

选择最好的工具进行电源完整性测试

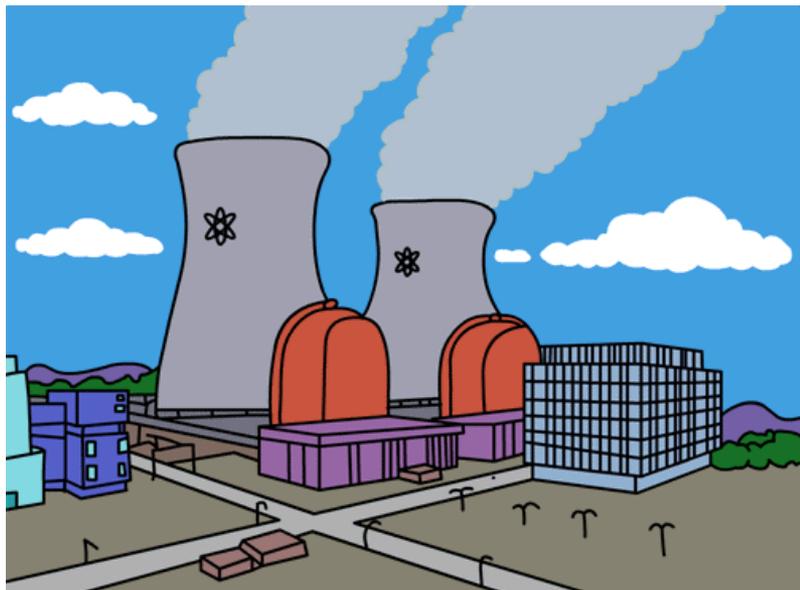
叶树栋
业务与市场拓展经理
数字测试
sandro_ye@keysight.com
186 1216 0975

2016年1月



“电源”无处不在

电源的产生 & 电源的集成



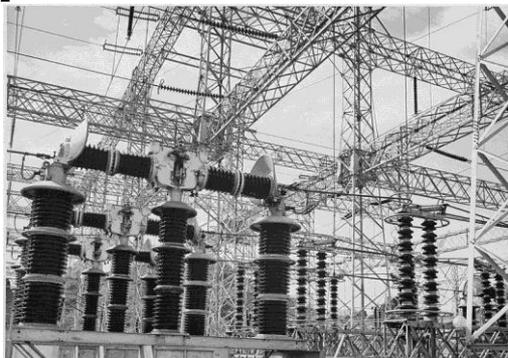
制造者：提供电源



消费者：消费电源

“电源”无处不在

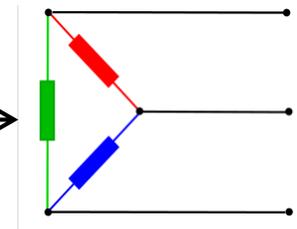
大功率



智能电网



三相



PL 逆变器

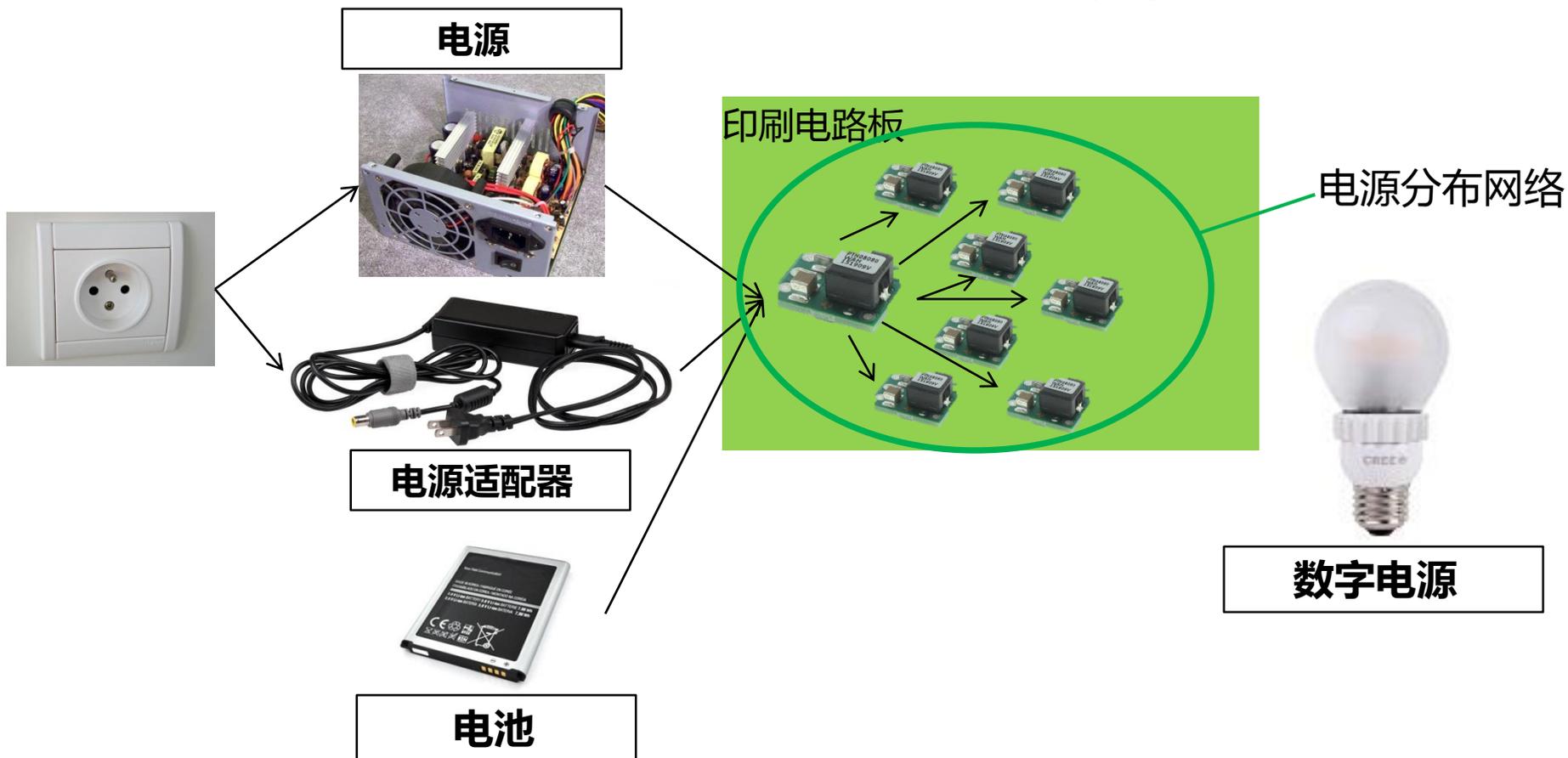


小功率

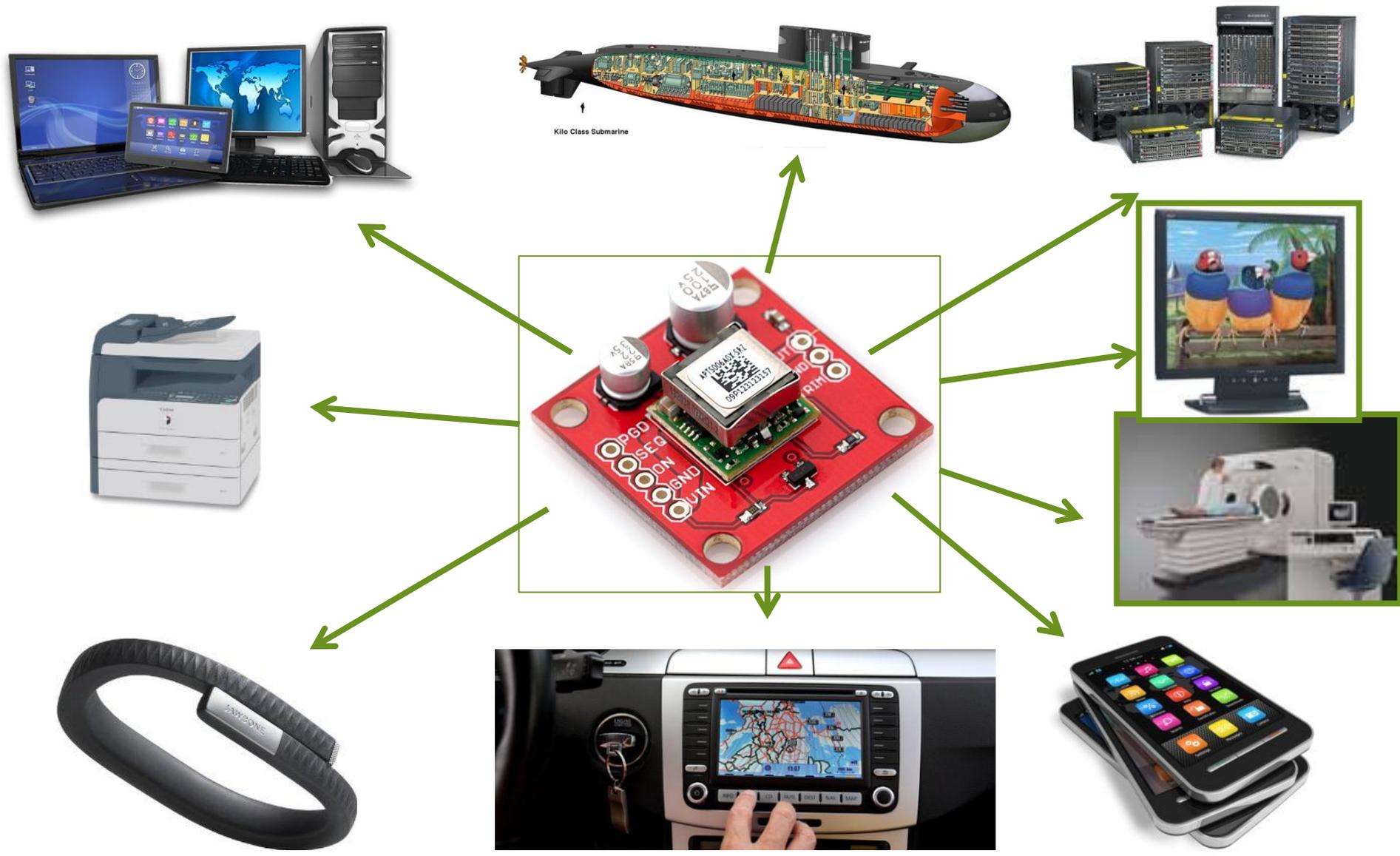
“电源”无处不在



小功率



“电源”无处不在



电源完整性与信号完整性的区别

THE DIFFERENCES BETWEEN SIGNAL INTEGRITY AND POWER INTEGRITY

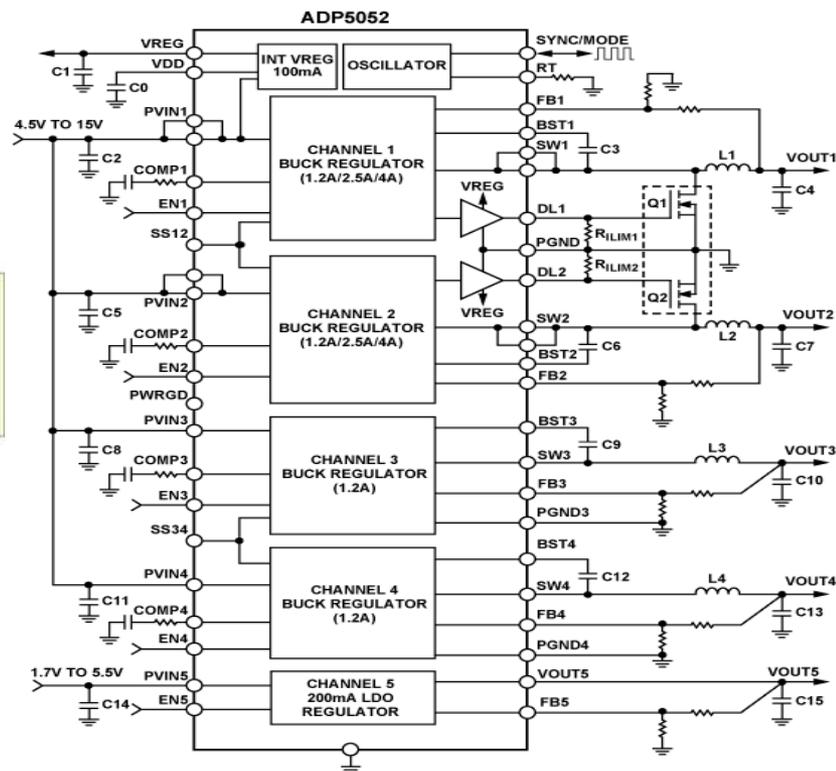
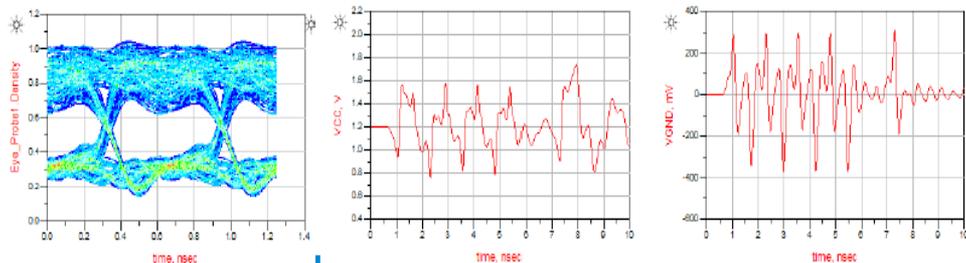
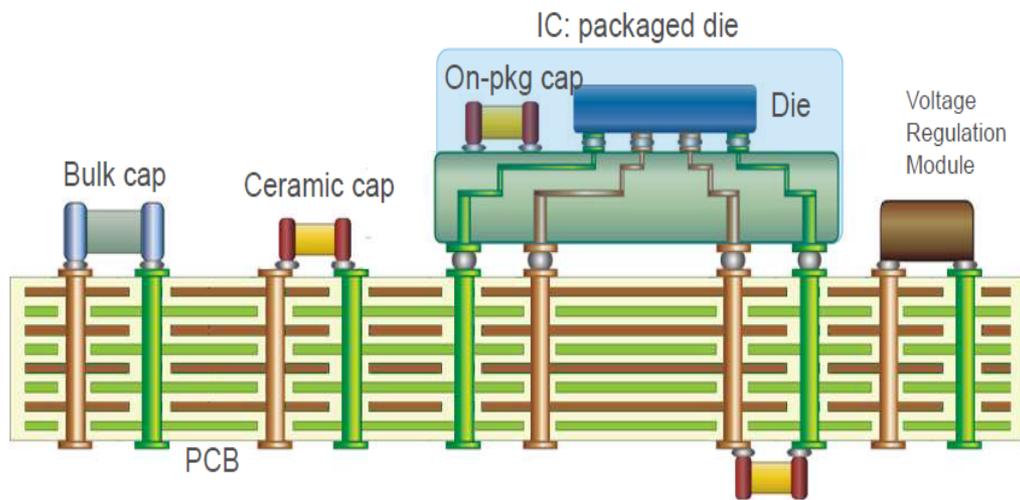
	Signal integrity	Power integrity
Became mainstream	-20 years ago	-5 years ago
Analysis based on	Transmission lines	Transmission planes
Typical impedance targets	-50 Ω	-m Ω
Subsets of analysis	Signal quality Timing Crosstalk	dc drop Decoupling Noise
Models needed	IBIS, Spice	Capacitors with parasitics
PCB design changes driven	Trace width Trace length Trace spacing	Amount of metal to carry current Number, value, mounting of caps Power/ground plane pairs, stackup

目录

- ➔ 现代电源测试的挑战
- 电源分配网络的仿真与测试
- 纹波噪声的仿真与精确测试
- 超微小信号的电压和电流测试
- 极端温度测试

更加复杂的电源设计

- 更加复杂的供电网络和电源分割
- 更大的瞬态工作电流对电源网络的阻抗提出更高要求
- 需要系统考虑电源完整性和信号完整性的互相影响

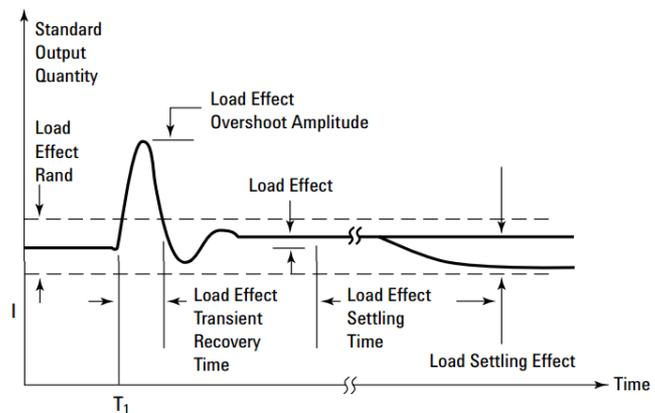
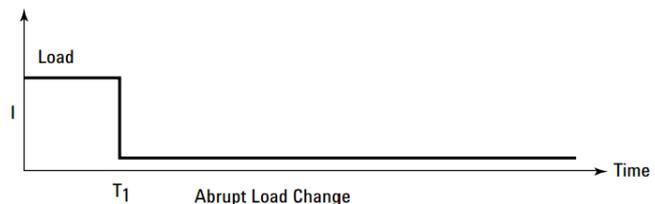
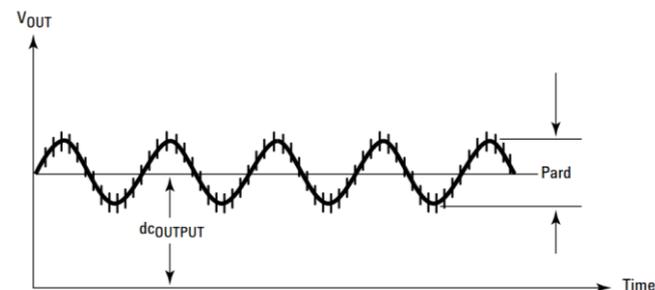


Reference :

www.Analog.com

更多的电源测试要求

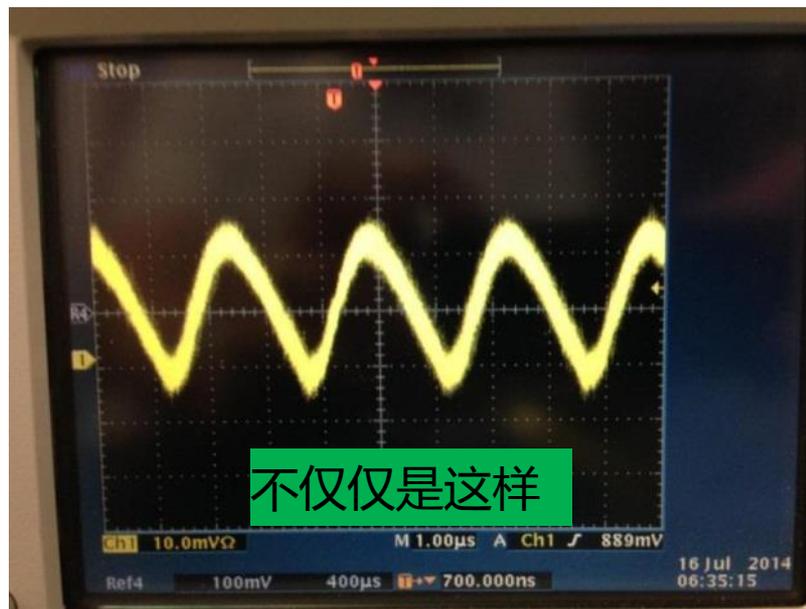
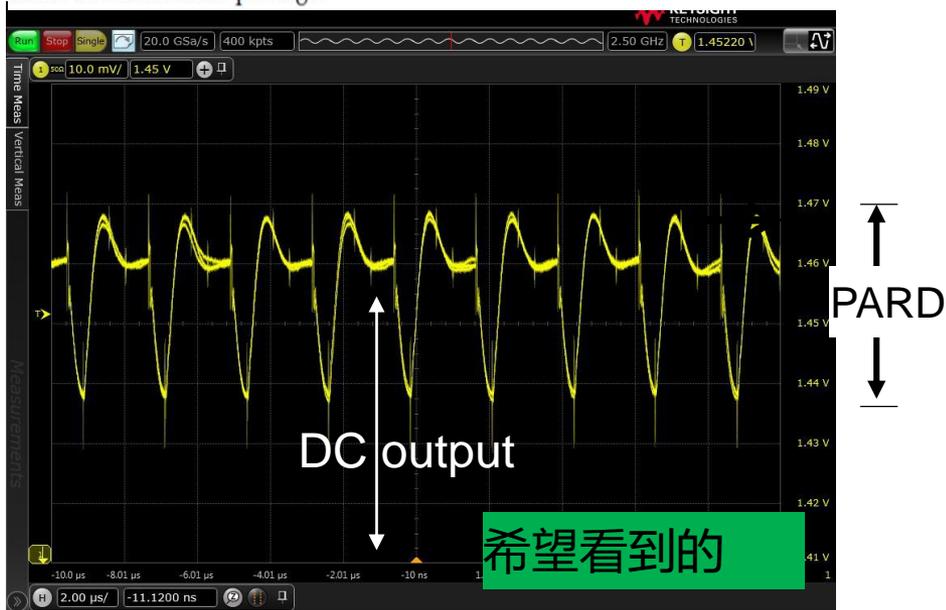
- 电源漂移
- PARD (Periodic and Random Disturbances周期和随机性干扰)——噪声, 纹波 和开关瞬态
- 静态和动态负载响应
- 可编程电源(power rail)响应
- 高频瞬态和噪声.
- 极端温度下的产品电气特性验证.



