Understanding Amplifiers

ROBIN GETZ
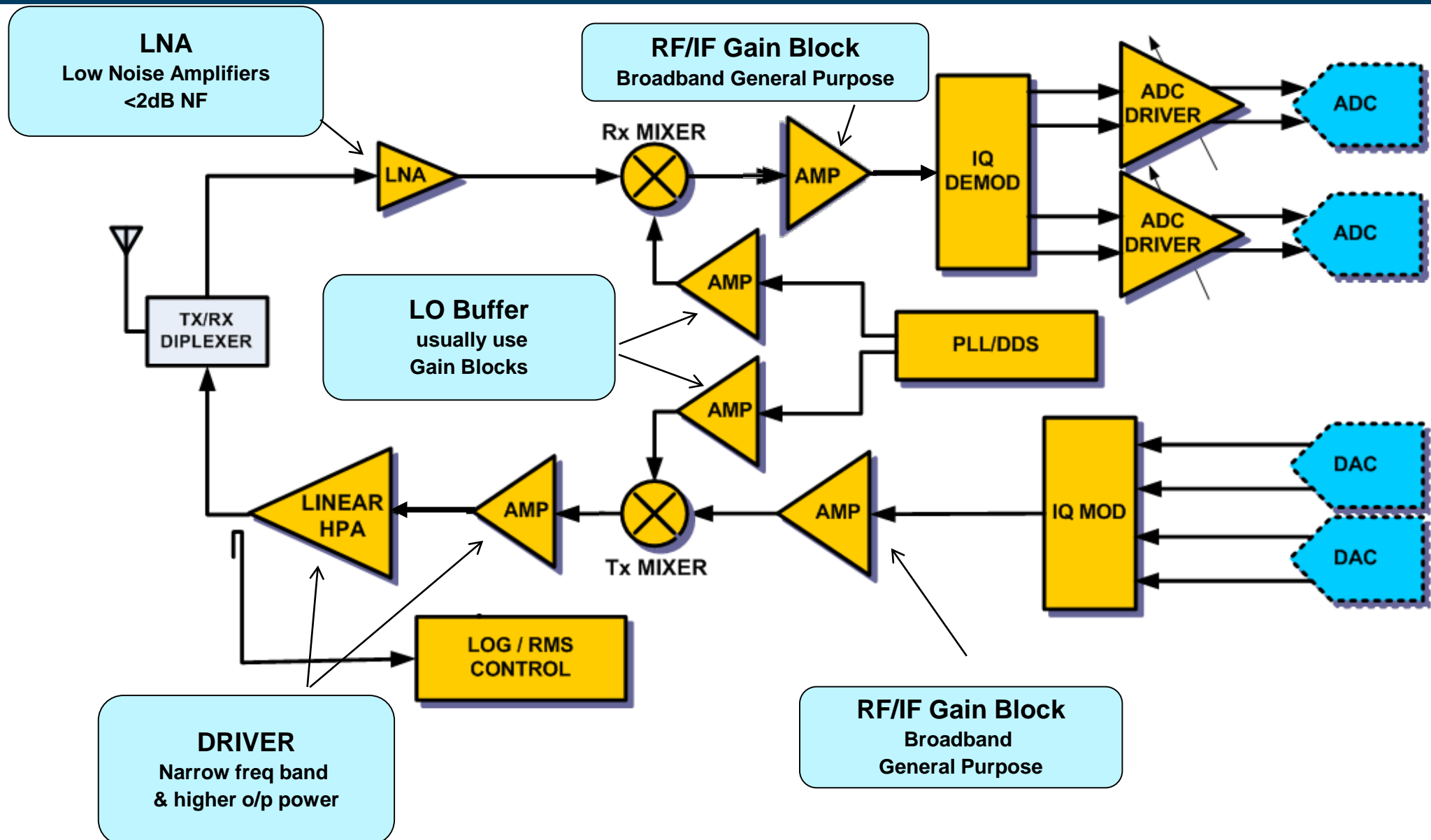
ENGINEER

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Communication, but further …

► Various forms of communication have evolved over the millennia.

► The spoken word can be transmitted from one person, and heard or received by another.

► In modern times town criers hold an annual contest to discover who can shout a comprehensible message over the greatest distance [1]. However, while the world record is for loudest crier is 112.8 decibels, it can only be understood at less than 100 meters.

► RF can do better!

► American Guild Of Town Criers Website, 1997 http://www.americantowncriers.com/

http://bernews.com/2017/04/town-crier-competition-2017-results/

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RF Amplifiers in Wireless Signal Chains

► The op-amps of the RF World

► Usually Fixed gain (specified in dB)

► Single-Ended Inputs and Outputs

► $\dfrac{Z_{in}}{Z_{out}}$ = 50 Ohms (with internal or external matching)

► Power Supply fed via inductor into RF Output

► Key Specs

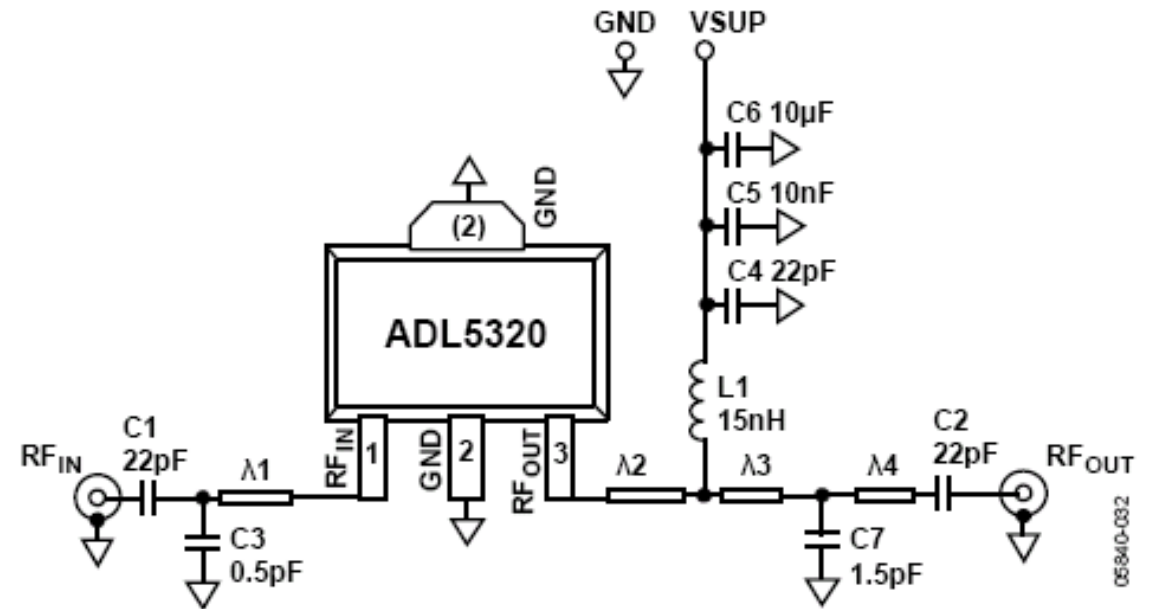 ▪ IP3 Distortion (dBm)
  ▪ Noise Figure (dB)
  ▪ Power Consumption

Figure 32. Evaluation Board, 1805 MHz to 2170 MHz

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RF Amplifiers vs. Op Amps

► RF Amps
- Input and Output Impedance is 50-1000 Ω
- Fixed Gain (usually)
- Specify Noise as Noise Figure (dB)
  - usually in a 50Ω system
- Specify power-handling capability as P1dB
- Specify Intermodulation Distortion
  - IP2, IP3
- DC Specs (e.g. offset voltage) are N/A

► Op Amps
- High Input Impedance
- Very Low Output Impedance
- Gain set using Feedback
- Specify Noise in nV/$\sqrt{Hz}$
- Specify Voltage Swing (rail-to-rail, etc.)
- Specify Harmonic Distortion
  - THD
- Offset Voltage, Bias Current, Offset Current
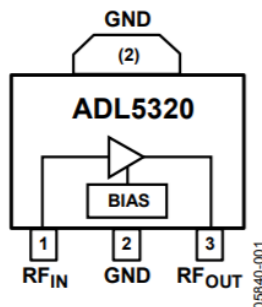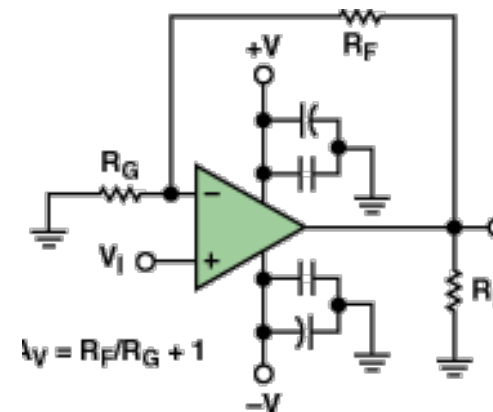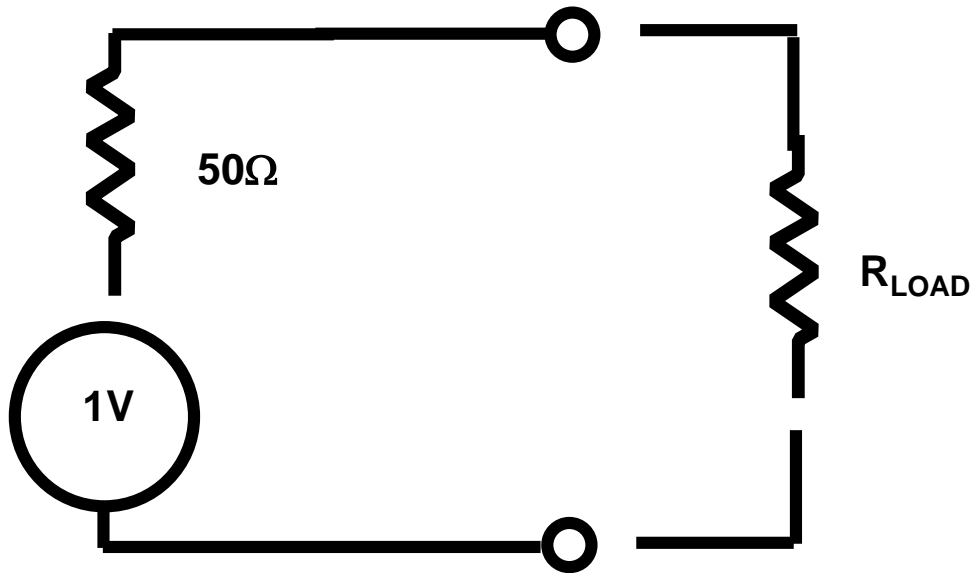
FUNCTIONAL BLOCK DIAGRAM

GND
(2)

ADL5320

BIAS

1 RF$_{IN}$ 2 GND   3 RF$_{OUT}$

05840-001

Figure 1.

+V   R$_F$

R$_G$

V$_I$

$A_V = R_F/R_G + 1$

−V

R$_L$

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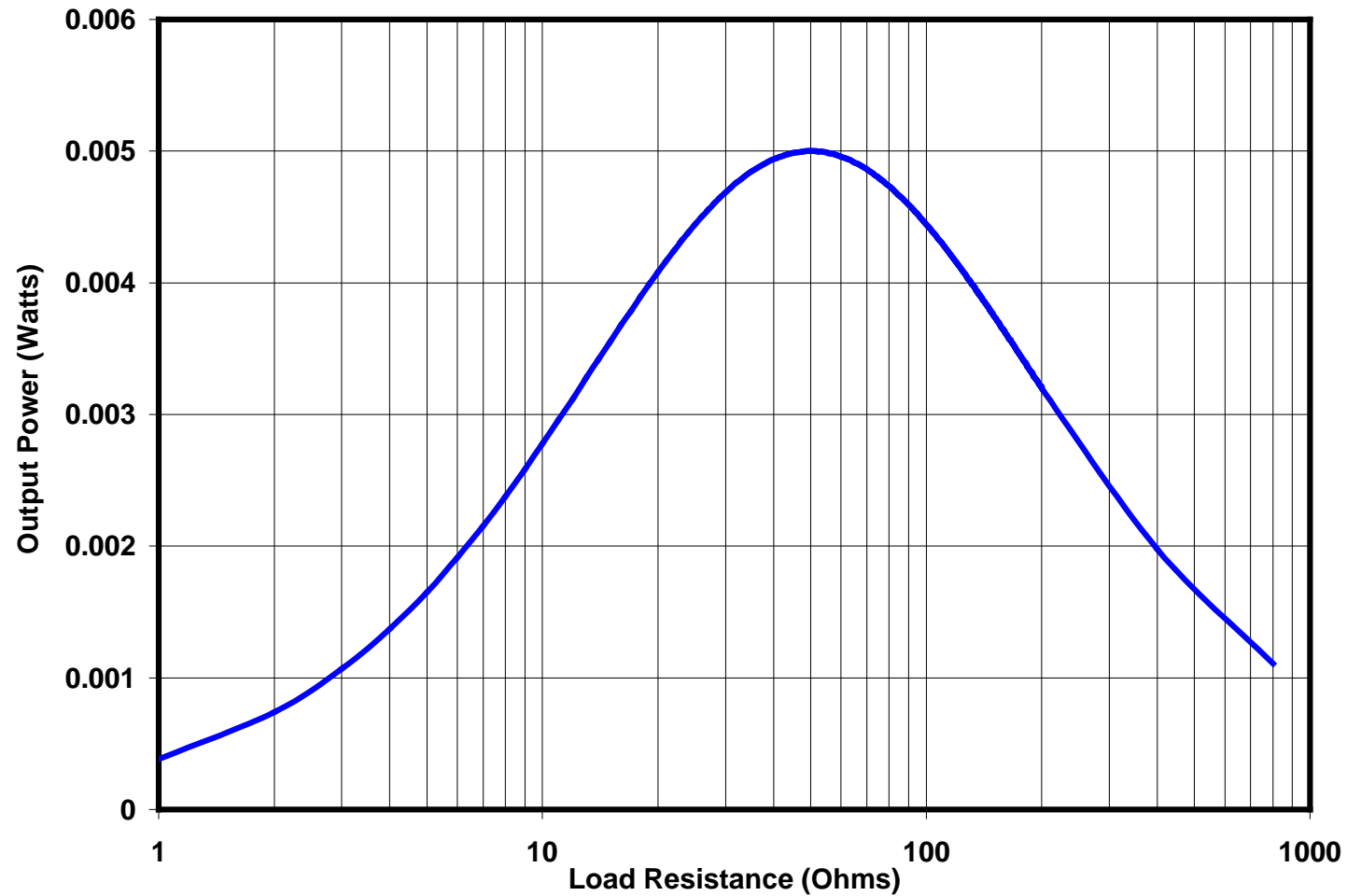# Impedance Matching and RF Power Transfer

►What is the Load Impedance for maximum power transfer?

50Ω

1V

R$_{LOAD}$

P$_{OUT}$/V$_{OUT}$

$$P_{OUT} = \frac{V_I^2 \times R_{LOAD}^2}{R_{LOAD}^2 \times R_{SOURCE}^2 \times 2R_{SOURCE}R_{LOAD}}$$
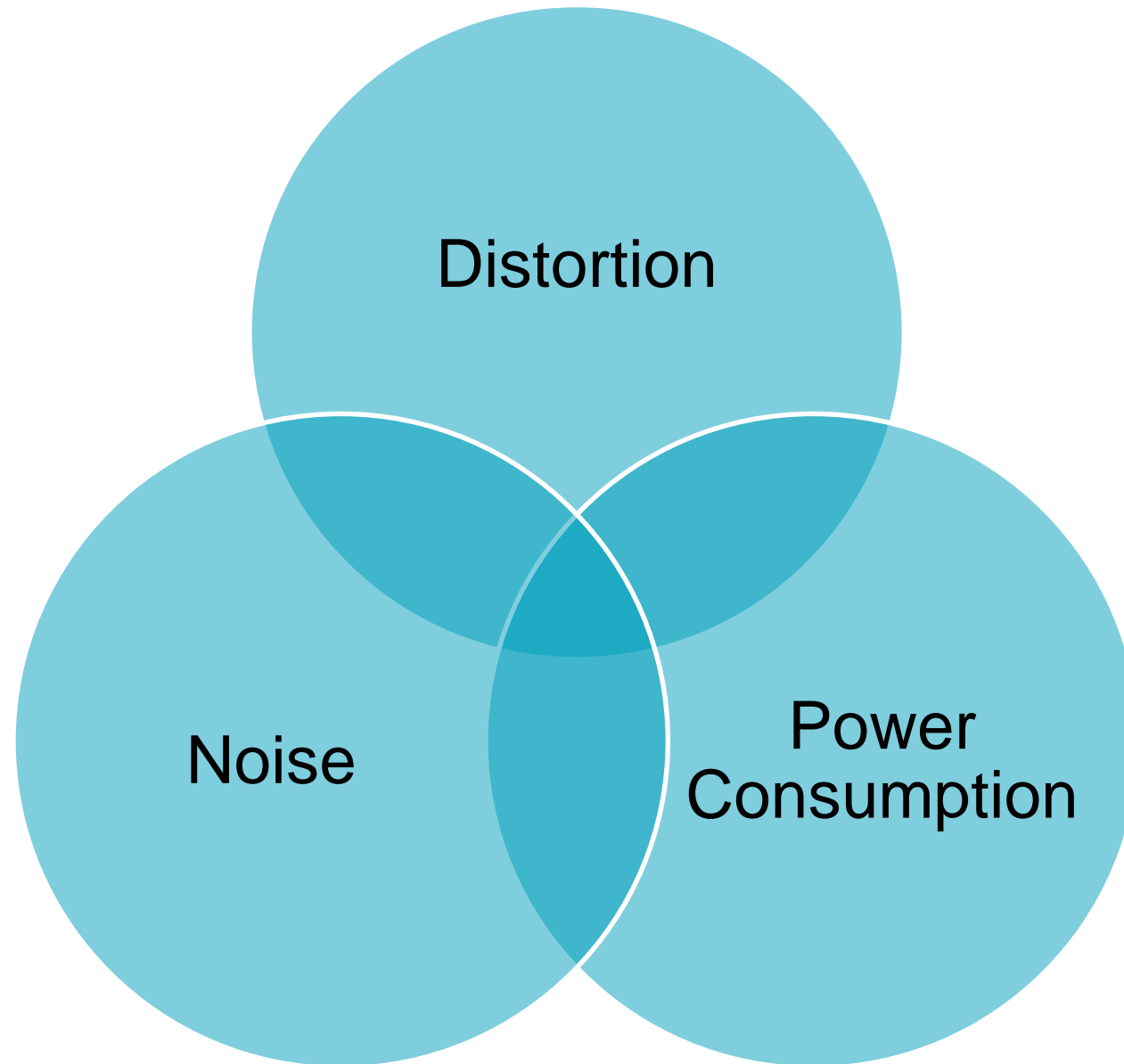
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Conditions for optimum power transfer

◆ **Surprise! It's 50 Ohms**

◆ **Matching Load to Source Resistance facilitates max power transfer**

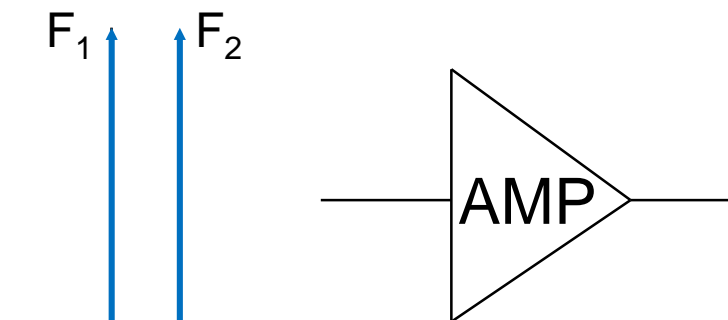ANALOG
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RF Amplifier Specifications

What are the Critical RF Amplifier Specifications?

Distortion

Distortion

Fundamentals

2nd harmonics

F_1 F_2

$2F_1$ $2F_2$

$2F_1-F_2$ $2F_2-F_1$

F_2-F_1 F_1+F_2

3rd order imd

2nd order imd

F_1 F_2

AMP
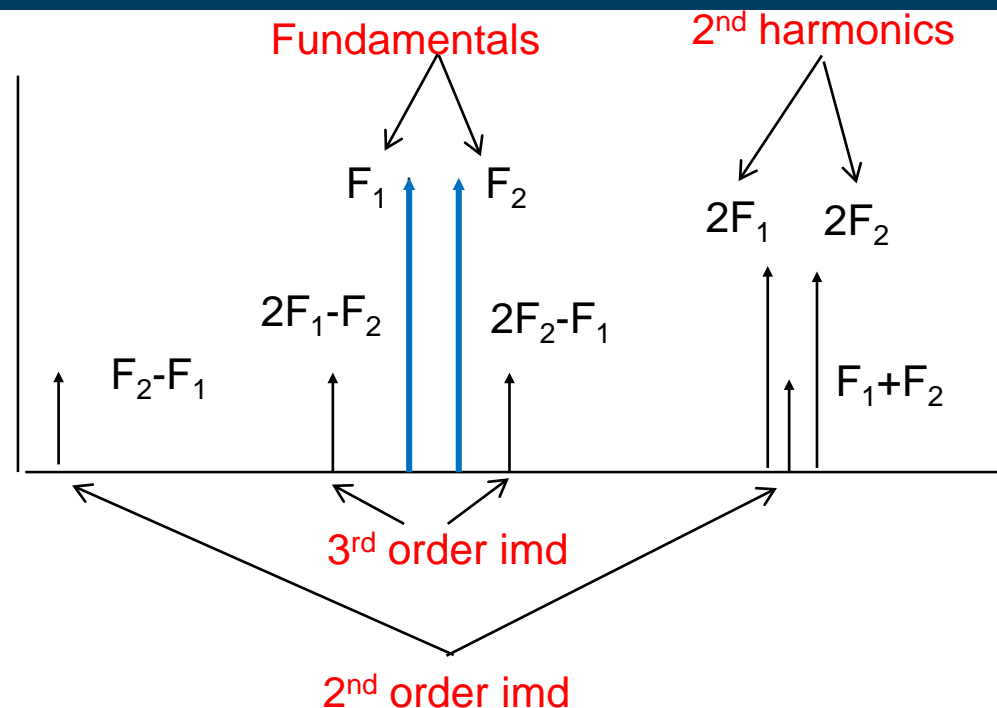
- ► In wireless systems, simple harmonics (i.e. 2nd, 3rd, 4th, etc) generally fall in another band and are eliminated by band filters.
- ► Of much greater concern are the harmonics which are produced when two signals intermodulate with one another or when a wideband carrier intermodulates with itself)
- ► IMD products are produced by all active components (mixers, amps, ADCs, DACs)

- ► Third Order IMD Products (close to carrier, nF_1+-mF_2, n+m=3) are most troublesome
  - ▪ In Transmitters: IMD causes interference in adjacent channels
  - ▪ In Receivers: Blocker inter-mod products can fall on the desired signal and de-sensitize the receiver
- ► Second Order IMD Products (F2-F1, n=m=1) cause problems in Direct Conversion Receivers
  - ▪ Example: Two RF tones 20 kHz apart produce a 20 kHz product close to baseband

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Third Order Products (IMD3) – A Closer Look
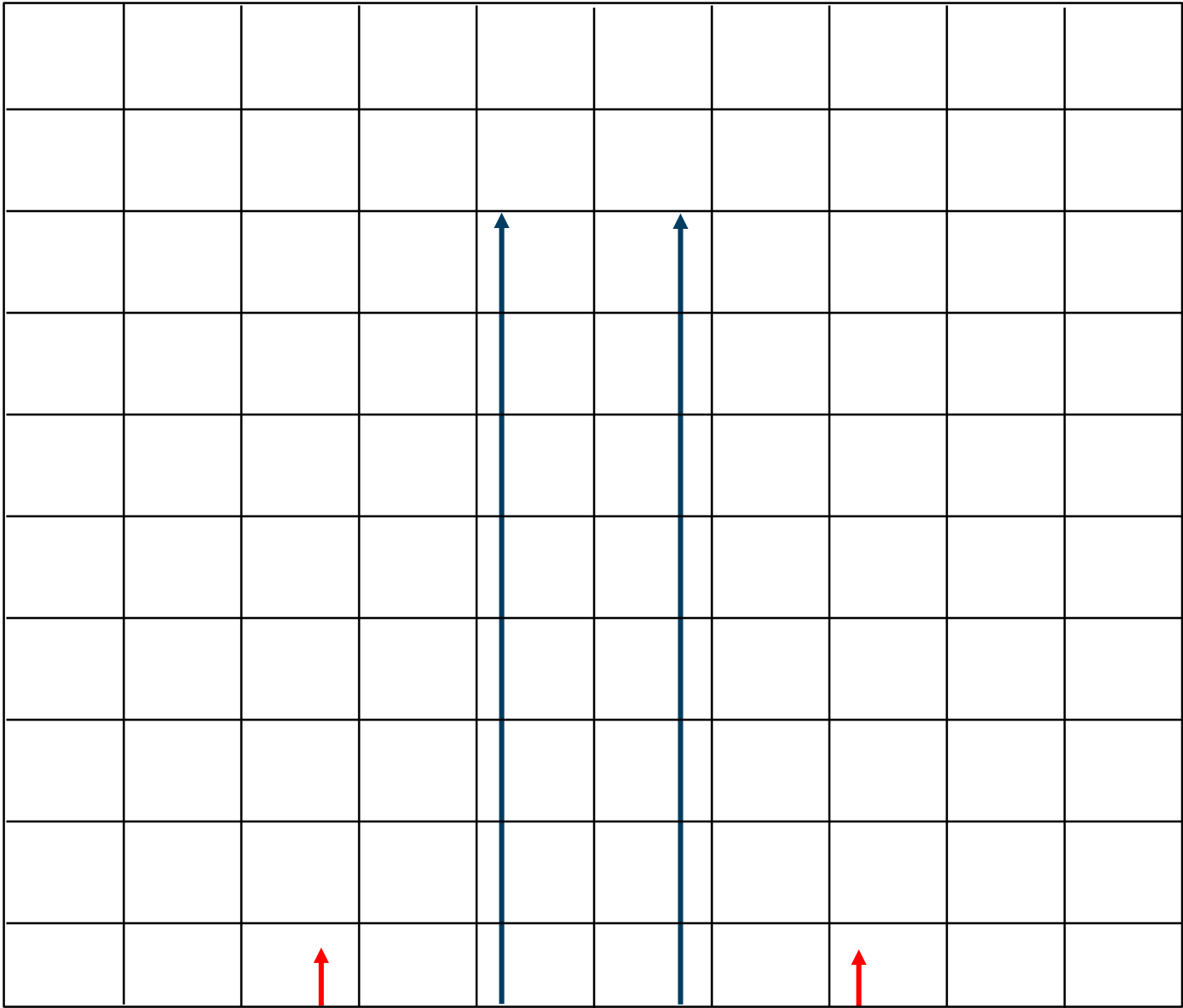
► Focus on Power of Fundamentals (dBm) and distance to IMD3 products (dBc)

