

UK Advanced Instrumentation Training

Circuit Design 3 & 4
Simulation LTspice 1 & 2

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2022 May 10

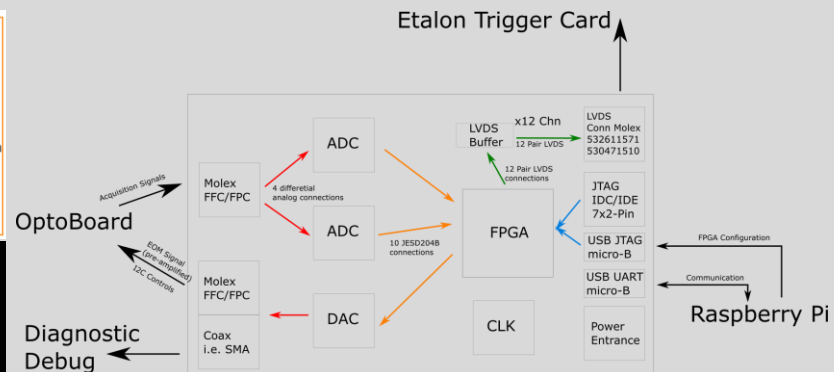
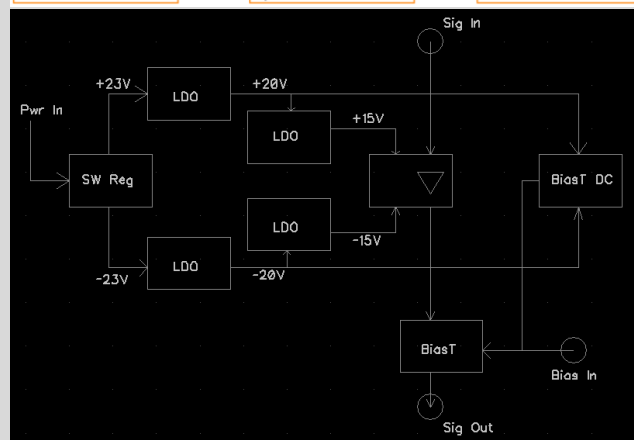
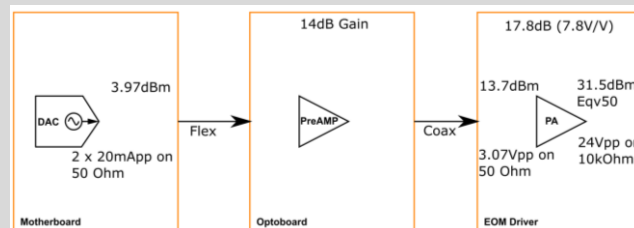


Circuit Design, Noise, Grounding

- Workflow
 - Analyze -> Block Diagram, Specs
 - Schematic -> Circuit topology, Constraints
 - Layout -> GERBER, BOM, Assembly-files
 - Manufacturing (fabrication, population, assembly)
 - Debug, Characterization -> Reports
 - (Revision)
- Simulation

Circuit Design, Noise, Grounding

- Workflow
 - Analyze -> Block Diagram, Specs

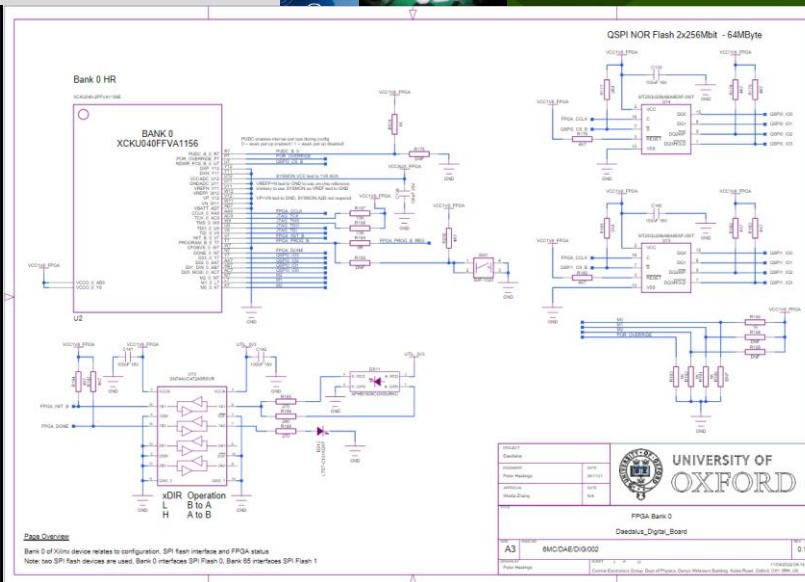
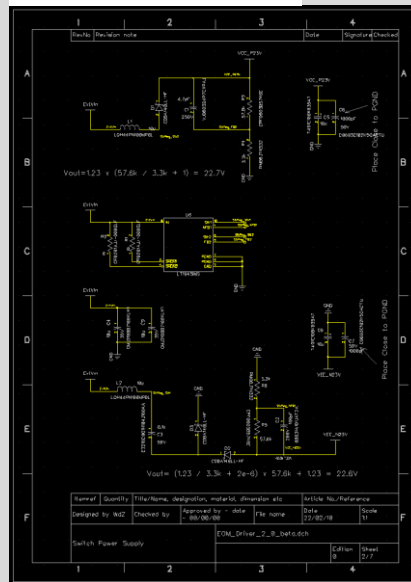
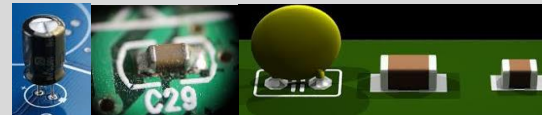
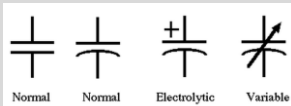


Recalculated Power Consumption at 3.8.9.2:

	Layer	Power Supply Net Name	Voltage (V)	Consumer	Current Input (mA)
ADP2384	1	VDD3V8	3.8	DAC + CLK	454
				Total	454
MAX15301	1	VDD3V3	3.3	LVDS + USB	155
				FPGA Fabric	TBD (Max725)
				DAC + CLK	5.7
				ADC	801
				Total	1686.7
MAX15301	1	VDD1V8	1.8	DAC + CLK	767
				2 ADCs	1572
				FPGA MGT	2983
				FPGA Fabric	2938
				Total	8260
MAX15301	1	VCCINT	0.95	FPGA Fabric	10262
				Total	10262

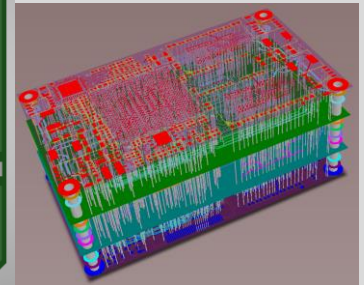
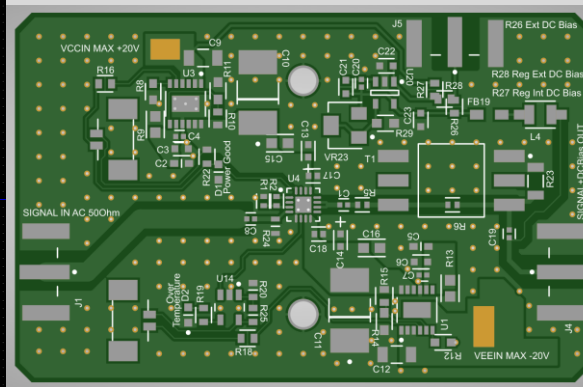
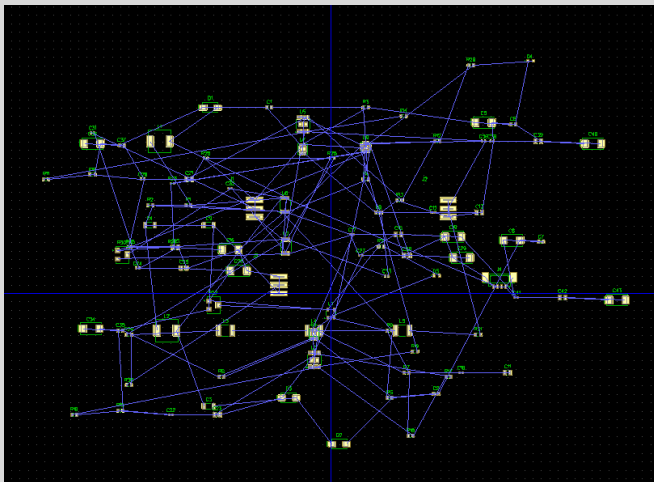
Circuit Design, Noise, Grounding

