Métodos de Compensación en Frecuencia

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Rev 1.0

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    - Sistemas de 1er orden
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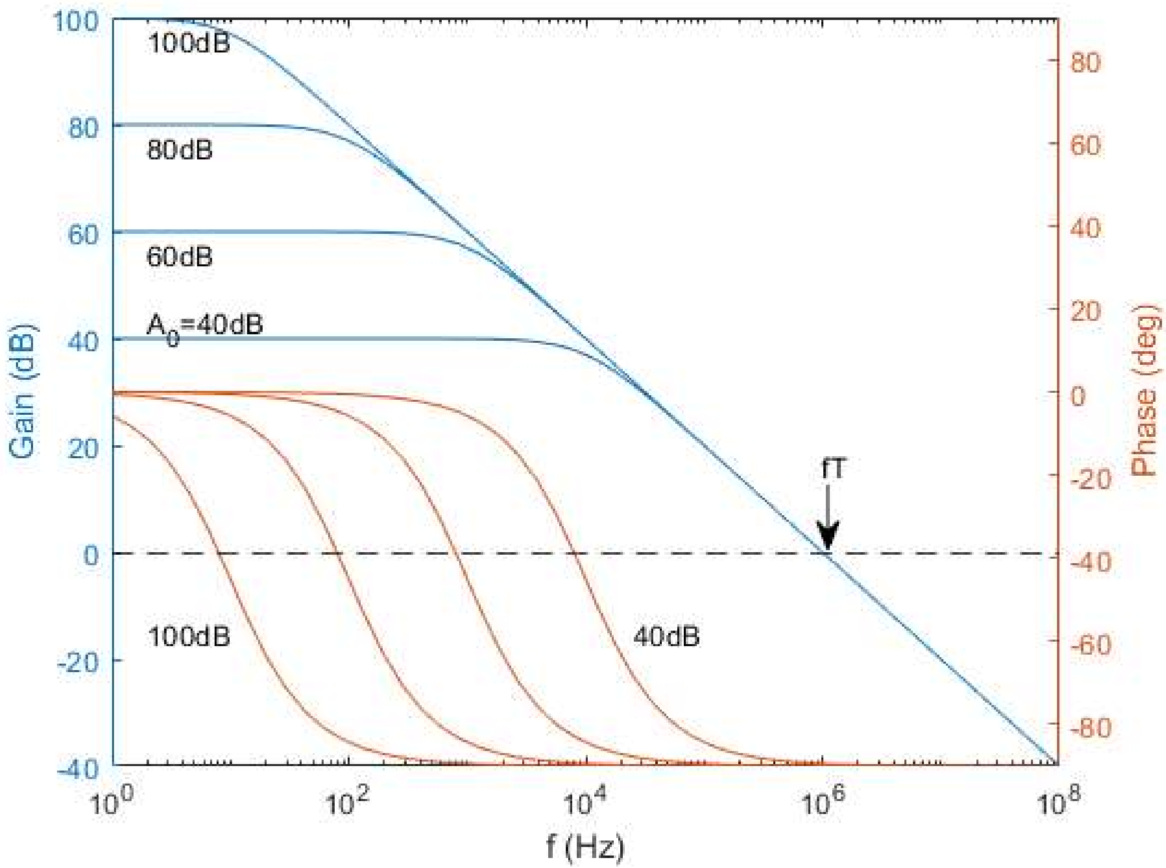
Sistemas de 1er orden (I)

Lazo Abierto: $A(\omega) = \dfrac{A_0}{1 + j\dfrac{\omega}{\omega_p}}$ $\Rightarrow A(\omega) = \dfrac{A_0}{1 + j\dfrac{\omega A_0}{\omega_T}}$



