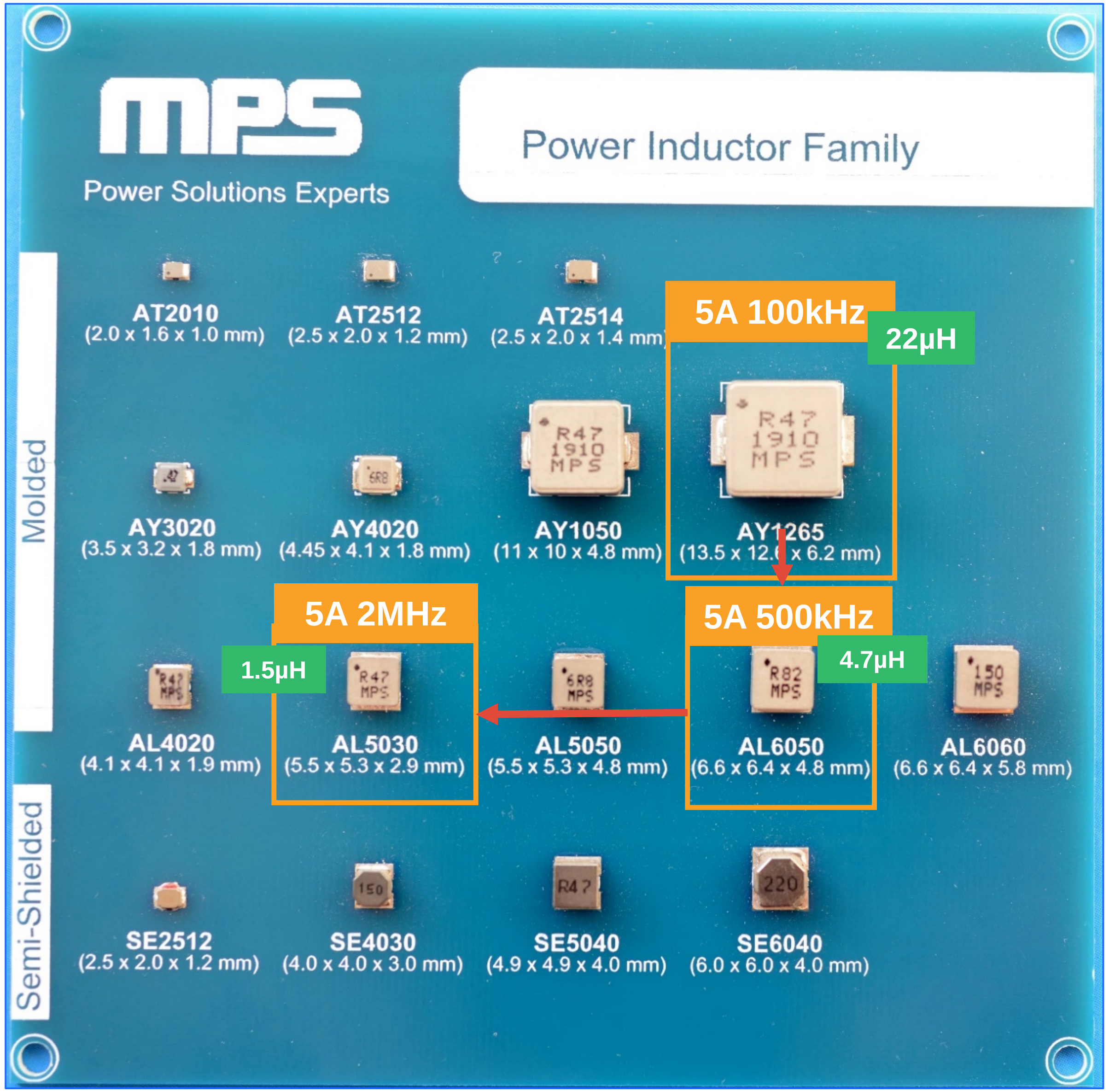
算例参数:

- 40% Inductor Ripple Current
- 10mV Peak-to-Peak Output Ripple
- 100mV Input Ripple

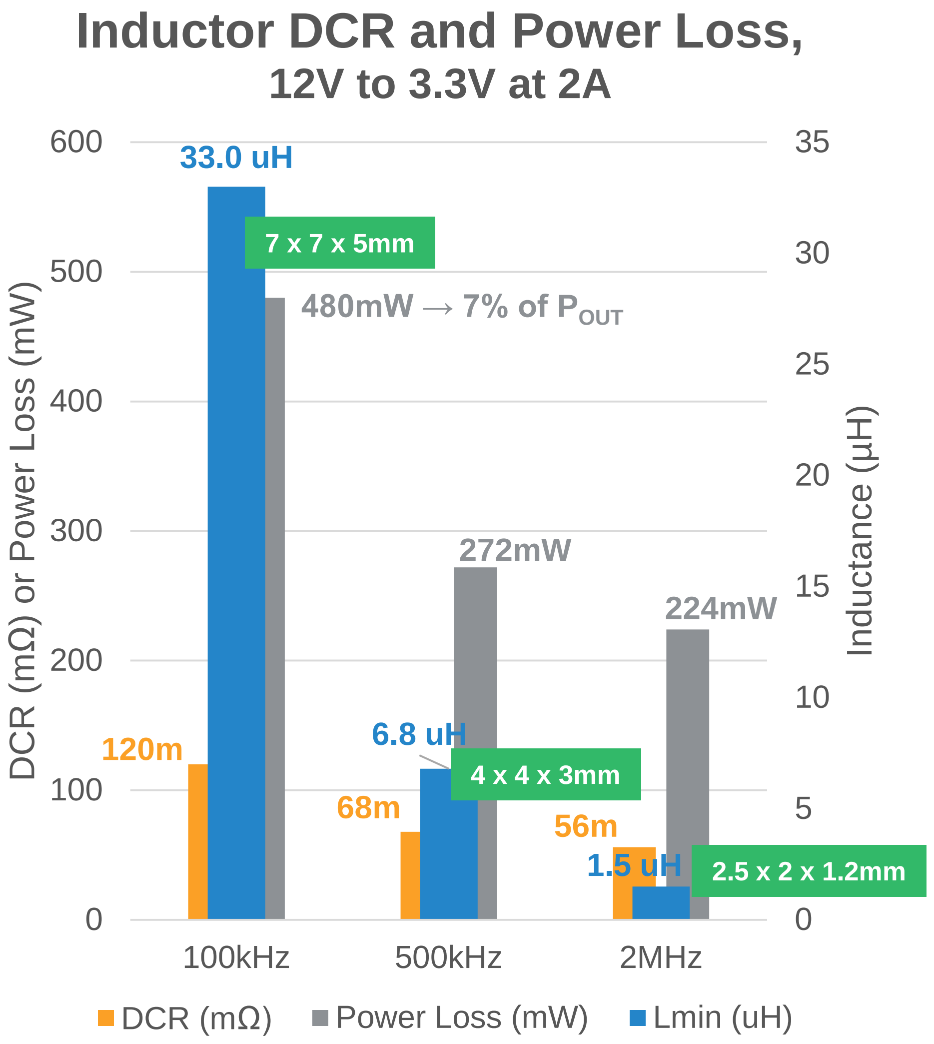
不同开关频率下所需电感尺寸(12V to 3.3V @2A)

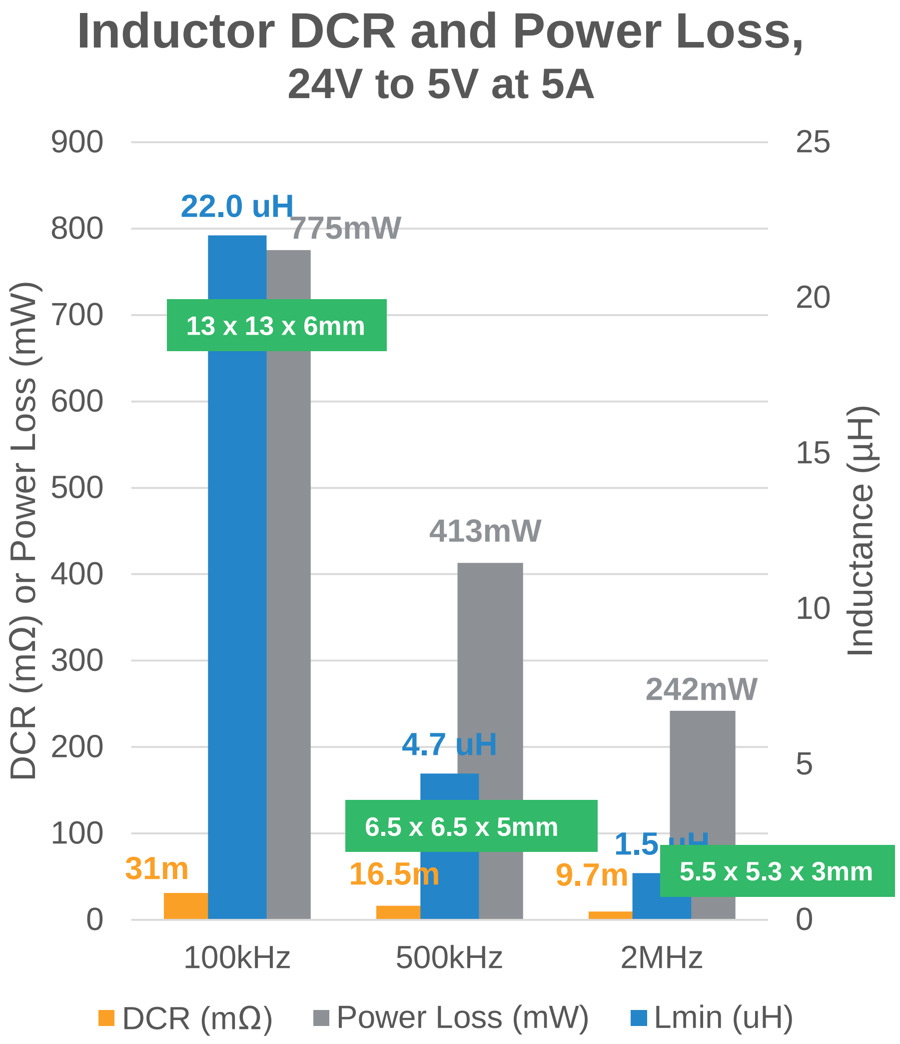


不同开关频率下所需电感尺寸(24V to 5V @5A)