更精确的纹波、噪声测试需求

- 现代芯片采用更低工作电压，要求更低的电源纹波和噪声
- 更高的开关切换频率需要更高的测量带宽
- 需要同时观察由于负载变化造成电压漂移、跌落

While the PCB capacitors are not needed for proper operation of the transceivers, however, proper filtering can be required on the PCB to achieve the input voltage ripple noise specification of 10 mV peak-to-peak (10 kHz to 80 MHz) when measured at the BGA ball of the package.



大量产品需要进行电源瞬变的抗扰度测试

电源瞬变测试：在实验室模拟实际现场可能会发生的电压波动，对产品进行“抗干扰”性能评估，确保产品能够在实际环境中正常工作及性能。

等级	在施加骚扰期间	在施加骚扰之后
一级	能执行其预先设计的所有功能	
二级	有一项或多项指标超出规定的偏差	自动恢复到正常工作范围内
三级	不执行其预先设计的一项或多项功能	能自动恢复到正常操作状态
四级	不执行其预先设计的一项或多项功能	需要通过简单的“操作或使用”复位动作，才能自动恢复到正常操作状态
五级	不执行其预先设计的一项或多项功能	如果不修理或不替换装置或系统，则不能恢复其正常操作。



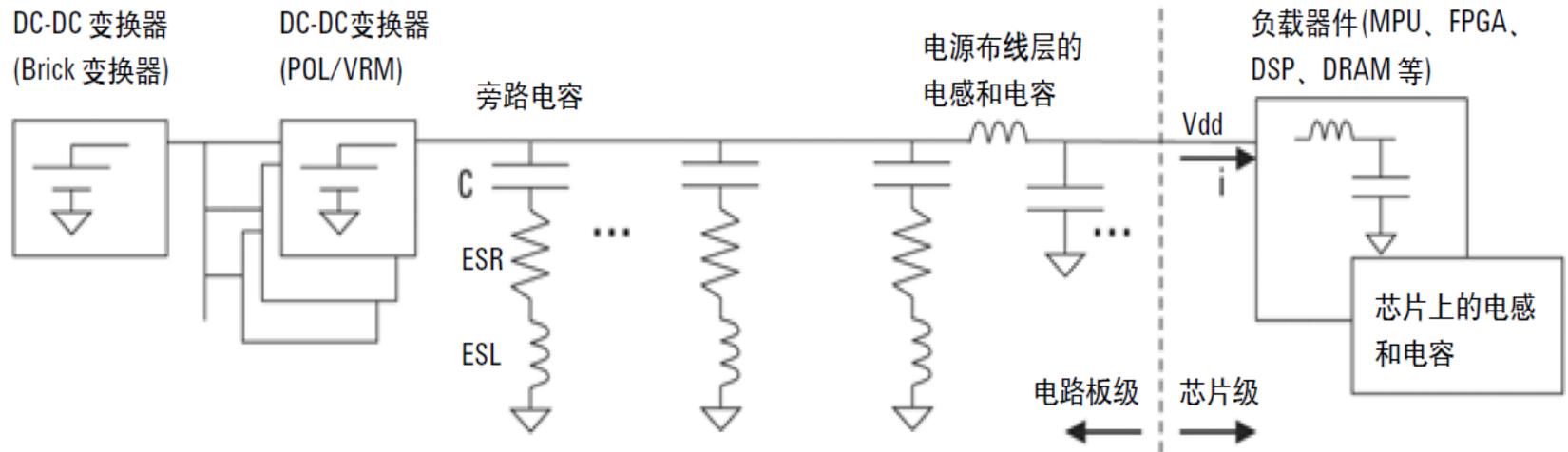
目录

现代电源测试的挑战

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- 纹波噪声的仿真与精确测试
- 超微小信号的电压和电流测试
- 电源抗干扰能力测试
- 开关电源的性能测试

典型的电源供电网络 (PDN)

PDN (Power Distritution Network) 通常包括电压变换器、PCB板电源布线层 (包括连接器、过孔、走线)、无源滤波网络 (包括储能电容、去耦电容、片上电容、滤波电感等)。



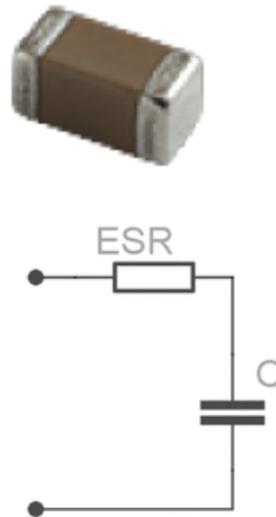
为使DC-DC 变换器能对大规模集成电路的负载变化作出快速响应，降低由于较大负载电流的变化造成的供电电压的瞬时波动，验证PDN网络的阻抗是否被限制在极低范围内是非常必要的。

PDN网络阻抗对于纹波噪声的影响

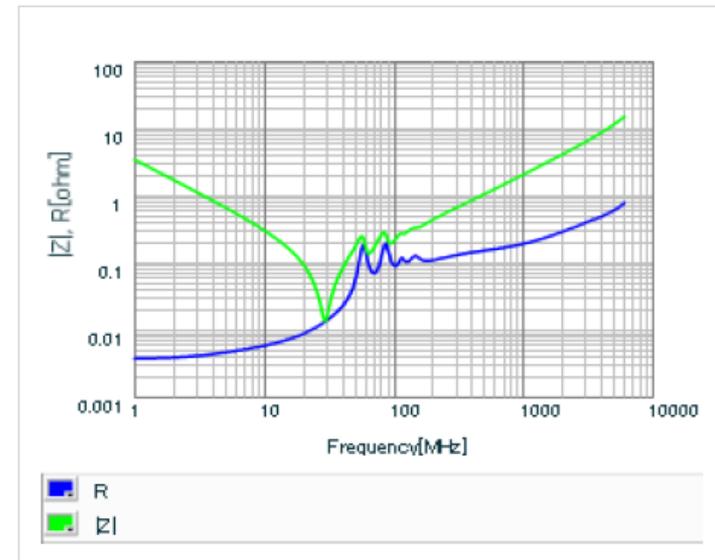
举例：供电电压为1V，允许的纹波噪声或者电压偏移为5%，电流变化范围为5A，则PDN的阻抗要求为：

$$Z_{\text{TARGET}} = \frac{1.0 \text{ V} \times 0.05}{5 \text{ A}} = 10 \text{ m}\Omega$$

Capacitance	47000pF ±5%
Rated voltage	50Vdc
Temperature characteristics (complied standard)	UJ(JIS)
Temperature coefficient	-750±120ppm/°C
Temperature range of temperature characteristics	20 to 85°C
Operating temperature range	-25 to 85°C



Frequency characteristics (ESR, Impedance)



如何优化在不同频率下的PDN阻抗

STEP 1

Establishing target impedance

$$Z_T = \frac{\Delta V}{\Delta I}$$

ΔV : Maximum allowable ripple voltage
 ΔI : Current Fluctuation (rated current when unknown)

STEP 2

Establishing maximum frequency f_T for IC power supply terminal
 100MHz when unknown

STEP 3

Establishing bulk capacitor capacitance

$$C_{bulk} \geq \frac{L_{Power}}{Z_T^2}$$

STEP 4

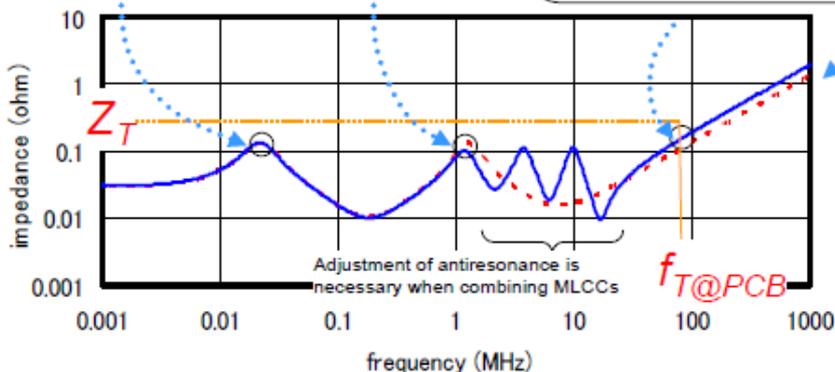
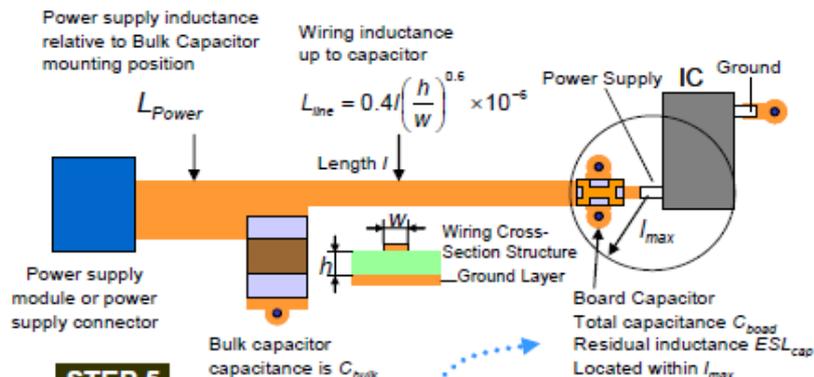
Establishing board capacitor capacitance

$$C_{board} \geq \frac{L_{bulk}}{Z_T^2}$$

STEP 5

Board capacitor is selected and placed taking maximum allowable wiring length l_{max} into consideration

$$l_{max} \approx 0.4 \frac{Z_T - 2\pi f_{T@PCB} ESL_{cap}}{f_{T@PCB} \left(\frac{h}{W}\right)^{0.5}} \times 10^5$$



Dashed line: When using one low-ESL capacitor for board capacitor

Placing a capacitor with capacitance more than C_{board} within l_{max}

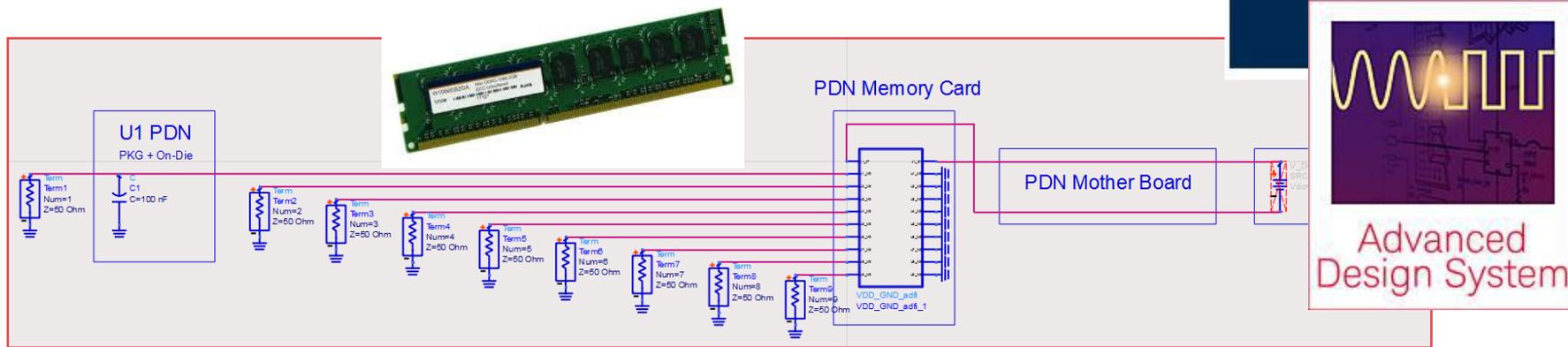
Solid line: When using a combination of MLCCs for board capacitor

When l_{max} does not exist for one capacitor, reducing ESL_{cap} by combining multiple capacitors, and enlarging l_{max} may be necessary. Total capacitance must be over C_{board} .
 Combination of capacitance is adjusted to keep antiresonance.

Figure8-20 An example of capacitor design to achieve target impedance and Decoupling for Digital ICs

借助ADS仿真软件进行PDN阻抗分析

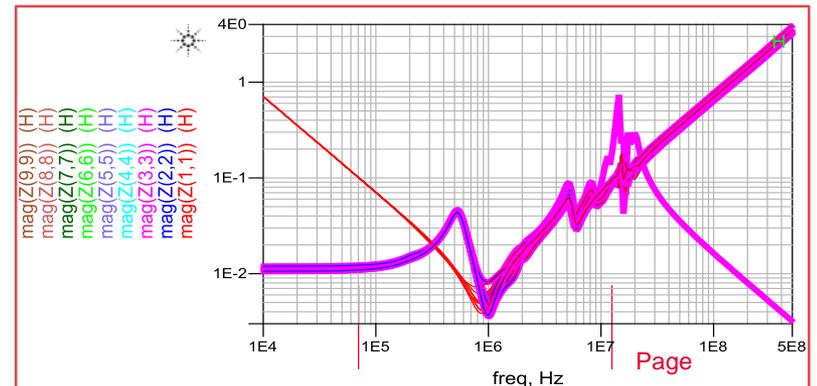
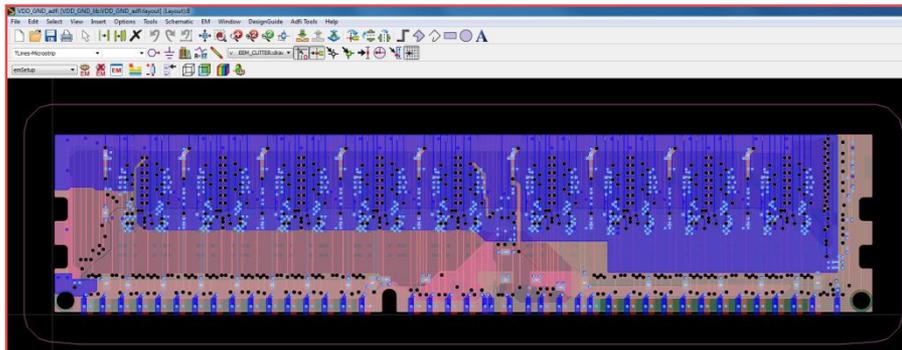
The behavior below 1 MHz is driven by the VRM and bulk capacitors on the PDN of the mother board. In the 100 KHz to 100 MHz range, the board level PDN design with decoupling capacitors will come into play. From 10 MHz, you need to take the package and on-die PDN into account.



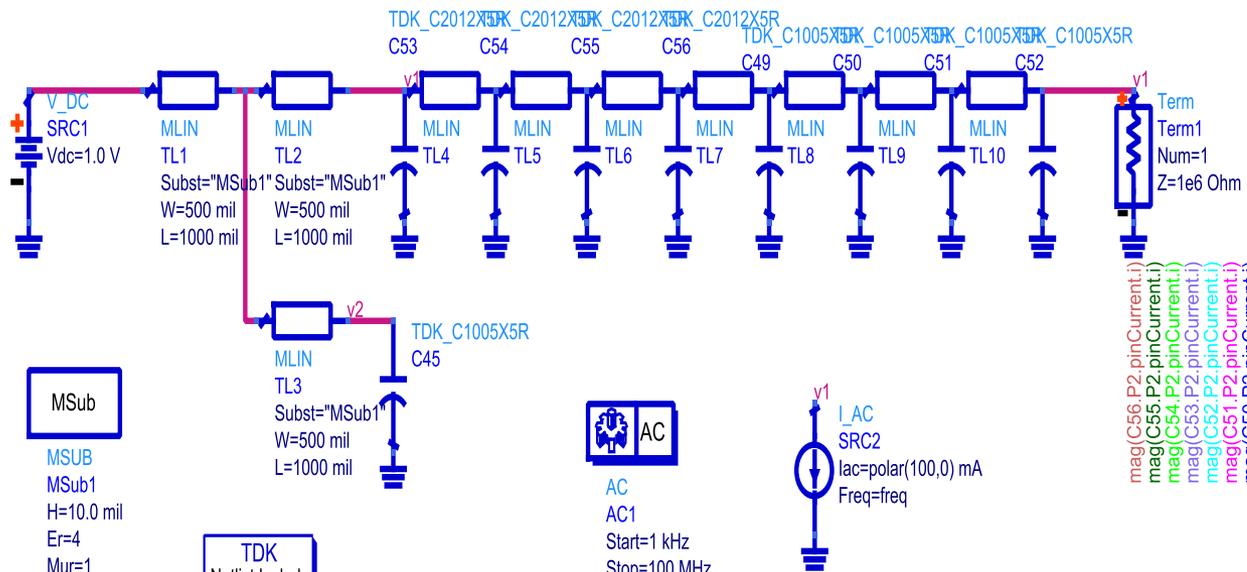
Select the nets and components of interest, define Ports, export to ADS



PDN Impedance Profile



用ADS软件进行PDN阻抗计算和电容优化



MSub

MSUB
 MSub1
 H=10.0 mil
 Er=4
 Mur=1
 Cond=5.8e7
 Hu=3.9e+034 mil
 T=18 um
 TanD=0.02
 Rough=0 mil
 Bbase=
 Dpeaks=