- Workflow
 - Schematic -> Circuit topology, Constraints



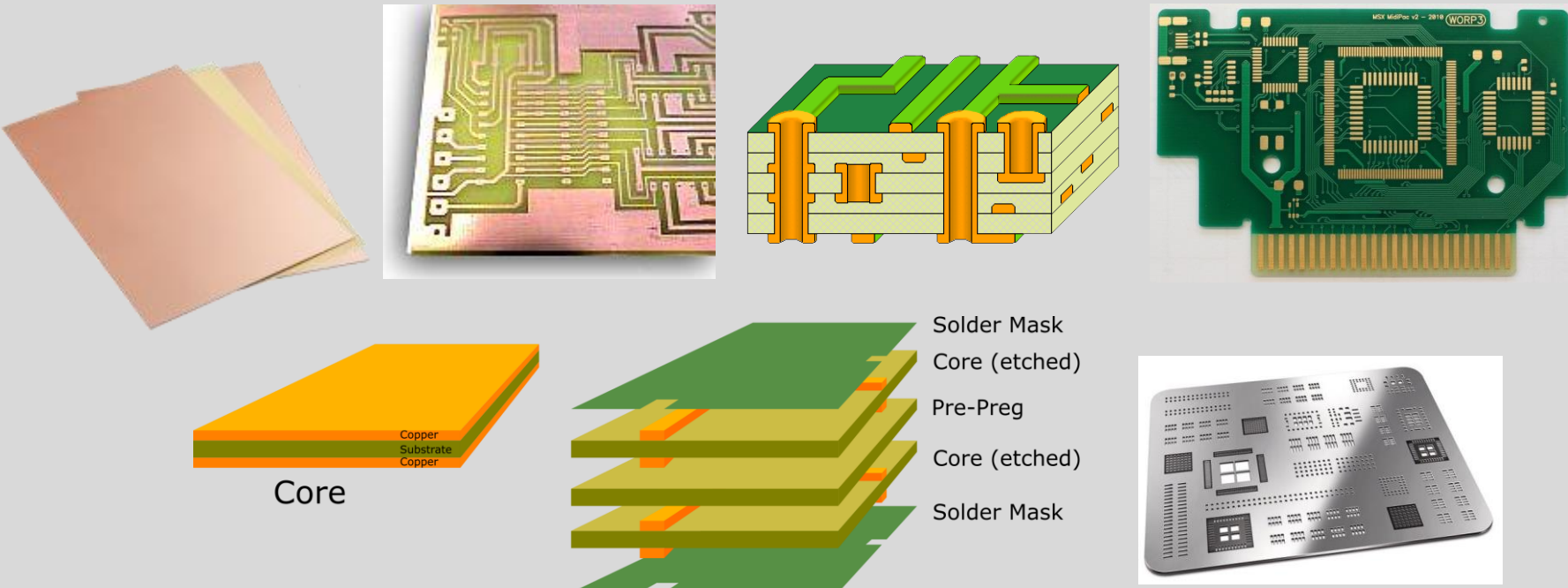
Circuit Design, Noise, Grounding

- Workflow
 - Layout -> GERBER, BOM, Assembly-files



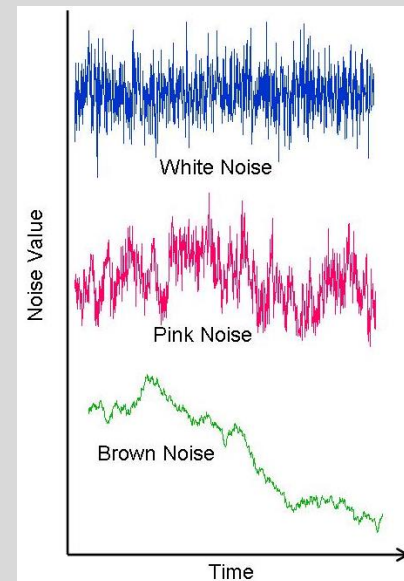
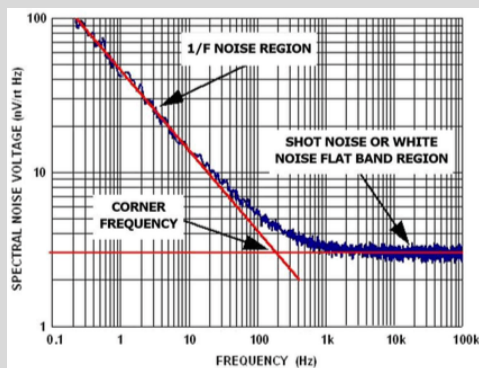
Circuit Design, Noise, Grounding

- Workflow
 - Manufacturing (fabrication, population, assembly)



Circuit Design, Noise, Grounding

- Noise
 - Thermal \sim quasi-white, Gaussian, $4kTR$; Conductor
 - Shot \sim white, Gaussian, $2e|I|$; Semiconductor
 - $1/f$, flicker $\sim f$ -depend; Anything
 - Burst ~ 2 -value, f -depend; Semiconductor



Circuit Design, Noise, Grounding

- Interference/Crosstalk
 - Data/Clock dependent \sim non-stationary, f -depend
- Systematic
 - Harmonics, Spurs $\sim f$ -depend; Amp-linearity, ADC, DAC
 - Quantization Noise \sim quasi-white, uniform; ADC
 - Aliasing/Mirror Noise \sim Signal x Sinc, uniform; ADC, DAC
 - Clock Phase Noise $\sim 1/f^\alpha$; resonant, quartz, PLL

Circuit Design, Noise, Grounding

Harmonics

Spurs/Crosstalk

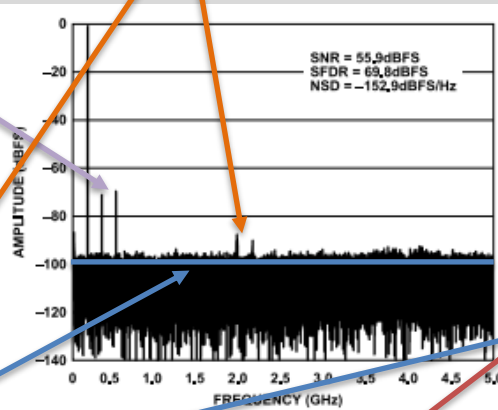
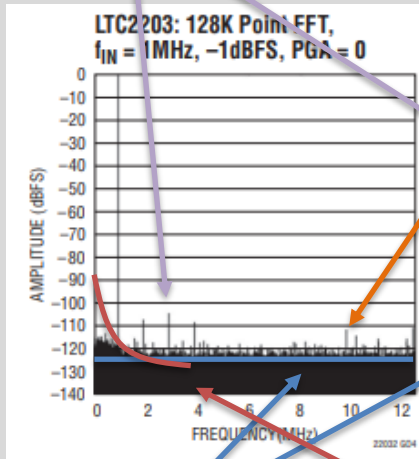


Figure 3. Single-Tone FFT with $f_{IN} = 170\text{ MHz}$, 10 GSPS

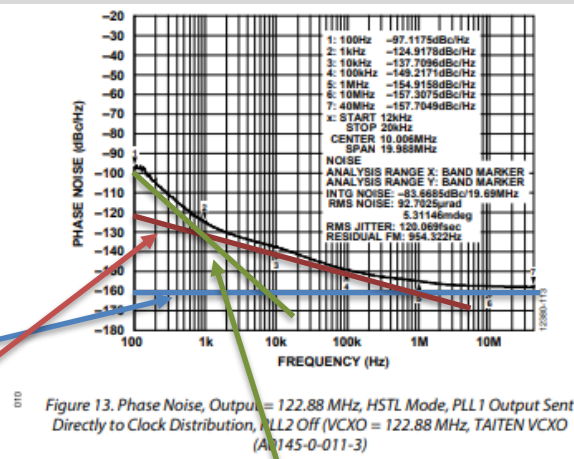


Figure 13. Phase Noise, Output = 122.88 MHz, HSTL Mode, PLL1 Output Sent Directly to Clock Distribution, PLL2 Off (VCXO = 122.88 MHz, TAITEN VCXO (A1145-0-011-3))

Thermal + Shot + Quantization

$1/f + (\text{Burst})$

$1/f^\alpha$

Circuit Design, Noise, Grounding

- Noise

- Units PSD vs PSD

$$\bar{P} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-T/2}^{T/2} \frac{x^2(t)}{R} dt$$

x is the random variable of noise, with the unit of voltage
 Resistivity R is sometimes ignored to 1, \bar{P} is average power

$$\bar{P} = \int_0^B S_x(f) df$$

B is the bandwidth, S_x is the power spectrum density,
 with the unit of Power per Bandwidth, i.e. dBm/Hz

$$x_{\text{RMS}} = \sqrt{\bar{P}R}$$

x_{RMS} is the root-mean-square of the noise, with the unit
 of voltage

$$v_n(f) = \sqrt{S_x(f)R} = \sqrt{\frac{\bar{x}^2}{RB}}$$

This is only in white noise, $v_n(f)$ is the voltage
 spectrum density, with the unit of $V/\sqrt{\text{Hz}}$

Circuit Design, Noise, Grounding

- Noise

- Conversion

- $0\text{dBm} = 0.632V_{\text{PP}} = 0.233 V_{\text{RMS}}$

- Quantify and Comparison

$$x_{\text{RMS}} = \sqrt{\bar{P}R}$$

$$v_n(f) = \sqrt{S_x(f)R} = \sqrt{\frac{\bar{x}^2}{RB}}$$

ADA4099-1/ADA4099-2

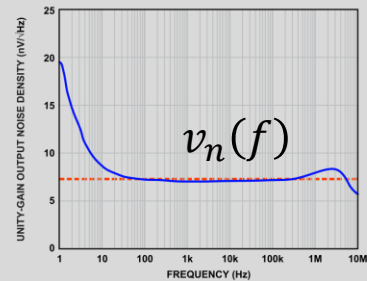


Figure 42. Unity-Gain Output Noise Density vs. Frequency

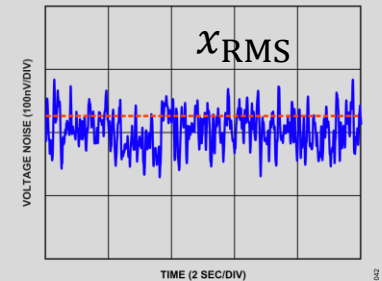


Figure 43. 0.1 Hz to 10 Hz Noise

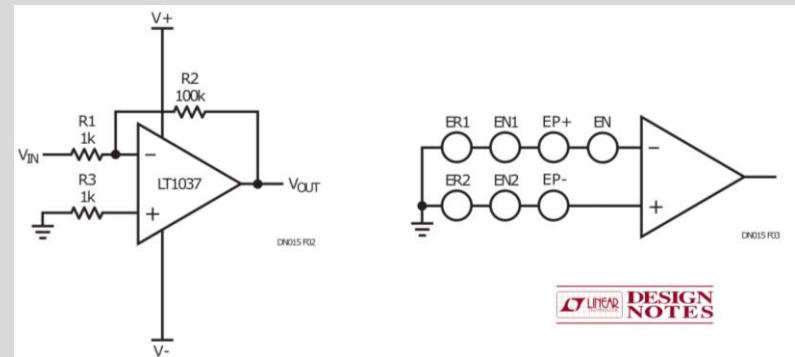
analog.com

- v_n as a number gives floor
- x_{RMS} at low frequency tells flicker

NOISE PERFORMANCE				
Input Voltage Noise	f = 0.1 Hz to 10 Hz	150	150	nV p-p
	1/f noise corner	6	6	Hz
Over-The-Top	f = 100 Hz	7	7	nV/√Hz
	f = 100 Hz, $V_{\text{CM}} > +V_S$	8	8	nV/√Hz
Input Current Noise	f = 100 Hz	0.5	0.5	pA/√Hz
	Over-The-Top	f = 100 Hz, $V_{\text{CM}} > +V_S$	5	5

Circuit Design, Noise, Grounding

- Noise
 - Paths
 - Signal Input
 - Resistive Components
 - Semiconductor Devices
 - Non-Linear (not LTI)
 - Power Supplies
 - Indirect Coupling