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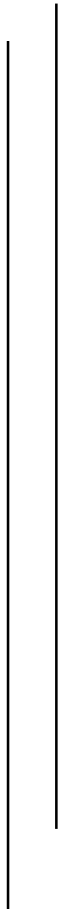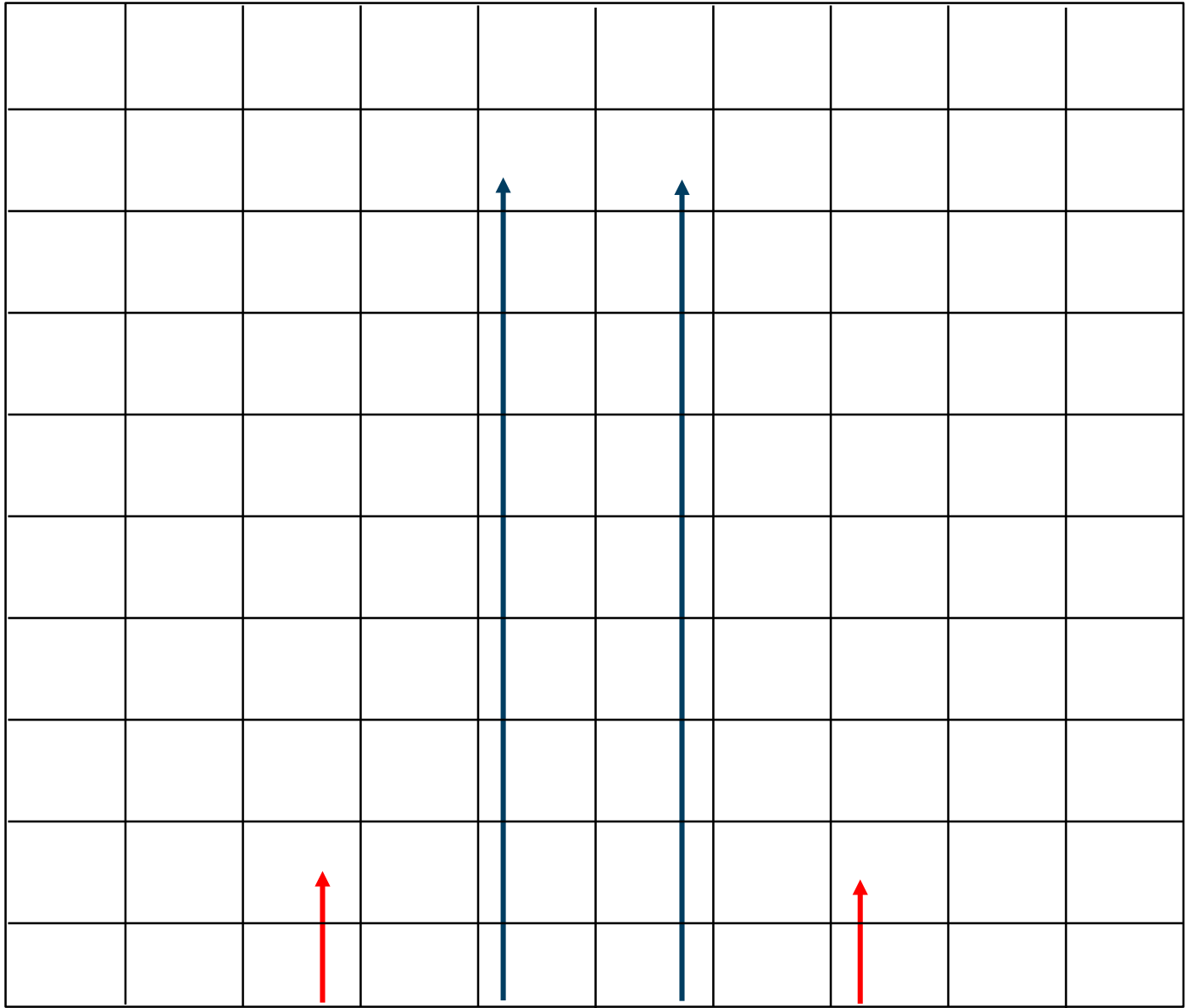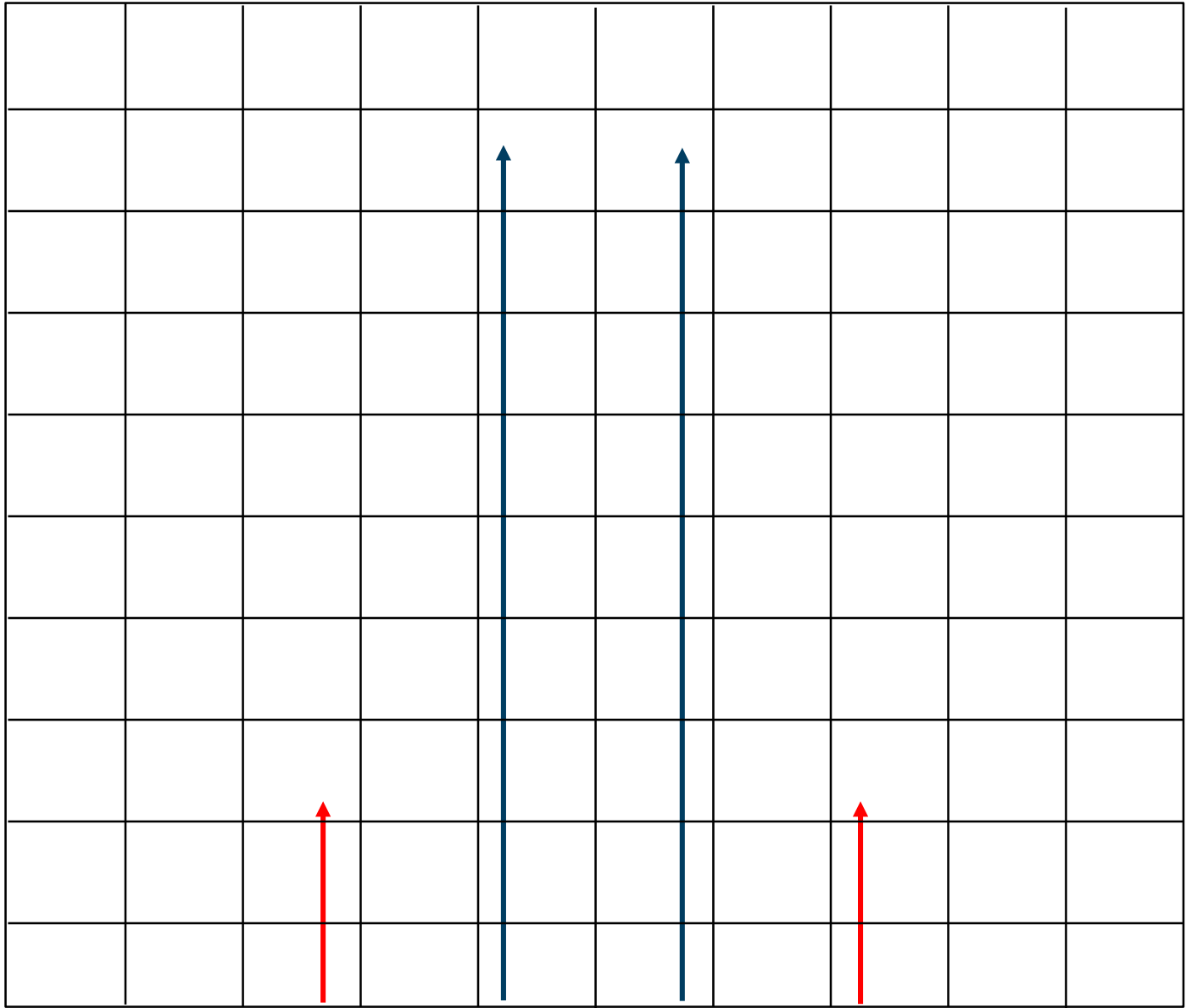AHEAD OF WHAT'S POSSIBLE™
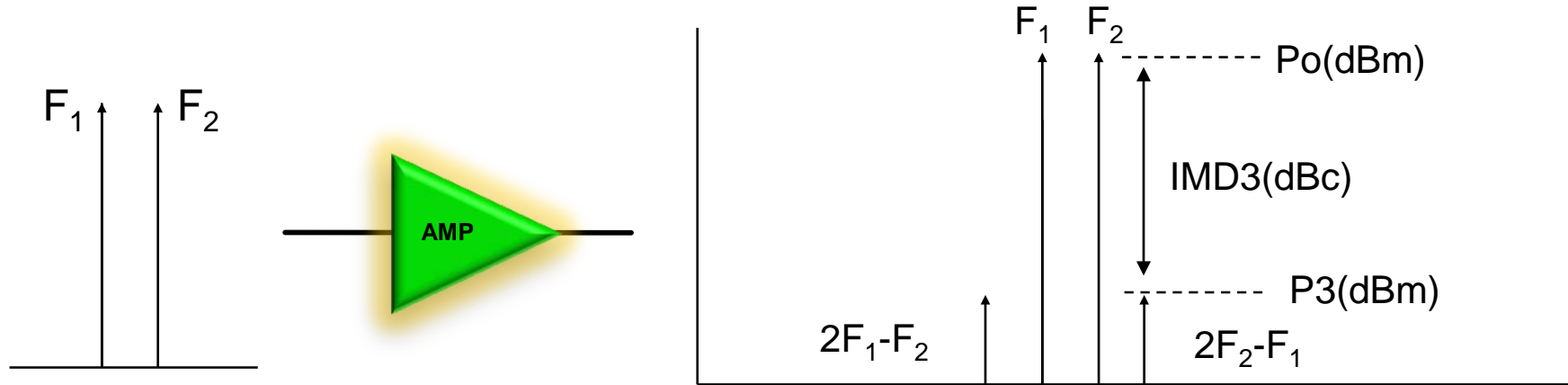
The Two Tone IMD Test
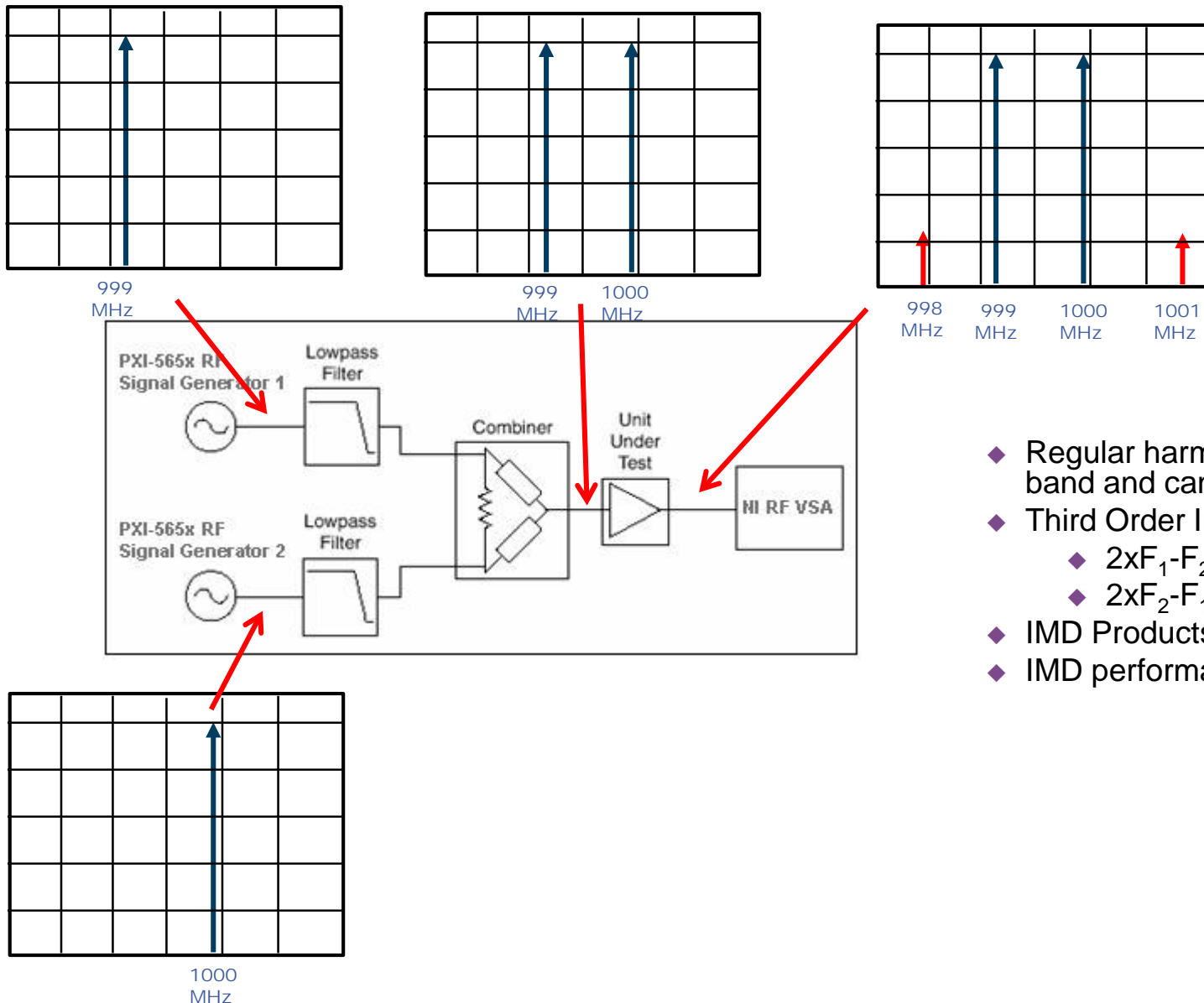
- Regular harmonics at 1998,2000,2997,3000 MHz, etc, fall out of band and can generally be filtered away.
- Third Order Intermodulation Distortion (IMD) Products at
  - $2xF_1-F_2$ (998 MHz)
  - $2xF_2-F_1$ (1001)
- IMD Products fall in band and cannot be filtered.
- IMD performance is closely related to Adjacent Channel Power Ratio

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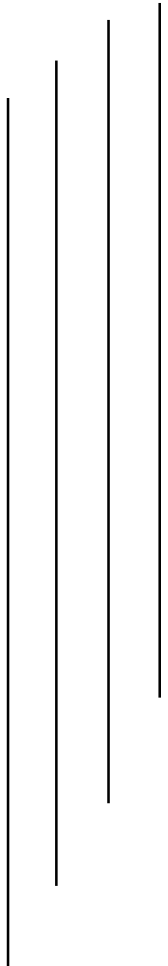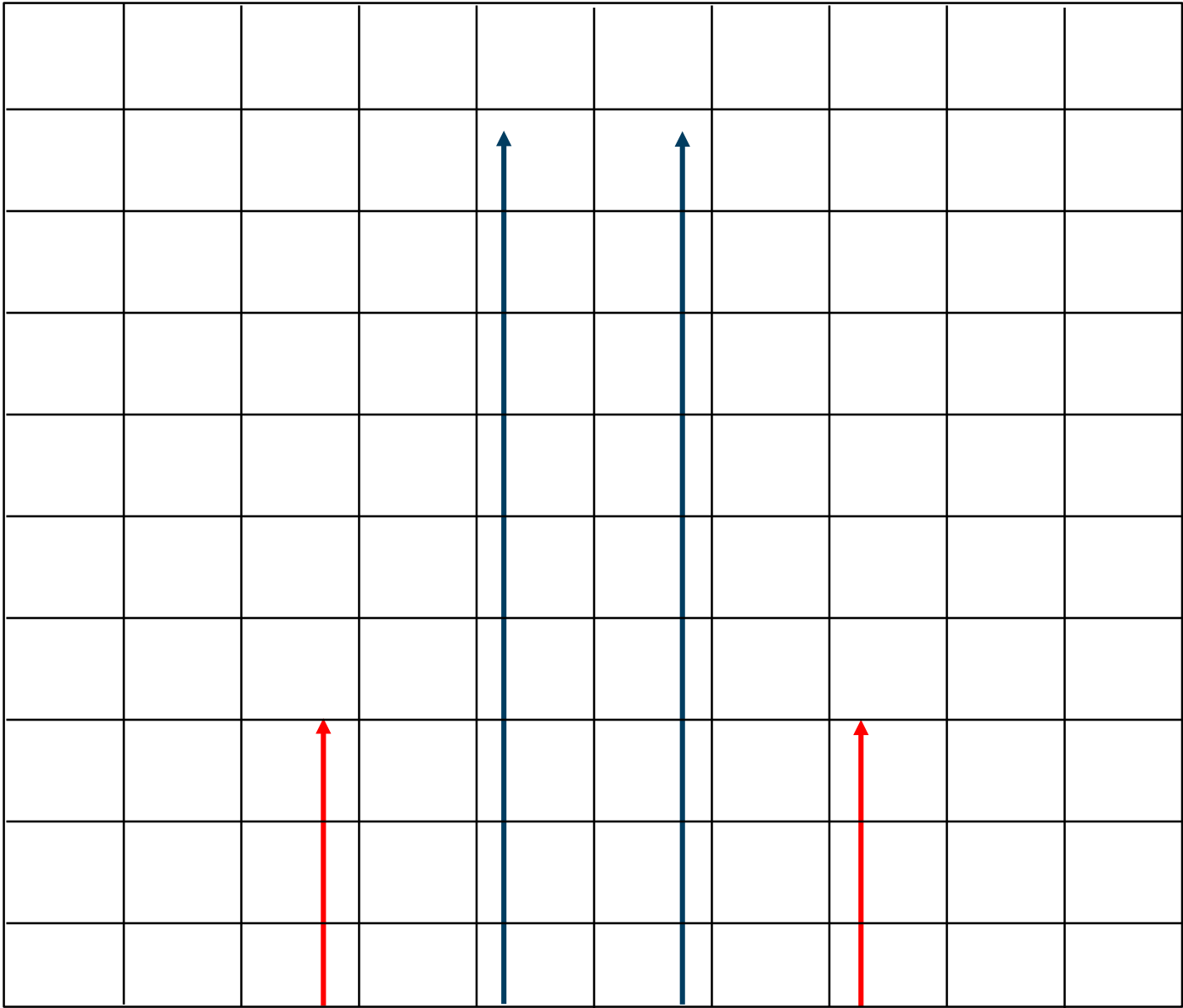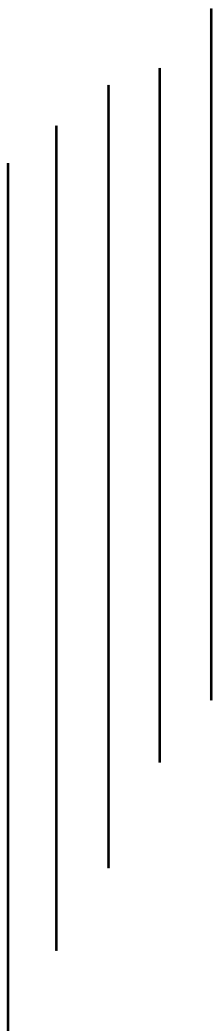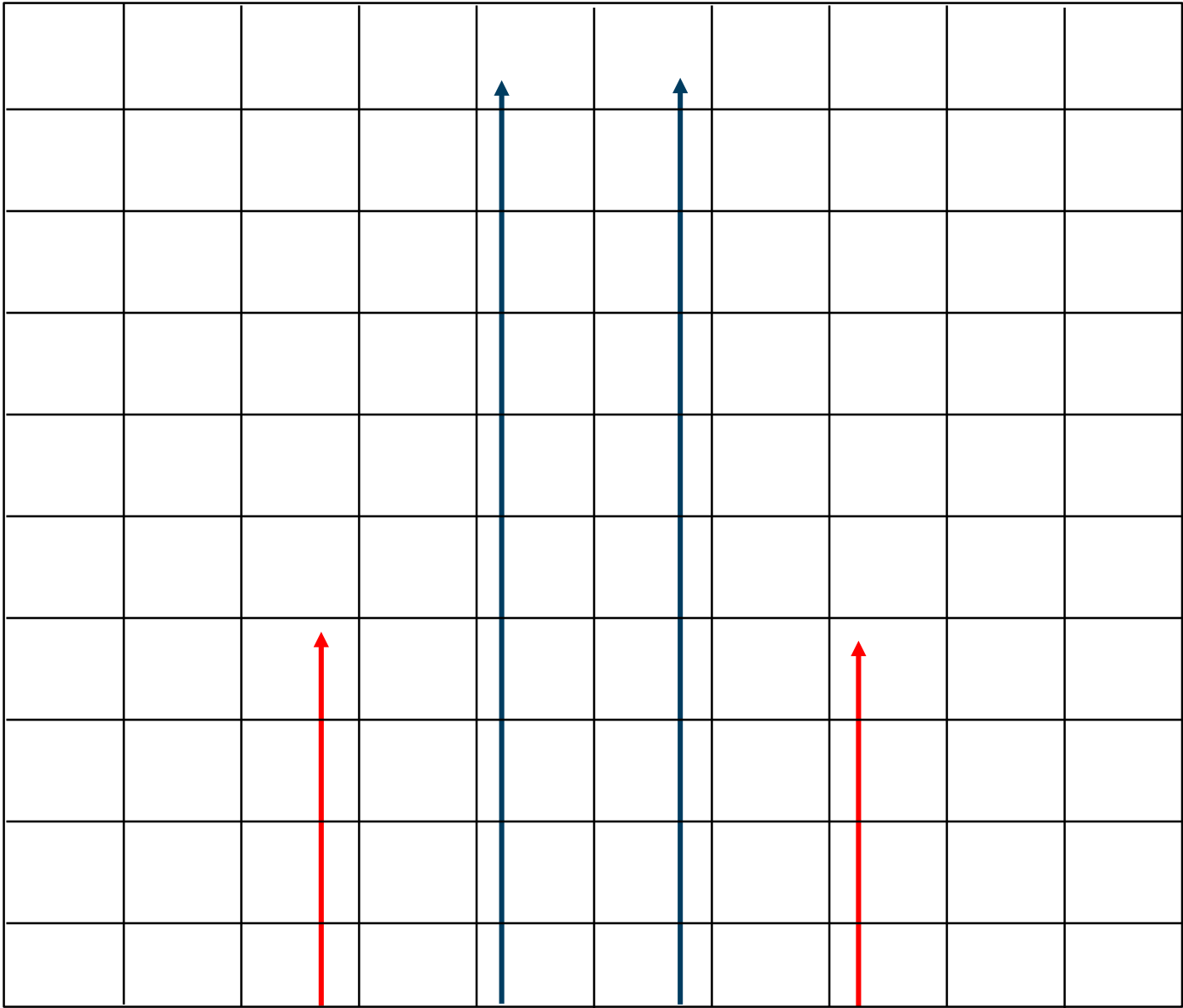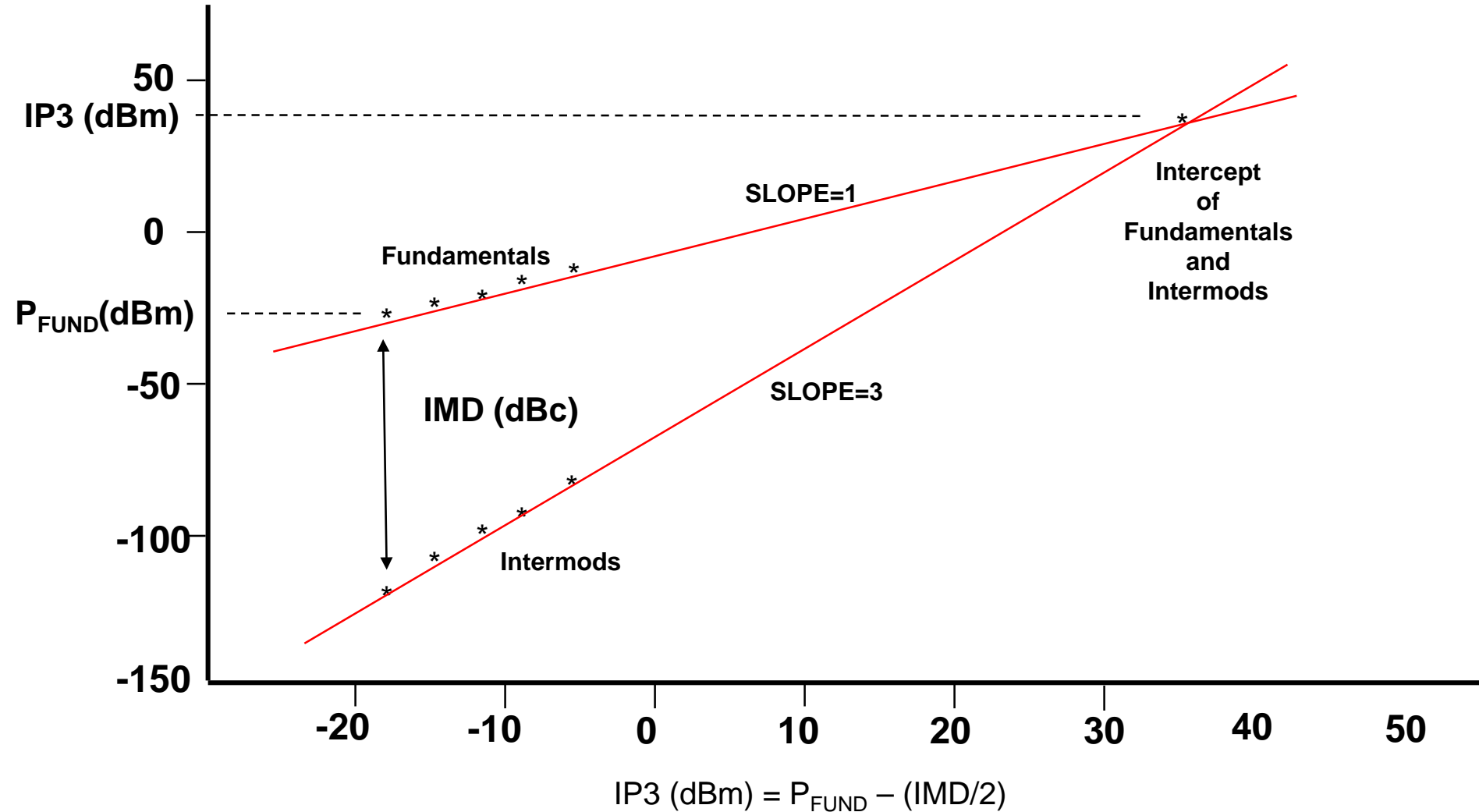
► Theoretical Power Level at which 3rd order IMD products become as large as the fundamental.