TDK

Netlist Include
 TDK_Netlist_Include
 TDK_NetlistInclude

S-PARAMETERS

S_Param
 SP1
 Start=1 kHz
 Stop=0.1 GHz
 Step=

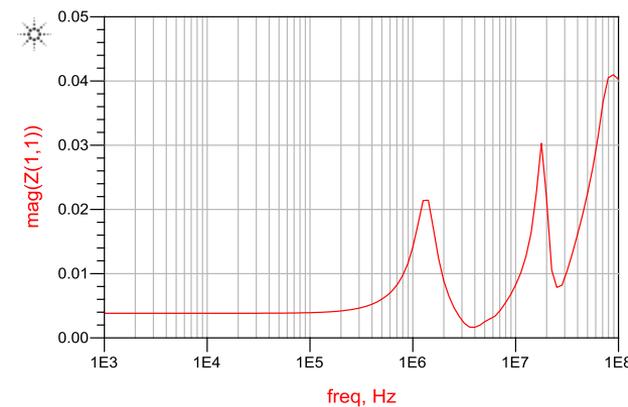
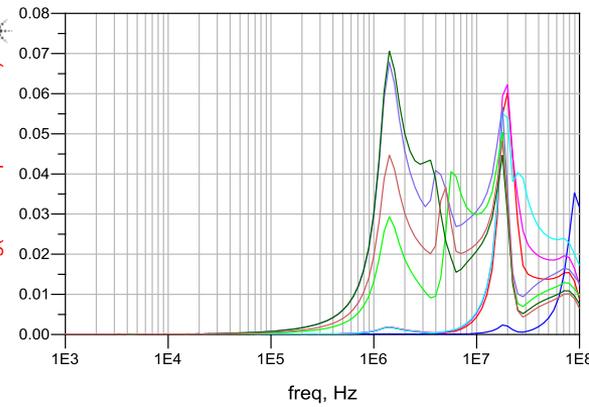
AC

AC1
 Start=1 kHz
 Stop=100 MHz
 Step=

I_LAC SRC2

Iac=polar(100,0) mA
 Freq=freq

mag(C56.P2.pinCurrent.i)
 mag(C55.P2.pinCurrent.i)
 mag(C54.P2.pinCurrent.i)
 mag(C53.P2.pinCurrent.i)
 mag(C52.P2.pinCurrent.i)
 mag(C51.P2.pinCurrent.i)
 mag(C50.P2.pinCurrent.i)
 mag(C49.P2.pinCurrent.i)



~~OPTIM~~

Optim
 Optim1
 SaveAllTrials=no

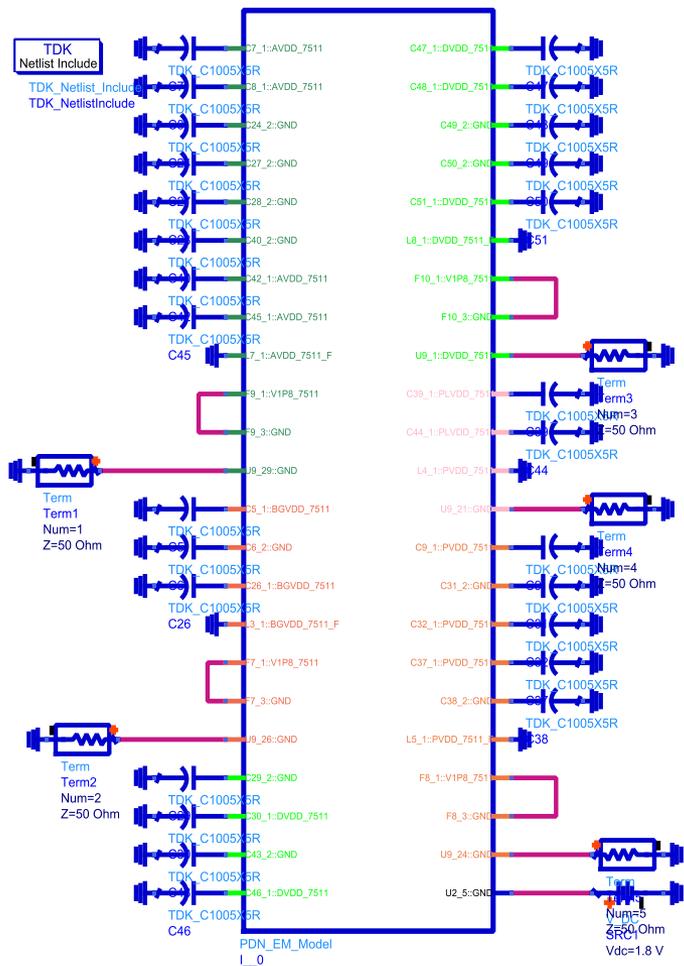
~~GOAL~~

Goal
 OptimGoal1
 Expr="mag(Z11)"
 SimInstanceName="SP1"
 Weight=1

~~GOAL~~

Goal
 OptimGoal2
 Expr="mag(Z11)"
 SimInstanceName="SP1"
 Weight=1

用ADS软件进行去耦电容的优化设计



OPTIM

Optim
Optim1
SaveAllTrials=no

GOAL

Goal
OptimGoal1
Expr="mag(Z11)"
SimInstanceName="SP1"
Weight=1.0

GOAL

Goal
OptimGoal2
Expr="mag(Z22)"
SimInstanceName="SP1"
Weight=1.0

GOAL

Goal
OptimGoal3
Expr="mag(Z33)"
SimInstanceName="SP1"
Weight=1.0

GOAL

Goal
OptimGoal4
Expr="mag(Z44)"
SimInstanceName="SP1"
Weight=1.0

GOAL

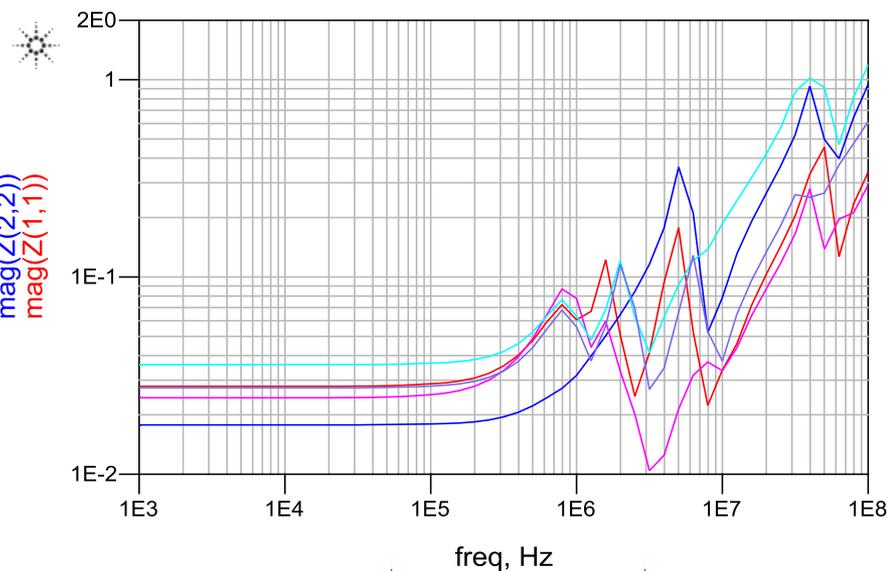
Goal
OptimGoal5
Expr="mag(Z55)"
SimInstanceName="SP1"
Weight=1.0

S-PARAMETERS

S_Param
SP1
Start=1 kHz
Stop=100 MHz
Step=

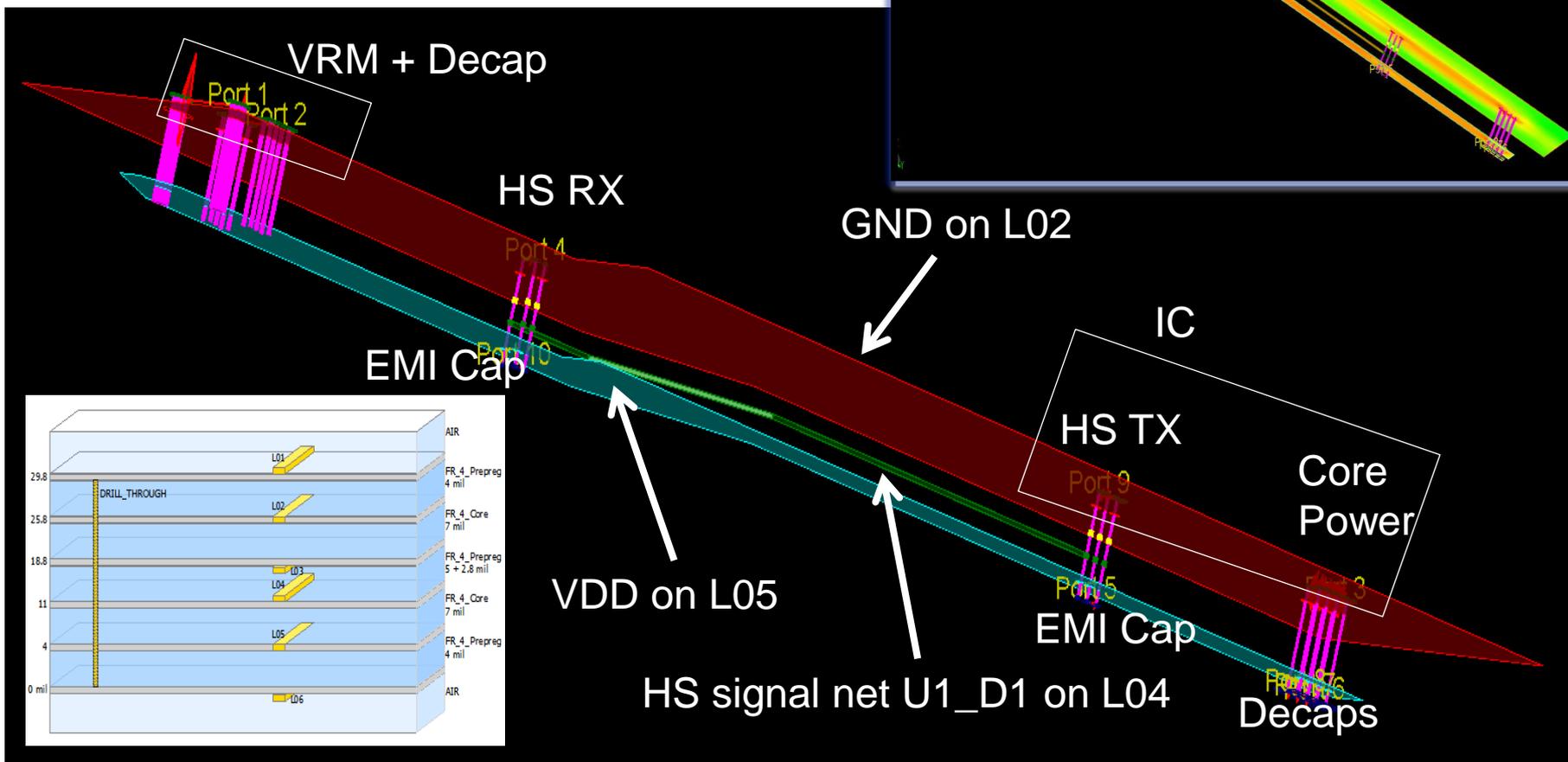
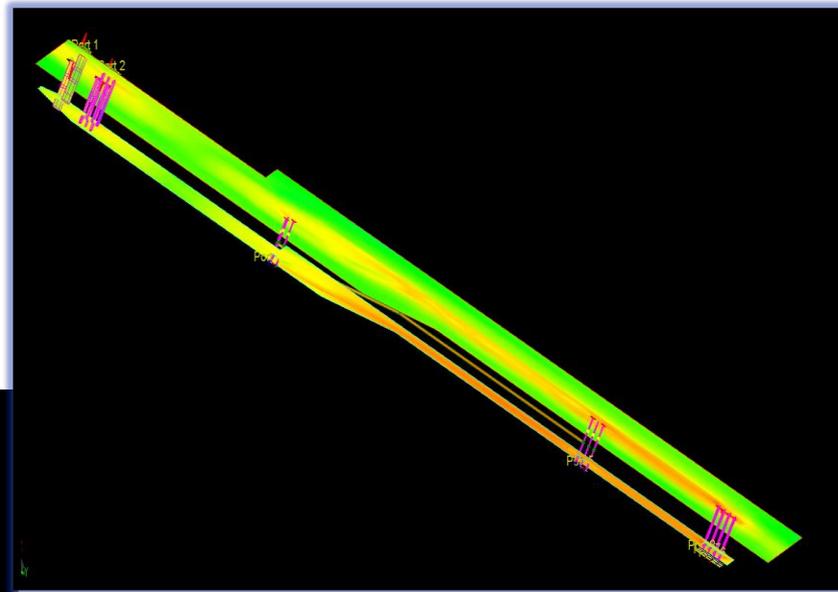
AVDD:23mA->1.2 Ohm
BGVDD:5mA -> 20Ohm
DVDD:97mA->0.3 Ohm
PLVDD:22mA->1.2 Ohm
PVDD:5mA->2 Ohm

mag(Z(5,5))
mag(Z(4,4))
mag(Z(3,3))
mag(Z(2,2))
mag(Z(1,1))



用ADS进行信号电流路径分析

Use the EM Excitation Add-on to look at the surface currents around 270 MHz...



电源器件的I-V曲线测试和IBIS建模

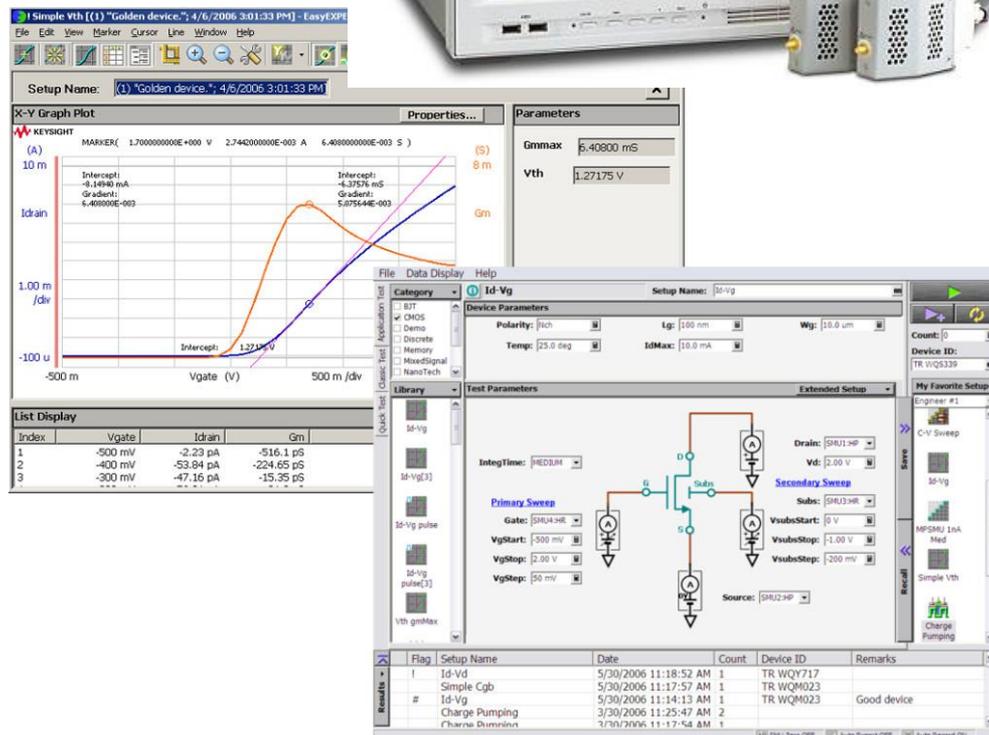
B1500半导体参数分析仪

-测量功能

-在 0.1 fA - 1 A / 0.5 μ V - 200 V 范围内执行精确的电流-电压 (IV) 测量，支持点测量、扫描测量、采样和脉冲测量

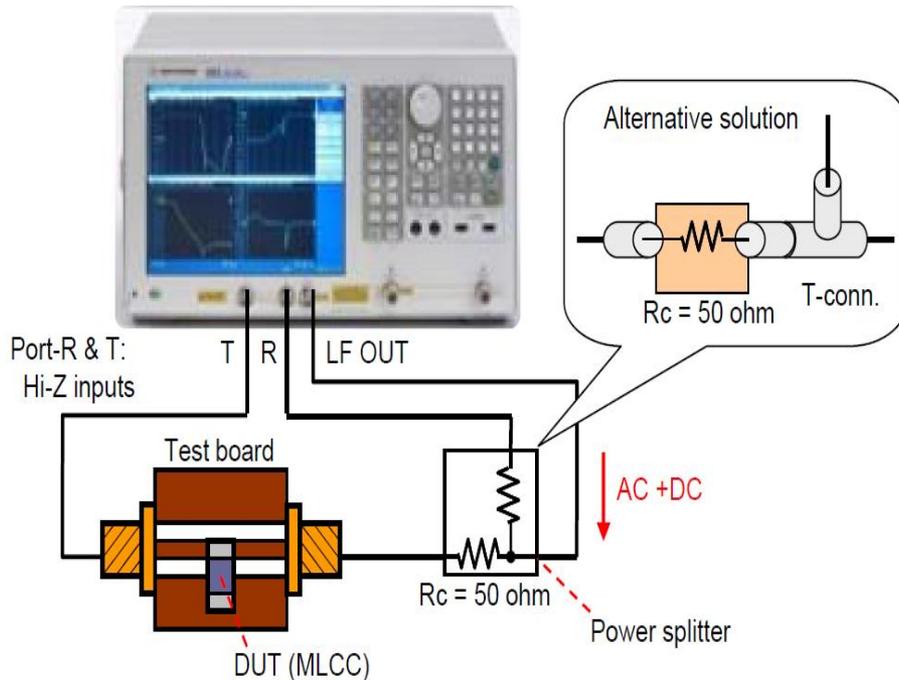
-在 1 kHz 至 5 MHz 频率范围内执行交流电容测量，支持准静态电容-电压 (QS-CV) 测量

-先进的脉冲 IV 测量和超快 IV 测量，最低采样间隔为 5 ns (200 MSa/s)