Circuit Design, Noise, Grounding

- Noise

- Paths

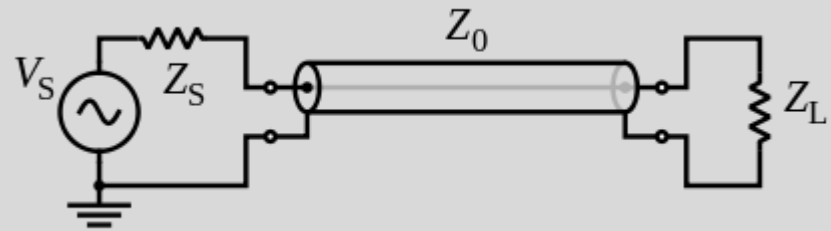
- Signal Input

- Antenna, transducer

-> matching network

- Previous Stage of Amps

-> termination

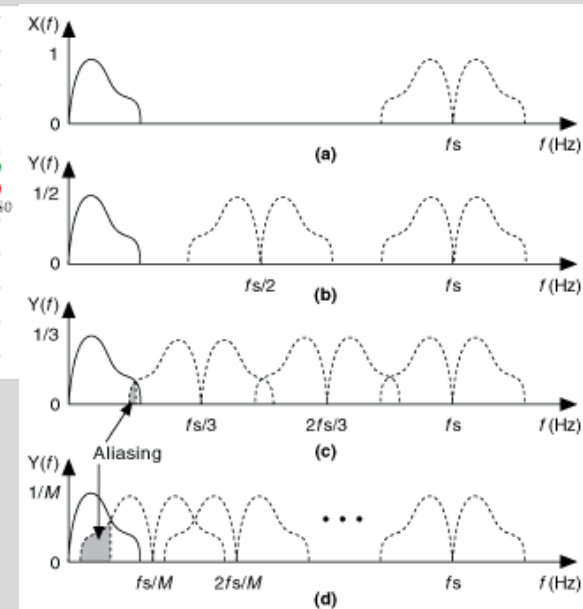
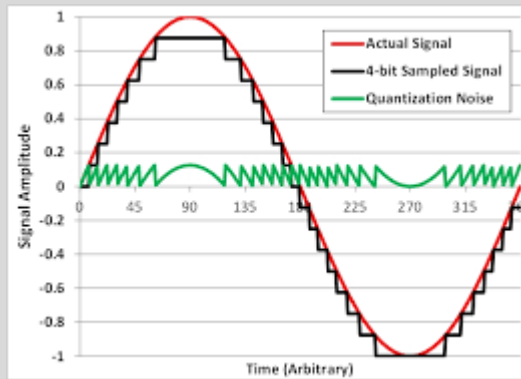


Source: Texas Instruments

$$F_n = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots$$

Circuit Design, Noise, Grounding

- Noise
 - Paths
 - Signal Input
 - ADC
 - Quantization ENOB
 - Aliasing

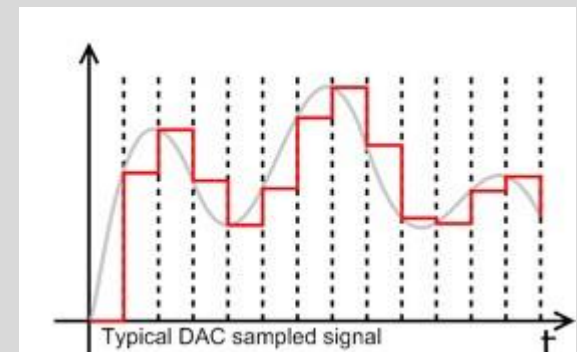
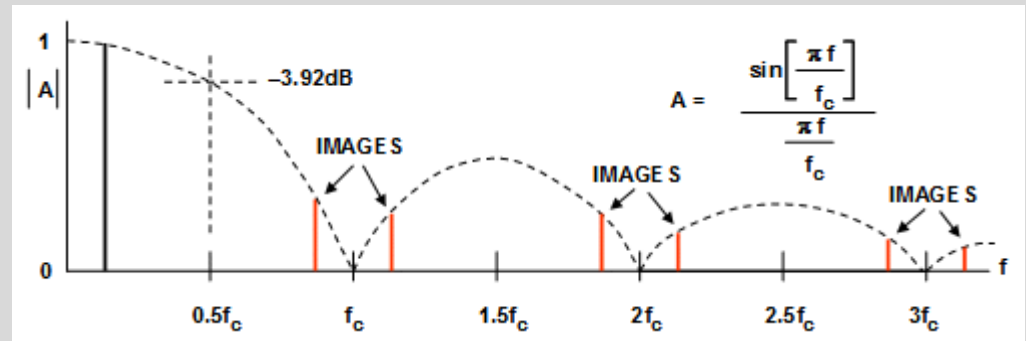


$$x[n] = \sum_n \int s(t) \delta(t - nT_S) dt$$

Circuit Design, Noise, Grounding

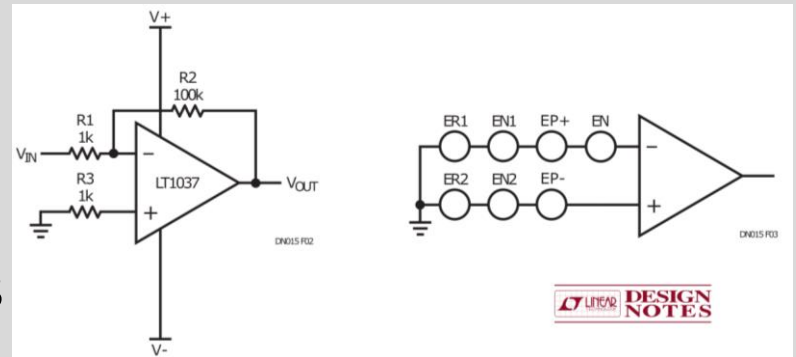
- Noise
 - Paths
 - Signal Input
 - DAC
 - Quantization ENOB
 - Mirror/Image

$$s(t) = \sum_n x[n] * \text{rect}\left(\frac{t}{T_S}\right)$$



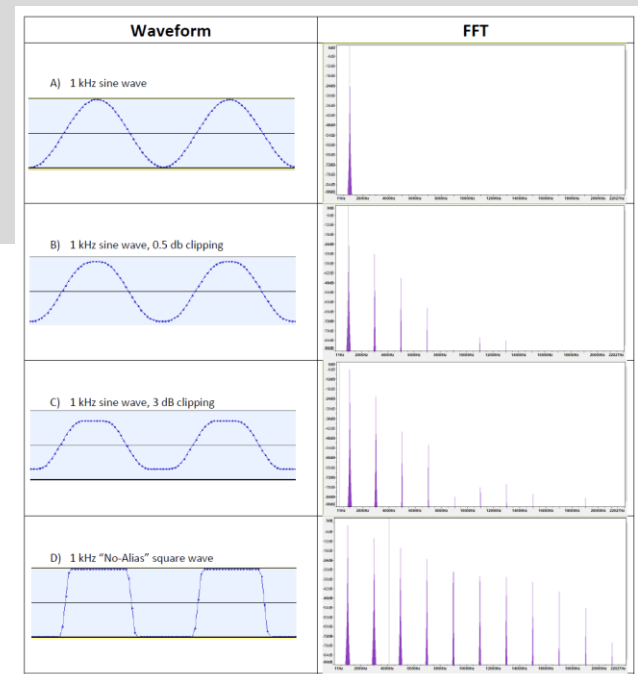
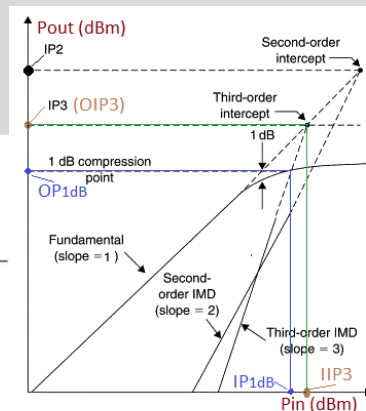
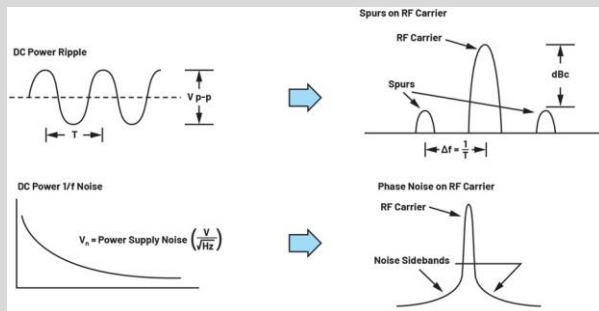
Circuit Design, Noise, Grounding

- Noise
 - Paths
 - Resistive Components
 - Semiconductor Devices



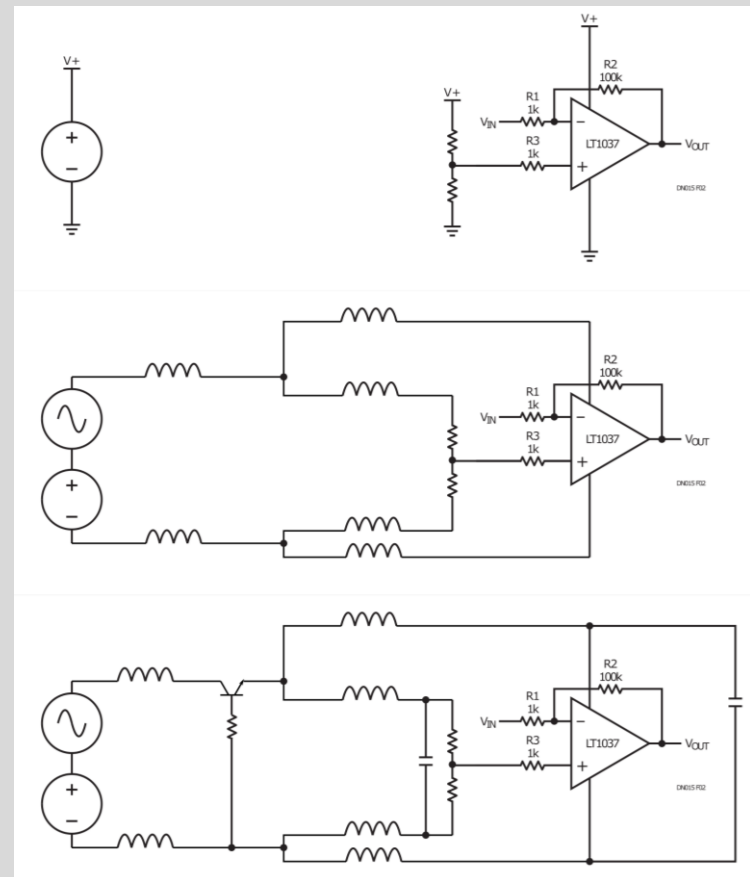
Circuit Design, Noise, Grounding

- Noise
 - Paths
 - Non-Linear (not LTI)