► IP3 can be input-referred or output-referred
  ▪ OIP3 = IIP3 + Gain

► The IP3 spec allows us to estimate the size of third order IMD3 products at any RF power level.

► Because IMD products change 3dB for each 1dB change in the fundamentals, distortion can be reduced by reducing fundamental power but this will also reduce signal-to-noise ratio (SNR)

► Balancing IMD and SNR is one of the toughest challenges facing RF circuit designers.

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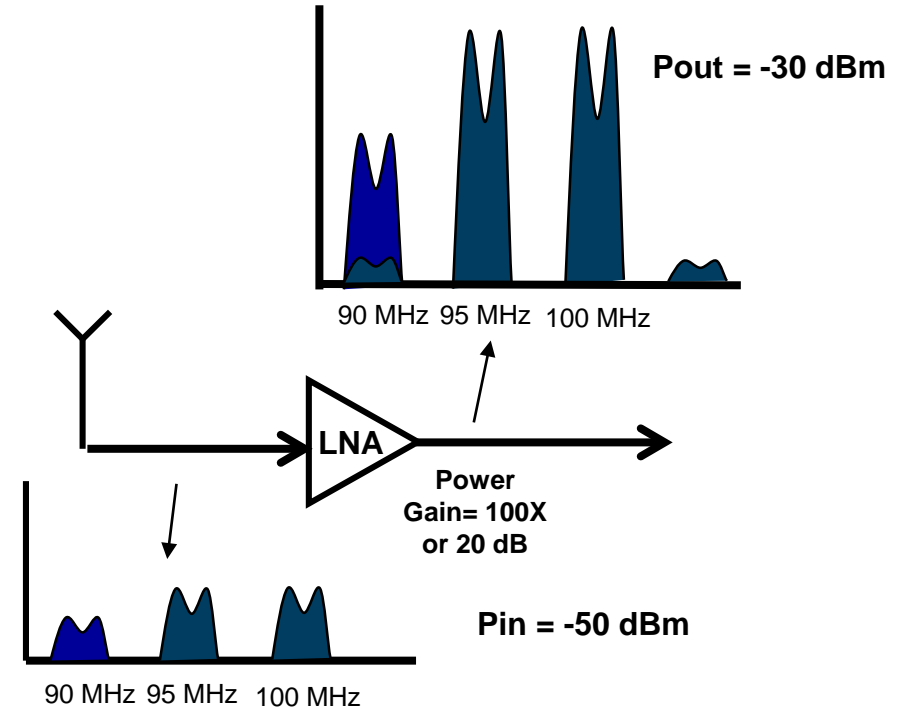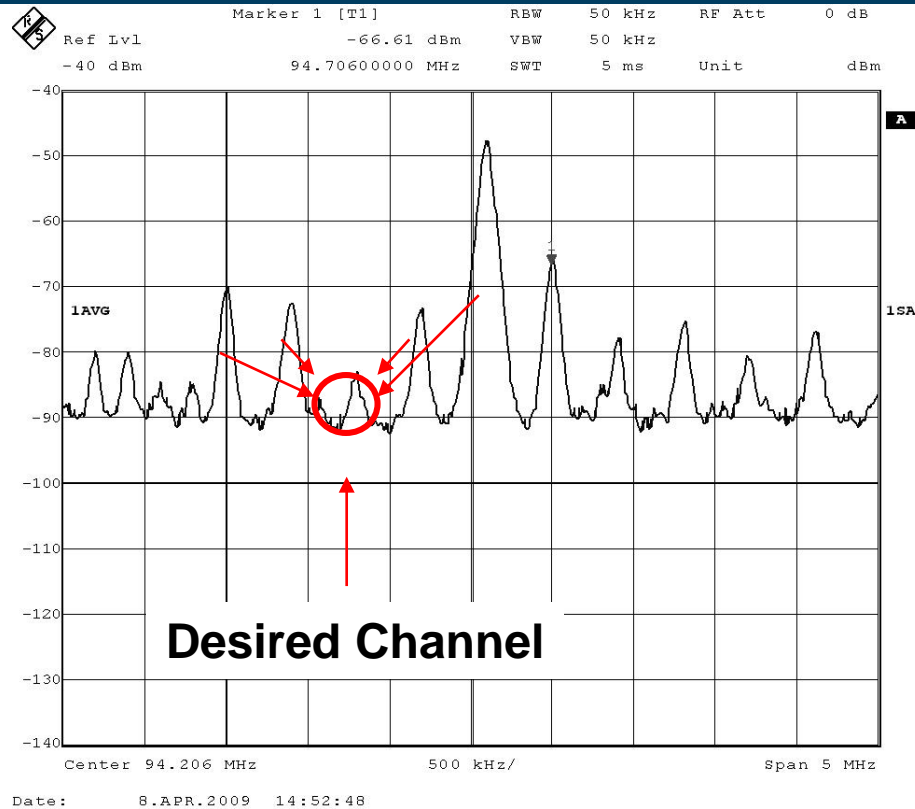
- ▶ Multiple IMD Risks from adjacent channels in LNA
- ▶ Solution: Amplifiers in Receivers must have both <u>Low Noise Figure</u> and <u>High IP3</u>

Newer spec : Noise Power Ratio (NPR)

► NPR is a dynamic test that is used to assess the performance of receiver components (mixer, ADC, amplifiers, etc) with a fully loaded Gaussian noise source.

► The noise level is adjusted such that the converter is loaded just below the point of clipping with a Nyquist-limited noise source.

► Then a narrow band of noise is removed with a deep notch filter.

► The noise within the notch is measured using FFT techniques to determine the ratio of noise density in the notch to the noise density without the notch.

► The results are expressed in decibels.

NPR = 60.83dB
NOTCH = 18.0MHz
NOTCH WIDTH = 3.0MHz
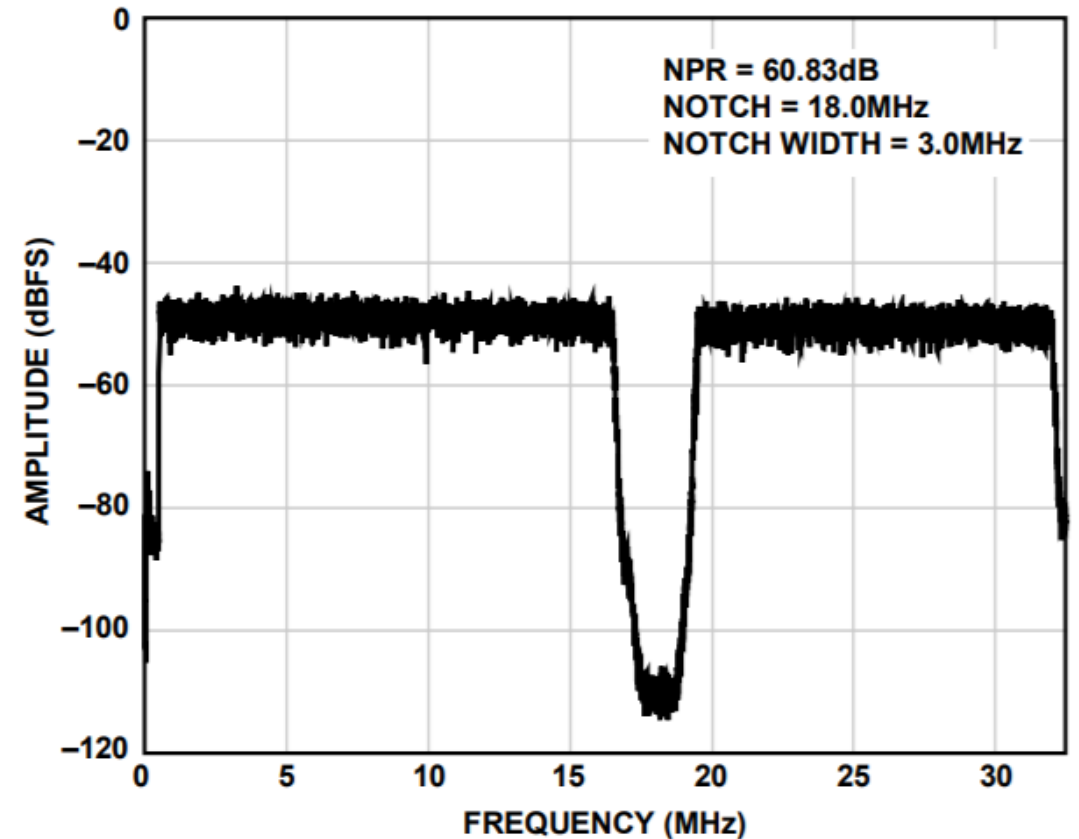
Figure 16. Typical NPR Response for a 12-Bit Converter

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Gain Block Performance generally rolls off vs. Frequency
(use selection tables carefully)

KEY SPECIFICATIONS
- Frequency Range: 50 MHz − 4 GHz
- Gain: 15.3 dB
- OP1dB: 19 dBm @ 900 MHz
- OIP3: 43 dBm @ 900 MHz
- Noise Figure: 3.7 dB @ 900 MHz
- 5 V Current: 83 mA
- Package: SOT-89

FEATURES
- Highest Dynamic Range Gain Blocks
- Matched 50 Ω Input and Output
- Internal Active Bias
- Temperature and Frequency Stable

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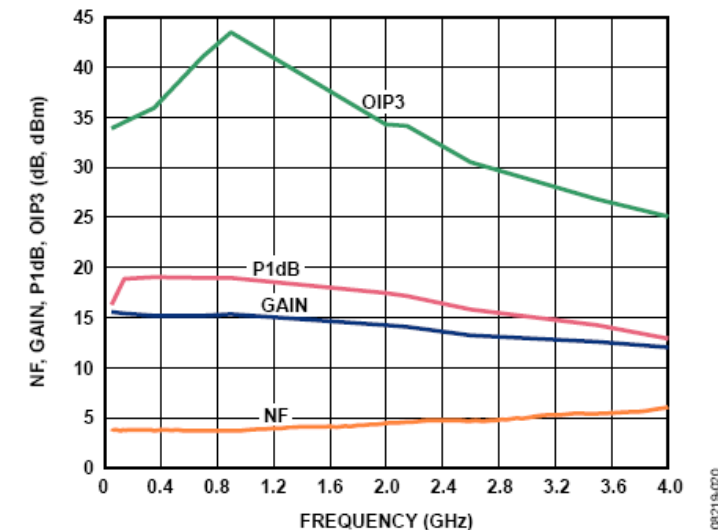
Output Swing and P1dB

Output Compression (P1dB) and Output Saturation

◆**Sweep input power to device until output power is 1 dB lower than it should be**

◆**P1dB is expressed in dBm and can be input or output referred.**

  ◆**OP1dB = IP1dB + Gain - 1**

   (include "-1" because gain is decreased by 1 dB at compression)

◆**Psat is a lesser used spec that expresses max Pout**

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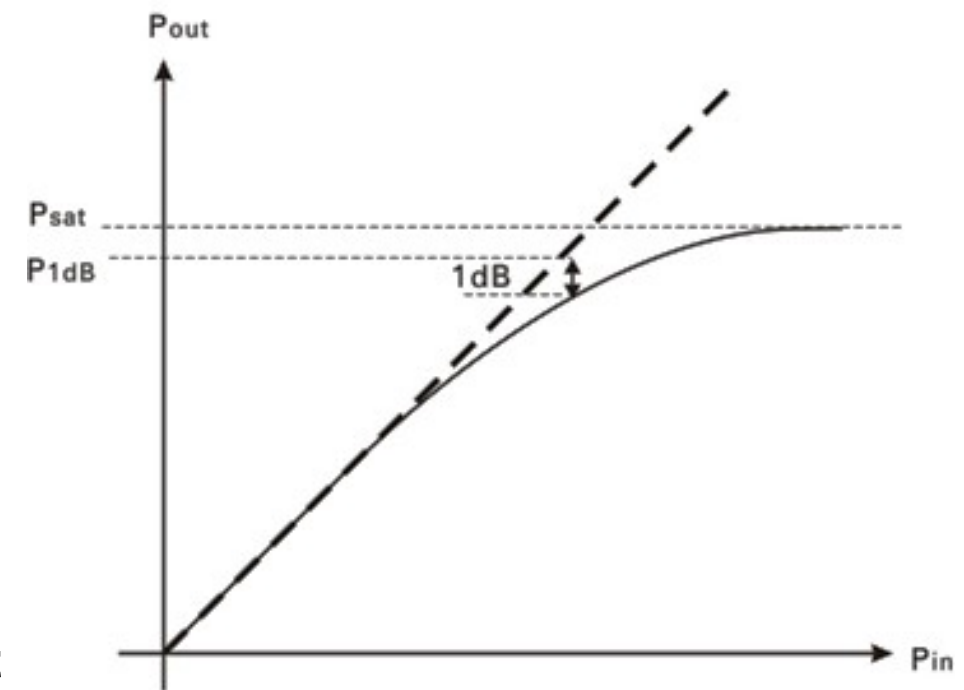
¼ Watt, ½ Watt and 1 Watt Amplifiers

► Wattage is OP1dB expressed in Watts

- 1 Watt Amplifier → 30 dBm OP1dB
- ½ Watt Amplifier → +27 dBm OP1dB
- ¼ Watt Amplifier → +24 dBm OP1dB

► Wattage designation of an RF Amplifier does <u>not</u> refer to power consumption (e.g. V_s x I_{sy}) but higher wattage amplifiers tend to have higher power consumption

Relationship between IP3 and P1dB

OUTPUT POWER (PER TONE) dBm

OIP3

THIRD ORDER INTERCEPT

10 dB

1 dB

OP1dB 1 dB COMPRESSIONPOINT

OIP3= Po-(IMD3/2)

(M = 1)

(M = 3)

INPUT POWER (PER TONE), dBm
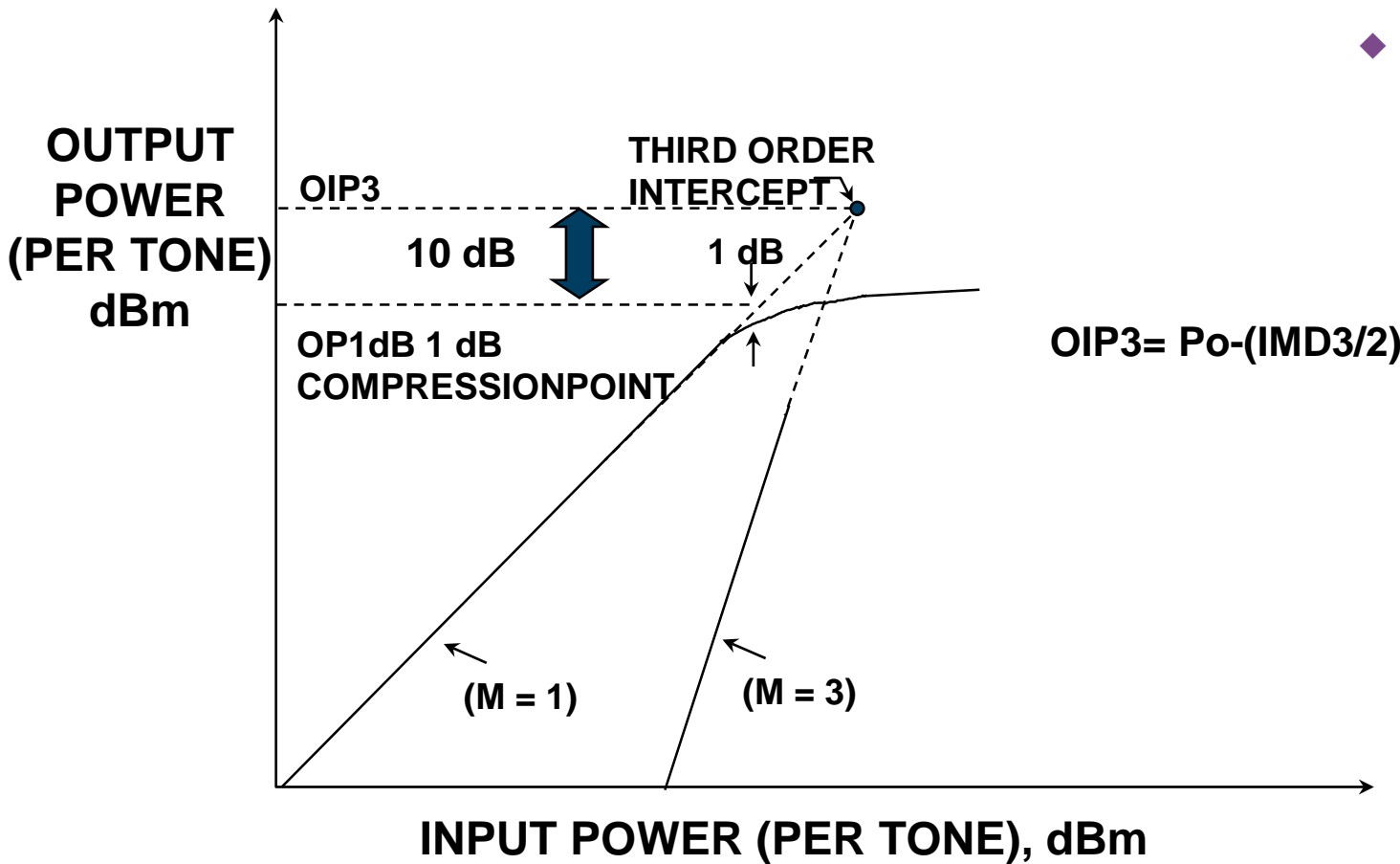
- ◆ **OIP3 is typically 10 dB higher than OP1dB but many RF Amplifiers incorporate internal distortion compensation….**

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OP1dB to OIP3 Delta
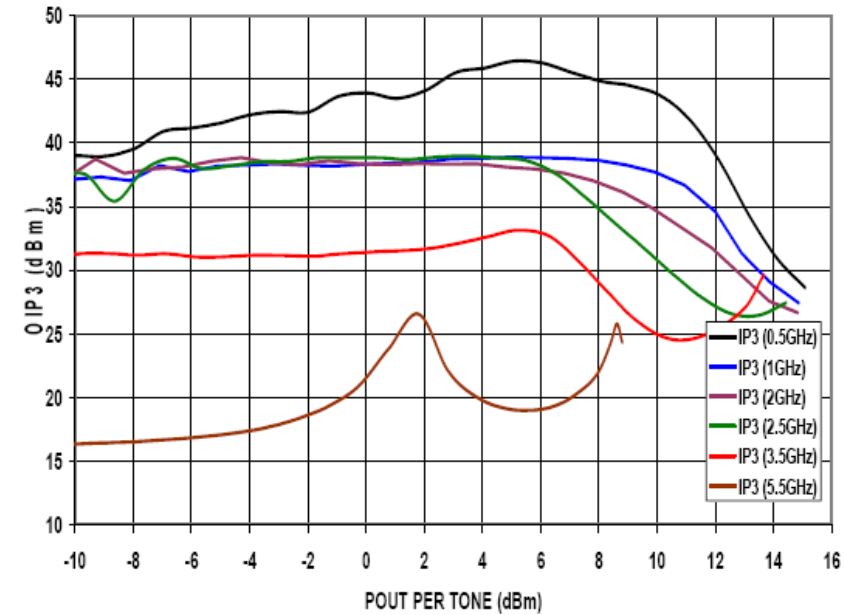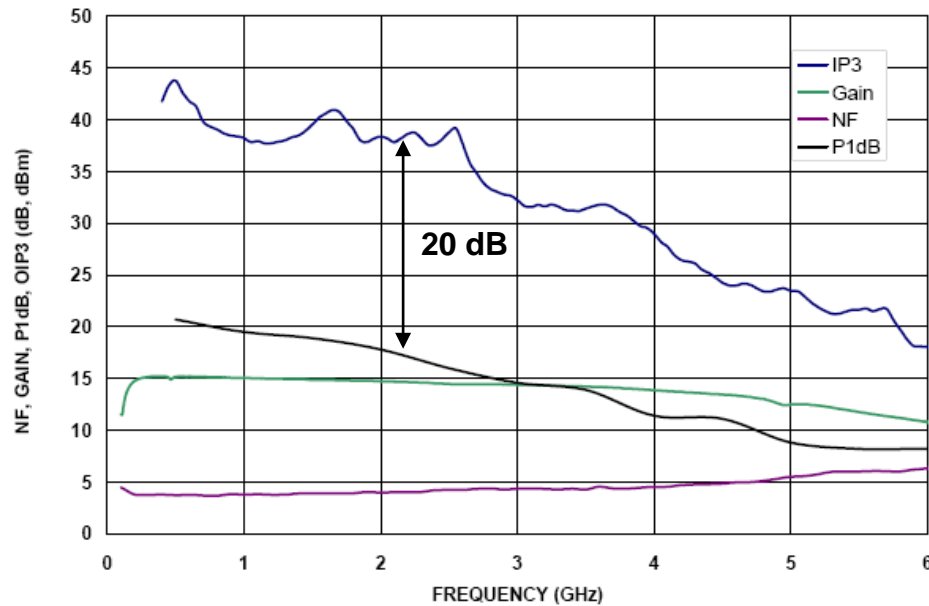
▶ In a classic transistor amplifier, OIP3 is typically about 10 dB greater than OP1dB.

▶ Many RF Amplifiers employ internal harmonic cancellation circuits to improve OIP3

▶ OP1dB remains constant so OIP3-OP1dB can be >> 10 dB.

