Semester S1

Basics of active and non-linear electronics

RF POWER AMPLIFIERS

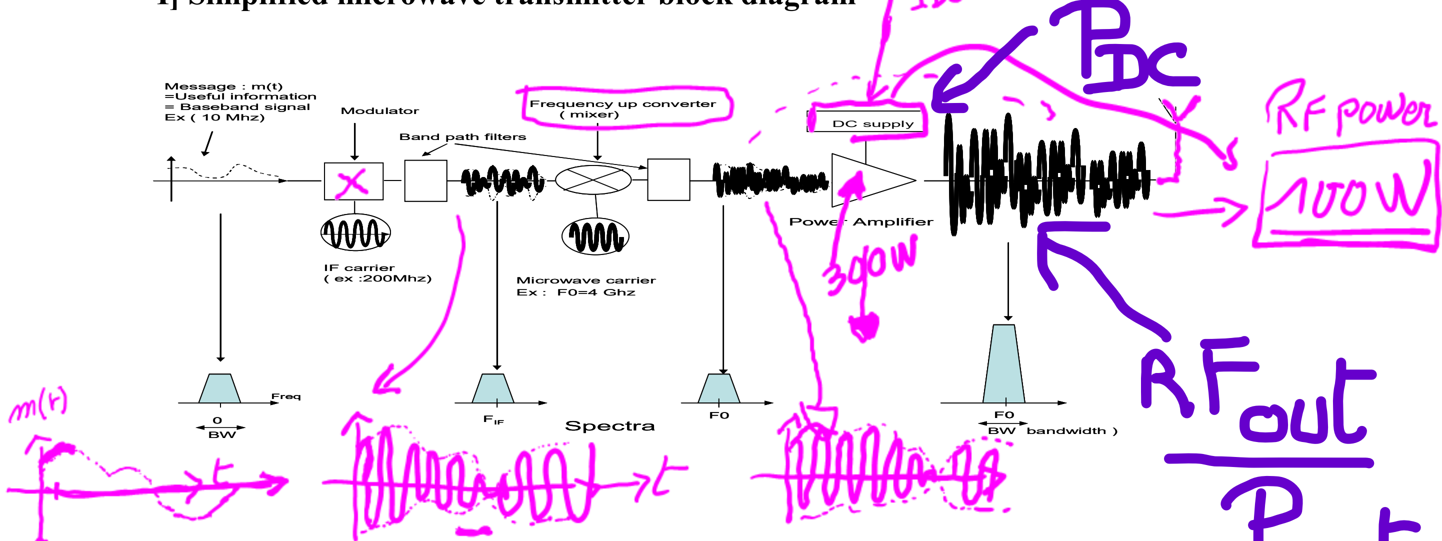
(J -M NEBUS)
nebus@xlim.fr.

Chapter I : General Presentation (1)

Summary N°1

I] Simplified microwave transmitter block diagram

V_{DC} 40V, I_{DC} 10A } $P_{DC} = 400W$



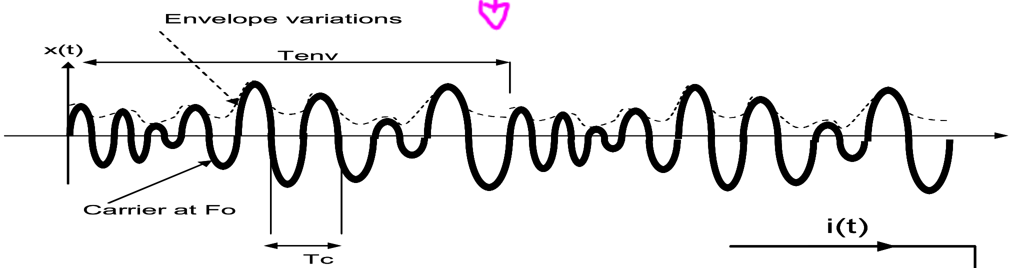
The main required performances for the Power amplifier (PA) are :

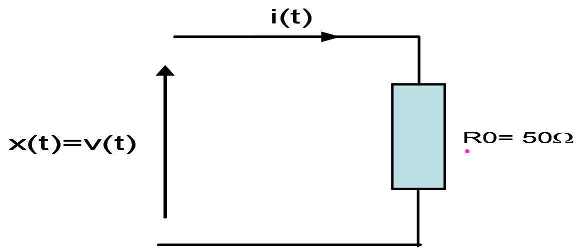
- Maximum energy efficiency, which is the ration between the output RF power and the DC power provided by the DC supply → $\eta = \frac{100W}{400W} = 25\%$
- No significant distortion of the shape of the amplified signal at the RF output (no distortion of the useful signal)