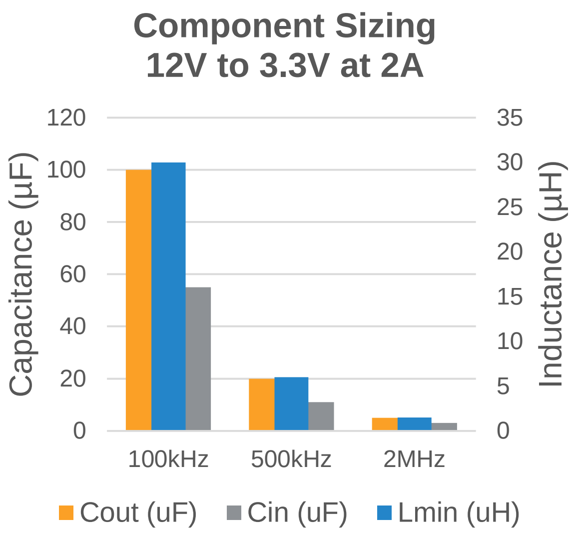


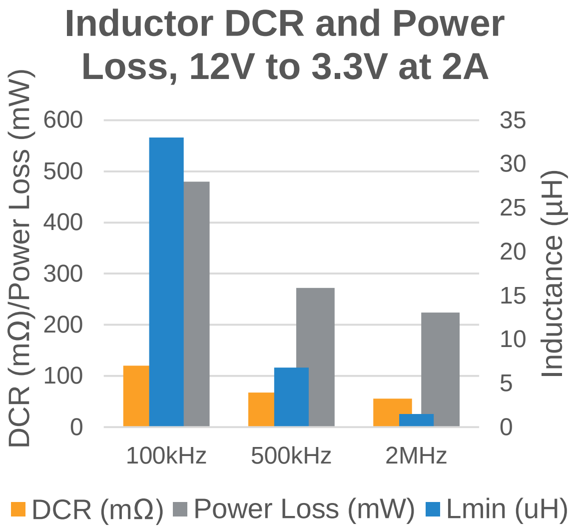
提高开关频率：电感尺寸及损耗减小

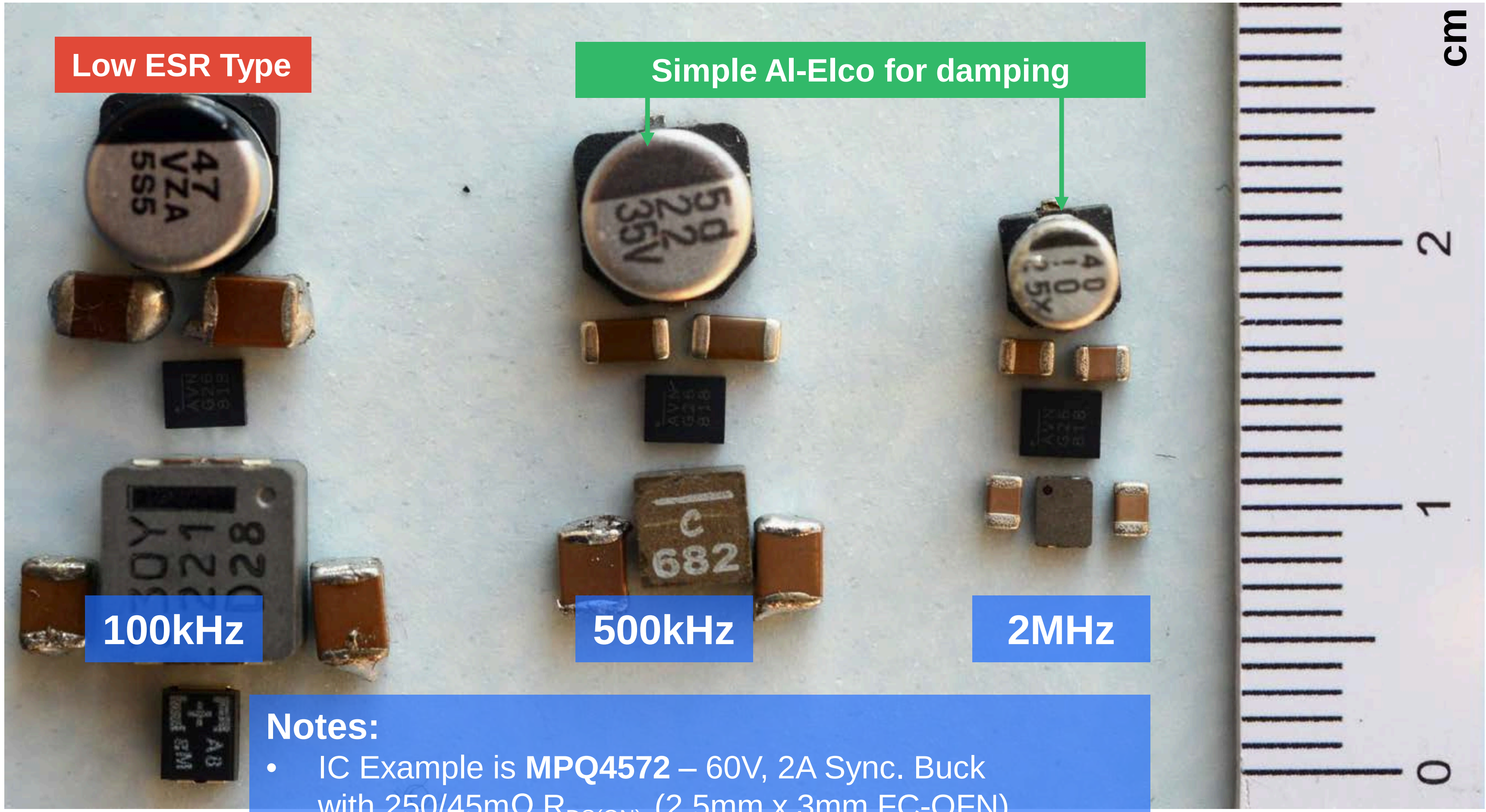




电源尺寸示例: 12V to 3.3V @ 2A





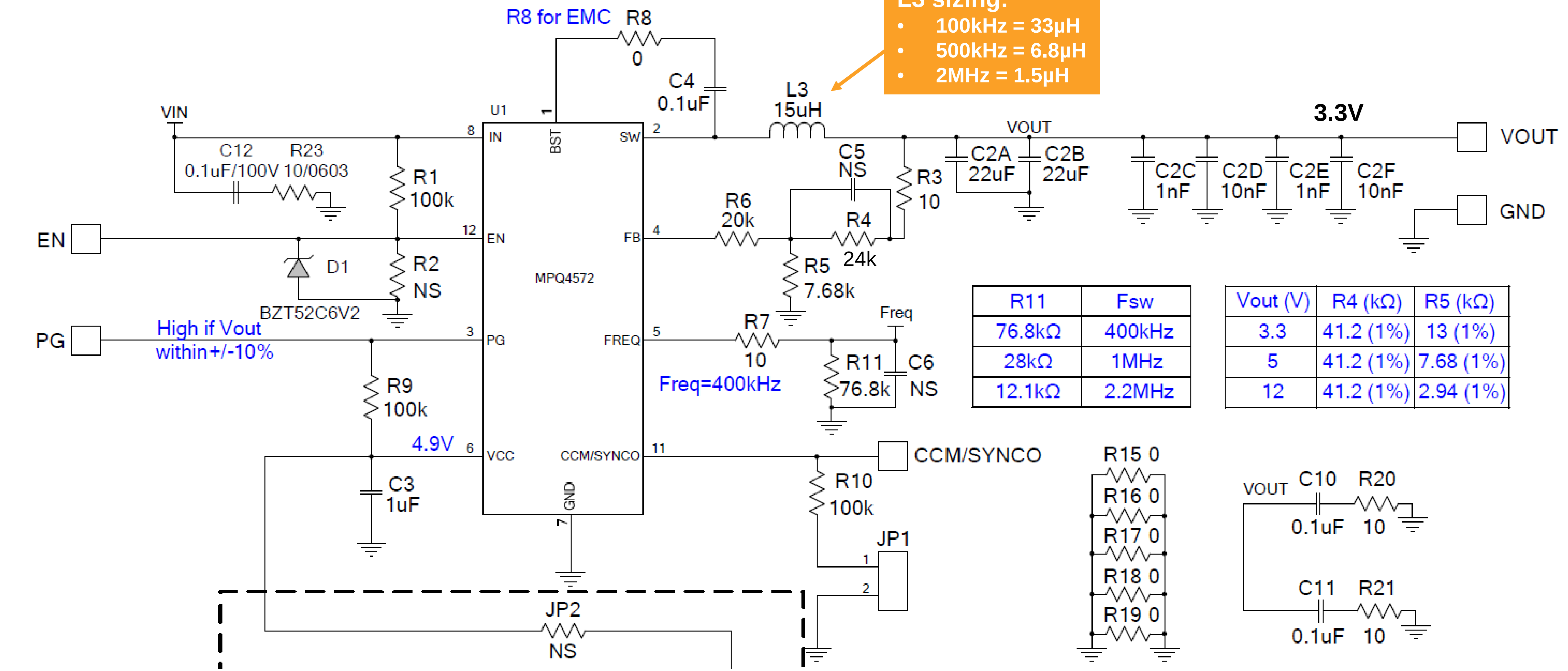


Notes:

- IC Example is **MPQ4572** – 60V, 2A Sync. Buck with 250/45mΩ $R_{DS(ON)}$ (2.5mm x 3mm FC-QFN)
- **C_{OUT} ESR** must be below 12mΩ!
- Assume effective MLCC capacity ~50% at used voltage

MPQ4572评估板原理图

L3 sizing:
- 100kHz = 33μH
- 500kHz = 6.8μH
- 2MHz = 1.5μH



R11	Fsw
76.8kΩ	400kHz
28kΩ	1MHz
12.1kΩ	2.2MHz

Vout (V)	R4 (kΩ)	R5 (kΩ)
3.3	41.2 (1%)	13 (1%)
5	41.2 (1%)	7.68 (1%)
12	41.2 (1%)	2.94 (1%)

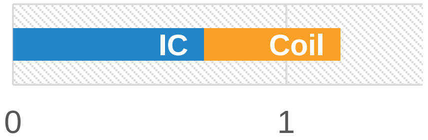
C_{OUT}(100kHz) = 2x 1210 22μF + 100μF

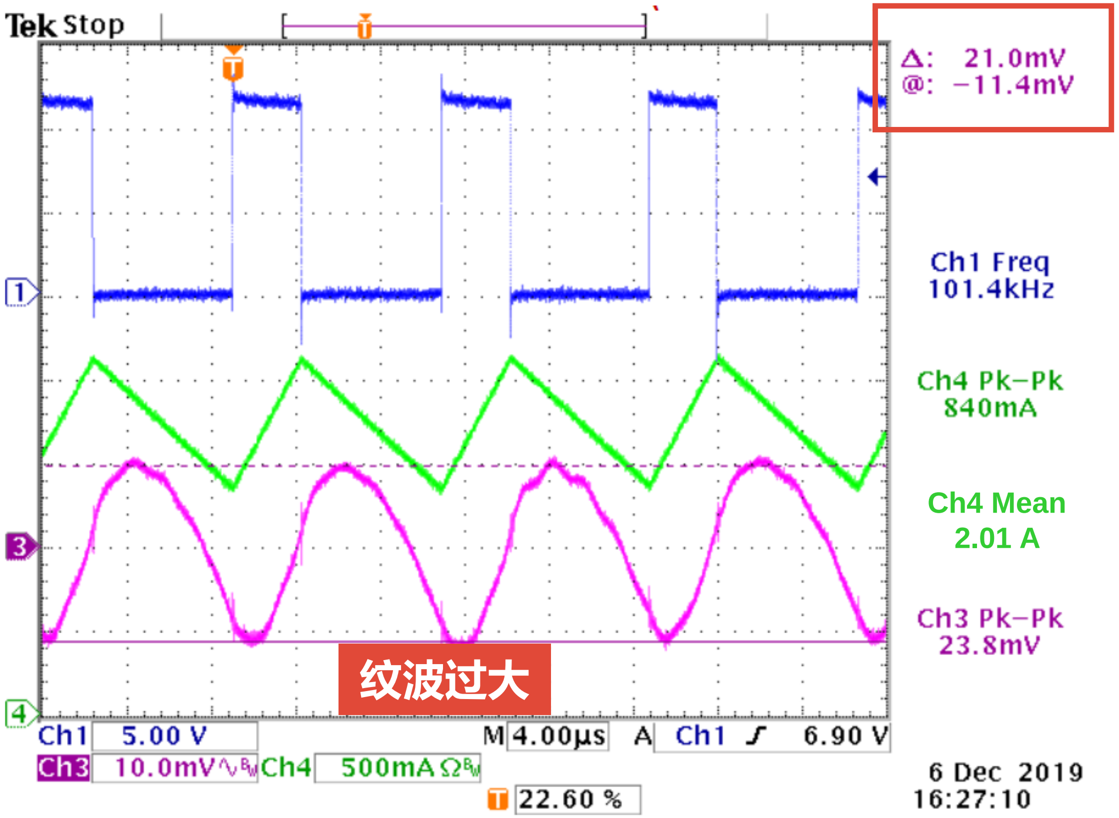
100kHz开关频率下电源性能

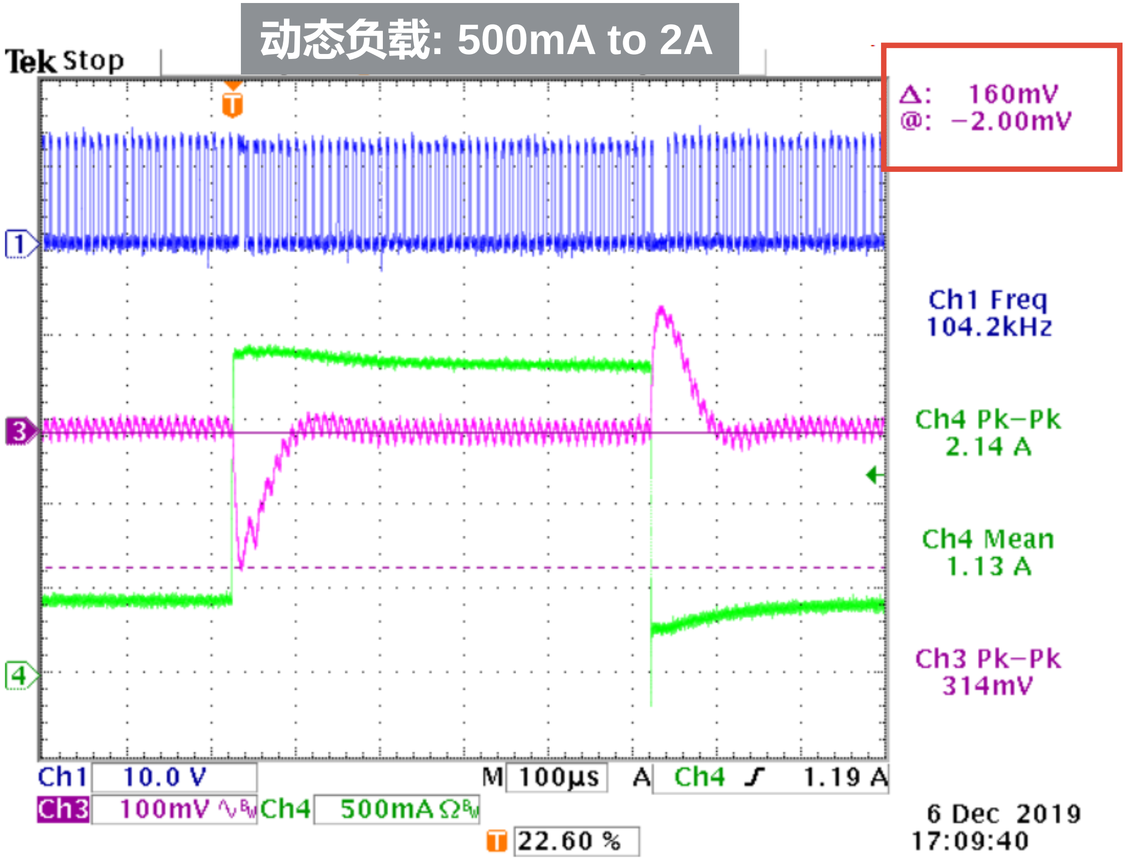
测试条件： 12V to 3.374V @ 2A

- L = 33µH (120mOhm)
- C_{OUT} = 2x 22uF (1210)+ 1x 100uF (70mOhm)
- 85% Efficiency
- 1.2W Power Loss

Power Loss (W)







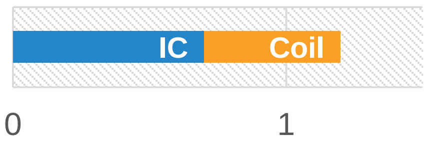
L= ETQP5N330YFM

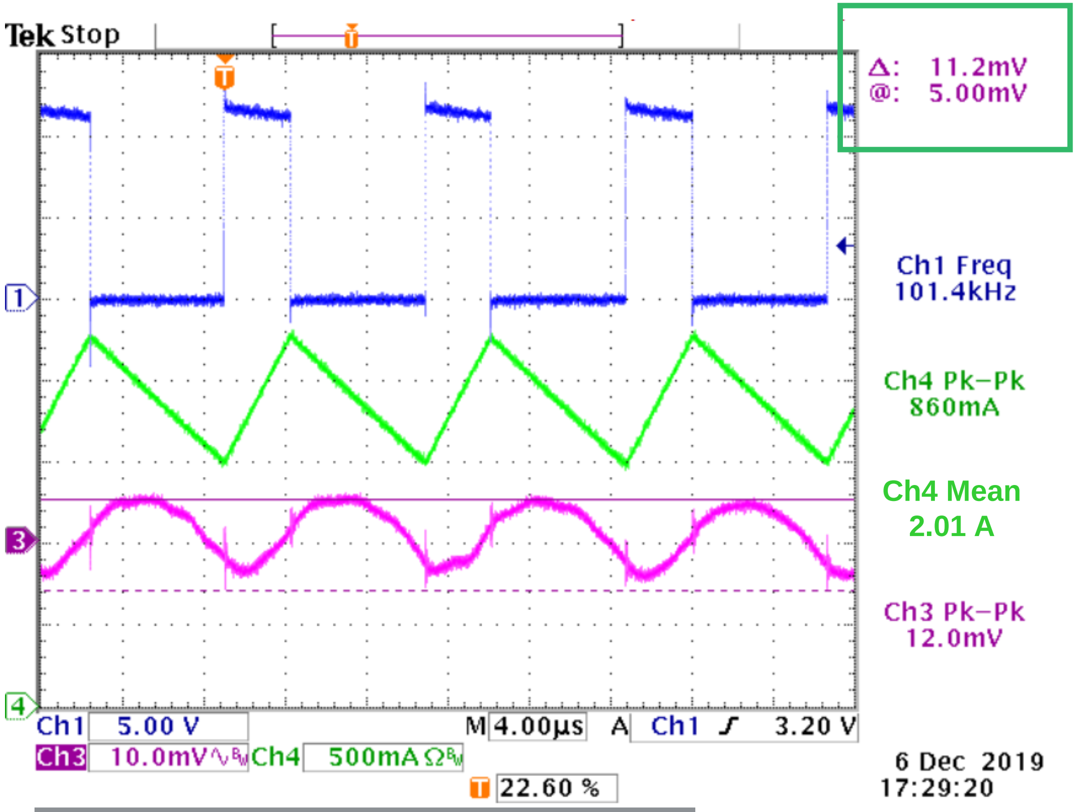
100kHz开关频率下电源性能(更换15mΩ输出电容)