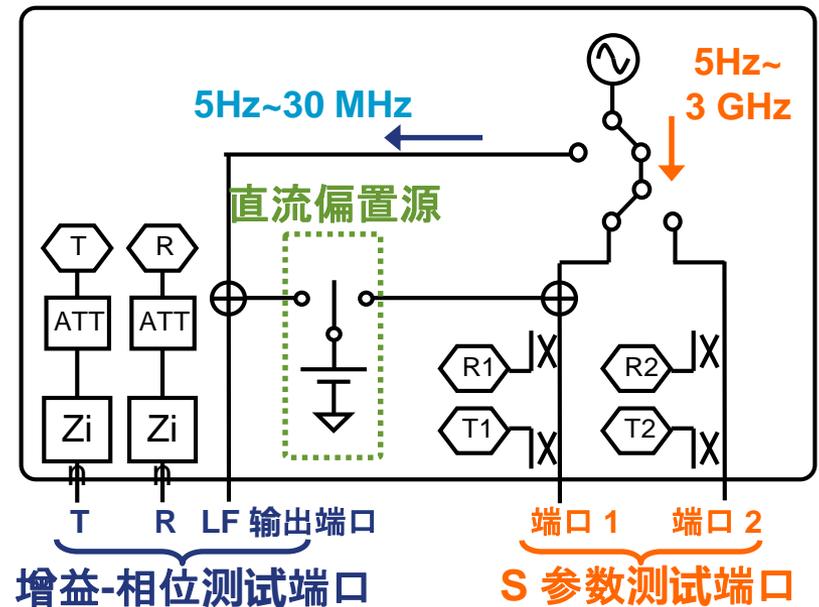


电源器件的S参数测试建模

E5061B 矢量网络分析仪



E5061B-3L5简化结构框图



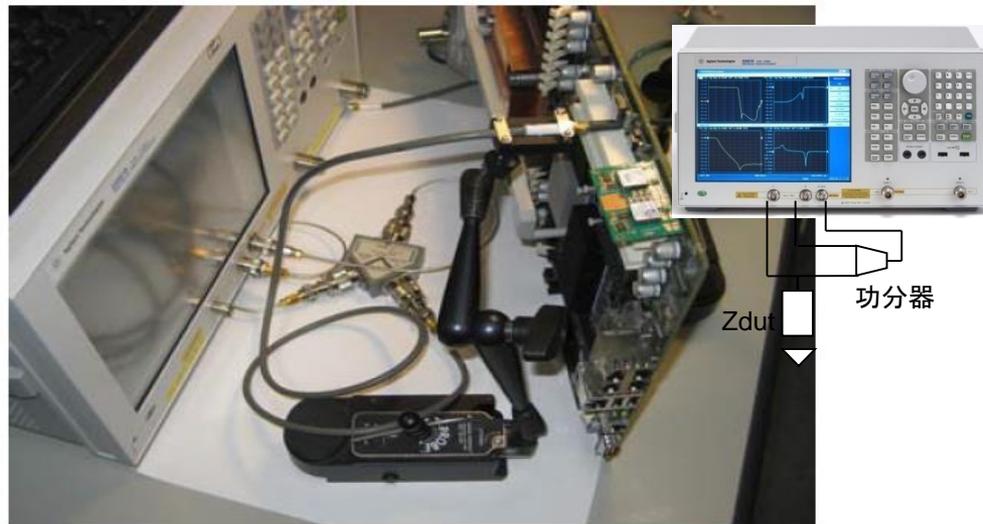
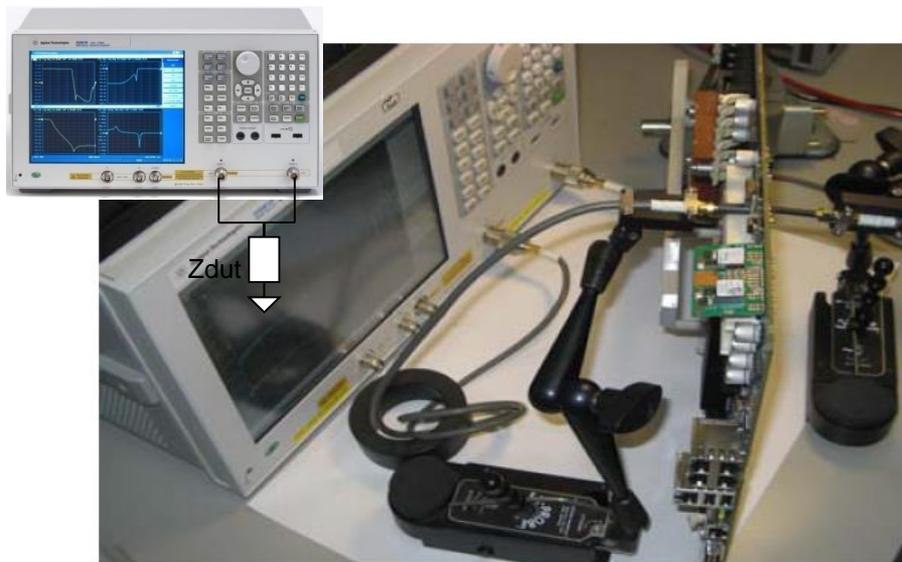
S 参数测试端口 : 5 Hz 至 3 GHz

增益相位测试端口 : 5 Hz 至 30 MHz ; 1M Ω /50 Ω 输入 ; 精确的毫欧和高衰减测量

内置直流偏置源 : 高达 +-40 Vdc (最大电流 100 mA_{dc}) ; 交流+直流输出

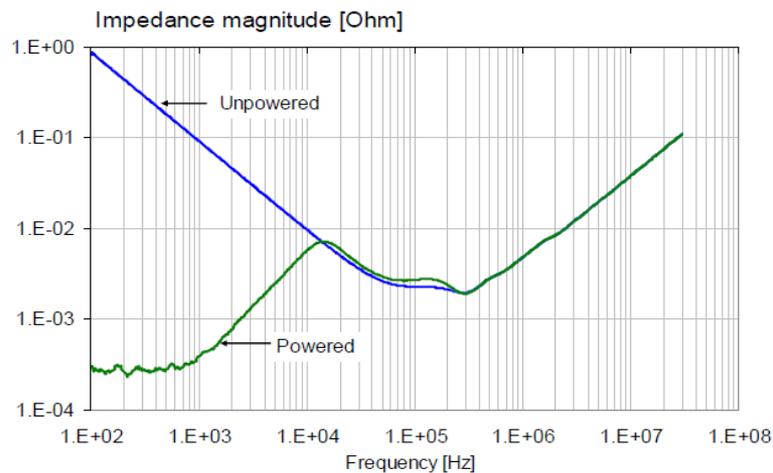
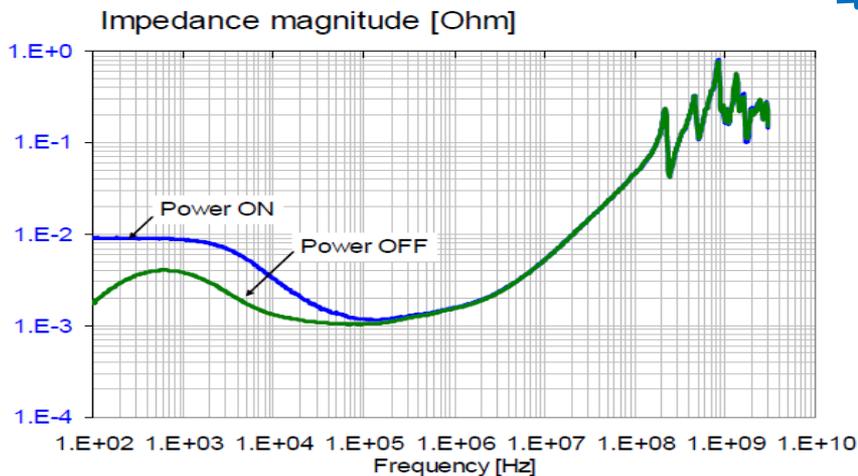
阻抗分析功能 (选件 005) : 绘制阻抗参数 ; 用于测试夹具的校准/补偿功能 ; 等效电路分析

系统级PDN阻抗和S参数测试



S参数法:在 S 参数端口上测试供电电路到 3GHz 范围内的 S21 参数。

增益-相位法:在增益-相位端口上的动态范围到低频频段仍然很高, 适用于测试毫欧级的阻抗。



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➔ 纹波噪声的仿真与精确测试

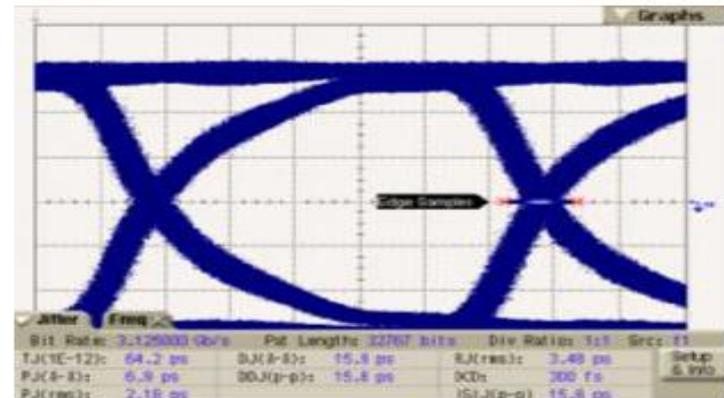
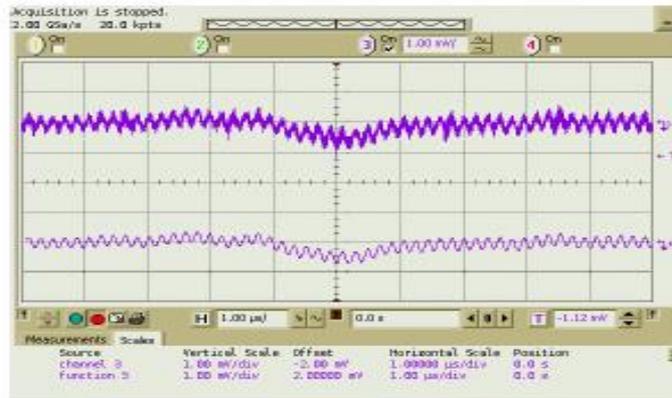
超微小信号的电压和电流测试

电源抗干扰能力测试

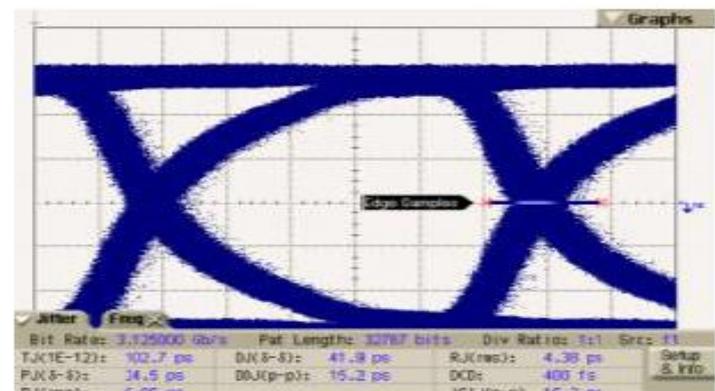
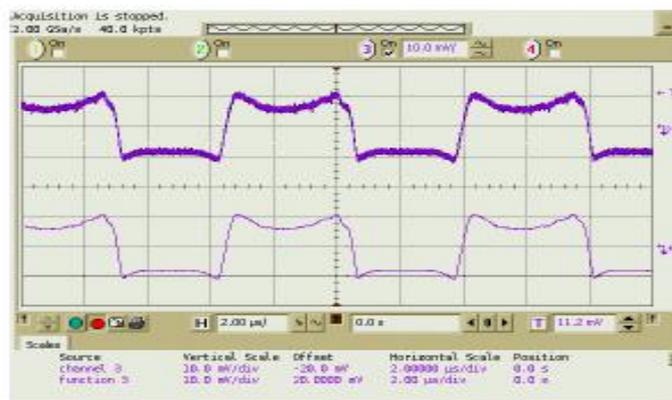
开关电源的性能测试

电源纹波对于高速信号质量的影响

‘GOOD’ switching supply <5mV pk-pk noise ~ 0.2UI jitter



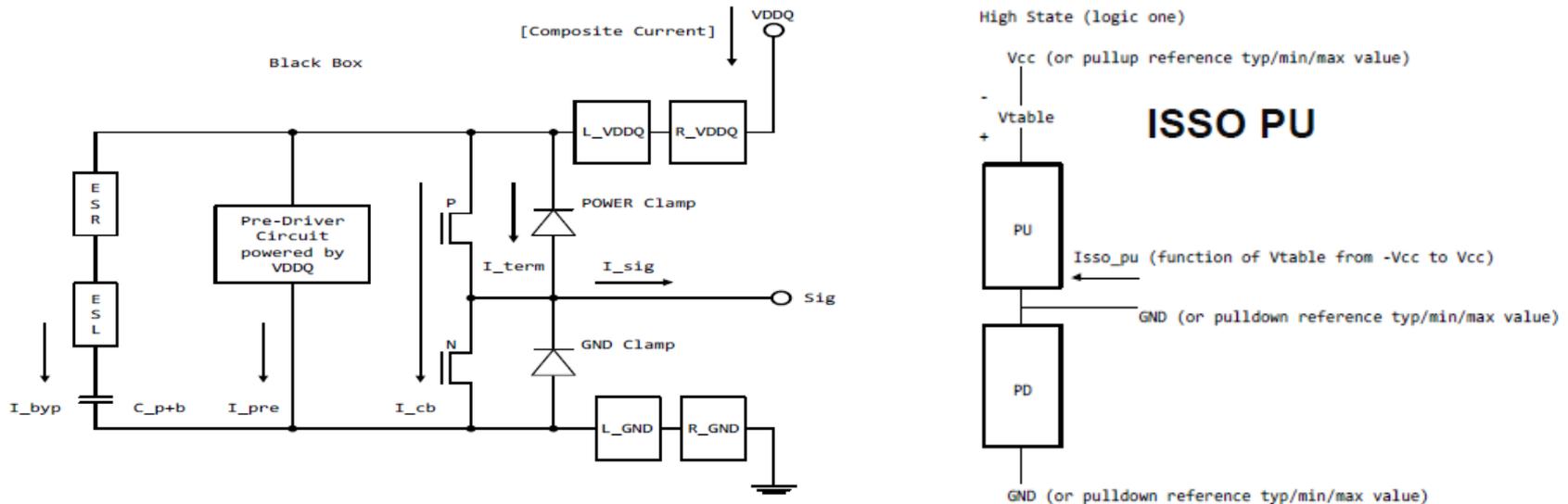
‘BAD’ switching supply ~20mV pk-pk noise >>> 0.32UI jitter



Reference : www.Xilinx.com © Copyright 2013 Xilinx
The Do's and Don'ts of High Speed Serial Design in FPGAs
High Speed Digital Design & Validation Seminars 2013

电源纹波噪声的仿真需求和信号仿真结合

IBIS 5.0规范对于SI-PI联合仿真的支持



BIRD 95.6 Power Integrity Analysis using IBIS

- Models VCC currents under specific loading conditions

BIRD 98.3 Gate Modulation Effect (table format)

- Models output impedance variation as a function of VCC voltage

BIRD 76.1 (v4.0) Additional Information Related to C_comp Refinements

- Models as IO pad capacitance to VCC and GND separately

新的S参数文件格式对电源仿真的支持

Touchstone v2.0 offers several accuracy improvements relative to Touchstone v1.0 format :

- ❖ Per port reference impedances in v2.0 format.
- ❖ This allows one to have data/address nets as well as power and ground nets in the same file (SI-PI model) with better accuracy.
- ❖ We normalize power nets to 100mOhm and signal nets to 50 ohms within same S-parameter model file.

[Version] 2.0

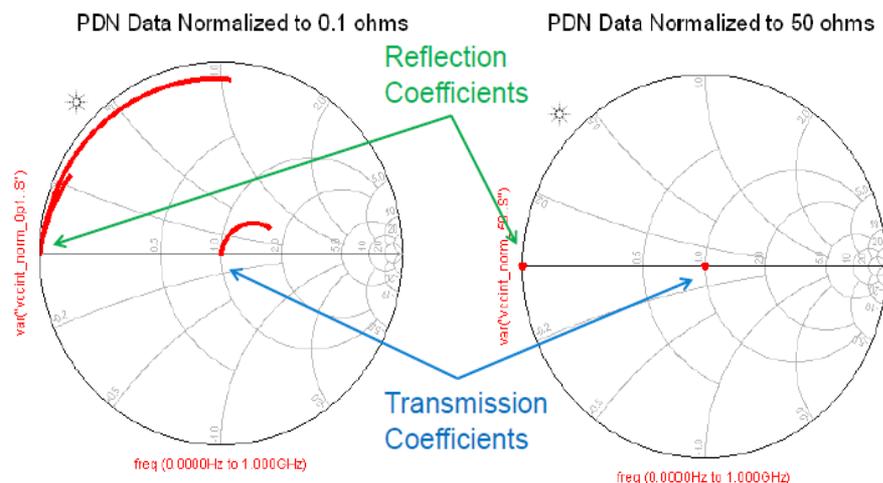
GHz S M A R 50

[Number of Ports] 4

[Reference]

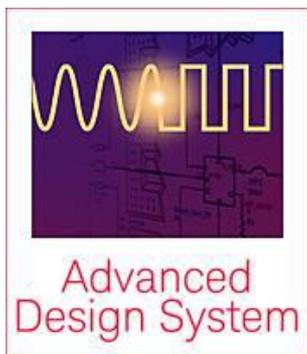
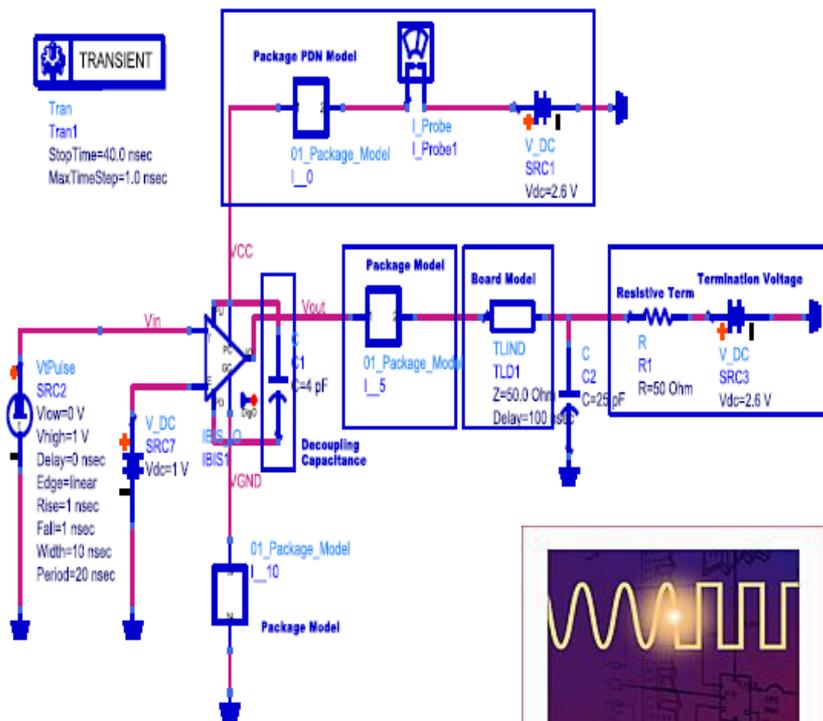
50 50 0.01 0.01

[Number of Frequencies] 50

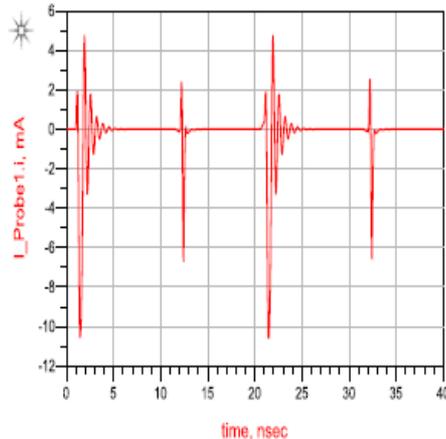


在ADS里进行SI-PI的联合仿真

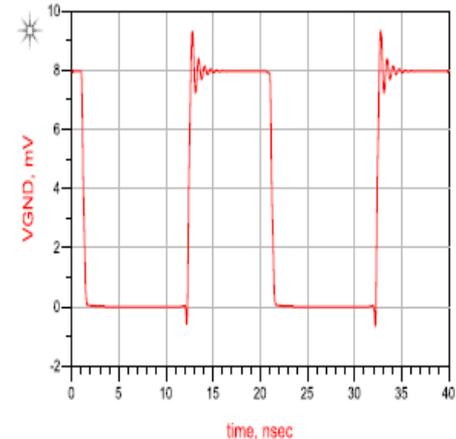
\examples\HSD\IBIS_PowerBird_9598
Support_wrk.7zads