II) Main signal characteristics

a) Time domain waveform of the signal at the power amplifier input

$$x(t) = A(t).\cos(wot + \varphi(t))$$





b) Instantaneous and average powers

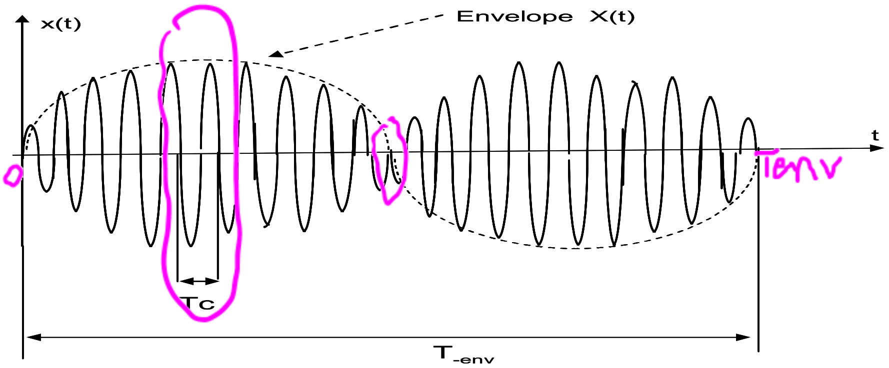
Instantaneous power — Average power

$$p(t)=v(t)\cdot i(t)=\frac{v(t)^2}{R0} \qquad P_{av}=\frac{1}{T}\int_0^T p(t)\cdot dt$$

c) Simple signal example

$$x(t)=A\cdot\cos(\Omega t)\cdot\cos(wot)=X(t)\cdot\cos(wot)$$ is the RF signal

$$X(t)=A\cdot\cos(\Omega t)$$ is the envelope signal



The average power of the RF signal is :

$$\cos^2(x) = \frac{1}{2}+\frac{1}{2}\cos(2x)$$

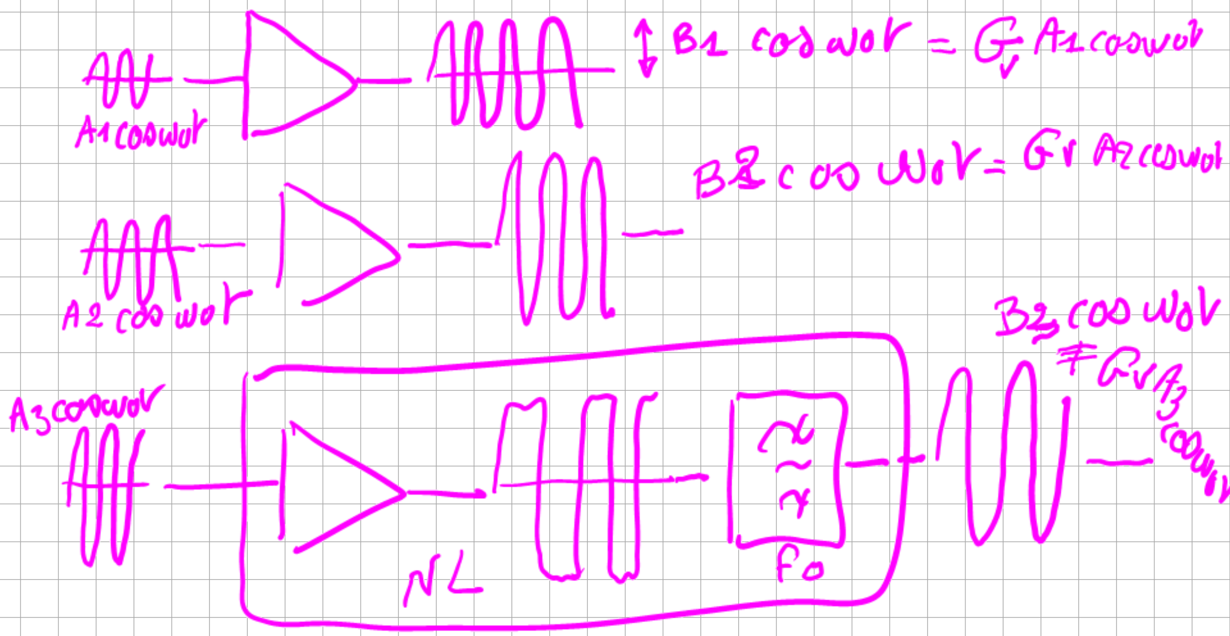
$$P_{av-RF}=\frac{1}{R0\cdot Tenv}\int_0^{Tenv}(A\cdot\cos(\Omega t).\cos(wot))^2 dt=\boxed{\frac{A^2}{4.R0}}$$

$$A^2\left(\frac{1}{2}+\frac{1}{2}\cos 2\Omega t\right) \times\left(\frac{1}{2}+\frac{1}{2}\cos 2wot\right)$$

The peak power of the RF signal is obtained when cos(Ωt)=1

$$P_{peak-RF}=\frac{1}{R0\cdot Tc}\int_0^{Tc}(A\cdot\cos(wot))^2 dt=\boxed{\frac{A^2}{2.R0}}$$

$$\frac{A^2}{2}+\frac{A^2}{2}\cos 2wot.$$


A1 cos w0t
B1 cos w0t = Gv A1 cos w0t
A2 cos w0t
B2 cos w0t = Gv A2 cos w0t
A3 cos w0t
NL
f0
B3 cos w0t ≠ Gv A3 cos w0t