测试条件： 12V to 3.374V @ 2A

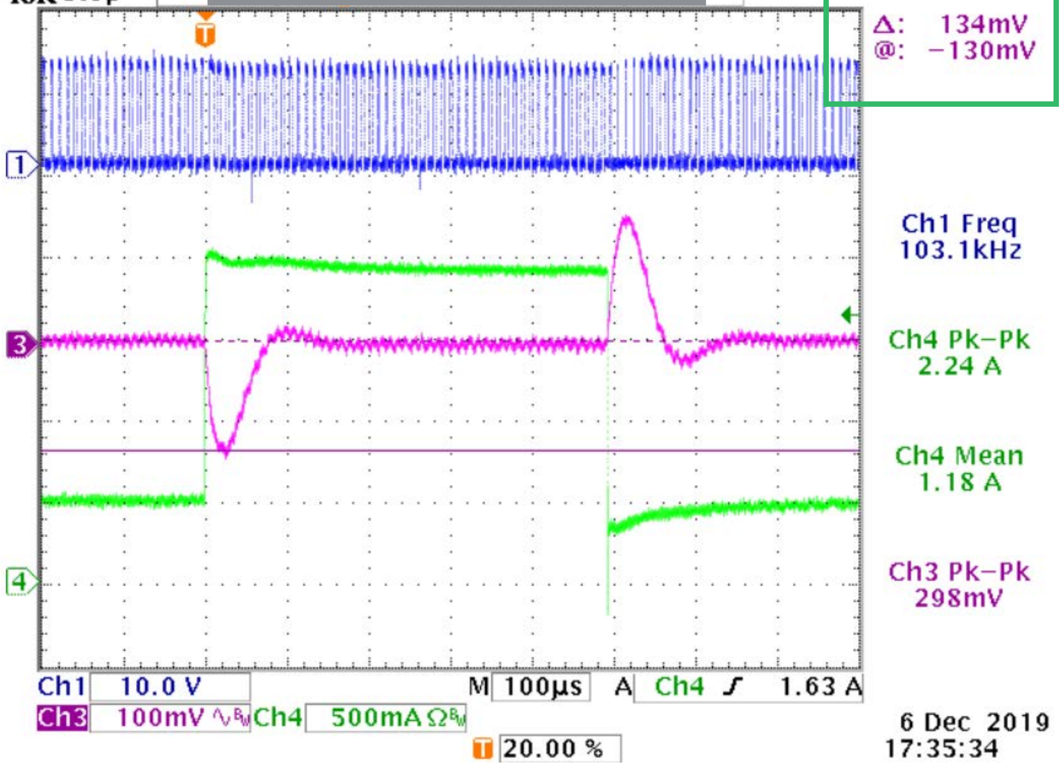
- L = 33µH (120mOhm)
- C_{OUT} = 2x 22uF (1210)+ 1x 100uF (15mOhm)
- 85% Efficiency
- 1.2W Power Loss

Power Loss (W)





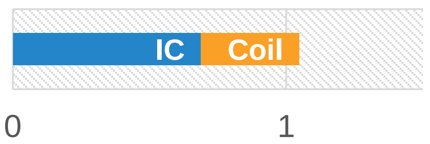
动态负载: 500mA to 2A

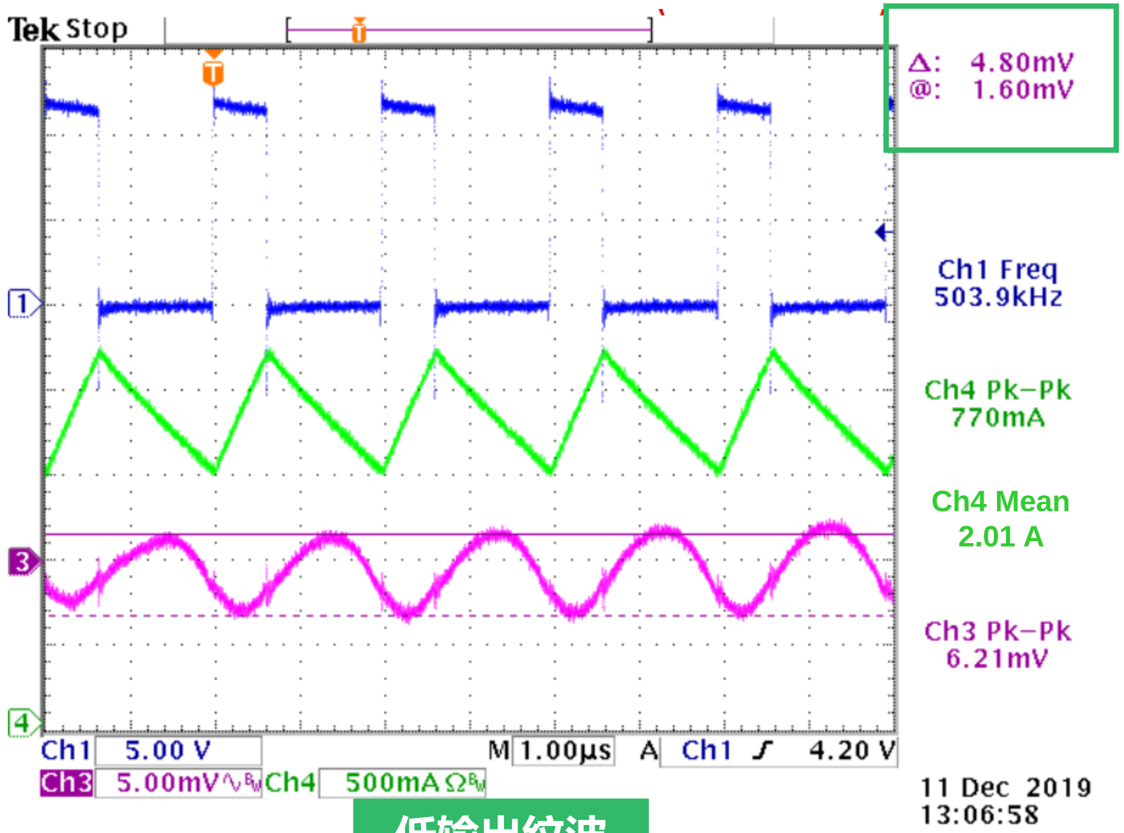


L = ETQP5N330YFM
C_{OUT} = EEFCX0J101R 7.3 x 4.3 x 1.9 mm

500kHz开关频率下电源性能

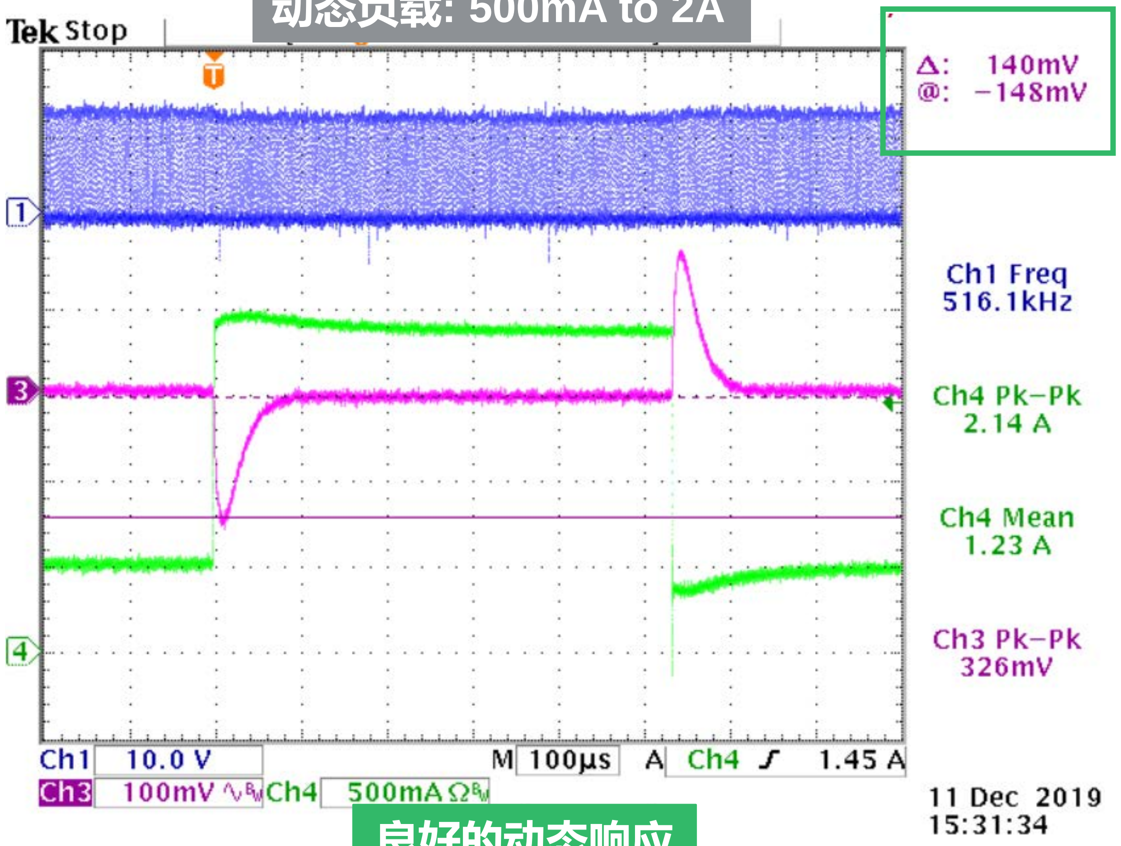
测试条件： 12V to 3.374V @ 2A
- L = 6.8 µH (68mOhm)
- C_{OUT} = 2x 22uF (1210)
- 86.6% Efficiency
- 1.05W Power Loss





低输出纹波

动态负载: 500mA to 2A

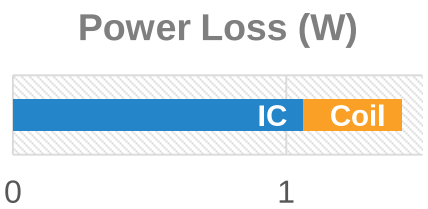


良好的动态响应

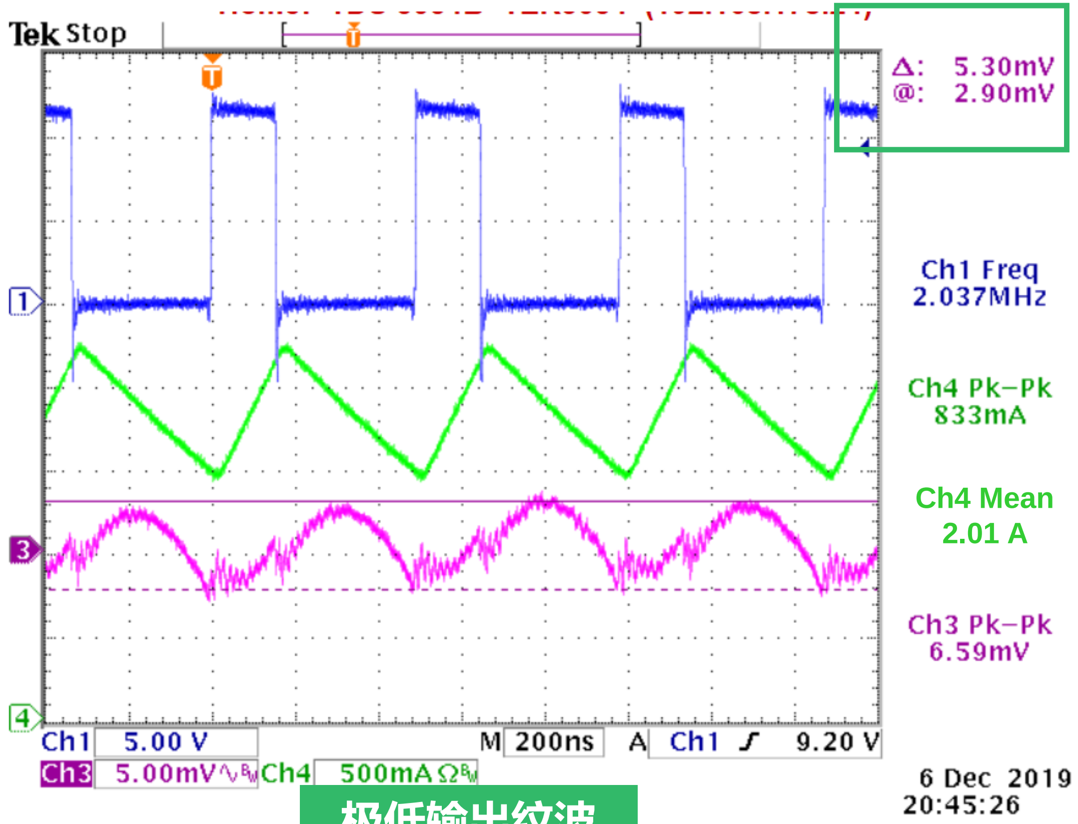
2MHz开关频率下电源性能

测试条件： 12V to 3.374V @ 2A

- L = 1.5 µH (56mOhm)
- C_{OUT} = 2x 10uF (0805)
- 82.5% Efficiency
- 1.42W Power Loss