▶ Harmonic Cancellation Algorithm is optimized for a particular power level and tends to degrade at higher frequencies

▶ Many people pick Amplifiers based on OP1dB (in dBm or Watts)

▶ Think "back-off from OIP3" not "back-off from P1dB" when selecting operating point

Cascaded IP3 and P1dB of RF Signal Chains
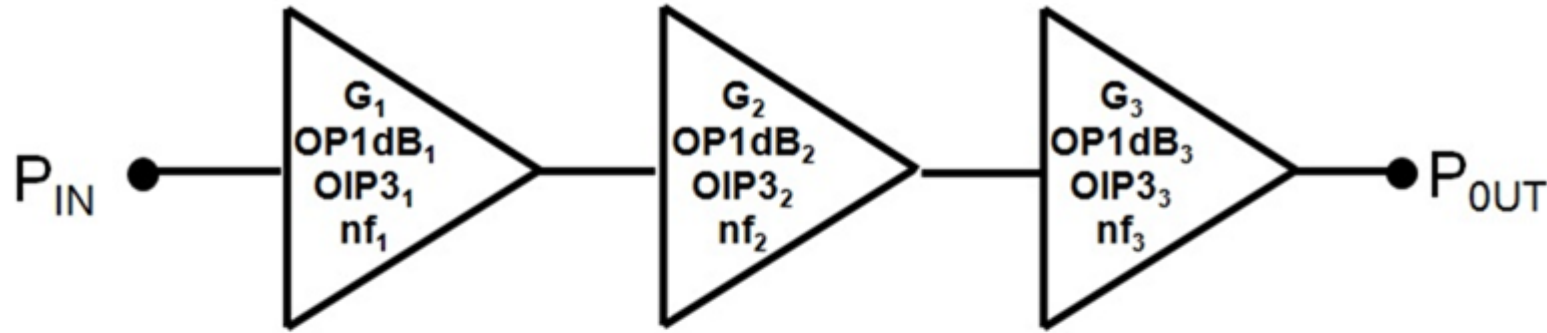
$$G = G1 \times G2 \times G3$$

$$\frac{1}{OIP3} = \frac{1}{(OIP3_1 \times G2 \times G3)} + \frac{1}{(OIP3_2 \times G3)} + \frac{1}{(OIP3_3)}$$

$$\frac{1}{OP1dB} = \frac{1}{(OP1dB_1 \times G2 \times G3)} + \frac{1}{(OP1dB_2 \times G3)} + \frac{1}{(OP1dB_3)}$$

- ◆ IP3 becomes more critical as gain and signal level increases (towards end of chain)
- ◆ IP3 at start of signal chain can be critical if large blockers are present
- ◆ All calculations must be performed in linear domain (i.e. IP3 and P1dB in Watts)

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ACLR/ACPR/ACP

and how it relates to IP3?

ACP/ACPR/ACLR

▶ ACPR: Adjacent Channel Power Ratio

▶ ACLR: Adjacent Channel Leakage Ratio

▶ ACP: Adjacent Channel Power

◆ **WCDMA/3G Test Model 1-64**

◆ **Channel BW = 3.84 MHz**

◆ **Channel Spacing = 5 MHz**
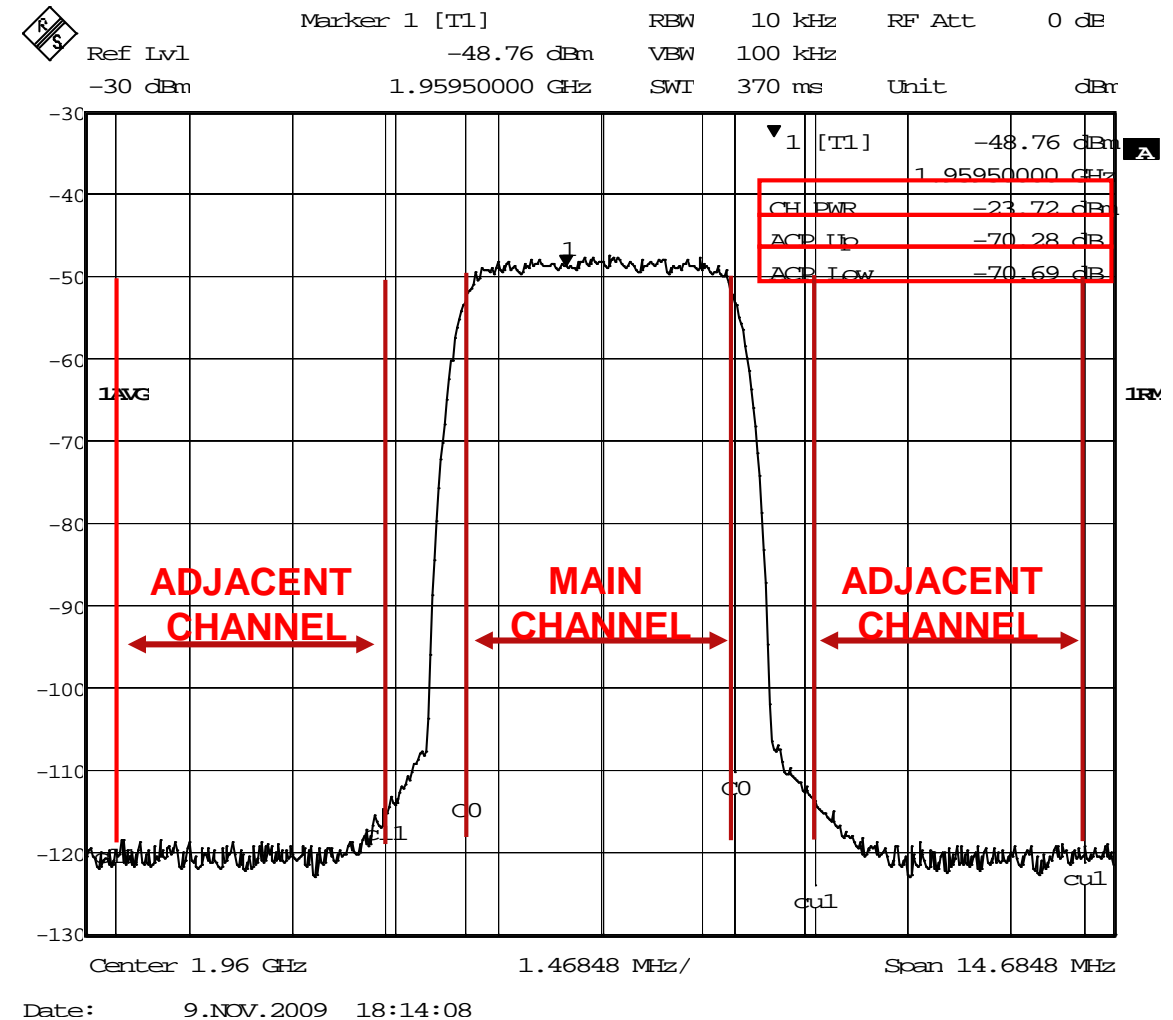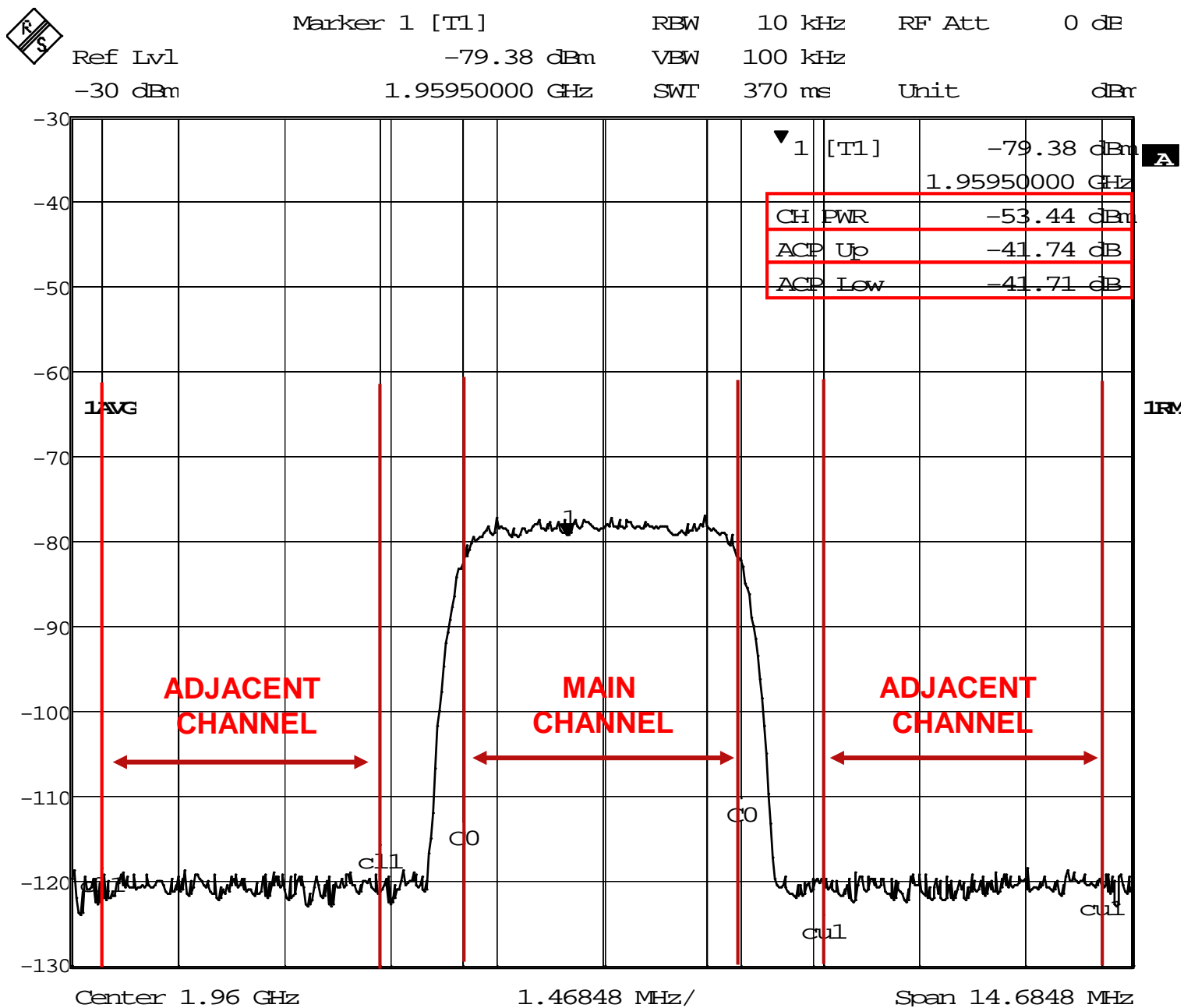
Marker 1 [T1]   RBW   10 kHz   RF Att   0 dE

Ref Lvl   −72.36 dBm   VBW   100 kHz

−30 dBm   1.95950000 GHz   SWT   370 ms   Unit   dBm

1 [T1]   −72.36 dBm
1.95950000 GHz
CH PWR   −47.44 dBm
ACP Up   −47.83 dB
ACP Low   −47.85 dB

1AVG   1RM

ADJACENT CHANNEL   **MAIN CHANNEL**   **ADJACENT CHANNEL**

Center 1.96 GHz   1.46848 MHz/   Span 14.6848 MHz

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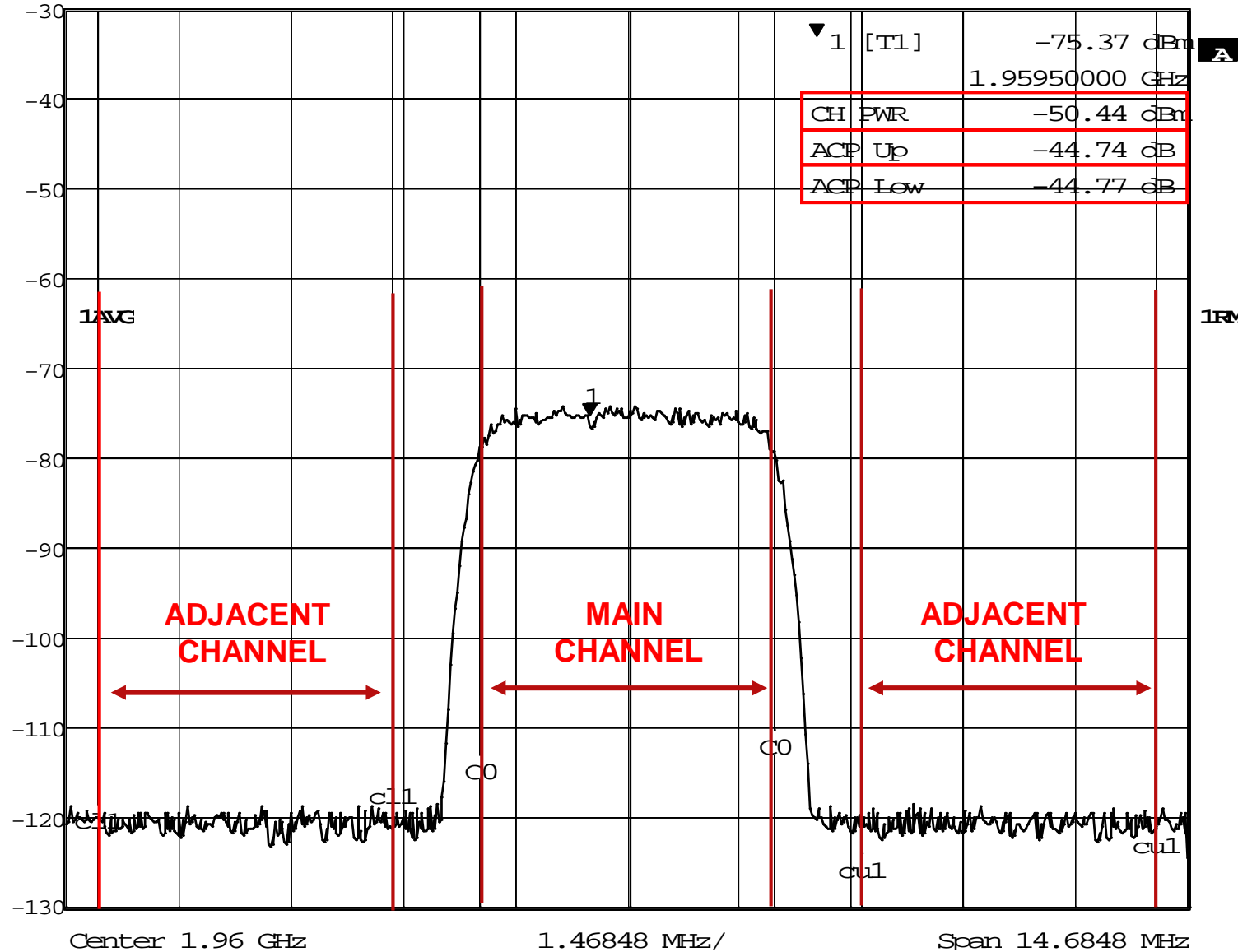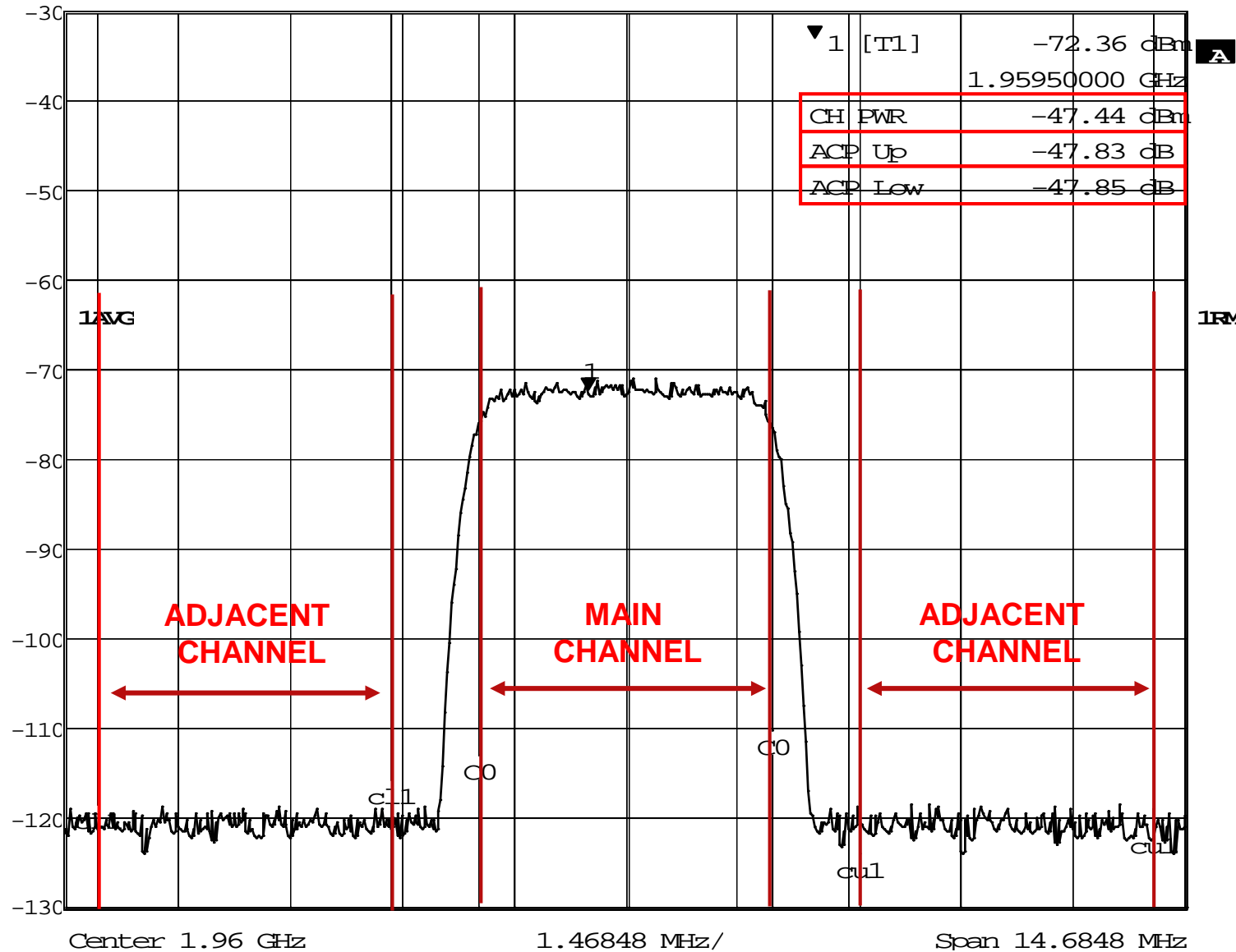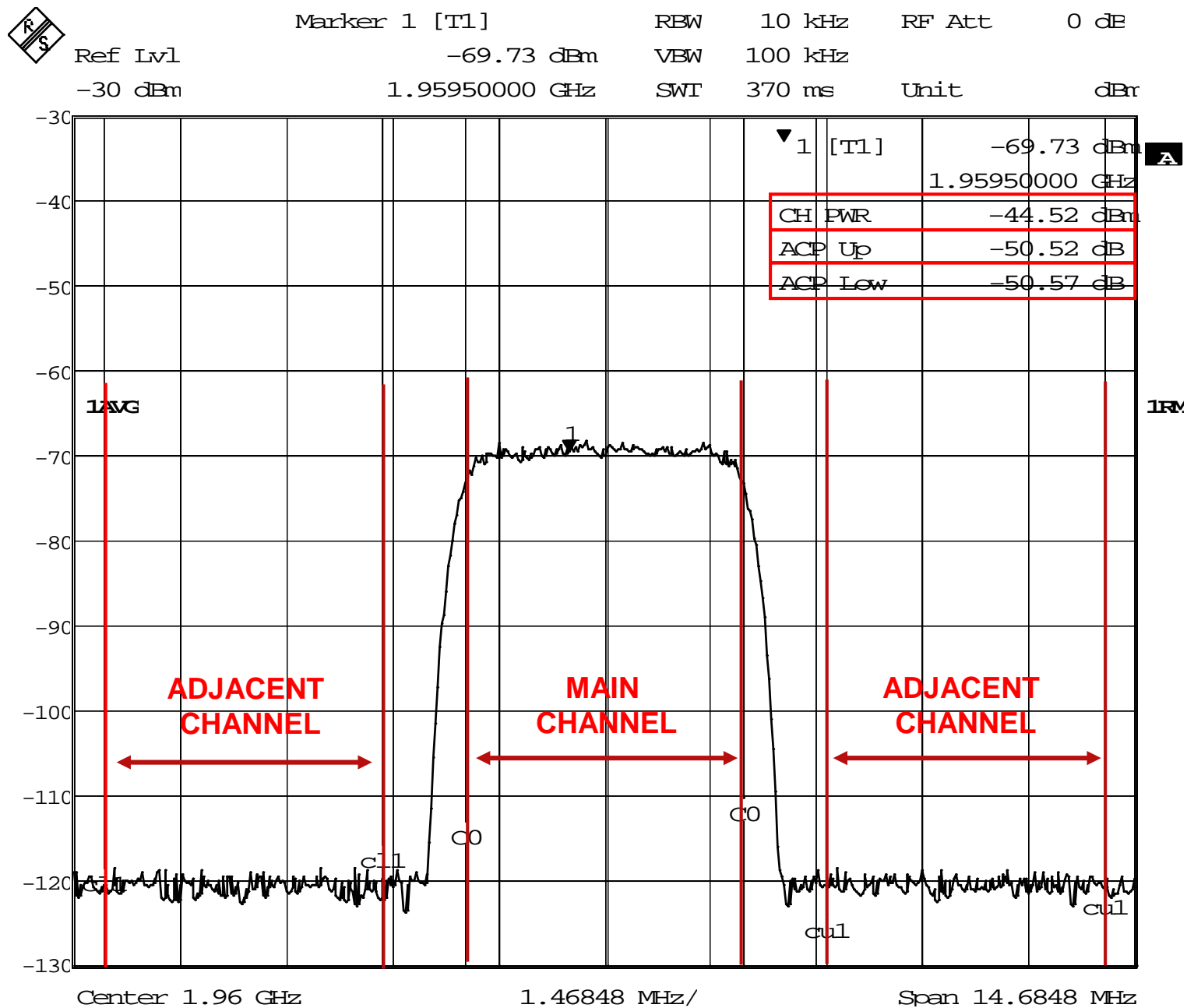
Marker 1 [T1] RBW 10 kHz RF Att 0 dE

Ref Lvl −66.81 dBm VBW 100 kHz

−30 dBm 1.95950000 GHz SWT 370 ms Unit dBm

▼1 [T1] −66.81 dBm A

1.95950000 GHz

CH PWR −41.53 dBm

ACP Up −53.57 dB

ACP Low −53.71 dB

1AVG 1RM

ADJACENT CHANNEL **MAIN CHANNEL** **ADJACENT CHANNEL**

C0 C0

cl1 cul

cu1

Center 1.96 GHz 1.46848 MHz/ Span 14.6848 MHz

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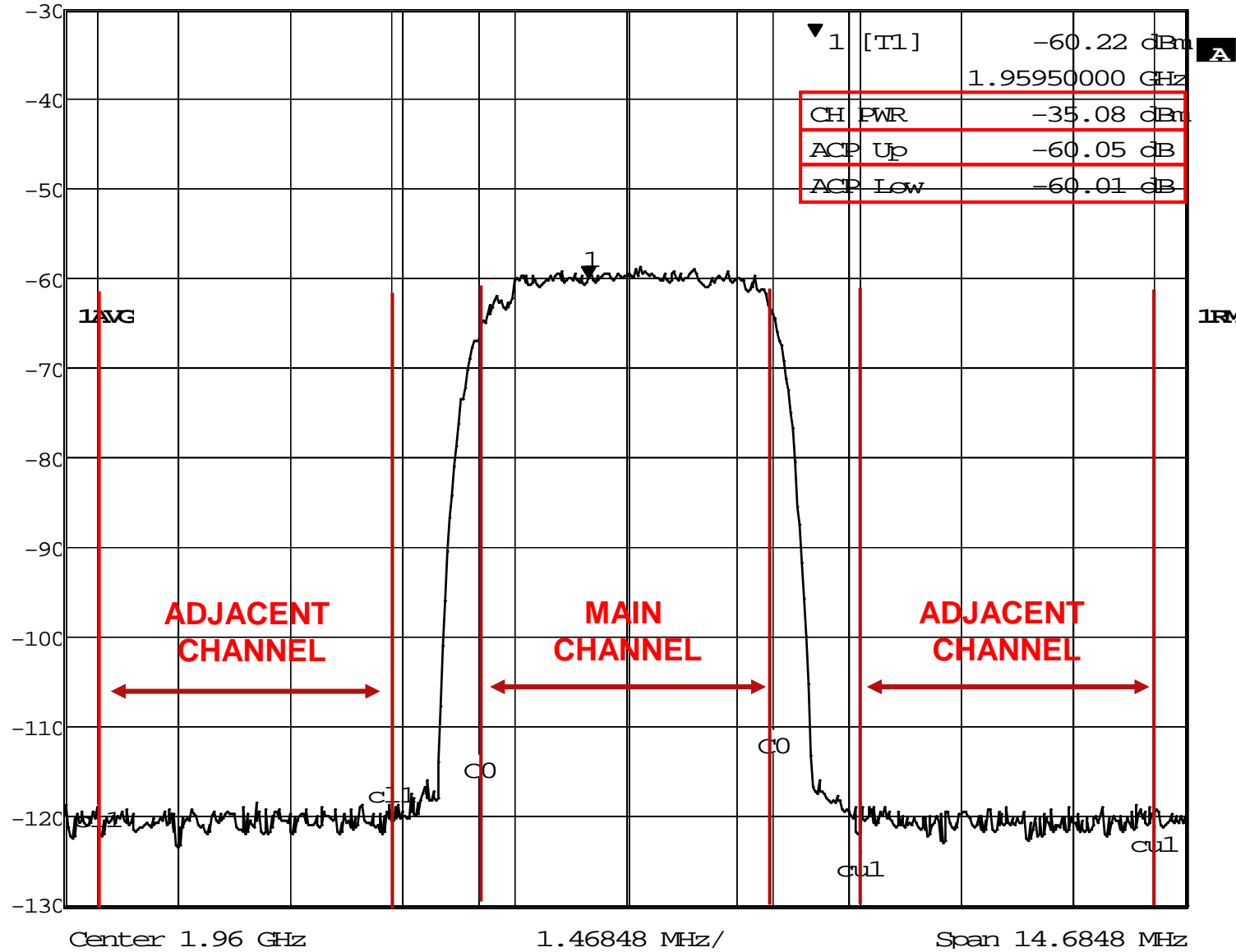
Marker 1 [T1]   RBW   10 kHz   RF Att   0 dB

