Diseño de Amplificadores Operacionales Integrados
Parte I

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Rev 1.0

Diseño de Circuitos Integrados

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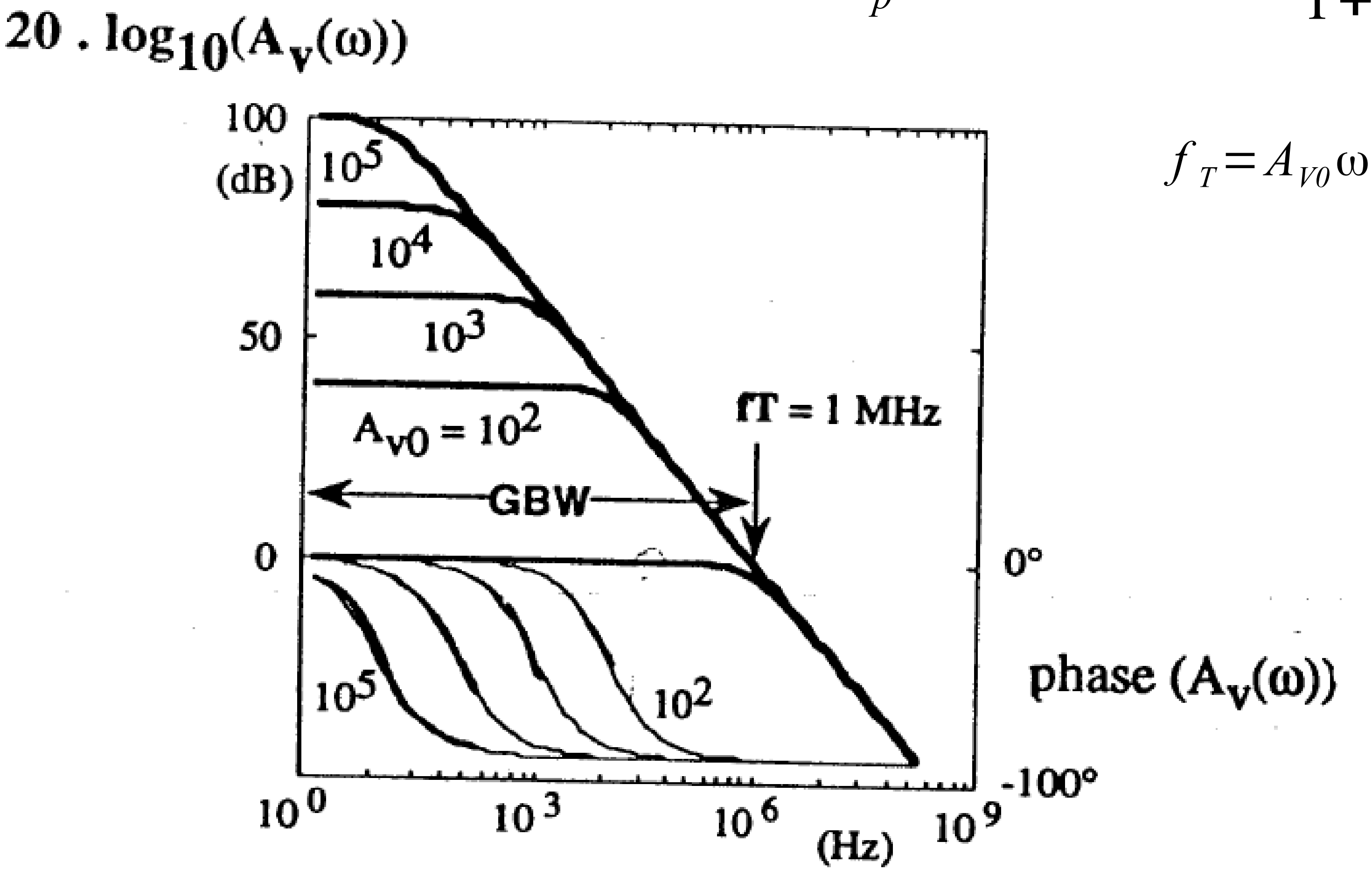
Indice

Sistemas de 1er orden (I)

Lazo Abierto: $A_V(\omega)=\dfrac{A_{V0}}{1+j\dfrac{\omega}{\omega_p}} \Rightarrow A_V(\omega)=\dfrac{A_{V0}}{1+j\dfrac{\omega A_{V0}}{\omega_T}}$



