Topic 3:
Heterodyne spectrum analyzer

Aims:
The aim of this TA is to understand the **functioning of a spectrum analyzer using a heterodyning technique and the main associated settings**. The purpose is to analyze the characteristics of a periodic electric spectrum signal and to interpret its time-frequency ratio.

Prerequisites:
Time-frequency ratio. Breaking down a periodic function into a Fourier series. Second-order filtering.

The spectrum analyzer is an instrument used to measure the spectrum of a signal (shown as frequency) by applying an input voltage.

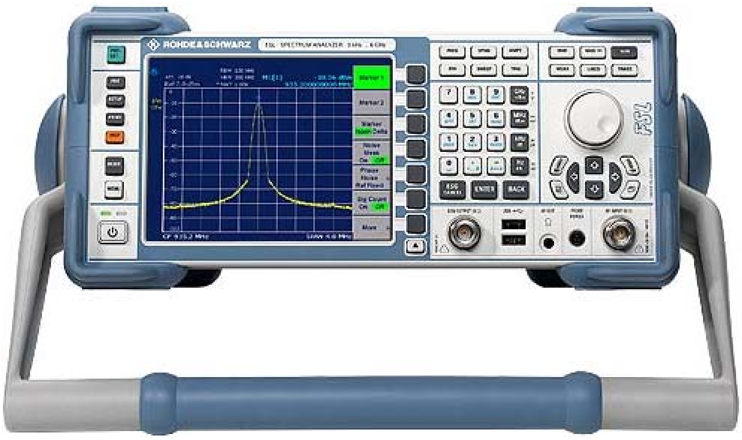


Figure 1: *Front view of a spectrum analyzer*

As with an oscilloscope, vertical and horizontal adjustments can be made:

- Vertical sensitivity (using several units: Volts or dBm)
- Frequency range (SPAN)

But in this case there are also other parameters:

- Setting the center frequency position (CENTER FREQUENCY)
- Resolution bandwidth (RBW)
- Speed of sweep (SWEEP TIME)

I- Vertical settings

On a spectrum analyzer, there is a choice of two types of vertical scale:

- a linear scale (as in an oscilloscope) where the units are Volts and its variants (mV, μV)
- a logarithmic scale, which is much more commonly used, and for this the basic unit is the decibel.

First, we will focus on definitions of the units dB, dBm, dBV, etc.

● Amplifier gain is expressed in dB

Example: If the input and output voltages of an amplifier are *10mV* and *100mV* respectively, the amplifier gain is *10* or $20\log_{10}\left(\frac{0.1}{0.01}\right) = 20dB$.

● $dBm = 10\log_{10}\left(\frac{Power\,in\,W}{10^{-3}W}\right)$

Example: With a *2V* effective voltage at the terminals and a resistance of 50Ω, the power dissipated in resistance is: $10\log_{10}\left(\frac{2^2/50}{10^{-3}}\right) = 19dBm$.

- $dBV = 20\log_{10}\left(\frac{voltage\,in\,V}{1\text{V}}\right)$,

<u>Example</u>: A *2V* voltage corresponds to $20\log_{10}\left(\frac{2}{1}\right) = 6dBV$.

Question 1: What is the value for the ratio of two voltages that corresponds to 0dB?

Question 2: What power (in mW) corresponds to 0dBm?

Question 3: What voltage (in Volts) corresponds to 10dBV?

Question 4: Consider a linear system with a gain of 60dB. An input voltage of Ve is applied. Calculate the value of the output voltage for the different values of Ve shown in the table below.

Ve	100μV	1mV	10mV
Vs			

Table 1

Question 5: Complete the table below,

dBm	Equivalent voltage for a charging resistance of 50Ω
-10	
-5	
0	224mV
+5	
+10	
+20	

Table 2

Question 6: The effective values of the spectral components of a periodic signal are given in Table 3. Complete the table.

F (kHz)	Effective value of peak (mV)	Power in dBm with 50Ω
5	224	
10	200	
15	10	
20	1	
25	0.1	

Table 3

Question 7: Plot $\left|V_{eff}(f)\right|$ the spectrum in mV of this signal onto Figure 2.

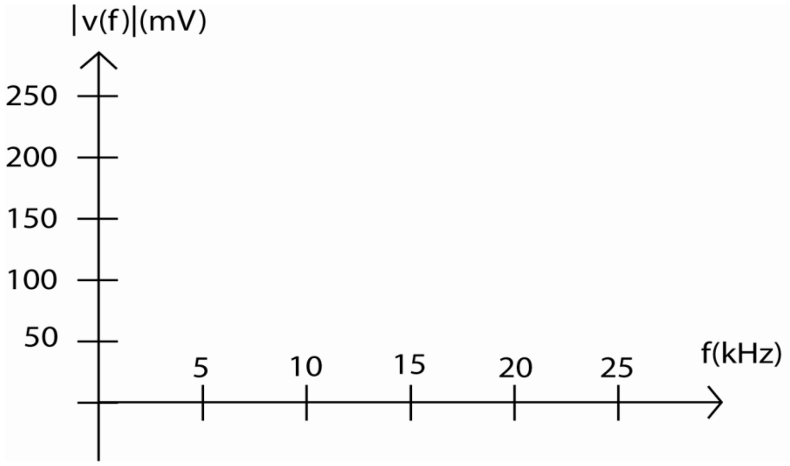


Figure 2

When the signal is to be shown with a logarithmic scale, a marker has to be put in place, called the reference level. This is by definition in the top part of the spectrum analyzer display screen. Scale is given by the number of dB per grid square of the screen. In our example, you can see "10dB/" which corresponds to a sensitivity of 10 decibels per grid square.