Ref Lvl   −54.63 dBm   VBW   100 kHz

−30 dBm   1.95950000 GHz   SWT   370 ms   Unit   dBm

1 [T1]   −54.63 dBm
1.95950000 GHz

CH PWR	−29.62 dBm
ACP Up	−65.29 dB
ACP Low	−65.35 dB

ADJACENT CHANNEL   MAIN CHANNEL   ADJACENT CHANNEL

Center 1.96 GHz   1.46848 MHz/   Span 14.6848 MHz

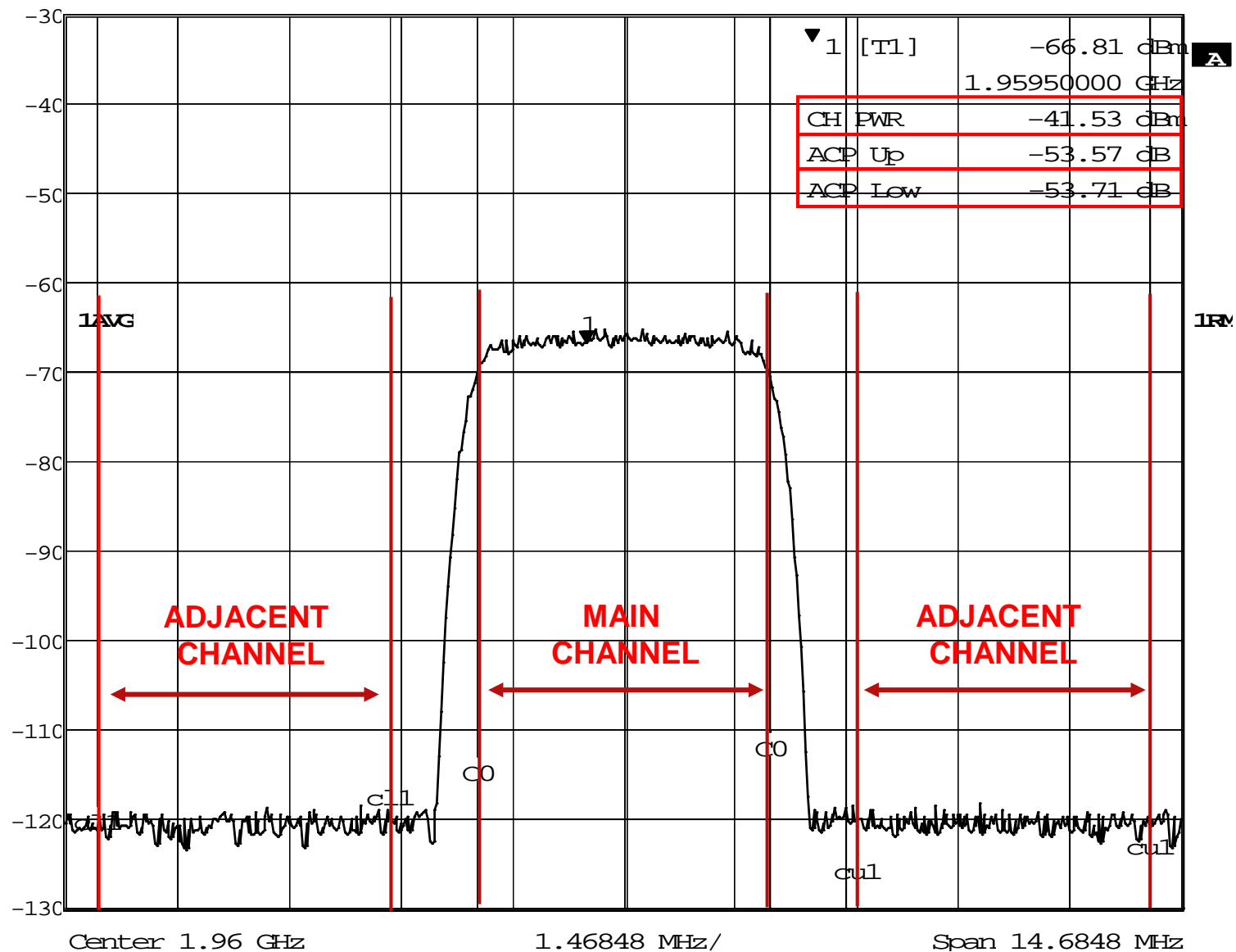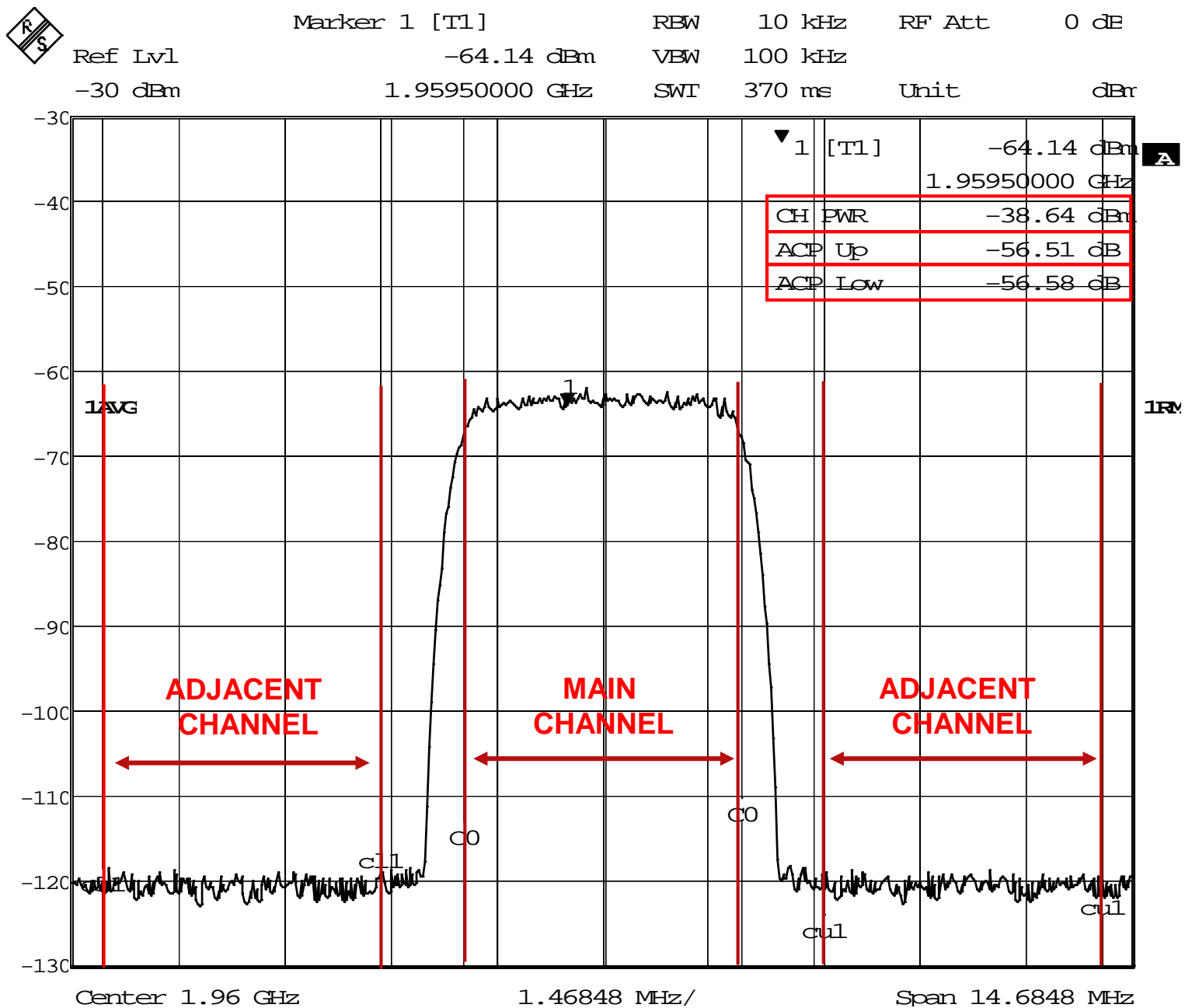Date: 9.NOV.2009 18:15:16

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Marker 1 [T1]   RBW 10 kHz RF Att 0 dB
Ref Lvl   -51.86 dBm VBW 100 kHz
-30 dBm   1.95950000 GHz SWT 370 ms Unit dBm

1 [T1] -51.86 dBm A
1.95950000 GHz
CH PWR -26.72 dBm
ACP Up -68.00 dB
ACP Low -67.98 dB

1AVG   1RM

ADJACENT CHANNEL **MAIN CHANNEL** **ADJACENT CHANNEL**

C0 cul C0 cu1

Center 1.96 GHz 1.46848 MHz/ Span 14.6848 MHz

Date: 9.NOV.2009 18:14:41

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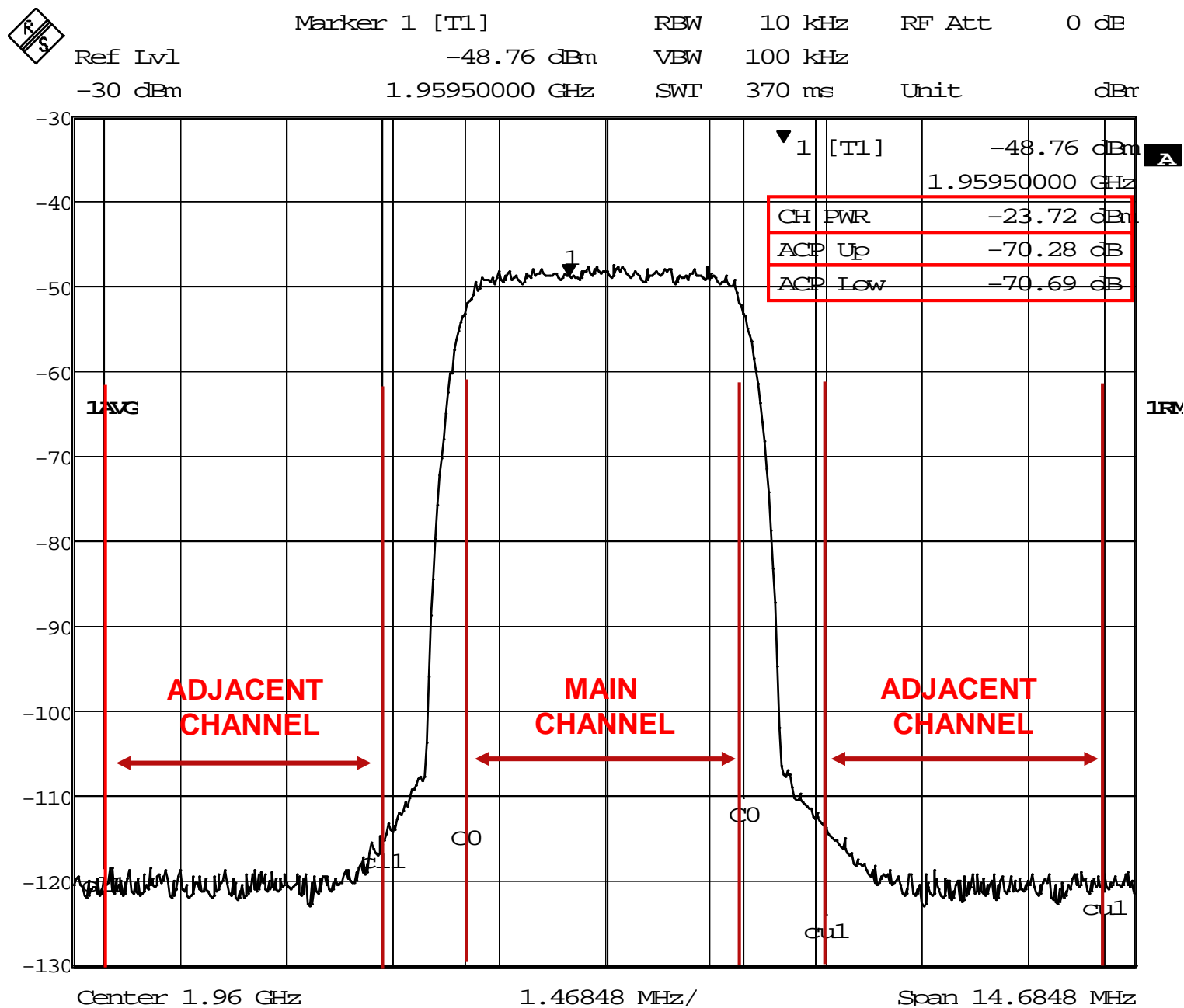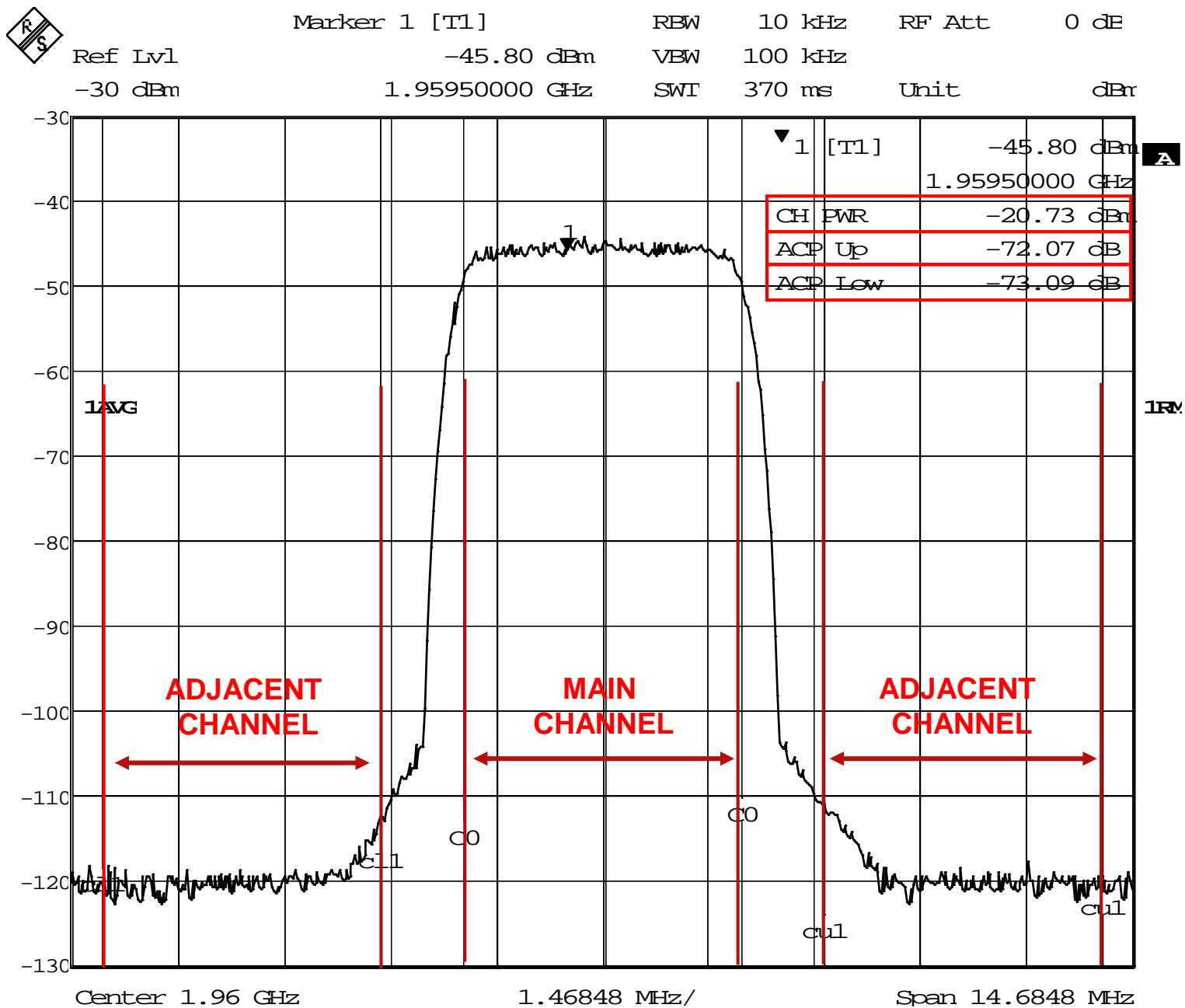
Marker 1 [T1]   RBW   10 kHz   RF Att   0 dE

Ref Lvl   −42.87 dBm   VBW   100 kHz

−30 dBm   1.95950000 GHz   SWT   370 ms   Unit   dBm
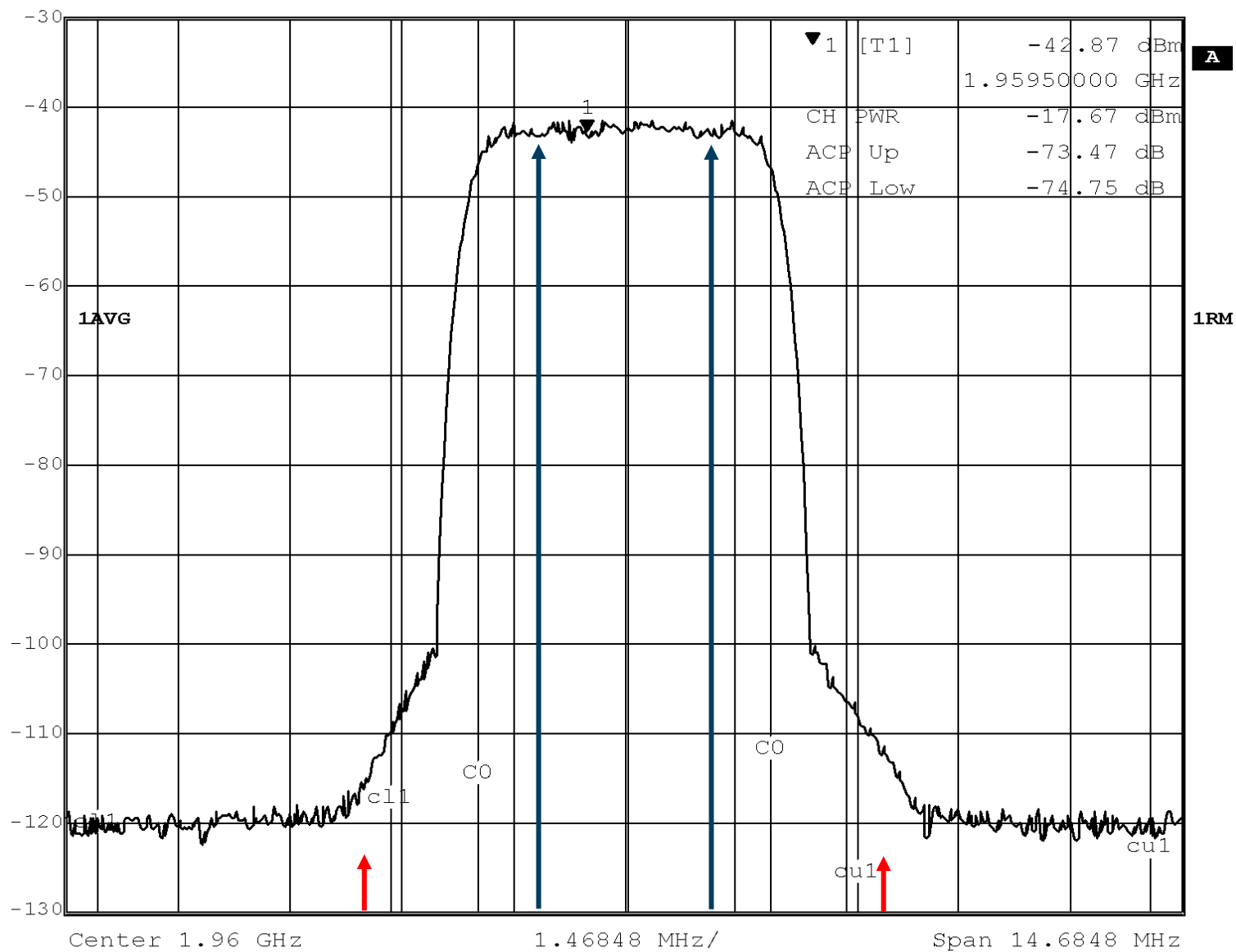
1 [T1]   −42.87 dBm   A
1.95950000 GHz
CH PWR   −17.67 dBm
ACP Up   −73.47 dB
ACP Low   −74.75 dB