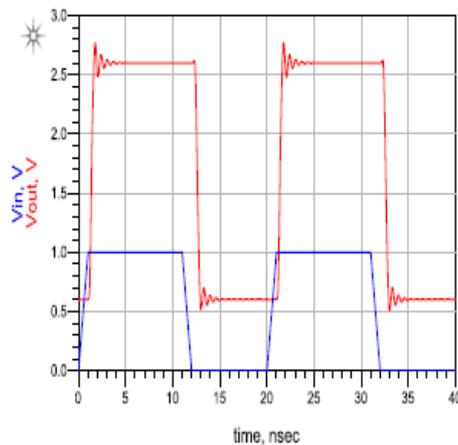
Switching Current Waveform at VCC from I_Probe1



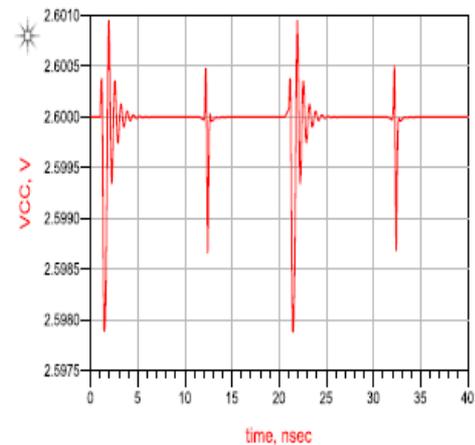
GND Bounce Waveform



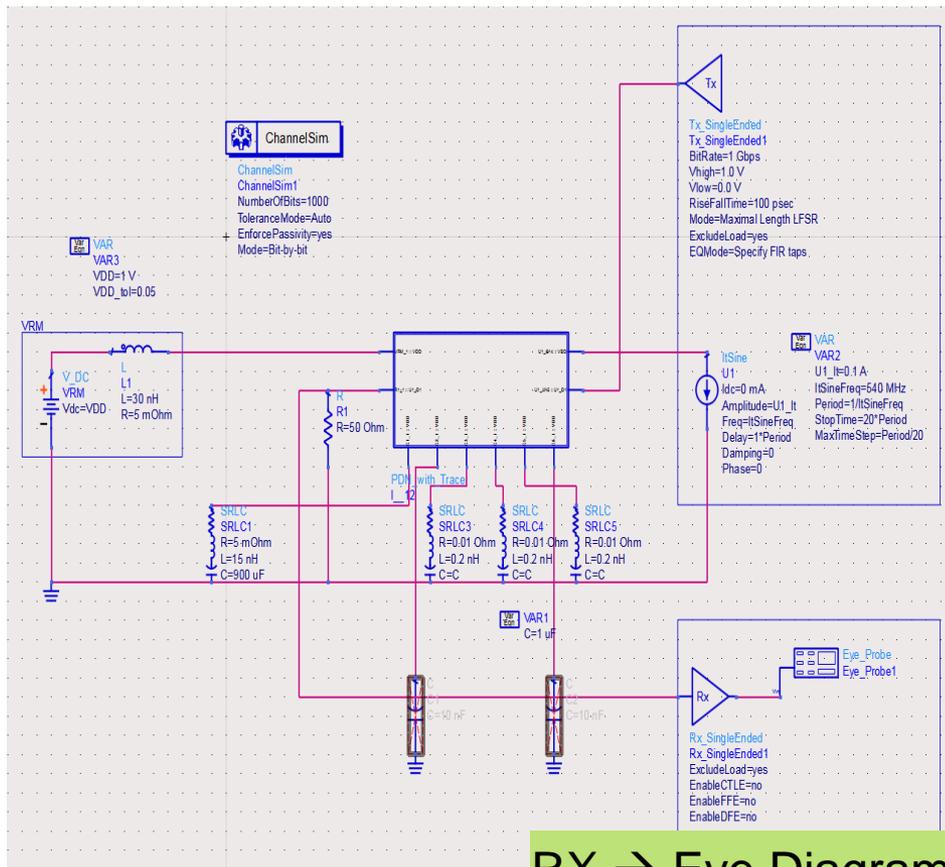
Signal Output Waveform



VCC Bounce Waveform

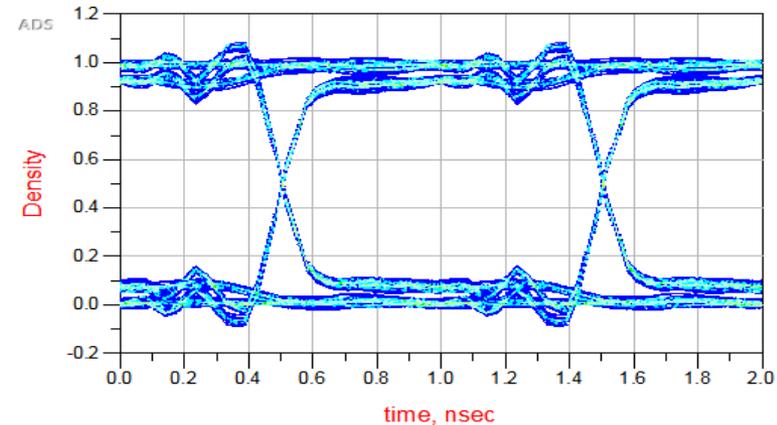


电流纹波对于高速信号干扰的仿真

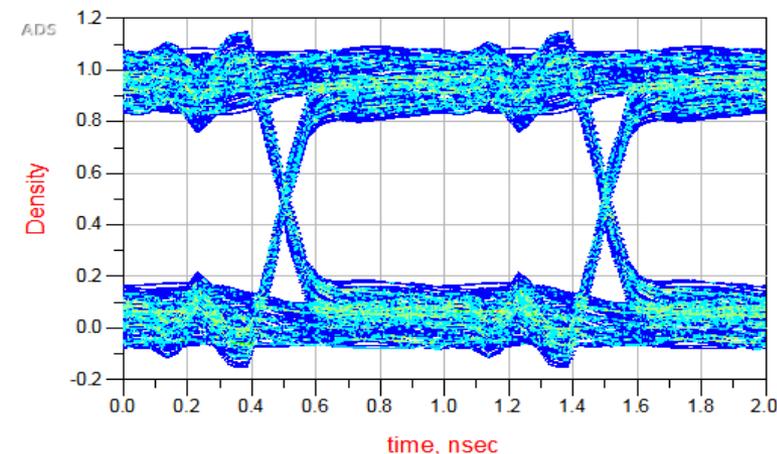


- ❖ 1 Gbps PRBS TX into signal path.
- ❖ IC Core sink current frequency is varied:100, 270 MHz.

IC Sink Current = 100 MHz

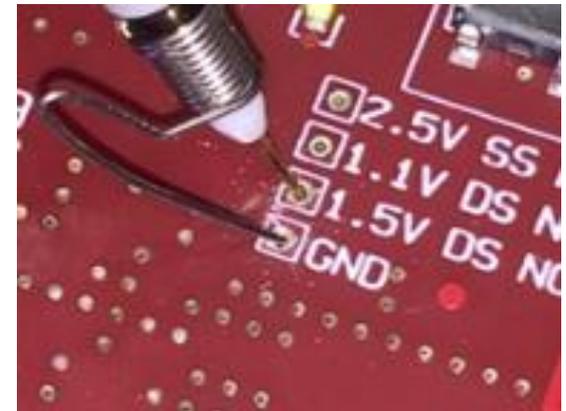


IC Sink Current = 270 MHz

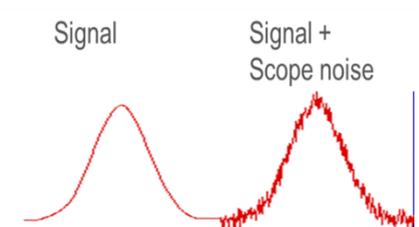
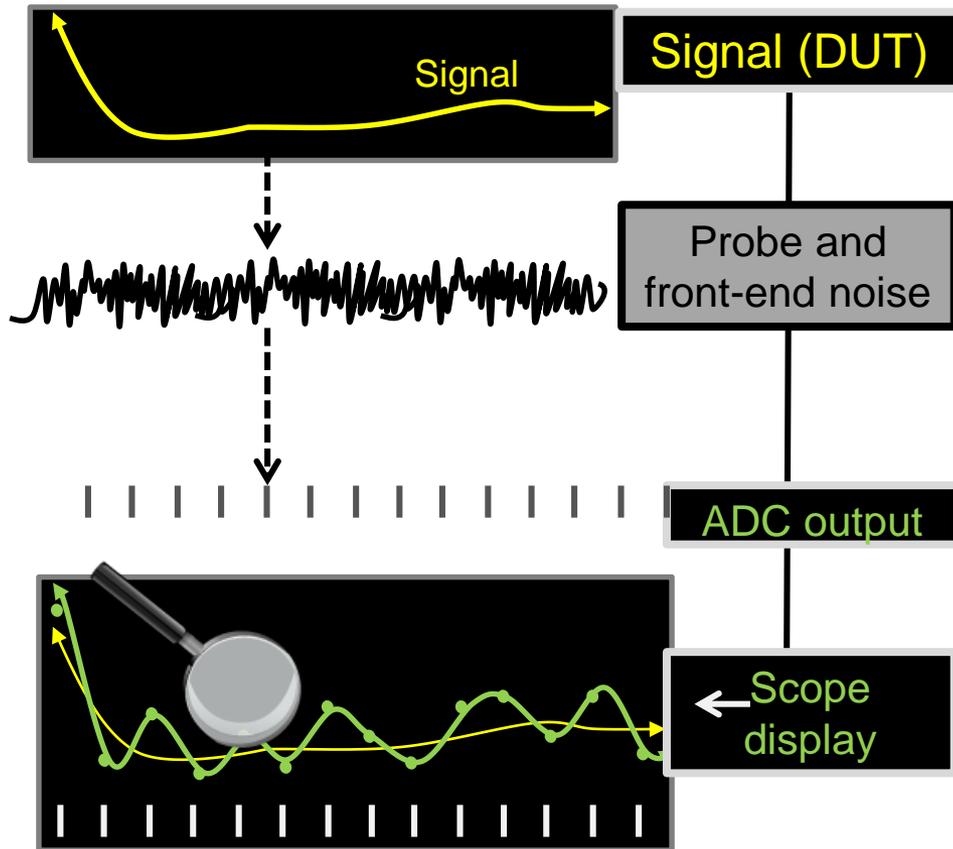


电源纹波、噪声测试的主要考虑因素

- ❖ 测量系统的底噪声
- ❖ 量程和电压测量范围
- ❖ 负载对被测系统的影响
- ❖ 带宽对测量的影响



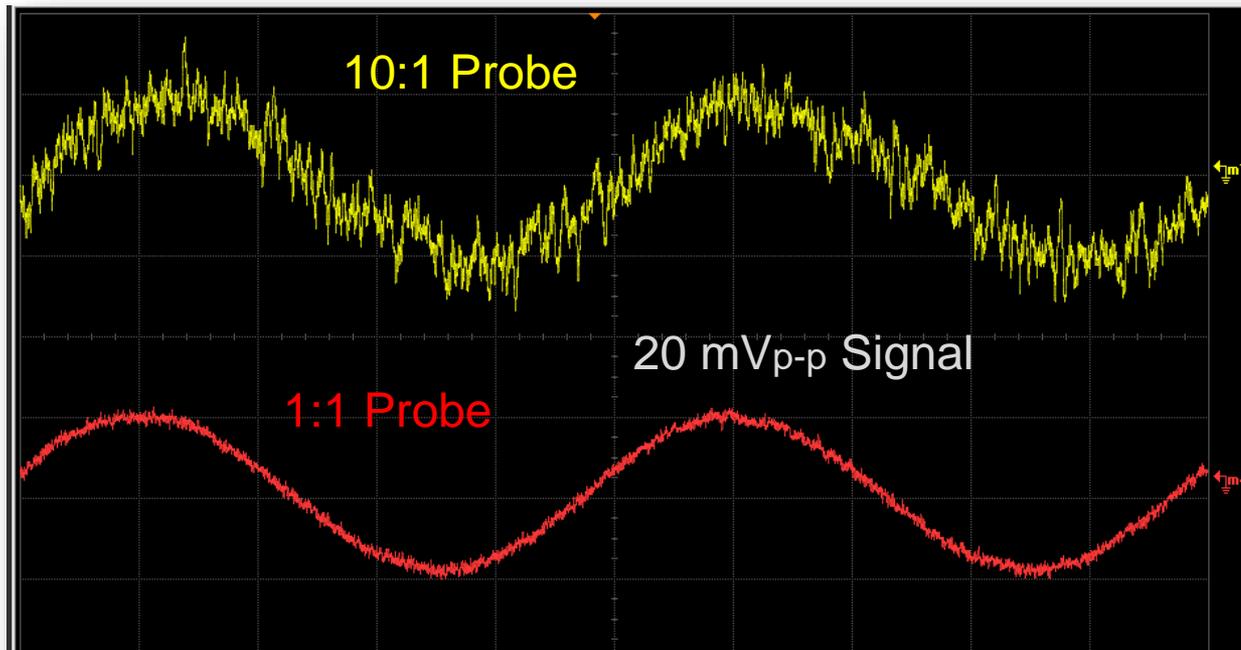
电源测试中噪声的来源



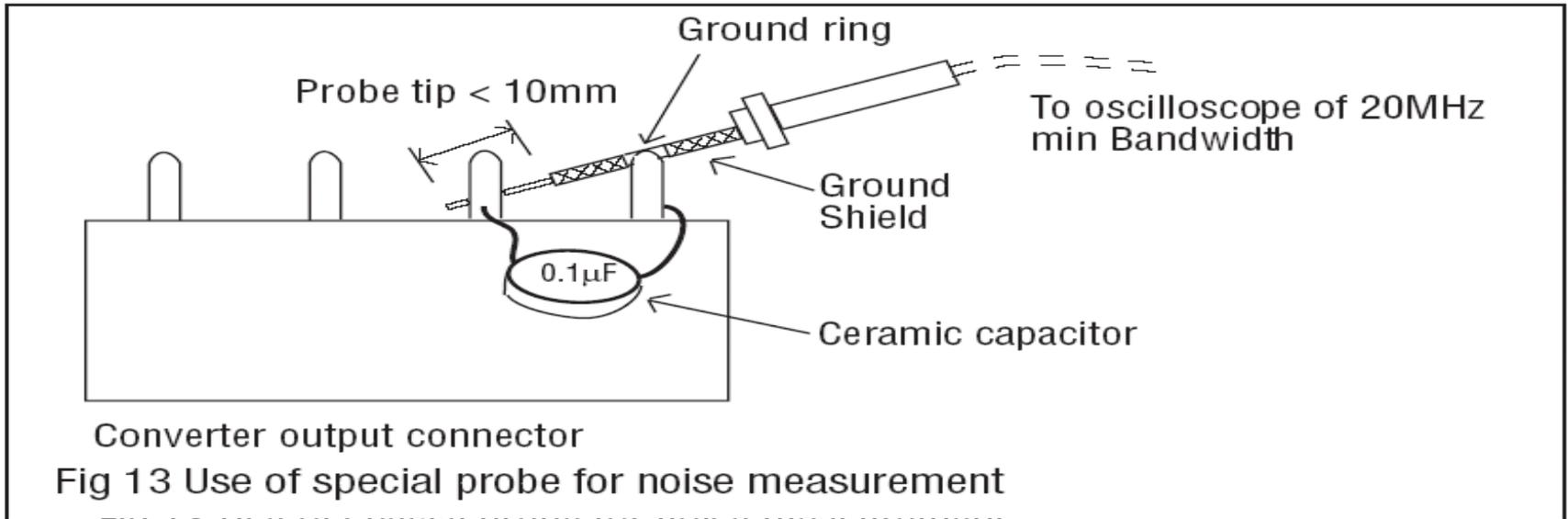
探头衰减比对底噪声的影响

N7020A: Attenuation ratio:

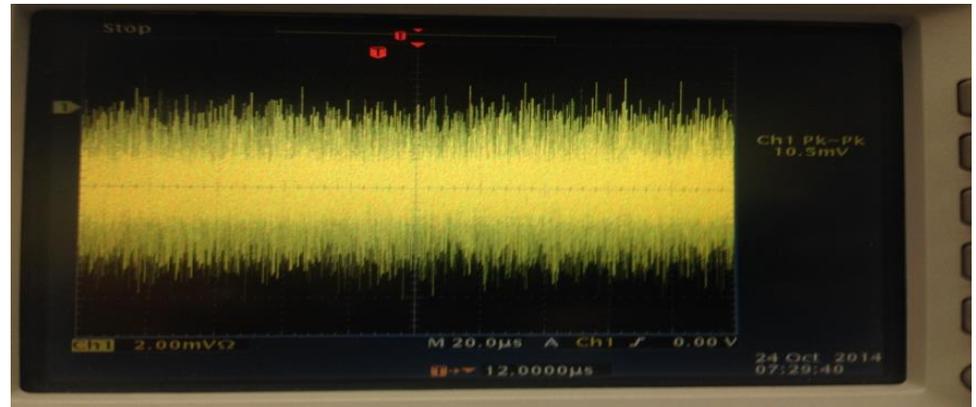
1:1 down to 1.09 mV/div



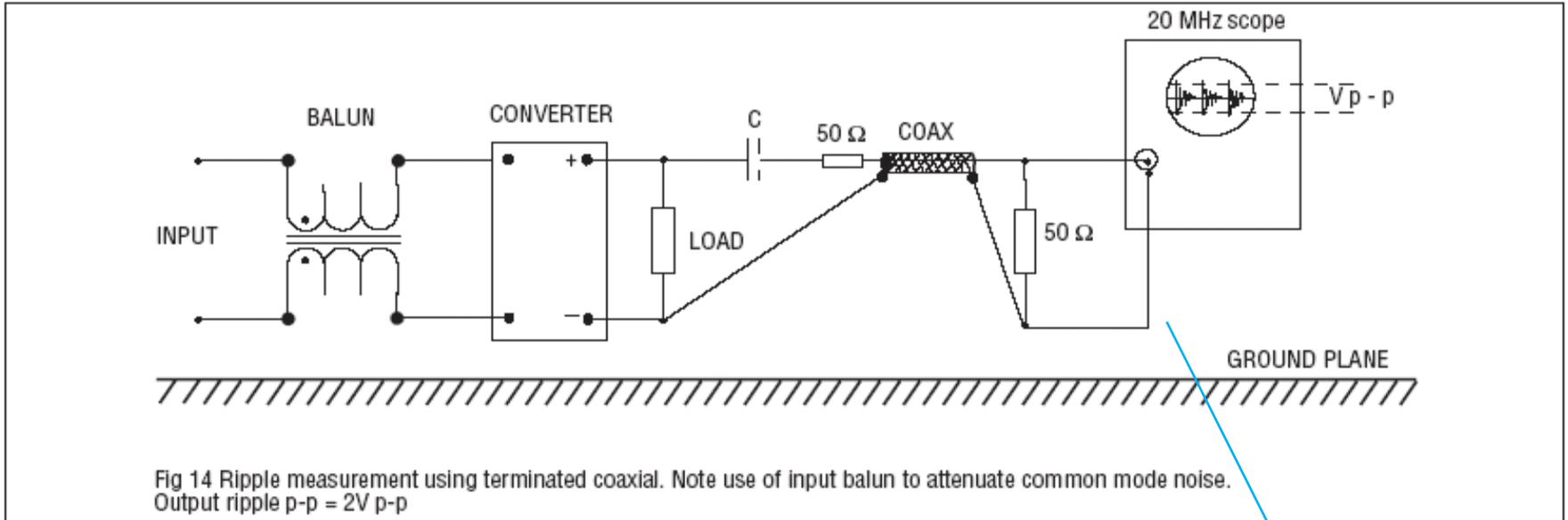
传统电源纹波测量方法1：通用探头



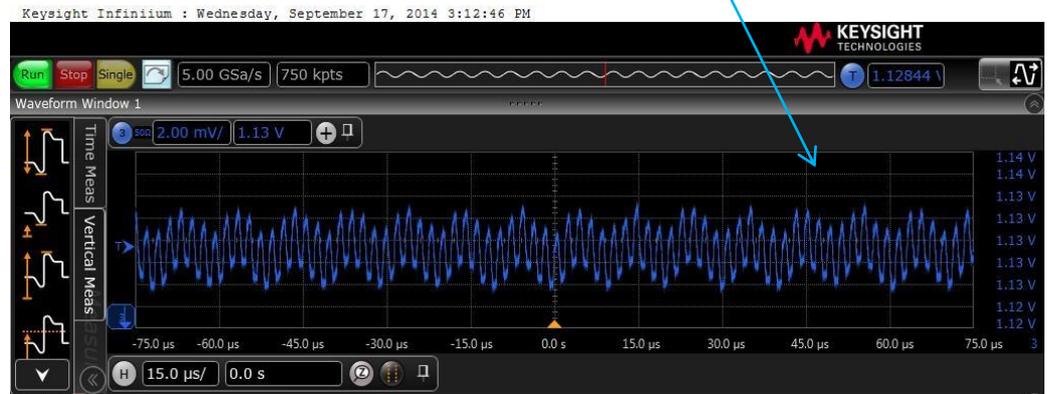
- ▶ 优点：连接方便，低成本。
- ▶ 缺点：探头衰减比对底噪声影响较大；容易受共模噪声影响；小衰减比的探头带宽有限；纹波测量和电压测量不能同时进行。