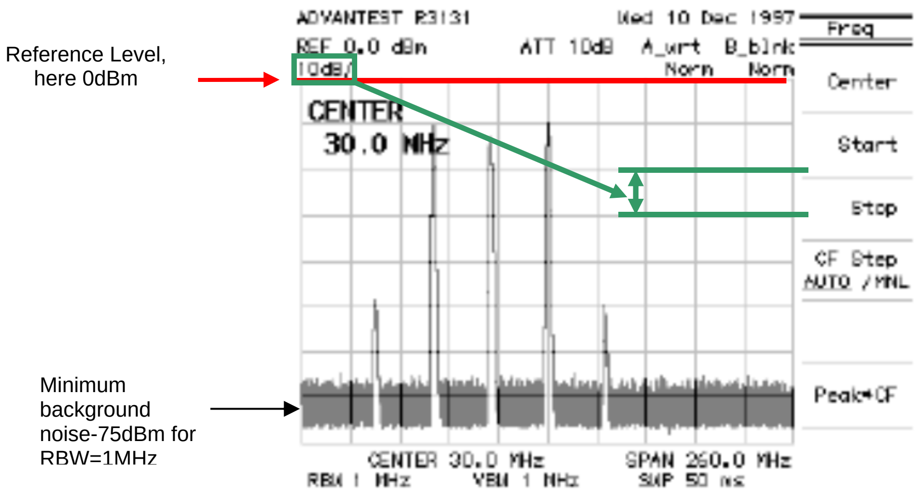


Figure 3: *Example of spectrum and associated indications*

Question 8: If we assume that the reference level is 0dBm, calculate the level in dBm and in µV that corresponds to the line along the bottom of the screen.

Question 9: On the spectrum in Figure 3, we can see a background noise. Determine its "mean" value in µV.

Question 10: In Figure 4, show the value of the reference level selected and the sensitivity, then **plot the spectrum in dBm** of the signal in Table 3, assuming that a background noise of 10µV is superimposed on this signal.

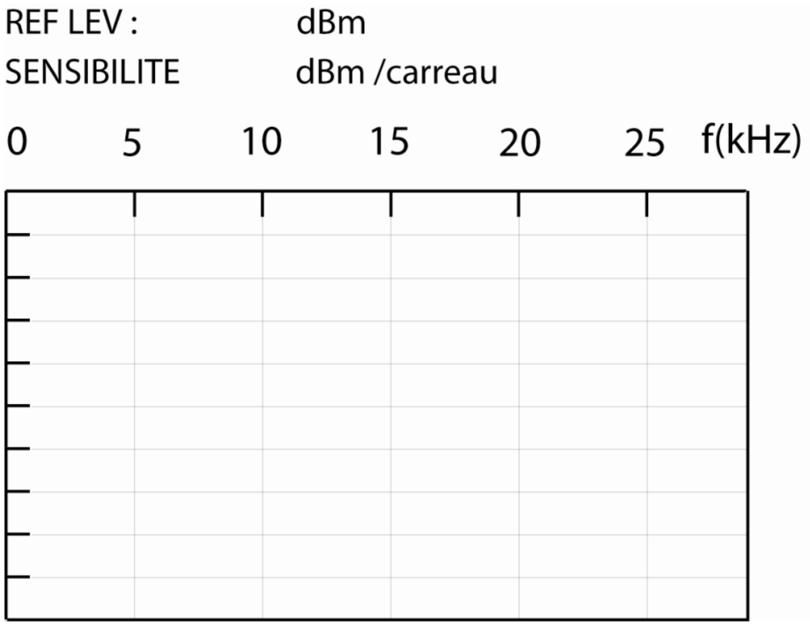


Figure 4: spectrum in dBm of the signal given in Table 3

II- Horizontal settings

For horizontal settings, two modes of adjustment are possible:

- either specify the extreme frequencies (START FREQUENCY and STOP FREQUENCY),
- or enter the center frequency and the frequency range directly (CENTER FREQUENCY and SPAN) as shown in Figure 5.

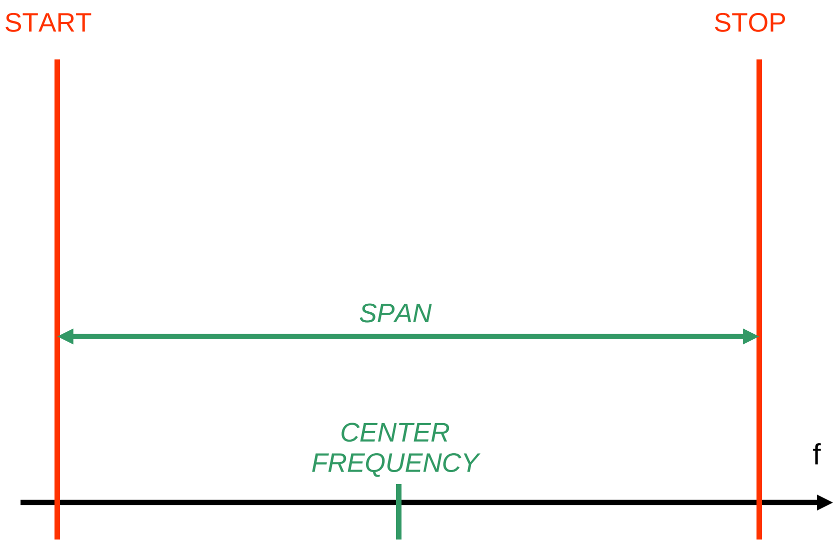


Figure 5 : possible modes of adjustment

Question 11: Consider the display screen shown in Figure 6. Find the values for the different horizontal settings START, STOP, CENTER FREQUENCY and SPAN. From this, deduce the frequency scale per grid square.