$$\omega_T = A_0\omega_p = GBW$$

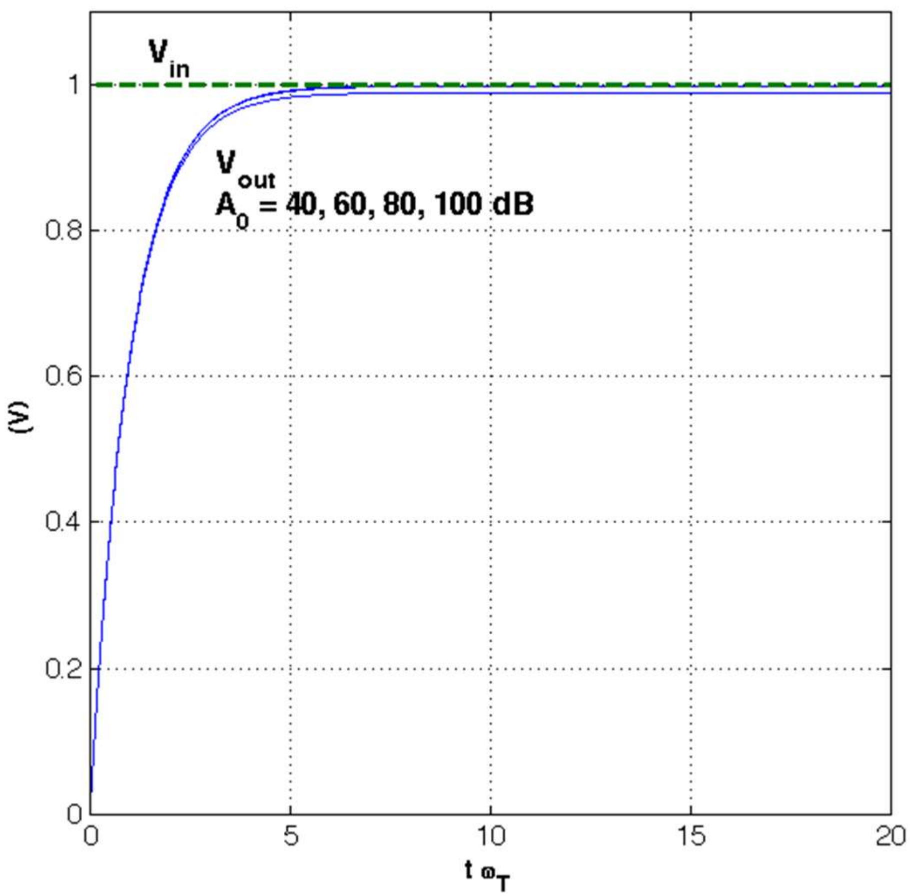
Es la constante de tiempo del sistema, determina la velocidad de respuesta del sistema.

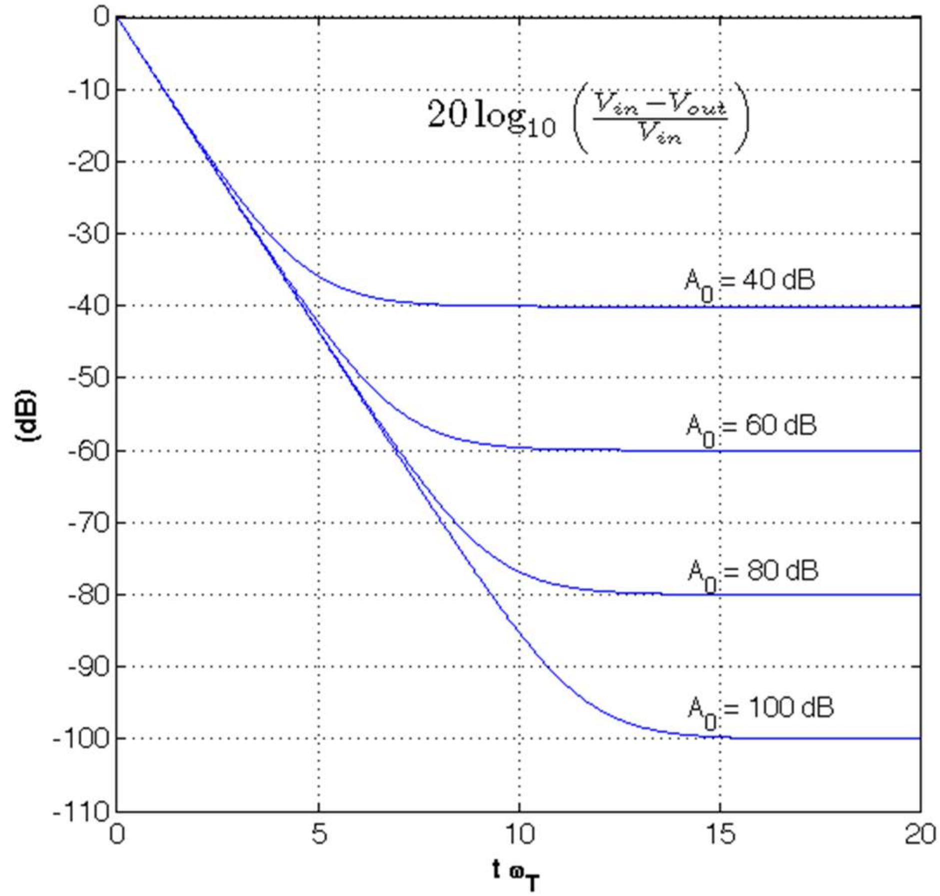
Sistemas de 1er orden (II)