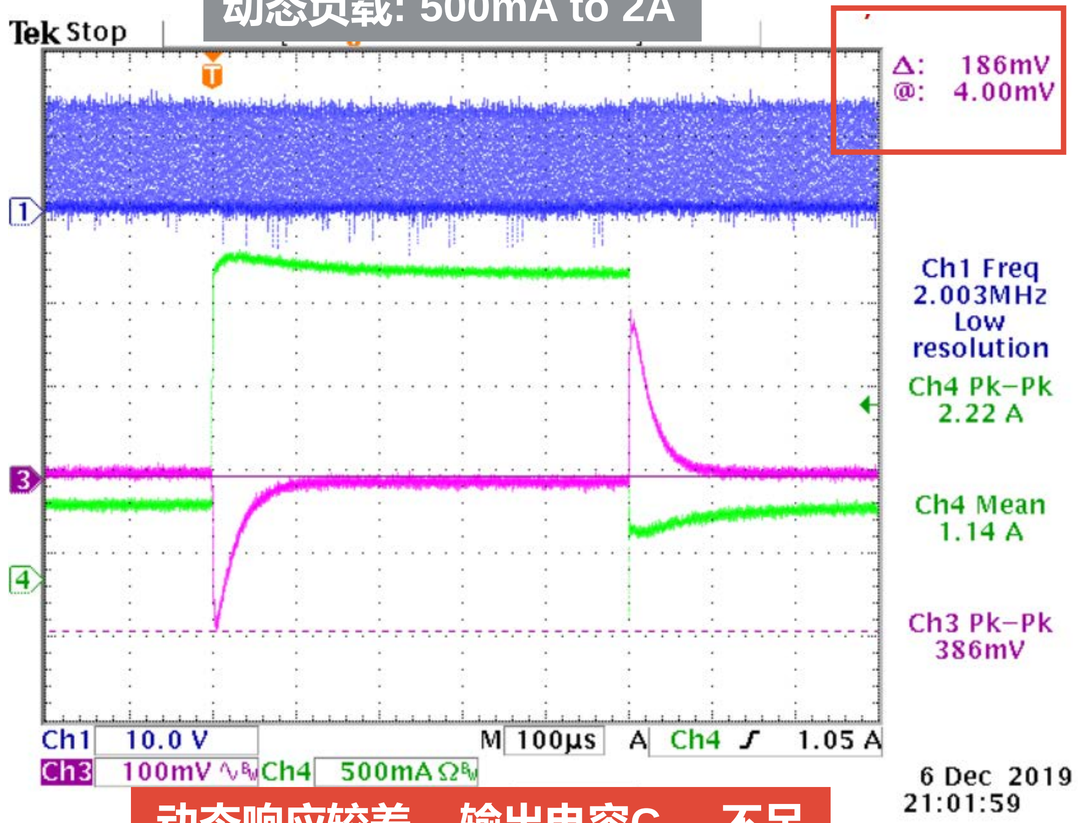


L = MPL-AT2512
Cout = JMK212AB7106KG



极低输出纹波

动态负载: 500mA to 2A



动态响应较差 – 输出电容C_{OUT}不足

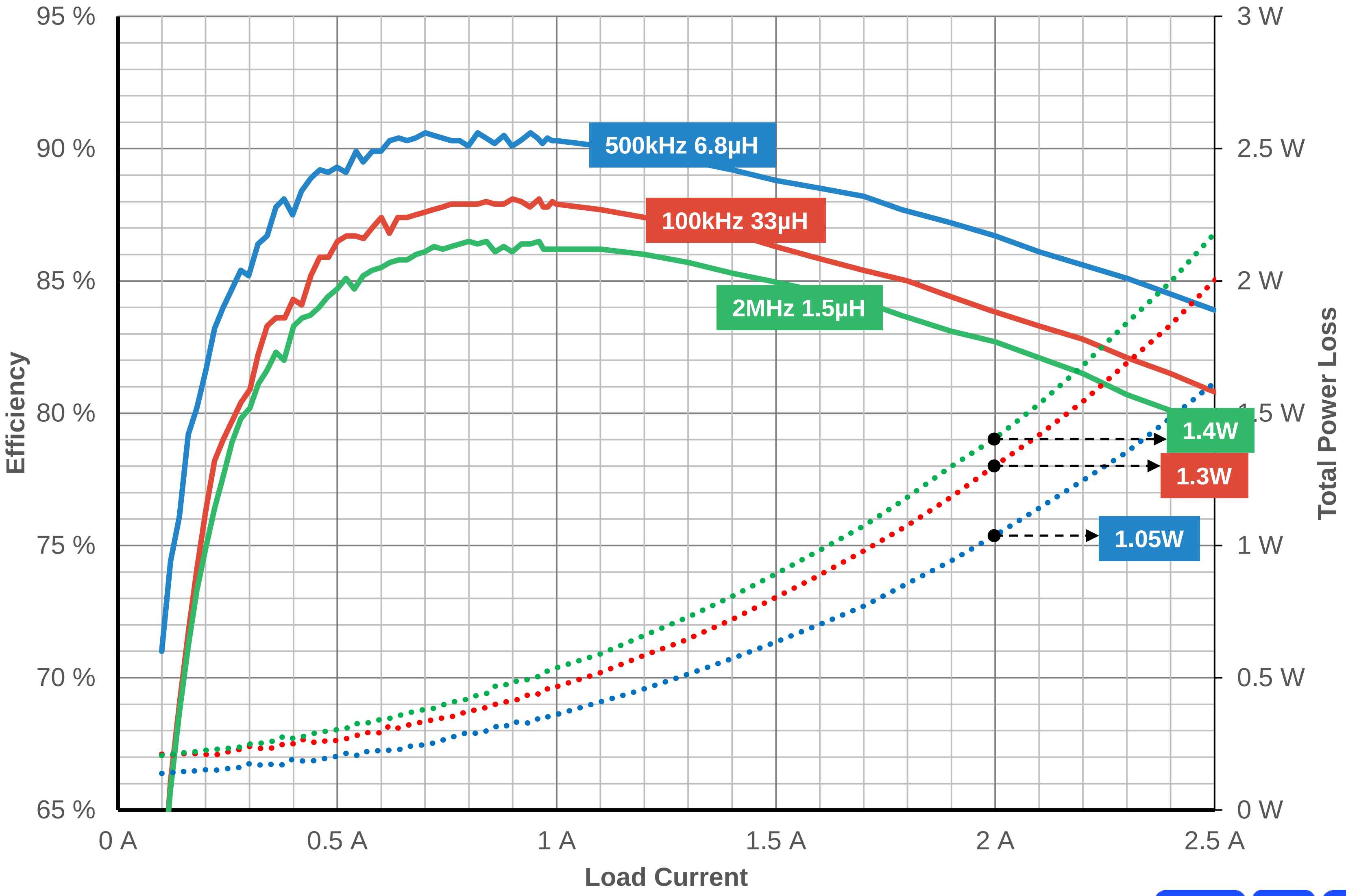
12V转3.3V效率曲线对比

测试基于MPQ4572评估板
(65V, 2A sync Buck - 250mΩ/45mΩ $R_{DS(ON)}$)

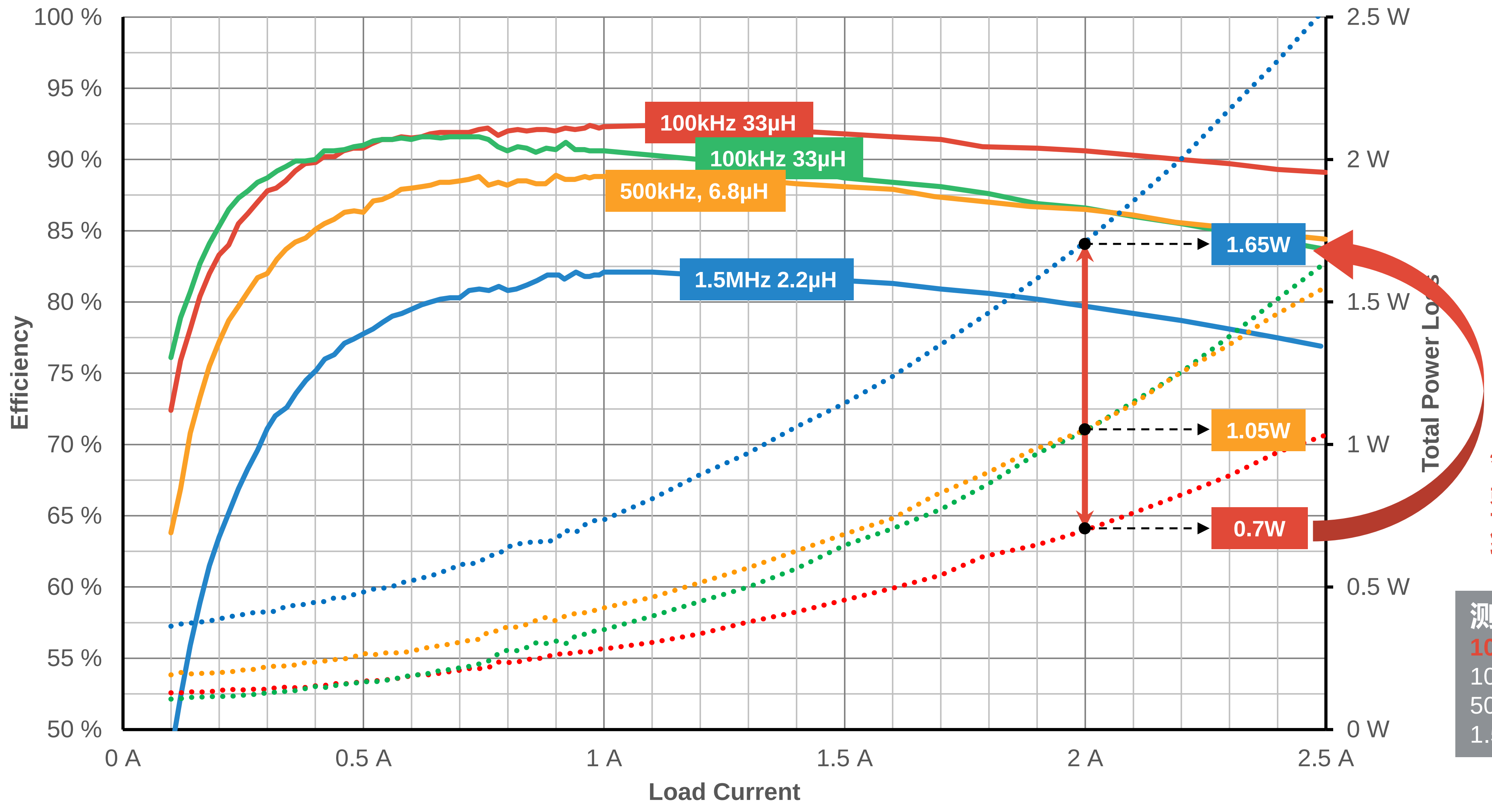
- Calculation shows lowest DCR loss in coil for 2MHz setup
- Real world **2MHz efficiency is lowest** due to **switch transition losses**

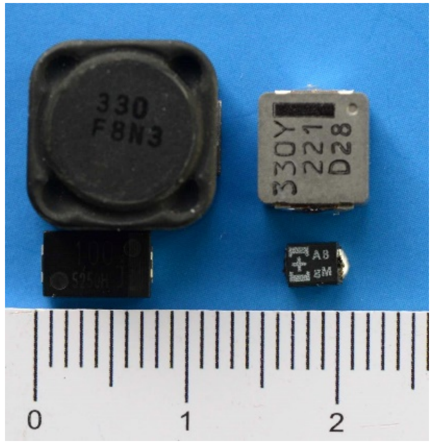
损耗构成?
1.4W(2MHz@2A):

✓ IC-FET R_{ON}: 406mW
✓ Coil DCR: 224mW
✓ Coil AC: ~150mW
✓ Remaining 620mW are transition losses and IC supply losses



24V转5V效率曲线对比





*** 开关频率从100kHz调整为1.5MHz，损耗增加约1W**

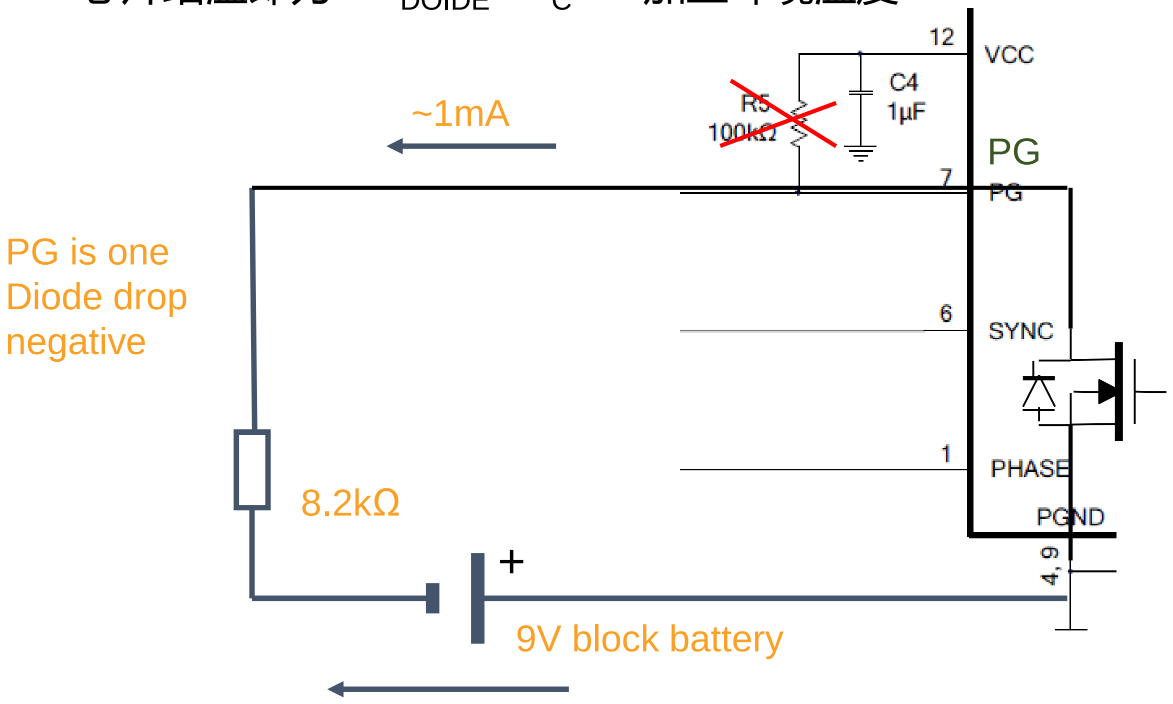
测试条件：

100kHz: 33µH 64mΩ 12 x 12mm
100kHz: 33µH 120mΩ 7 x 7mm
500kHz: 6.8µH 68mΩ 4 x 4mm
1.5MHz: 2.2µH 70mΩ 2.5 x 2mm