The peak to average power ratio (PAPR) of the RF signal is

$$PAPR=\frac{P_{peak-RF}}{P_{Av-RF}}=2 \qquad 10\log(PAPR)=3dB$$

The instantaneous envelope power is defined as

$x(t) = A\cos\Omega t$

$i(t)$ $50\,\Omega$ $v(t)$

$$P_{env}(t)=\frac{(X(t))^2}{R0}=\frac{(A\cdot\cos(\Omega t))^2}{R0}$$

The average envelope power is

$$P_{av-env}=\frac{1}{R0\cdot Tenv}\int_0^{Tenv}(A\cdot\cos(\Omega t))^2dt=\frac{A^2}{2R0}$$

The peak power of the envelope is obtained when cos(Ωt)=1

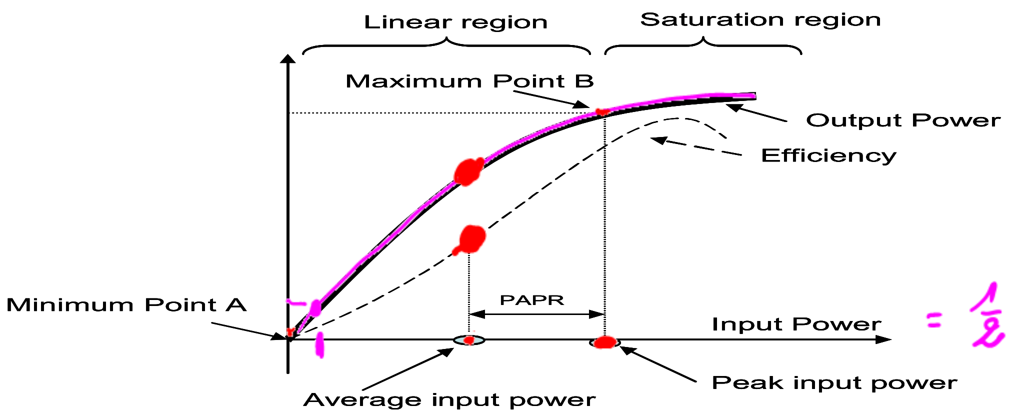
$$P_{peak-env}(t)=\max(P_{env}(t))=\frac{A^2}{R0}$$

Here again the PAPR of the envelope signal is equal to 2

We have the relationships :

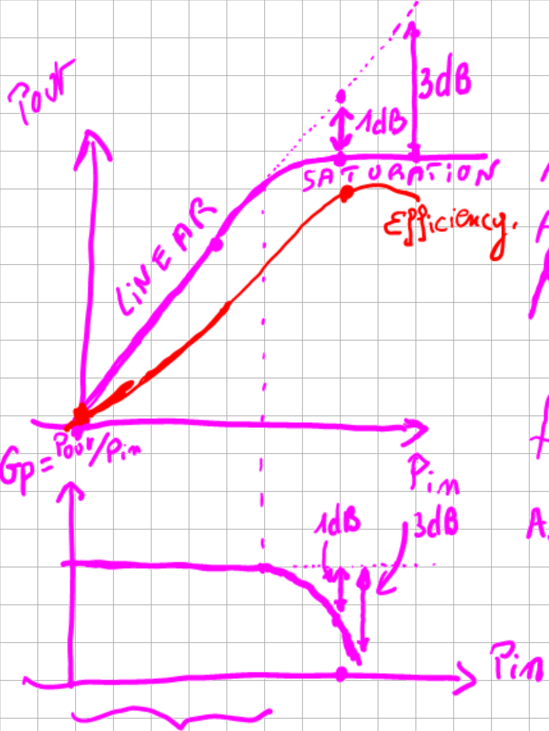
$$P_{av-RF}=\frac{P_{av-env}}{2} \qquad P_{peak-RF}=\frac{P_{peak-env}}{2}$$

