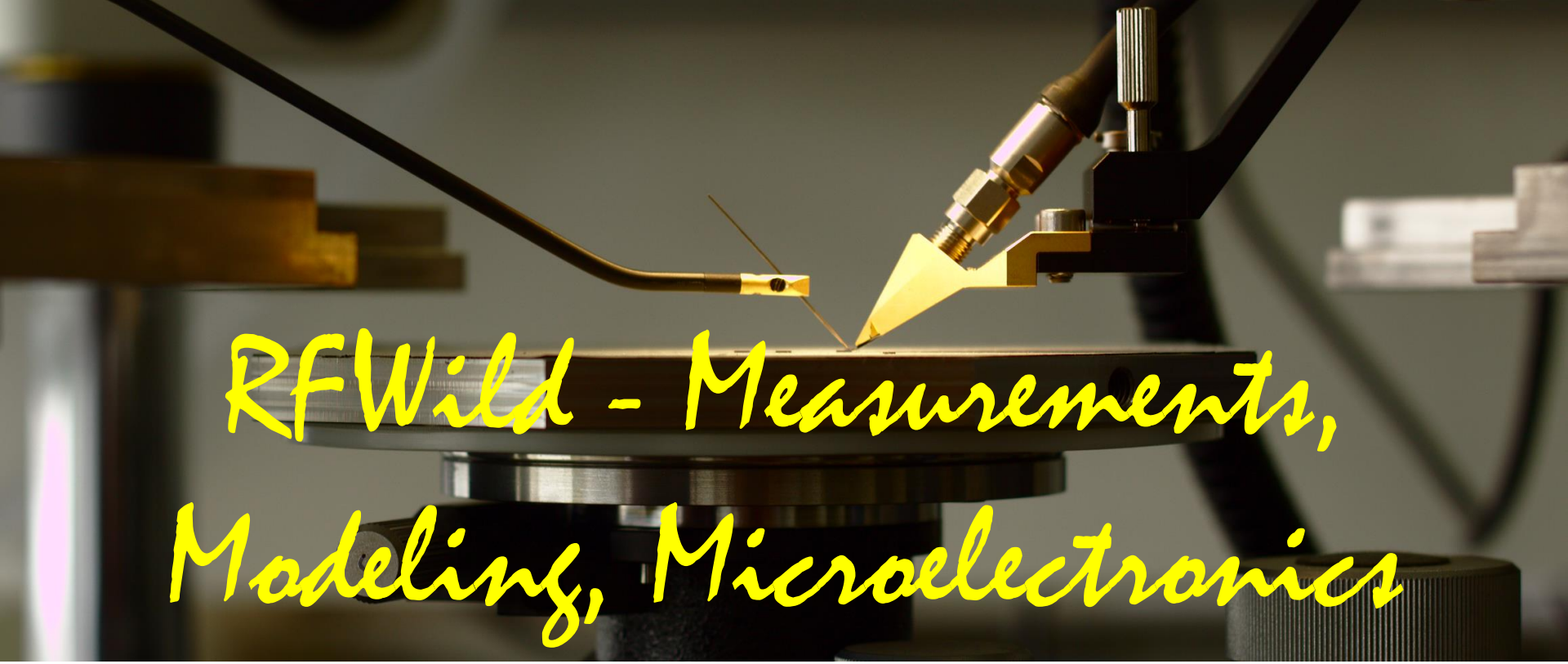


RFWild - Measurements, Modeling, Microelectronics

INSTITUTO FEDERAL DE EDUCAÇÃO, CIÊNCIA E TECNOLOGIA
PARAÍBA

RF Microelectronics – Signals: properties, simulation & measurements

Outline

- Introduction to signals:
  - Properties
  - Units
- Simulation of signals :
  - Time-domain
  - Frequency domain
- Introduction to measurements:
  - Signal generator, spectrum analyzer and oscilloscope
  - Time and frequency domain measurements

Introduction to signals

- Let´s begin by the “simple” case of a sine:

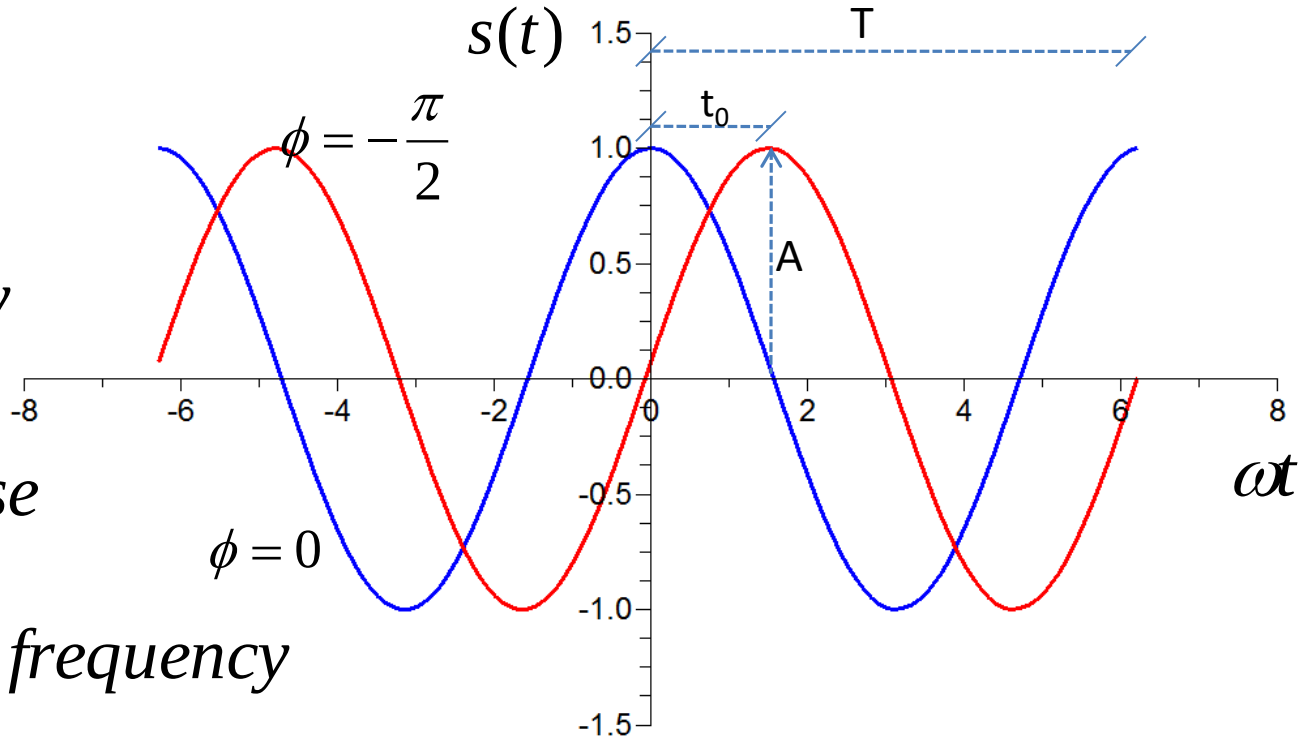
$$s(t) = A\cos(\omega t + \phi)$$

$$A = amplitude$$

$$f = \frac{1}{T} = frequency$$

$$\phi = \frac{-t_0}{T} \cdot 2\pi = phase$$

$$\omega = 2\pi f = angular\ frequency$$



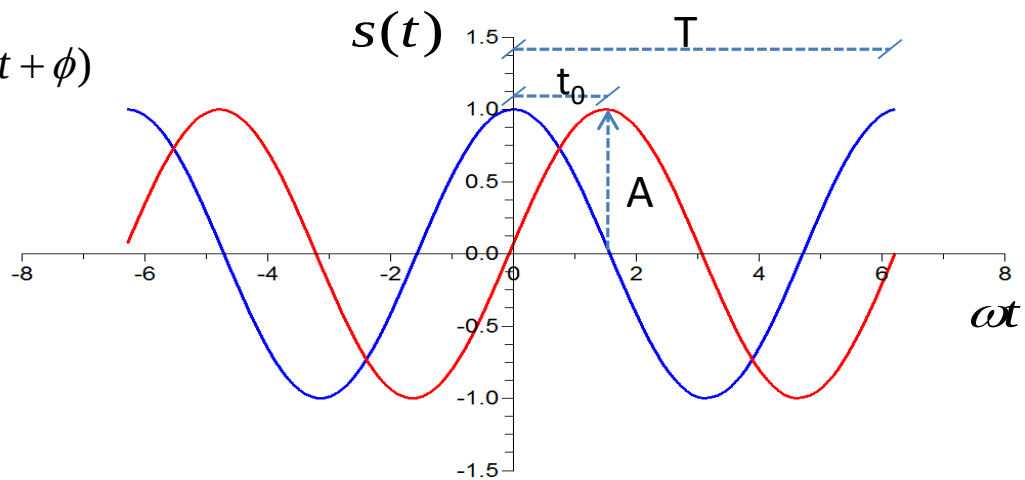
Introduction to signals

$$s(t) = A\cos(\omega t + \phi)$$

$$\omega = 2\pi f$$

$$f = \frac{1}{T}$$

$$\phi = \frac{-t_0}{T} \cdot 2\pi$$



In this case, we say the red curve is **delayed** with respect to the blue curve, (or the blue curve is **in advance** with respect to the blue curve.

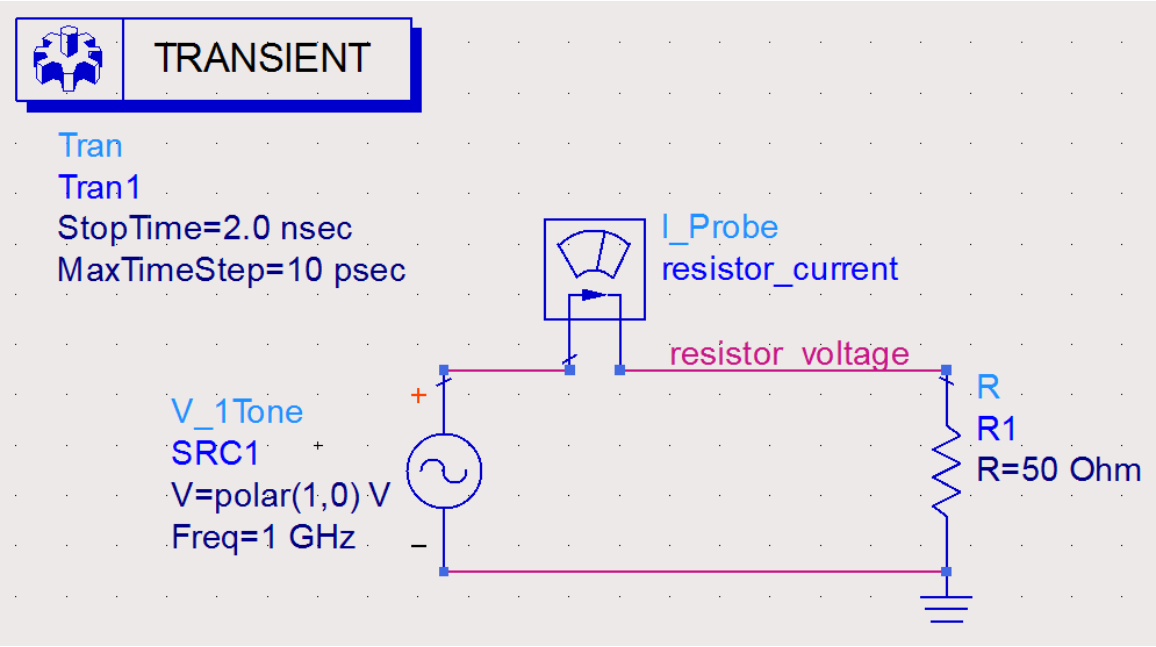
- Determine the expression of s(t) if:

$$A = 1; T = 10^{-9} s; t_0 = -0.25 ns$$

$$A = 2; T = 10^{-10} s; t_0 = 0.5 \cdot 10^{-10} s$$

Introduction to signals

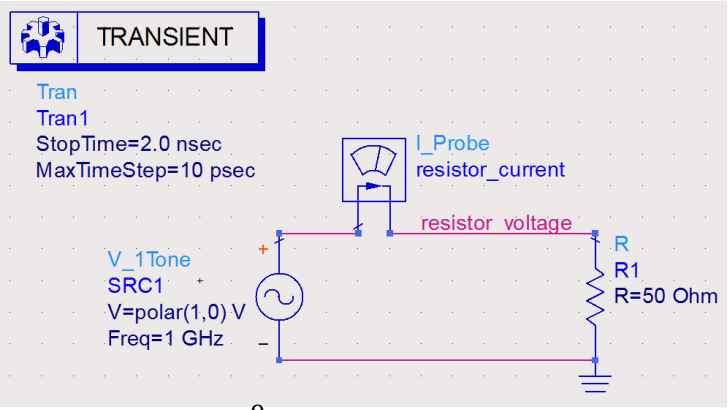
- What happens if we apply a 1V, 1GHz voltage signal to a (50 Ω) resistor?