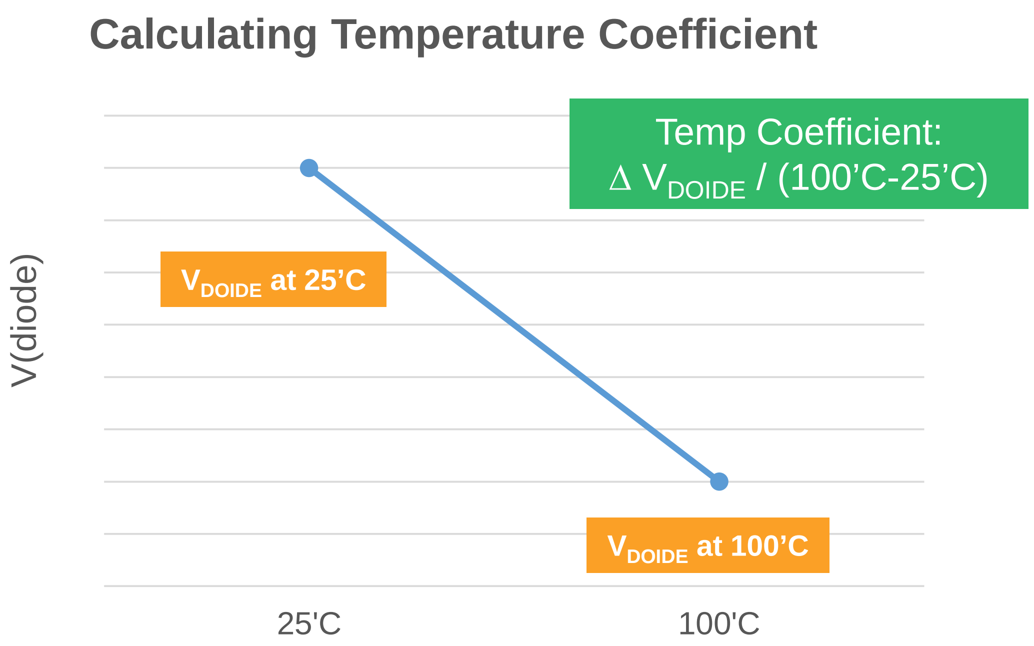
芯片结温计算方法 – 基于片上二极管

测量方法 – 利用PG管脚体二极管温度特性

1. 测量25°C和100°C下的V_{DOIDE}
   - 测量时采用相同的输入电压V_{IN}
2. 计算温度相关系数Temperature Coefficient:
   - MPQ4430在1mA电流下T_C=-1.55mV/K
3. 测量空载下的V_{DOIDE}
4. 测量特定负载条件下的 V_{DOIDE}
5. 芯片结温即为∆ V_{DOIDE} / T_C °C 加上环境温度



实验条件:
12V to 3.3V at 2A
MPQ4430 – 40V, 3.5A Low Iq Sync Buck

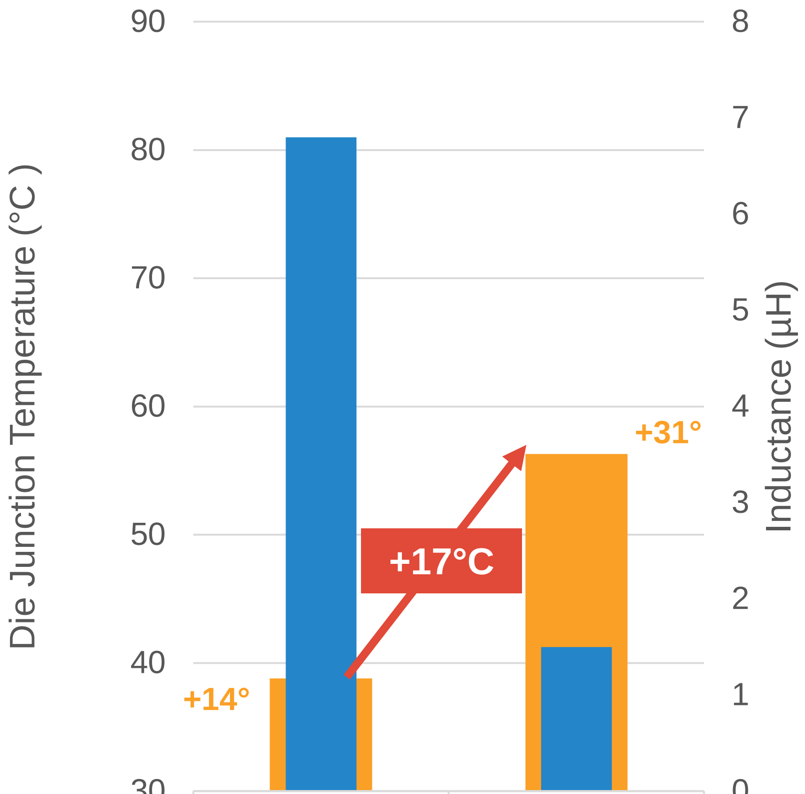


计算示例:
MPQ4430 PG-Pin body diode has -1.55mV/K at 1mA current.

开关频率对芯片结温的影响

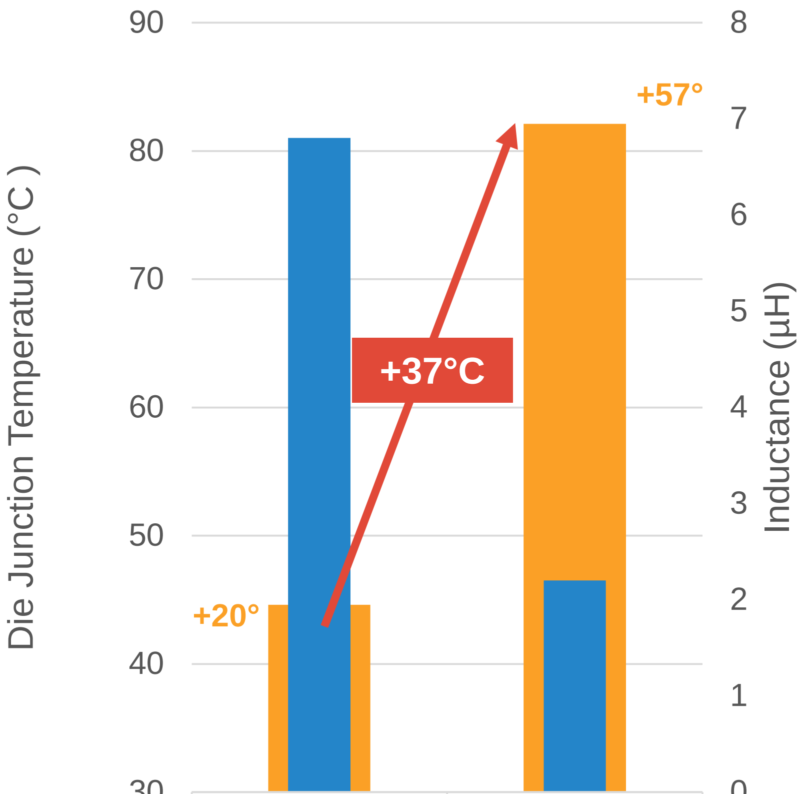
*基于前述测量方法

Die Junction Temperature, 12V to 3.3V at 2A



	500kHz	2MHz
TJ	38.8	56.3
Lmin (uH)	6.8	1.5

Die Junction Temperature, 24V to 3.3V at 2A



	500kHz	2MHz
TJ	44.6	82.1
Lmin (uH)	6.8	2.2

占空比限制: $T_{ON,min}$

- **$T_{ON,min}$ 是上管最短的OFF-ON-OFF 时序.**
  (Charge FET Gate → Sense Current → Discharge Gate)

For given V_{OUT} and $T_{ON,min}$: $$V_{IN,max} = \frac{V_{OUT}}{T_{ON,min} * F_{SW}}$$

The higher the F_{SW}, the lower the max. Vin for fixed frequency operation

$$F_{SW,max} = \frac{V_{OUT,min}}{T_{ON,min} * V_{IN,max}}$$

算例:
$T_{ON,min}$ of 100ns
V_{OUT} = 3.3V
$V_{IN,MAX}$ = 36V
Max. Fsw ≤ 0.92 MHz

In real world effective duty-cycle is

D.C.real = $V_{OUT}/(V_{IN} * \eta)$

算例:
$T_{ON,min}$ of 100ns
V_{OUT} = 3.3V
$V_{IN,MAX}$ = 36V
and η = 80%
Max. Fsw ≤ 1.15MHz

占空比限制: $T_{OFF,min}$

- $T_{OFF,min}$ 是下管最短的OFF-ON-OFF 时序
  (Charge FET Gate → Sense Current → **Charge BST-Cap** → Discharge Gate)

For given V_{OUT} and $T_{OFF,min}$: $$V_{IN,min} = \frac{V_{OUT}}{(1-T_{OFF,min} * F_{SW})}$$

The higher the F_{SW}, the lower the max. Vin for fixed frequency operation.

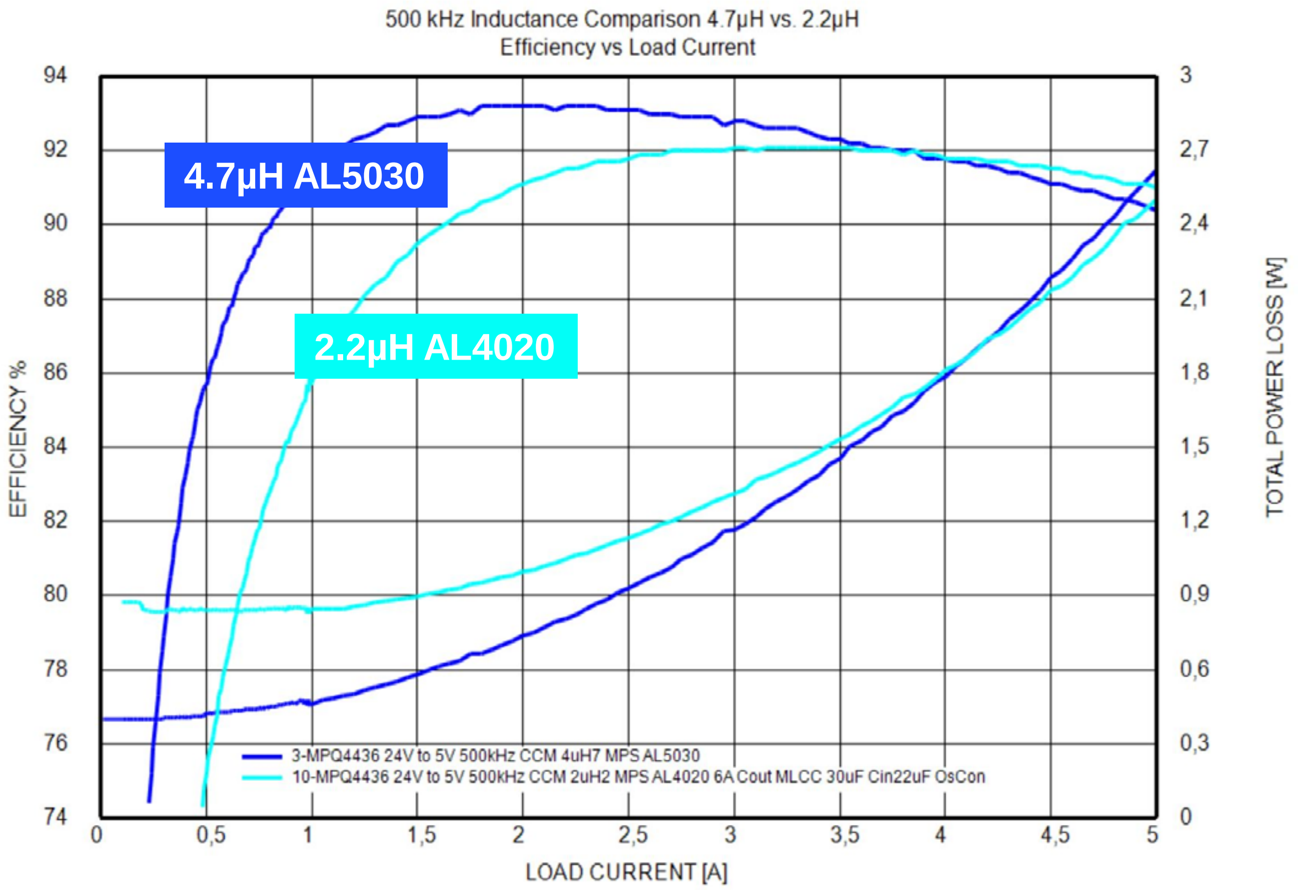
$$F_{SW,max} = \left(1 - \frac{V_{OUT}}{V_{IN,min}}\right) * \frac{1}{T_{OFF,min}}$$

算例:
$T_{OFF,min}$ of 100ns
V_{OUT} = 3.3V
$V_{IN,min}$ = 3.8V
Max. Fsw ≤ 1.3MHz
In real world drop across FETs, Coil and PCB trace will require lower Fsw.

*** Modern ICs fold back Fsw at low input voltage down to Drop-Out Mode.**

替换方案 – 允许更大的电感电流纹波

Operate the circuit with higher ΔI_L, increase from 40% to 50% or 60%

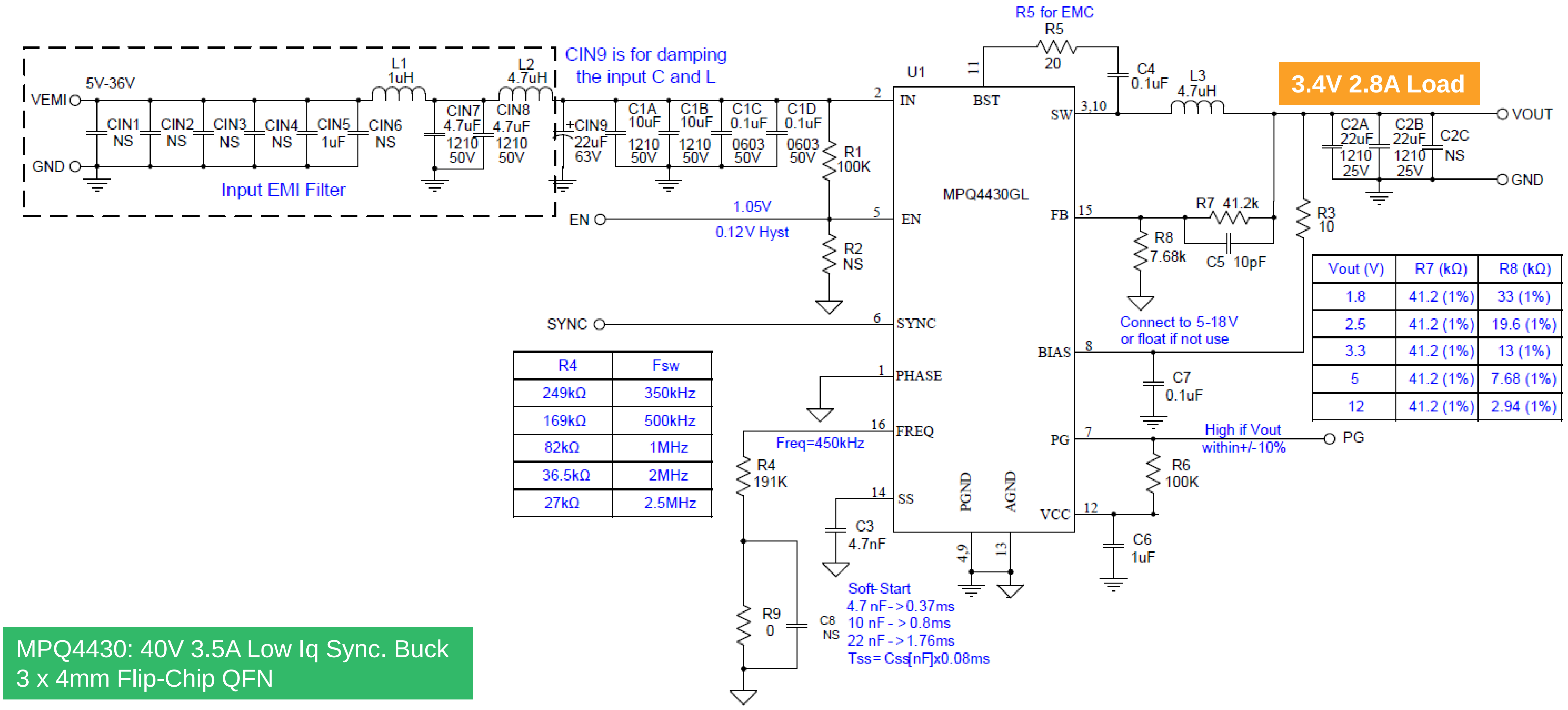


Example with 500kHz using *2.2µH: ΔI_L=2.44A; Ipk=6.22A instead of 2A and 6A respectively*.
Cout of 3x 10uF (25V, 1206)