传统电源纹波测量方法2：自制电缆



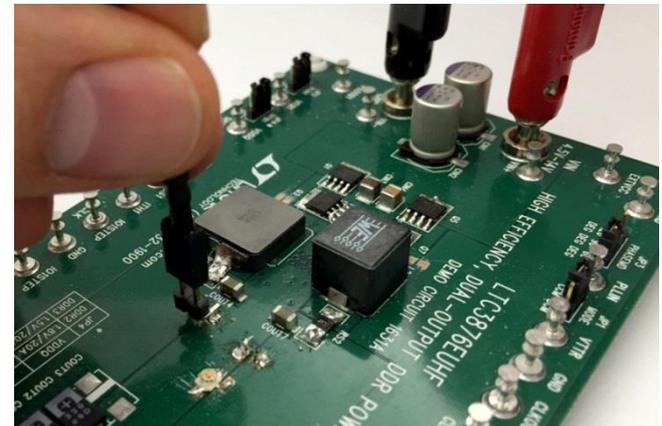
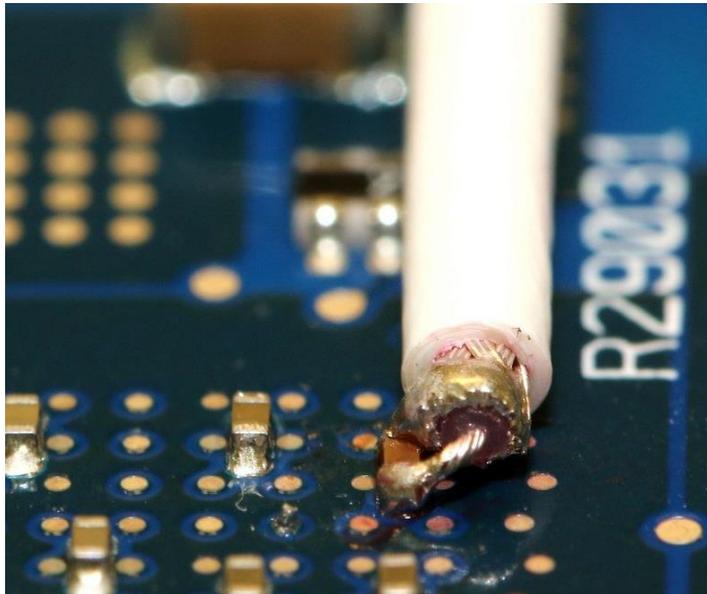
- ▶ 优点：低成本，低衰减比。
- ▶ 缺点：一致性不好；隔直电容参数及带宽不好控制；纹波测量和电压测量不能同时进行。



N7020A高带宽、低噪声探头

N7020A高带宽低噪声探头：

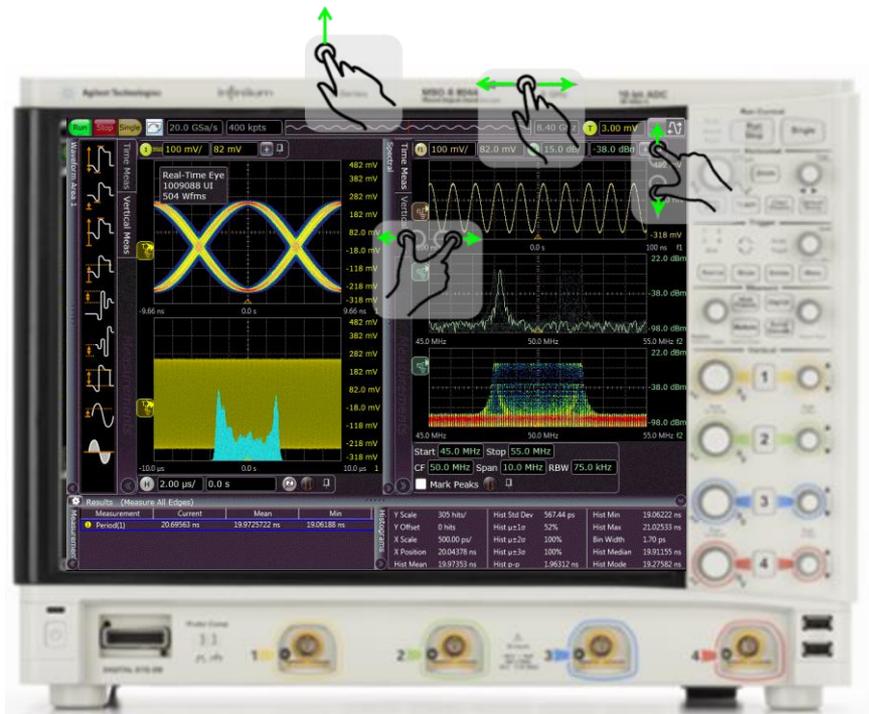
- ❖ 高达2GHz带宽
- ❖ 低噪声，衰减比仅为1.1:1
- ❖ 高达+/- 24V的偏置范围
- ❖ 高输入阻抗：50 K Ω @ DC



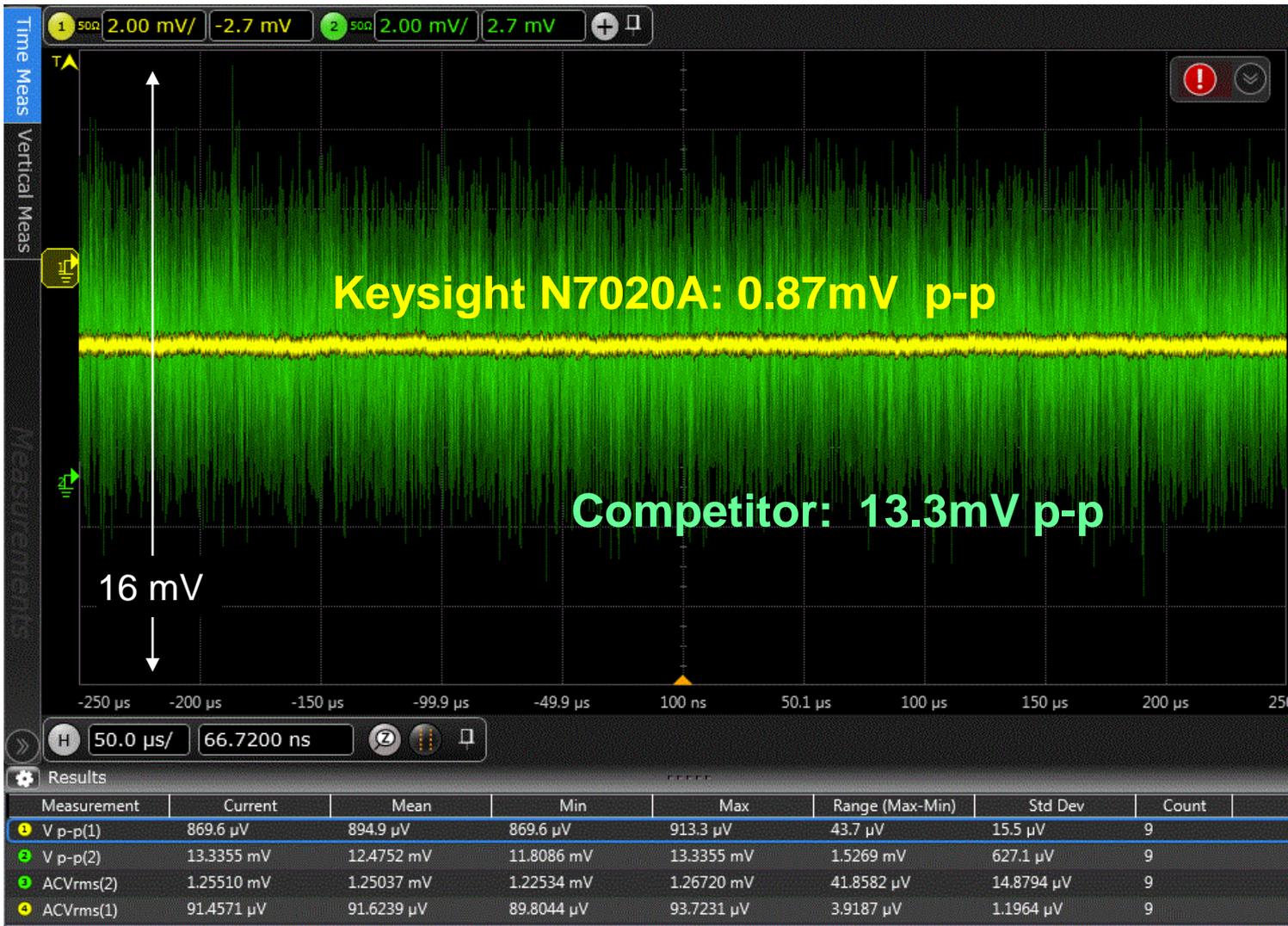
S系列高精度示波器

- ❖ 高达8GHz带宽，支持灵活的模拟和数字带宽滤波器
- ❖ 业内唯一的10bit-ADC，提供最优的信号分辨率
- ❖ 低噪声前端，最小满量程16mV
- ❖ 丰富分析功能，支持容性触屏和多点触控

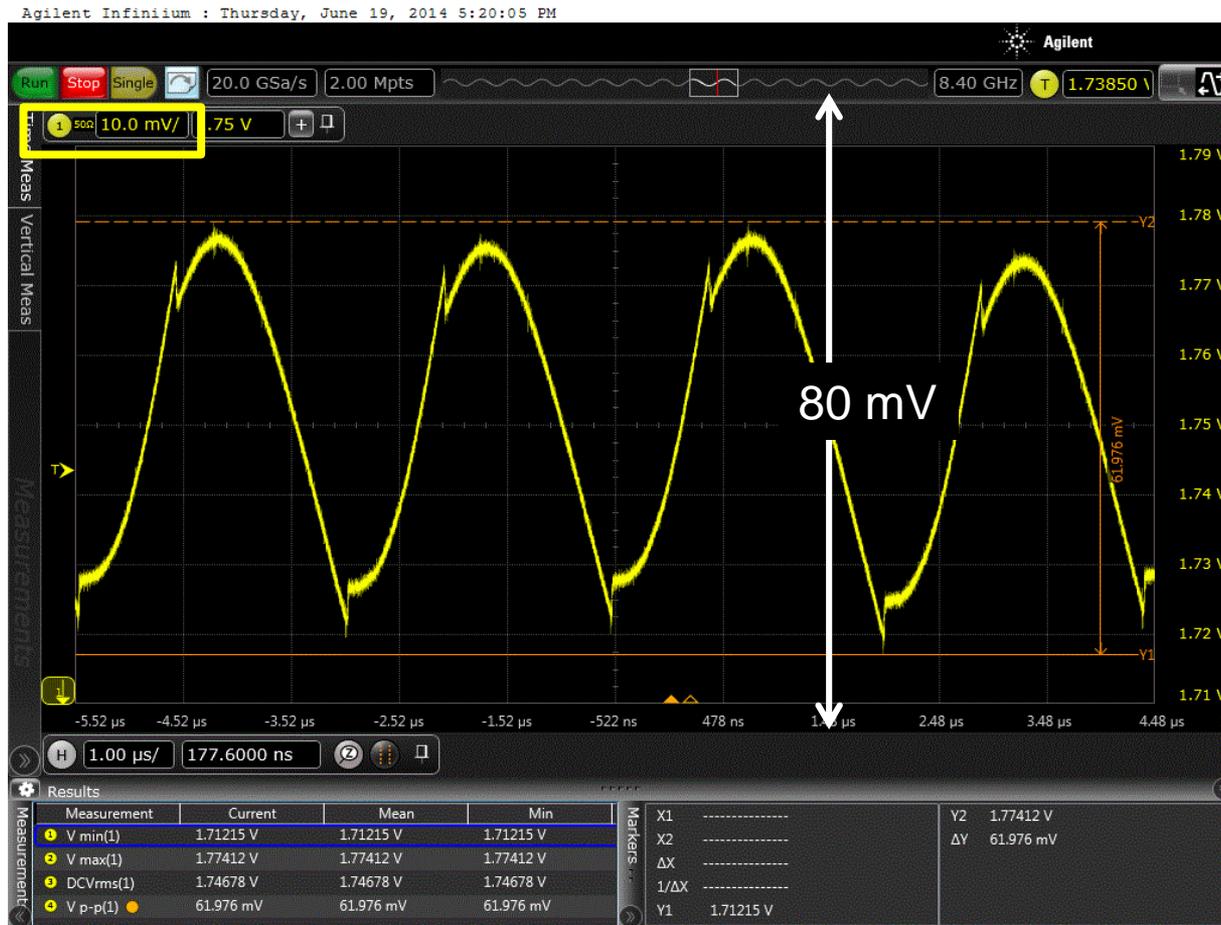
mV/div	Full scale value (Volts)	Infiniium S104A noise (mV)
1.000E-03	8 mV	0.09
2.000E-03	16 mV	0.09
5.000E-03	40 mV	0.095
10.000E-03	80 mV	0.111
20.000E-03	160 mV	0.16
50.000E-03	400 mV	0.45



S系列示波器加N7020A探头的底噪声指标



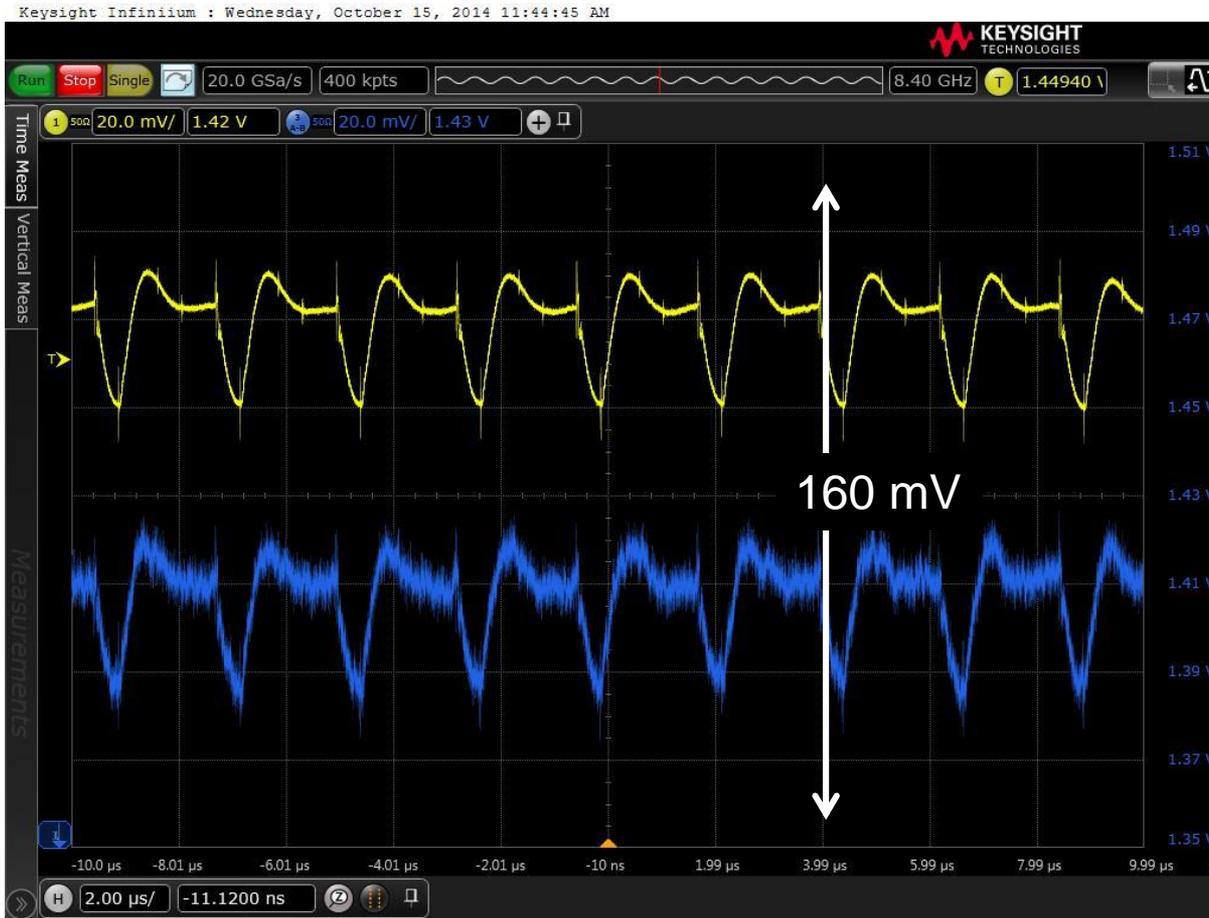
正确的量程设置



- Vertical setting = 10 mV/div
- Full scale = 80 mV

Noise Floor:
111uV rms

错误的量程设置



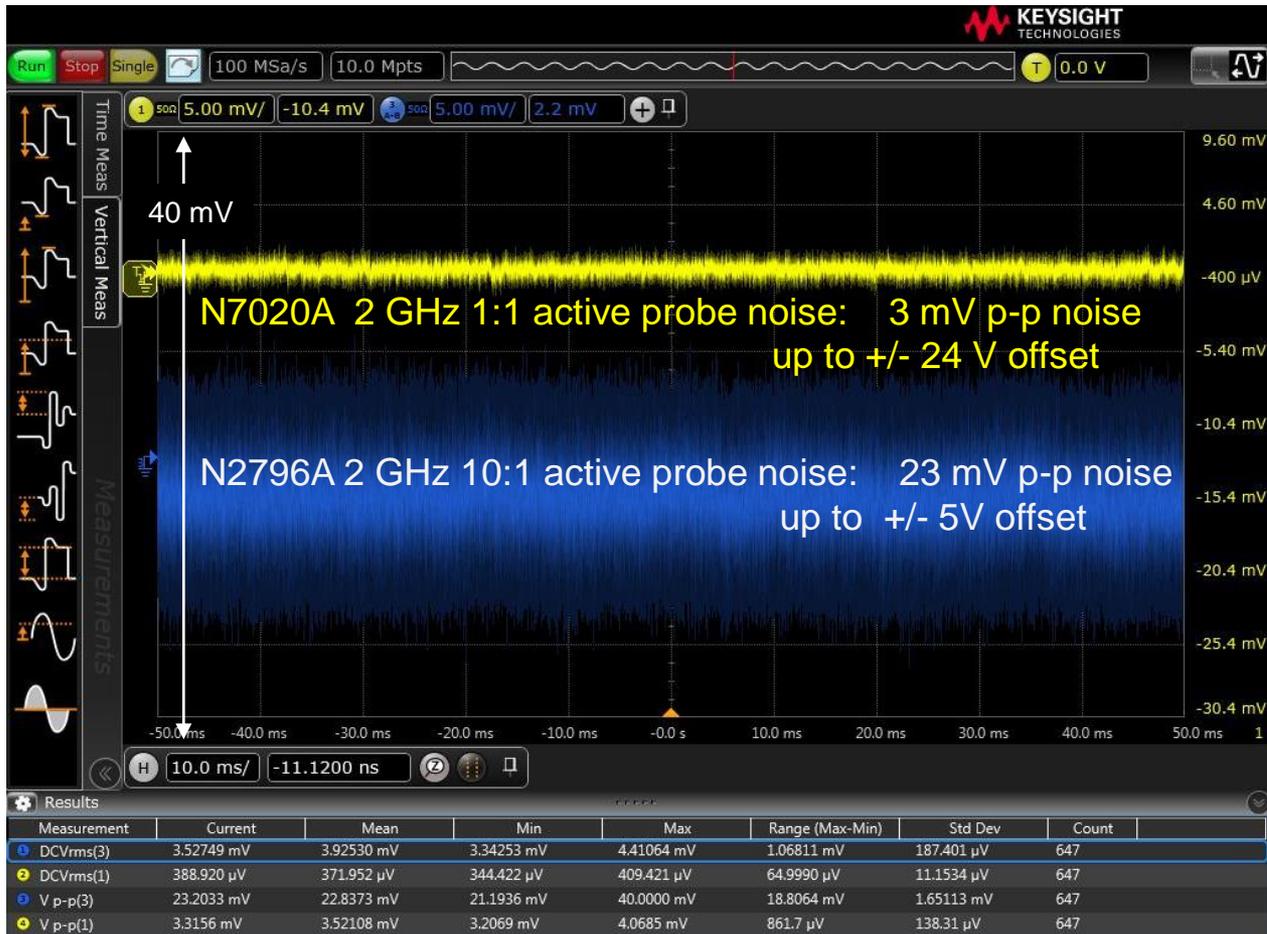
- Vertical setting = 20 mV/div
- Full scale = 160 mV