Lazo Cerrado: $\mathrm{H}(\omega) = \dfrac{A(\omega)}{1+A(\omega)} = \dfrac{1}{1+j\dfrac{\omega}{\omega_T}}$

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 dominante (ω_{dp}) — Polo no dominante (ω_{ndp})

Producto Ganacia por Ancho de Banda:

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

Posición relativa del polo no dominante:

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

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

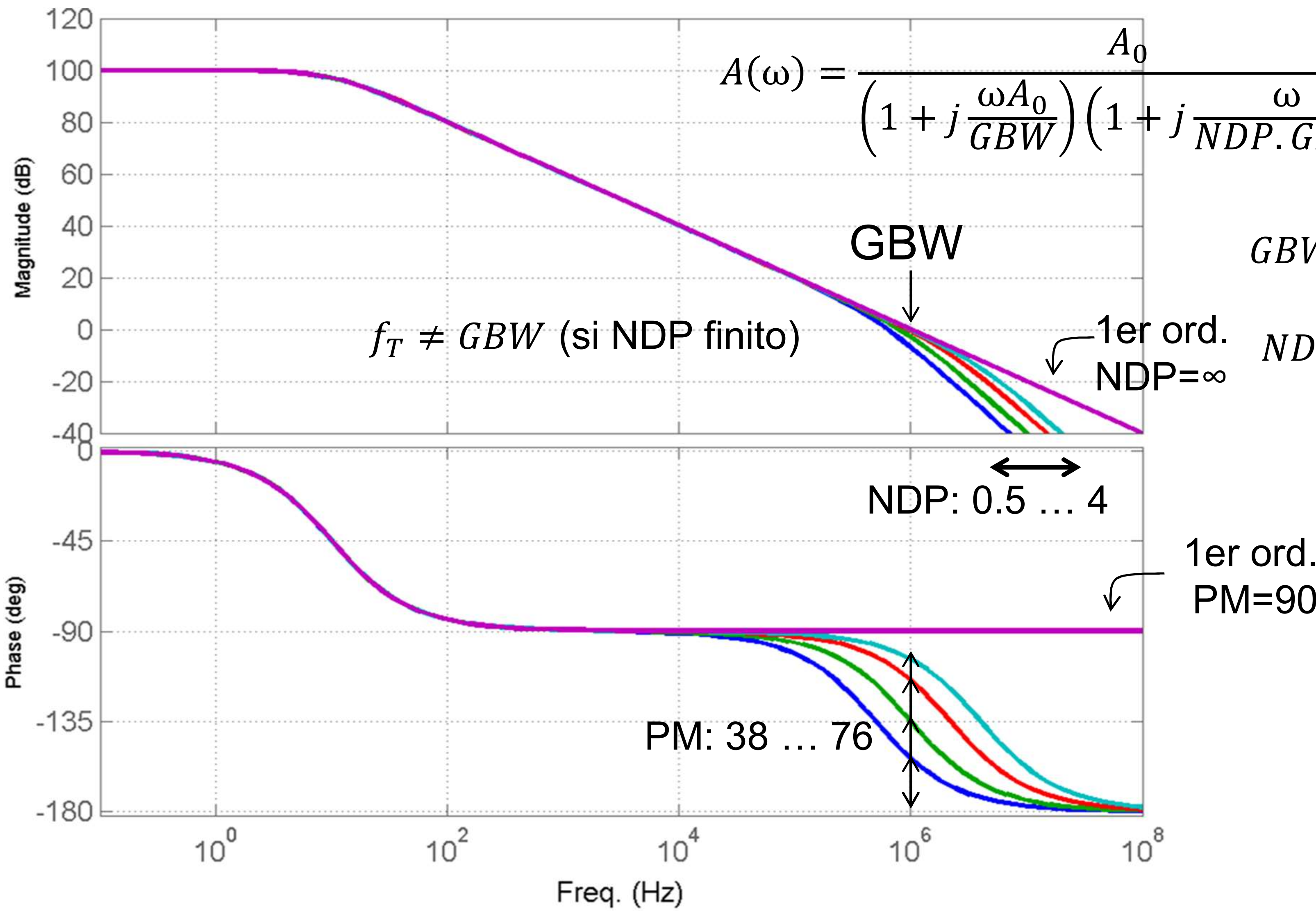
Sistemas de 2do orden (II)

