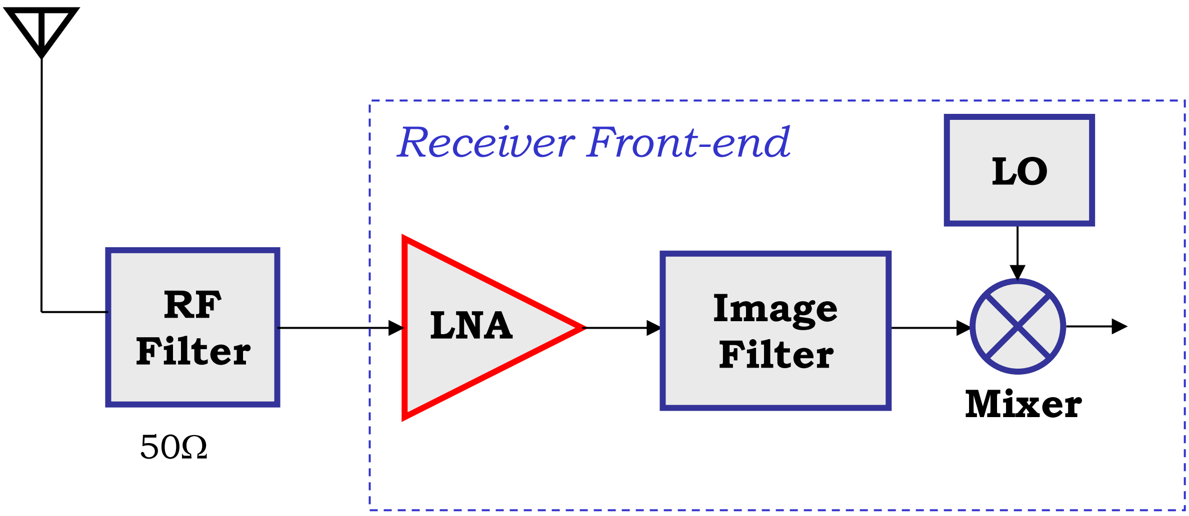
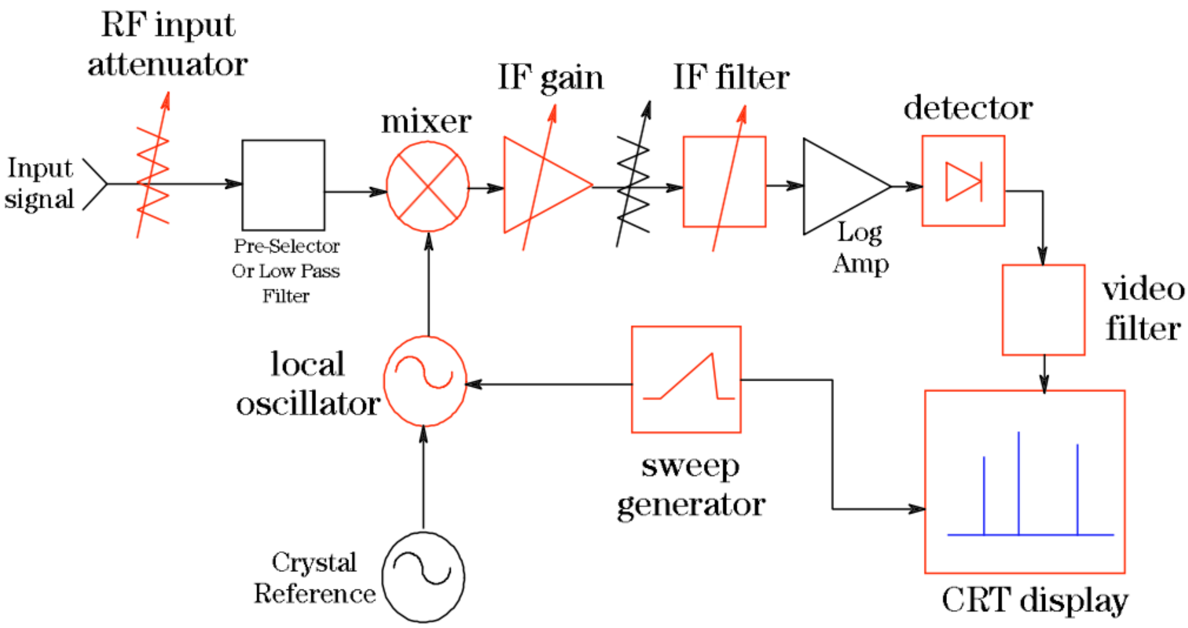
TSEK03 LAB 2:
Characterization of an LNA

Ver. 2018-09-28





1 Introduction

In this laboratory exercise, we will characterize the performance of a low-noise amplifier (LNA) operating in the FM broadcast band.