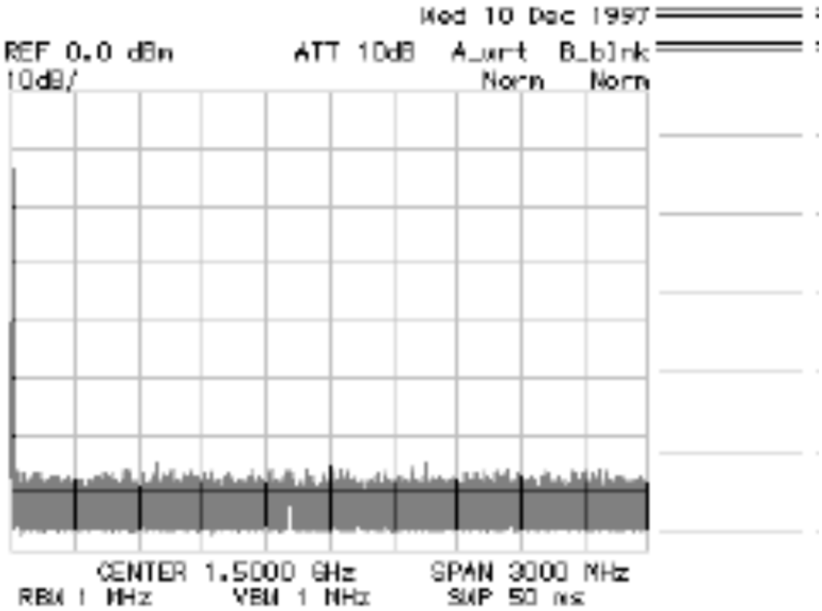


Figure 6: measured spectrum

III- Operation of an analyzer in detail and main settings

III-1. Principle of heterodyning

If we look at the screen in Figure 3, we see that the peaks representing the frequencies in the signal being studied have **a non-zero width**. This is a result of the settings chosen for these two parameters, which are:

- resolution bandwidth (RBW),
- sweep time (SWP).

To understand the role of these other settings, it is necessary to understand the internal workings of the analog spectrum analyzer, especially in relation to the **principle of heterodyning**. This technique consists in using multiplication to transpose the frequency of the observed signal in the bandwidth of a bandpass filter with a fixed center frequency. This is because it is difficult to produce a bandpass filter with a center frequency that can be tuned across a wide range of frequencies (from a few kHz to several tens of GHz) as shown in Figure 7. *This technique is particularly well described in the work by Christoph Rauscher, "Fundamentals of Spectrum Analysis" published by Rohde & Schwarz.*

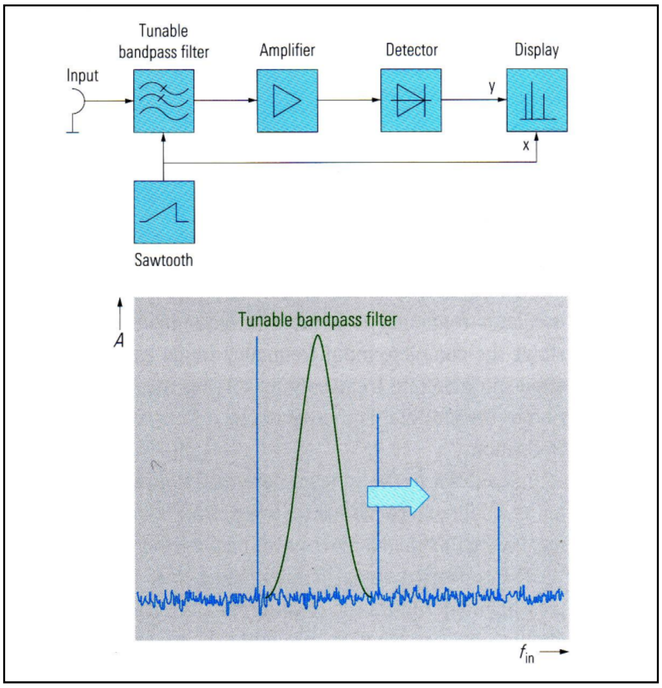


Figure 7: *Bandpass filter with tunable voltage*

The block diagram of a commercially available spectrum analyzer is shown in Figure 8.

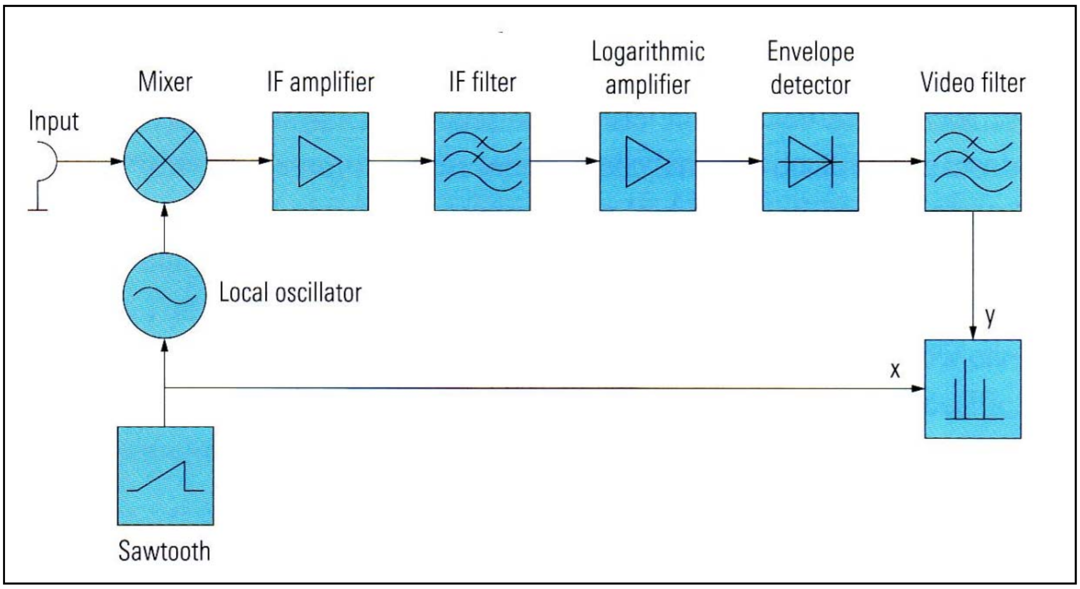


Figure 8: *Block diagram of a commercially available spectrum analyzer*

For the purposes of these exercises, we will study a simplified structure, which is shown in Figure 9. Basically, it consists of:

- a multiplier (also called a "mixer")
- a voltage controlled oscillator (VCO)
- a sawtooth generator
- a bandpass filter
- an envelope detector
- an oscilloscope used in X-Y mode

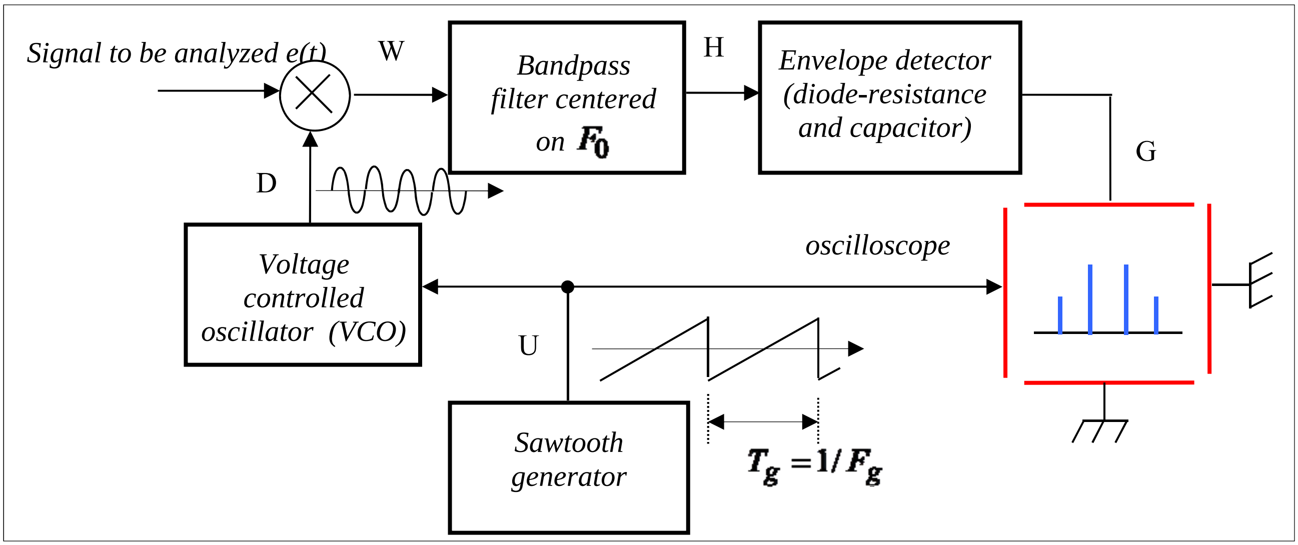


Figure 9: *Block diagram of a spectrum analyzer*

The frequency–voltage feature of the VCO is shown in Figure 10.

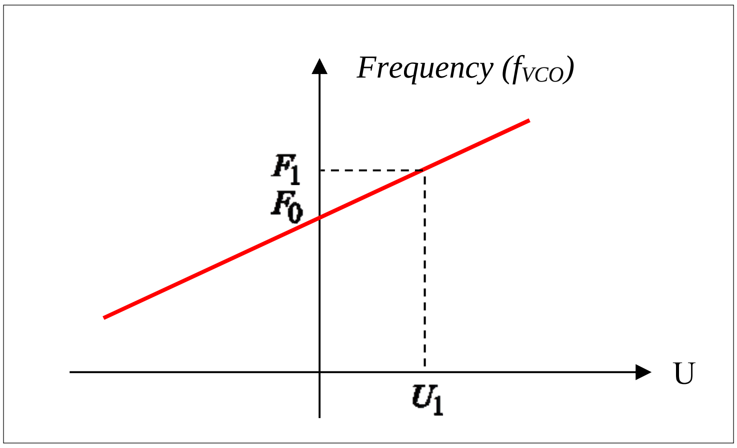


Figure 10: *Frequency-voltage feature of the VCO*

- Signal to be analyzed:

First, we assume that the signal $e(t)$ is cosinusoidal so that: $e(t) = A\cos(\omega_e t)$. Frequency F_e of signal *e(t)* is equal to $1MHz$, its amplitude *A* is equal to *2V*.

- Sawtooth generator:

For a given voltage U_1 of the sawtooth generator, the frequency of the VCO is equal to F_1. The *max.* and *min.* values of the sawtooth are *+5V* and *-5V*.

- VCO:

The frequency–voltage features of the *VCO* are: $F_{VCO} = F_0 + aU$ with $F_0 = 100MHz$ and $a = 1MHz/V$. The output voltage *D(t)* of the VCO is written: $D(t) = B\cos(\omega_{VCO} t)$ with $\omega_{VCO} = 2\pi F_{VCO}$. $B = 4V$ is given.

- Bandpass filter:

Next, we assume that the bandpass filter has an ideal transfer function of type $\delta(f - F_0)$, i.e. a filter that only allows the frequency $F_0 = 100MHz$ to pass, with a unit gain.

- Envelope detector: We assume a perfect envelope detector.

The oscilloscope screen consists of 10 horizontal and vertical divisions. The dot is at the top right of the screen when $U = G = 5V$ and at the bottom left when $U = G = -5V$.

Question 12: Write the expression for the *W(t)* output signal of the multiplier and draw its spectrum. The circuit multiplier has an instrument function $k = 1V^{-1}$.

Question 13: Complete the table below and identify the U values for the VCO commands for which the frequencies (F_{VCO}-F_e) and (F_{VCO}+F_e) are 100MHz.

U (V)	F_{VCO} (MHz)	F_{VCO}-F_e(MHz)	F_{VCO}+F_e (MHz)
-5			
-4			
-3			
-2			
-1			
0			
1			
2			
3			
4			
5			

Question 14: Calculate the amplitude of the 2 spectral components of W(t) at (F_{VCO}-F_e) and (F_{VCO}+F_e)

Question 15: Transfer to the screen in Figure 9 the graph observed after the filtering operation and envelope detection when U varies from -5V to +5V.