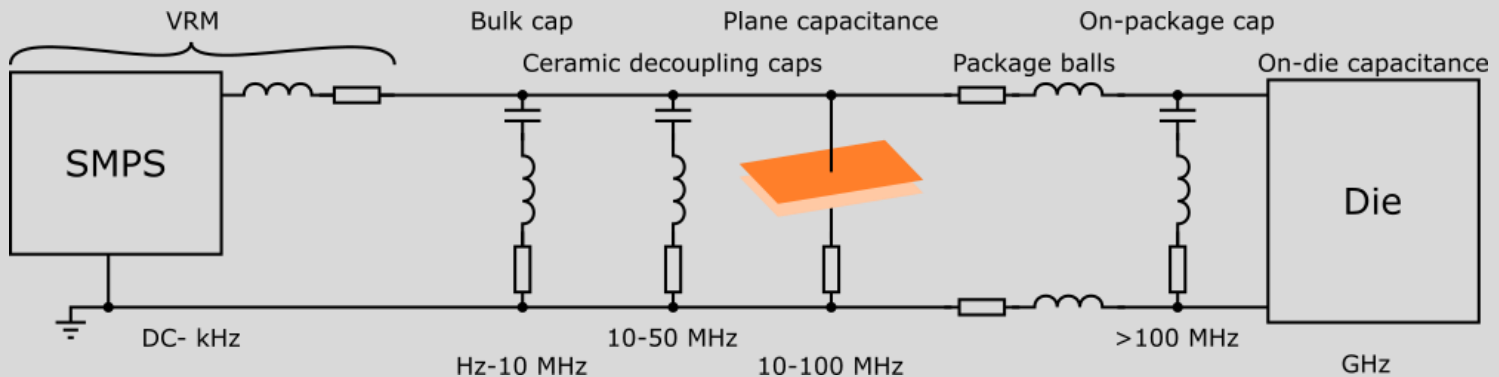
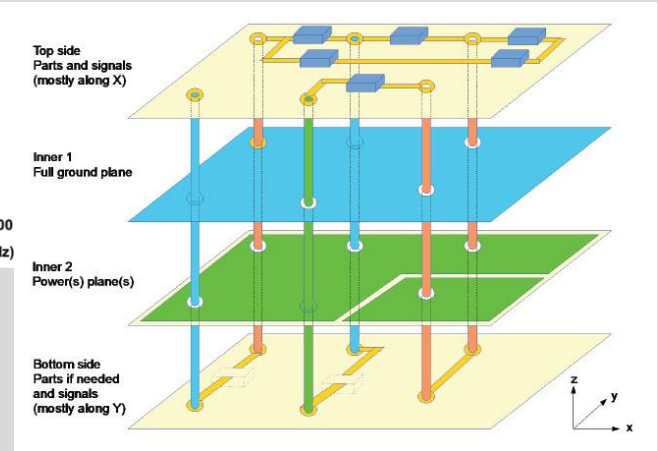
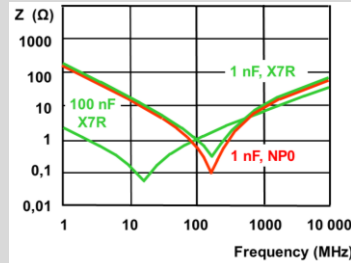
Circuit Design, Noise, Grounding

- Noise
 - Paths
 - Power Supplies
 - Indirect Coupling
 - Power integrity



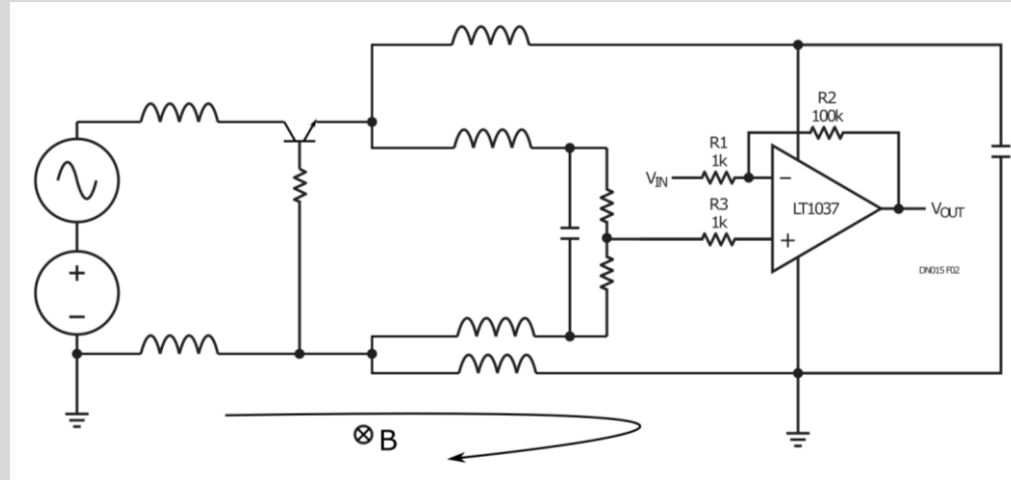
Circuit Design, Noise, Grounding

- Noise
 - Paths
 - Power Supplies
 - Indirect Coupling



Circuit Design, Noise, Grounding

- Grounding



Circuit Design, Noise, Grounding

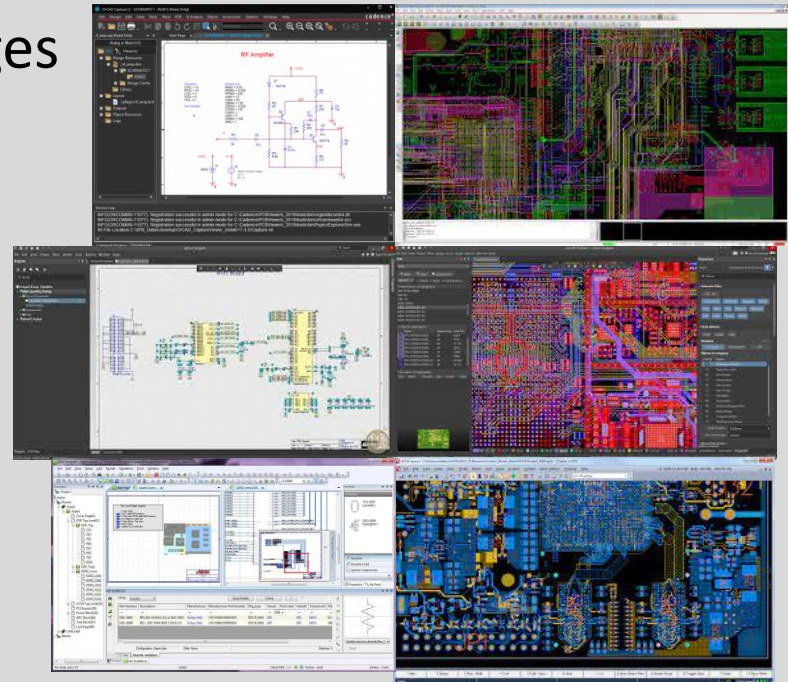
- Circuit Design SW Packages



- OrCAD/Allegro



ALTIUM
DESIGNER



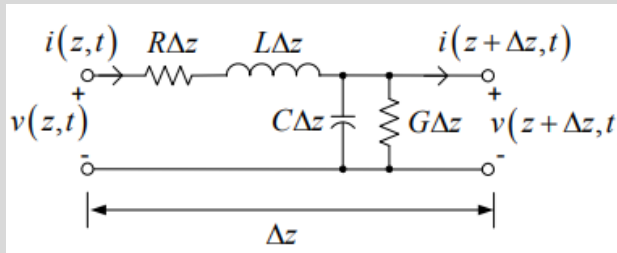
- 30th May 1500 & 2nd Jun 1100 by Dr Daniel Weatherill

Circuit Design, Amplifier, Clock

- Transmission Line Theory

$$v(z,t) = L\Delta z \frac{\partial i(z,t)}{\partial t} + v(z + \Delta z, t)$$

$$i(z,t) = C\Delta z \frac{\partial v(z + \Delta z, t)}{\partial t} + i(z + \Delta z, t)$$



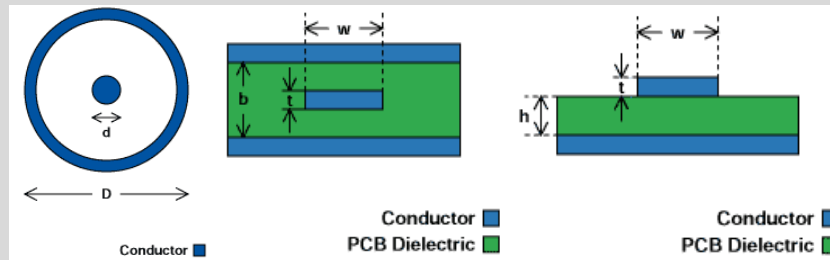
$$\frac{\partial v(z,t)}{\partial z} = -L \frac{\partial i(z,t)}{\partial t}$$

$$\frac{\partial i(z,t)}{\partial z} = -C \frac{\partial v(z,t)}{\partial t}$$

$$\frac{\partial^2 V}{\partial t^2} - u^2 \frac{\partial^2 V}{\partial x^2} = 0$$

$$\frac{\partial^2 I}{\partial t^2} - u^2 \frac{\partial^2 I}{\partial x^2} = 0$$