The following equipment is needed to complete the lab: two signal generators, an oscilloscope, a spectrum analyzer, a noise generator, two low-pass filters (100 MHz), two fixed 6 dB attenuators, a variable attenuator (0-120 dB), two variable voltage sources (0-30 V), a multimeter, and a power combiner/splitter.

Recommended reading: Razavi (course book): Chapter 5 (LNA), 2.3 (Noise), 2.4.2 (Dynamic Range).

2 Preparation tasks

Read through this lab manual and the two Application Notes, links on the course page, and answer the questions in sections 3.1a and 3.2a.

3 Exercises

3.1 Introductory measurements

a) Throughout this lab we will use a spectrum analyzer. How is the power spectrum measured by the spectrum analyzer?

First we want to investigate whether the signal generator we use is a perfectly linear device or not. Connect the signal generator together with a 6 dB attenuator to the spectrum analyzer, see Fig. 1. Use a carrier frequency of 100 MHz together with an output power of 6 dBm.

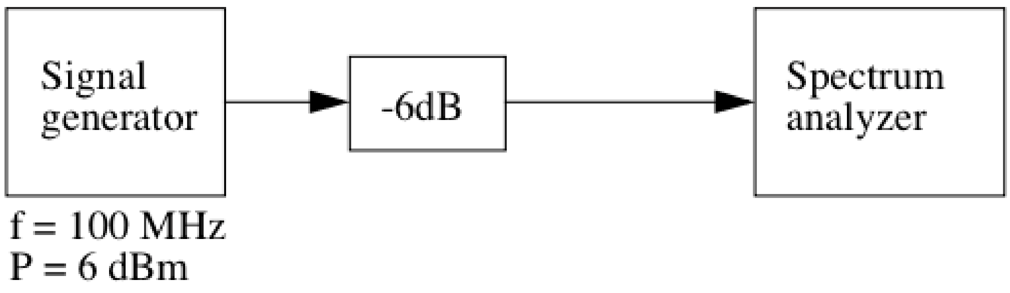


Fig. 1

b) Specify the different frequencies shown on the Spectrum analyzer together with their corresponding power levels.

c) Explain why there are more than one single frequency component.

d) Estimate the theoretical expected power level at the fundamental frequency.

e) Explain the difference between the measured and the expected power level.

Connect a 100 MHz low-pass (LP) filter between the attenuator and the Spectrum analyzer, see Fig. 2.

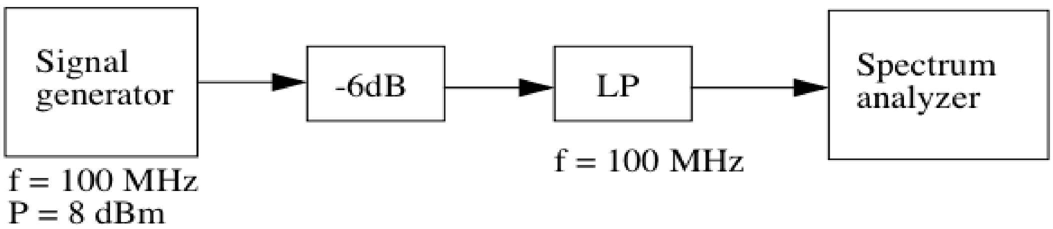


Fig. 2

f) Specify the power levels at the fundamental frequency, the second harmonics and third harmonics respectively. Explain why the result is different!

3.2 1 dB compression point measurement

a) What is the definition of the 1 dB compression point?

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Keep the same measurement setup as before but also connect a variable attenuator between the LP and the Spectrum analyzer, see Fig. 3. Change the RF level of the Signal generator to 7 dBm. Make sure that the power level after the variable attenuator is correct (the expected power level after the variable attenuator should equal the negative value of the variable attenuation).

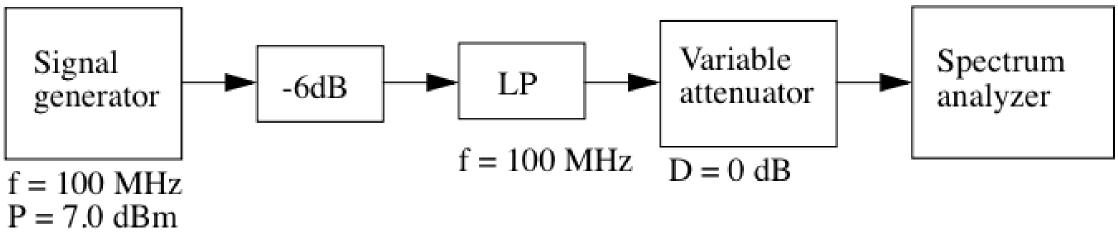

Fig. 3

b) What is the power level shown on the Spectrum analyzer?

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Before connecting the amplifier make sure that the variable attenuation equals 40 dB (i.e. you have to choose a high attenuation because we do not yet know the gain of the amplifier!).