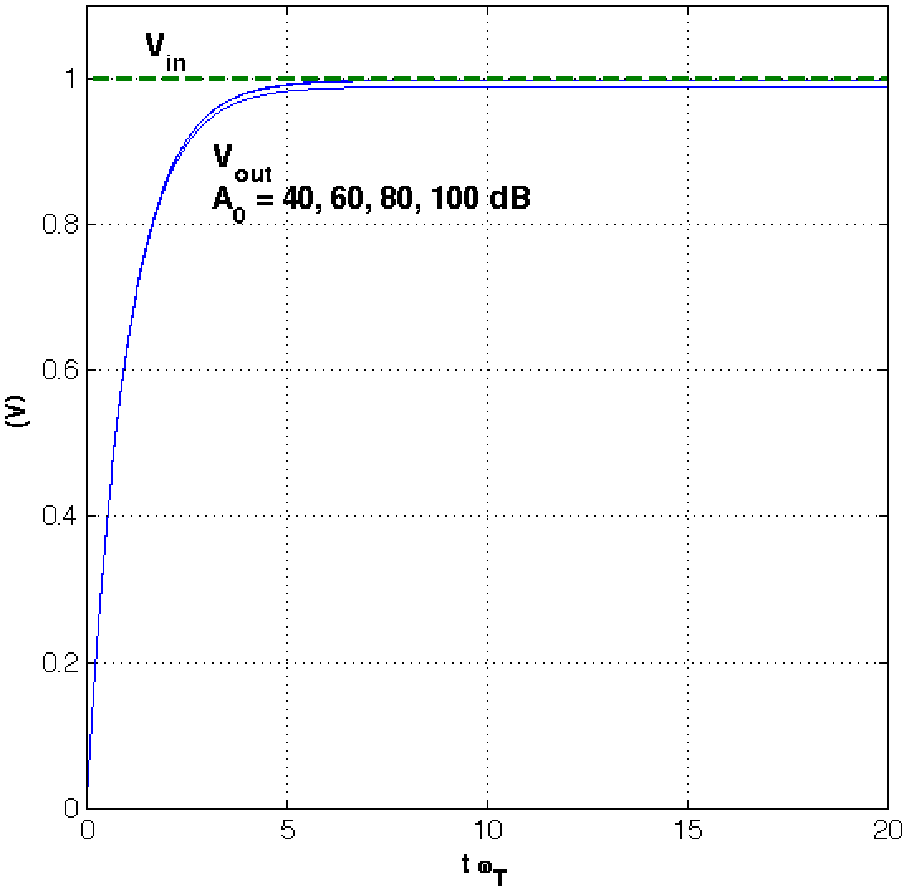
$$f_T=A_{V0}\omega_p=GBW$$

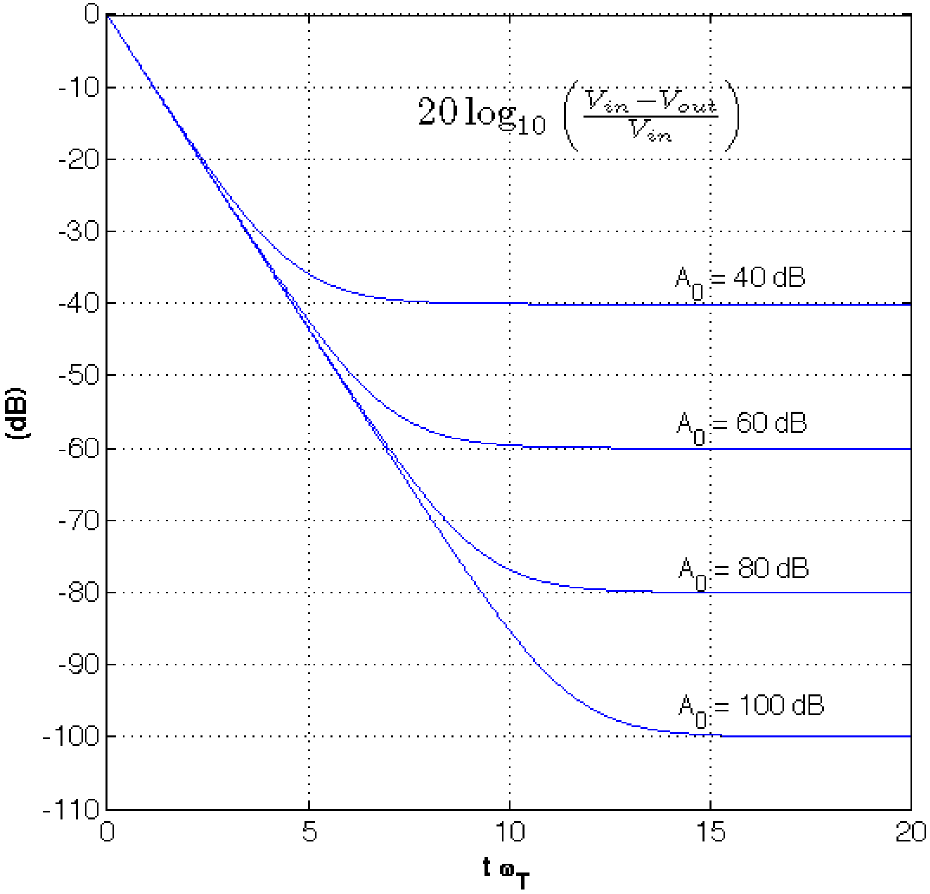
Sistemas de 1er orden (II)

Lazo Cerrado: $H(\omega) = \dfrac{A_V(\omega)}{1 + A_V(\omega)}$

Realimentación
Unitaria

Respuesta al escalón:
Dos formas de verlo





Sistemas de 2do orden (I)

Transferencia en Lazo Abierto:

$$A(\omega)=\frac{A_0}{\left(1+j\frac{\omega}{\omega_{dp}}\right)\left(1+j\frac{\omega}{\omega_{ndp}}\right)}$$

Polo no dominante

Polo dominante

Producto Ganacia por Ancho de Banda:

$$GBW=A_0\,\omega_{dp}$$

Posición relativa del polo no dominante:

$$NDP=\frac{\omega_{ndp}}{GBW}$$

$$A(\omega)=\frac{A_0}{\left(1+j\frac{\omega\,A_0}{GBW}\right)\left(1+j\frac{\omega}{NDP\,GBW}\right)}$$

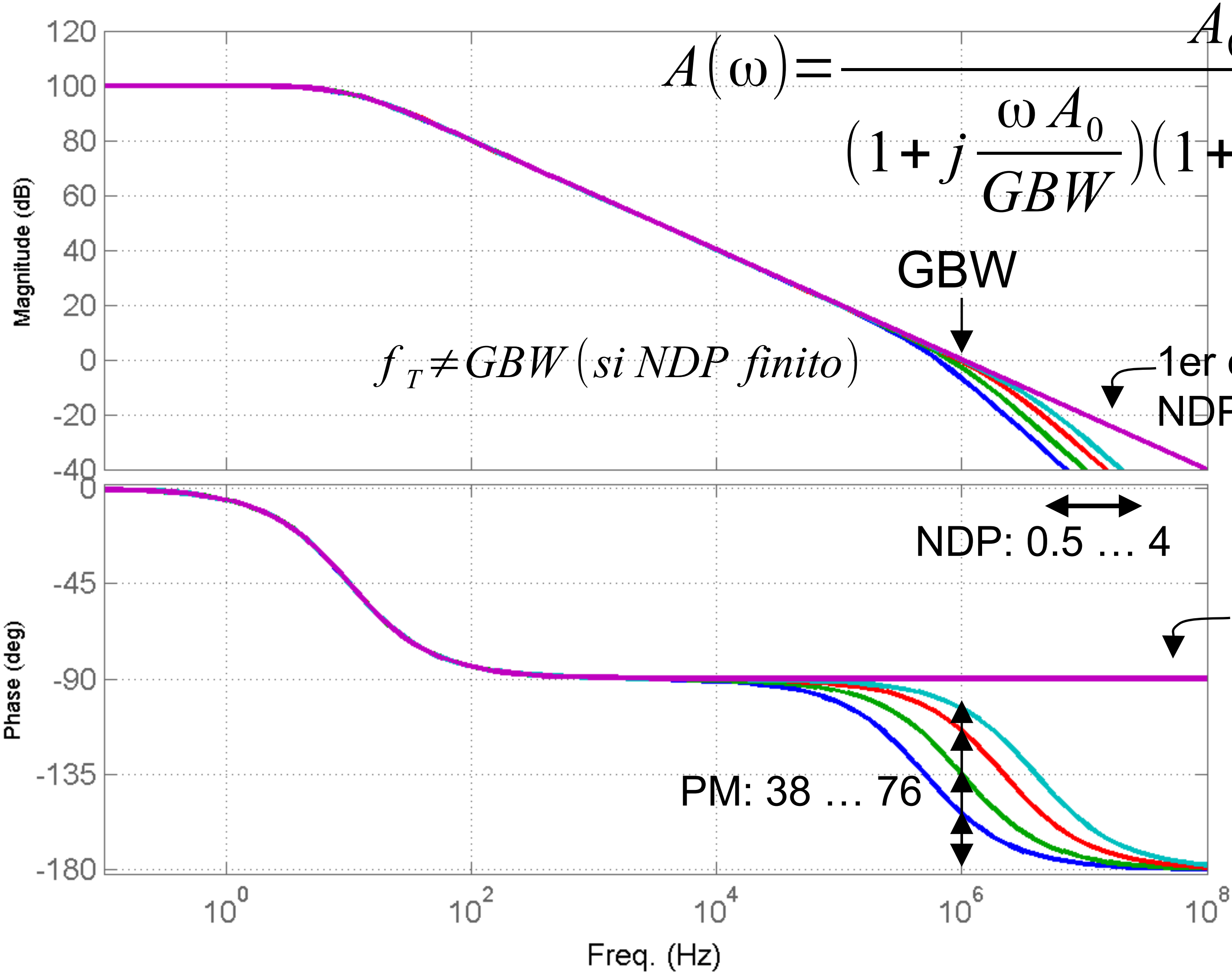
Sistemas de 2do orden (I)

Lazo Abierto:

$$A(\omega)=\frac{A_0}{\left(1+j\frac{\omega A_0}{GBW}\right)\left(1+j\frac{\omega}{NDP\,GBW}\right)}$$

$$GBW=A_0\,\omega_{dp}$$

$$NDP=\frac{\omega_{ndp}}{GBW}$$



GBW

$f_T \neq GBW$ (si NDP finito)