Try to calculate "instantaneous" current and power

Introduction to signals

- What happens if we apply a 1V, 1GHz voltage signal to a (50 Ω) resistor?



$$resistor\_voltage(t) = 1 \cdot \cos(2\pi 10^9 t)$$

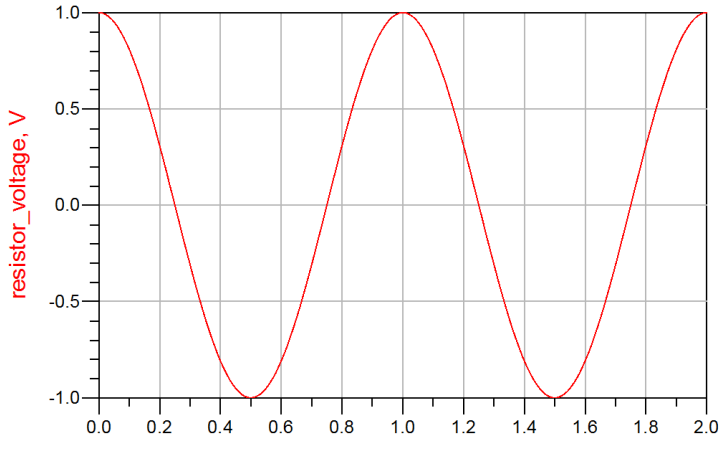
$$resistor\_current(t) = \frac{1}{50} \cdot \cos(2\pi 10^9 t)$$

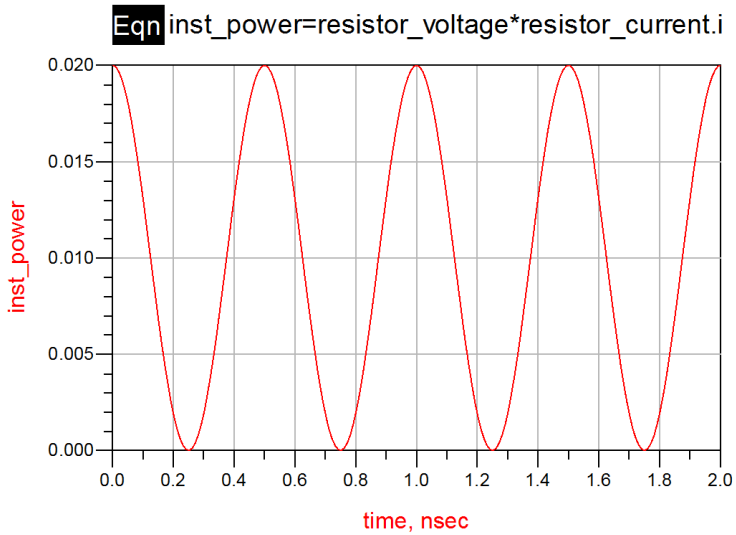
$$inst\_power(t) = 1 \cdot \cos(2\pi 10^9 t) \cdot \frac{1}{50} \cdot \cos(2\pi 10^9 t) \Rightarrow$$

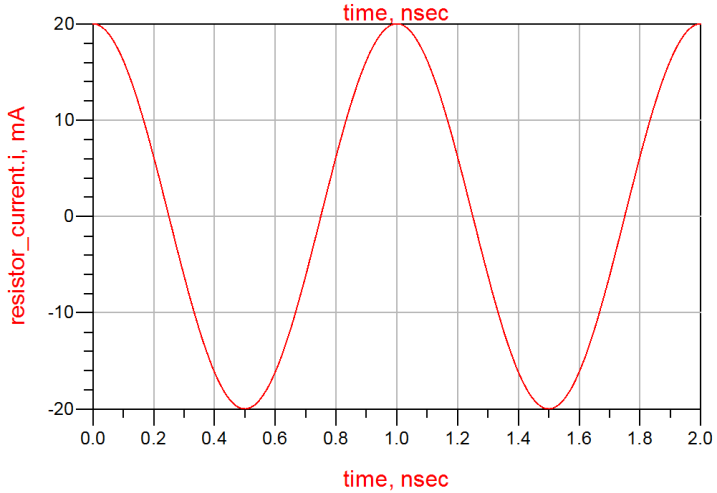
$$inst\_power(t) = \frac{1^2}{2 \cdot 50} + \frac{1^2}{2 \cdot 50} \cdot \cos(2 \cdot 2\pi 10^9 t) \quad \begin{cases} P_{DC} = 0.01W \\ P_{f=2GHz} = 0.01W_{peak} \end{cases}$$

Introduction to signals

- Look at the simulation results:







$$resistor\_voltage(t) = 1 \cdot \cos(2\pi 10^9 t)$$

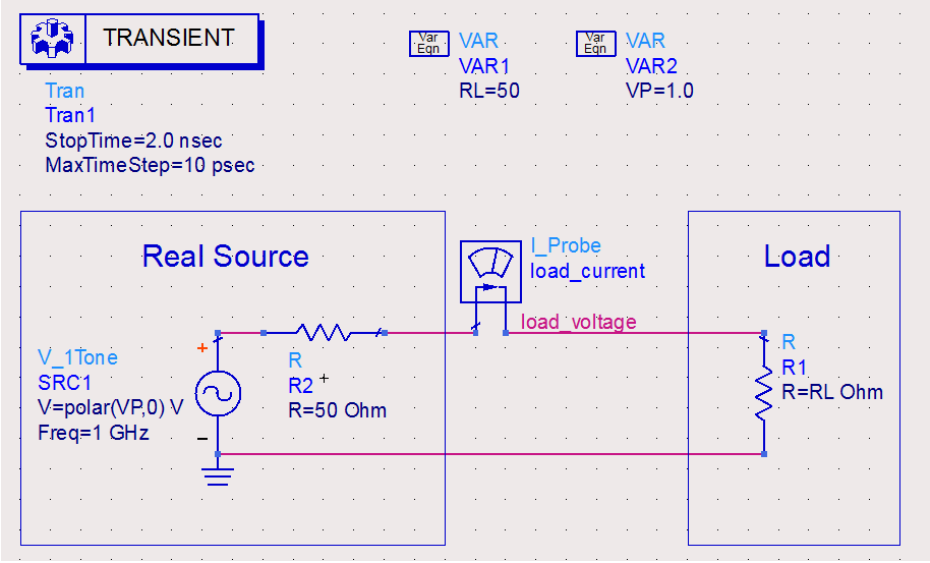
$$resistor\_current(t) = \frac{1}{50} \cdot \cos(2\pi 10^9 t)$$

$$inst\_power(t) = 0.01W + 0.01W \cdot \cos(2 \cdot 2\pi 10^9 t)$$

Sounds good?

Introduction to signals

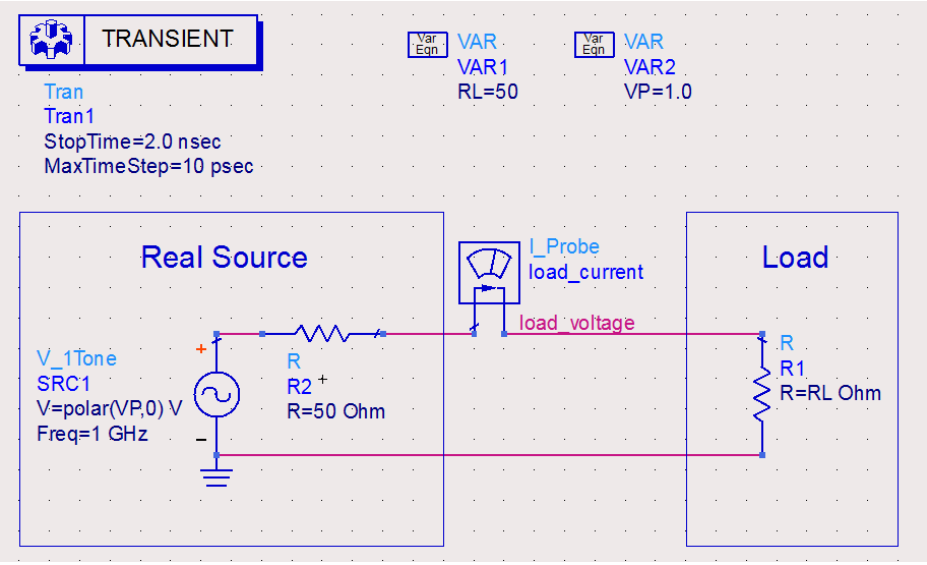
- As you know, ideal voltage (or current) sources do not exist: Real sources have internal impedances!
- We will consider RF sources with a nominal 50Ω internal impedance:



Let´s do some math again: try to calculate the DC (mean) available power of the source

Introduction to signals

- The avaliable power of the source corresponds to the power delivered when the load is the complex conjugate of the internal impedance (more on this later). In this case, if RL=50Ω!



$$load\_voltage(t) = \frac{V_P}{2} \cdot \cos(2\pi 10^9 t)$$

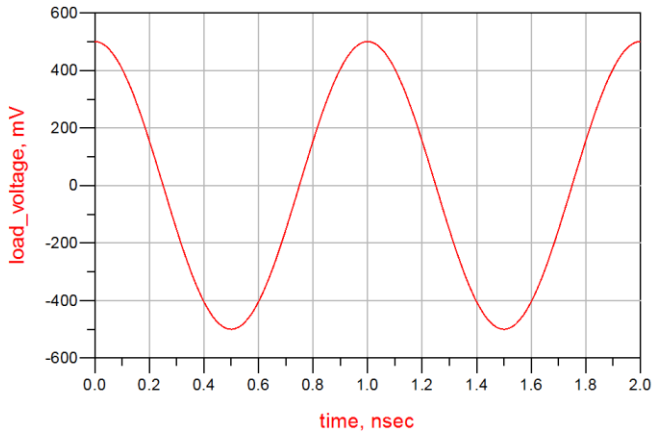
$$load\_current(t) = \frac{V_P}{2 \cdot 50\Omega} \cdot \cos(2\pi 10^9 t)$$

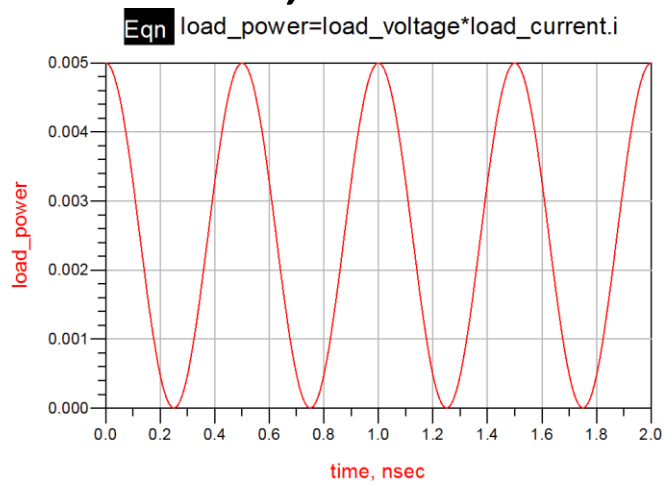
$$load\_power(t) = \frac{V_P^2}{8 \cdot 50\Omega} + \frac{V_P^2}{8 \cdot 50\Omega} \cdot \cos(2 \cdot 2\pi 10^9 t)$$

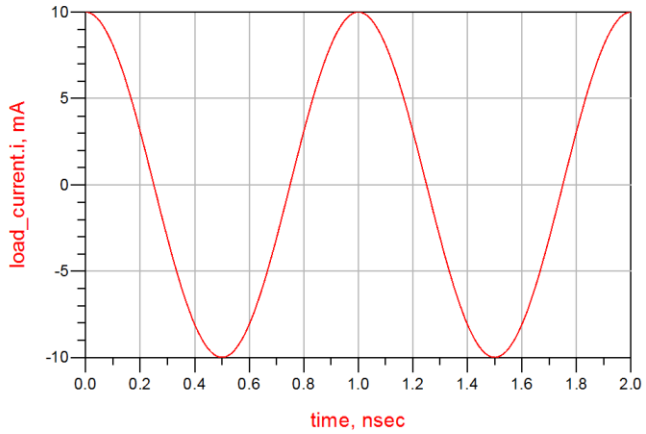
Available power
(load independent!)

Introduction to signals

- Check the results for VP=1V, RL=50 Ω:







$$load\_voltage(t) = \frac{1}{2} \cdot \cos(2\pi 10^9 t)$$

$$load\_current(t) = \frac{1}{2 \cdot 50\Omega} \cdot \cos(2\pi 10^9 t)$$

$$load\_power(t) = \boxed{\frac{1^2}{8 \cdot 50\Omega}} + \frac{1^2}{8 \cdot 50\Omega} \cdot \cos(2 \cdot 2\pi 10^9 t)$$

Available power=2.5 mW

Introduction to signals

- Let´s TALK ABOUT POWER!!
- Power in physical systems may vary by several orders of magnitude.
  - Human ear may detect a huge range of sound (power) levels
  - Portable phones are able to detect signals from about 10^{-13} W (yes, 0.1 pW!!!) to some mW
- We should use a logarithmic scale: Decibels!!