Connect the LNA (DUT = Device Under Test), See Fig. 4. The supply voltage of the amplifier is 15 V. Make sure the supply voltage has the correct polarity. **Wrong polarity will permanently damage the LNA. Always turn on the DC first and then the RF signal. Turn off the RF signal first before the DC.**

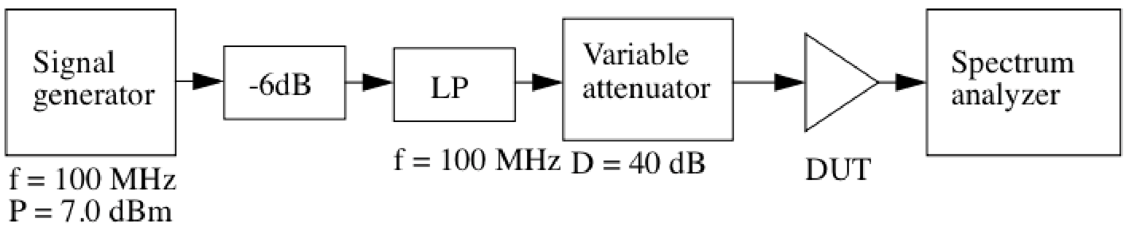

Fig. 4

c) Measure the output power level of the amplifier at different input power levels. Complete Table 1 below with variable attenuation (D), input power (P_{in}), output power (P_{out}), and amplifier gain (G). Plot P_{out} as a function of P_{in} in Fig. 5, next page.

D (dB)	P_{in} (dBm)	P_{out} (dBm)	G (dB)

Table 1

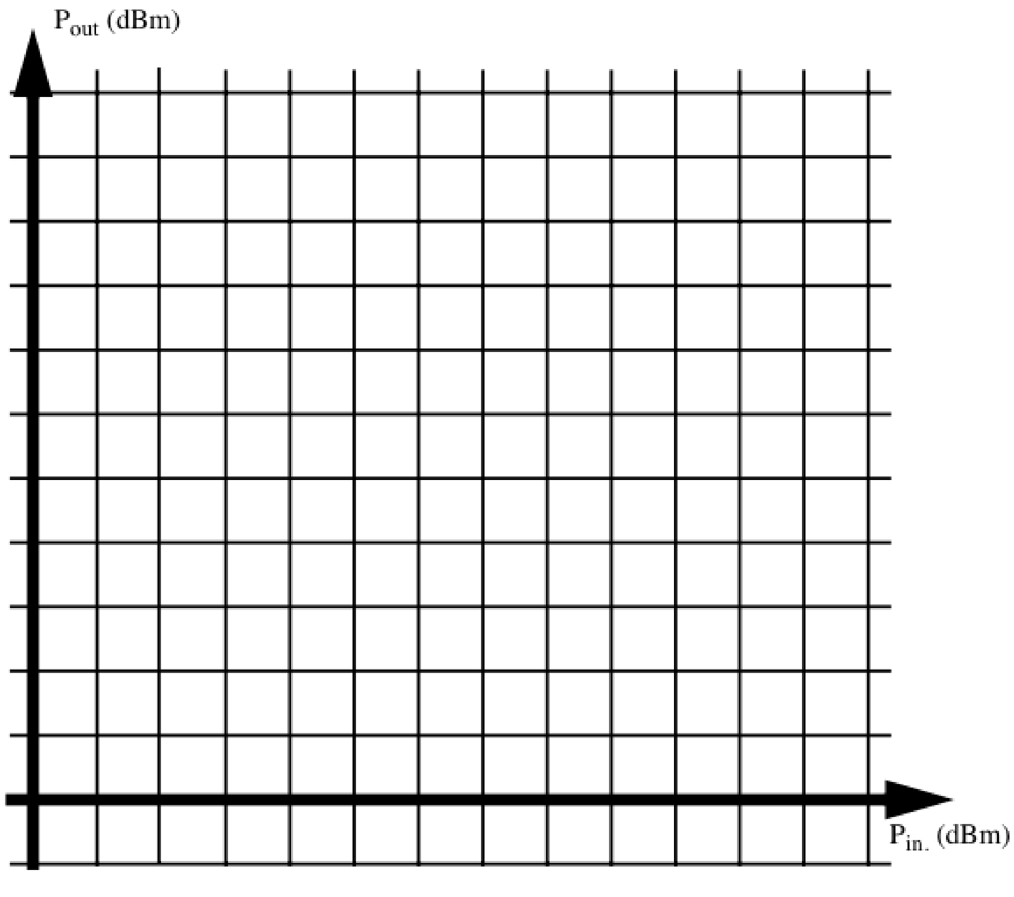

Fig. 5

d) What is the 1 dB compression point of the amplifier? (For LNAs, input compression point is usually given, for power amplifiers output compression point.)

3.3 Harmonic distortion

Keep the same measurement set up as in the previous exercise but connect a power combiner/splitter to the output of the amplifier, Fig. 6.