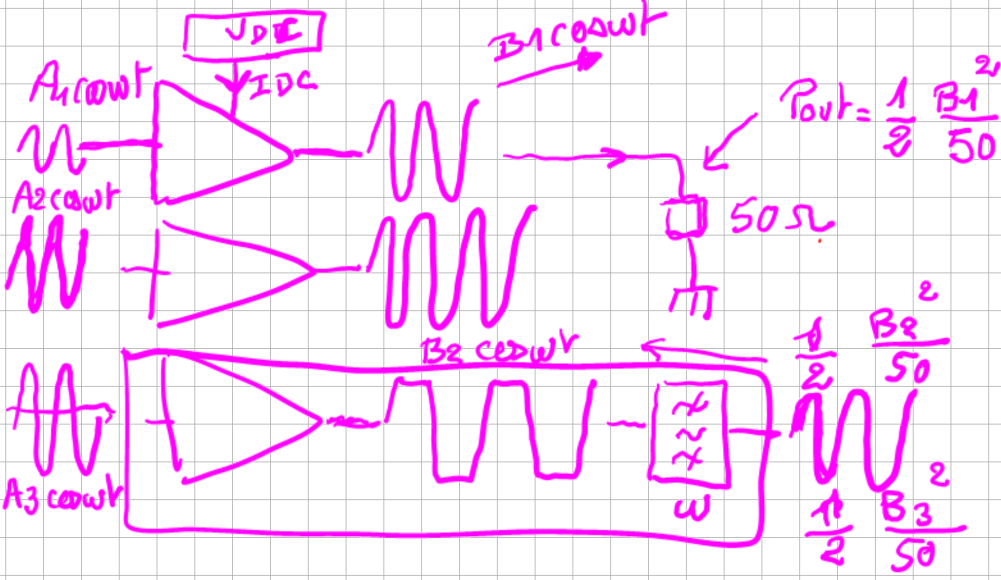
III) Power amplifiers driven by modulated signals



$= \frac{1}{2}\frac{(B)^2}{R_0}$

$= \frac{1}{2}\frac{(A)^2}{R_0}$

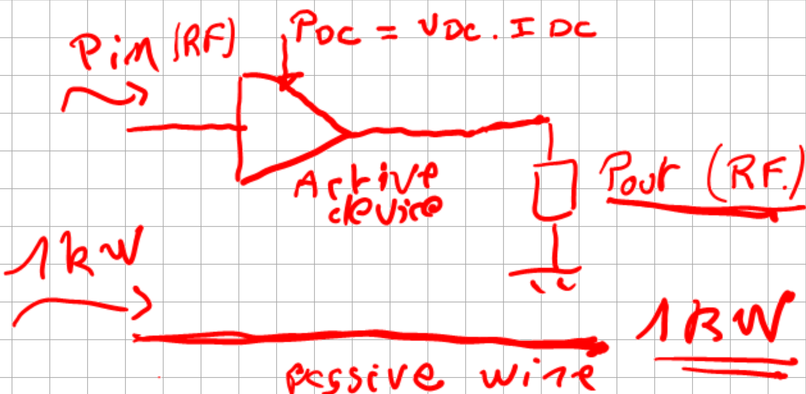


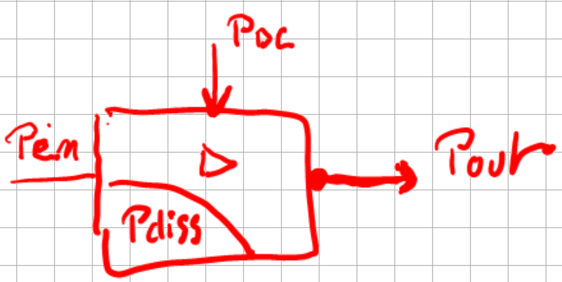


$$\underbrace{\text{efficiency} = \frac{P_{out}}{P_{DC}}}$$

$$\boxed{PAE = \frac{P_{out} - P_{in}}{P_{DC}}}$$

Power added efficiency.





$$P_{in} + P_{DC} = P_{out} + P_{diss}$$

$$P_{diss} = P_{in} + P_{DC} - P_{out}$$

$$= P_{DC}\left(1 - \frac{P_{out} - P_{in}}{P_{DC}}\right) = P_{DC}\,(1 - PAE)$$

Operation in the linear region is required in order to get and amplified modulated signal without any significant distortions

Average output power level is lower than the maximum saturated power that the power amplifier can achieve. In a same manner, the average efficiency is lower than the maximum value of efficiency.

When the PA is driven by an input modulated signal it operates dynamically between points A and B and has a quite complex behaviour

For the non-linear analysis and design procedure a static constant wave approach will be followed and explained during the following courses.

IV) Main Power amplifier specifications and conclusion

Main specifications

- Frequency bandwidth, Power gain and gain flatness , Group delay
- Input and output RF powers , DC consumption and power added efficiency
- Different Linearity figures of Merit → Intermodulation.

Conclusion :

Illustration of the quasi static analysis approach shown and explained during the next courses

Summary N°2

IV) Main Power amplifier specifications and conclusion

a) Quasi Static approach for the analysis

The behaviour of the amplifier is characterised in a steady state regime.

A purely sine wave signal (Continuous wave (CW) signals) is applied at the RF input of the power amplifier.