开关频率对电源EMI/EMC性能的影响

Pre-Compliance measurements for Conducted Emission (voltage-method acc. to CISPR25) tested with MPQ4430 EVB

示例: MPQ4430评估板

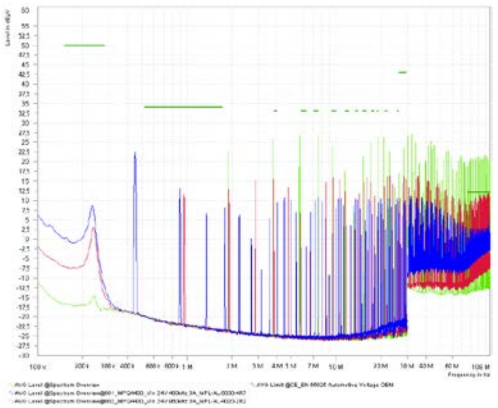


R4	Fsw
249kΩ	350kHz
169kΩ	500kHz
82kΩ	1MHz
36.5kΩ	2MHz
27kΩ	2.5MHz

Vout (V)	R7 (kΩ)	R8 (kΩ)
1.8	41.2 (1%)	33 (1%)
2.5	41.2 (1%)	19.6 (1%)
3.3	41.2 (1%)	13 (1%)
5	41.2 (1%)	7.68 (1%)
12	41.2 (1%)	2.94 (1%)

MPQ4430: 40V 3.5A Low Iq Sync. Buck
3 x 4mm Flip-Chip QFN

传导发射测试结果 (CE) From 100kHz – 108MHz



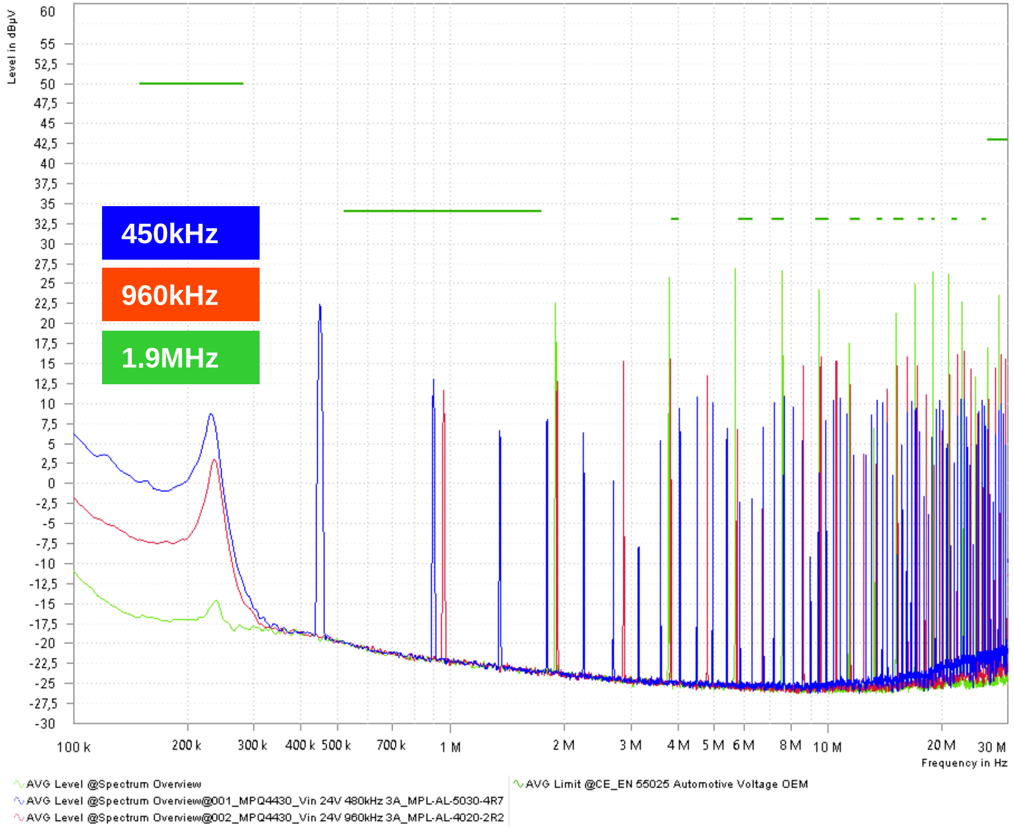
测试条件
- V_{OUT} of 3.4 V 2.8A
- R8 = 7.68 kohm
- C5= 33 pF

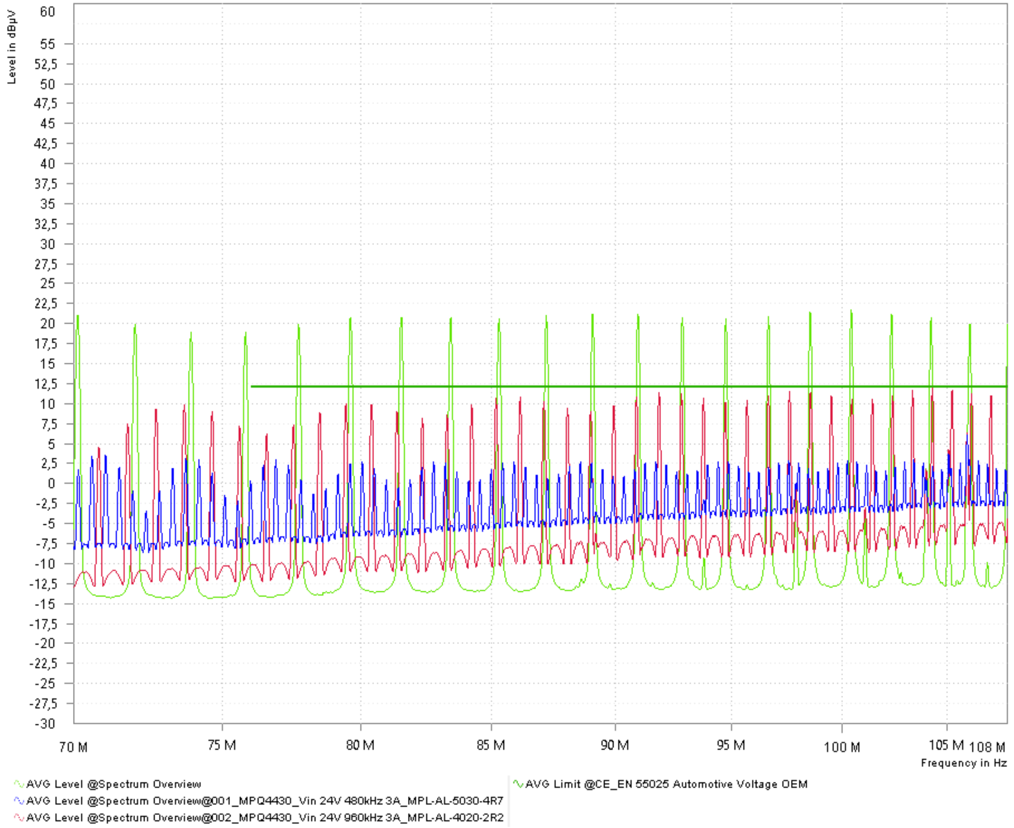
450 kHz 开关频率
- R4 = 191 kohm
- **Main Coil:** MPL-AL-5030 4R7 (5.5 x 5.3 x 2.9 mm)

960 kHz 开关频率
- R4 = 191 kohm
- **Main Coil:** MPL-AL-4020 2R2 (4.1 x 4.1 x 1.9 mm)

1900 kHz 开关频率
- R4 = 191 kohm
- **Main Coil:** MPL-AL-4020 1R0 (4.1 x 4.1 x 1.9 mm)

- **All Test are Average**





传导发射测试结果 (CE) From 100kHz – 30MHz

测试条件

- V_{OUT} of 3.4 V 2.8A
- R8 = 7.68 kohm
- C5= 33 pF

450 kHz 开关频率

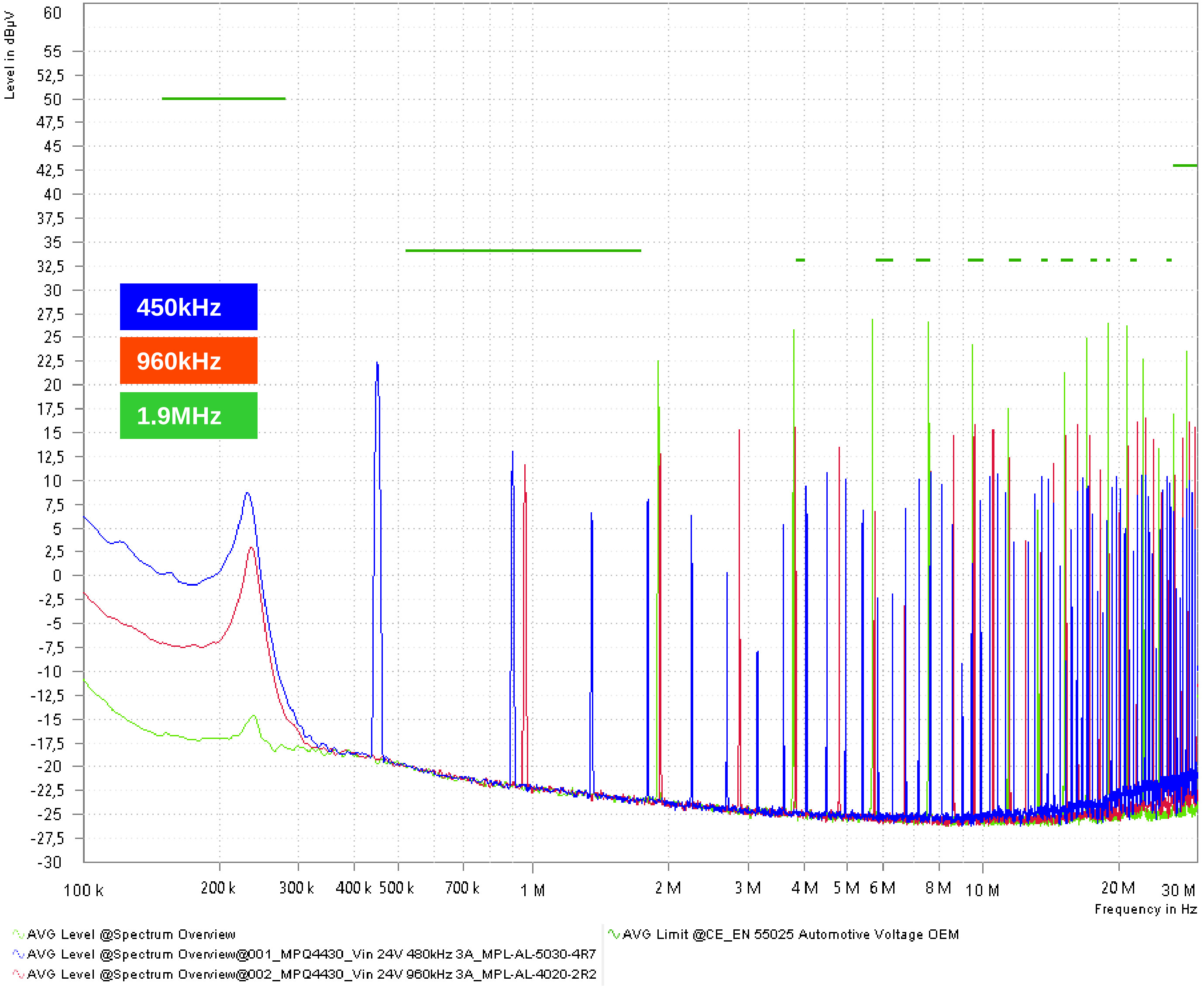
- R4 = 191 kohm
- **Main Coil:** MPL-AL-5030 4R7 (5.5 x 5.3 x 2.9 mm)

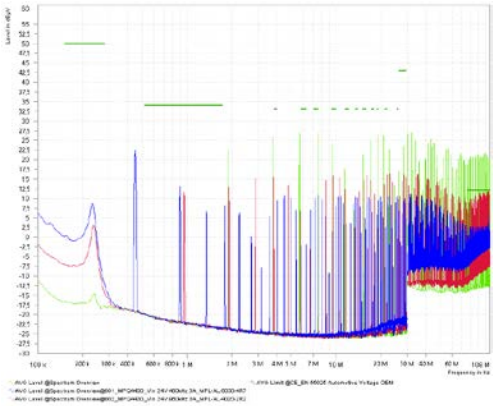
960 kHz 开关频率

- R4 = 191 kohm
- **Main Coil:** MPL-AL-4020 2R2 (4.1 x 4.1 x 1.9 mm)

1900 kHz 开关频率

- R4 = 191 kohm
- **Main Coil:** MPL-AL-4020 1R0 (4.1 x 4.1 x 1.9 mm)