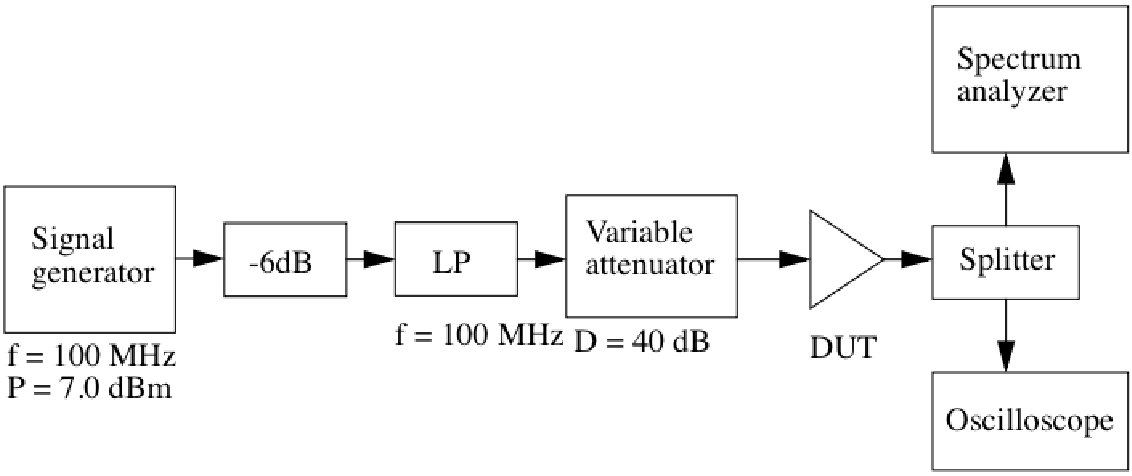

Fig. 6

Harmonic distortion is defined as distortion components which are integer multiples of the fundamental signal frequency (i.e. they are harmonically related to the fundamental frequency). Symmetric distortion is dominated by odd order frequencies while asymmetric distortion instead corresponds to even order frequencies.

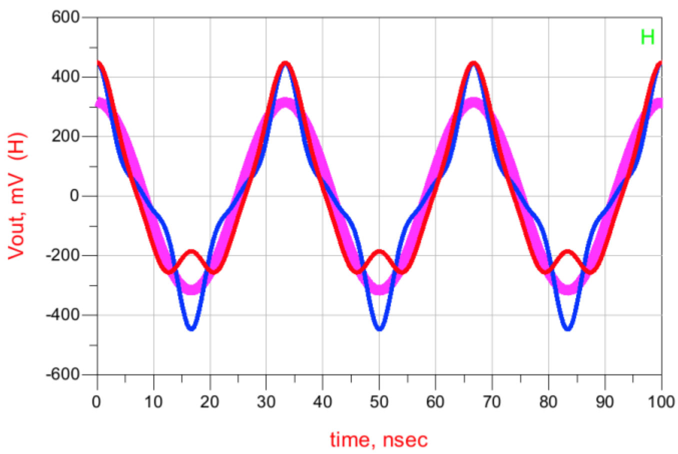

Fig. 7. Symmetric distortion (odd order frequencies, red) and asymmetric distortion (even order frequencies, blue). No distortion = thick line.

Increase now the power level until harmonic distortion becomes visible on the oscilloscope. As a rule of thumb we say that this happens when the total power level of the distortion components is about 1 % to 5 % of the corresponding value of the fundamental tone. Verify whether this is true or not!

3.4 Third order intercept point measurement

Make the following measurement set up:

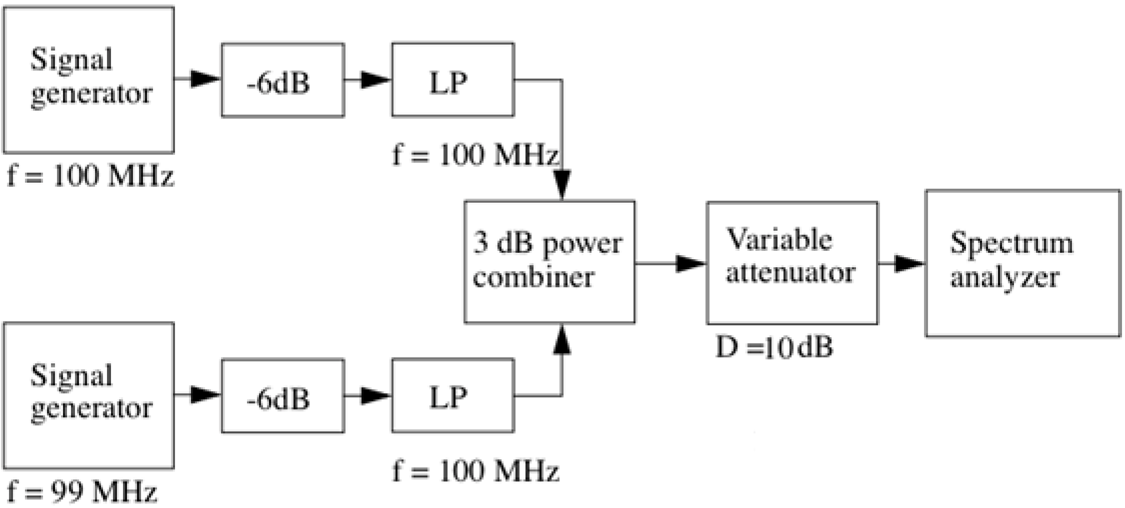

Fig. 8

a) Estimate the required output power levels of the two signal generators so that the corresponding power levels after the variable attenuator equal -15 dBm if the variable attenuation equals 10 dB.

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b) What are the measured power levels of the fundamental frequencies?

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c) Is there is any discrepancy between your estimated power level and the corresponding measured value? If so, adjust then the output power level of the Signal generator so that the Signal analyzer shows -5 dBm.

Decrease the variable attenuation to 0 dB (D = 0 dB). The Signal analyzer should now show 0 dBm for the two fundamental frequencies.

d) At this point, the Signal analyzer may show some third order intermodulation products (IM). What is the reason behind this intermodulation?

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e) Change the maximum input level to the internal mixer by choosing (for the R&S Spectrum Analyzer): AMPT, RF ATTEN MANUAL and adjust the level. What happens to the IM? Why?

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Make the following measurement setup:

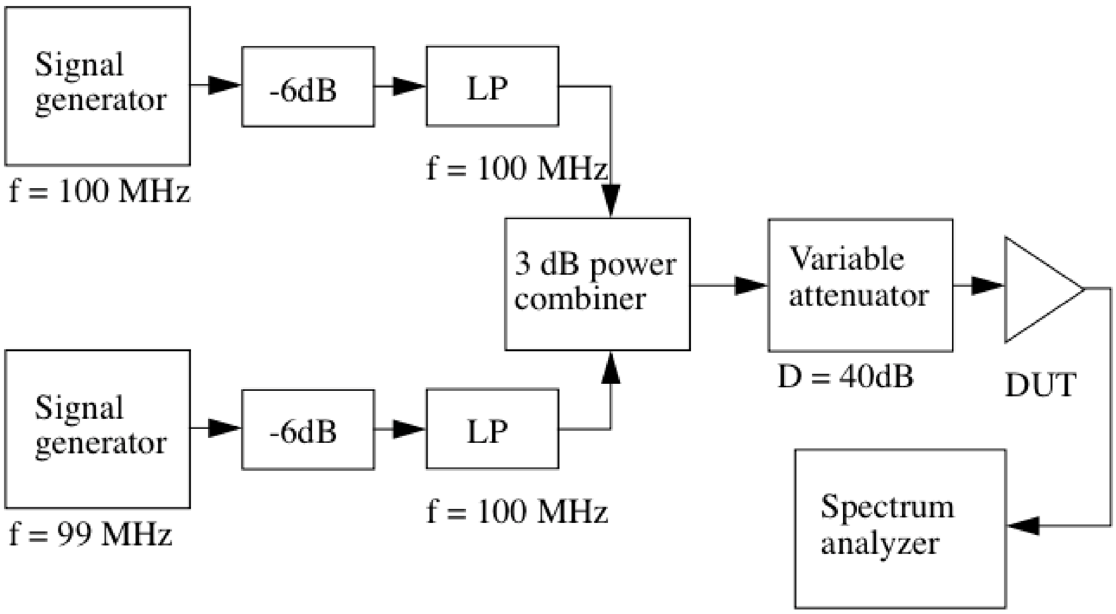

Fig. 9

Make sure the internal attenuation in the Signal analyzer is set to auto by pressing AMPL, RF ATTEN AUTO.

Choose initially a very low input power level (Pin) to the DUT. If we choose a variable attenuation D of 40 dB, this is expected to result in a power level of each fundamental frequency of -40 dBm at the input of the amplifier.

f) Measure the output power (Pout) and the third order intermodulation products (P_{IM3}) of the DUT as a function of the input power P_{in} and enter the values in Table II (next page).

You can mark these measurement values in the figure below or instead only mark the values from a single measurement and assume a slope of the lines corresponding to P_{out} and P_{IM3} equal 1 and 3 respectively. We then find P_{IP3} from the extrapolated crossing of the two lines.