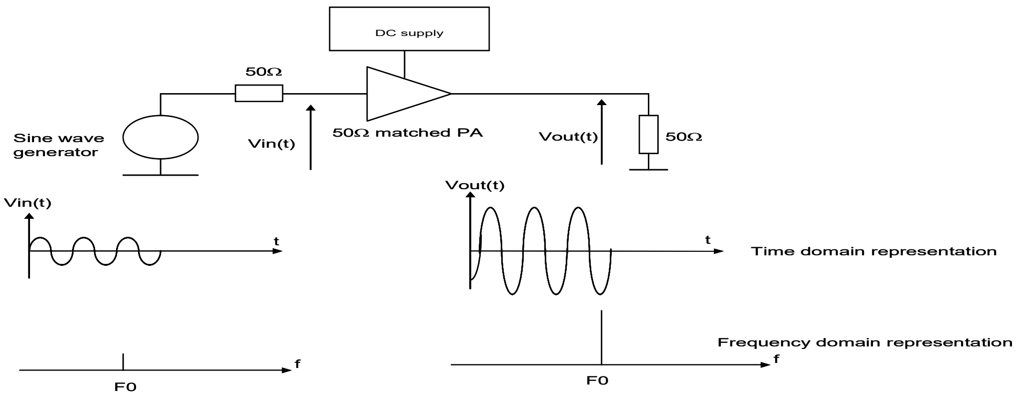
The frequency of the signal is fixed at the centre frequency of the bandwidth and the power level is swept from low level up to the maximum level until the amplifier reaches the saturation regime.

Then the frequency of the signal can be swept to analyse the behaviour of the amplifier over the required frequency bandwidth and to check that there is not a lot of frequency dispersion of the power characteristics.

b) Small signal analysis (linear behaviour)

A low-level sine wave signal drives the RF input of the power amplifier ensuring that it operates in its linear regime. The frequency of the signal is set at the center frequency of the frequency bandwidth and both the magnitude and phase shift of the output RF signal are analysed .

Then the procedure is repeated for several frequencies (F1 , F2,……) covering the frequency bandwidth (Fmin- Fmax) required and keeping always a low level to have a linear behaviour of the amplifier .



For three different frequencies we have :

$$V\text{in}_0(t) = A.\cos(w_0 t) \qquad Vout_0(t) = B_0.\cos(w_0(t-\tau_0)) = B.\cos(w_0 t + \varphi_0) = B.\cos(2\pi f_0 t - 2\pi f_0 \tau_0)$$
$$V\text{in}_1(t) = A.\cos(w_1 t) \qquad Vout_1(t) = B_1.\cos(w_1(t-\tau_1)) = B.\cos(w_1 t + \varphi_1) = B.\cos(2\pi f_1 t - 2\pi f_1 \tau_1)$$
$$V\text{in}_2(t) = A.\cos(w_2 t) \qquad Vout_2(t) = B_2.\cos(w_2(t-\tau_2)) = B.\cos(w_2 t + \varphi_2) = B.\cos(2\pi f_2 t - 2\pi f_2 \tau_2)$$

The input RF power is fixed to

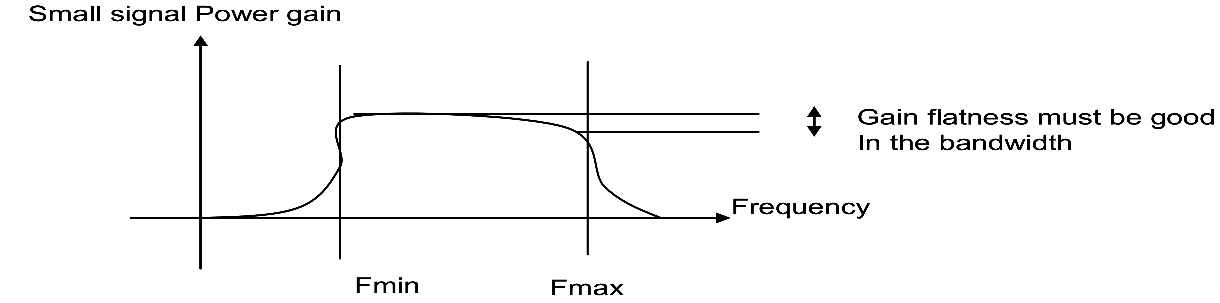
$$Pin = \frac{A^2}{2R_0}$$

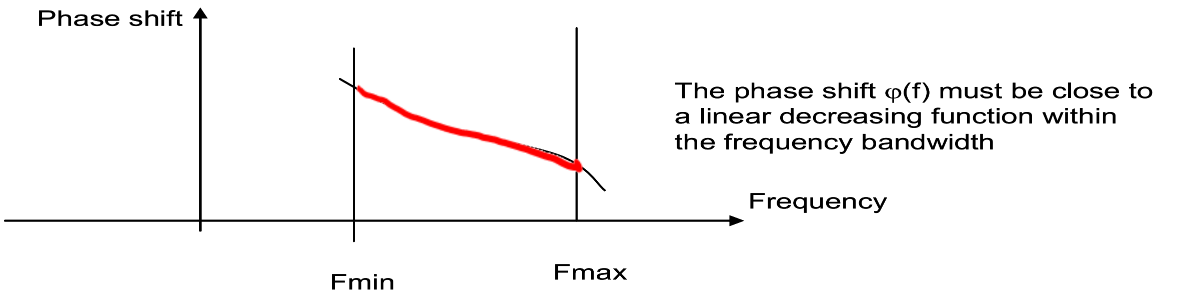
If the output power is not exactly the same for the different frequencies we have not an ideal gain flatness versus frequency.