1er ord.
NDP=∞

NDP: 0.5 … 4

1er ord.
PM=90

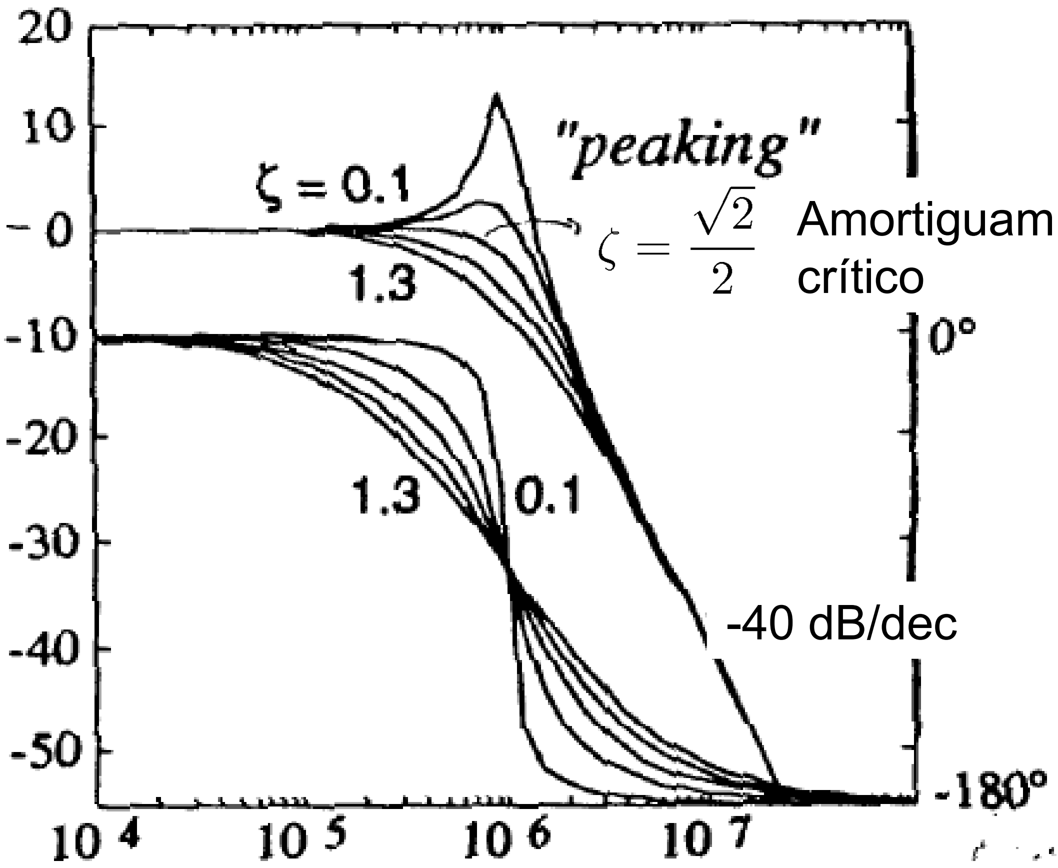
PM: 38 … 76

Sistemas de 2do orden (II)

Lazo Cerado:

$$A(\omega) = \frac{1}{1 + \jmath 2\zeta \frac{\omega}{\omega_n} + (\jmath \frac{\omega}{\omega_n})^2}$$

Bode:



$\zeta = \frac{\sqrt{2}}{2}$ Amortiguamiento crítico

-40 dB/dec

$$\zeta = \frac{\sqrt{NDP}}{2}$$

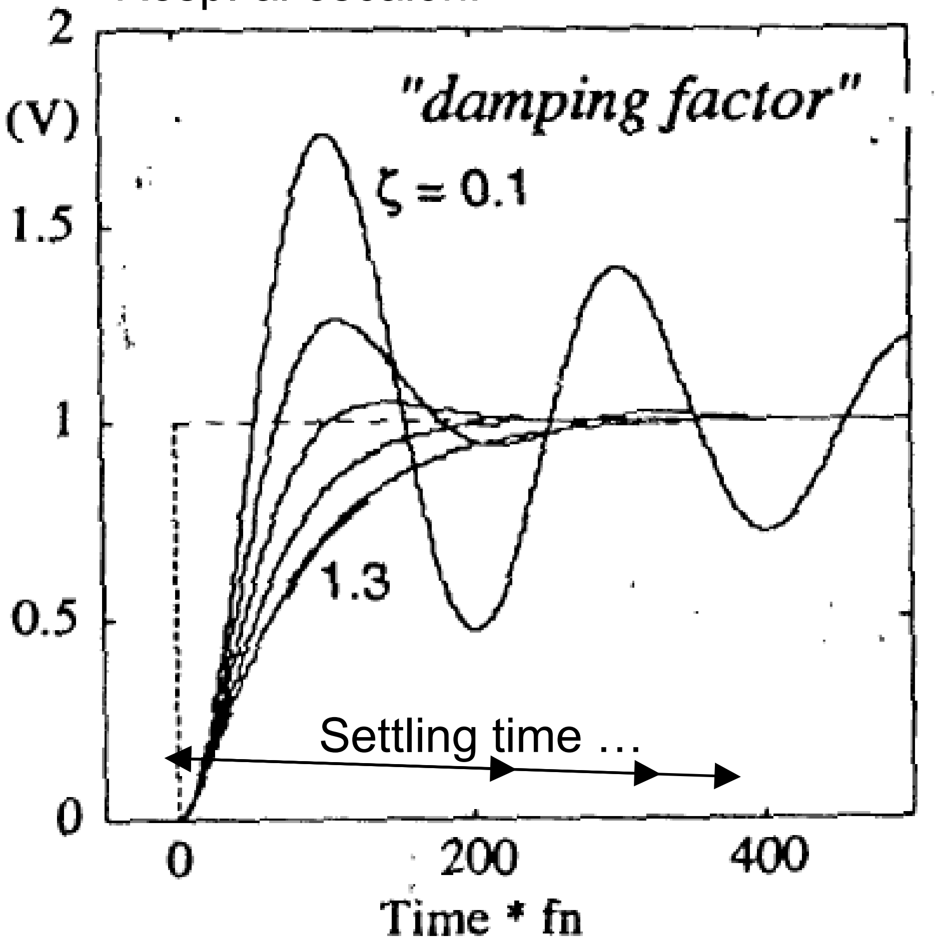
$$\omega_n = GBW\sqrt{NDP}$$

Sistemas de 2do orden (II)

Lazo Cerado:

$$A(\omega) = \frac{1}{1 + \jmath 2\zeta \frac{\omega}{\omega_n} + (\jmath \frac{\omega}{\omega_n})^2}$$

Resp. al escalón:



$$\zeta = \frac{\sqrt{NDP}}{2}$$

$$\omega_n = GBW\sqrt{NDP}$$

Sistemas de 2do orden (III)

NDP	PM (º)	ζ	Peaking (dB)	Sobre Tiro (%)	Sett. Time x GBW	
					err: 5%	err: 1%
0.5	38.7	0.35	3.6	30.5	11.2	16.3
1	51.8	0.5	1.25	16.3	5.3	8.8
2	65.5	0.71	0	4.3	2.1	4.7
2.2	67.3	0.74	-	3.1	2.1	4.5
4	76.3	1	-	0	2.4	3.3
Inf	90	inf	-	0	3.0	4.6

1er ord.

Open Loop

Closed Loop

Sistemas de 2do orden (III)

Amortiguamiento crítico:

NDP	PM (º)	ζ	Peaking (dB)	Sobre Tiro (%)	Sett. Time x GBW	
					err: 5%	err: 1%
0.5	38.7	0.35	3.6	30.5	11.2	16.3
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4	76.3	1	-	0	2.4	3.3
Inf	90	inf	-	0	3.0	4.6

1er ord.

Open Loop

Closed Loop

Sistemas de 2do orden (III)

Elección usual de diseño:

NDP	PM (º)	ζ	Peaking (dB)	Sobre Tiro (%)	Sett. Time x GBW	
					err: 5%	err: 1%
0.5	38.7	0.35	3.6	30.5	11.2	16.3
1	51.8	0.5	1.25	16.3	5.3	8.8
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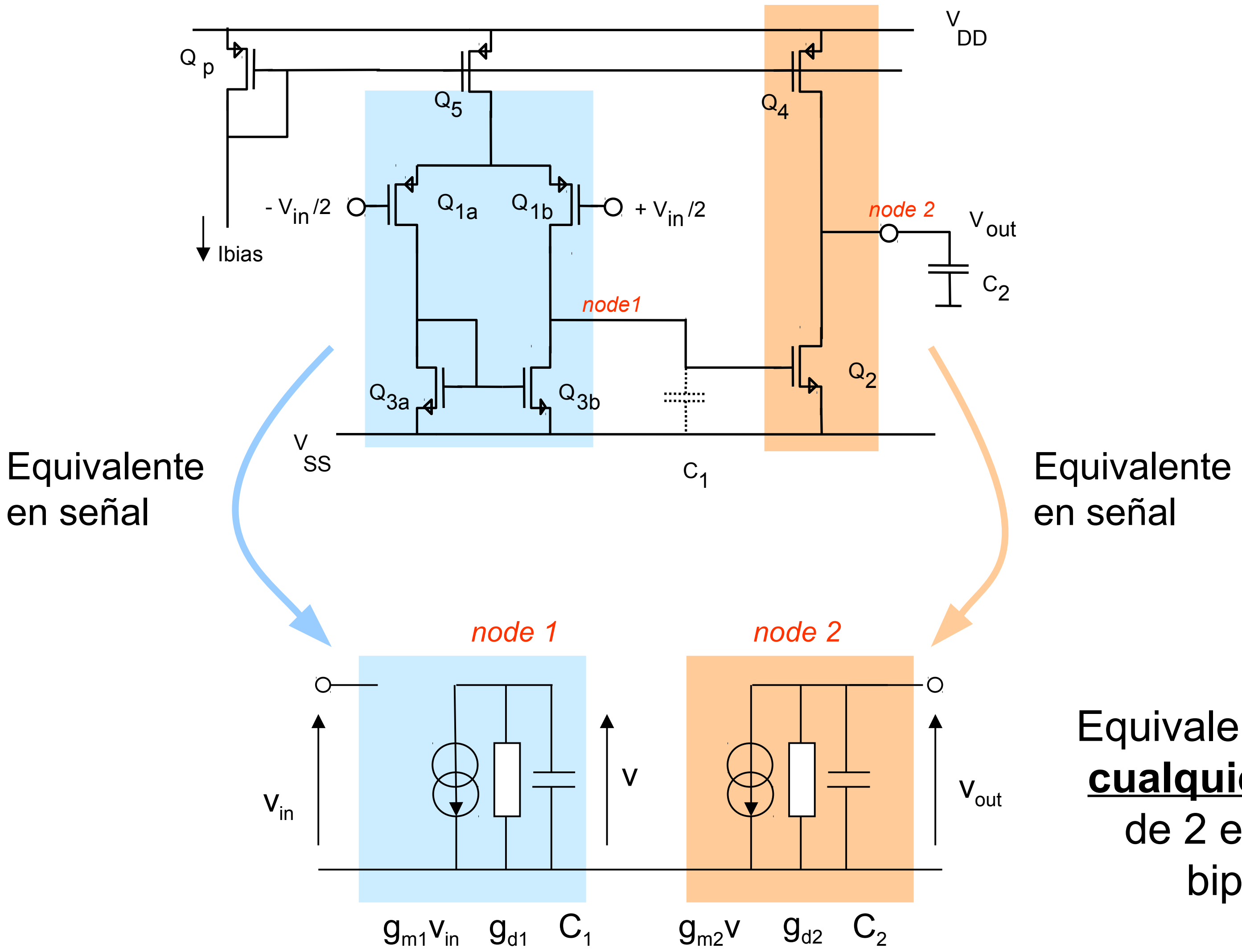
Inf	90	inf	-	0	3.0	4.6

1er ord.

Open Loop

Closed Loop

Amplificador 2 etapas: Amplificador MOS

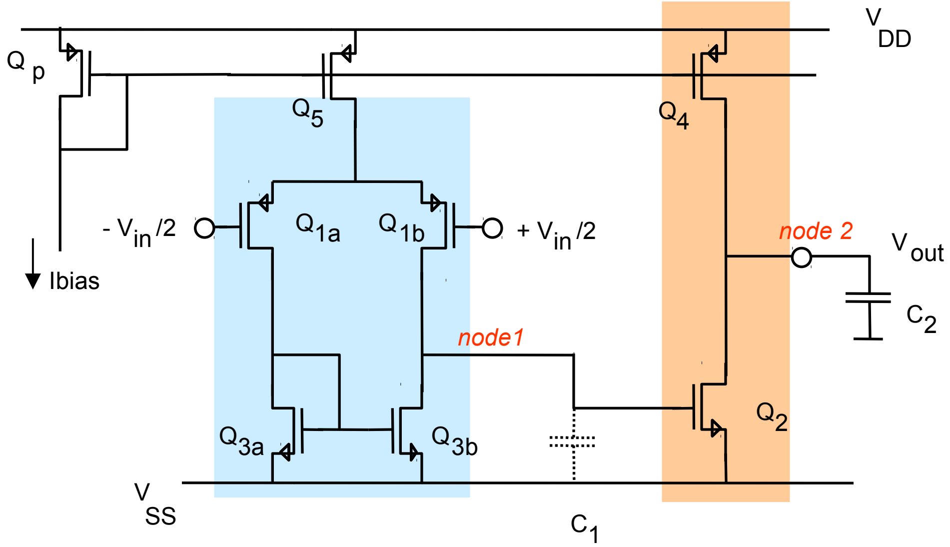


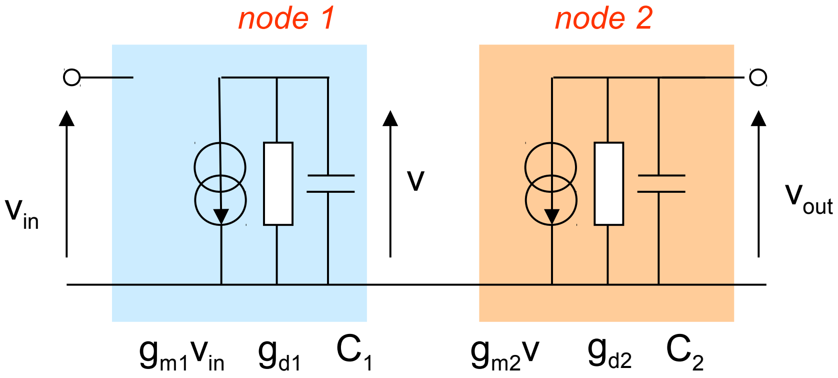
Equivalente en señal

Equivalente en señal

Equivalente en señal de **cualquier** amplificador de 2 etapas (MOS, bipolar, etc.)

Amplificador 2 etapas: Sin compensar





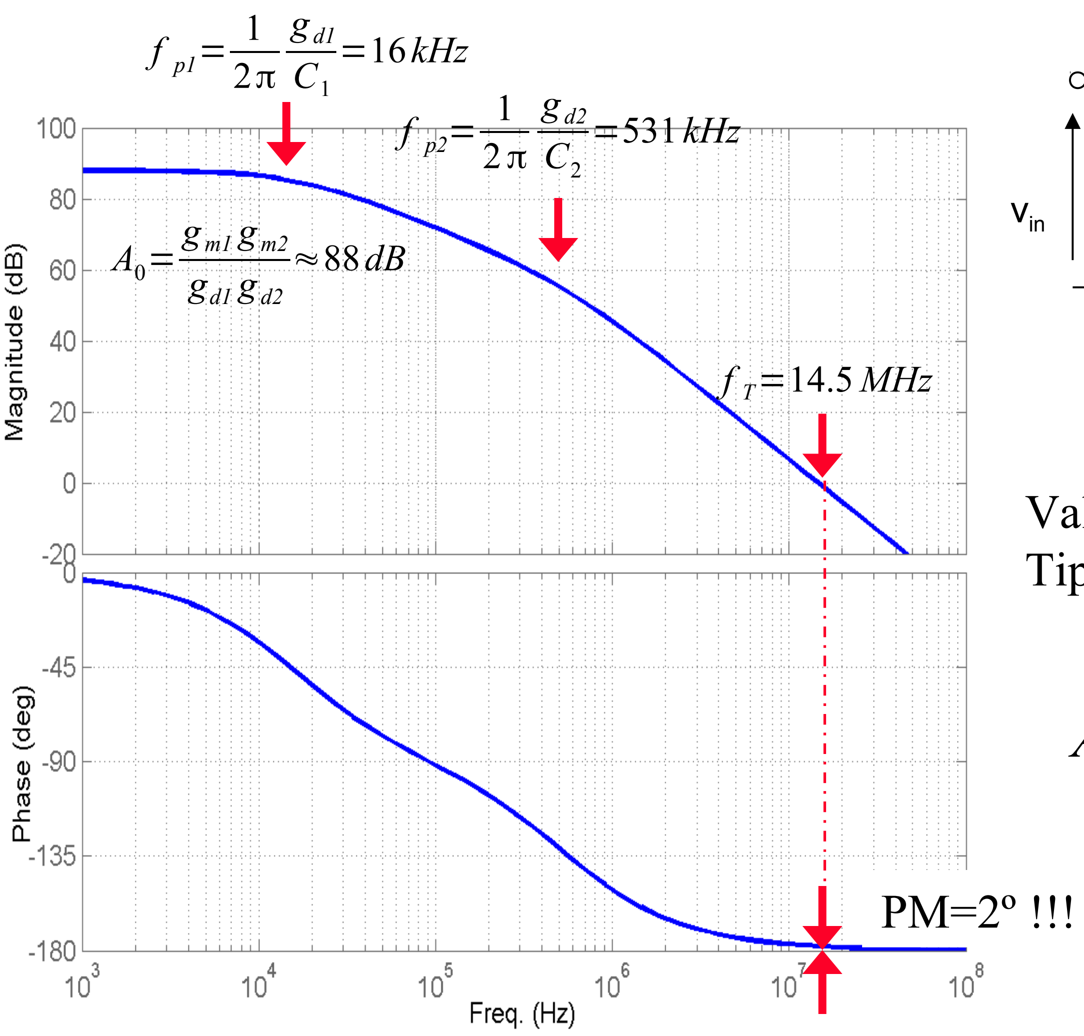
Valores Tipicos:

$$g_{m1} = 50\mu A/V \qquad g_{m2} = 500\mu A/V$$
$$g_{d1} = 10^{-7}\Omega^{-1} \qquad g_{d2} = 10^{-5}\Omega^{-1}$$
$$C_1 = 1pF \qquad C_2 = 3pF$$

$$A(\omega)=\frac{A_0}{\left(1+j\frac{\omega}{\omega_{p1}}\right)\left(1+j\frac{\omega}{\omega_{p2}}\right)}$$

$$A_0=\frac{g_{m1}g_{m2}}{g_{d1}g_{d2}}, \quad \omega_{p1}=\frac{g_{d1}}{C_1}, \quad \omega_{p2}=\frac{g_{d2}}{C_2}$$

Amplificador 2 etapas: Sin compensar



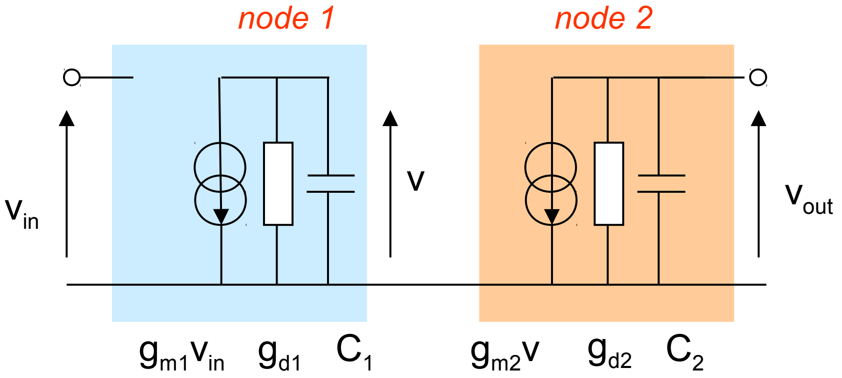
$$f_{p1}=\frac{1}{2\pi}\frac{g_{d1}}{C_1}=16\,kHz$$

$$f_{p2}=\frac{1}{2\pi}\frac{g_{d2}}{C_2}=531\,kHz$$

$$A_0=\frac{g_{m1}g_{m2}}{g_{d1}g_{d2}}\approx 88\,dB$$

$$f_T=14.5\,MHz$$

PM=2º !!!



Valores Tipicos:

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$$g_{d1}=10^{-7}\Omega^{-1} \qquad g_{d2}=10^{-5}\Omega^{-1}$$

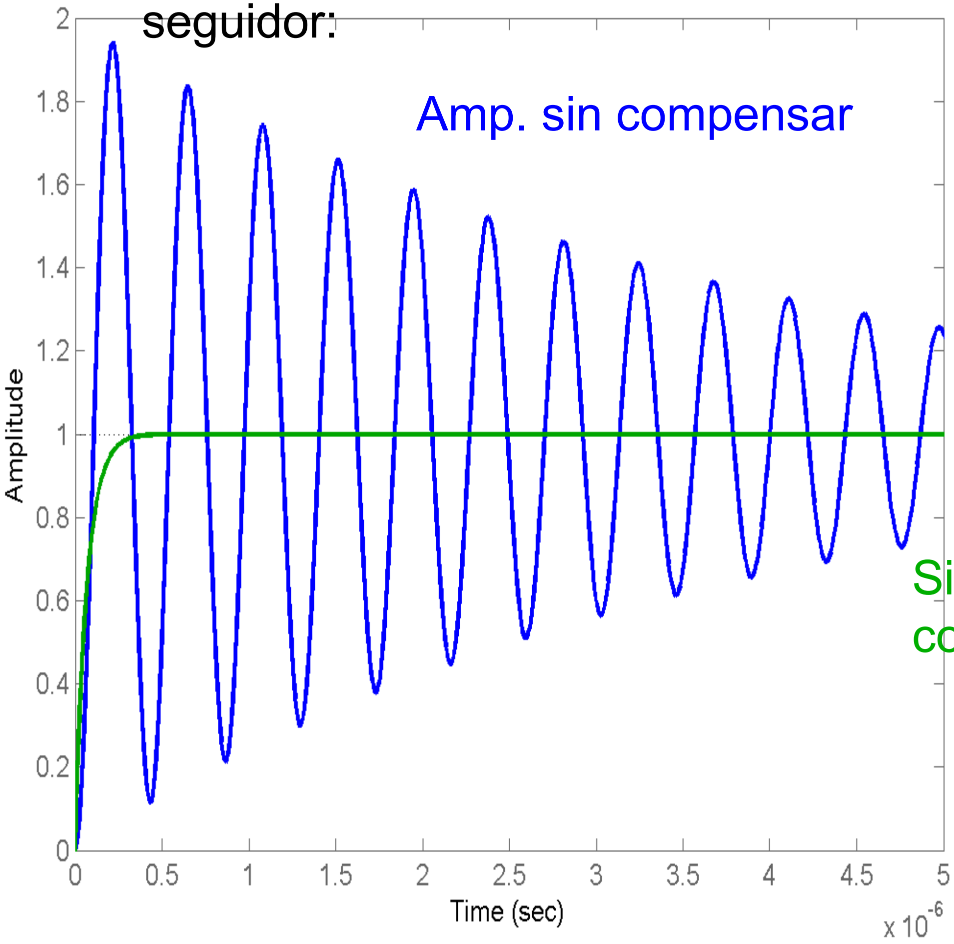
$$C_1=1pF \qquad C_2=3pF$$

$$A(\omega)=\frac{A_0}{\left(1+j\frac{\omega}{\omega_{p1}}\right)\left(1+j\frac{\omega}{\omega_{p2}}\right)}$$

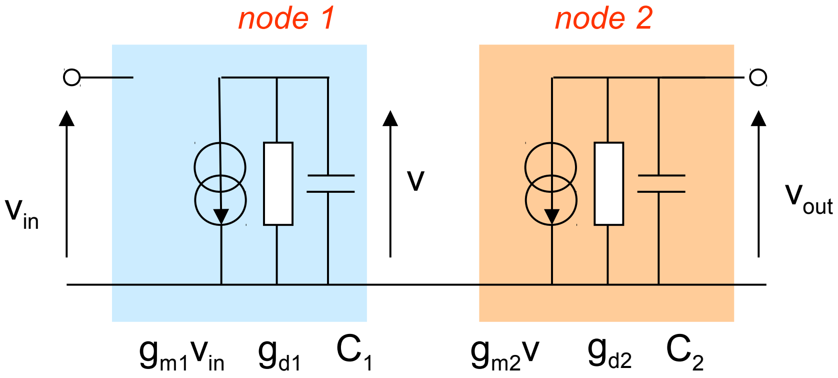
$$f_T\neq GBW\left(A_0 f_{p1}=400\,MHz\right)$$

Amplificador 2 etapas: Sin compensar

Respuesta al escalón del amp. en configuración seguidor:



Sist. de 1er orden con el mismo f_T y A_0.