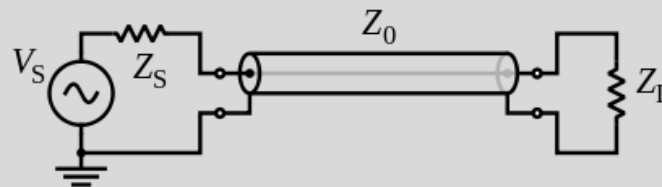
$$u = \frac{1}{\sqrt{LC}}$$



$$V(x) = V_1 e^{-jkx} + V_2 e^{+jkx}$$

$$I(x) = \frac{V_1}{Z_0} e^{-jkx} - \frac{V_2}{Z_0} e^{+jkx}$$

$$Z_0 = \sqrt{\frac{L}{C}}$$



Circuit Design, Amplifier, Clock

- Signal Integrity
 - Designing and Maintaining Trace Structure
 - Termination

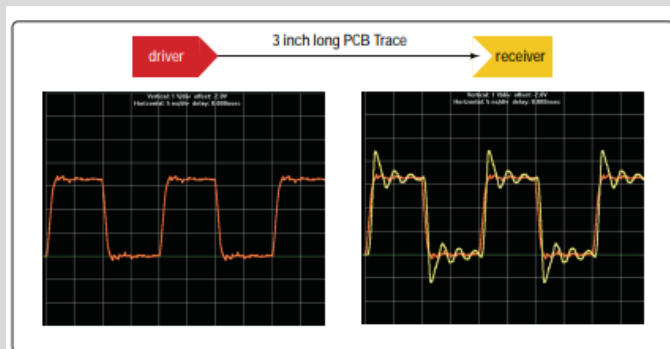
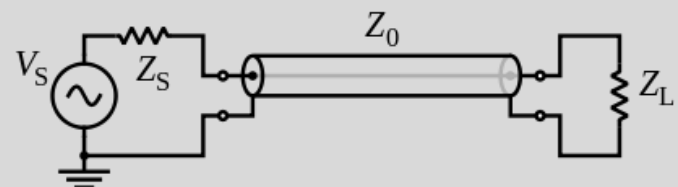
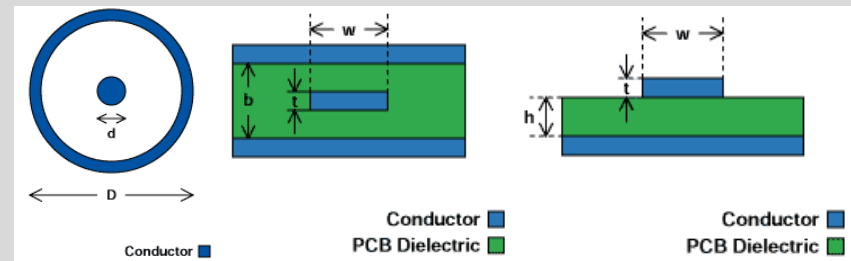


Figure 1. A signal as it emerges from the driver chip (left) is distorted by multiple reflections from impedance discontinuities at both ends (right).

Source: Keysight



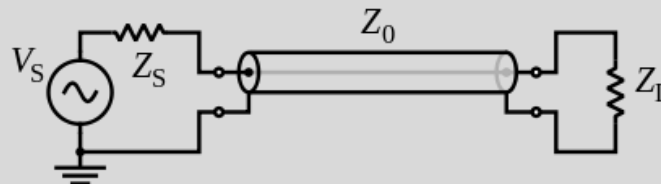
Circuit Design, Amplifier, Clock

- Scattering Parameter (S-Parameter)



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$


S_{11} is the input port voltage reflection coefficient
 S_{12} is the reverse voltage gain
 S_{21} is the forward voltage gain
 S_{22} is the output port voltage reflection coefficient.



Circuit Design, Amplifier, Clock


- Scattering Parameter (S-Parameter)

CMA-81+
SMT Gain Block, DC - 6000 MHz, 500



Generic photo used for illustration purposes only

- Ceramic, hermetically sealed nitrogen filled
- Low profile case, 0.045
- High IP3, +38 dBm



Data, Drawings & Downloads

- DATASHEET
- View Data
- View Graphs
- S-PARAMETERS

Mini-Circuits Laboratory
 iDate: 11/3/2015 at 1:45:13 PM
 IS2P DATA File Format
 IType: MMIC Amplifier
 IModel: CMA-81+
 IS/N: Unit 1
 IFixture: TB-829-81+ NO PORT EXTENSION.
 IPIN OUT: PORT 1 - PIN 2, PORT 2 - PIN 7, GROUND - 1,3,4,5,6,8,Bottom Center Paddle
 ITEST CONDITIONS: Temp= +85 (Deg C) RF Power= +25.00 (dBm) V limit=5(V) I limit=250(mA) Z=50 OHM
 IWAFFER/LOT#: n/a DATE CODE: 1448
 INetwork Analyzer: PNA-X N5242A S/N 71484 CAL DUE: 12/11/2015
 IP_Supply/Multimeter: HP E3632A S/N 63249 CAL DUE: 12/11/2015

HMC1049LP5E

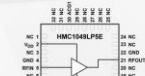
Global pHEMT MMIC Low Noise Amplifier, 0.3 - 20 GHz

Overview Evaluation Kits Documentation Tools & Simulations Reference Materials Design Resources

View All Data Sheets (2)

Data Sheet Rev. 8

S-Parameters



#	Hz	S	dB	R	50
1	Frequency	S11	Deg	S21	Deg
14	10000000	-44.3357200	-166.7859000	10.5643500	179.1727000
15	15000000	-38.1764500	-83.7452500	10.5889700	179.9357000
16	20000000	-42.6544600	167.7492000	10.5664400	178.6488000
17	25000000	-39.2277800	159.5075000	10.5462600	178.8562000
18	30000000	-43.5065400	178.5663000	10.5655900	177.9172000
19	35000000	-45.7234300	-162.4352000	10.5566000	177.6096000
20	40000000	-42.7495200	-168.8238000	10.5678200	177.2186000
21	45000000	-41.7412000	-172.4569000	10.5645000	176.8549000
22	50000000	-41.7112100	-172.0631000	10.5706900	176.5308000
23	55000000	-40.9887200	-171.4834000	10.5617000	176.2349000
24	60000000	-40.5970600	-173.2739000	10.5600300	175.9174000
25	65000000	-40.4775000	-173.6170000	10.5591500	175.5924000
26	70000000	-39.8875100	-168.1615000	10.5574100	175.2423000
27	75000000	-39.6015700	-166.5091000	10.5573000	174.9256000

Agilent Technologies, E8361A, UC43140893, A.06.04.32

iDate: Wednesday, November 18, 2012 13:50:33

ICorrection: S11(Full 2 Port(1,2)) S21(Full 2 Port(1,2)) S12(Full 2 Port(1,2)) S22(Full 2 Port(1,2))

IS2P File: Measurements: S11, S21, S12, S22:

GHz S dB R 50

7	0.01	-2.404	-11.185	19.791	170.825	-39.68	70.612	-12.811	177.269
8	0.10998	-9.163	-64.832	17.03	156.889	-28.235	13.797	-7.916	172.448
9	0.20996	-13.177	-62.163	16.620	148.303	-27.393	-9.018	-7.766	155.6
10	0.30994	-15.535	-93.74	16.519	137.192	-27.165	-25.482	-7.761	141.733
11	0.40992	-16.953	-105.416	16.465	125.605	-27.073	-39.5	-7.745	128.004
12	0.5099	-18.051	-119.821	16.497	113.637	-26.972	-52.631	-7.773	114.765
13	0.60988	-18.887	-128.091	16.337	100.94	-27.044	-65.903	-7.571	102.589
14	0.70986	-18.973	-143.089	16.306	89.493	-27.005	-77.713	-7.52	89.117
15	0.80984	-19.327	-158.168	16.297	77.6	-26.937	-89.845	-7.5	76.342
16	0.90982	-19.671	-174.056	16.298	65.561	-26.856	-101.935	-7.501	63.655
17	1.0098	-19.878	-169.391	16.314	53.504	-26.791	-114.001	-7.489	51.038
18	1.10978	-20.069	-153.053	16.356	41.451	-26.714	-126.062	-7.486	38.615
19	1.20976	-20.33	-136.8	16.407	29.389	-26.636	-138.179	-7.538	26.456
20	1.30974	-20.619	-121.384	16.457	17.241	-26.558	-150.476	-7.538	14.6
21	1.40972	-20.975	-106.042	16.538	4.789	-26.486	-162.915	-7.631	2.946
22	1.5097	-21.196	-92.108	16.639	-8.001	-26.44	-175.463	-7.745	-8.515
23	1.60968	-21.502	-79.294	16.714	-20.955	-26.413	-171.873	-7.848	-19.713
24	1.70966	-21.715	-69.223	16.751	-33.999	-26.443	-159.341	-7.921	-30.536
25	1.80962	-21.544	-60.676	16.727	-47.11	-26.508	-147.074	-7.946	-41.117
26	1.90962	-20.897	-51.647	16.659	-60.31	-26.576	-135.068	-7.924	-51.671
27	2.0096	-19.986	-40.849	16.587	-73.361	-26.624	-123.303	-7.899	-62.406
28	2.10958	-19.116	-29.105	16.508	-86.045	-26.645	-111.609	-7.877	-73.466
29	2.20956	-18.243	-16.012	16.408	-98.481	-26.617	-100.072	-7.851	-84.998