ADJACENT CHANNEL   MAIN CHANNEL   ADJACENT CHANNEL

Center 1.96 GHz   1.46848 MHz/   Span 14.6848 MHz

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Date: 9.NOV.2009 18:12:07
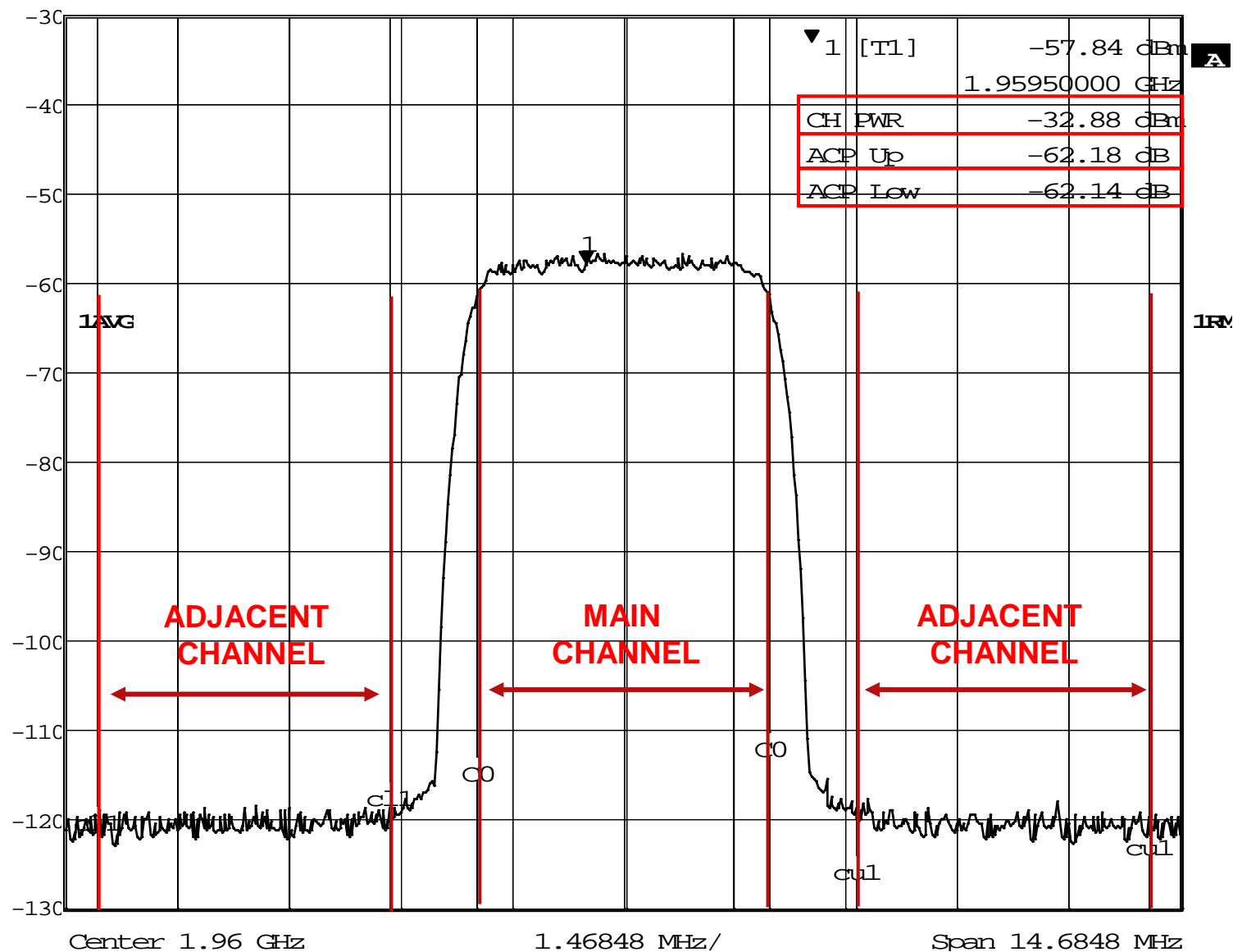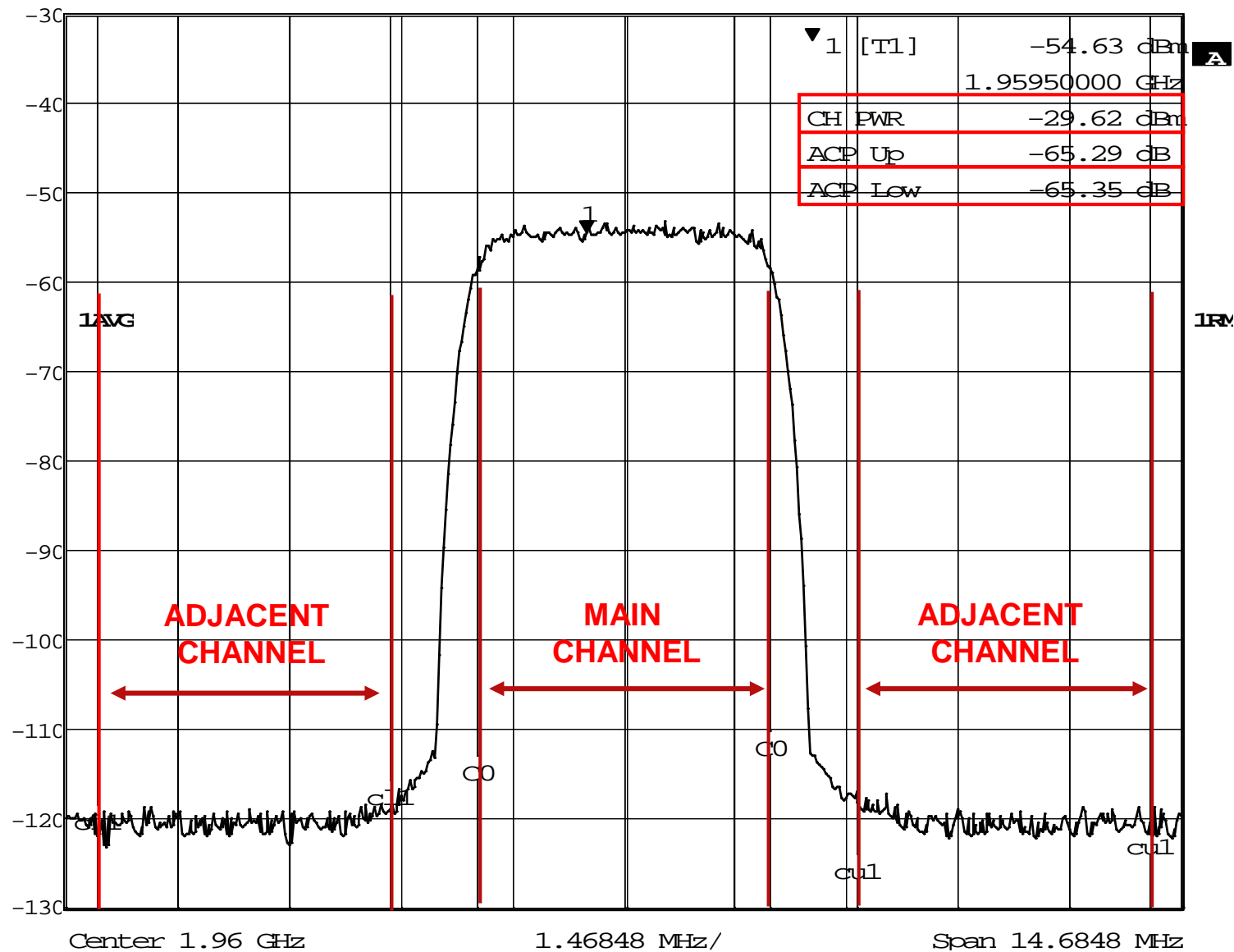
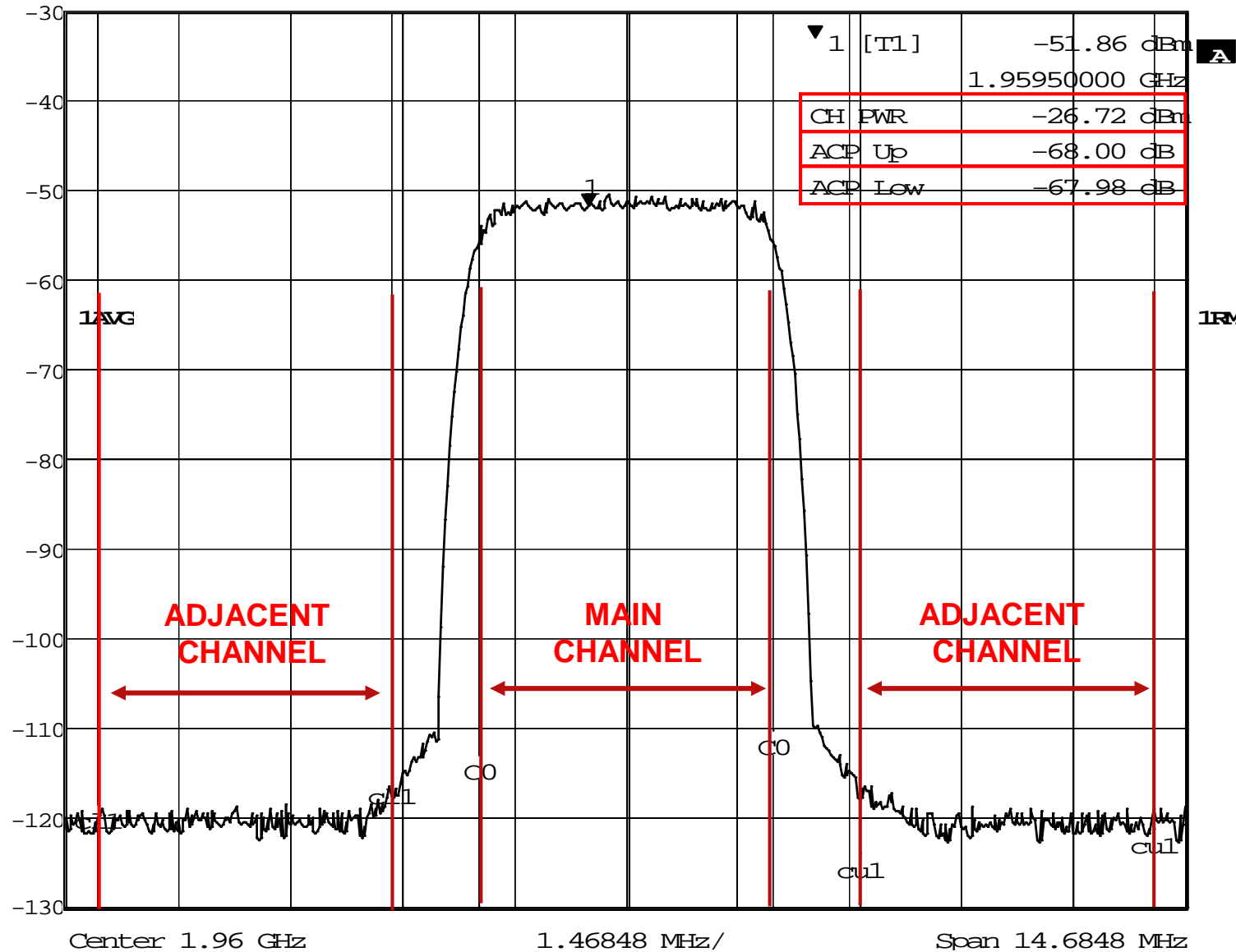Marker 1 [T1]   RBW   10 kHz   RF Att   0 dE
Ref Lvl   −39.64 dBm   VBW   100 kHz
−30 dBm   1.95950000 GHz   SWT   370 ms   Unit   dBm

▼ 1 [T1]   −39.64 dBm A
                  1.95950000 GHz
CH PWR   −14.66 dBm
ACP Up   −73.94 dB
ACP Low   −75.62 dB

1AVG   1RM

C0   C0
cll   C0   cul
                       cul

Center 1.96 GHz   1.46848 MHz/   Span 14.6848 MHz

Date: 9.NOV.2009   18:11:19

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Marker 1 [T1]			RBW	10 kHz	RF Att	0 dB
Ref Lvl		−32.02 dBm	VBW	100 kHz		
−30 dBm		1.95950000 GHz	SWT	370 ms	Unit	dBm

▼1 [T1]   −32.02 dBm
1.95950000 GHz
CH PWR   −6.91 dBm
ACP Up   −61.66 dB
ACP Low   −66.20 dB

1AVG   1RM

Center 1.96 GHz   1.46848 MHz/   Span 14.6848 MHz

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Date: 9.NOV.2009   18:09:34

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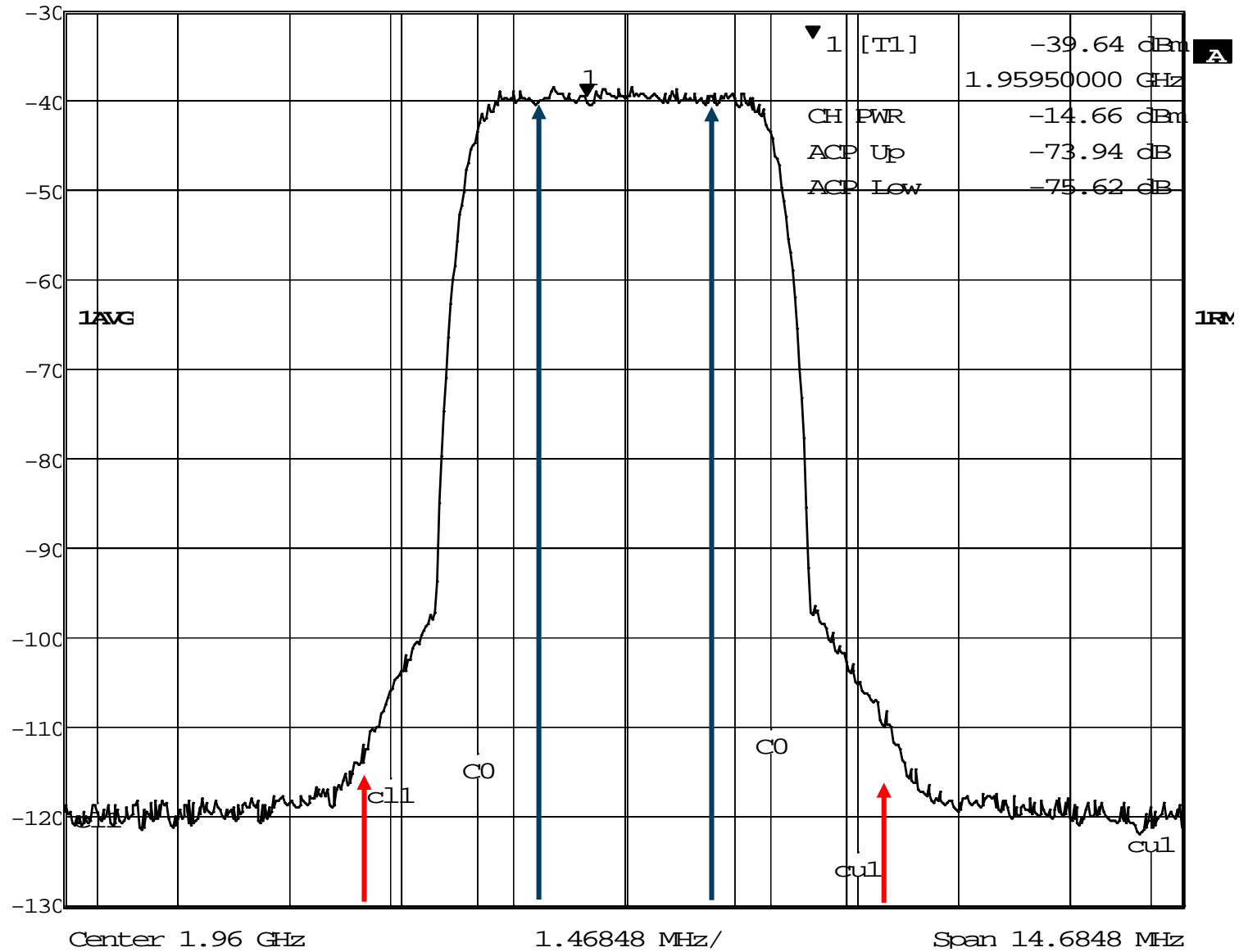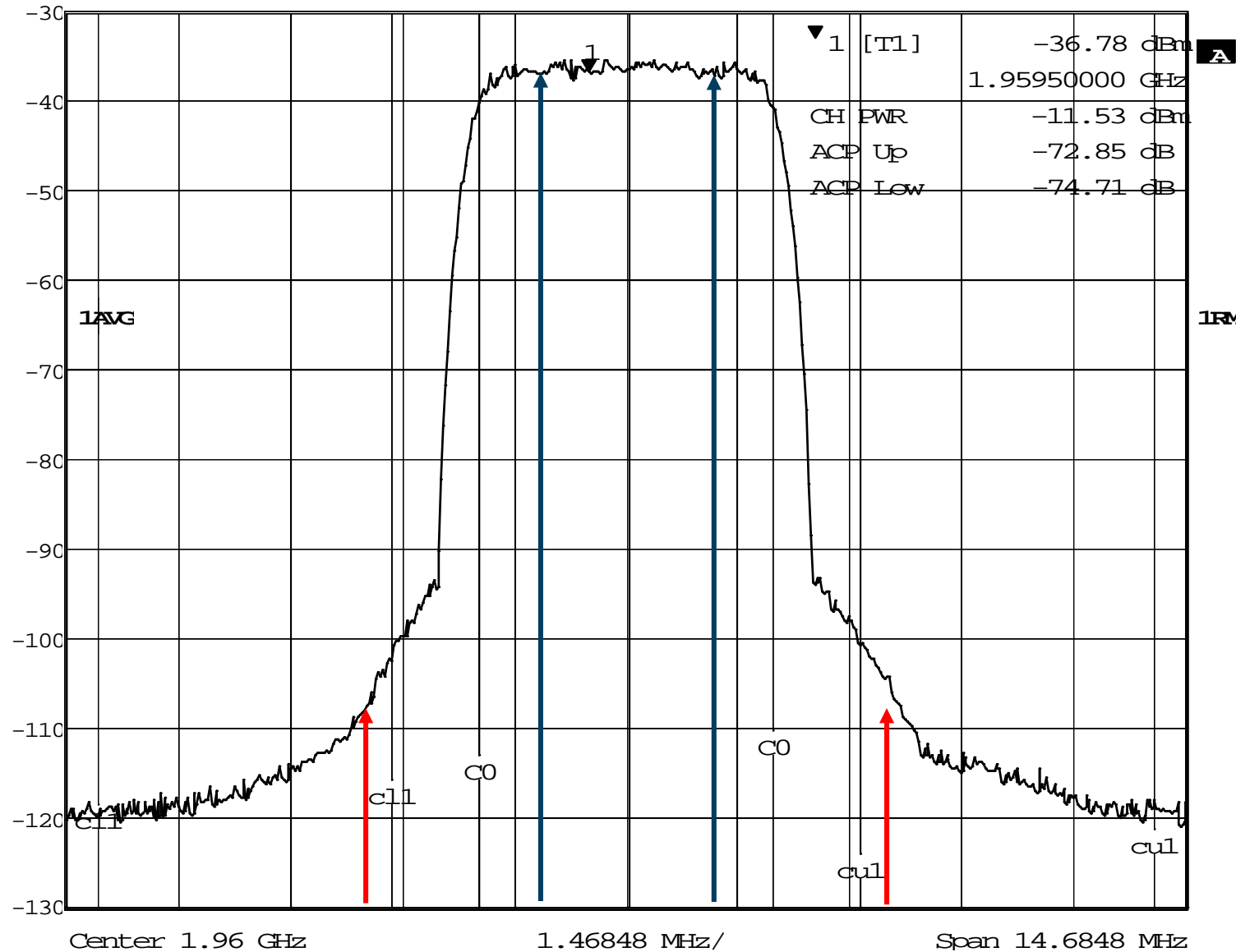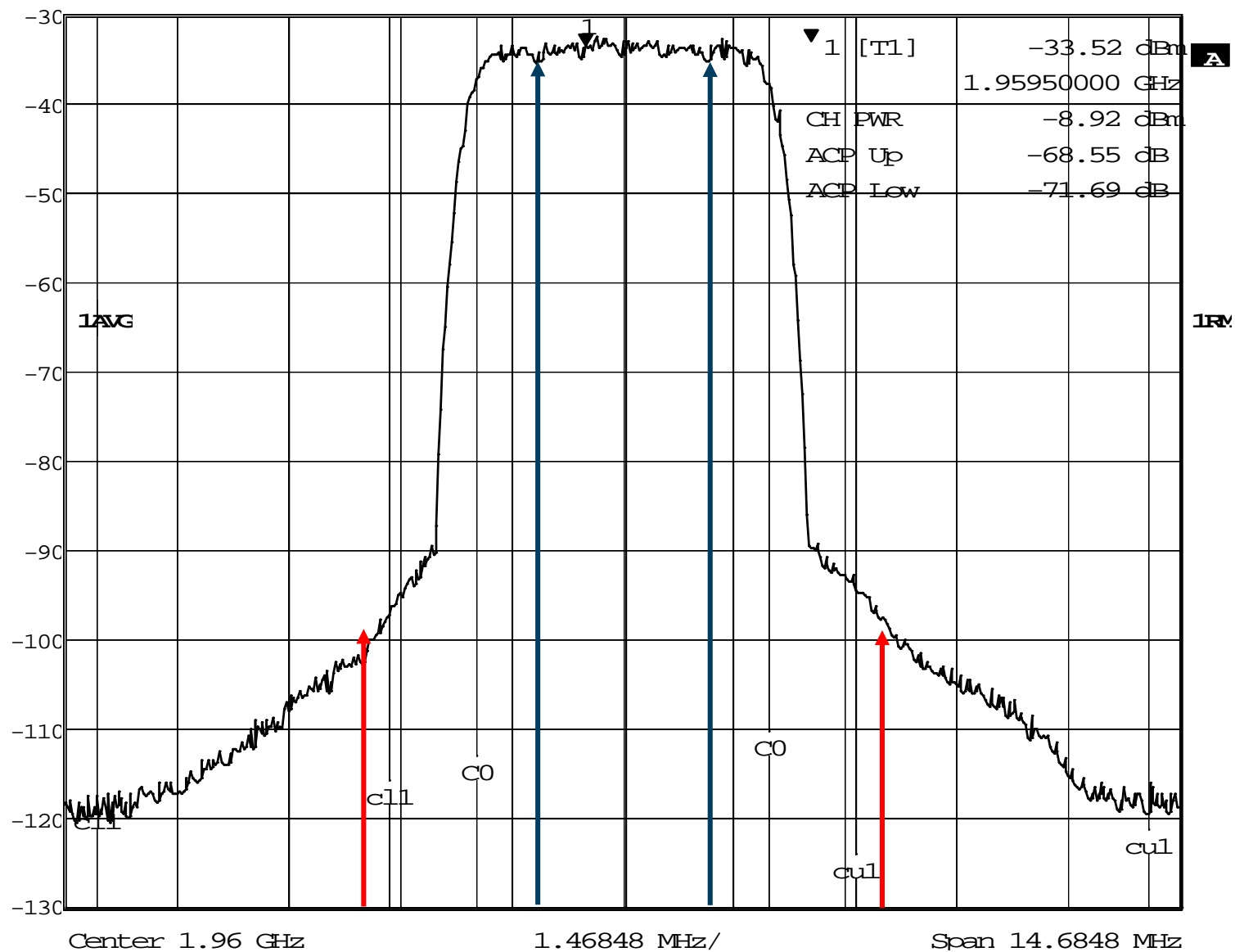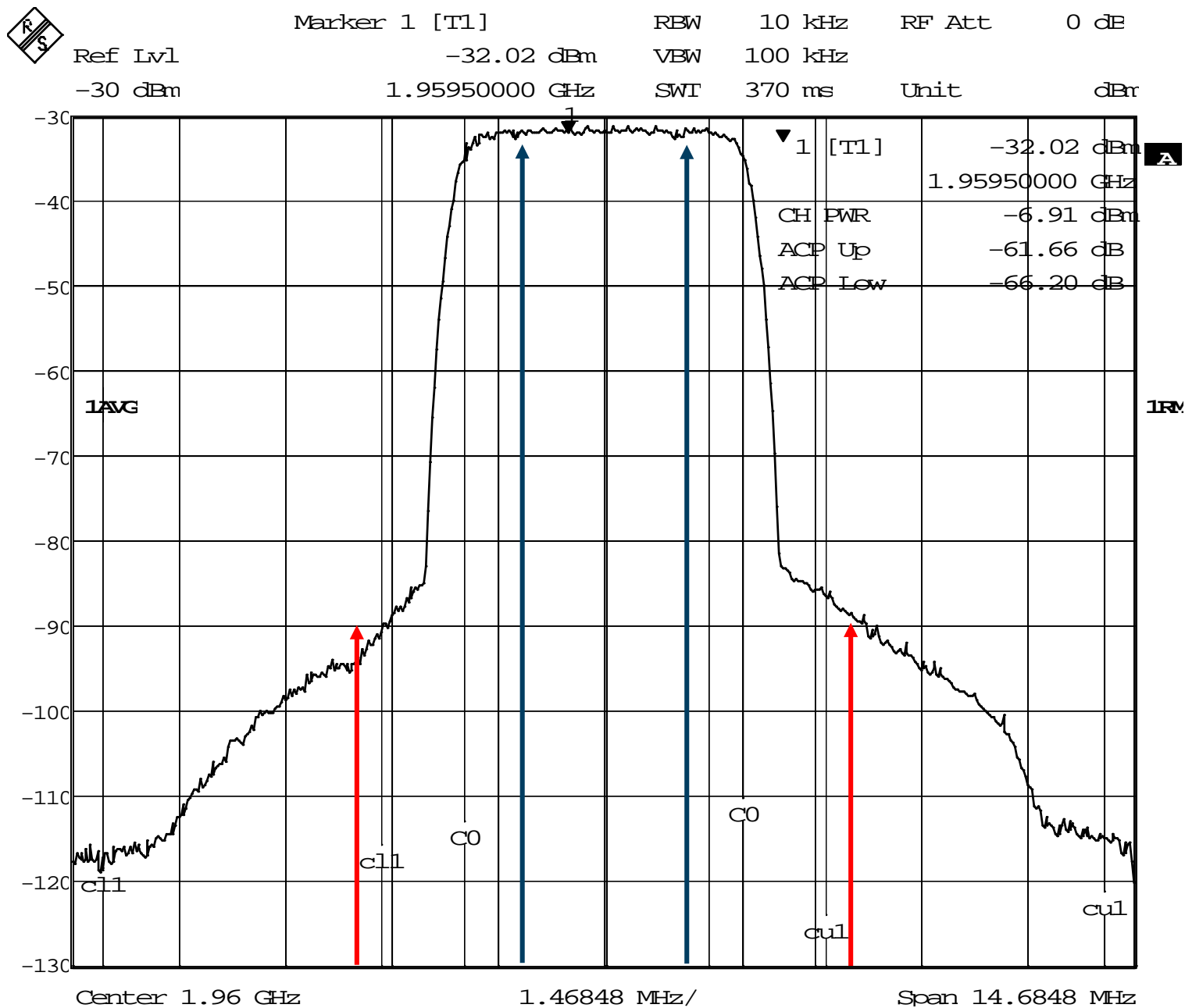
Typical ACP Profiles vs. Pout
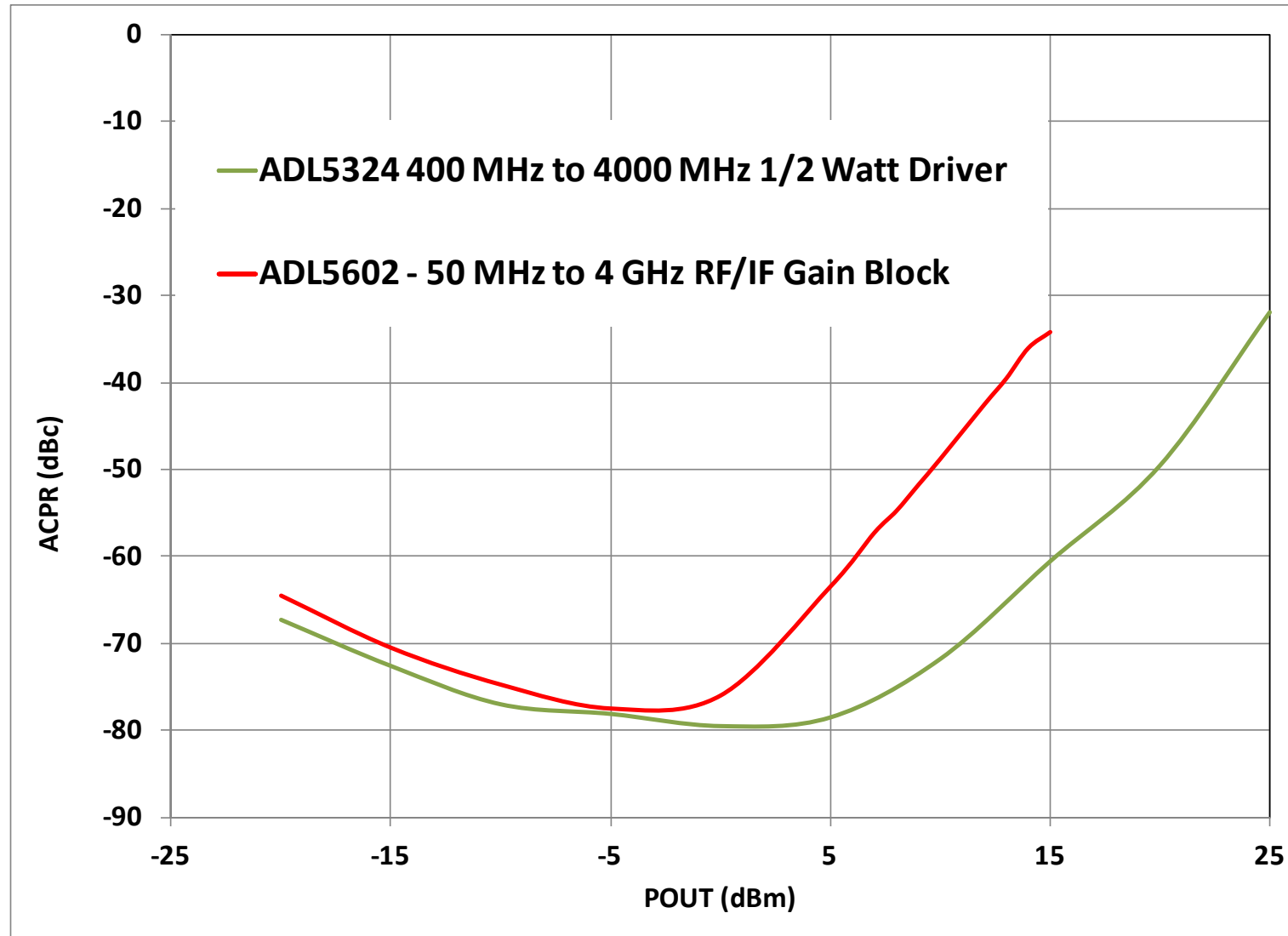
Power Consumption

▶ 100 mA Amplifier with 5 V supply will consume 0.5 W

▶ Since signal chain contains multiple amplifiers, power budget rises fast

▶ For RF Amps that can operate at lower supply voltage (e.g. 3.3V), there is a double benefit because supply current also reduces.