Introduction to signals

- But what is a Decibel?
  - It is a logarithmic "unit" which represents a relation (a priori of power) with respect to a given reference.
  - It is very usefull to represent physical variables which vary a lot:

$$Gain(dB) = 10\log(\frac{P}{P_{REF}})$$

Remember:
Gain is unitless!

$$Gain(dB) = 10\log(\frac{P}{P_{REF}}) = 10\log(\frac{\frac{V^2}{R}}{\frac{V_{REF}^2}{R}}) = 20\log(\frac{V}{V_{REF}})$$

Introduction to signals

- Let´s do some math:

$$Gain(dB) = 10\log(\frac{P}{P_{REF}}) \qquad Gain(dB) = 20\log(\frac{V}{V_{REF}})$$

- What is the gain (in dB) of an amplifier having an input power of 1 mW and output power of 1 W? Answer:30 dB
- What is the (power) loss in an attenuator whose input voltage is 1 V (peak) and output voltage is 10 mV (peak)? Answer: 40 dB (-40 dB)

Introduction to signals

- With Decibels in mind, we may know think about power units!! Units commonly used:
  - dBm (dB scale with respect to 1 mW)
  - dBW (dB scale with respect to 1 W)

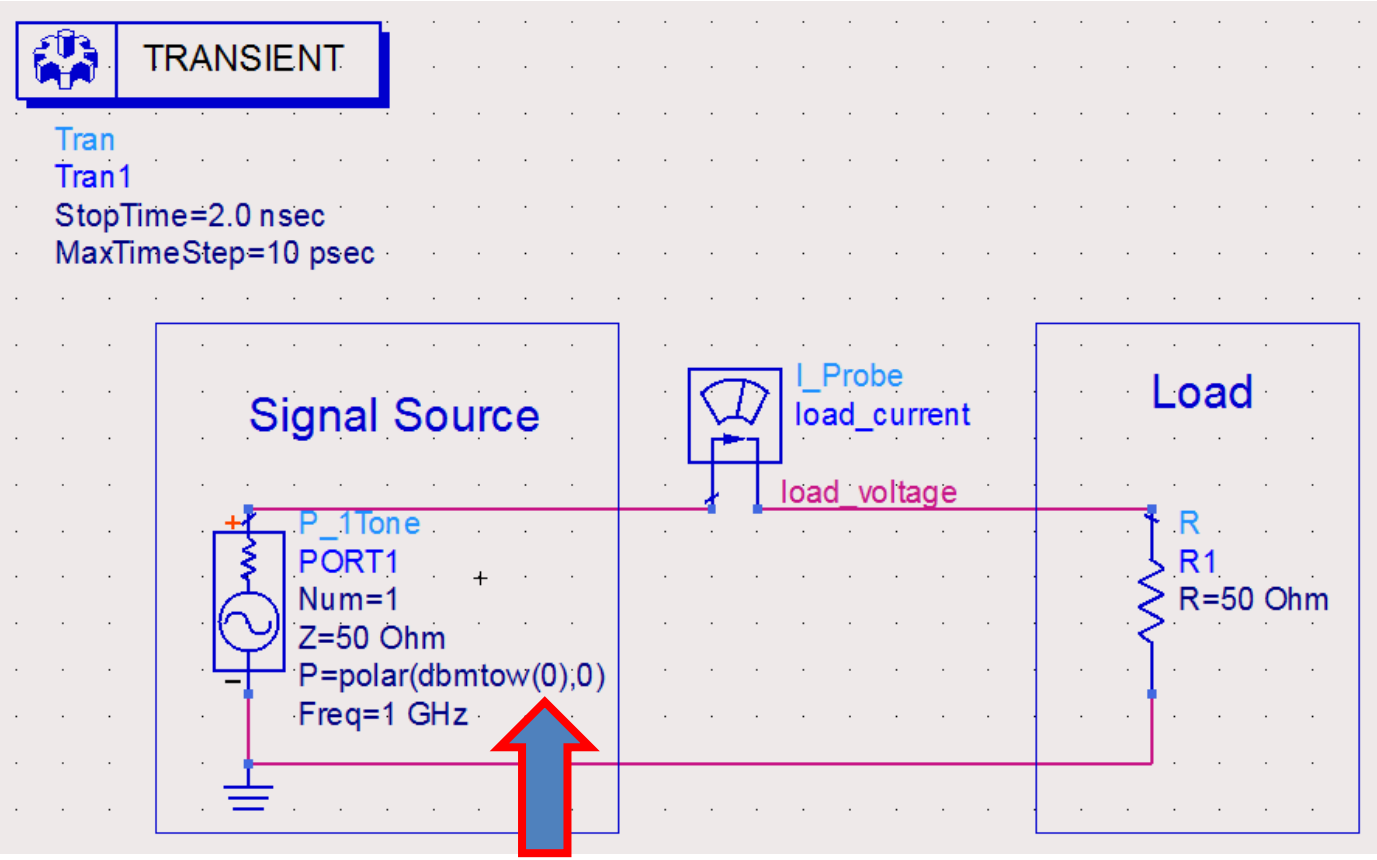
$$0dBW = 1W \qquad 10dBm = 10mW = -20dBW$$

$$0dBm = 1mW \qquad -20dBm = 10\mu W = -50dBW$$

Short-range wireless transceivers generally transmit power levels around 0 dBm (1 mW) and are able to receive signals with a power level down to about -100dBm (10^{-13} W). In this latter case, the signal in the (50 Ω) antenna has 2.2 μV_{RMS}!!

Introduction to signals

- Let´s use hereafter the signal source below.

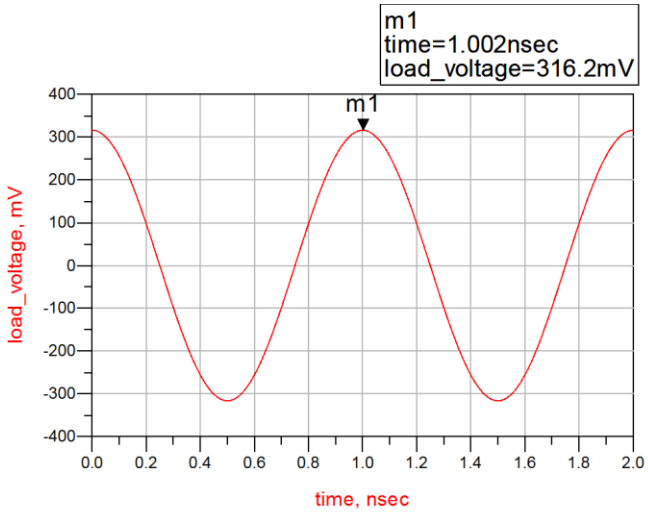


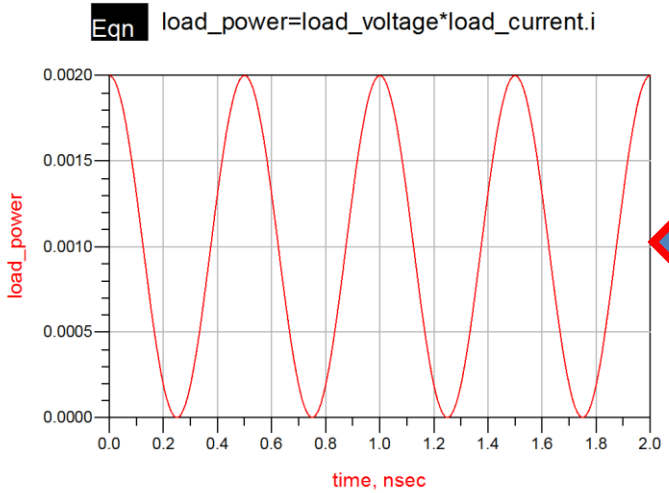
Power in dBm

Calculate peak voltage and current in the load

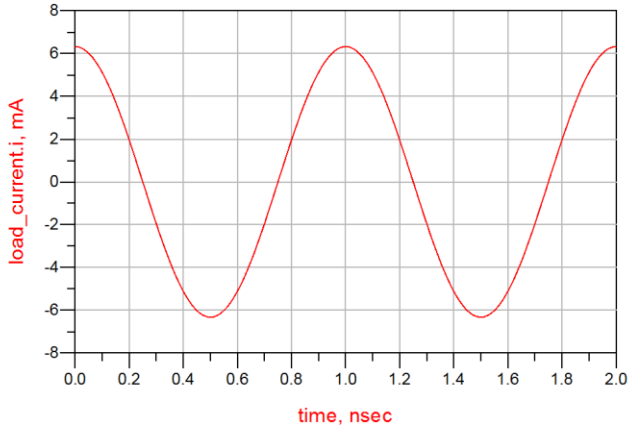
Introduction to signals

- Check the numbers:



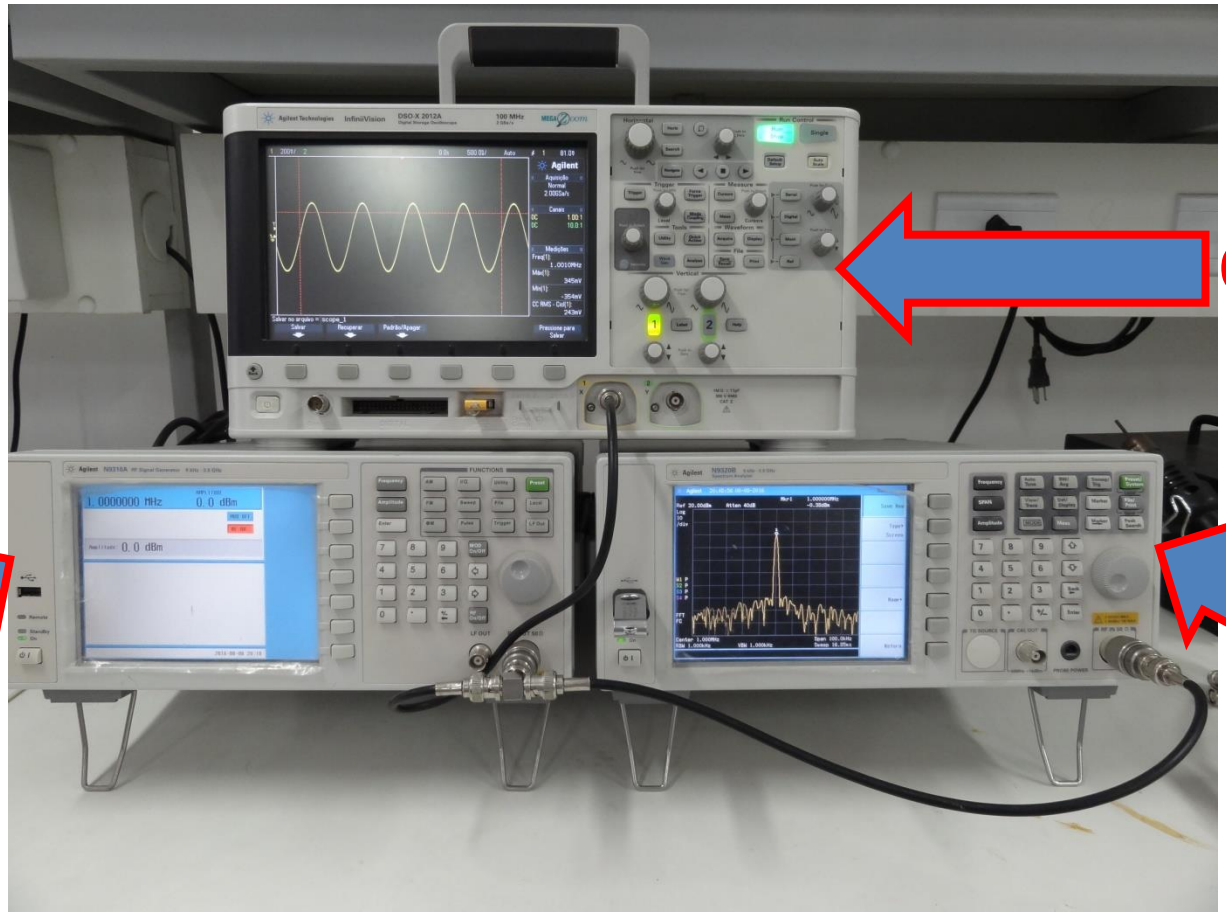


1 mW
(0 dBm)