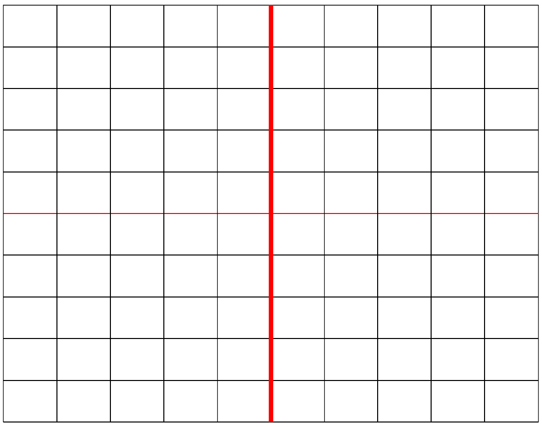


Figure 9: *Oscilloscope screen*

Question 16: The input stage of the analyzer is modified as shown in Figure 10. Keeping the same numerical values as in the previous question, draw the newly obtained spectrum on the screen below.

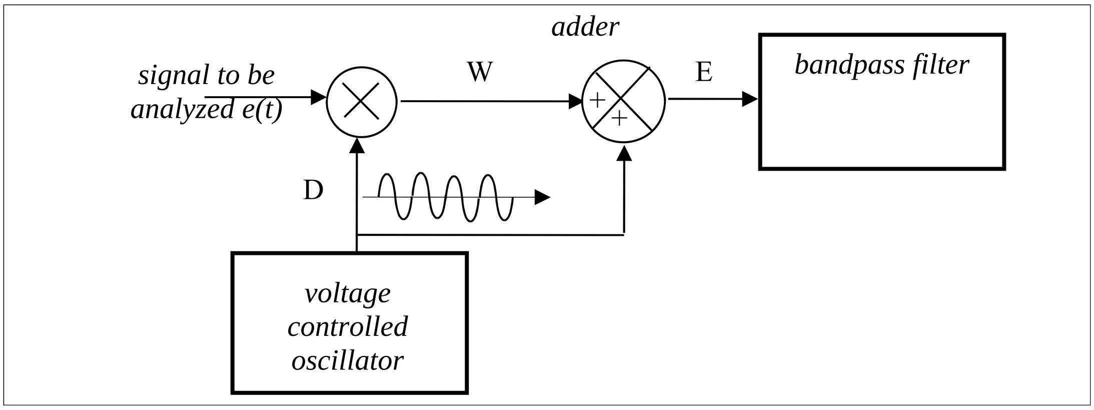
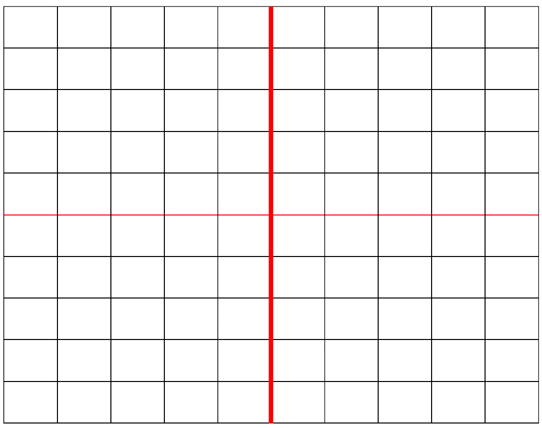


Figure 10: *Input stage of a spectrum analyzer*



Oscilloscope screen

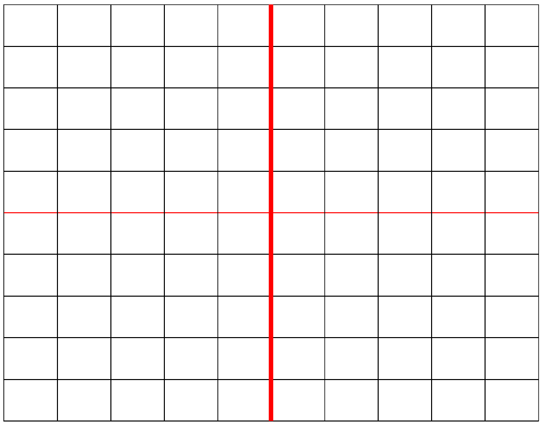
Question 17: The input impedance of the analyzer is 50Ω. In order not to destroy the input stage of the analyzer, power should not exceed $25dBm$, deduce the maximum **effective value** of the input voltage.

III-2. Description of main settings

- ***"SPAN" setting***

The gradient of the frequency–voltage feature of the VCO has now been modified: $F = F_0 + aU$ with $F_0 = 100MHz$ and $a = 0.2MHz/V$. The other numerical values remain unchanged.

Question 18: Draw the newly obtained spectrum on the screen below.



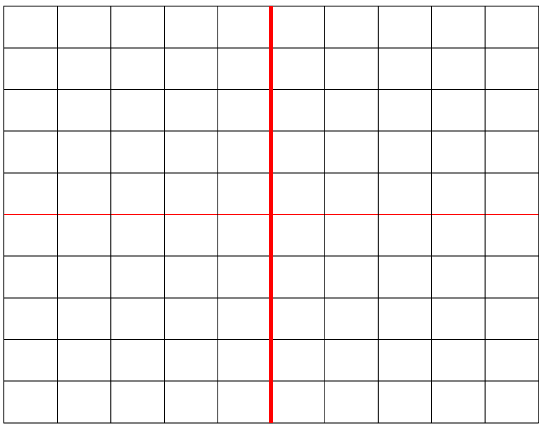
Oscilloscope screen

The "SCAN" setting is used to control frequency deviation during analysis.