D (dB)	**P_{in} (dBm)**	**P_{out} (dBm)**	**P_{IM3} (dBm)**

Table II

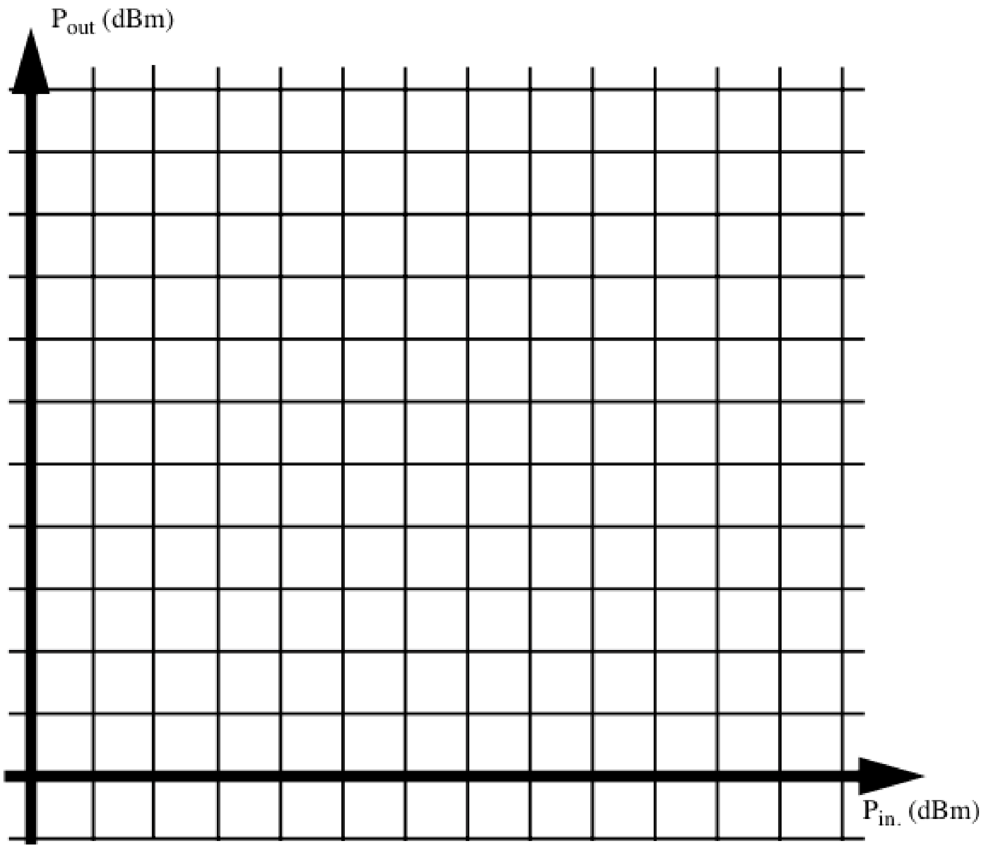

Fig. 10

g) What is the output third order intercept point (P_{IP3}) of the amplifier?

3.5 Noise figure measurement

a) To make sure that we measure the noise of the LNA and not the noise floor of the spectrum analyzer, we need to make sure we amplify the LNA input noise enough. To do this we use two LNAs in series. To calculate the noise ratio of the LNAs we first need to know the gain of the amplifiers. Measure the gain of LNA1 and LNA2.

Gain of LNA1: G_1= ___________________________

Gain of LNA2: G_2= ___________________________

b) Connect the LNAs, Signal analyzer and noise generator as in Fig. 11. The noise generator will generate a noise corresponding to a 50 Ω resistor with no supply voltage and the noise of a 50 Ω resistor amplified with 15.33 dB when the supply voltage is on (excess noise ratio (ENR) = 15.33 dB). Set the Spectrum analyzer to RF ATTEN AUTO, LOW NOISE and RES BW AUTO.

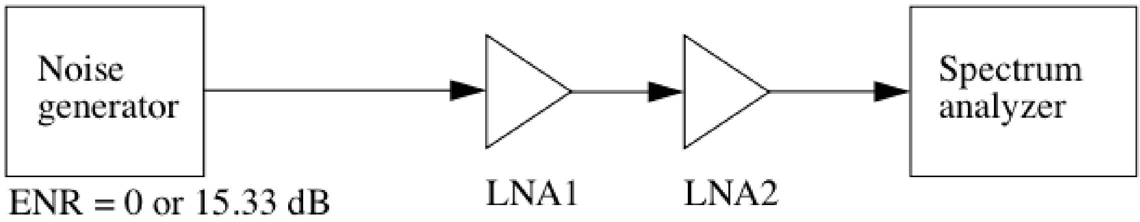

Fig. 11

Measure the output noise power when ENR = 0 and ENR = 15.33 dB

Output noise, ENR = 0: N_{outT2}= ___________________________

Output noise, ENR = 15.33 dB: N_{outENR}= ___________________________

c) Since the noise factor of both LNA1 and LNA2 are unknown, we need to make the same measurements one more time with the setup as in Fig, 12.