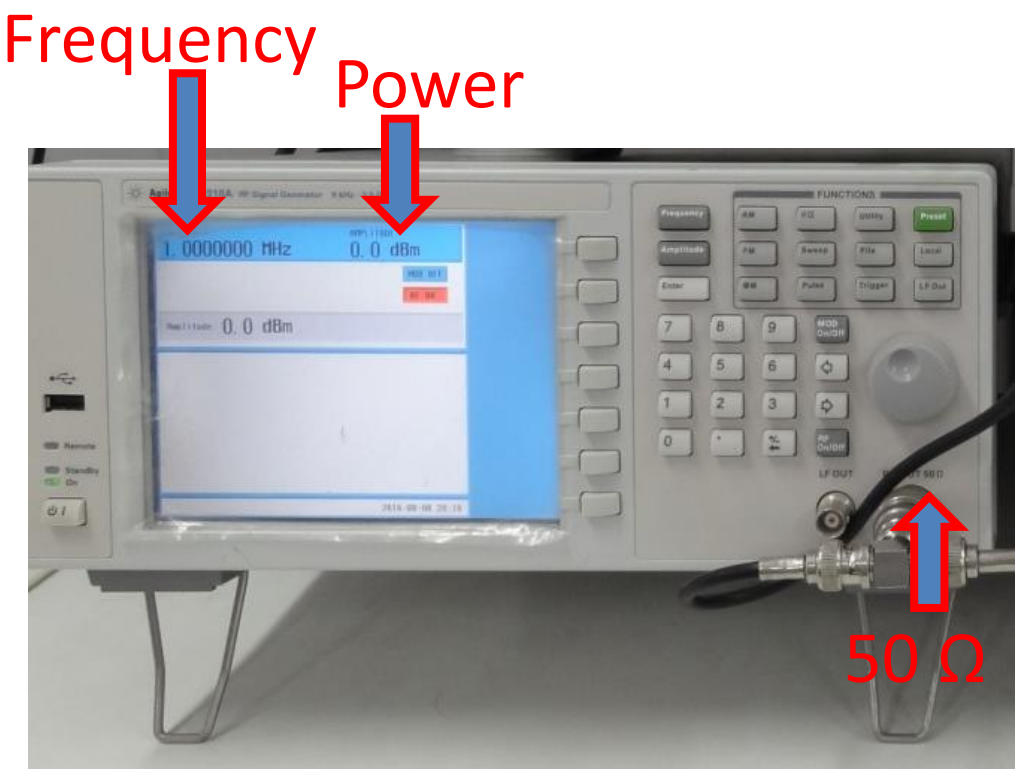
Introduction to measurements

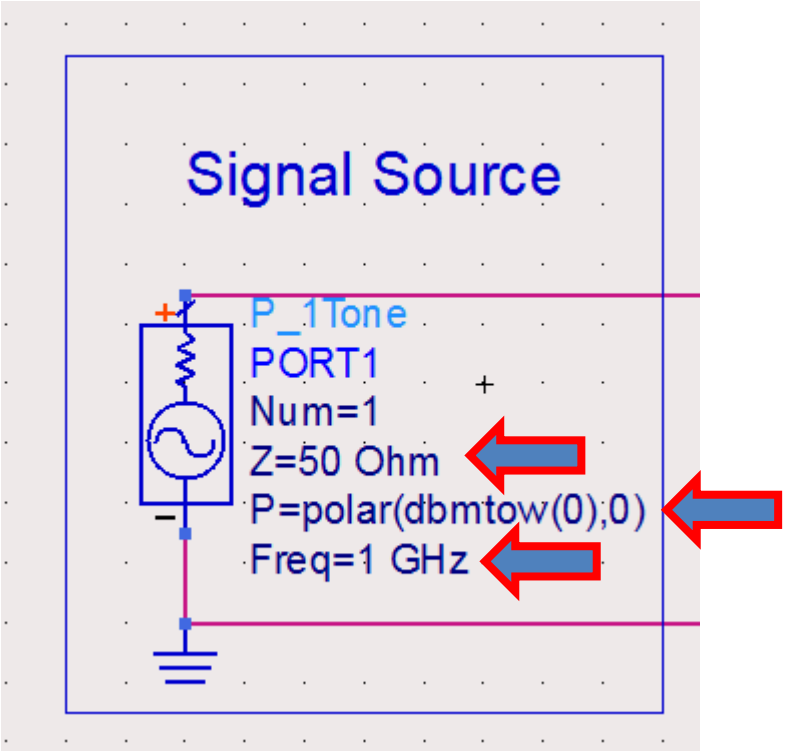
- How does an RF signal source look like?



Introduction to measurements

- Compare with our simulation model:

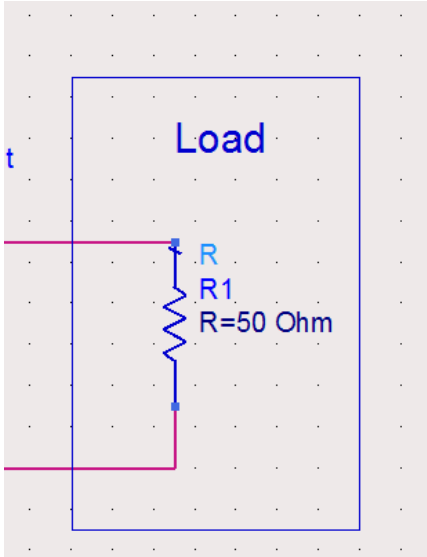




Introduction to measurements

- What about our spectrum analyzer?

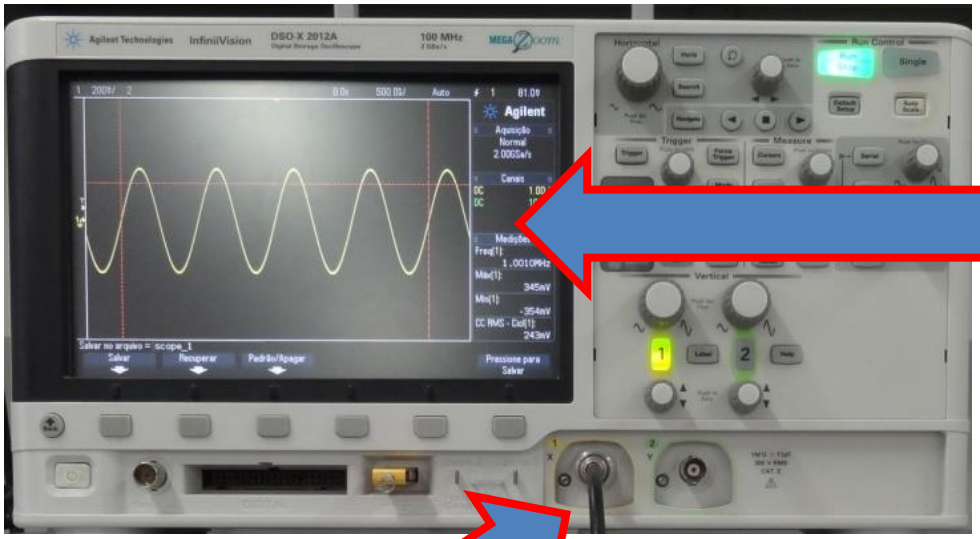
RF in
50 Ω



It works as a (nominally) 50 Ω load!

Introduction to measurements

- And what about the oscilloscope???



We will use the oscilloscope to see the signals in the time domain

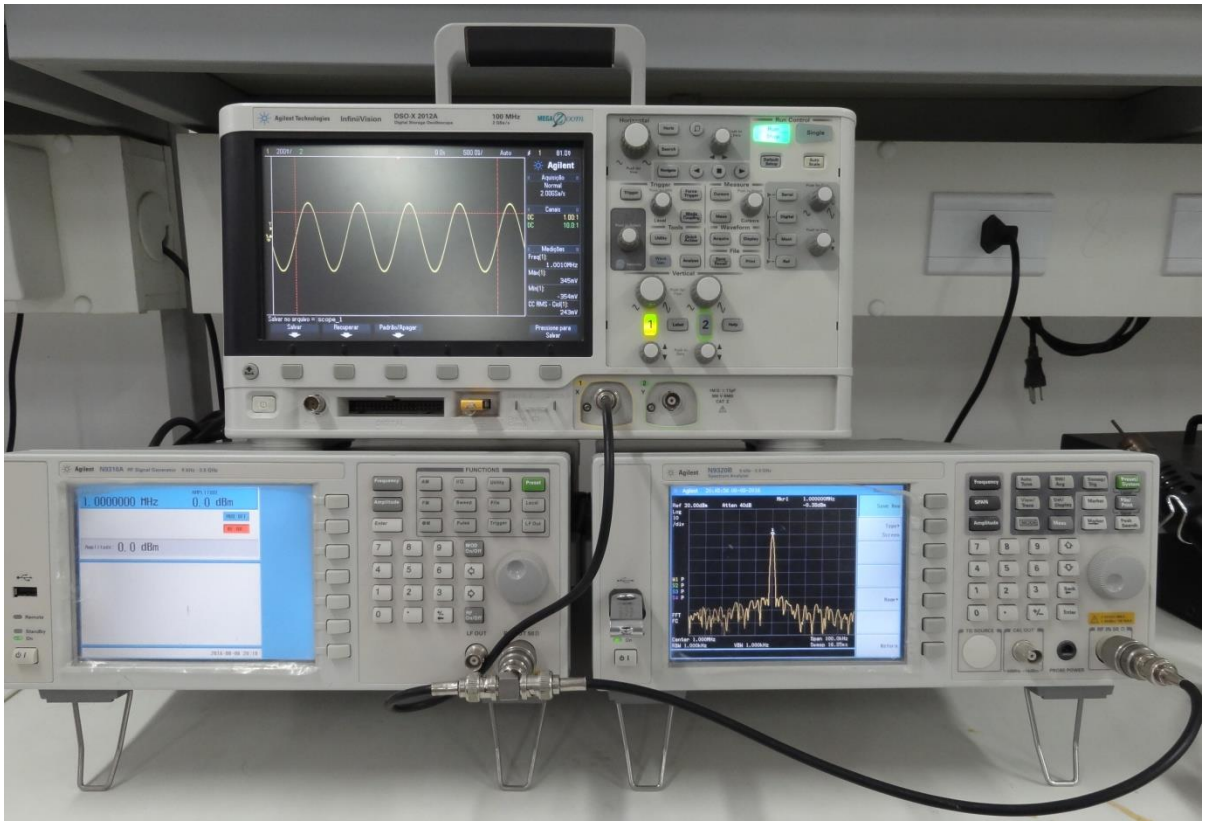
1 MΩ //11 pF

Until 10 MHz, its impedance is about 30 x greater than 50Ω (open circuit!)

Introduction to measurements

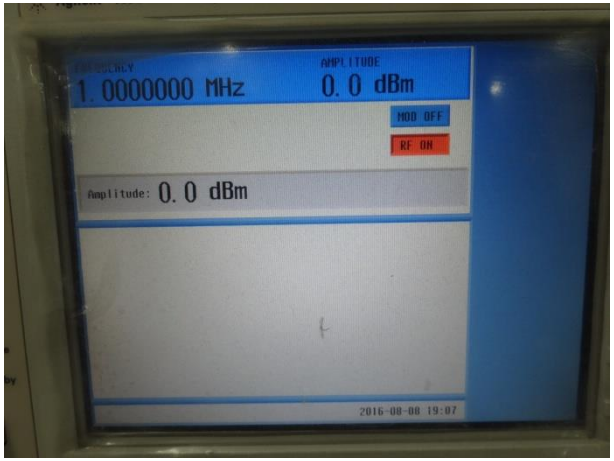
- Are you ready for the FUN??? Let´s MEASURE!

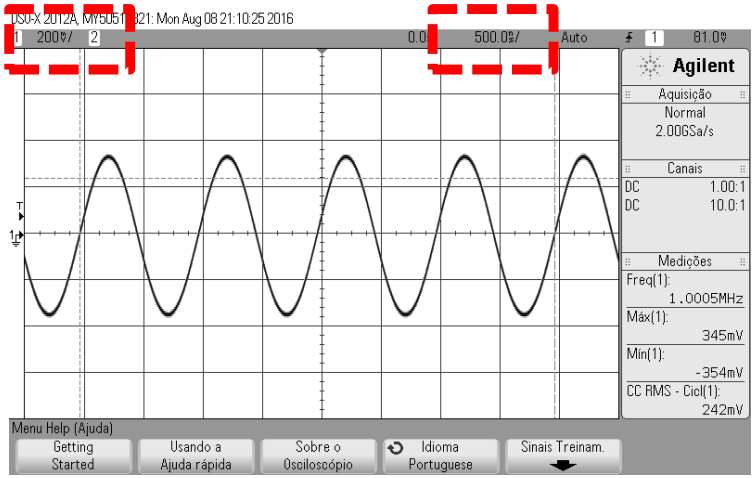
We will use this setup:



Introduction to measurements

- Set the source to 0 dBm, 1 MHz:

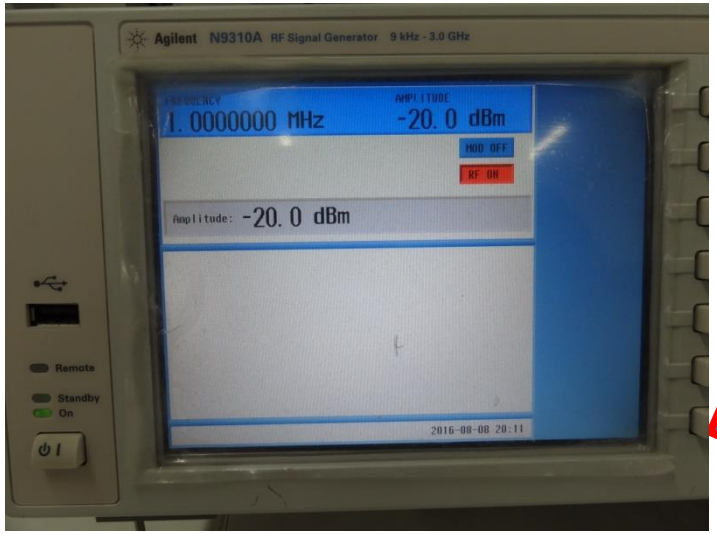


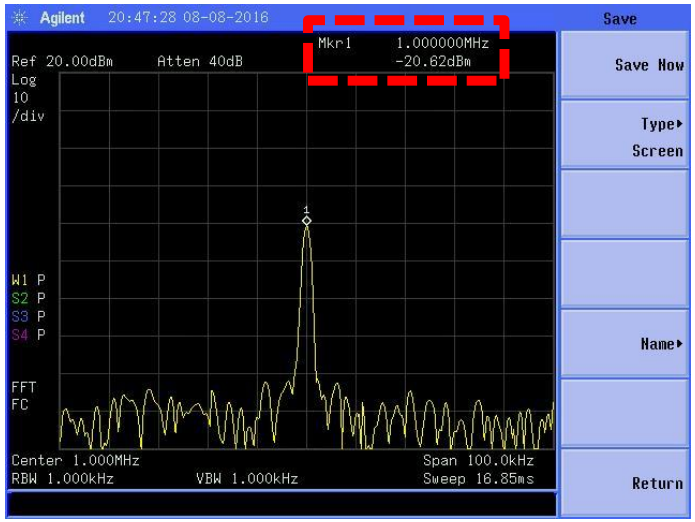


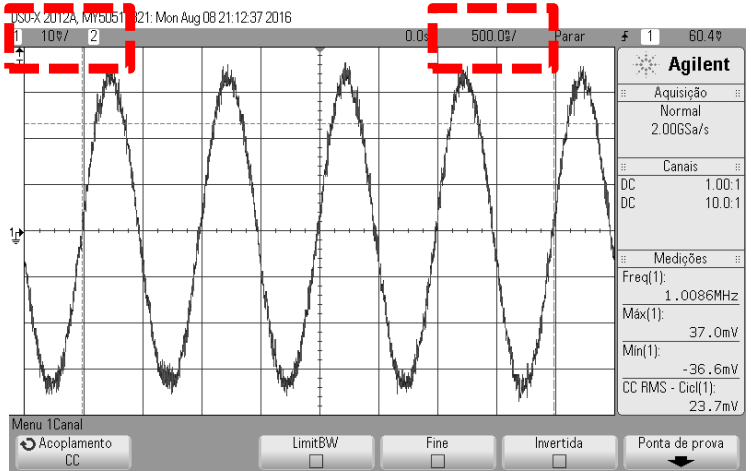
Check the numbers!!
(look closely☺)