▶ People typically trade-off supply current and OIP3 (higher I_{SY} is ok if the OIP3 is correspondingly lower)

▶ It is very common to describe a device in terms of its OP1dB, expressed in watts (e.g. a ½ Watt device or a 1 Watt device). So a ½ Watt device does not have a power consumption of ½ Watts (but it can deliver ½ Watts when driven into compression

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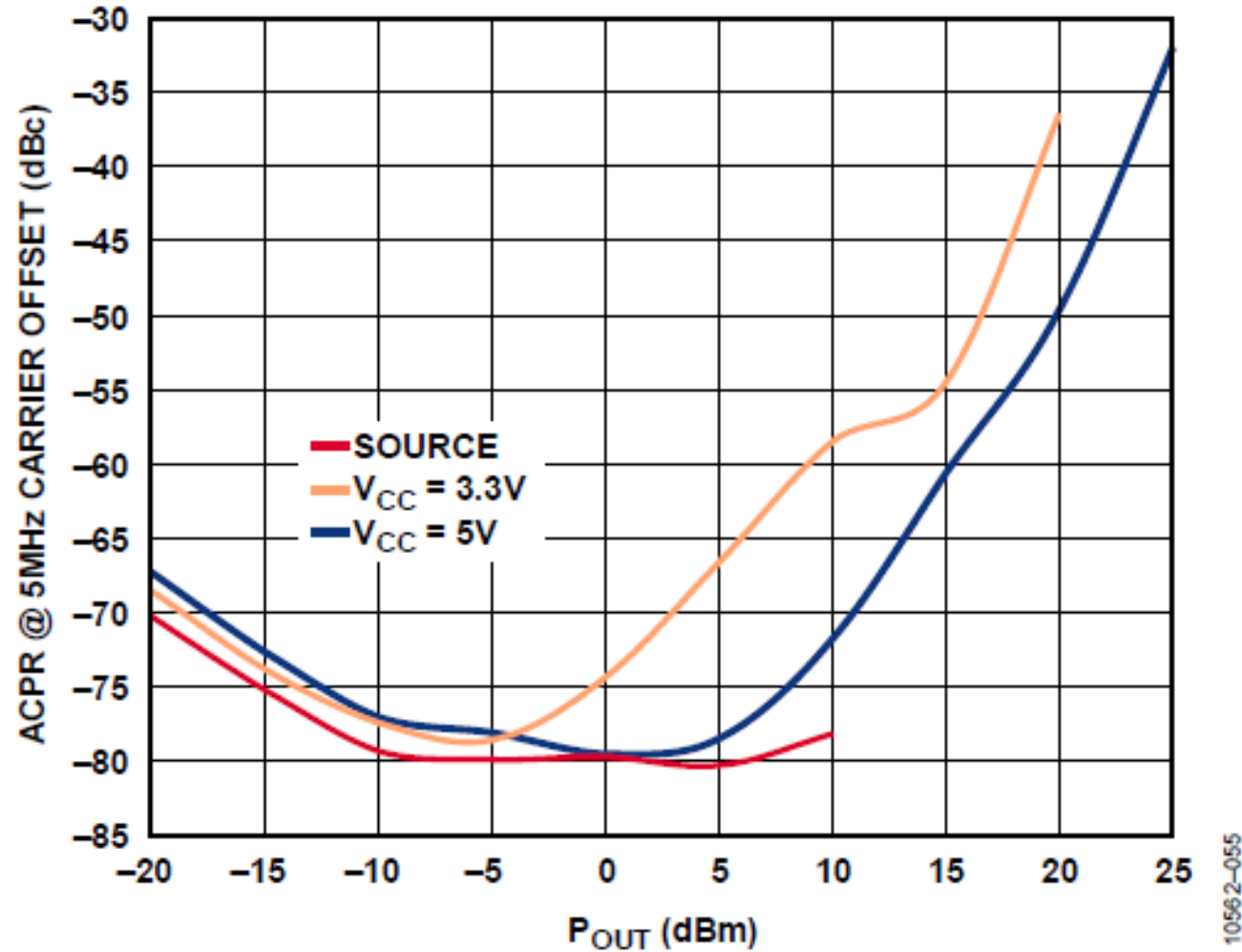
Figure 2. ACPR vs. Output Power, Single Carrier W-CDMA,
TM1-64 at 2140 MHz

Noise

$$N_I = kT$$
$$(-173.8 \text{ dBm/Hz})$$

GAIN

$$N_0$$
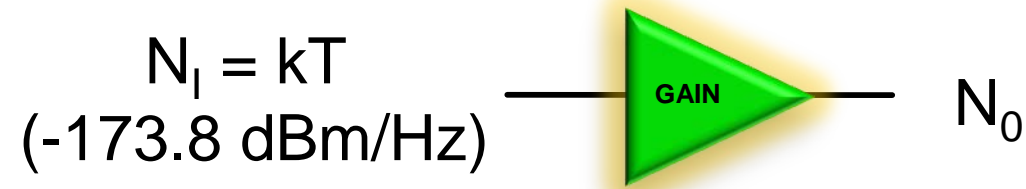
Output Noise Floor (dBm/Hz) = N_I (dBm/Hz) + Gain(dB) + Noise Figure (dB)

► Noise is either specified as

- Noise Figure (dB)
- Noise Factor (no units) (Noise Figure = 10 log (Noise Factor)
- Noise Spectral Density or Noise Floor (dBm/Hz)
- Noise Spectral Density (nV/√Hz)

► Noise figure expresses degradation in SNR (not just the increase in noise)

► Noise spectral density (NSD) in nV/√Hz is the voltage equivalent of power spectral density (N_0) in dBm/Hz

► RF Engineers always think about power (even when they shouldn't!)

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Cascaded Noise Performance of RF Signal Chains
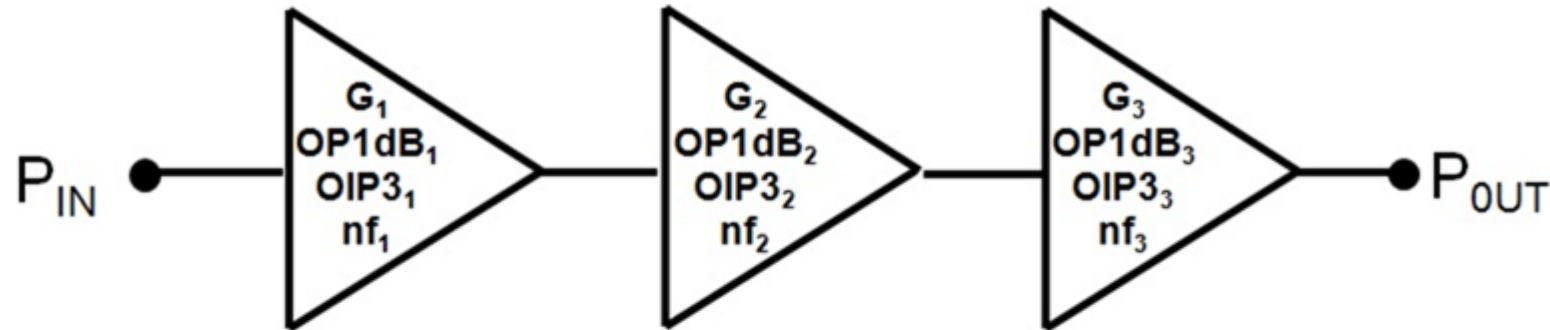
$$G = G1 \times G2 \times G3$$

$$nf = nf_1 + \frac{nf_2 - 1}{(G1)} + \frac{nf_3 - 1}{(G1 \times G2)}$$

- ◆ **Noise Figure of first stage dominates overall noise figure**
- ◆ **Influence of NF of second and third stages is diminished by gain of first stage**
- ◆ **All calculations must be performed in linear domain (i.e. using Noise Factor instead of Noise Figure)**

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ADIsimRF – Signal Chain Simulator

- **Cascaded noise, distortion and gain calculations for RF components**
- **Contains device data for RF components, ADCs and DACs**
- **Useful tool for calculating cascaded performance and deciding how well devices fit together**
- **www.analog.com/adisimrf**

RF Signal Chain Calculator - Direct Conversion Transmitter.sgc

File   Stage   Selection Tables   Reference Data   Mode   Help

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10
Transmit	Dual DAC	LPF	IQ-ModPLL	DGA	Amp	Amp	RF SAW Tx	Device	Device	Device
Toggle Tx/Rx	AD9122V1	Temp Part	ADRF6702V2	DSA32dB	ADL5320	ADL5604	B3669	PartNumber	PartNumber	PartNumber
Output Freq(MHz)	0	0	2140	2140	2140	2140	2140			
Zin(Ohms)	100	100	250	50	50	50	50			
Zout(Ohms)	100	100	50	50	50	50	50			
Power Gain(dB)	0	-0.5	6.8	-5	13.2	14	-3			
Voltage Gain(dB)	0	-0.5	-0.2	-5	13.2	14	-3			
Output IP3(dBm)	36	100	29.1	100	42	42.1	100			
Output P1dB(dBm)	1	100	13.1	90	25.7	28.6	100			
Pout(dBm)	-9.6	-10.13	-4.21	-9.21	3.99	17.99	14.99			
Pout Backoff(dB)	10.6	110.1	17.3	99.2	21.7	10.6	85			
Peak Backoff (dB)	0.6	100.1	7.3	89.2	11.7	0.6	75			
Noise Figure(dB)	10	0.5	8.9	5	4.4	3.8	3			
Voltage(V)	3.3	0	5	0	5	5	0			
Current(mA)	370	0	290	0	104	318	0			

Input

Number of Stages:	10	
Input Power:	-9.63	dBm
Analysis Bandwidth:	3.84	MHz
PEP-to-RMS Ratio:	10	dB
P1dB Backoff Warning:	10	dB
Peak Backoff Warning:	0	dB

Analysis

Power Gain:	24.6	dB
Output Power (rms):	15	dBm
Output P1dB:	22	dBm
Output Voltage (rms):	1.26	Vrms
Output Voltage (pp):	11.22	Vpp
Pwr Consumption:	4.78	W

Noise Figure:	13	dB
Output NSD:	-136.2	dBm/Hz
Output NSD:	34.74	nV/rtHz
Output Noise Floor:	-70.3	dBm
SNR:	85.3	dB

Output IP3:	38.4	dBm
IMD (Po/2 per tone):	-52.9	dB
SFDR:	72.5	dB
ACLR (est.):	-52	dB

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Distortion and Noise Contribute to Output Spectral Quality

►Increasing output power improves SNR at the cost of degraded Adjacent Channel Power Ratio

Figure 2. ACPR vs. Output Power, Single Carrier W-CDMA, TM1-64 at 2140 MHz

RF Amplifier Specs - Conclusions

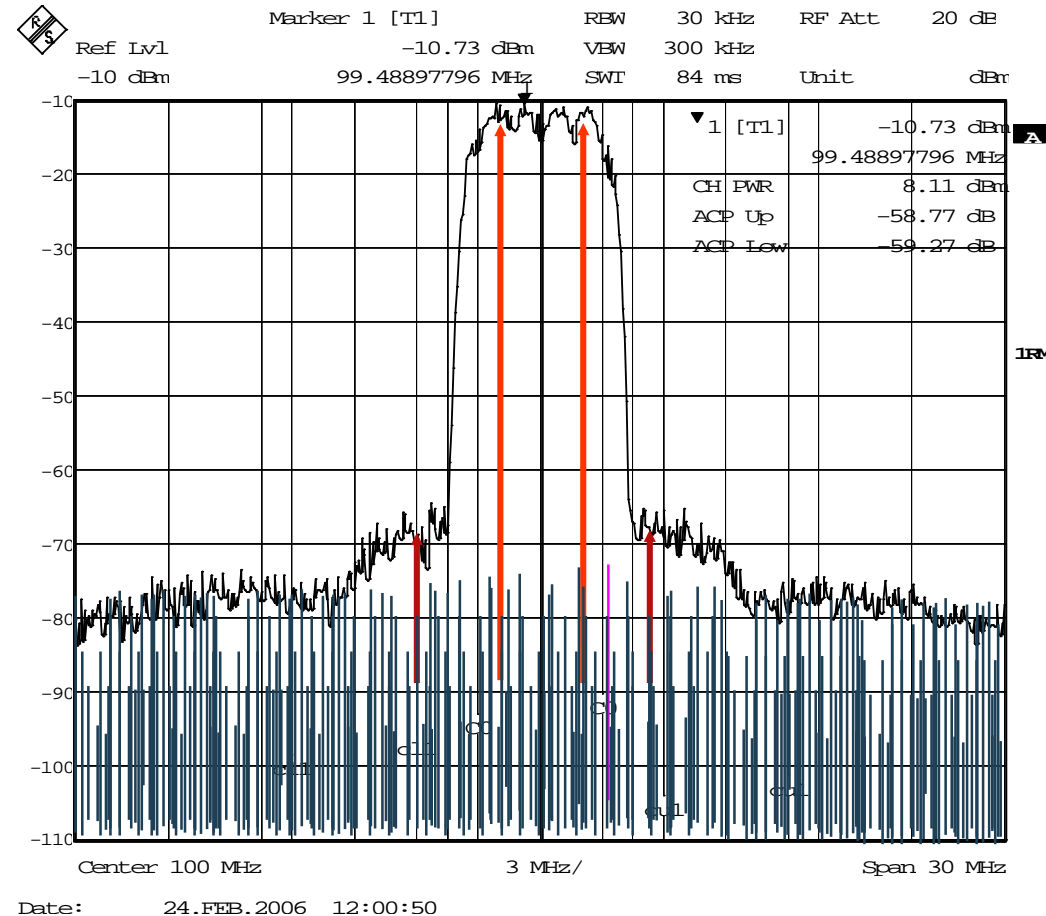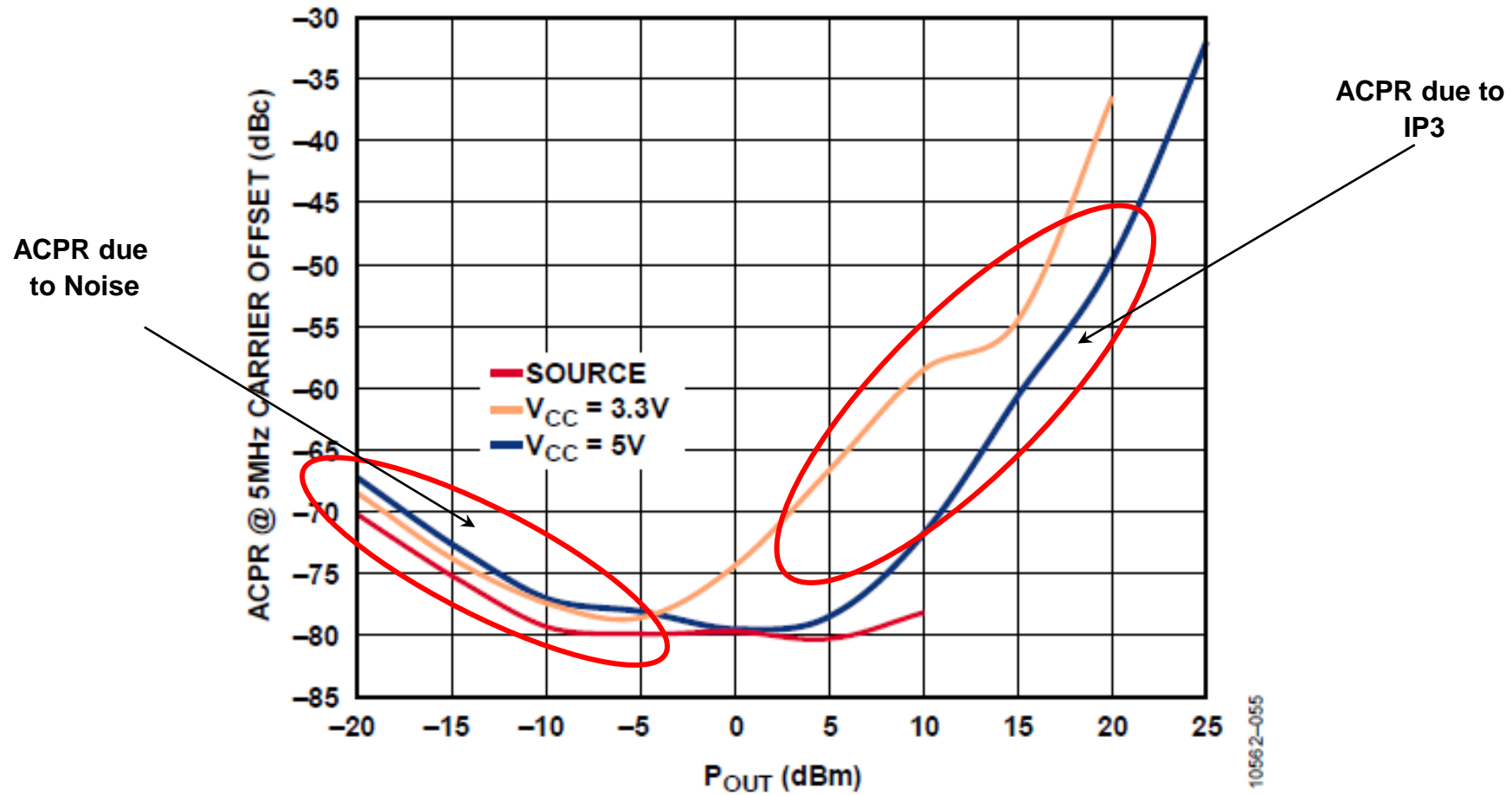► IP3 is critical in transmitters because it predicts spectral distortion for a particular output power level

► IP3 is critical in receivers because it predicts blocker immunity at a particular input level.

► OIP3 vs. Output Power is supposed to be constant and it often is not.

► (WCDMA) ACP is a useful metric for comparing amplifiers, even in non-WCDMA systems.

► IP3 and ACP are closely correlated

► Noise affects ACP at low power levels

► Systems with signals that have high peak-to-average ratio operate massively backed off from OP1dB → IP3/ACP are more important than P1dB

► Delta between OIP3 an OP1dB is supposed to be constant at 10 dB and it often is not

► Everyone trades off IP3/P1dB and Power Consumption

► When a someone asks for a ½ Watt PA, you need to say "let's talk" because their needs may be satisfied by a cheaper ¼ Watt PA with high IP3 with lower power consumption.

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Some examples

HMC7748

- ▶ 2 GHz to 6 GHz

- ▶ 58 dB typical small signal gain
  - Increasing the volts by 794.32 times
  - Increasing the power (Watts) by 630957.34 times

- ▶ 43 dBm typical saturated output power (19.95W)

- ▶ 48 dBm typical output IP3

- ▶ 6 dB maximum noise figure

- ▶ Operates from 12 V and 28 V supplies

- ▶ Built-in bias sequencing
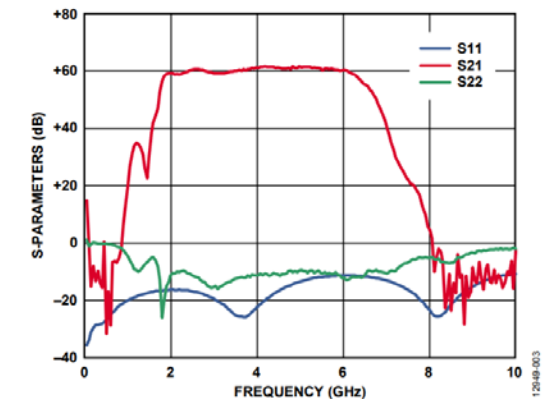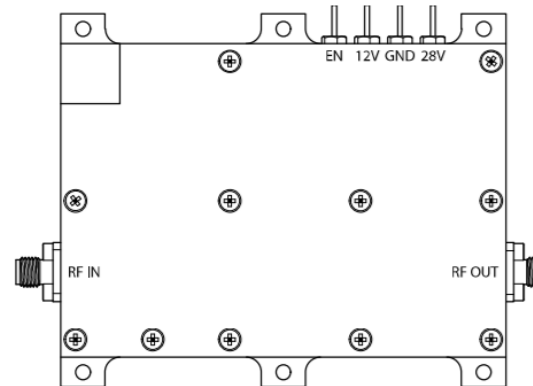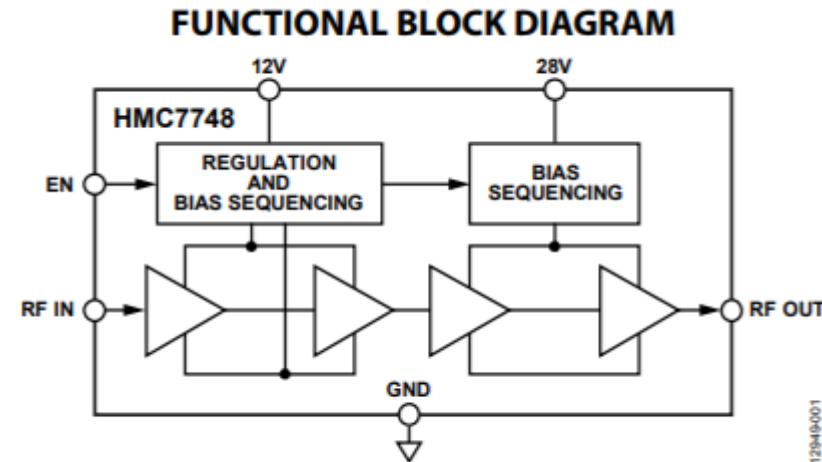
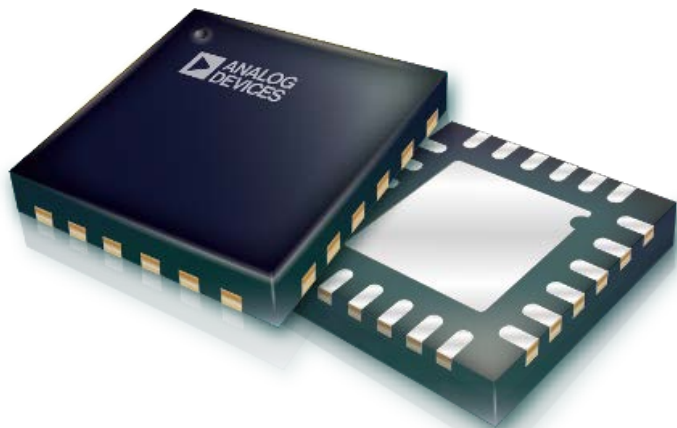- ▶ Enable pin to provide shutdown capability

FUNCTIONAL BLOCK DIAGRAM

Figure 1.

Figure 2. Pin Configuration

Figure 3. S-Parameters vs. Frequency at 25°C

Table 3. Pin Function Descriptions

Pin No.	Mnemonic	Description
J1	RF IN	RF Input. RF IN has a frequency range of 2 GHz to 6 GHz, and input signals of −10 dBm and a maximum of −8 dBm.
J2	RF OUT	RF Output. RF OUT has a frequency range of 2 GHz to 6 GHz.
J3	28V	28 V, 4 A Supply.
J4	GND	Ground Connection.
J5	12V	12 V, 0.7 A Supply.
J6	EN	Enable. Pull this pin to ground to enable the PA.

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Some examples

ADL5606

▶ Operation from 1800 MHz to 2700 MHz

▶ Gain of 24.3 dB at 2140 MHz

▶ OIP3 of 45.5 dBm at 2140 MHz

▶ P1dB of 30.8 dBm at 2140 MHz

▶ Noise figure of 4.7 dB at 2140 MHz
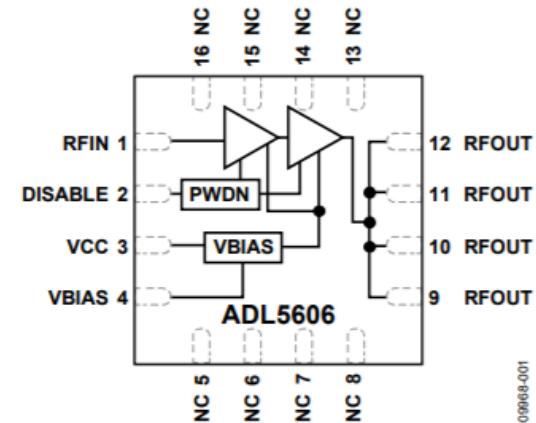
▶ Power supply: 5 V

FUNCTIONAL BLOCK DIAGRAM

Figure 1.