- ***"CENTER FREQUENCY" setting***

The y-intercept of the frequency–voltage feature of the VCO has now been modified: $F = (F_0 + 1MHz) + aU$ with $F_0 = 100MHz$ and $a = 1MHz/V$. The other numerical values remain unchanged.

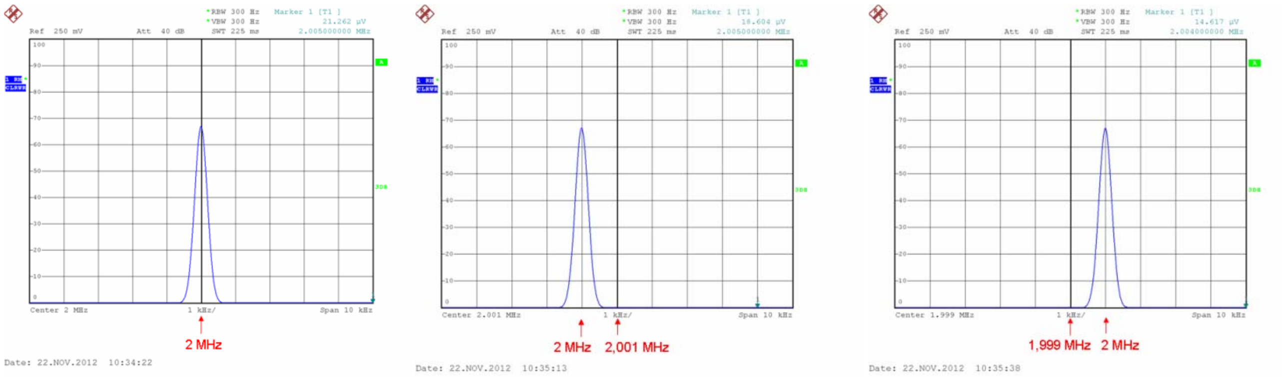
Question 19: Draw the newly obtained spectrum on the screen below.



Oscilloscope screen

Adjusting “CENTER FREQUENCY” controls the position of the lines on the screen. It is often interesting to bring a line into the middle of the screen to be able to measure its amplitude correctly on a smaller “SPAN”.

For information, Figure 11 shows the effect of this parameter on a sinusoidal input signal of frequency 2MHz and amplitude 500mV$_{pp}$.



CENTER FREQUENCY = 2MHz	CENTER FREQUENCY = 2.001MHz	CENTER FREQUENCY = 1.999MHz

Figure 11: *Influence of “CENTER FREQUENCY” setting*

- ***“RBW” setting***

The bandpass filter is applied using a **voltage - current converter** followed by an *L*-*C* cell as shown in Figure 12. Resistance *R* represents losses from the *L*-*C* circuit around frequency $F_0 = 100MHz$.

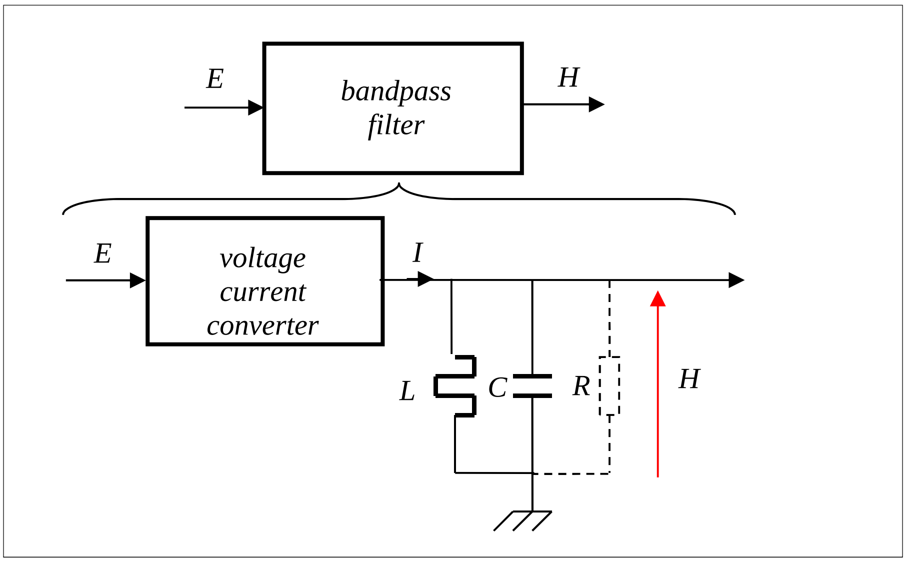


Figure 12: *Producing the bandpass filter*

Question 20: Write the complex gain H / I, put it in the form:

$$\frac{H}{I} = \frac{R}{1 + jQ(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega})}$$

Give the expression for Q and ω_0 as a function of R, L and C.

Question 19: Plot the trend of the module and the argument of $T = \frac{H/I}{R}$, what is the value of the module for frequency F_0?