Introduction to measurements

- Set the source to -20 dBm, 1 MHz:



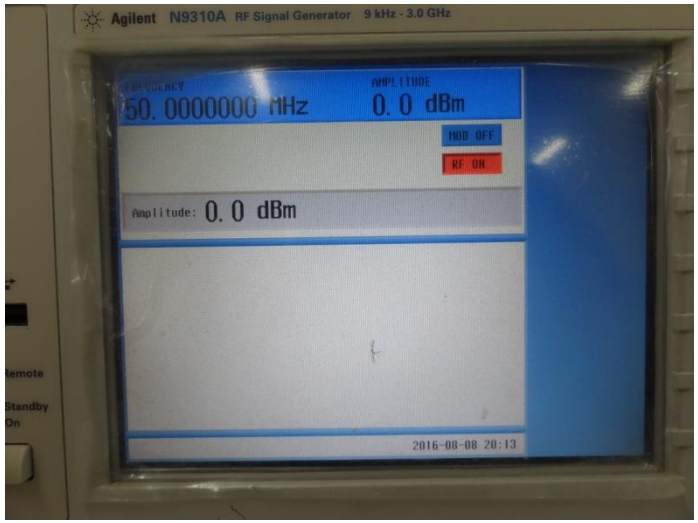


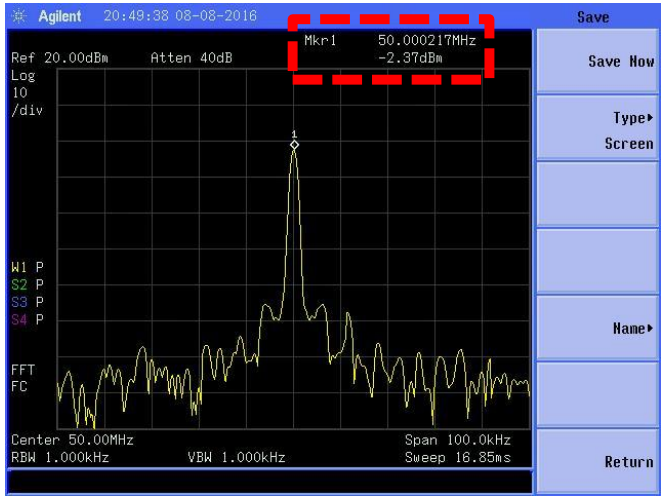


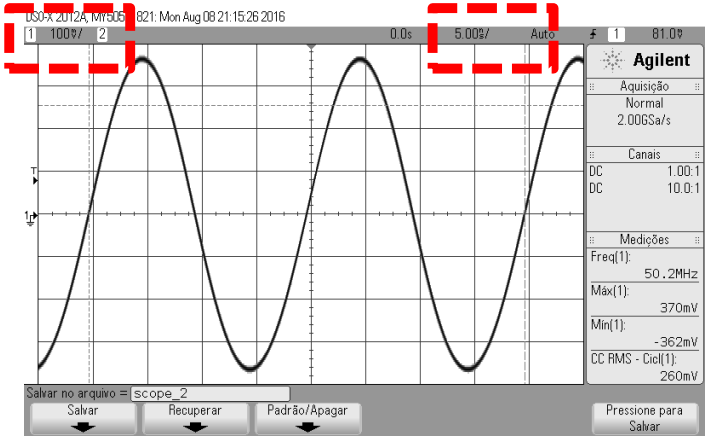
Check the numbers!!
(look closely☺)

Introduction to measurements

- Set the source to 0 dBm, 50 MHz:







Check the numbers!!
(look closely☺)

Introduction to modulated signals

- Relation between wavelength (λ) and the signal´s frequency (*f*):

$$\lambda = \frac{c}{f} = \frac{3 \cdot 10^8 m/s}{f}$$

Propogation speed in the medium considered

- To obtain a "satisfactory" performance in the transmission of electromagnetic signals, the physical length of the antenna should be on the order of λ (generally λ/4).

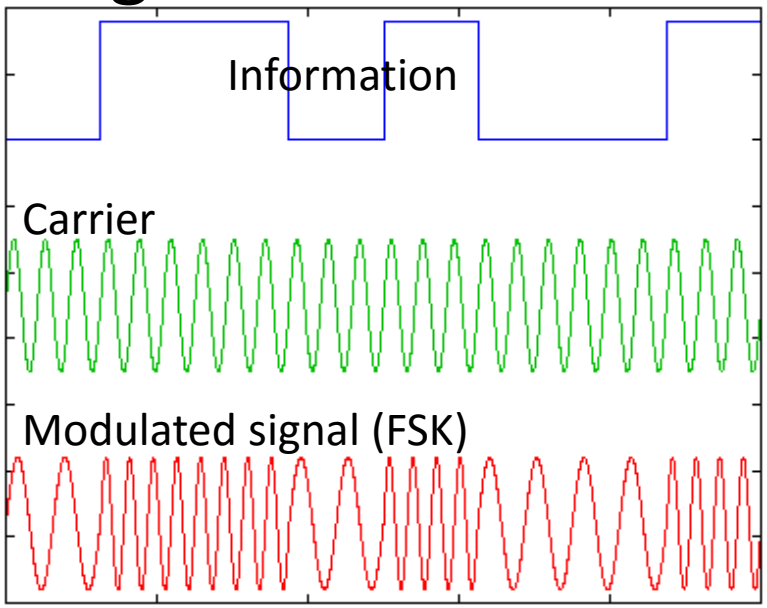
If we decided to transmit audio signals (eg. 10kHz) directly through electromagnetic waves, the antenna should have about 7,5 km!!!

Introduction to modulated signals

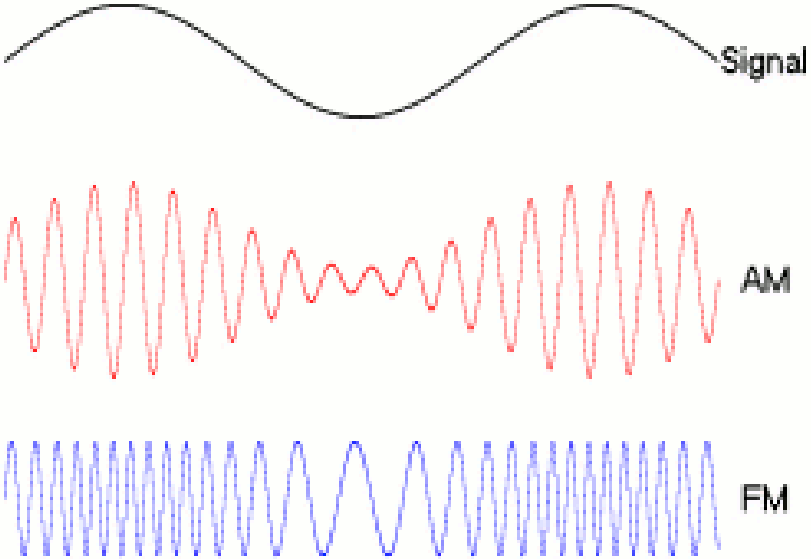
- We deal with that by modulating a carrier!

Modulate is the process of varying a signal´s (carrier) parameter according to the information to be transmitted.

Digital modulation:



Analog modulation:



Introduction to modulated signals

- Let´s start by the "simple" case of AM DSB FC created by a single modulating tone:

$$AM_{DSBFC}(t) = \left[1 + M \cdot \cos(\omega_m t)\right] \cdot K \cos(\omega_c t)$$

Modulation index

Modulating frequency

Carrier frequency

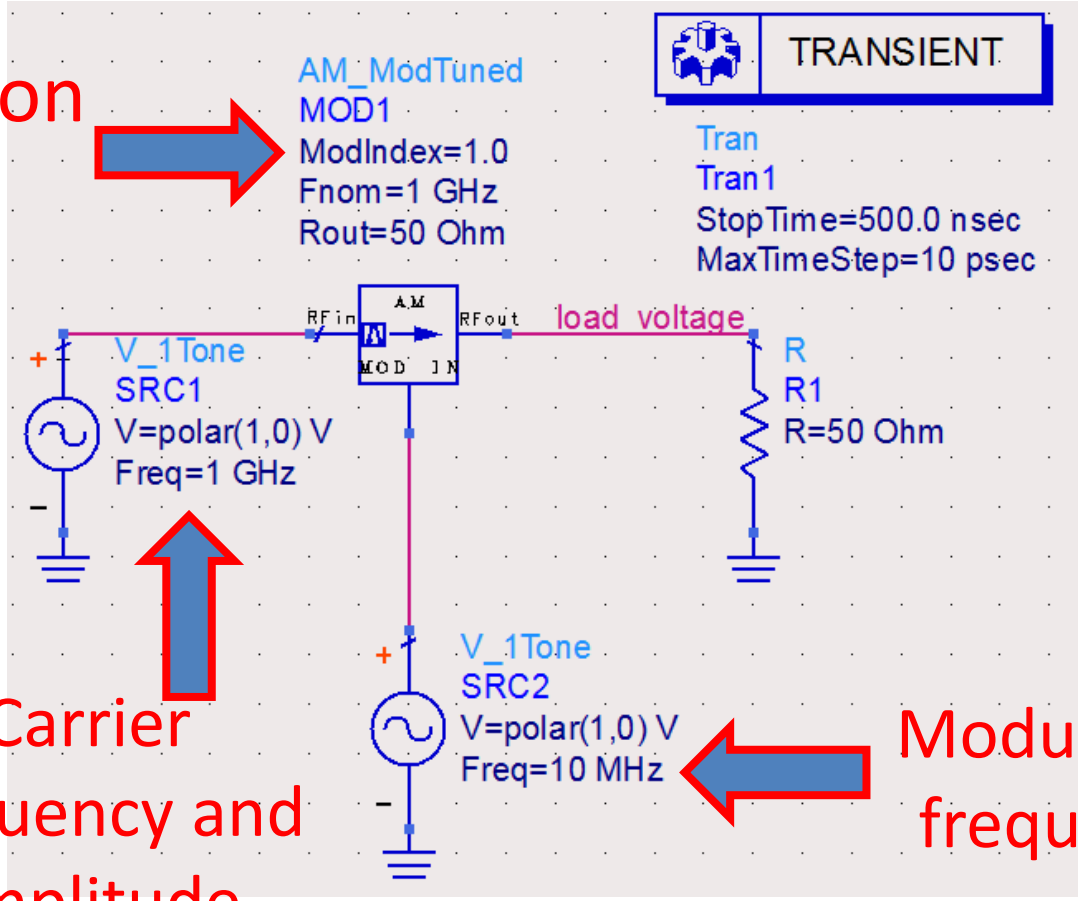
If M=1 (100% modulation) and K=1 (carrier amplitude):

$$AM_{DSBFC}(t) = \left[1 + \cos(\omega_m t)\right] \cdot \cos(\omega_c t)$$

Introduction to modulated signals

- Let´s simulate that with the setup below:

Modulation index

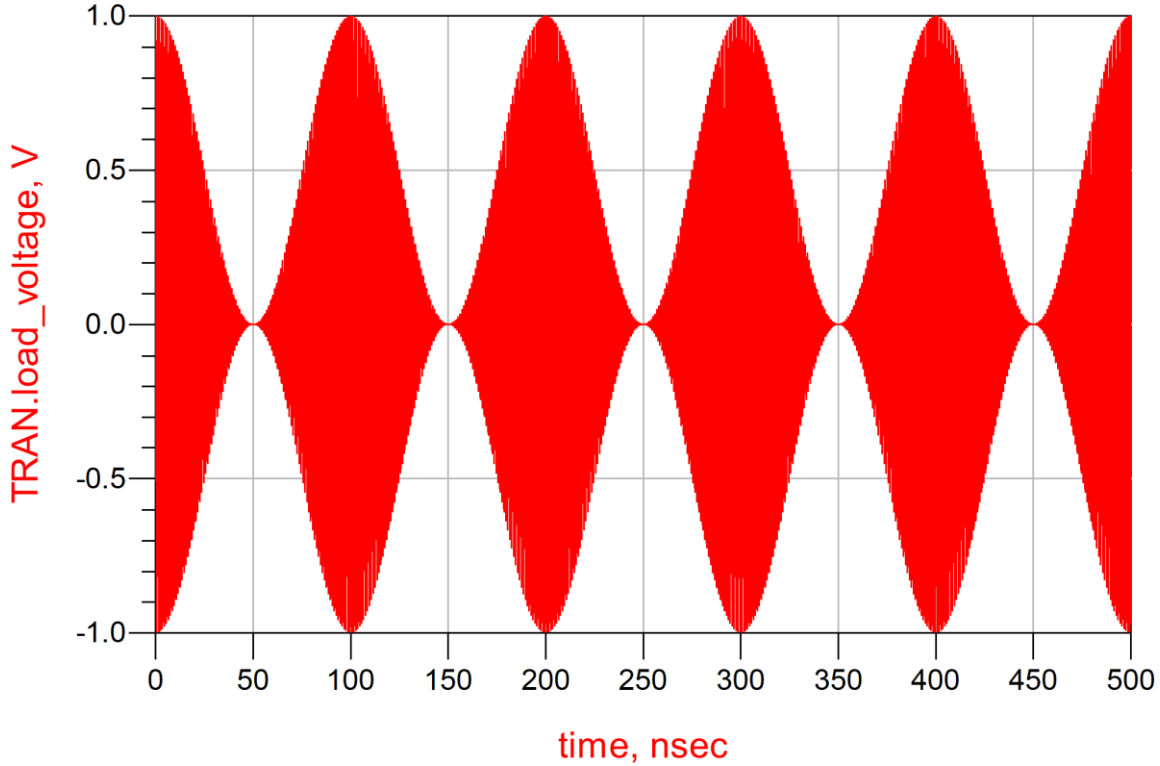


Carrier frequency and amplitude

Modulating frequency

Introduction to modulated signals

- Look at the results:



$$AM_{DSBFC}(t) = \left[1 + \cos(\omega_m t)\right] \cdot \cos(\omega_c t)$$

Introduction to modulated signals

- For a generic carrier amplitude, but as long as M=1:

$$AM_{DSBFC}(t) = \left[1+\cos(\omega_m t)\right]\cdot K\cos(\omega_c t) \Rightarrow =$$

$$AM_{DSBFC}(t) = \begin{cases} \frac{K}{2}\cos\left[(\omega_c-\omega_m)t\right]+ \\ K\cos(\omega_c t)+ \\ \frac{K}{2}\cos\left[(\omega_c+\omega_m)t\right] \end{cases}$$

Lower sideband

Carrier

Upper sideband

Notice that for M=1, the sidebands have HALF de VOLTAGE of the carrier. This means -6 dB!!!

Introduction to measurements

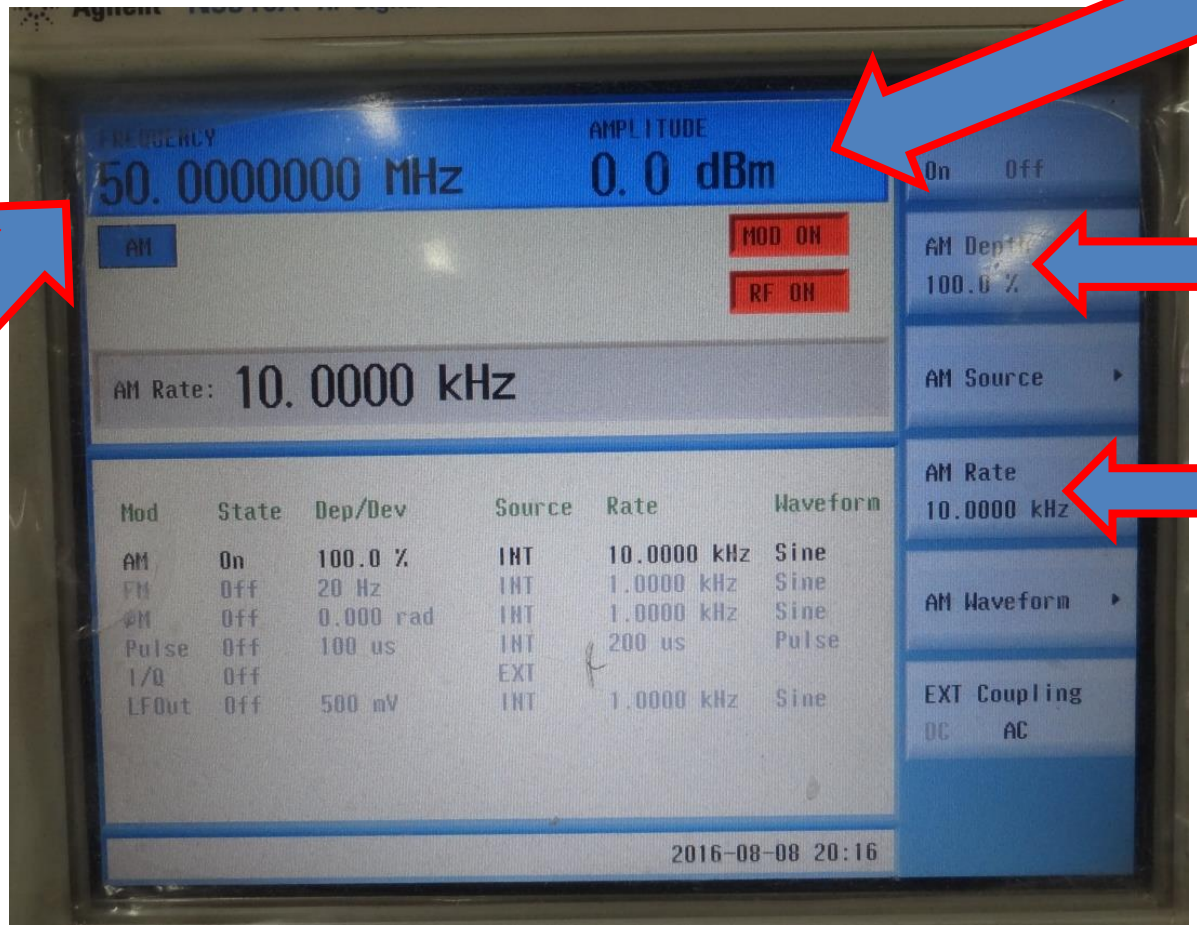
- Let´s check that with measurements:

Carrier power (0 dBm)

M=1

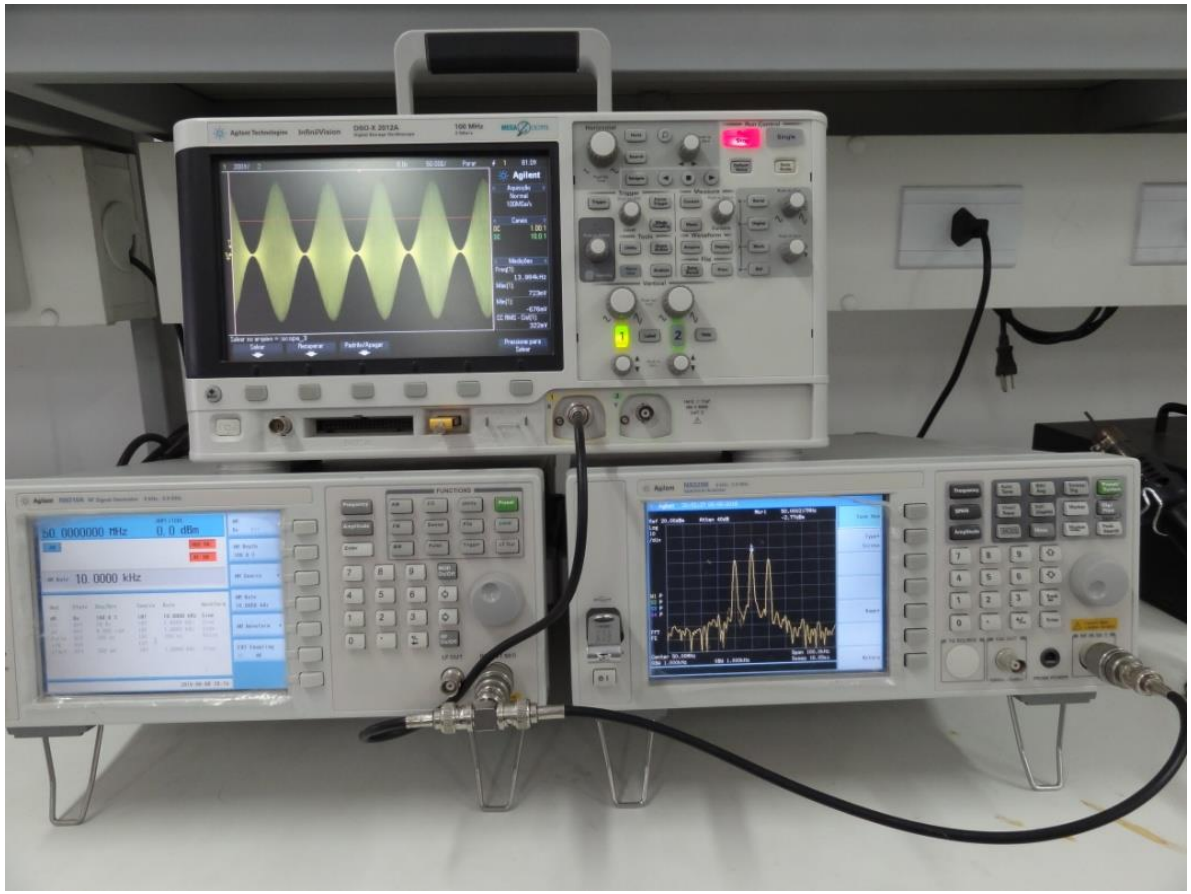
Carrier frequency (50 MHz)

Modulating frequency (10 kHz)



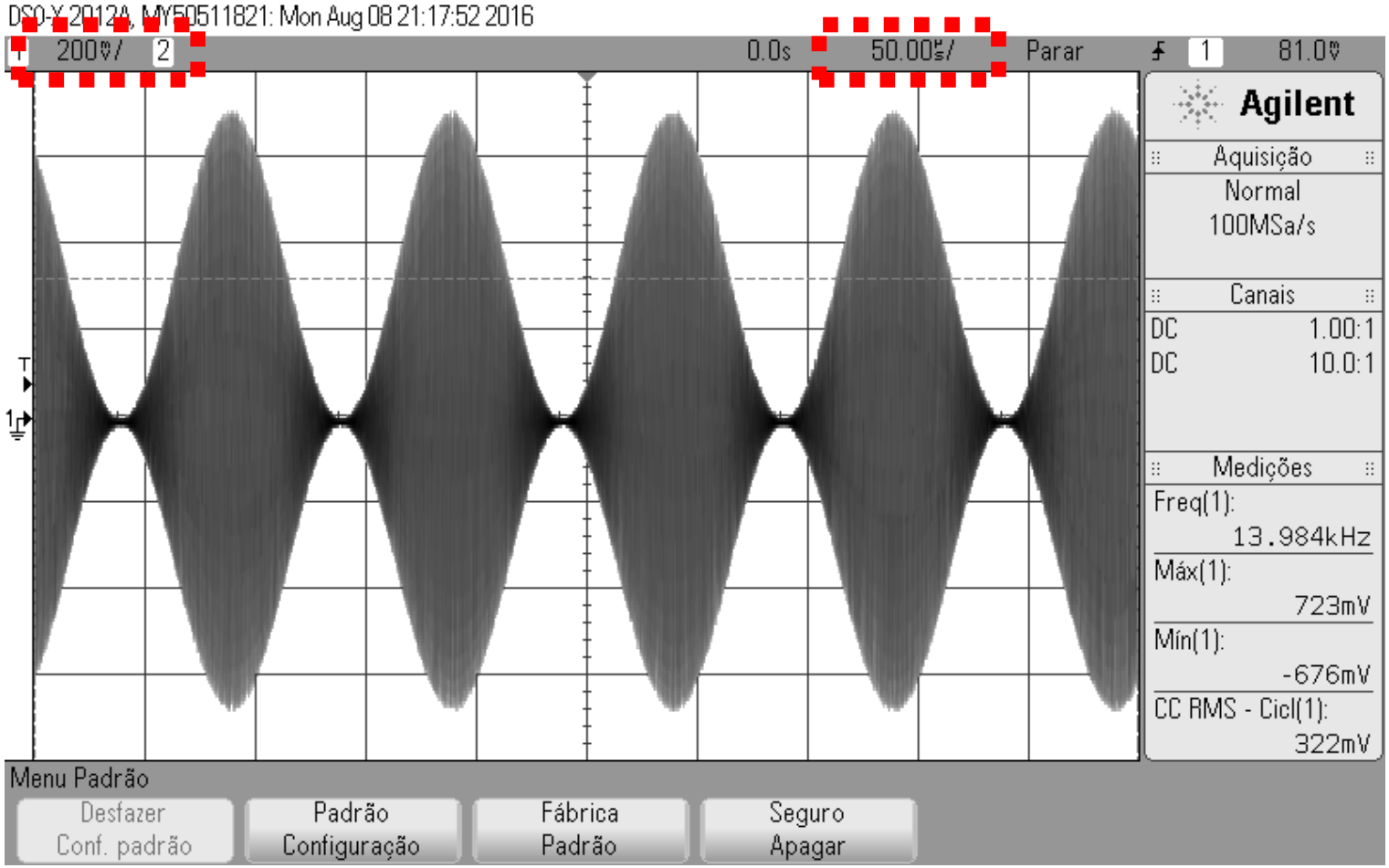
Introduction to measurements

- The setup should look like this:



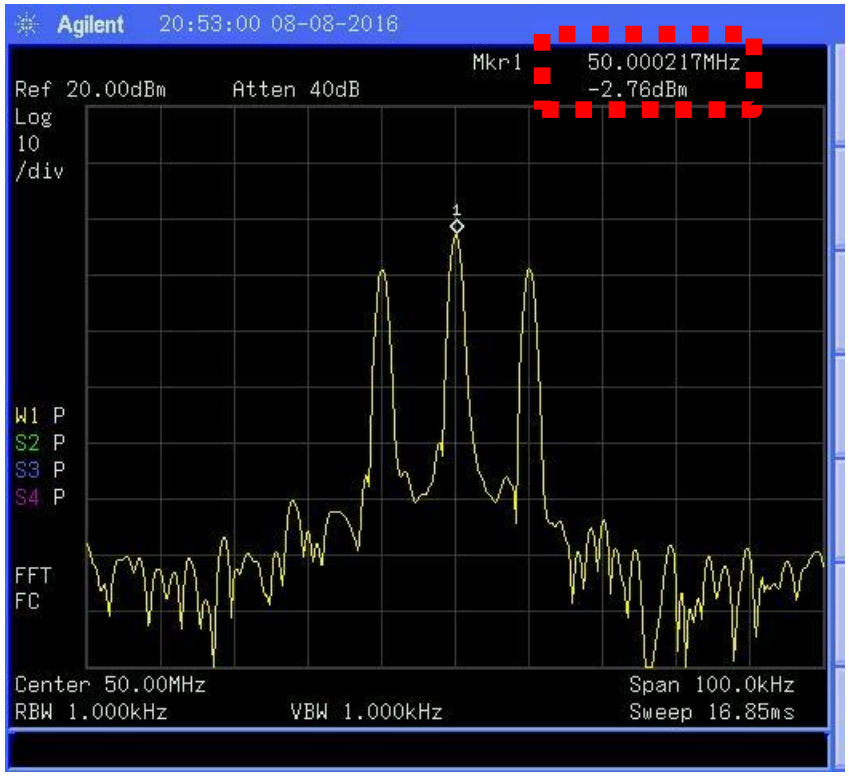
Introduction to measurements

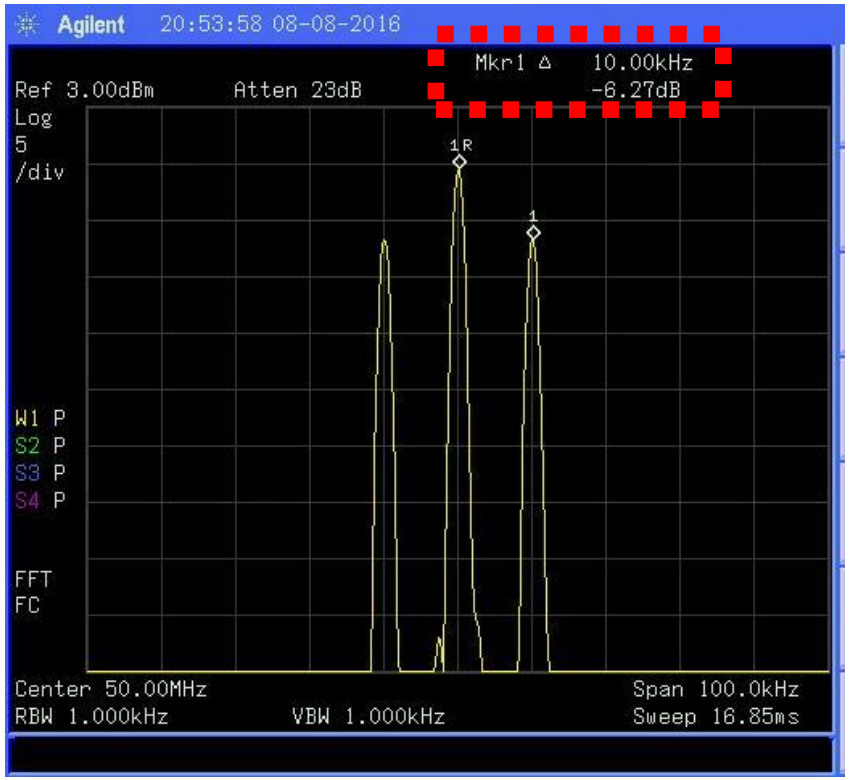
- Check the time-domain waveform:



Introduction to measurements

- Look at the frequency domain measurements:





Sounds good?

Introduction to modulated signals

- What if we change to M=0.5?

$$AM_{DSBFC}(t) = \left[1 + 0.5 \cdot \cos(\omega_m t)\right] \cdot K \cos(\omega_c t) \Rightarrow =$$

$$AM_{DSBFC}(t) = \begin{cases} \frac{K}{4}\cos\left[(\omega_c - \omega_m)t\right] + \\ K\cos(\omega_c t) + \\ \frac{K}{4}\cos\left[(\omega_c + \omega_m)t\right] \end{cases}$$

Lower sideband

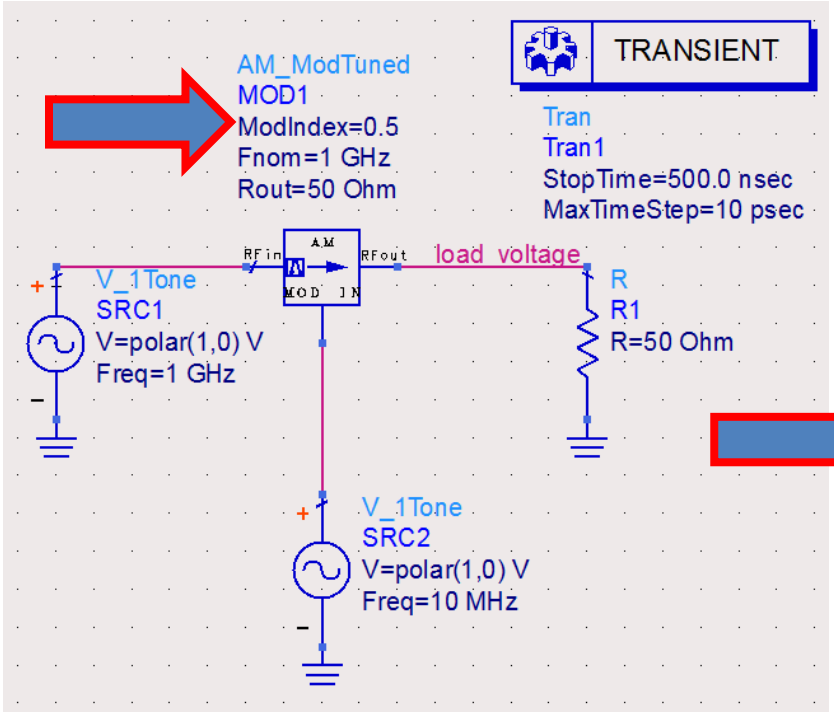
Carrier

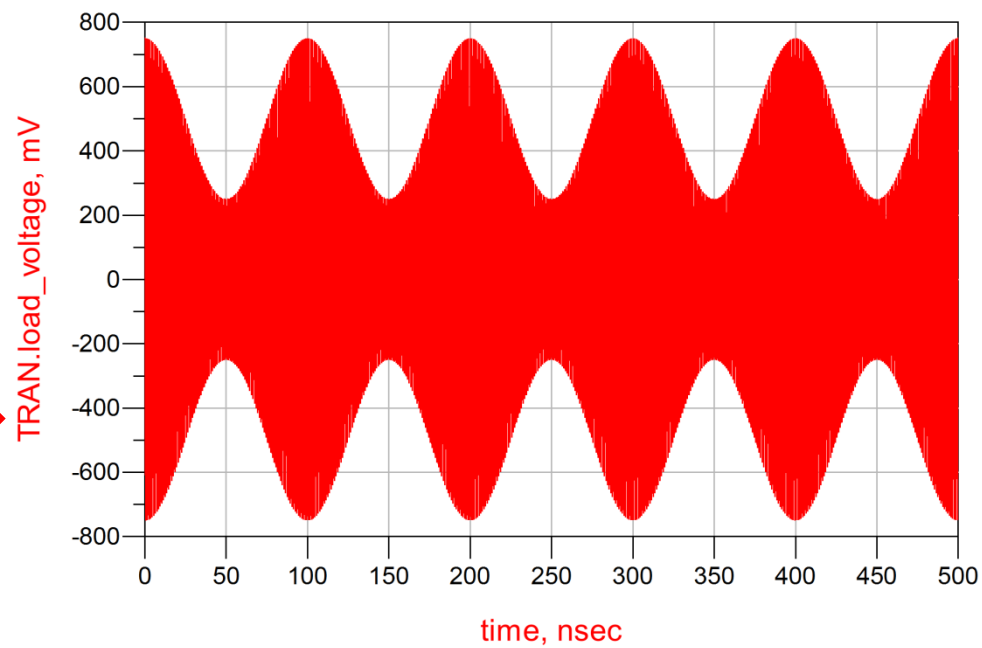
Upper sideband

Notice that for M=0.5, the sidebands have a QUARTER of the VOLTAGE of the carrier. This means -12 dB!!!

Introduction to modulated signals

- Let´s look at the simulation results:

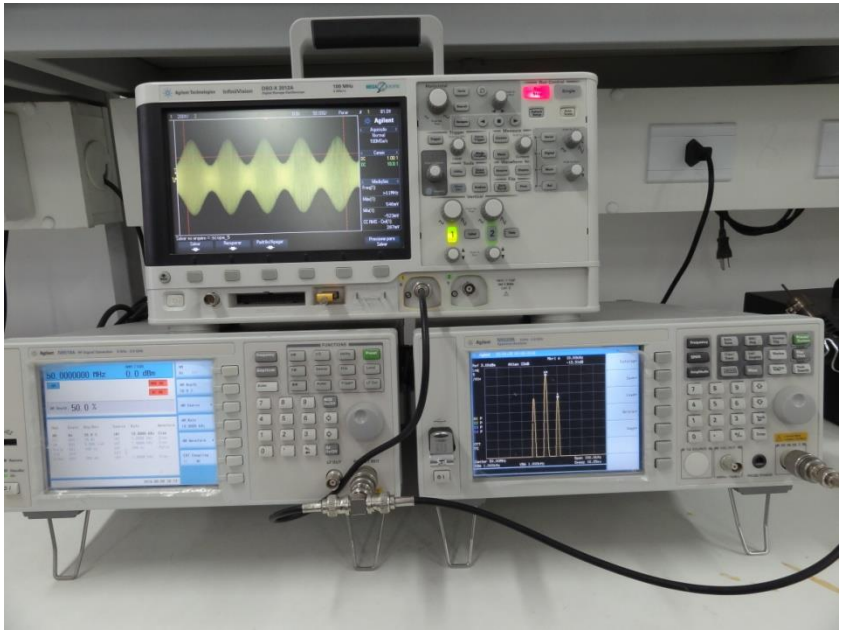




Introduction to measurements

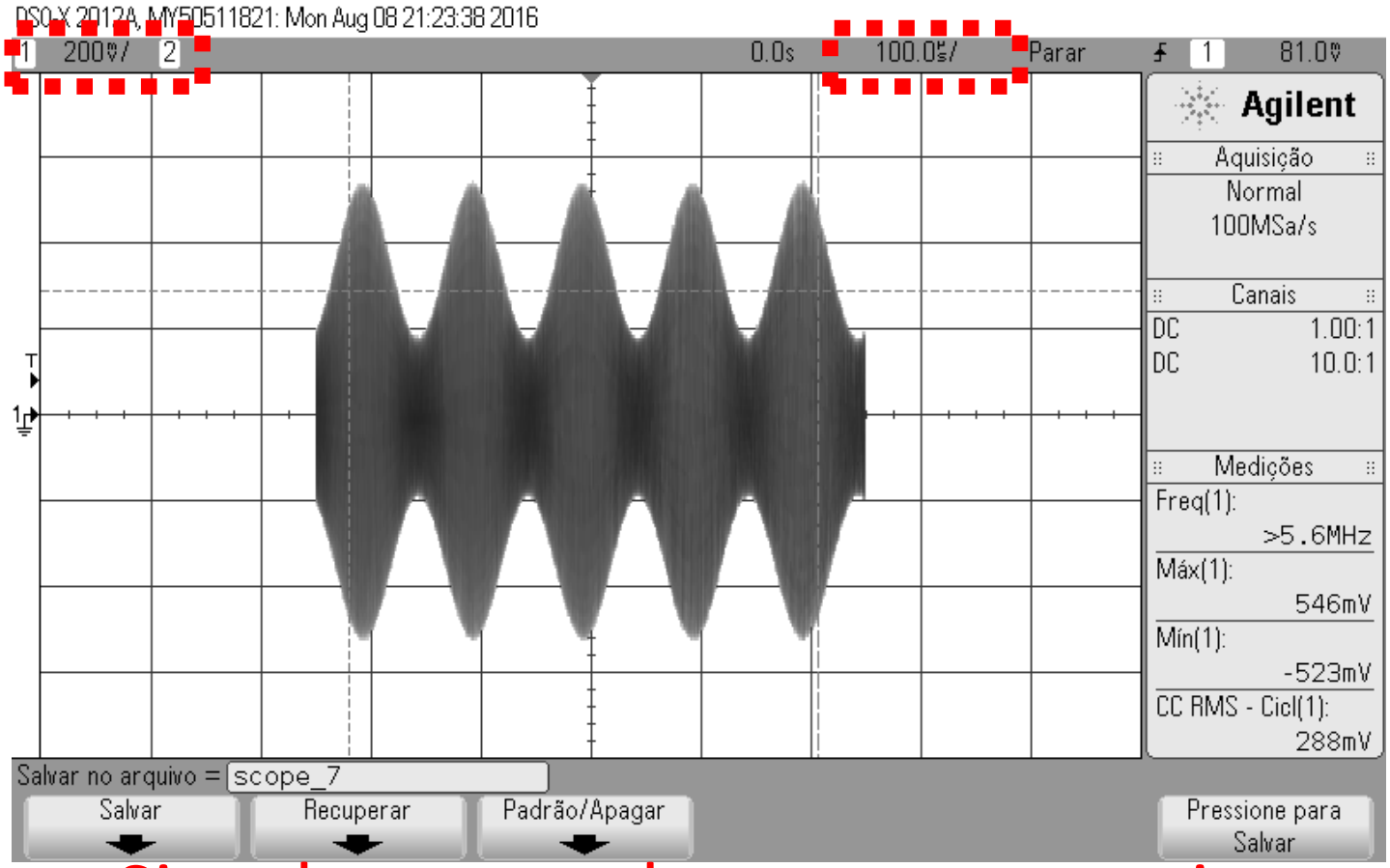
- Let´s check that with measurements:

M=0.5



Introduction to measurements

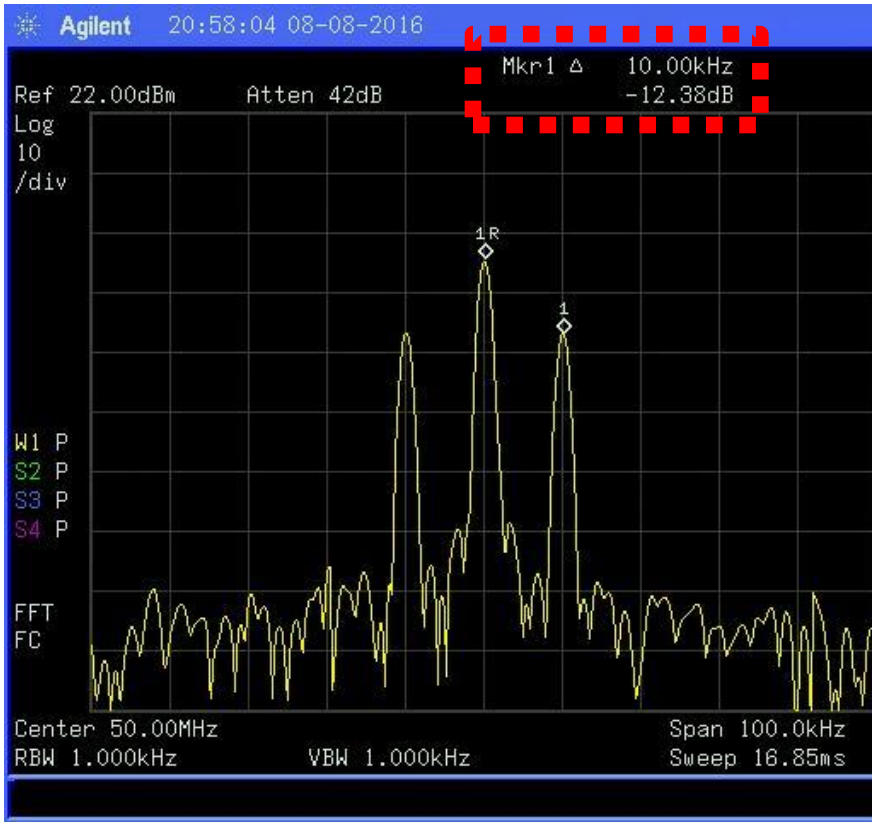
- Check the time-domain waveform:



Signal truncated to ease measuring

Introduction to measurements

- Look at the frequency domain measurements:



Sounds good?

Introduction to modulated signals

- OK for AM, but what about the "marvelous" FM?
  - The mathematics is much more involved.
  - We will try to keep it simple (more on this later), and focus on the single-tone modulation:

Maximum frequency deviation

$$FM_{SINGLETONE}(t) = A_C \cos\left[\omega_c t + \frac{\Delta f}{f_m}\sin(\omega_m t)\right]$$

Carrier amplitude

Carrier frequency

Modulating frequency

Introduction to modulated signals

- What about the spectrum (google it!)?

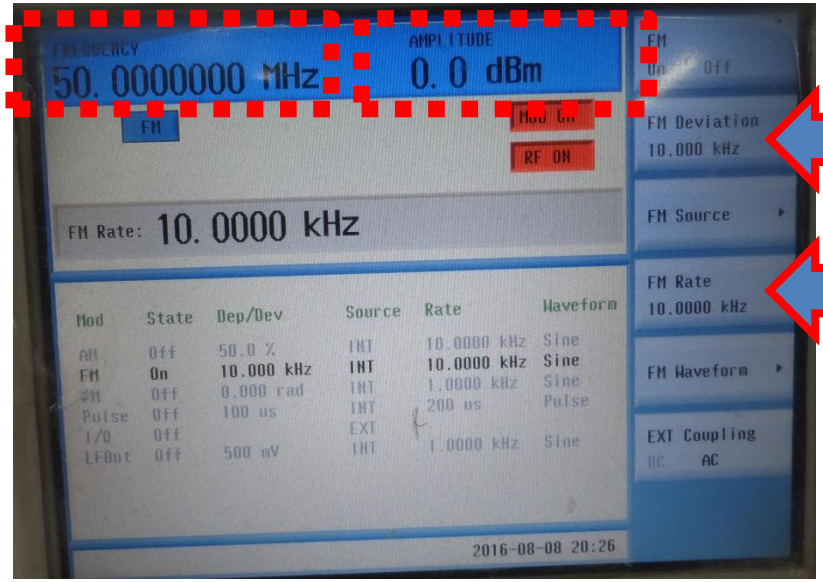
$$FM_{SINGLETONE}(t) = A_C \cos\left[\omega_c t + \frac{\Delta f}{f_m}\sin(\omega_m t)\right]$$

$$\frac{\Delta f}{f_m} = \text{Modulation index}$$

Modulation index	Sideband amplitude									
	Carrier	1	2	3	4	5	6	7	8	9
0.00	1.00									
0.25	0.98	0.12								
0.5	0.94	0.24	0.03							
1.0	0.77	0.44	0.11	0.02						
1.5	0.51	0.56	0.23	0.06	0.01					
2.0	0.22	0.58	0.35	0.13	0.03					
2.41	0	0.52	0.43	0.20	0.06	0.02				
2.5	−0.05	0.50	0.45	0.22	0.07	0.02	0.01			
3.0	−0.26	0.34	0.49	0.31	0.13	0.04	0.01			

Introduction to measurements

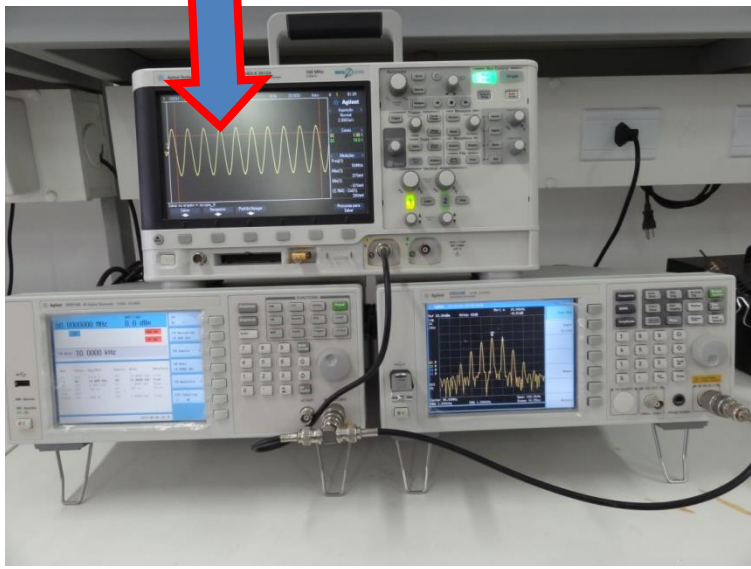
- Let´s check that with measurements:



Δf=10kHz

f_m=10kHz

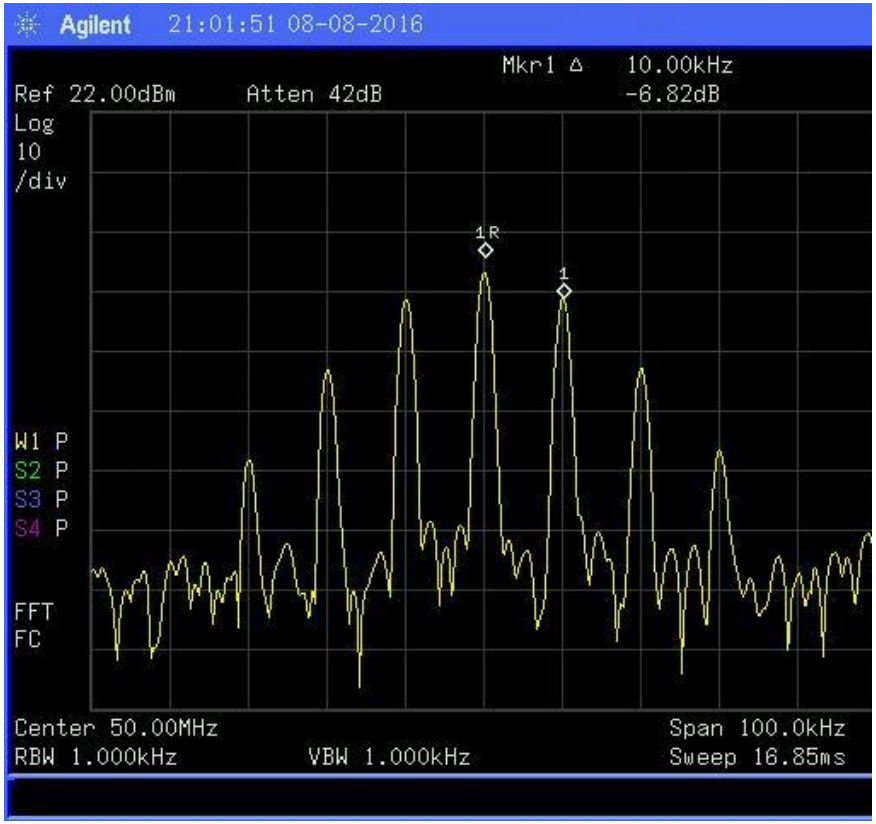
Constant amplitude signal!!



Introduction to measurements

- Look at the frequency domain measurements:

Modulation index	Carrier	1	2	3	4
0.00	1.00				
0.25	0.98	0.12			
0.5	0.94	0.24	0.03		
1.0	0.77	0.44	0.11	0.02	
1.5	0.51	0.56	0.23	0.06	0.01
2.0	0.22	0.58	0.35	0.13	0.03

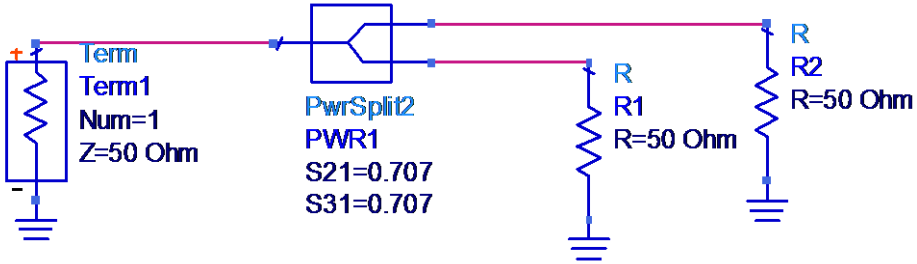


Proposed exercices

- Execute the following conversions:
  - 20dBm = _____W
  - -40dBW = _____dbm
  - G=10V/V = _____dB
  - G=1mA/μA = _____dB

Proposed exercices

A *Power Divider* (or *Power Splitter*) is a passive component which can be used to divide (split) the power of a source between two loads (supposedly the same). They are common in houses and buildings in which the same antenna (source) is divided between 2 television sets (loads). It can be imagined as a 3-port device (1 input, 2 outputs) which transform each of the two 50 Ω loads into a 100 Ω, and put them in parallel, so the source "sees" a 50 Ω load. Consider the circuit below, composed by a signal source ("Term"), a *Power Divider* ("PwrSplit2") and 50 Ω loads.



Supposing that the source of signal has na internal impedance of 50 Ω and available power of -80 dBW, calculate the power, in dBm, in each of the loads (P_L).

Proposed exercices

- According to the Friss equation for transmission of signals, the ratio between the power received by na antenna (P_{RX}) and the transmitted power (P_{TX}) is:

$$\frac{P_{RX}}{P_{TX}} = G_{TX} \cdot G_{RX} \cdot \left(\frac{\lambda}{4\pi R}\right)^2$$

- In this equation, G_{TX} and G_{RX} indicate the TX and RX antenna gain respectively (with respect to the isootropic condition, in which power is evenly radiated in all directions), λ is the wavelength and R is the distance between the antennas. Supposing that a 2.4GHz transceiver is able to operate with a received power as low as -100 dBm and transmit 20dBm,if G_{TX}=G_{RX}=0dB, what is the greatest distance between the antennas?

Proposed Experiments

- Change the frequency and amplitude of a single tone, and observe it on the oscilloscope and spectrum analyzer. Check values.
- Change the modulating frequency and modulation index of an AM modulated signal, and observe it on the oscilloscope and spectrum analyzer. Check values.
- Change the modulating frequency and frequency deviation of a FM modulated signal, and observe it on the spectrum analyzer. Check values.