*COMPLIANT TO JEDEC STANDARDS MO-220-WGGC-3
WITH EXCEPTION TO THE EXPOSED PAD.
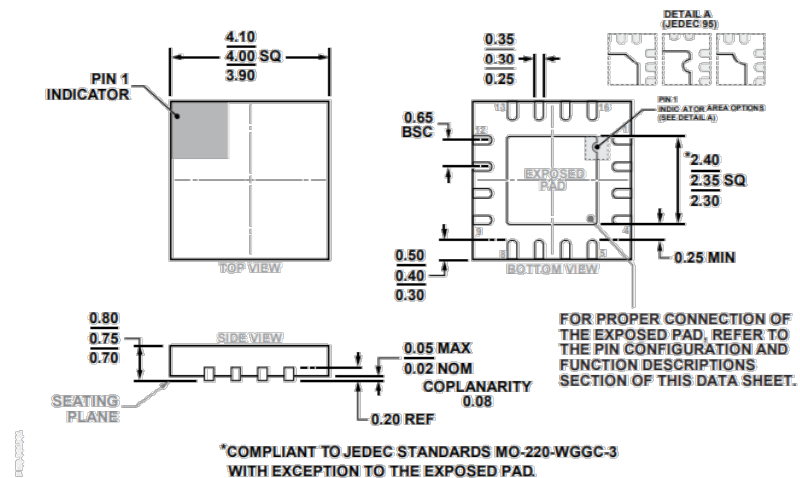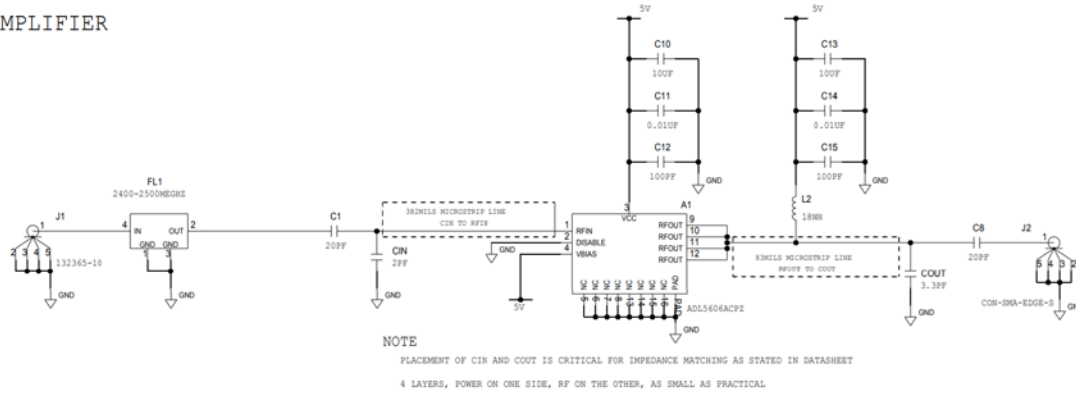
Figure 40. 16-Lead Lead Frame Chip Scale Package [LFCSP]
4 mm × 4 mm Body and 0.75 mm Package Height
(CP-16-20)
Dimensions shown in millimeters

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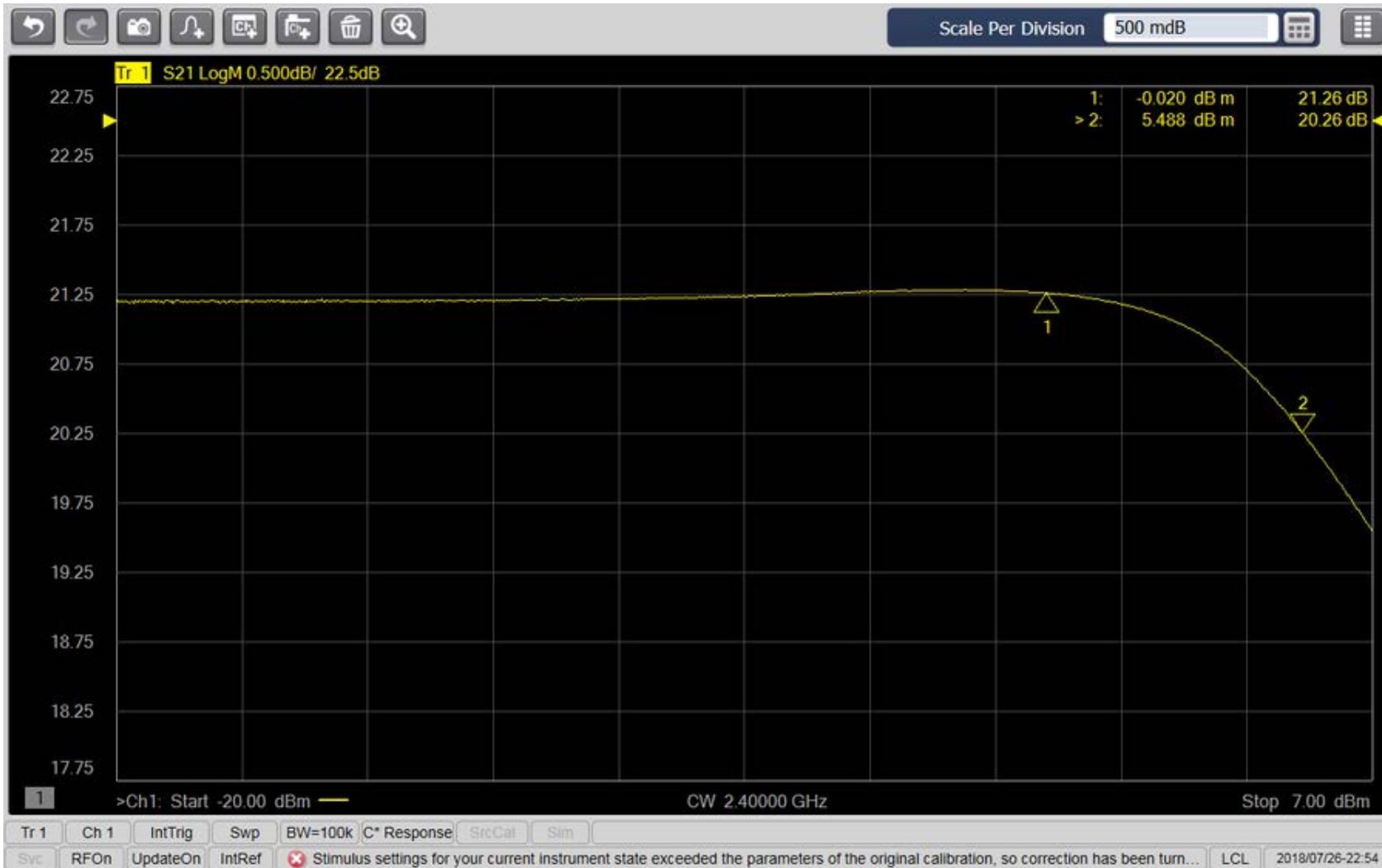
▶ Stick it on a PCB with SMA connectors
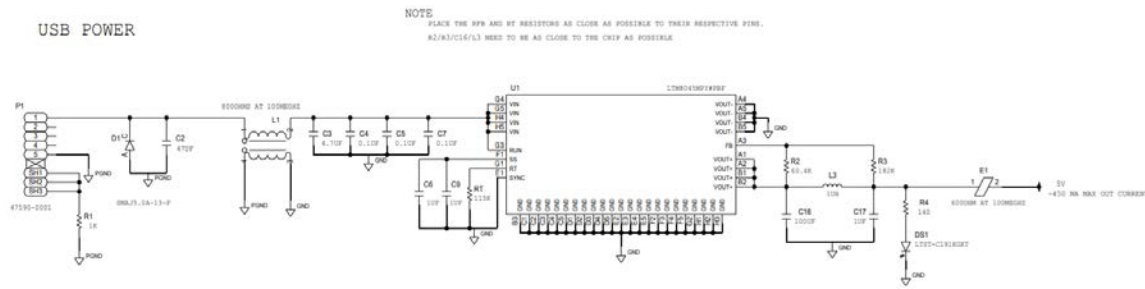
▶ Add a 2400 – 2500 SAW Filter

P1dB (measured)

► No compression up to:

  ► 0 dBm (input)

  ► 21.26 dBm (output)

► P1dB =

  ► 5.5 dBm (input)

  ► 25.76 dBm (output)

Power?

USB POWER

► Power it from USB connector (no bias – T, works with any radio, including the PLUTO-SDR)

| dBm	mW	Volts$_{rms}$	Volts$_{pp}$
-10	0.1	70.711 mV	199.970 mV
0	1	223.607 mV	632.360 mV
5	3.16	0.398 V	1.125 V
10	10	0.707 V	2.000 V
15	31.6	1.257 V	3.556 V
20	100	2.236 V	6.324 V
25	316	3.976 v	11.246 V
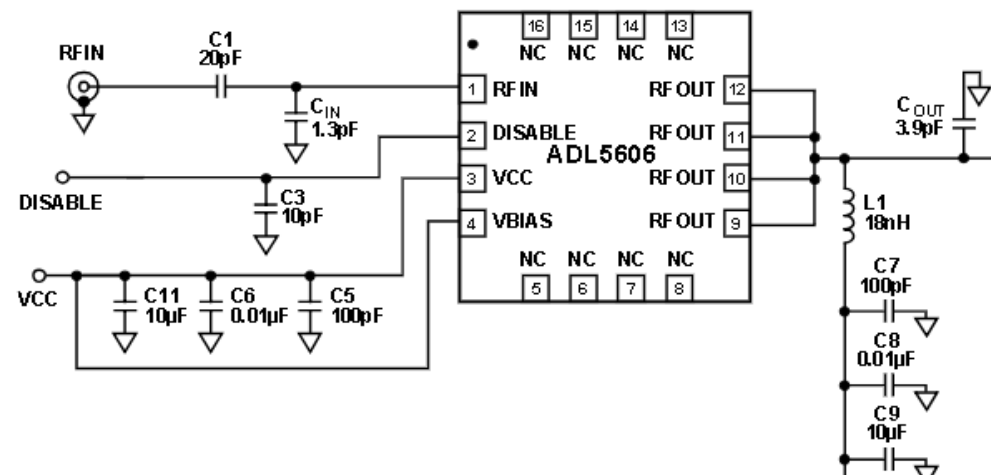
► The output stage (RFOUT) is connected to Vcc through the inductor L1.

► From a DC perspective, inductors become short circuits, and RFOUT is sitting at 5.0V,

► allowing a 10V$_{peak-peak}$ swing from the amplifier.

68

Fixed gain RF Amplifier
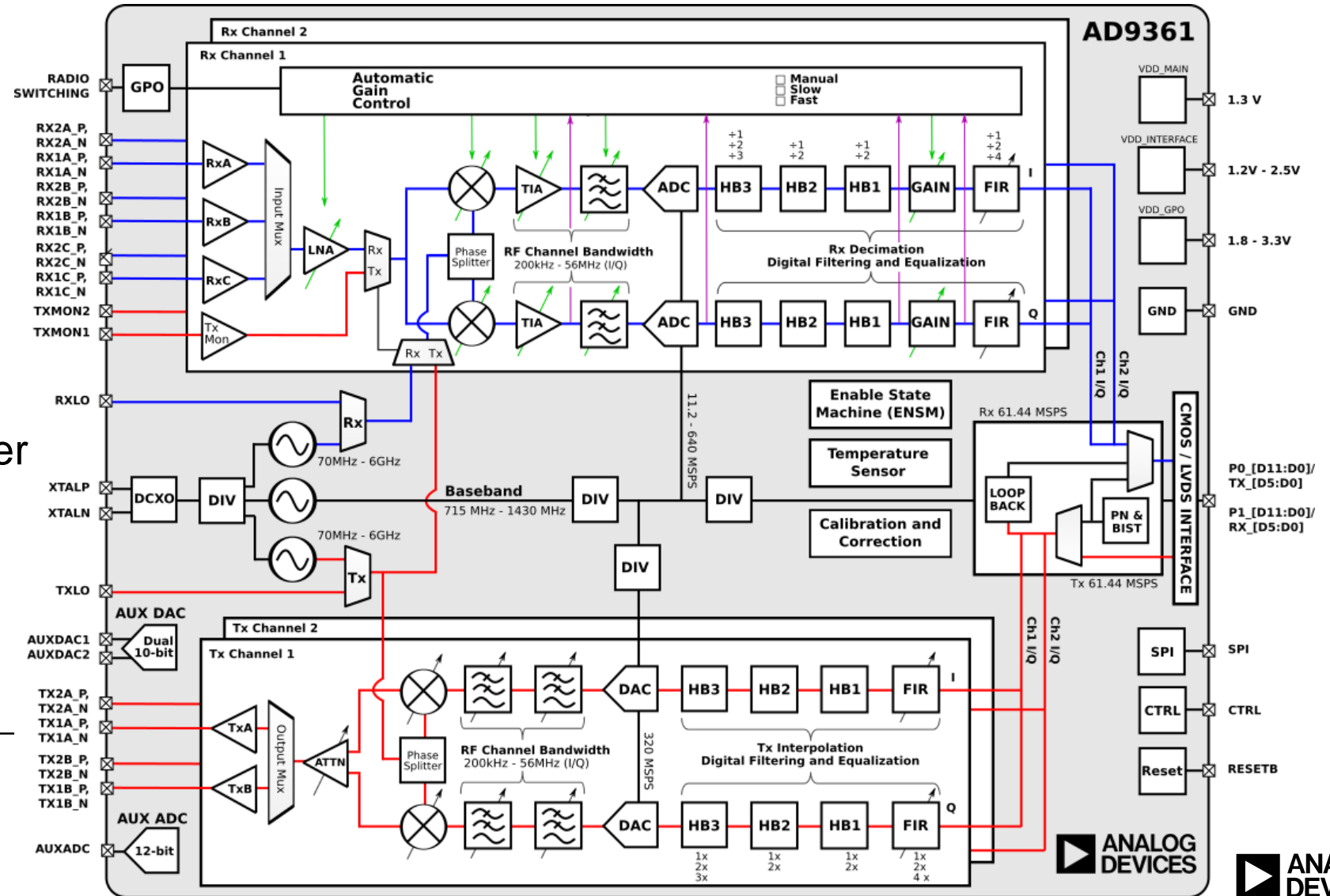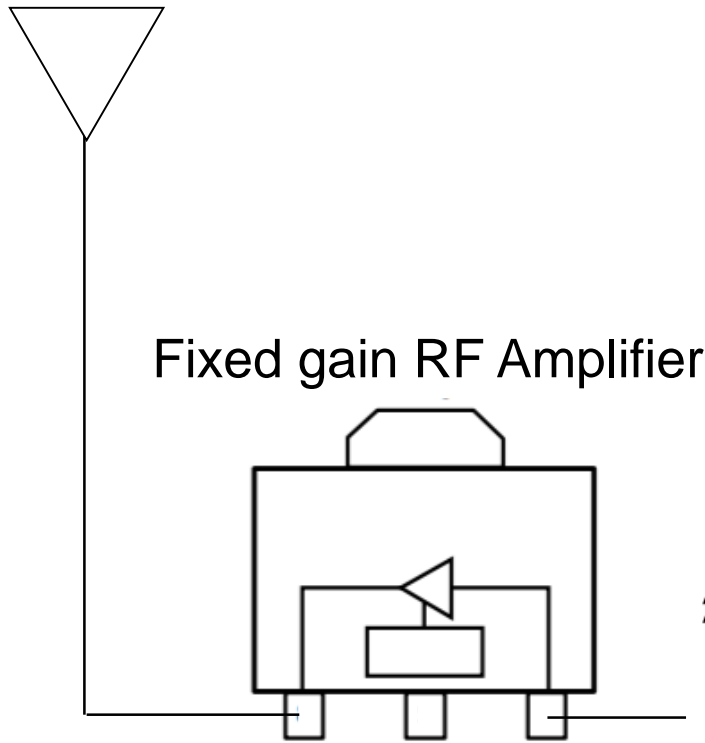
Performance Data (meets or exceeds AD9363 specs)

► Tx:
  ▪ EVM (64 QAM, LTE10) of -40dB

AD9361	without	amp	with amp			
output	power	evm	power	evm	Gain	EVM loss
0	**-34.4**	**-36**	-17	-36	17.4	0
-5	-39.1	-40.9	-17	-38	22.1	2.9
-10	-43.2	-40.1	-22.6	-37	20.6	3.1
-15	-48.7	-40	**-27.5**	**-37.6**	21.2	2.4
-20	-53.5	-39.6	-32.3	-37.9	21.2	1.7
-25	-55.6	-37.9	-37.4	-37.1	18.2	0.8
-30	-63.5	-35.3	-42	-35	21.5	0.3

Thermal issues

EVAL-CN0417-EBZ
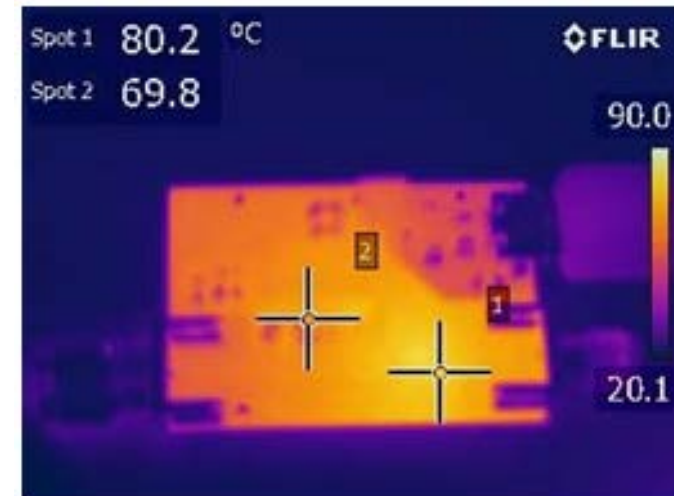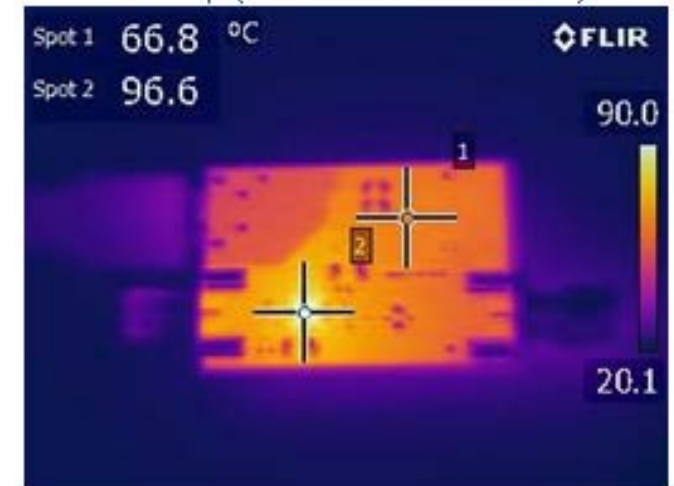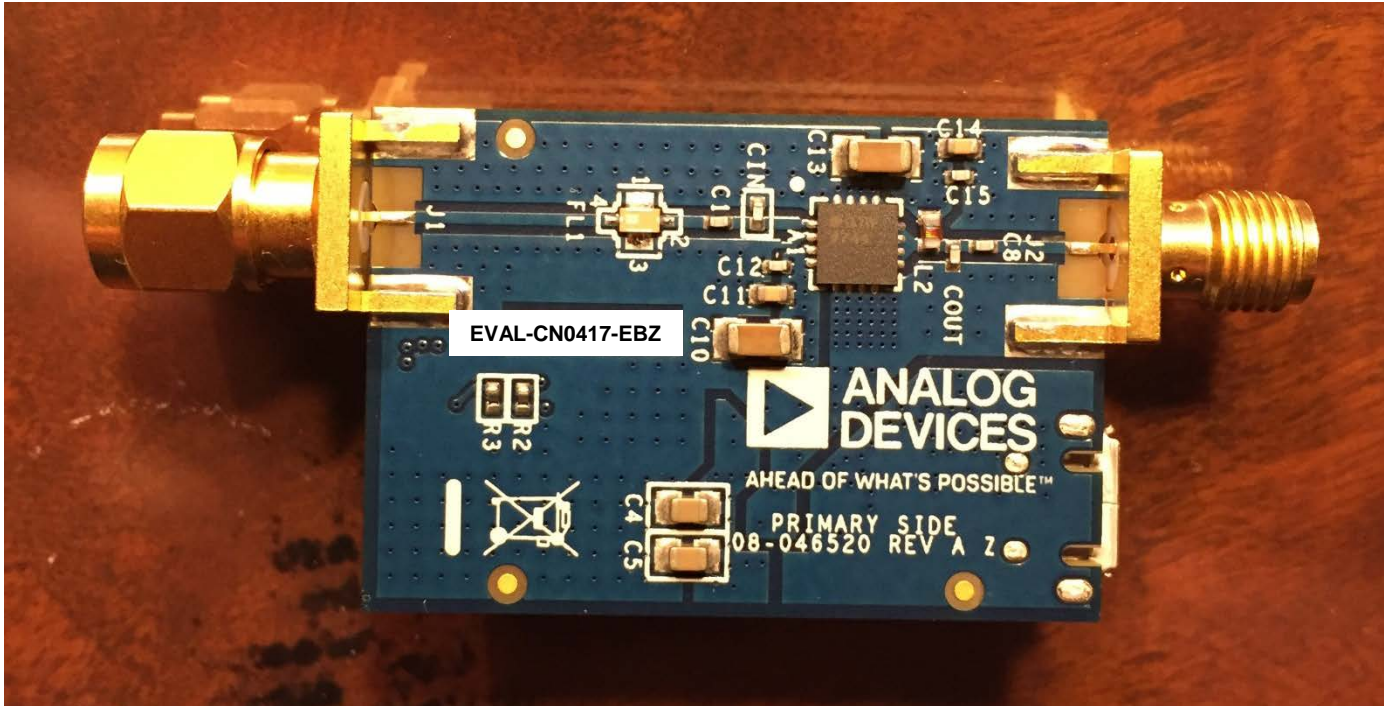
Spectra is a scarce resource, that everyone needs to respect

▶ The RF spectrum needs to be shared.

▶ Just because you don't want to send a signal, doesn't mean you aren't.

▶ Just because you don't want someone else to receive your signal, doesn't mean they will not.

▶ This can have large safety, security, or economic impact.

https://en.wikipedia.org/wiki/File:United_States_Frequency_Allocations_Chart_2016_-_The_Radio_Spectrum.pdf

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Regulation? (FCC is local, but most countries have similar organizations)

► In the US, in the 2.4–2.4835 GHz band, which is described by FCC sections 15.247 and 15.249:

- The permitted peak transmit power measured at the antenna input of a frequency hopping system with at least 75 hopping frequencies is +30 dBm.
- For systems with less than 75 but at least 15 hopping frequencies, a peak transmit power of +21 dBm is allowed.
- For systems that don't hop, 0 dBm is allowed. (spec'ed as 50 mV/m), for those with a ham license.

► End users assemble intentional radiators

- End users may need certification
  - If a individual or company wants to bring a product to the US market which includes a wireless transmitter, they must have the transmitter tested in a laboratory that is authorized by the FCC.

► If you are contacted by the FCC (or anyone else) about a matter of spectrum interference, immediately stop using the device, don't use it again.

► Home-built or used transmitters, like all Part 15 transmitters, are not allowed to cause interference to licensed radio communications and must accept any interference that they receive.

► If the Commission determines that the operator of a transmitter has not attempted to ensure compliance by employing good engineering practices then that operator may be fined up to $10,000 for each violation and $75,000 for a repeat or continuing violation.

► *The Communications Act of 1934*
- *Section 301* - requires persons operating or using radio transmitters to be licensed or authorized under the Commission's rules (47 U.S.C. § 301)
- *Section 302(b)* - prohibits the manufacture, importation, marketing, sale or operation of these devices within the United States (47 U.S.C. § 302a(b))
- *Section 333* - prohibits willful or malicious interference with the radio communications of any station licensed or authorized under the Act or operated by the U.S. Government (47 U.S.C. § 333)
- *Section 503* - allows the FCC to impose forfeitures for willful or repeated violations of the Communications Act, the Commission's rules, regulations, or related orders, as well as for violations of the terms and conditions of any license, certificate, or other Commission authorization, among other things.
- Sections 510 - allows for seizure of unlawful equipment (47 U.S.C. § 510)

► *The Commission's Rules*
- *Section 2.803* - prohibits the manufacture, importation, marketing, sale or operation of these devices within the United States (47 C.F.R. § 2.803)
- *Section 2.807* - provides for certain limited exceptions, such as the sale to U.S. government users (47 C.F.R. § 2.807)

► *The Criminal Code* (Enforced by the Department of Justice)
- *Title 18, Section 1362* - prohibits willful or malicious interference to US government communications; subjects the operator to possible fines, imprisonment, or both (18 U.S.C. § 1362)
- *Title 18, Section 1367(a)* - prohibits intentional or malicious interference to satellite communications; subjects the operator to possible fines, imprisonment, or both (18 U.S.C. § 1367(a))

► Check out :
- https://www.fcc.gov/enforcement

DANGER
OPINIONS AHEAD

Thanks