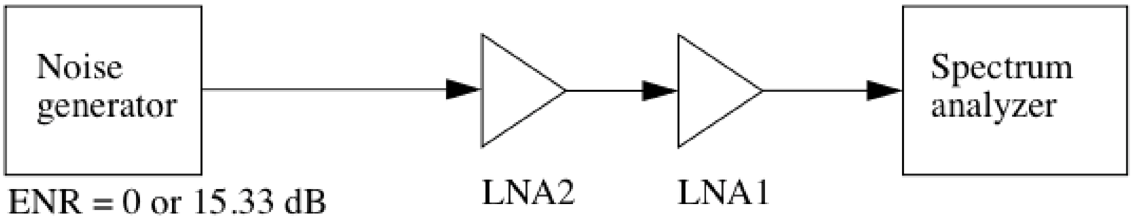

Fig. 12

With this setup, measure the output noise power when ENR = 0 and ENR = 15.33 dB

Output noise, ENR = 0: N_{outT2}= ___________________________

Output noise, ENR = 15.33 dB: $N_{outENR2}$=_________________________

d) In the appendix you will find a derivation of how to calculate the noise factor from the measurements in b), c) and d). Use equation (8), (12) and (10) to calculate the noise factor of the LNAs. Also, calculate the noise figure (equation (2)) (Note: N_{outT}, $Nout_{ENR}$, N_{outT2}, $Nout_{ENR2}$, G1 and G2 are in linear scale. ENR are in dB scale.).

NR_{LNA1} = _______________________ NF_{LNA1} = _______________________

NR_{LNA2} = _______________________ NF_{LNA2} = _______________________

3.6 Estimation of the dynamic range of the amplifier

Given a certain bandwidth B, we can now estimate both the 1 dB Compression Dynamic Range (DR) and the Spurious Free Dynamic Range (SFDR). Assume that the signal bandwidth B of an FM-radio channel equals 100 kHz and the minimum signal-to-noise ratio (SNR_{min}) is 0. The 1 dB Compression Dynamic Range (DR) is then given by:

$$DR = P_{1dBout} + 174 - 10\log B - NF - G$$

The Spurious Free Dynamic Range (SFDR) is instead given by:

$$SFDR = 2/3 * (P_{IP3out} + 174 - 10\log B - NF - G)$$

where

G = amplifier gain of the DUT [dB]
NF = noise figure of the DUT [dB]
B = signal bandwidth [Hz]
P_{1dBout} = output power level of the DUT at 1 dB gain compression [dBm]
P_{IP3out} = output power level of the DUT at the third order intercept point [dBm]

a) Specify the 1dB Compression Dynamic Range (DR) of the DUT.

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b) Specify the corresponding Spurious Free Dynamic Range (SFDR) of the DUT!

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Please comment on the difference between these two dynamic range estimations. Assume that the amplifier is to be used in a radio receiver, in what way can DR and SFDR be related to the dynamic range of the receiver?

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4.0 Appendix Noise figure measurement calculations

The most frequently used definition of noise figure (NF) is:

$$NF = SNR_{in} - SNR_{out} \qquad (1)$$

Where SNR_{in} is the signal to noise ratio at the device input (in dB) and SNR_{out} is the signal to noise ratio at the device output.

Noise ratio (NR) is defined as:

$$NR = 10^{NF/10} \qquad (2)$$

Noise ratio can then be written as:

$$NR = \frac{S_{in}/N_{in}}{S_{out}/N_{out}} \qquad (3)$$

Where S_{in} is the input signal power and N_{in} is the input noise power etc.

IF the gain of the device is G then

$$S_{out} = S_{in} \cdot G \qquad ,(3) \Rightarrow$$

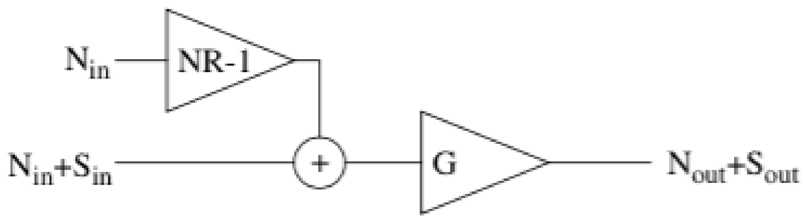
$$NR = \frac{S_{in} \cdot N_{out}}{S_{in} \cdot G \cdot N_{in}} = \frac{N_{out}}{G \cdot N_{in}} \qquad (4)$$