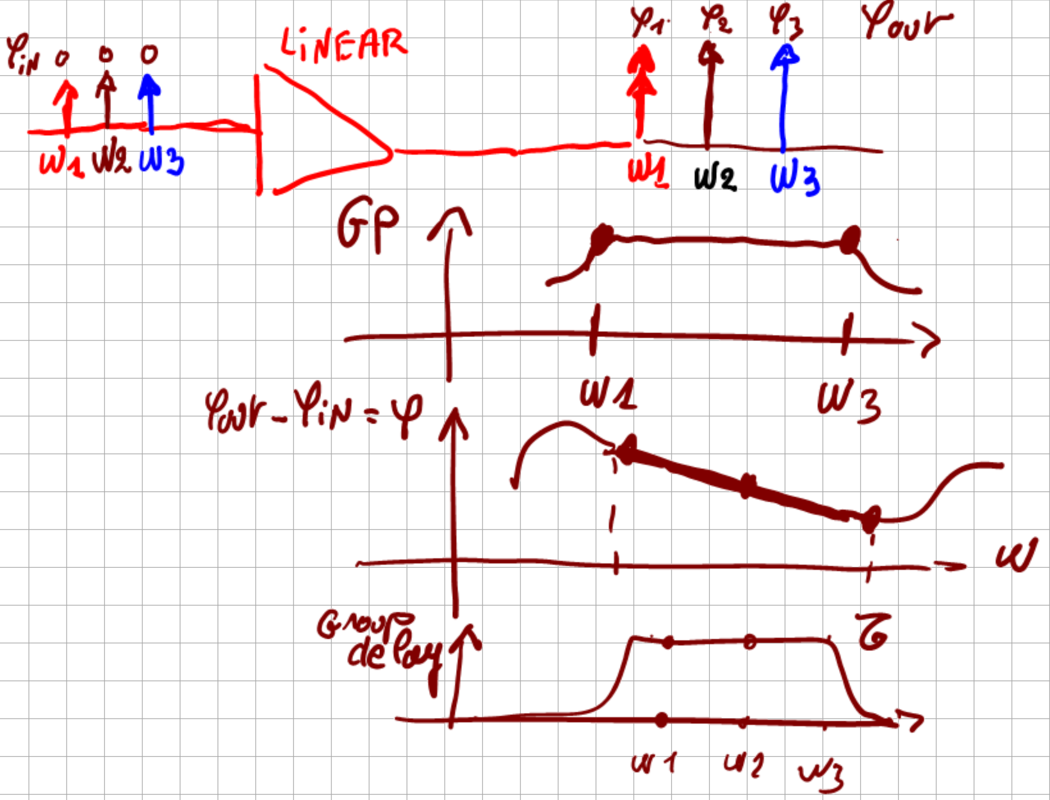
$$Pout_0 = \frac{B_0^2}{2R_0} \qquad Pout_1 = \frac{B_1^2}{2R_0} \qquad Pout_2 = \frac{B_2^2}{2R_0}$$