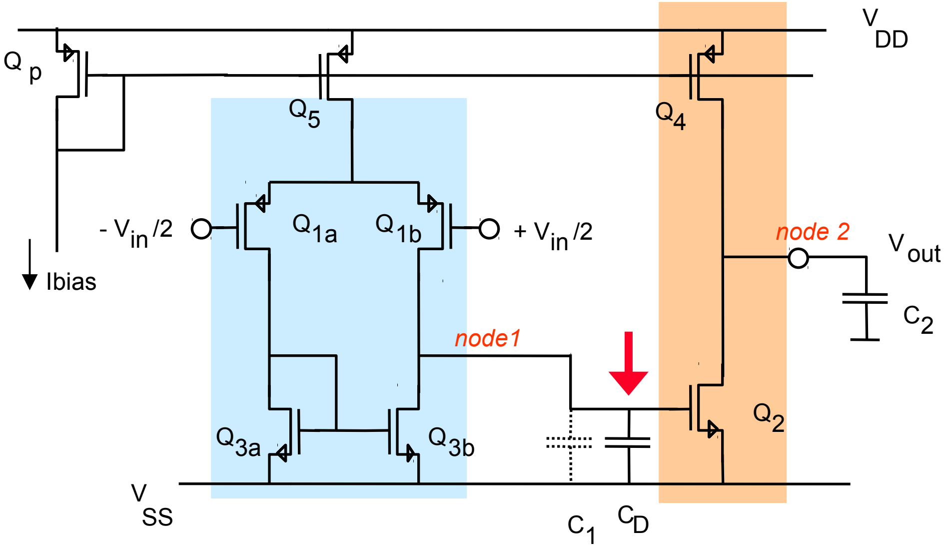


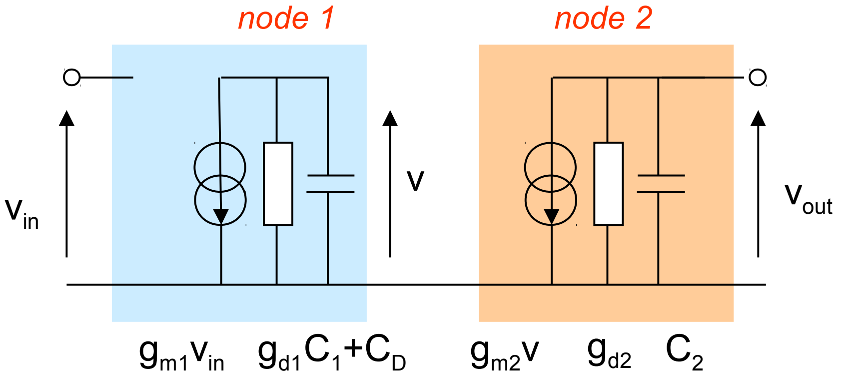
$$g_{m1} = 50\mu A/V \qquad g_{m2} = 500\mu A/V$$

$$g_{d1} = 10^{-7}\Omega^{-1} \qquad g_{d2} = 10^{-5}\Omega^{-1}$$

$$C_1 = 1pF \qquad C_2 = 3pF$$

Amplificador 2 etapas: Compensación Directa





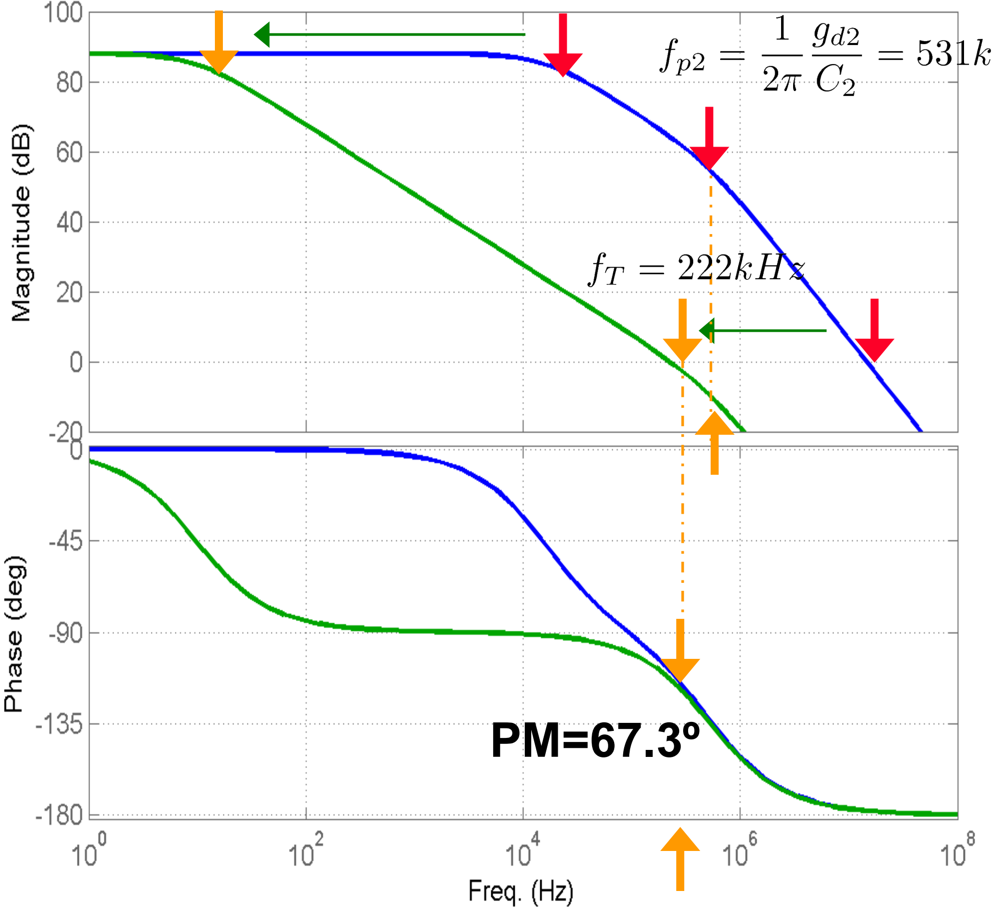
Valores Tipicos:

$$g_{m1} = 50\mu A/V \qquad g_{m2} = 500\mu A/V$$
$$g_{d1} = 10^{-7}\Omega^{-1} \qquad g_{d2} = 10^{-5}\Omega^{-1}$$
$$C_1 = 1pF \qquad C_2 = 3pF$$

Si agrego C_D $\quad f_{p1}\downarrow \;\Rightarrow\; f_T\downarrow \;\Rightarrow PM\uparrow$

Amplificador 2 etapas: Compensación Directa

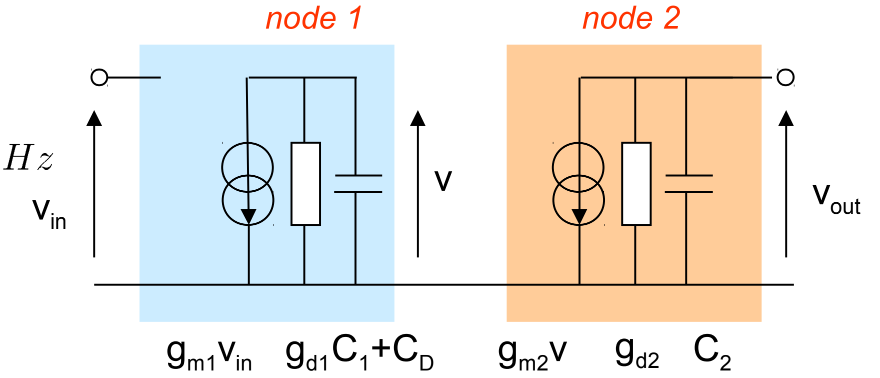
$$f_{p1} = \frac{1}{2\pi}\frac{g_{d1}}{C_1 + C_D} = 9.6Hz$$



$$f_{p2} = \frac{1}{2\pi}\frac{g_{d2}}{C_2} = 531kHz$$

$$f_T = 222kHz$$

PM=67.3º



Valores Tipicos:

$$g_{m1} = 50\mu A/V \qquad g_{m2} = 500\mu A/V$$

$$g_{d1} = 10^{-7}\Omega^{-1} \qquad g_{d2} = 10^{-5}\Omega^{-1}$$

$$C_1 = 1pF \qquad C_2 = 3pF$$

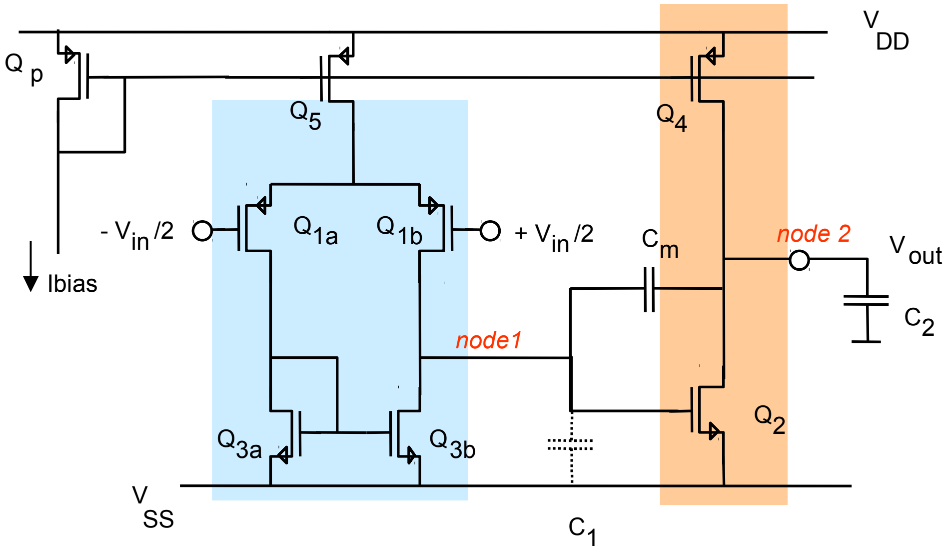
Criterio usual: $f_{p2} = 2.2 f_T$

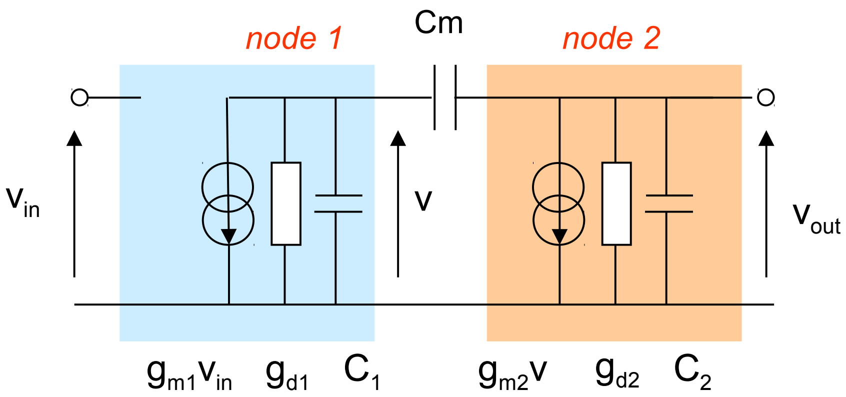
$$\Rightarrow f_{p2} = 2.2 A_0 f_{p1}$$

$$\Rightarrow \frac{g_{d2}}{C_2} = 2.2\frac{g_{m1}g_{m2}}{g_{d1}g_{d2}}\frac{g_{d1}}{C_1 + C_D}$$

$\Rightarrow C_D = 1.65nF$!!! Imposible de integrar!!!

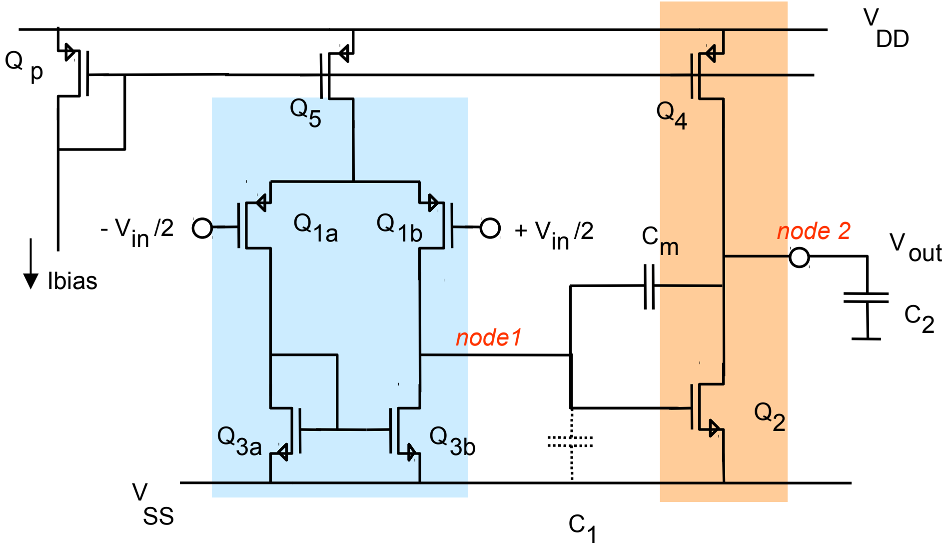
Amplificador Miller:

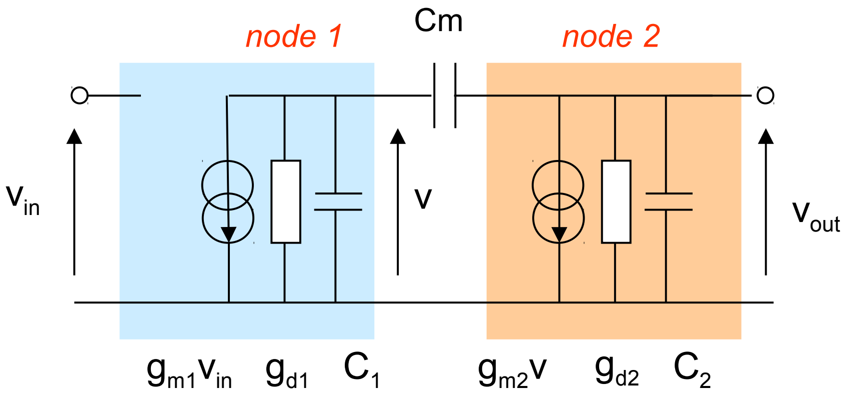




$$A(s) = \frac{\frac{g_{m1}g_{m2}}{g_{d1}g_{d2}}\left(1 - s\frac{C_m}{g_{m2}}\right)}{1 + s\left(\frac{C_1}{g_{d1}} + \frac{C_2}{g_{d2}} + \frac{C_m}{g_{d1}g_{d2}}(g_{m2} + g_{d2} + g_{d1})\right) + s^2\left(\frac{C_1C_2 + C_m(C_1 + C_2)}{g_{d1}g_{d2}}\right)}$$

Amplificador Miller:





zero RHP : $\omega_z = \dfrac{g_{m2}}{C_m}$

(resta fase)

$$A(s) = \frac{\dfrac{g_{m1}g_{m2}}{g_{d1}g_{d2}}\left(1 - s\dfrac{C_m}{g_{m2}}\right)}{1 + s\left(\dfrac{C_1}{g_{d1}} + \dfrac{C_2}{g_{d2}} + \dfrac{C_m}{g_{d1}g_{d2}}(g_{m2} + g_{d2} + g_{d1})\right) + s^2\left(\dfrac{C_1C_2 + C_m(C_1+C_2)}{g_{d1}g_{d2}}\right)}$$

$\omega_{p1} \ll \omega_{p2}$

Hipotesis :

- Polo dominante
- Efecto Miller domina

$$\omega_{p1} \simeq \frac{g_{d1}}{\frac{g_{m2}}{g_{d2}}C_m} \ll \frac{g_{d1}}{C_1}$$