If we se N_{out} as amplified input noise (N_{in} G) and device generated noise (N_d) we can specify N_d as

$$N_{out} = G \cdot N_{in} + N_d \qquad ,(4) \Rightarrow$$

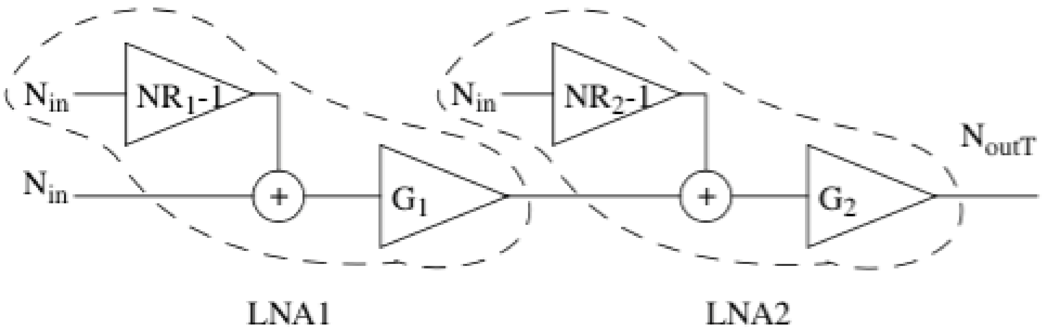
$$NR = \frac{G \cdot N_{in} + N_d}{G \cdot N_{in}} = 1 + \frac{N_d}{G \cdot N_{in}} \Leftrightarrow N_d = (NR - 1) \cdot G \cdot N_{in} \qquad (5)$$

From (4) and (5) we can see the device as a noise-free device with added input noise as in the figure below

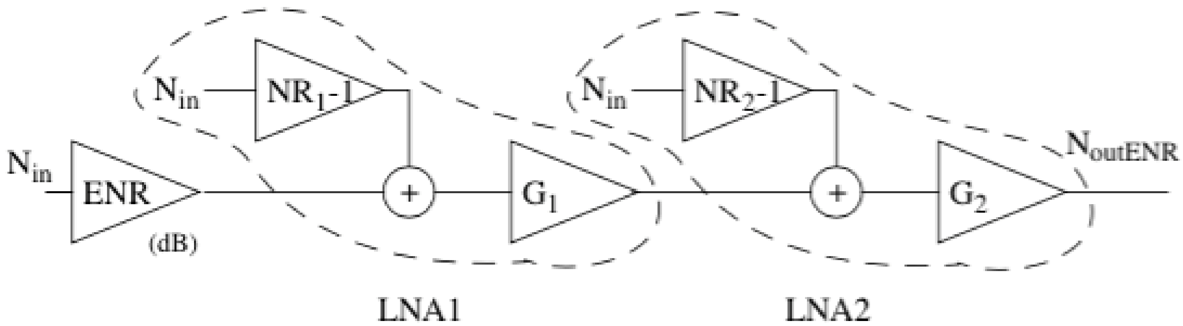


NF is defined when the input noise is specified as the resistive thermal noise of the characteristic impedance of the device input. In this (and most cases) 50Ω.

With the input terminated, the test setup can be seen as in the figure below.



With the noise generator active, as in the figure below.



And in written

$$N_{outT} = ((N_{in} + N_{in} \cdot (NR_1 - 1)) \cdot G_1 + N_{in} \cdot (NR_2 - 1)) \cdot G_2 \qquad (6)$$

$$N_{outENR} = ((N_{in} \cdot 10^{ENR/10} + N_{in} \cdot (NR_1 - 1)) \cdot G_1 + N_{in} \cdot (NR_2 - 1)) \cdot G_2 \qquad (7)$$

Let us define Y as N_{outENR}/N_{outT}

$$Y = \frac{N_{outENR}}{N_{outT}} =$$

$$\frac{(7)}{(6)} = \frac{((N_{in} \cdot 10^{ENR/10} + N_{in} \cdot (NR_1 - 1)) \cdot G_1 + N_{in} \cdot (NR_2 - 1)) \cdot G_2}{((N_{in} + N_{in} \cdot (NR_1 - 1)) \cdot G_1 + N_{in} \cdot (NR_2 - 1)) \cdot G_2} =$$

$$\frac{(10^{ENR/10} + (NR_1 - 1)) \cdot G_1 + NR_2 - 1}{NR_1 \cdot G_1 + NR_2 - 1} \qquad (8)$$

Solving (8) for NR_1 yields

$$NR_1 = \frac{10^{ENR/10} - 1 - 1/G_1}{Y - 1} - \frac{NR_2}{G_1} \qquad (9)$$

If we do not know NR_2 we can witch places of LNA_1 and LNA_2 and repeat the measurement (measuring Y_2).

Then

$$NR_2 = \frac{10^{ENR/10} - 1 - 1/G_2}{Y_2 - 1} - \frac{NR_1}{G_2} \qquad (10)$$

Put (10) into (9) and solve for NR_1 results in

$$NR_1 = \frac{G_2}{G_2 \cdot G_1 - 1} \cdot \left(\frac{(10^{ENR/10} - 1 - 1/G_1) \cdot G_1}{Y - 1} - \frac{10^{ENR/10} - 1 - 1/G_2}{Y_2 - 1} \right) \qquad (11)$$

If $G_1 >> 1$ and $G_2 >> 1$, (11) can be approximated as

$$NR_1 = \frac{10^{ENR/10} - 1}{Y - 1} - \frac{10^{ENR/10} - 1}{(Y_2 - 1) \cdot G_1} \qquad (12)$$