Lazo Abierto:

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

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

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

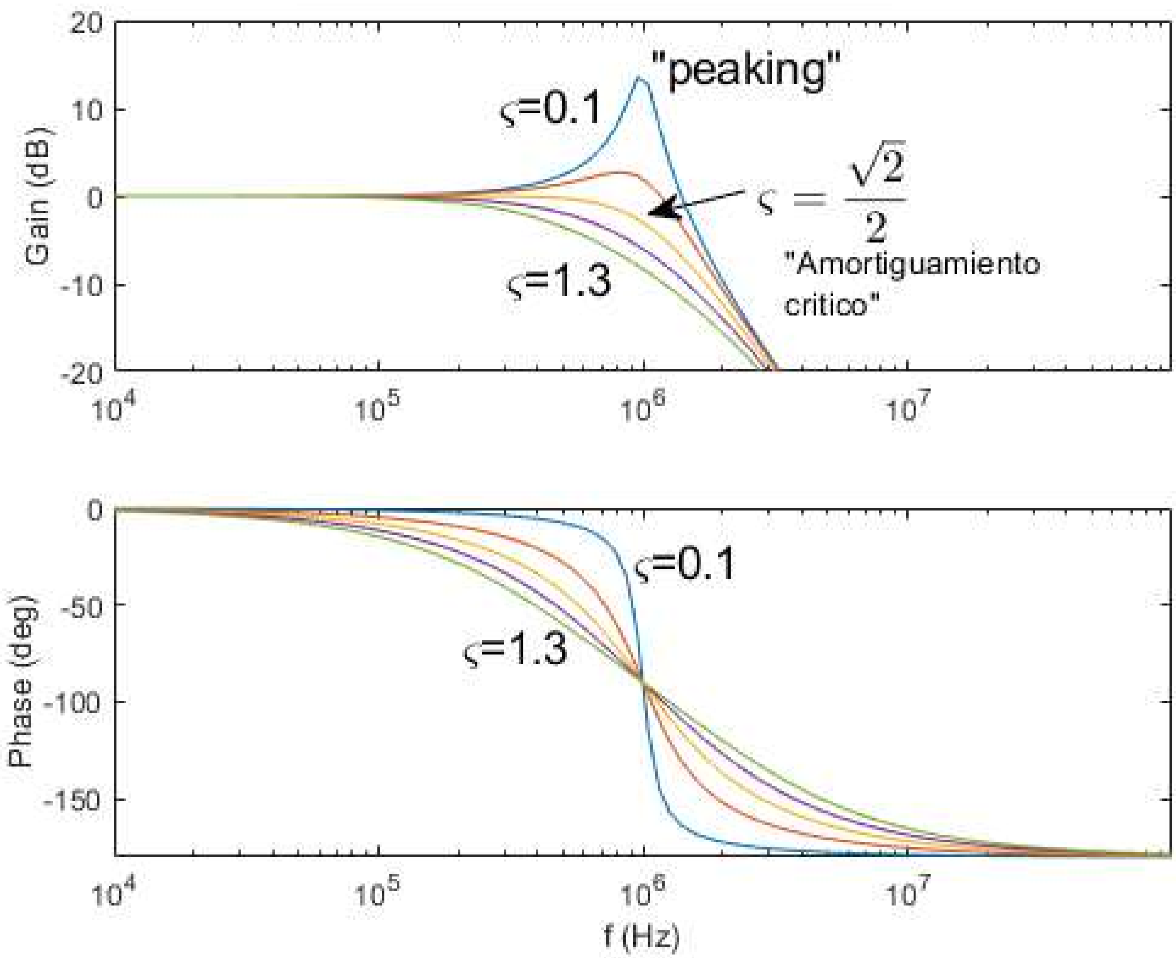


Sistemas de 2do orden (III)

Lazo Cerado:

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

Bode:



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

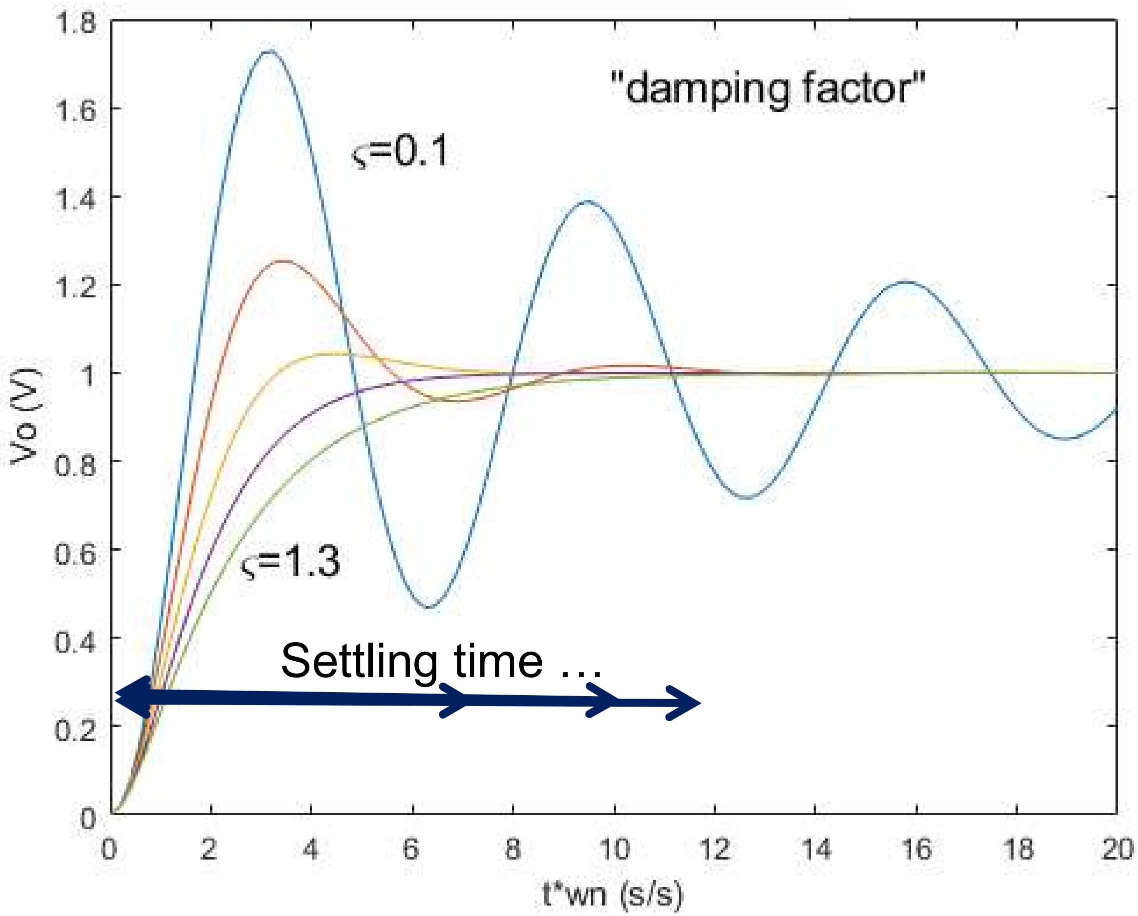
$$\omega_n = GBW\sqrt{NDP}$$

Sistemas de 2do orden (IV)

Lazo Cerado:

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

Respuesta al escalón:



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

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

Márgenes de Estabilidad

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. (→ Inf)

Open Loop | Closed Loop

Márgenes de Estabilidad