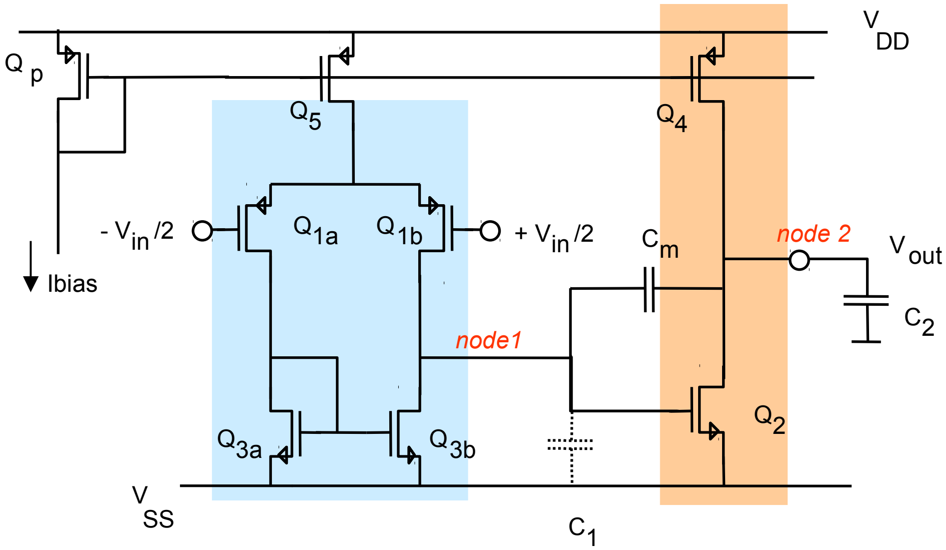
"pole splitting"

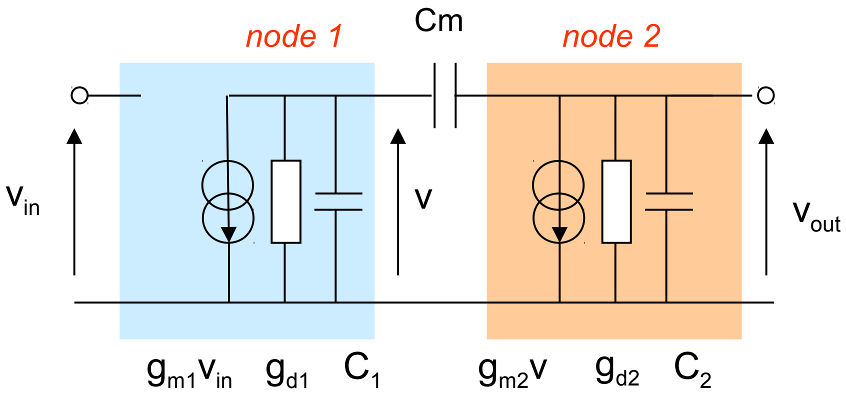
$$\frac{g_{m2}}{g_{d1}g_{d2}}C_m \gg \frac{C_1}{g_{d1}}, \frac{C_2}{g_{d2}}, \frac{C_m}{g_{d1}}, \frac{C_m}{g_{d2}}$$

$$\omega_{p2} \simeq \frac{g_{m2}C_m}{C_1C_2 + C_m(C_1 + C_2)} \gg \frac{g_{d2}}{C_2}$$

Gracias a efecto Miller, Cm es integrable

Amplificador Miller:





$$\left.\begin{aligned} A_0 &= \frac{g_{m1}g_{m2}}{g_{d1}g_{d2}} \\ \omega_{p1} &\simeq \frac{g_{d1}}{\frac{g_{m2}}{g_{d2}}C_m} \end{aligned}\right\} \Rightarrow \boxed{GBW = \frac{g_{m1}}{C_m}}$$

$$\omega_{p2} \simeq \frac{g_{m2}C_m}{C_1C_2 + C_m(C_1 + C_2)}$$

$$NDP = \frac{\omega_{ndp}}{GBW} \rightarrow NDP = \frac{g_{m2}}{g_{m1}} \frac{C_m^2}{C_1C_2 + C_m(C_1 + C_2)}$$

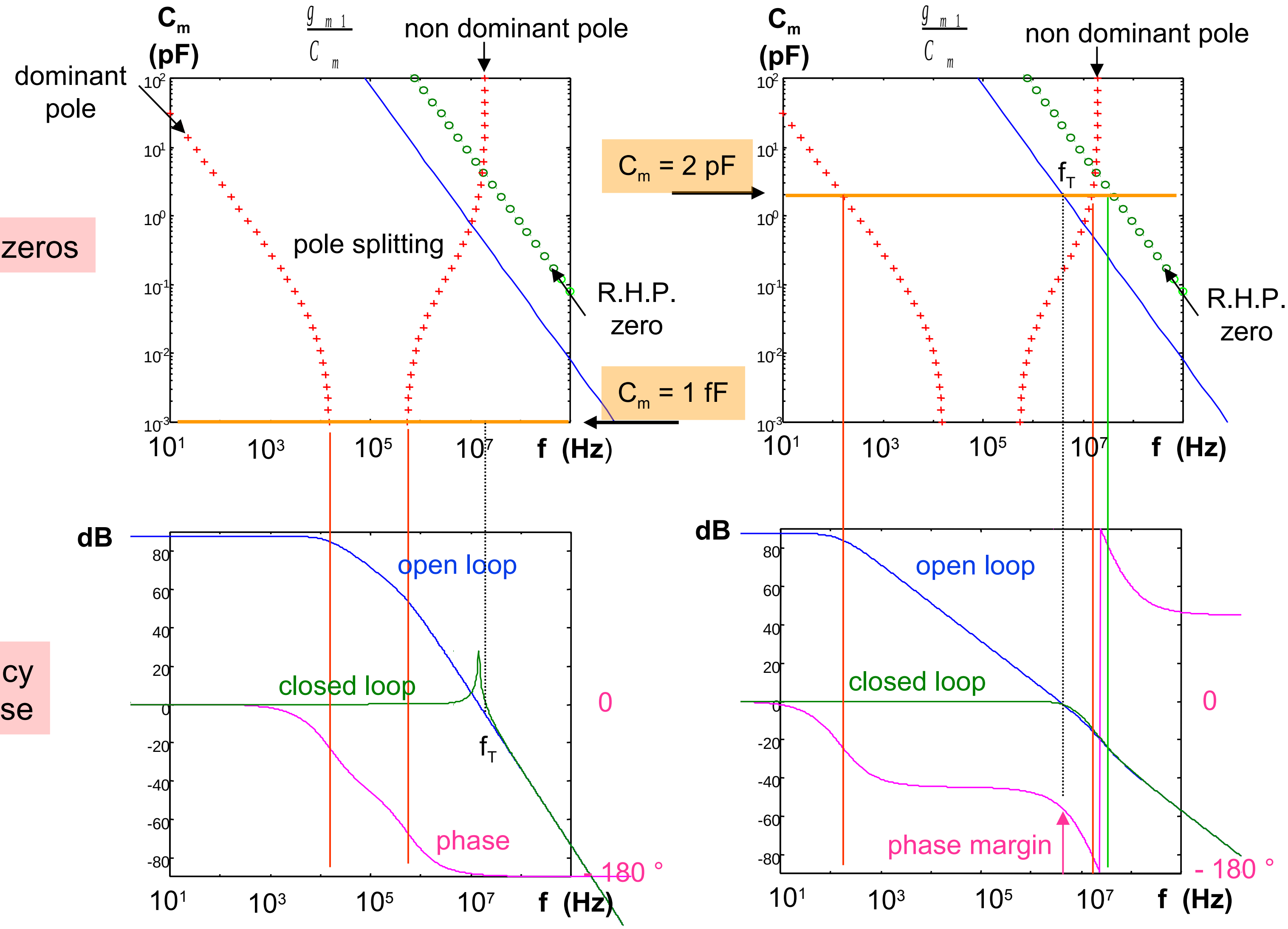
$$\omega_z = \frac{g_{m2}}{C_m}$$

$$Z = \frac{\omega_z}{GBW} \rightarrow Z = \frac{g_{m2}}{g_{m1}}$$

Amplificador Miller:

poles - zeros

frequency response



Tomado de P.Jespers – “Interfacing Microsystems” IWS 2001

Resumen Compensacion Amps. 2 Etapas

Compensación	**fp1**	**fp2**	**fz**	**fT**	**PM**
Sin compensar	16 kHz	531 kHz	-	14.5 MHz	2º
Directa	9.6 Hz	531 kHz	-	222 kHz	67.3º
Miller	228 Hz	20 MHz	58 MHz	5.5 MHz	69.2º

Cm=1.36 pF

- Ventajas de la compensación Miller:
  - Gracias a efecto Miller, Cm es pequeña e integrable
  - Gracias a efecto “pole splitting”, no baja mucho el f_T (buen compromiso velocidad – consumo)