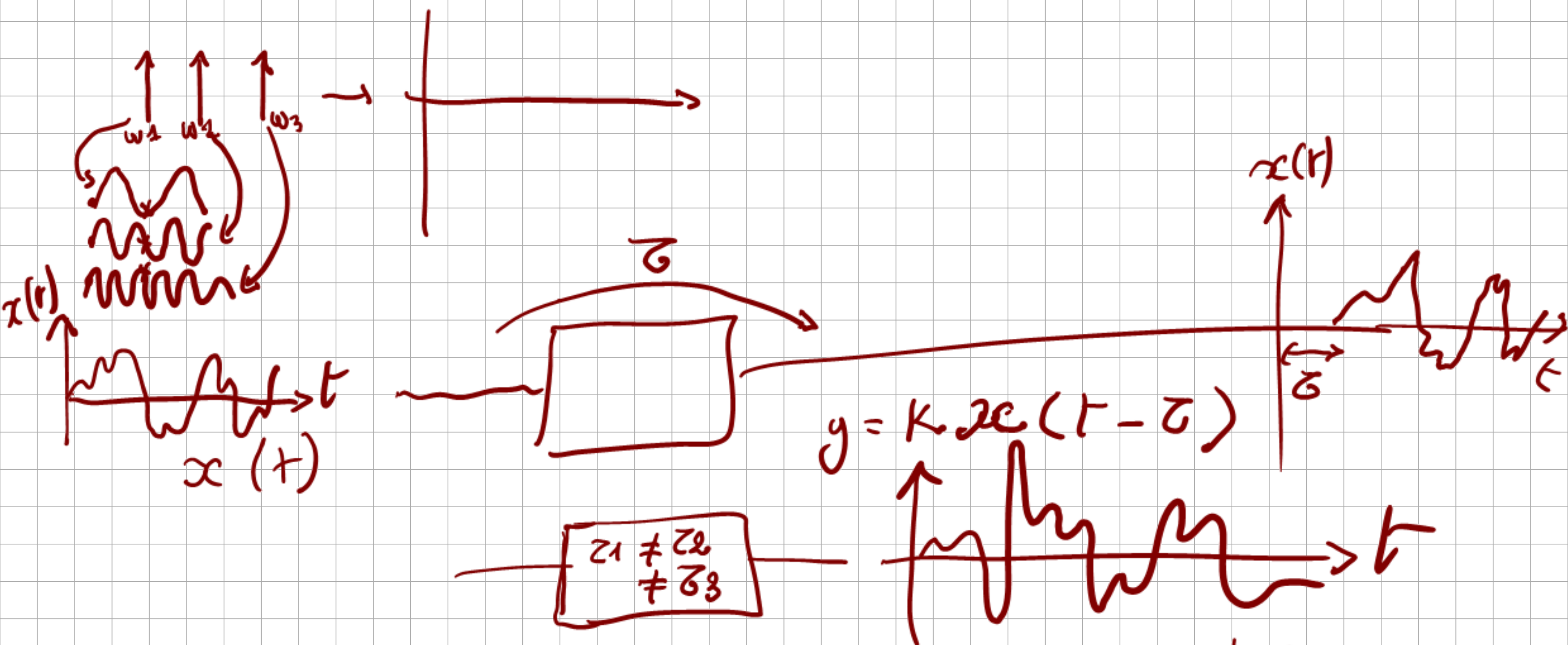
$$Gp_0 = \frac{B_0^2}{A^2} \qquad Gp_1 = \frac{B_1^2}{A^2} \qquad Gp_2 = \frac{B_2^2}{A^2}$$

If the phase shift φ (respectively φ0 , φ1 , φ2) is not a linear decreasing function versus frequency the time delay τ is not constant (τ0 , τ1 , τ2 are not equal).









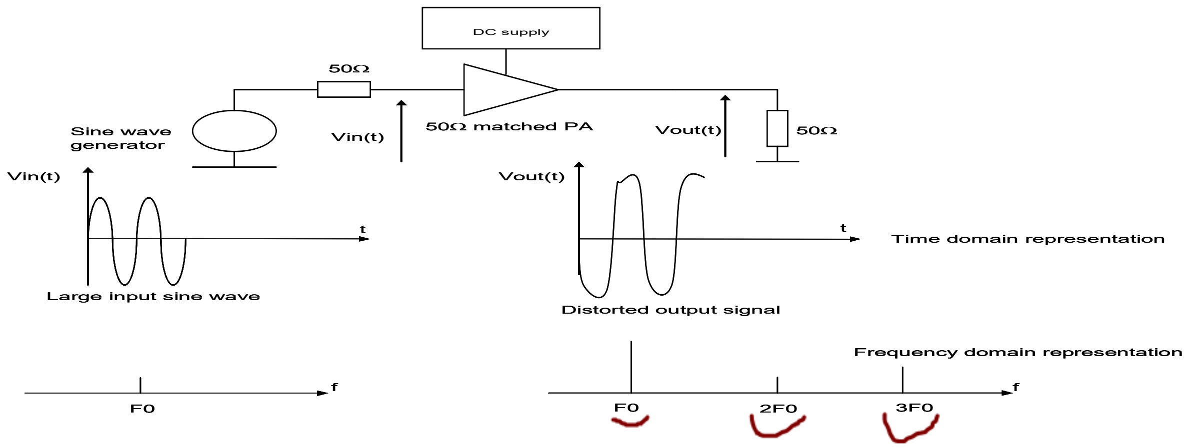
Linear - distorsion

If the gain flatness is very good and the time delay τ which is the derivative of the phase shift φ versus frequency is constant over the entire frequency bandwidth there will be no linear distortion of any modulated signal travelling across the amplifier. Otherwise, the signal can be distorted but the distortion does not depend on the power level of the signal. It depends on the frequency dispersion of the transfer function of the amplifier .That is the reason why it is commonly called linear distortion.

c) Large signal analysis (non-linear behaviour)

If the magnitude of the input sine wave signal is increased a lot , the power amplifier operates in a non-linear regime and the output signal is distorted . Clipping occurs.

The output signal can be expressed in terms of Fourier serie expansion and harmonic components of the fundamental operating frequency appear in the output signal spectrum.