NDP	PM (º)	ζ	Peaking (dB)	Sobre Tiro (%)	Sett. Time x GBW	
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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

Amortiguamiento crítico:

1er ord.

Open Loop **Closed Loop**

Márgenes de Estabilidad

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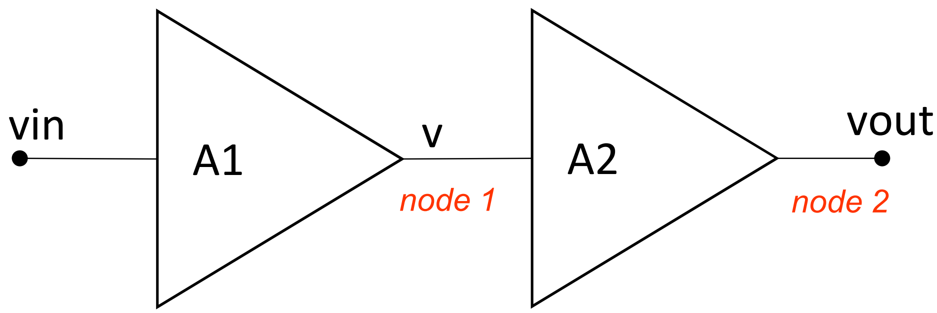
Inf	90	inf	-	0	3.0	4.6

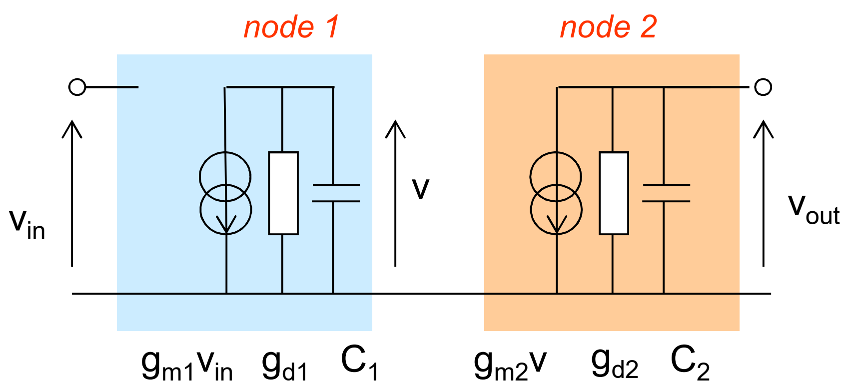
Elección usual de diseño: (fila 2.2)

1er ord. (fila Inf)

Open Loop (NDP, PM) — **Closed Loop** (ζ, Peaking, Sobre Tiro, Sett. Time x GBW)