Noise Floor:
160uV rms

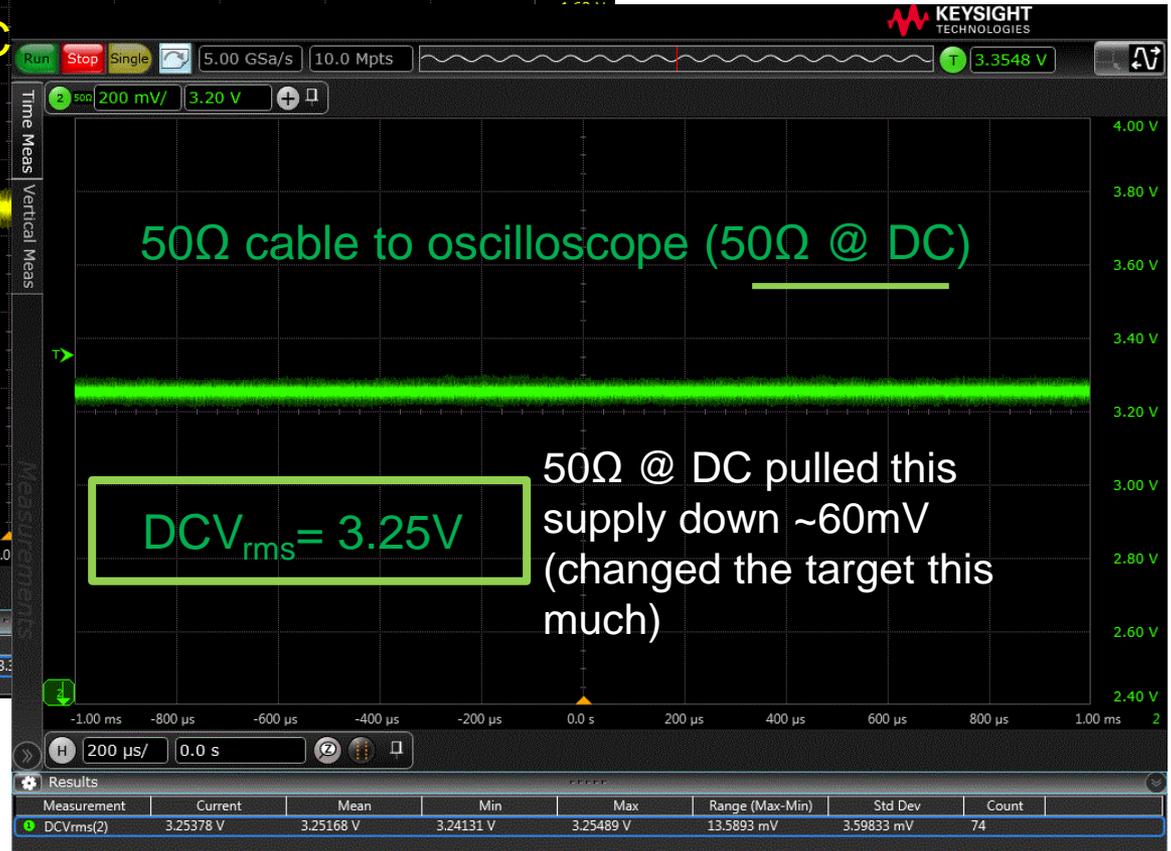
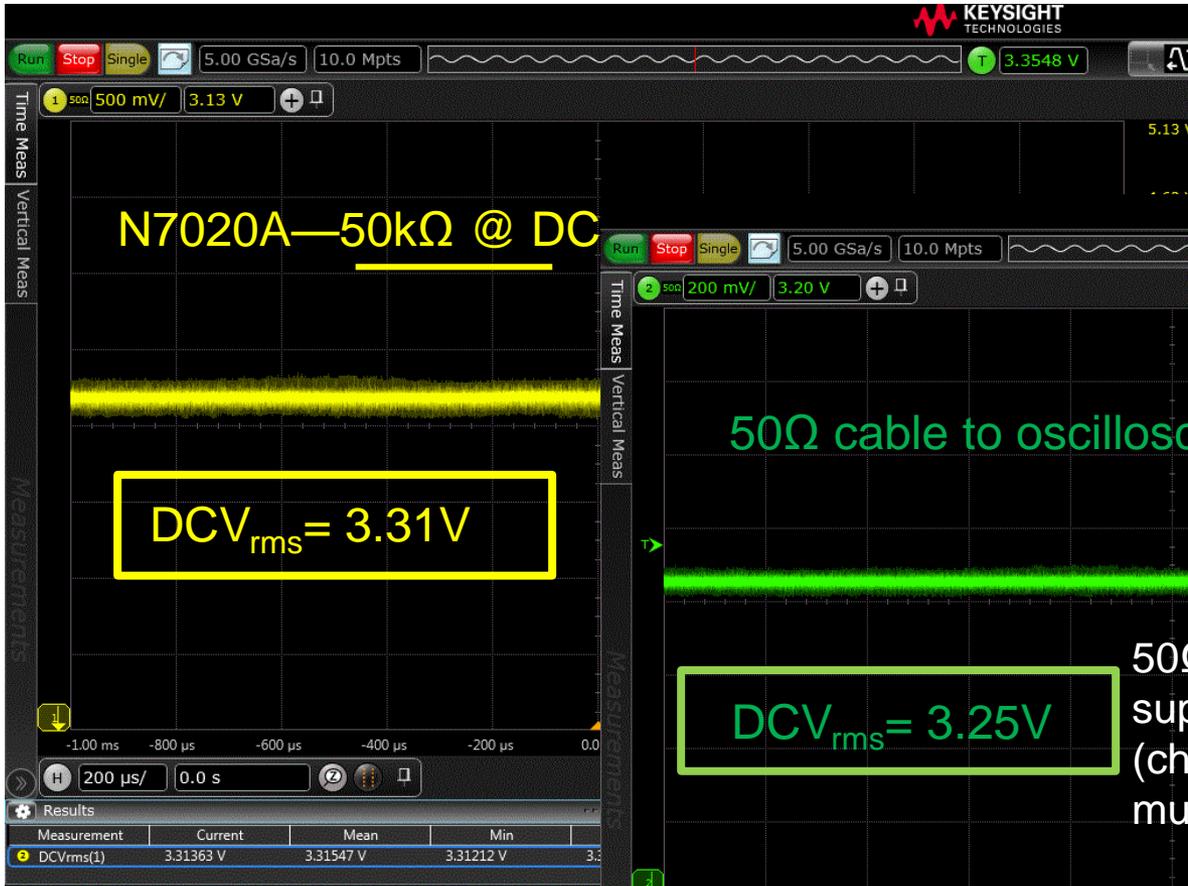
Increased noise by 44% (10mV/div to 20 mV/div)

不同探头的偏置范围

N7020A: Offset range: +/-24V



探头负载对被测电路的影响



不同带宽测量到的纹波噪声

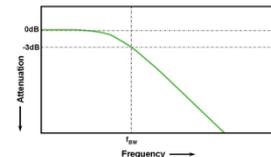


N2870A 35 MHz, 1:1

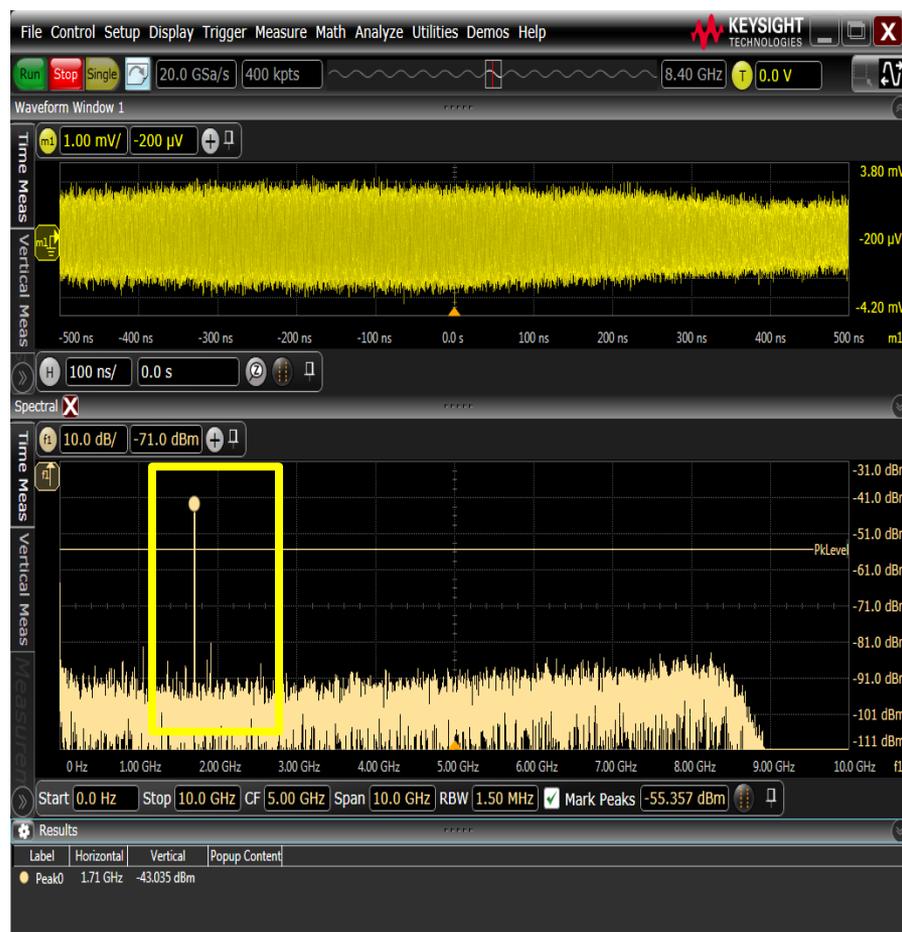
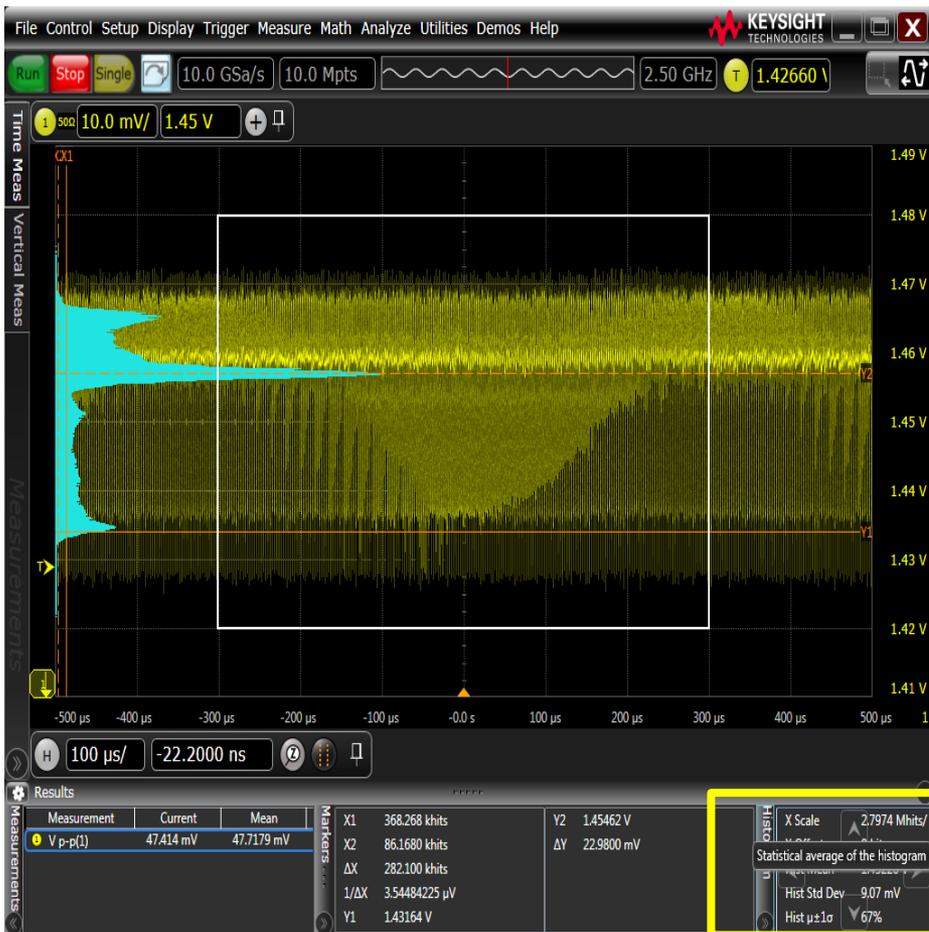


N7020A 2 GHz, 1.1:1

根据需要进行灵活带宽限制



对电源噪声进行直方图统计和频谱分析



电源纹波、噪声测试的完美组合

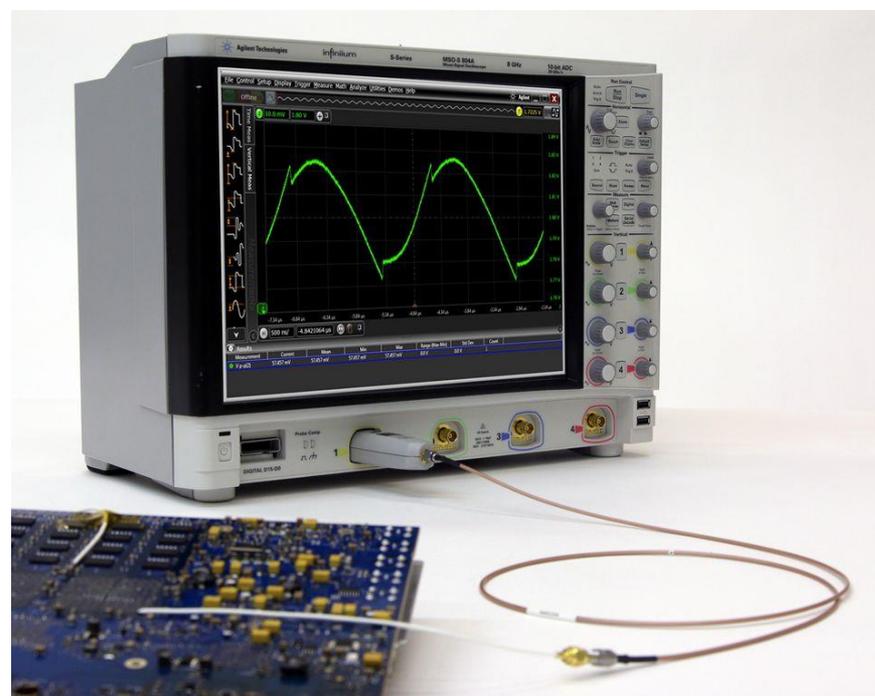
业界最出色的信号完整性

- 8 GHz 带宽和平坦的频率响应确保高信号保真度
- 20 GSa/s 最大采样率
- 10 位模数转换器 (ADC) 保证高垂直分辨率
- 低噪声前端，6.4 位系统有效位数 (ENOB)

最先进的平台

- 15 英寸电容触摸屏支持多点触控
- 英特尔 i5 主板配备 8G RAM，可以提供卓越的处理速度
- 标配固态驱动器可大幅提升开机速度并实现高可靠性
- USB 3.0 和以太网接口提供高达 200 MB/s 的数据卸载速度