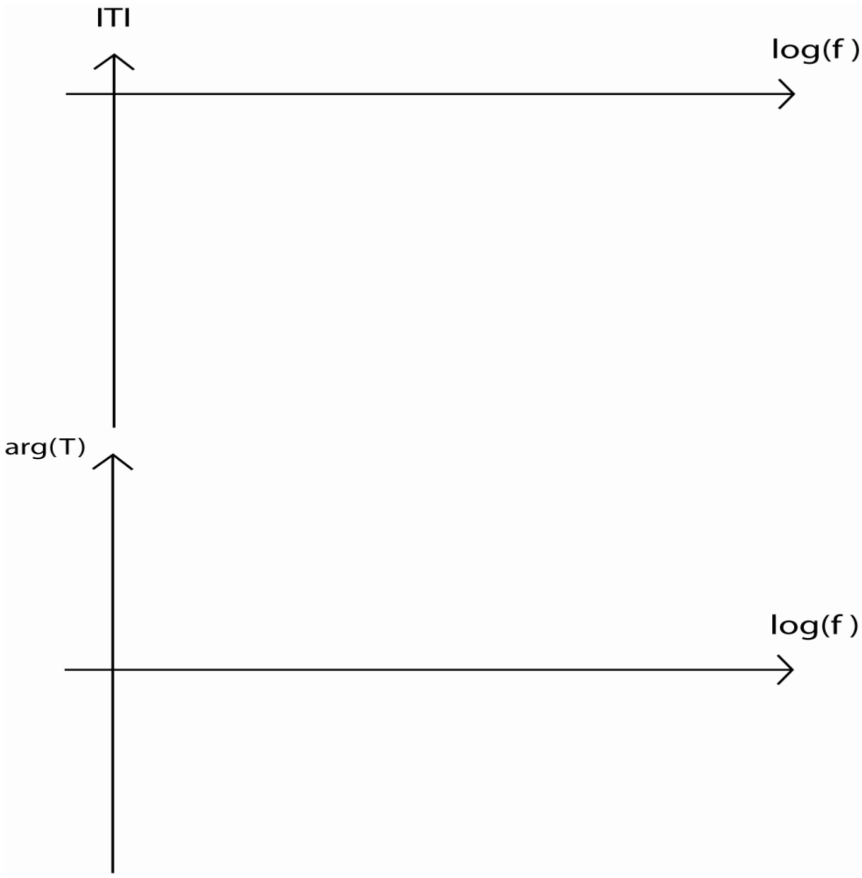


Figure 13: Bode diagram trend

Question 20: The bandwidth at -3dB is equal to F_0 / Q. To simplify, the frequency response curve of the bandpass filter is given a "gate" function, as shown in Figure 14.

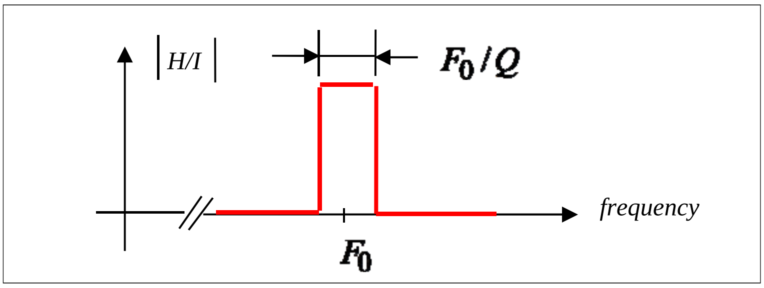
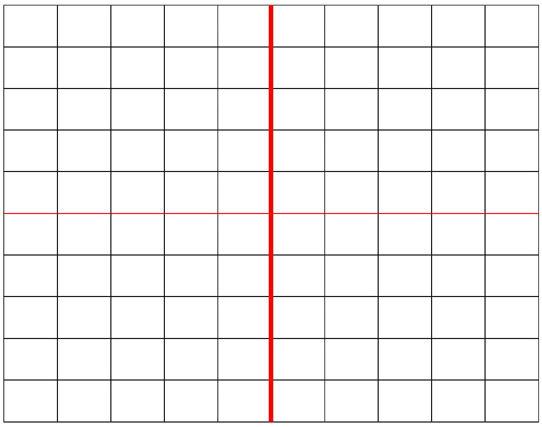


Figure 14: *Approximation of the frequency response of the filter by a "gate" function*

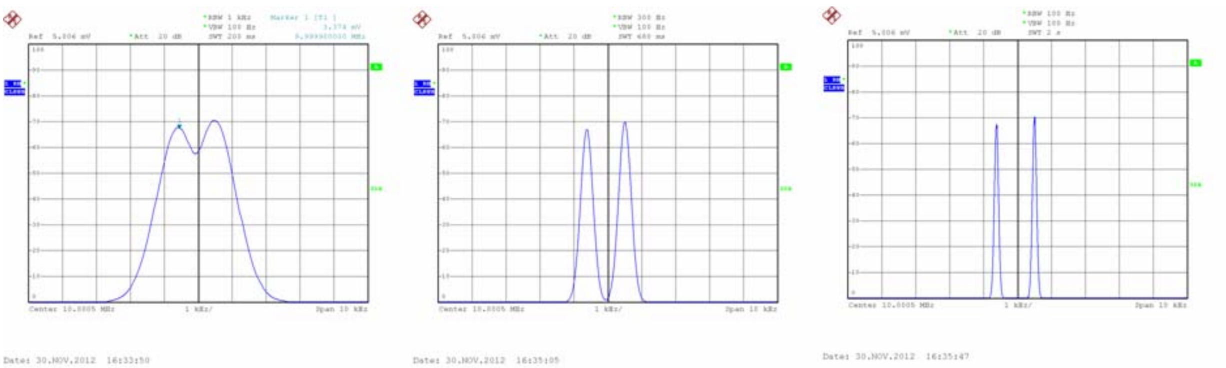
Consider that the gain of the voltage–current converter is $10^{-5}\,A/V$, given that $Q = 500$, $R = 100k\Omega$, draw the new spectrum on the screen below. Zoom onto the interesting areas.



Oscilloscope screen

Adjusting bandwidth to -3dB corresponds to the influence of filter width on analysis resolution. It is identified by the RBW or "Resolution Bandwidth" function. **For it to be effective, the value of RBW should be less than the minimum difference between two frequencies being observed**.

For information, Figure 15 shows the influence of RBW when differentiating between two sinusoidal signals of 10.001MHz and 10.0005MHz and with the same amplitude (Δf = 500Hz). The analysis is carried out with SPAN constant at 10kHz.