Circuit Design, Amplifier, Clock

- Matching Network

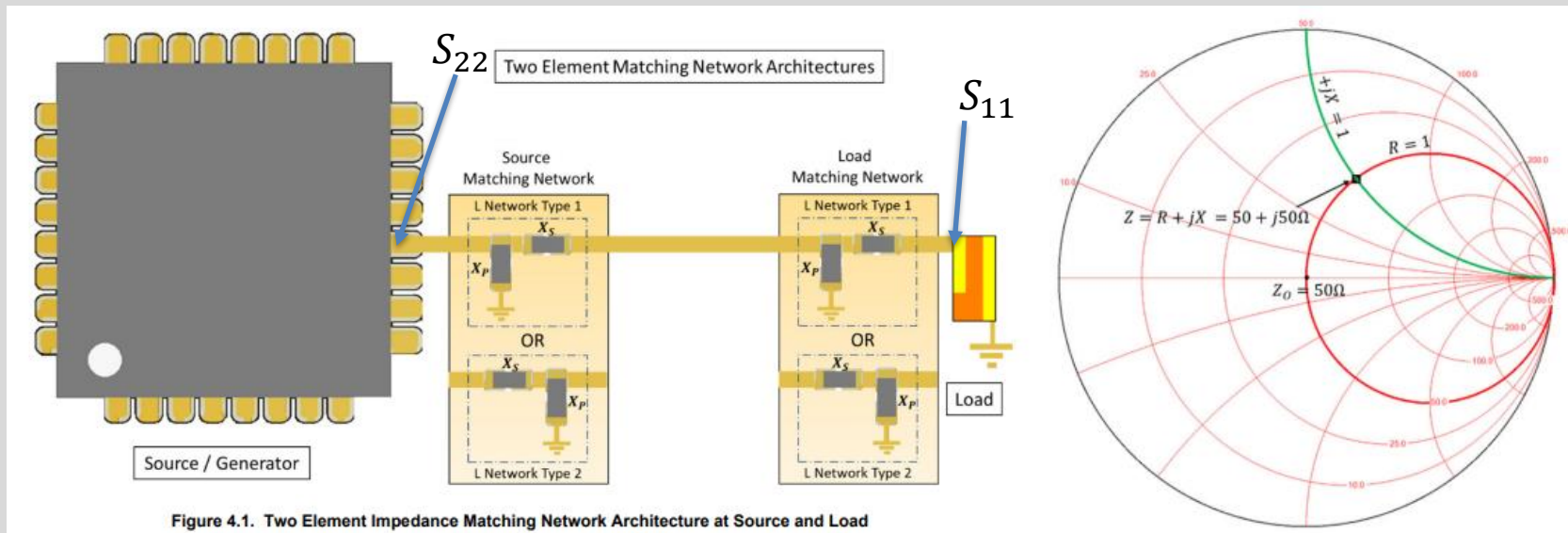
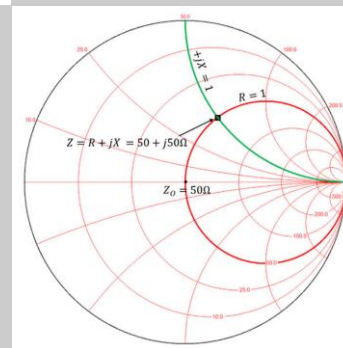
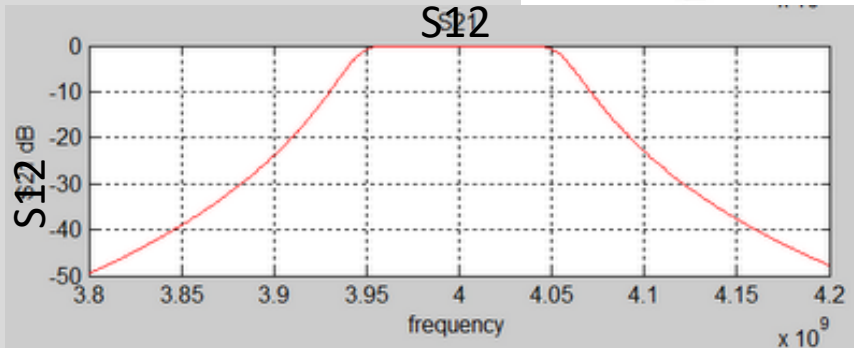
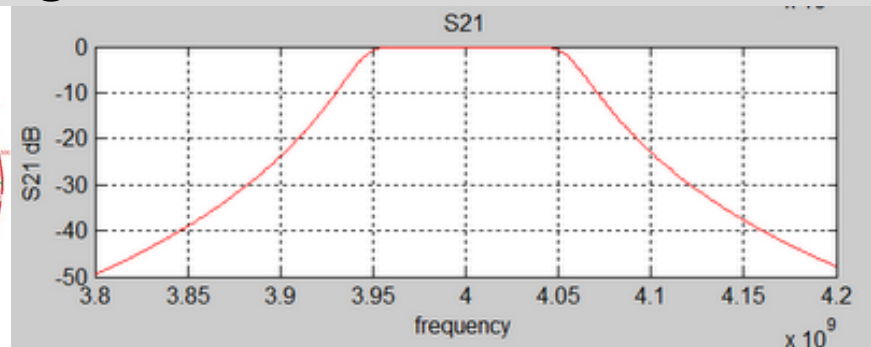
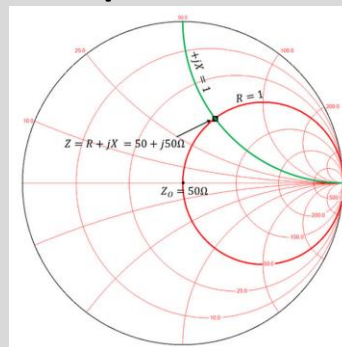


Figure 4.1. Two Element Impedance Matching Network Architecture at Source and Load

Source: SiLabs

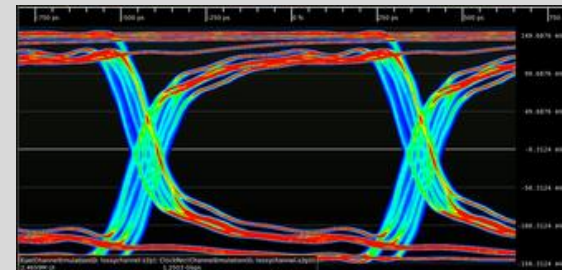
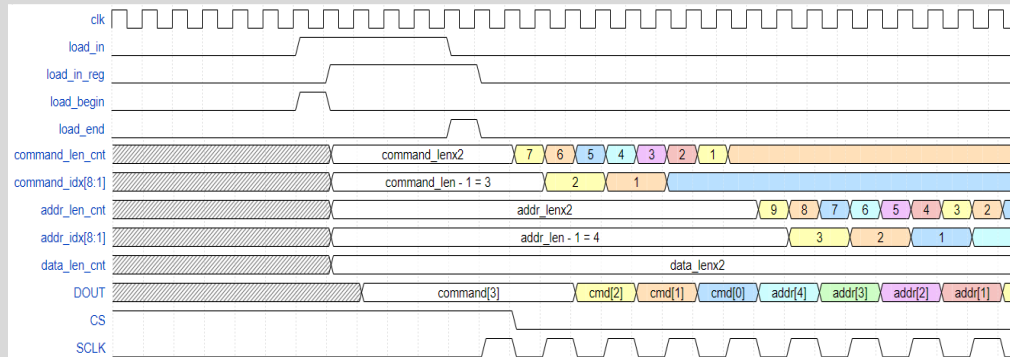
Circuit Design, Amplifier, Clock

- Simulation of Amplifier Design



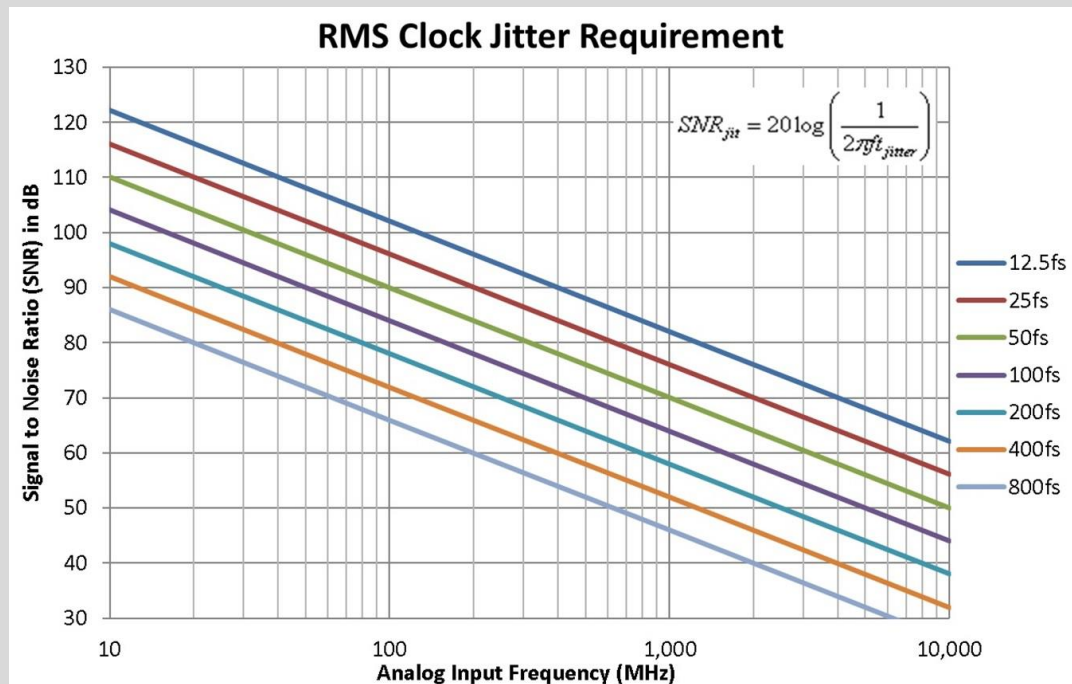
Circuit Design, Amplifier, Clock

- Clock Jitter/Phase noise in Digital System/Comms



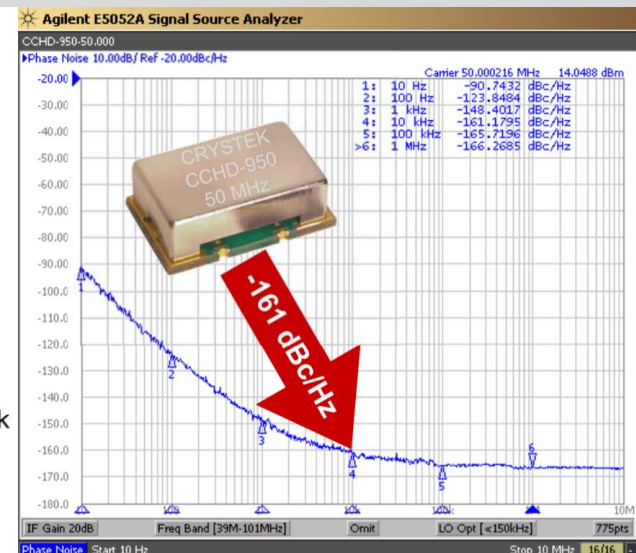
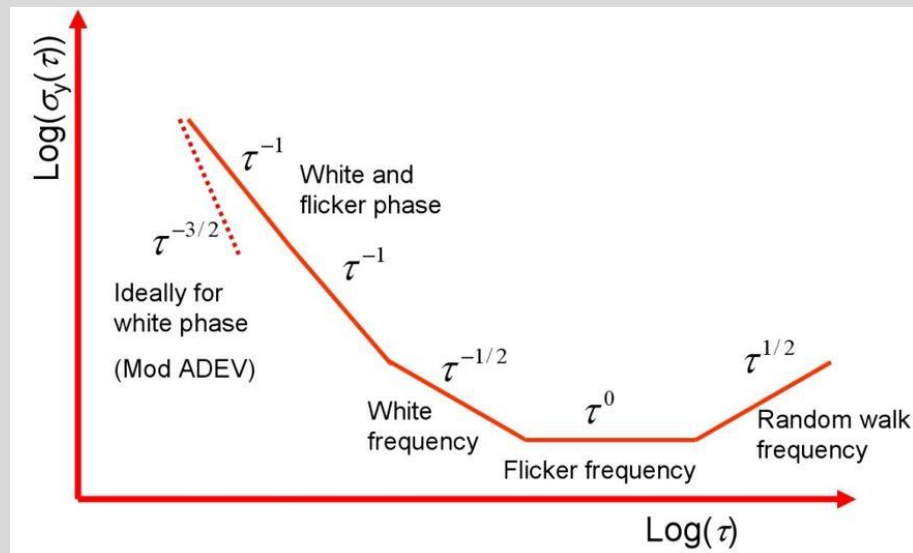
Circuit Design, Amplifier, Clock