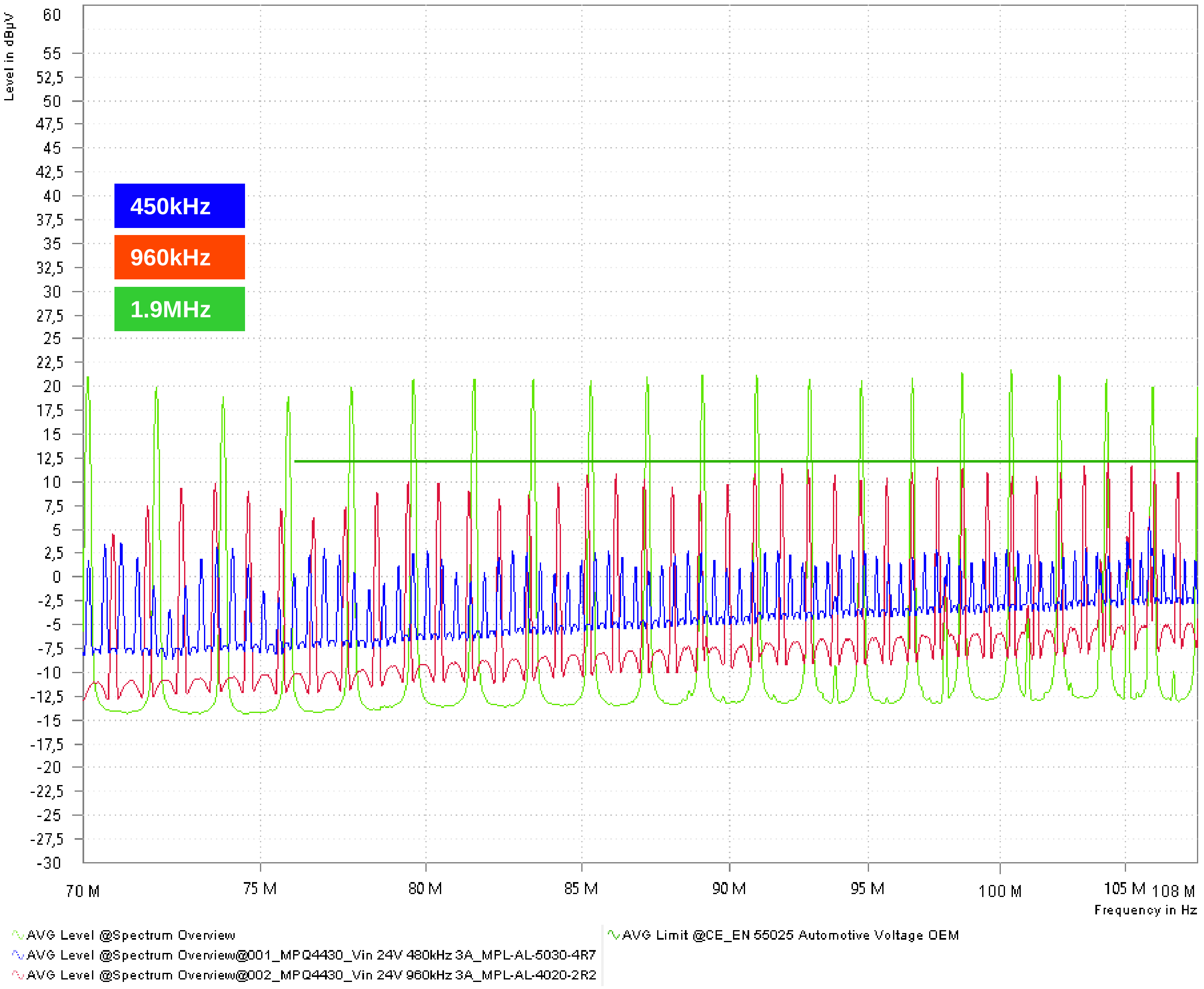
传导发射测试结果 (CE) From 70MHz – 108MHz

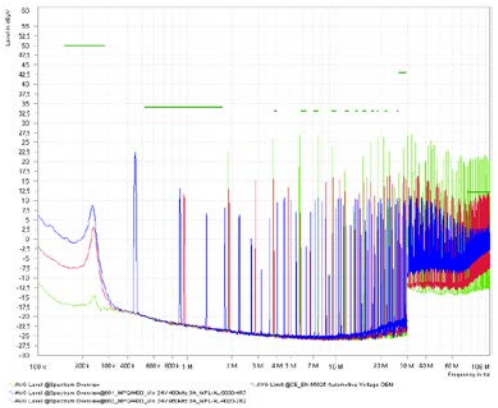
测试条件
- V_{OUT} of 3.4 V 2.8A
- R8 = 7.68 kohm
- C5= 33 pF

450 kHz 开关频率
- R4 = 191 kohm
- **Main Coil:** MPL-AL-5030 4R7 (5.5 x 5.3 x 2.9 mm)

960 kHz 开关频率
- R4 = 191 kohm
- **Main Coil:** MPL-AL-4020 2R2 (4.1 x 4.1 x 1.9 mm)

1900 kHz 开关频率
- R4 = 191 kohm
- **Main Coil:** MPL-AL-4020 1R0 (4.1 x 4.1 x 1.9 mm)





Automotive OEM Limit

传导发射测试结果 (CE) From 70MHz – 108MHz

测试条件

- V_{OUT} of 3.4 V 2.8A
- R8 = 7.68 kohm
- C5= 33 pF

450 kHz 开关频率

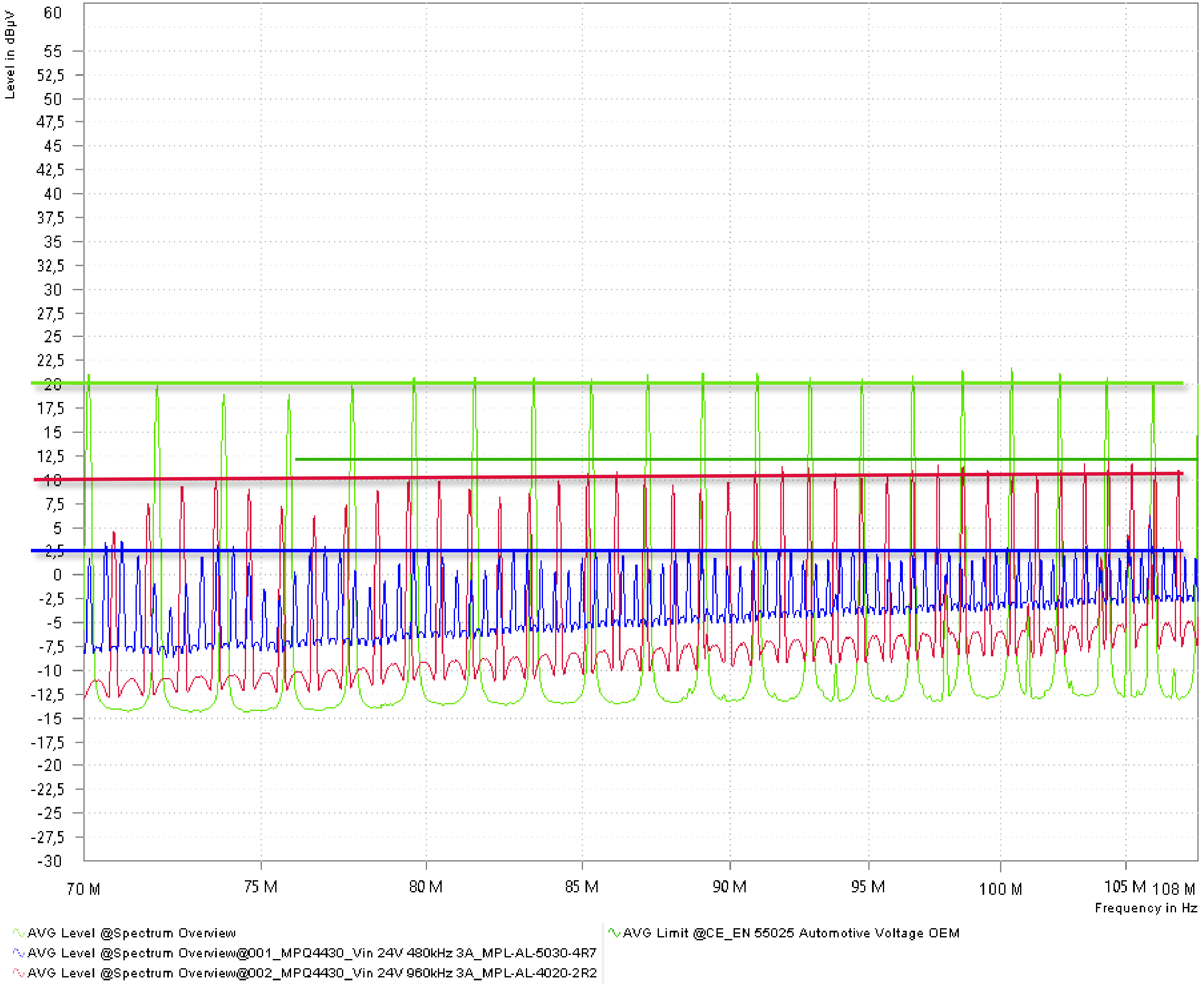
- R4 = 191 kohm
- **Main Coil:** MPL-AL-5030 4R7 (5.5 x 5.3 x 2.9 mm)

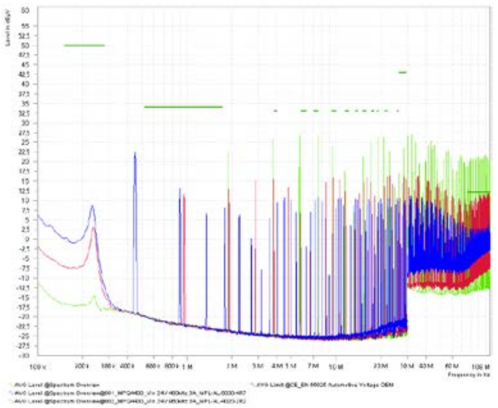
960 kHz 开关频率

- R4 = 191 kohm
- **Main Coil:** MPL-AL-4020 2R2 (4.1 x 4.1 x 1.9 mm)

1900 kHz 开关频率

- R4 = 191 kohm
- **Main Coil:** MPL-AL-4020 1R0 (4.1 x 4.1 x 1.9 mm)





1.9MHz

960kHz

450kHz

+10dB

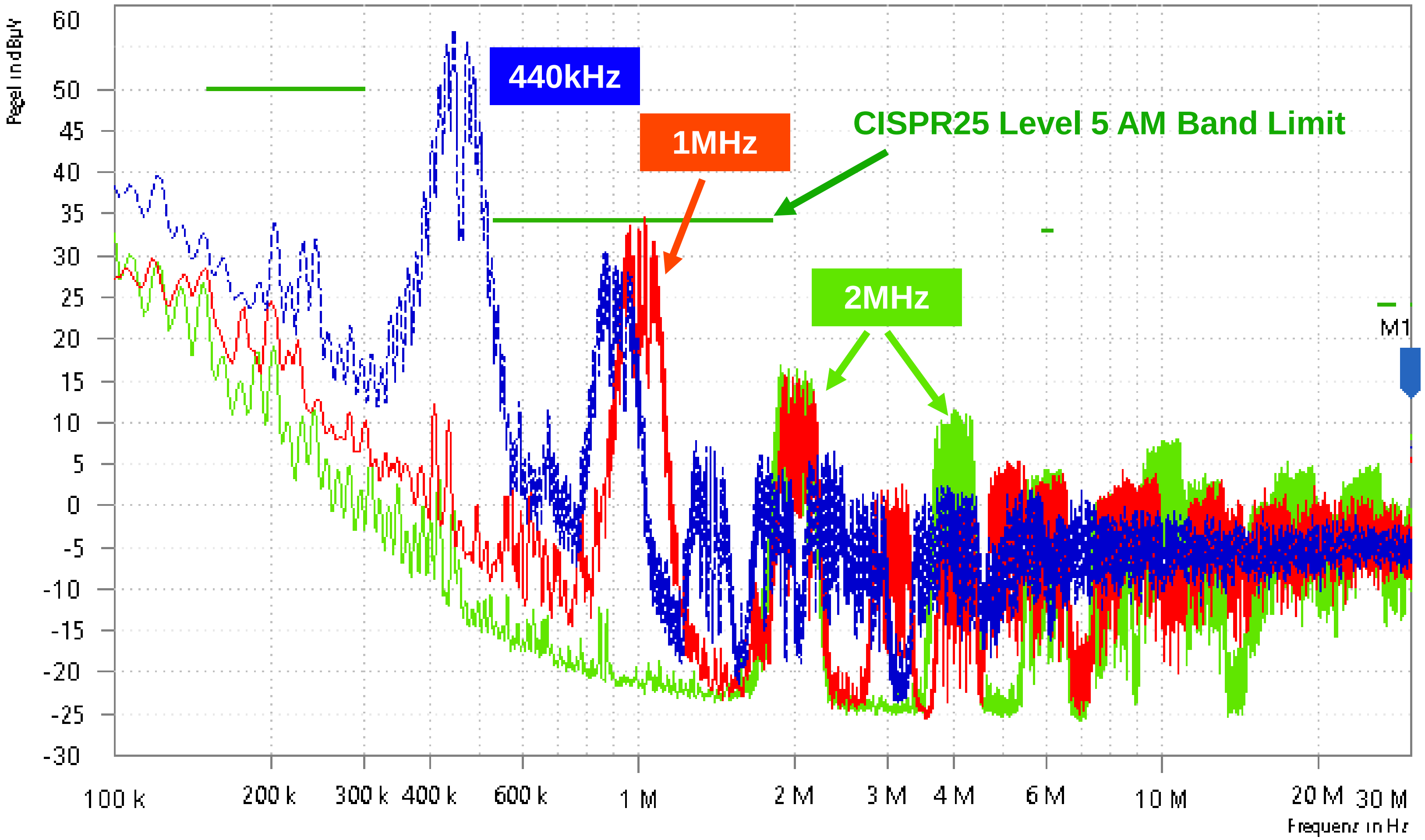
+7.5dB

抖频技术(SSFM)帮助优化电源EMI特性

Example with MPQ4313:
45V 3A Sync. Buck with SSFM + Reduced EMC Filtering

EMC Input Filter

440kHz vs 1MHz vs 2MHz – 低频段辐射发射(RE)