RBW = 1kHz RBW = 300Hz RBW = 100Hz

Figure 15: *Influence of "RBW" setting*

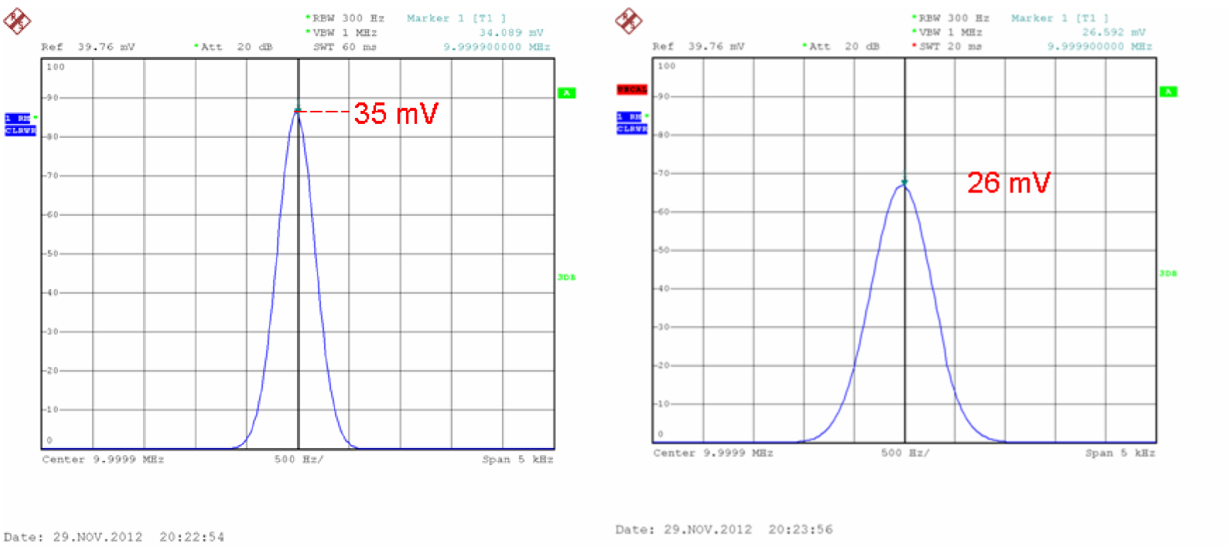
Clearly, the lower the RBW the better the resolution will be, but also the longer the sweep time will be. This compromise has to be adjusted using the "SWEEP TIME" parameter.

- ***"SWEEP TIME" setting***

The characteristics of the VCO are as follows: $F = (F_0 + 1MHz) + aU$ with $F_0 = 100MHz$ and $a = 0.2 MHz / V$, the frequency of the signal e(t) remains unchanged.

Question 21: Show the curve of signals E, H and G over a period $T_g = 1/F_g$ of the sawtooth generator. Obviously it is advantageous to obtain the spectrum as quickly as possible, so in principle it is best to take a short T_g (SWEEP TIME). In practice, the narrower the bandwidth F_0 / Q of the bandpass filter (RBW), the greater the value of T_g, try and explain why.

For information, Figure 16 shows the influence of sweep time on the spectrum of a sinusoidal signal of amplitude 100mVpp (V_{eff} = 35mV) and frequency 10MHz.



SWT = 60ms
RBW = 300Hz
Here we measure the expected value.

SWT = 20ms
RBW = 300Hz
Here we do not measure the expected value. The instrument shows **"UNCAL"**

Figure 16: *Influence of "SWEEP TIME" setting*

REMEMBER: It is important to remember that a spectrum analyzer determining the spectrum of analog signals (representation of frequency) works on the principle of heterodyning (technique which consists in using multiplication to transfer to a voltage controlled oscillator (VCO) the frequencies of the signal being observed in the bandwidth of a bandpass filter with a fixed center frequency). The main parameters are: vertical settings for amplitude (in voltage or power) and horizontal settings (SPAN, CENTER FREQUENCY, RBW, SWEEP TIME) which should be fully understood in order to carry out a useful interpretation of the resulting spectrum.

IV- Applied exercise *(taken from an S3 exam paper)*

Q1- What is the power contained in each line of the signal for which the spectrum is plotted in Figure 1 ?

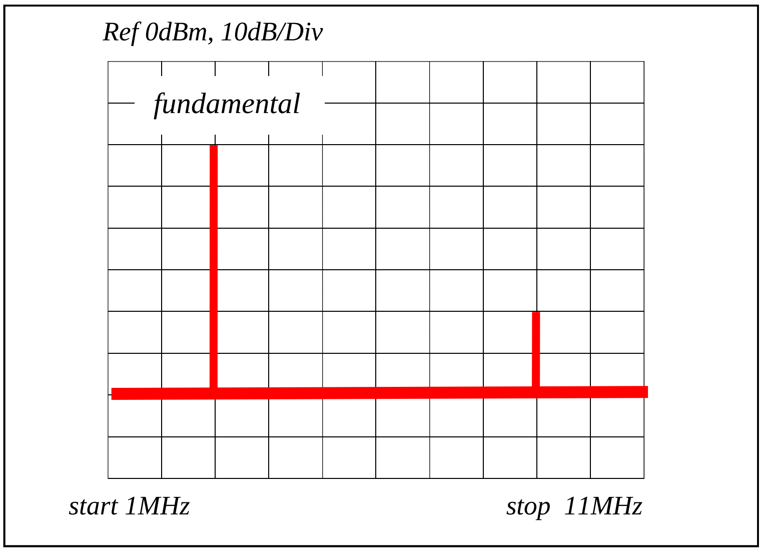


Figure 1: *Signal spectrum*

Q2- Deduce the effective value U_{eff} and peak value U_C of the fundamental given that the input impedance of the spectrum analyzer is 50Ω.

Q3- Calculate the distortion factor *D* of the signal (in %).

Q4- A spectrum analyzer is attacked by the following signal: $e(t) = 2.cos(2\pi.10^4 t) + 3.cos(2\pi.10{,}1.10^3 t)$

Q4-a) Review what the "*RBW*" function represents in a spectrum analyzer.

Q4-b) Give the value, with justification, of the *RBW* when observing two separate peaks on the spectrum analyzer screen.