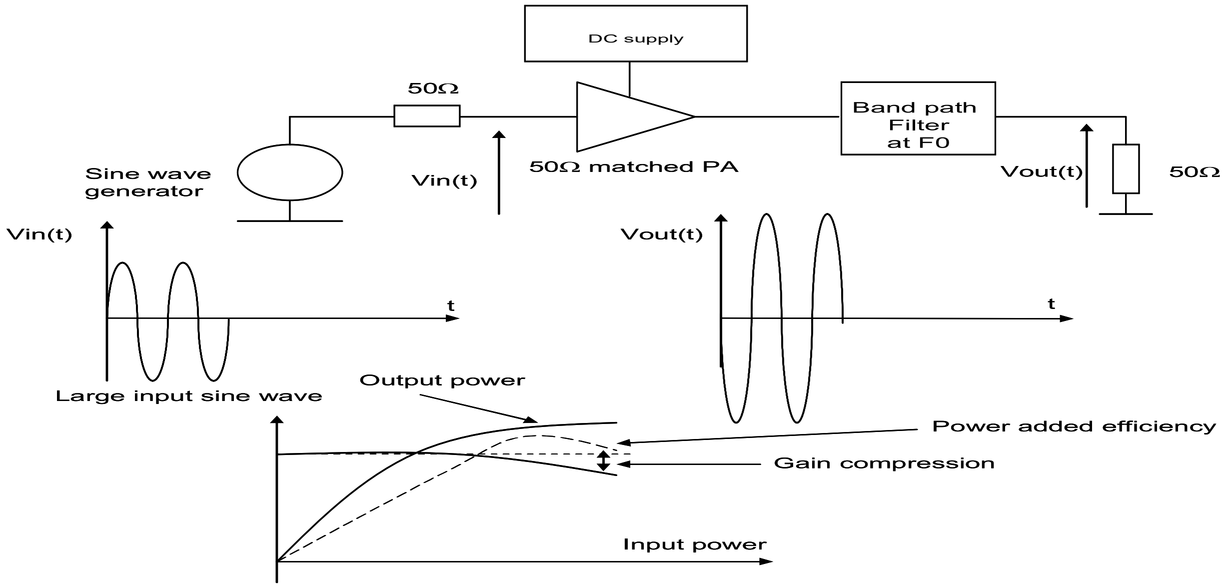


If a band path filter is connected at the output of the power amplifier, harmonic components are removed.

The relationship between the input signal at F0 and the output signal at F0 is the describing function of the non-linearity at the fundamental frequency for an input sine wave.

Now if a power sweep of the signal is applied at the PA input, the power of the output signal increases linearly at low and medium power levels but it does not increase linearly at high power level .

Consequently, the power gain does not remain constant and gain compression occurs indicating the saturation regime of the power amplifier.



The gain compression is also called the AM/AM conversion.

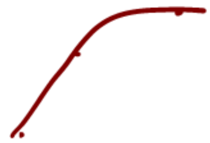
We can also note that in the non-linear region there is a variation of the phase shift of the output signal versus the magnitude of the input signal, which is commonly called AM/PM conversion.

In the presence of these non-linear characteristics, the output signal is distorted and distortions are non-linear distortions.

For any amplifier, it it important to check that there is no significant frequency dispersion of these curves when the frequency of the input sine wave is varied from Fmin to Fmax

Note that when the amplifier is driven simultaneously with 2 tones (2 microwave sine wave signals at different frequencies with frequency spacing of few tens of MHZ for example) intermodulation products appear in the output signal spectrum . This point will be studied in a training exercise session.

$$x(t) = A\cos\omega_0 t \;\longrightarrow\; \boxed{N\text{-}L \,\Big|\, f_0} \;\longrightarrow\; y(t) = B\cos\omega t$$



$$y(t) = a\,x(t) + b\,x(t)^2 - c\,x(t)^3$$

$$x(t) = A\cos\omega t$$

$$y(t) = aA\cos\omega t + bA^2\left(\frac{1}{2} + \frac{1}{2}\cos 2\omega t\right) - cA^3\left(\frac{3}{4}\cos\omega t + \frac{1}{4}\cos 3\omega t\right)$$

$$\cos^3 x = \frac{3}{4}\cos x + \frac{1}{4}\cos 3x$$

$$y(t) = \frac{bA^2}{2} + \left(aA - \frac{3}{4}cA^3\right)\cos(\omega t) + \frac{bA^2}{2}\cos 2\omega t - \left(\frac{cA^3}{4}\right)\cos 3\omega t$$

$$x(t) = A\cos\omega t \;\longrightarrow\; \boxed{NL \,\Big|\, \tilde{x}} \;\longrightarrow\; \left(aA - \frac{3}{4}cA^3\right)\cos\omega t$$

$$x(t) = A(t)\cos\omega_0 t \;\longrightarrow\; \boxed{NL \,\Big|\, \tilde{x}} \;\longrightarrow\; \left(aA(t) - \frac{3}{4}cA(t)^3\right)\cos\omega t$$

$$x(t) = \cos\Omega t\,\cos\omega_0 t$$

$$\left[aA\cos\Omega t - \frac{3}{4}cA^3\left(\frac{3}{4}\cos\Omega t + \frac{1}{4}\cos 3\Omega t\right)\right] \times \cos\omega t$$