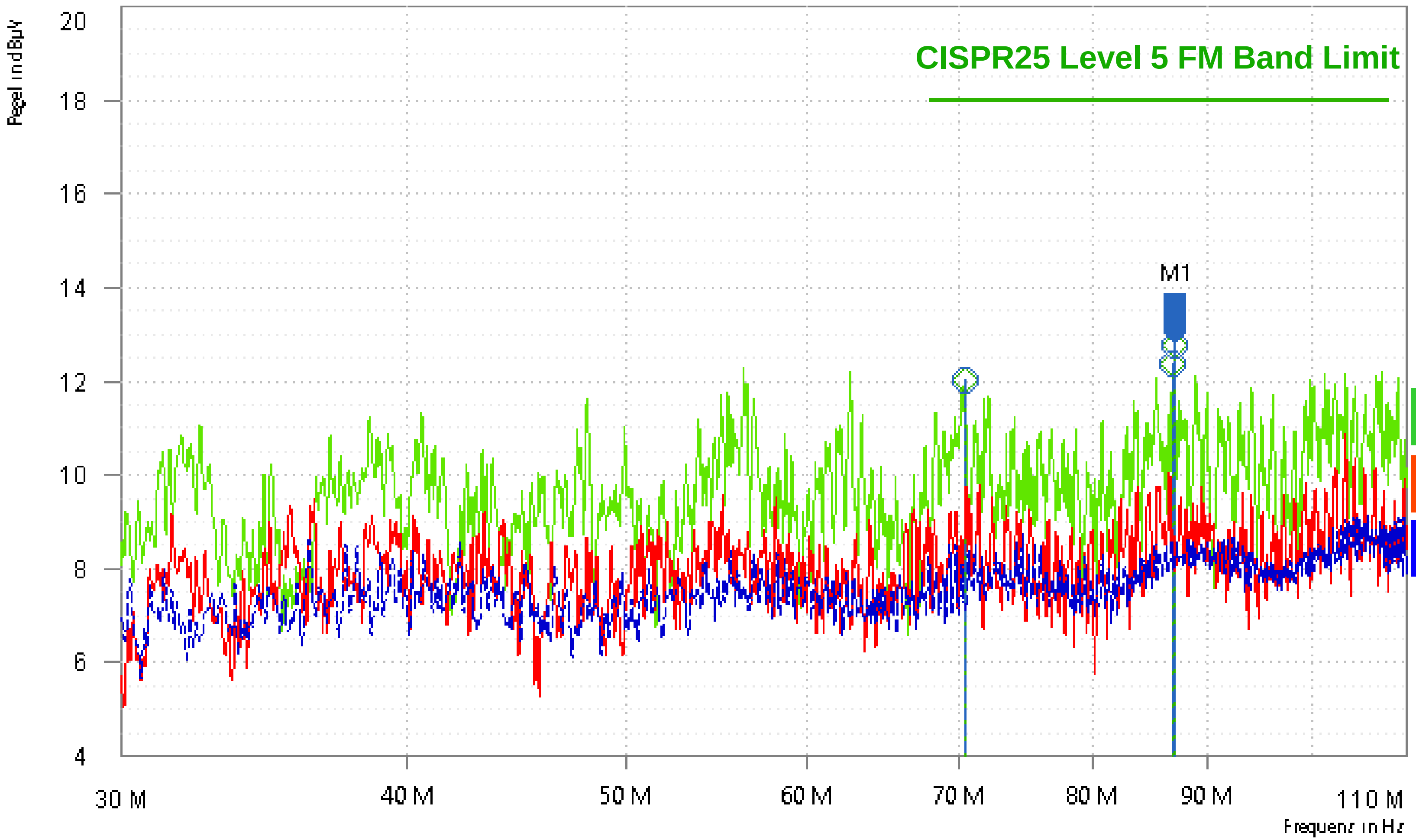


测试条件:

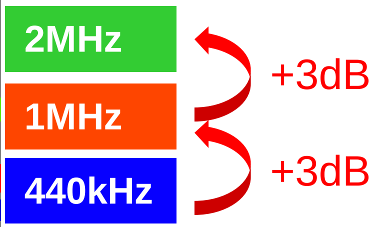
- 440kHz: IHLP2525 6.5 x 6.5 x 3mm 6.8µH 54mΩ
- 1MHz: AY5030 5 x 5 x 3mm 3.3µH 32mΩ
- 2MHz: AY4020 4 x 4 x 2mm 1.5µH 35mΩ

- Note 1MHz config needs a bit more input filter

440kHz vs 1MHz vs 2MHz – 高频段辐射发射(RE)

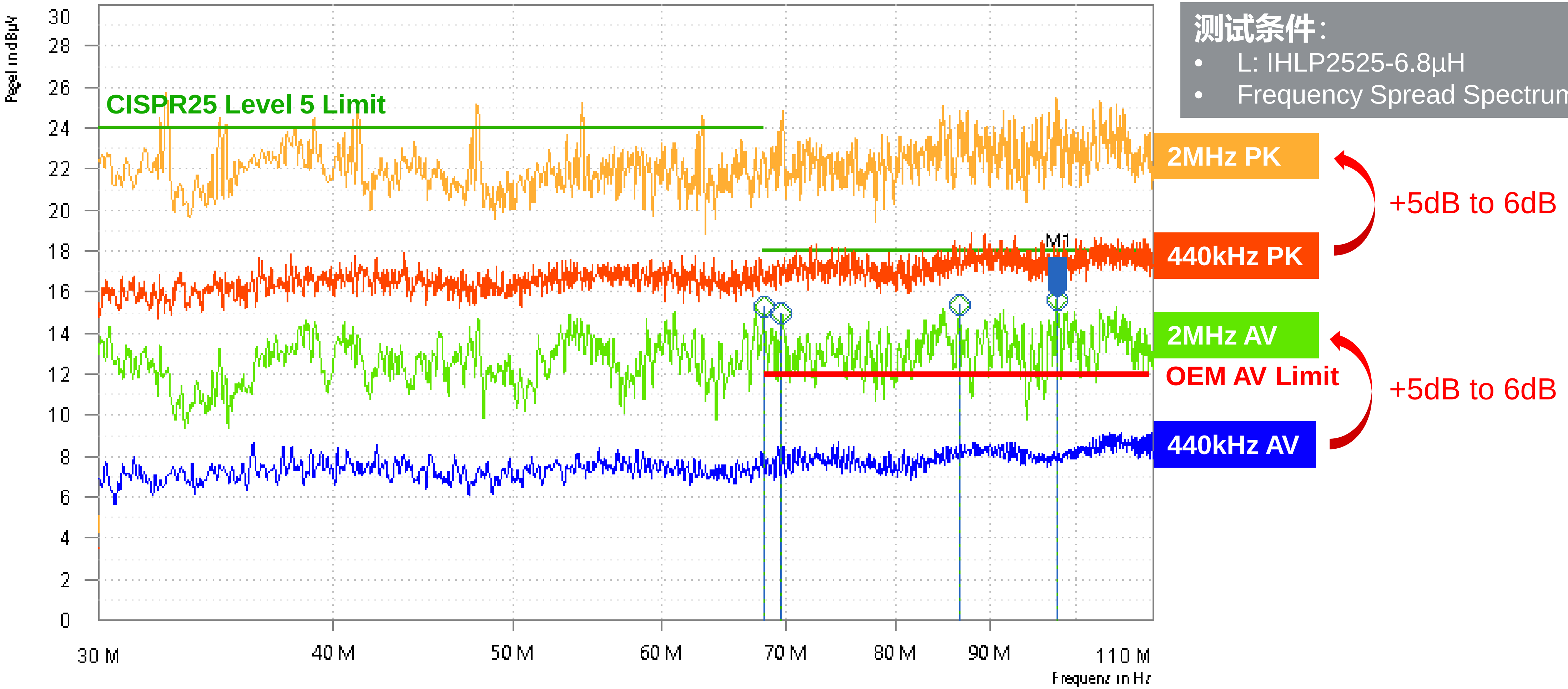


测试条件:
- 440kHz: IHLP2525 6.5 x 6.5 x 3mm 6.8µH 54mΩ
- 1MHz: AY5030 5 x 5 x 3mm 3.3µH 32mΩ
- 2MHz: AY4020 4 x 4 x 2mm 1.5µH 35mΩ



- In theory, the noise level should increase by 3dB for double F_{SW} with Spread Spectrum.
- With fixed frequency it would be an increase of 6dB.
- The increase in noise level is offset slightly as the inductor (antenna) size and height reduced also with switching frequency

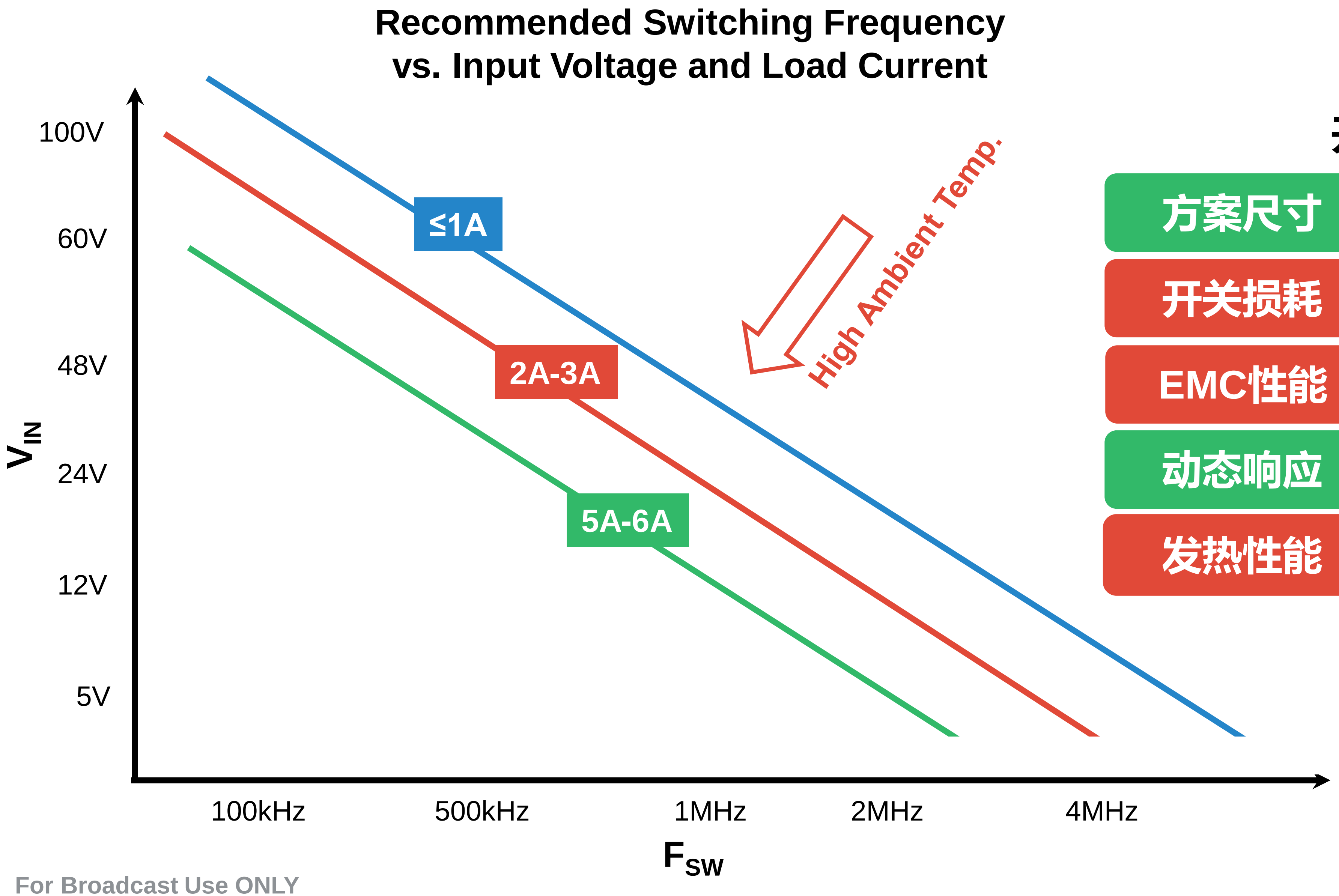
440kHz vs 2MHz – 高频段辐射发射(RE)



测试条件:
- L: IHLP2525-6.8µH
- Frequency Spread Spectrum

Note: for a deeper dive into EMC/EMI, check out our webinar, "Automotive EMI Benefits of Spread Spectrum" at monolithicpower.com/webinars

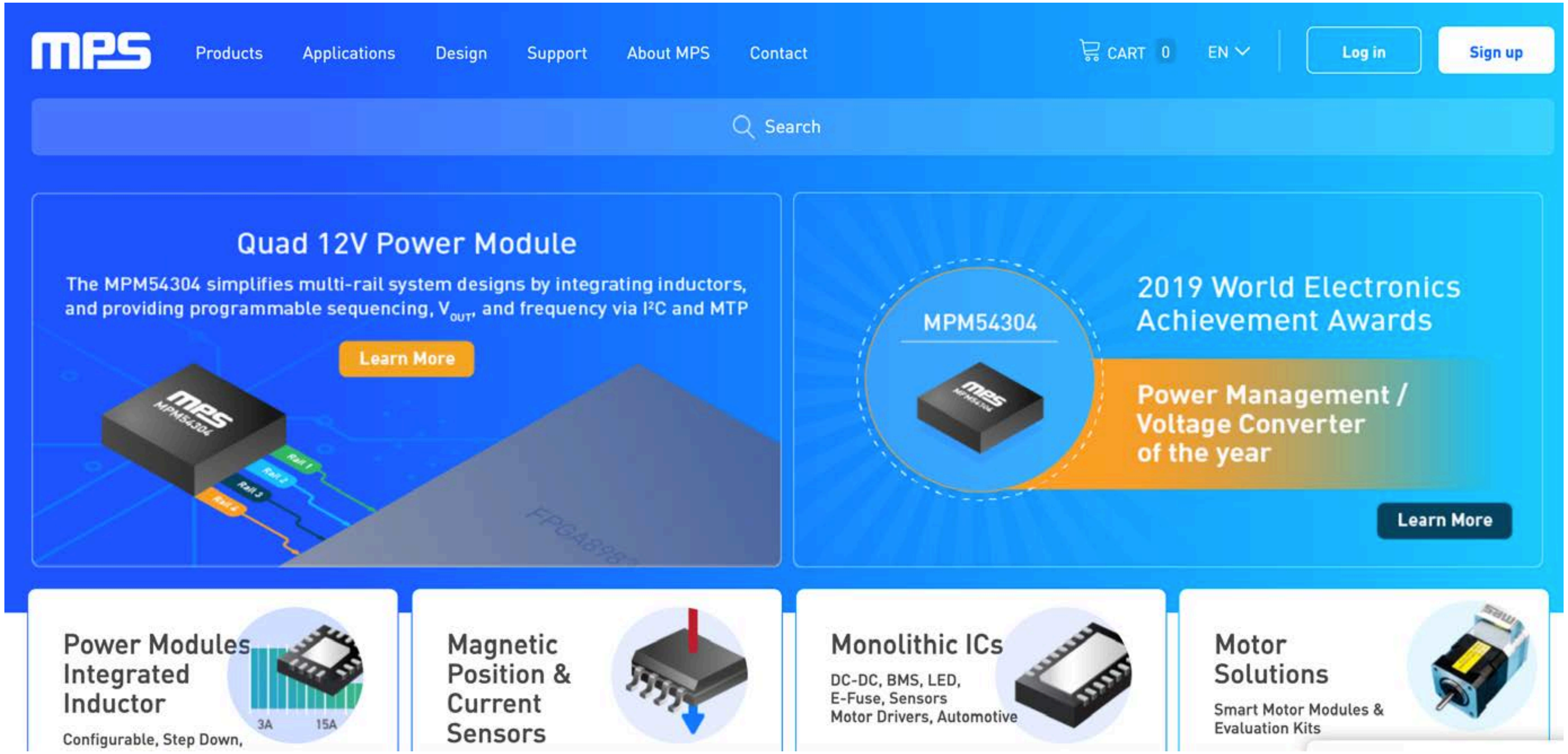
总结回顾



开关频率越高：

- 方案尺寸：更小，成本更低
- 开关损耗：随输入电压增高而增大
- EMC性能：高频段尖峰更高
- 动态响应：略有优化
- 发热性能：更热

Q&A



更多电源管理解决方案，欢迎访问： **MonolithicPower.com**