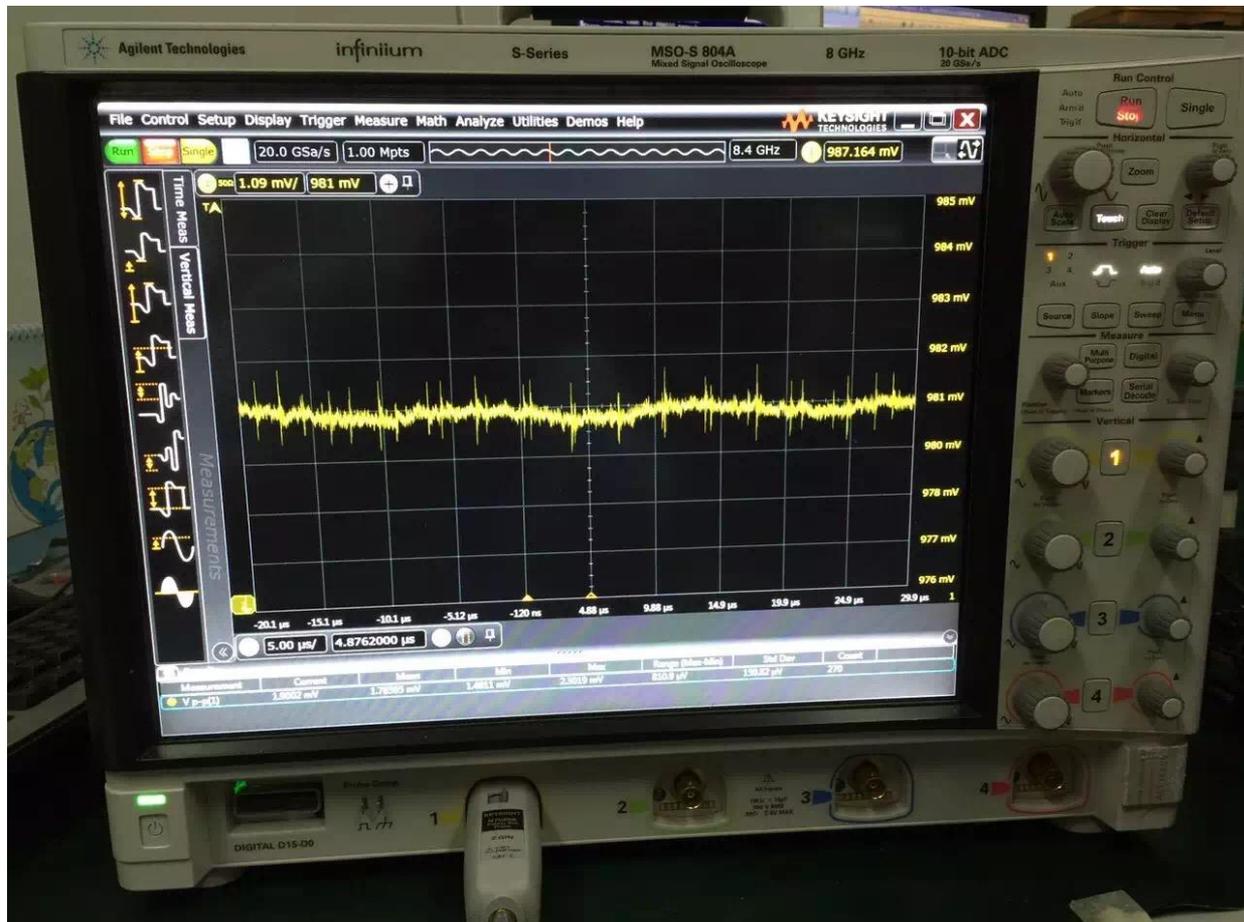
S系列示波器 + N7020A低噪声探头



测试实例分享：北京某高端路由器/交换机实测

测试需求：1V电源供电

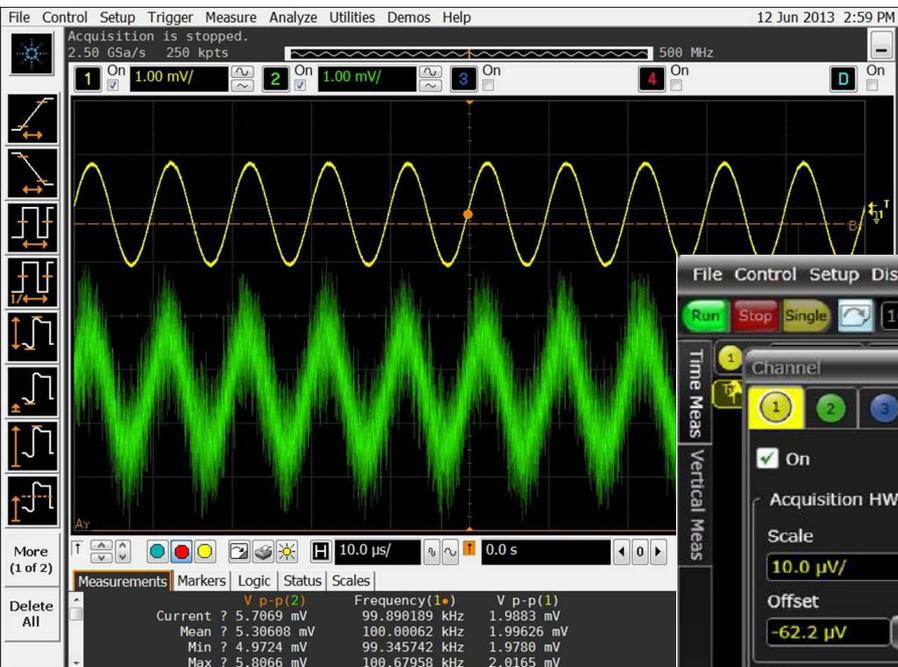
- $V_{pp} < 3\text{mV}$ (20M带宽内)
- $V_{pp} < 10\text{mV}$ (80M带宽内)



及其微小信号的测试

测量小信号: $\leq 500\text{kHz}$, $3\mu\text{V} \sim 1.2\text{V}$ 差分, $\pm 12\text{V}$ 共模

- 采用N2820A/21A电压电流探头
- 最小可测电流: 500nA
- 最小可测电压: $3\mu\text{V}$



File Control Setup Display Trigger Measure Math Analyze Utilities Demos Help
Run Stop Single 10.0 GSa/s 10.0 Mpts
KEYSIGHT TECHNOLOGIES
Probe Configuration
1 N2820A 2 No probe detected 3 No probe detected 4 No probe detected
Probe System
External Scaling
External Scaling 1.0000 : 1 0.0 V
N2825A Probe Head Rsense User Defined 1 Select Head...
N2820A Probe Amp 500 kHz US52460023 Options...
Probe Offset...
Probe System Characteristics
Bandwidth 500.0 kHz
Resistance 1.0 GΩ
Max Input ±35.0 A
Signal Range ±16.0 A
CM Range ±17.0 A
Off Setup...
Probe...
Probe Cal...
Trigger...
External Scaling
Units Volt Offset 0.0
Gain Ratio 1.0000 : 1
-82.2 μV
-92.2 μV
-102 μV
-265 μs -165 μs -64.7 μs 35.3 μs 135 μs 235 μs 335 μs 435 μs 535 μs 635 μs 735 μs 1
H 100 μs/ 235.320000 μs

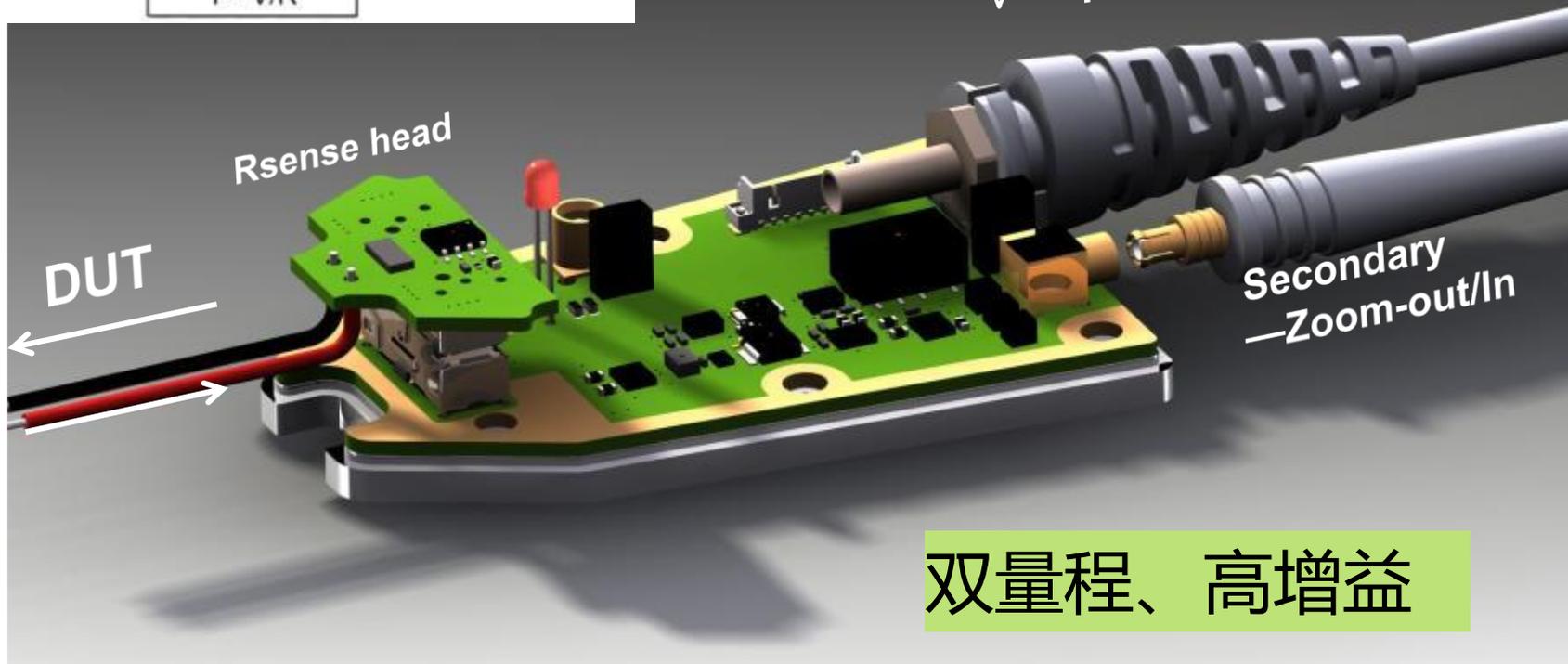
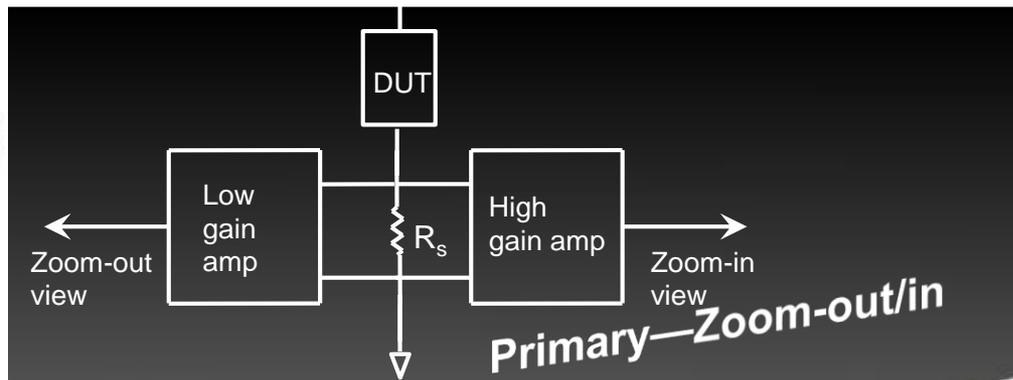
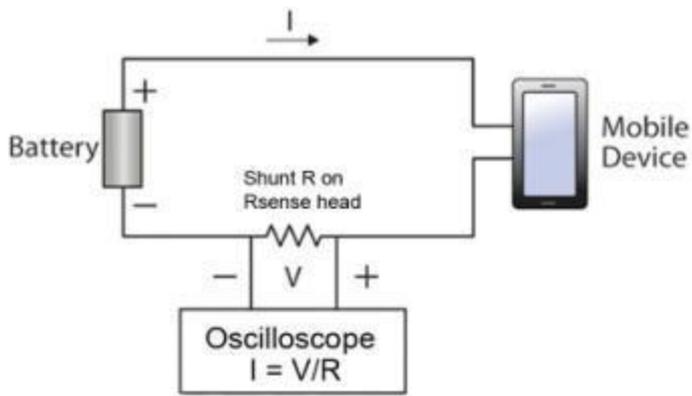
N2820A微弱信号测量探头

- ❖ Measure AC/DC currents as low as **50 μA** , and as high as **5 A**
- ❖ Dynamic range >20,000:1
- ❖ Bandwidth
 - ❖ 3 MHz Zoom-Out Ch
 - ❖ 500 kHz Zoom-In Ch
- ❖ Make-before-break (MBB) interface
- ❖ Selectable R_{sense} : 20 m Ω , 100 m Ω and user defined

N2820A 2-channel

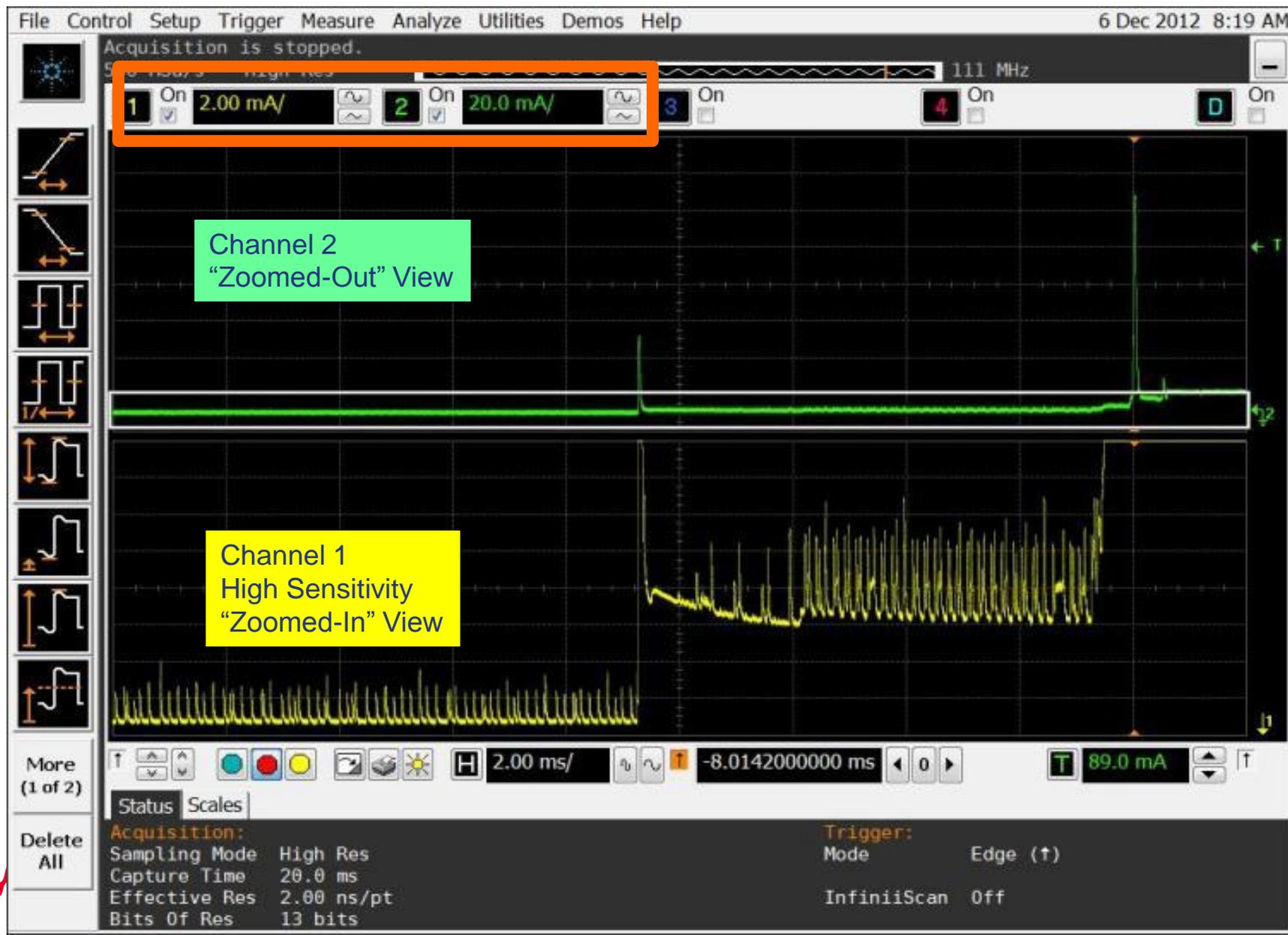


N2820A探头的内部结构



双量程、高增益

N2820A测量到的微弱电流变化波形



心跳瞬间：第一次对视、第一次牵手、第一次.....

测试需求：心率测试
- 医院类可穿戴设备



其它电源测试常用探头及附件

- U1880A时滞校正夹具，用于电压、电流探头的时延校正
- 电流探头 (AC/DC)
 - 1147B 50MHz, 15A/30A 电流探头，智能接口
 - N2893A 100MHz, 15A/30A 电流探头，智能接口
 - N2780B 2MHz, 500A电流探头(需要N2779A外部供电模块)
 - N2781B 10MHz, 150A电流探头(需要N2779A外部供电模块)
 - N2782B 50MHz, 30A电流探头(需要N2779A外部供电模块)
 - N2783B 100MHz, 30A电流探头(需要N2779A外部供电模块)
- 高压差分探头
 - N2790A 100MHz 1.4KV高压差分探头，智能接口
 - N2791A 25MHz 700V高压差分探头，USB供电
 - N2891A 70MHz 7KV高压差分探头，智能接口
- 无源探头(用于电源纹波，PSRR测量)
 - N2870A 1:1, 35MHz 无源探头
 - 10070D 1:1, 20MHz 无源探头
- 高压探头
 - 10076B 100:1, 4KV,250MHz无源探头
 - N2771B 1000:1, 30KV, 50MHz无源探头



极端温度测试：就像在热恋，眼里只有男/女神



N7007A
Single-ended Passive
400 MHz
10M Ω input R
2 m long cable
-40 to +85 °C

N7013A
Probing kit for differential probe
70 MHz
Compatible with N2790A, N2791A, N2792A, and N2818A
70 cm long cable
-40 to +85 °C

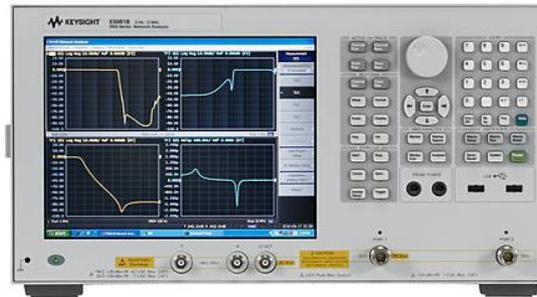
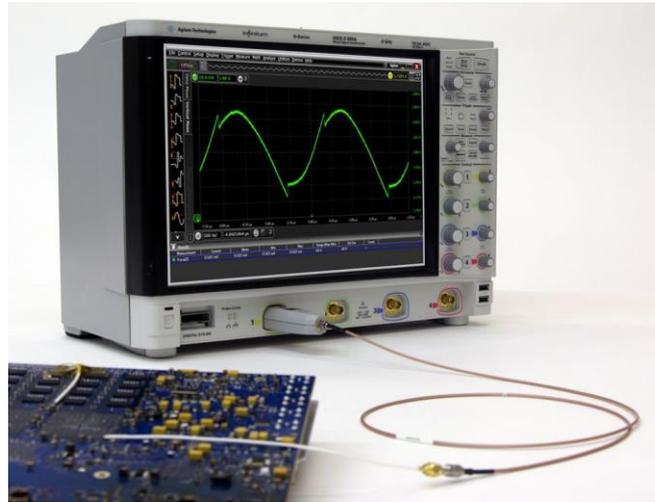
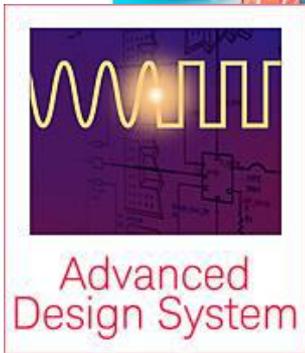
N2797A
Single-ended Active
1.5 GHz
1M Ω input R
2 m long cable
-40 to +85 °C

InfiniiMax + N5450B
extension cable + probe head
Differential & SE Active
1.5 GHz – 16 GHz
50 k Ω input R
-55 to +150 °C

N2820A/21A
High-sensitivity current probe
Current
3 MHz
1.5 G Ω input R
-55 to +150 °C

Keysight 提供最完整的极端温度测试探头解决方案

Keysight电源完整性测试方案



谢谢！