- Clock Jitter/Phase noise in DAQ



Circuit Design, Amplifier, Clock

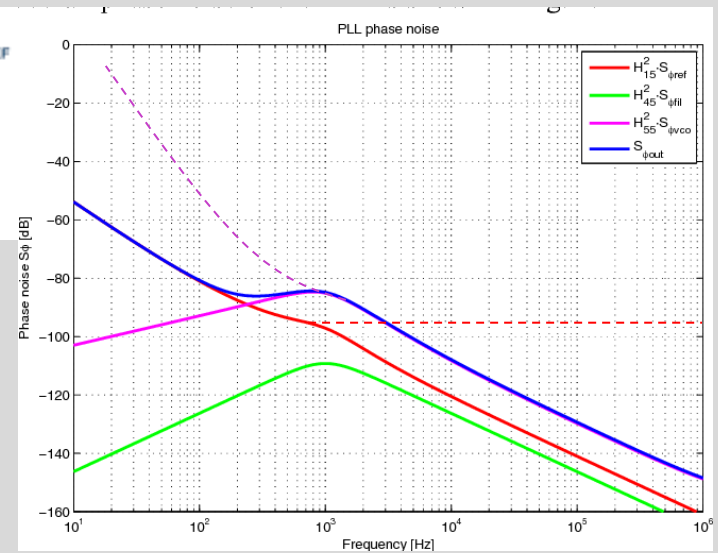
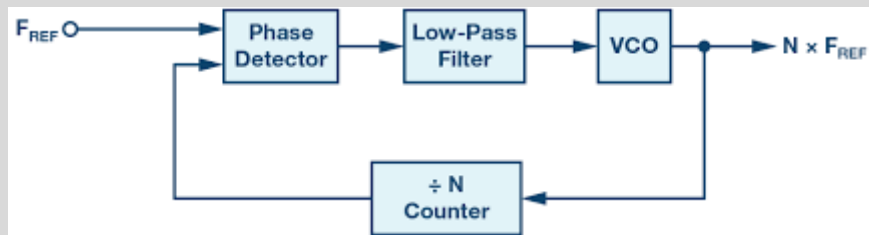
- Clock Jitter/Phase noise



Source: NIST

Circuit Design, Amplifier, Clock

- Phase Locked Loop



Circuit Design, Amplifier, Clock

• How to read datasheet

HMC1049LP5E

FEATURES

- Low noise figure: 1.8 dB
- P1dB output power: 14.5 dBm
- P_{SAT} output power: 17.5 dBm
- High gain: 15 dB
- Output IP3: 29 dBm
- Supply voltage: $V_{DD} = 7$ V at 70 mA
- 50 Ω matched input/output (I/O)
- 32-lead, 5 mm x 5 mm LFCSP package: 25 mm²

APPLICATIONS

- Test instrumentation
- High linearity microwave radios
- VSAT and SATCOM
- Military and space

GENERAL DESCRIPTION

The HMC1049LP5E is a GaAs MMIC low noise amplifier (LNA) that operates between 0.3 GHz and 20 GHz. This LNA provides 15 dB of small signal gain, 1.8 dB noise figure, and an IP3 output of 29 dBm, yet requires only 70 mA from a 7 V supply. The P1dB output power of 14.5 dBm enables the LNA to function as a local oscillator (LO) driver for balanced, I/Q, or image rejection mixers. V_{DD} can also be applied to Pin 21, although Pin 21 requires a bias tee with $V_{DD} = 4$ V. The HMC1049LP5E amplifier I/Os are internally matched to 50 Ω , and the device is supplied in a compact, leadless 5 mm x 5 mm LFCSP package.

Figure 1.

HMC1049LP5E

SPECIFICATIONS

$T_A = 25^\circ\text{C}$, $V_{DD} = 7$ V, $I_{DD} = 70$ mA¹.

Table 1.

Parameter	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Unit
FREQUENCY RANGE	0.3			1			14		20	GHz
GAIN	13.5	16.5		12	15		10	13		dB
Gain Variation Over Temperature		0.006			0.019			0.017		dB/°C
NOISE FIGURE		2.5	3.5		1.8	2.5		2.7	4.0	dB
RETURN LOSS										
Input		15			13			14		dB
Output			8		15			13		dB
OUTPUT										
Output Power for 1 dB Compression (P1dB)		15			14.5			13		dBm
Saturated (P_{SAT})		18			17.5			16		dBm
Output Third-Order Intercept (IP3) ²		31			29			26		dBm
TOTAL SUPPLY CURRENT		70			70			70		mA

¹ Adjust V_{DD} between -2 V to 0 V to achieve $I_{DD} = 70$ mA typical.
² Measurement taken at P_{1dB} to $I_{DD} = 8$ dBm.

HMC1049LP5E Data Sheet

ABSOLUTE MAXIMUM RATINGS

Table 2.

Parameter	Rating
Drain Bias Voltage (V_{DD})	10 V
Drain Bias Voltage (RF Out/ V_{DD})	7 V
RF Input Power	18 dBm
Gate Bias Voltage, V_{GG}	-2 V to +0.2 V
Channel Temperature	175°C
Continuous P_{DSS} ($T = 85^\circ\text{C}$) (Derate 37.1 mW/°C Above 85°C)	3.34 W
Thermal Resistance (Channel to Ground Paddle)	26.9°C/W
Temperature	
Storage Temperature	-65°C to +150°C
Operating Temperature	-40°C to +85°C
ESD Sensitivity (HBM)	Class 1A

Table 3. Typical Supply Current vs. V_{DD}

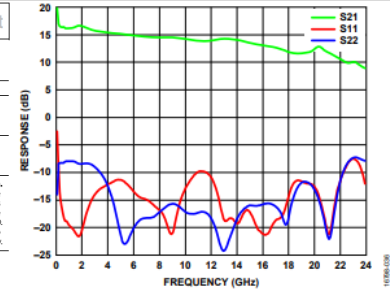
V_{DD} (V)	I_{DD} (mA)
5	70
6	70
7	70

¹ Adjust V_{DD} to achieve $I_{DD} = 70$ mA.

ESD CAUTION

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.

Stresses at or above those listed under Absolute Maximum Ratings may cause permanent damage to the product. This is a stress rating only; functional operation of the product at these or any other conditions above those indicated in the operational section of this specification is not implied. Operation beyond the maximum operating conditions for extended periods may affect product reliability.



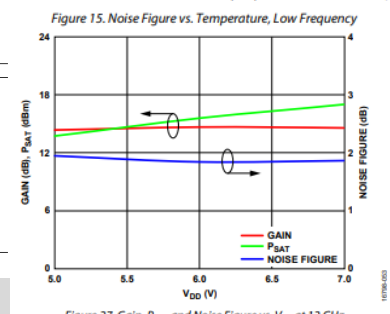
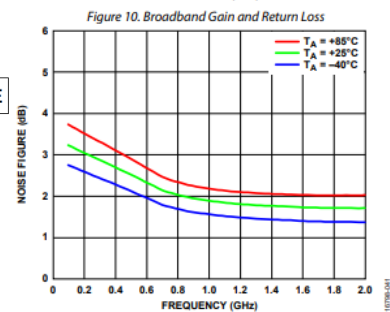
HMC1049LP5E Data Sheet

PIN CONFIGURATION AND FUNCTION DESCRIPTIONS

Table 4. Pin Function Descriptions

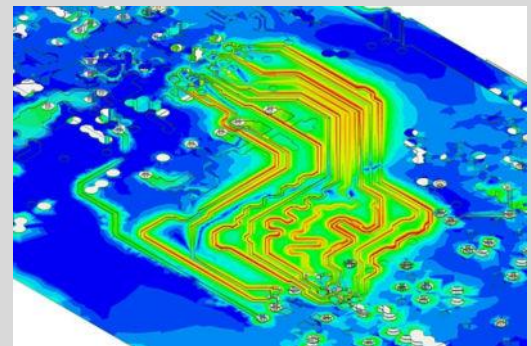
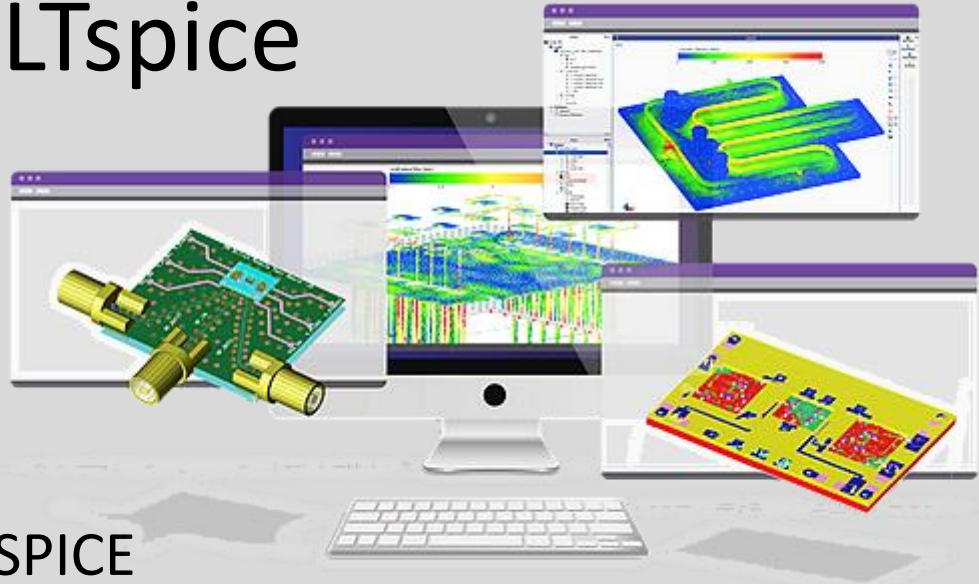
Pin No.	Mnemonic	Description ¹
1, 3, 6 to 12, 14, 17 to 20, 23 to 29, 31, 32	NC	No Connect. These pins are not connected internally; however, all data was measured with these pins connected to RF/dc ground externally (see the Typical Performance Characteristics section for data plots).
2	RFIN	RF Input. This pin is dc-coupled and matched to 50 Ω .
5	V_{DD}	Power Supply Voltage for the Amplifier. External bypass capacitors (100 pF and 0.01 μ F) are required.
30	RFOUT/ V_{DD}	Low Frequency Termination. An external bypass capacitor of 100 pF is required.
21	RFOUT/ V_{DD}	RF Output/Alternate Power Supply Voltage for the Amplifier. An external bias tee is required when used as an alternative V_{DD} . This pin is dc-coupled and matched to 50 Ω .
15, 16	ACG2, ACG3	Low Frequency Termination. External bypass capacitors of 100 pF are required.
13	V_{GG}	Gate Control for Amplifier. Adjust the voltage to achieve $I_{DD} = 70$ mA. External bypass capacitors of 100 pF, 0.01 μ F, and 4.7 μ F are required.
4, 22	GND	Ground. Connect Pin 4 and Pin 22 to RF/dc ground.
0	EP	Exposed Pad. The exposed ground paddle must be connected to RF/dc ground.

¹ See the Interface Schematics section for pin interfaces.



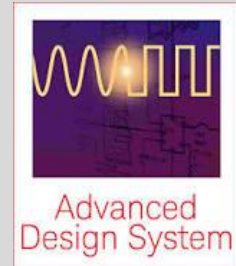
Simulation - LTspice

- Schematic Level
- Layout Level
- Structural model – SPICE
- Behavioral model – IBIS
- Scattering model – S-parameter



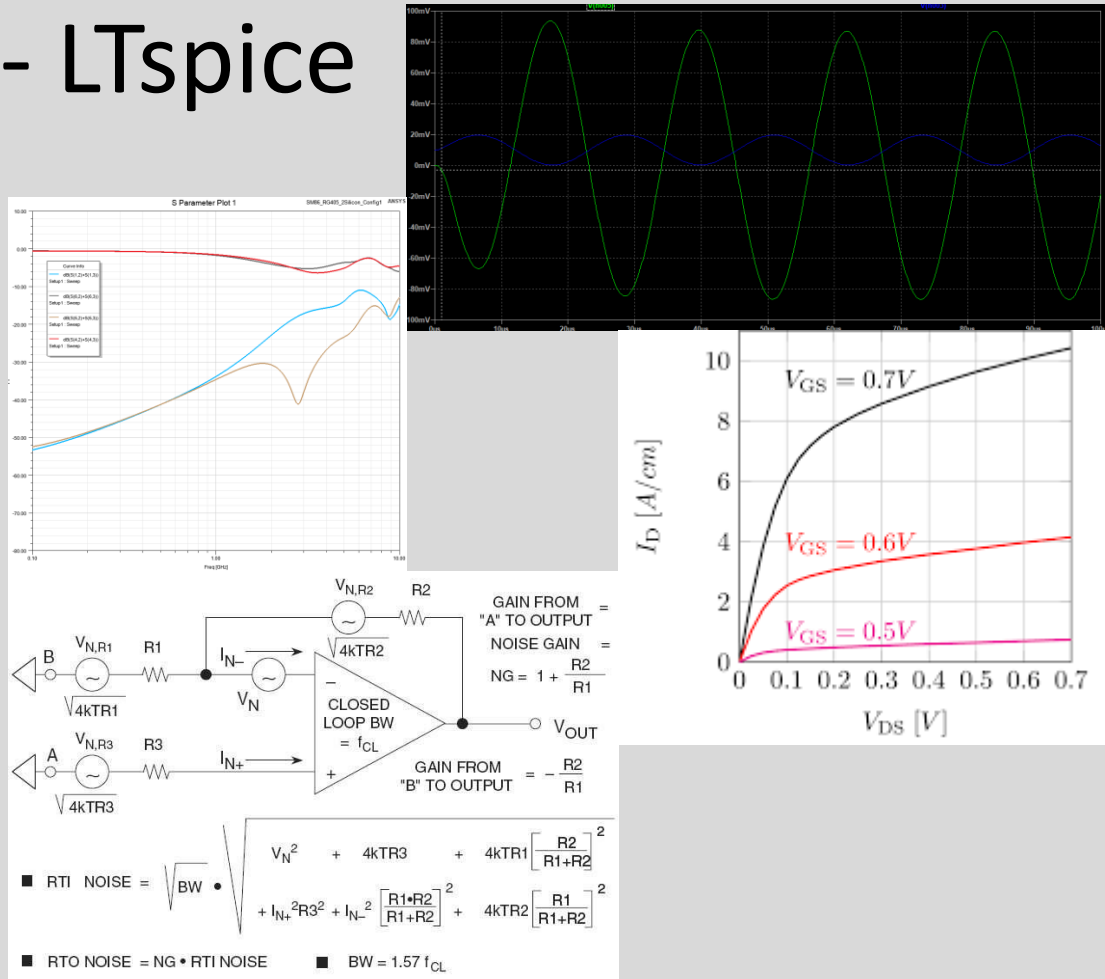
Simulation - LTspice

- ADS by Keysight
- Electronics Desktop by Ansys
- LTspice by Analog Devices
- Qucs (under GPL license)



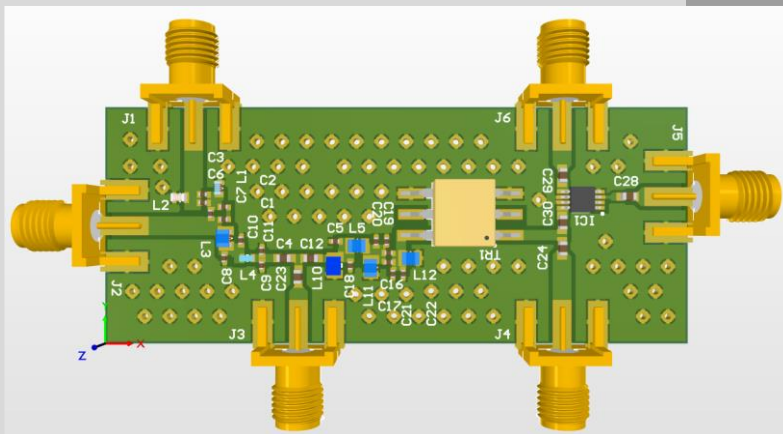
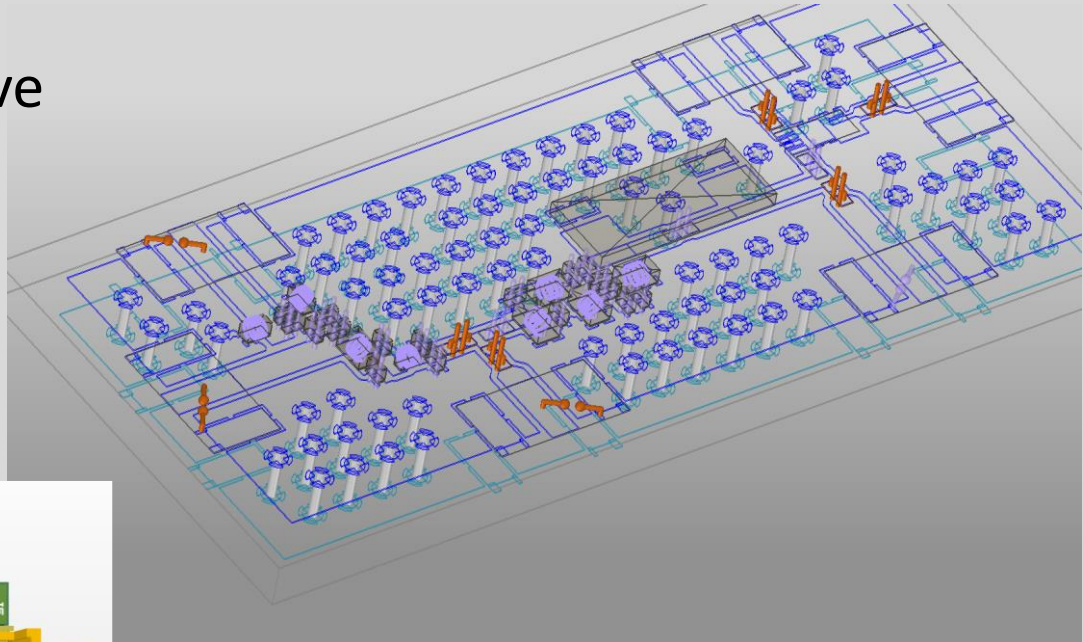
Simulation - LTspice

- Transient
- AC
- DC Sweep
- Noise



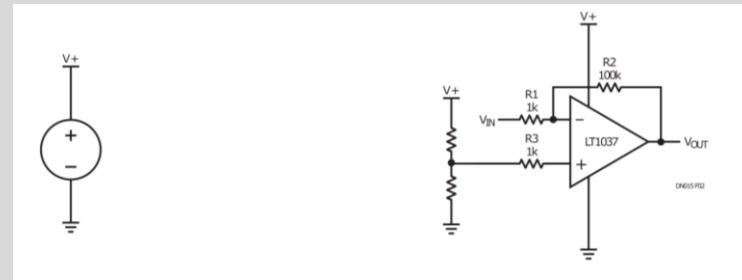
Simulation - LTspice

- Layout Level - SIwave




Simulation - LTspice

- Transient
- AC
- Noise



Simulation – Qucs – Match Circuit



Low Noise Amplifier,
0.01 GHz to 10 GHz

Data Sheet HMC8411LP2FE

FEATURES

- Low noise figure: 1.7 dB typical
- Single positive supply (self biased)
- High gain: 15.5 dB typical
- High OIP3: 34 dBm typical
- 6-lead, 2 mm x 2 mm LFCSP

FUNCTIONAL BLOCK DIAGRAM

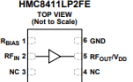


Figure 1.

APPLICATIONS

- Test instrumentation
- Military communications