Amplificadores 2 etapas: Modelo Norton





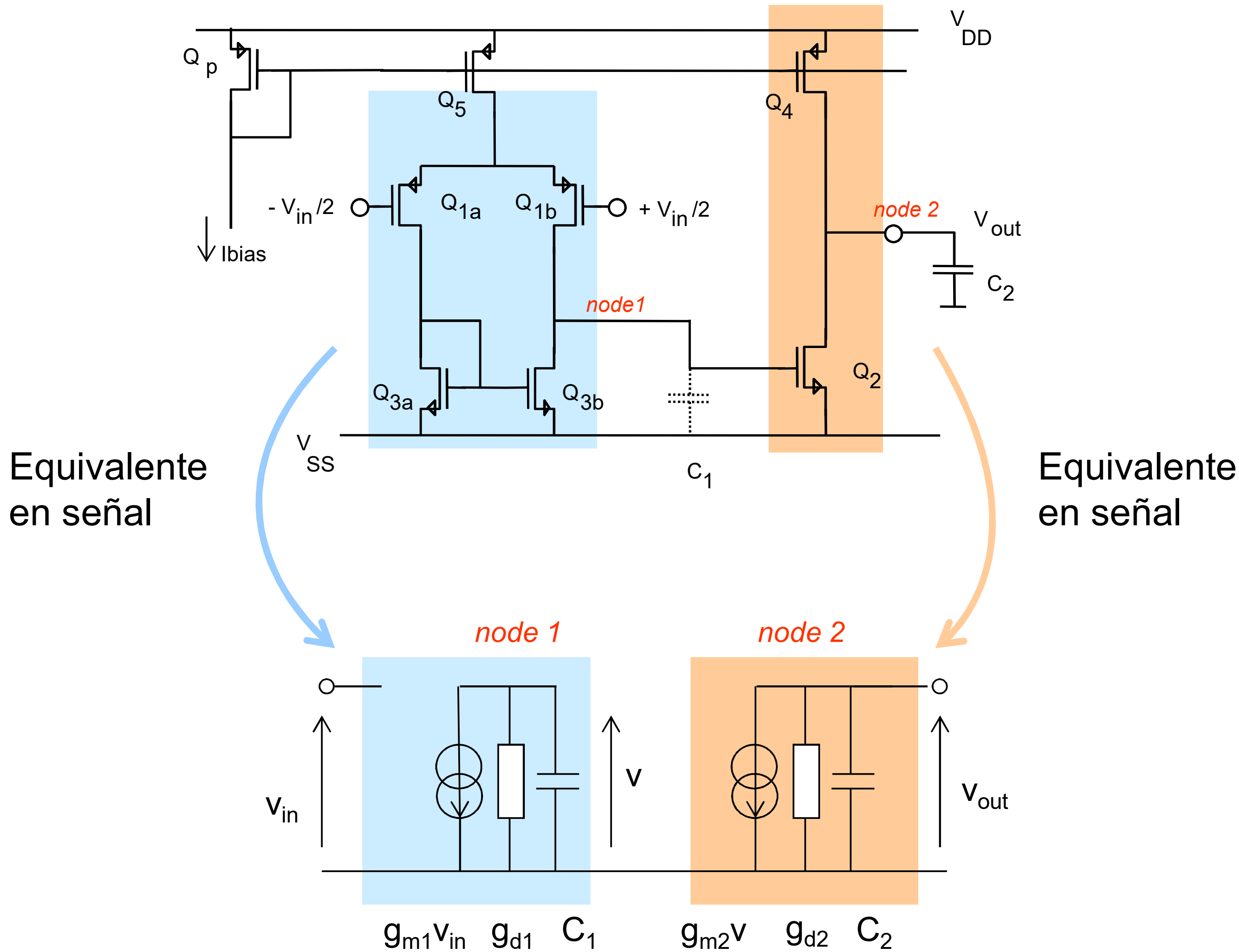
Equivalente Norton de **<u>cualquier</u>** amplificador de 2 etapas

Es un Sistema Lineal de 2do Orden:

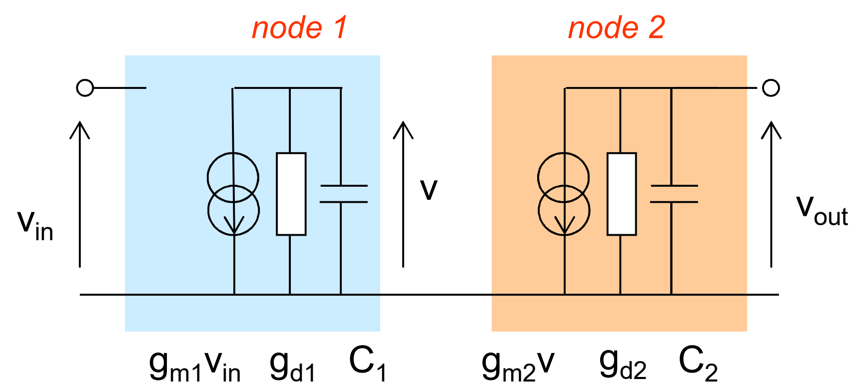
$$A(\omega) = \frac{A_0}{\left(1 + j\frac{\omega}{\omega_{p1}}\right)\left(1 + j\frac{\omega}{\omega_{p2}}\right)}$$

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

Ejemplo: Amplificador MOS



Estabilidad de un Amp. de 2 Etapas



Valores Tipicos:

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

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

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

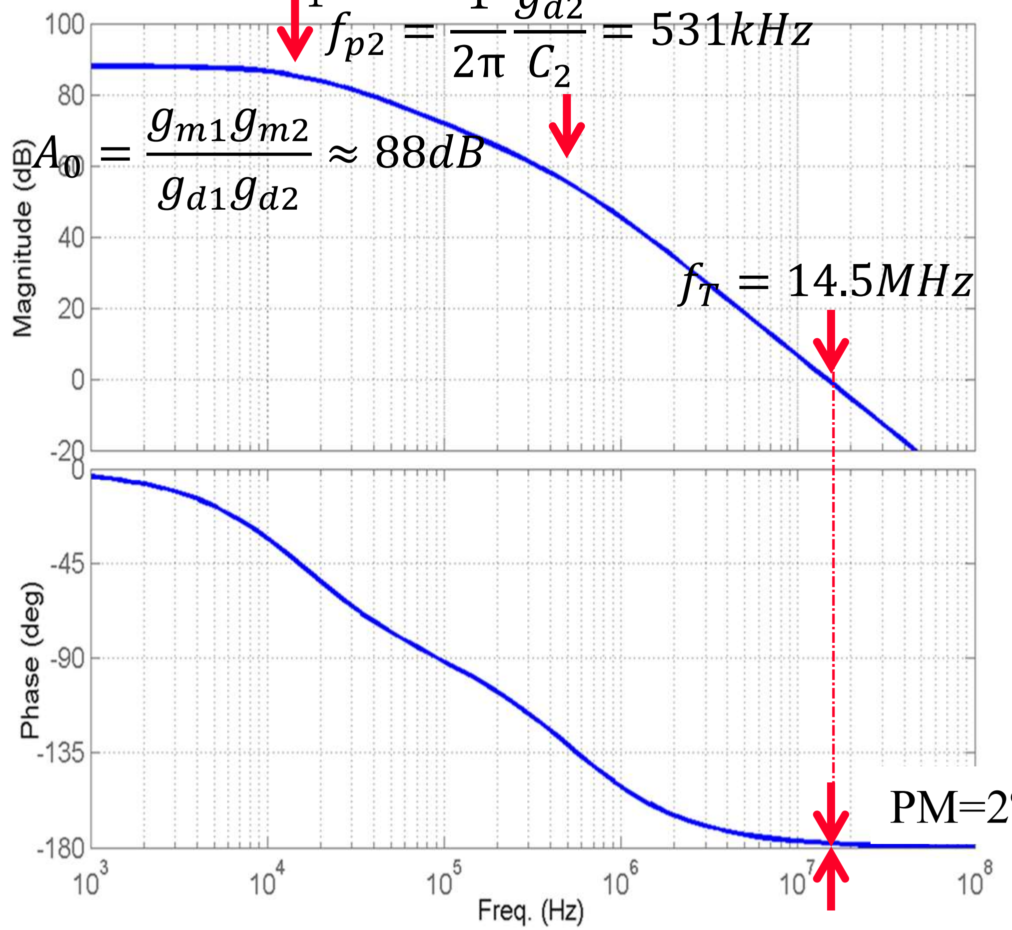
Estabilidad de un Amp. de 2 Etapas

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

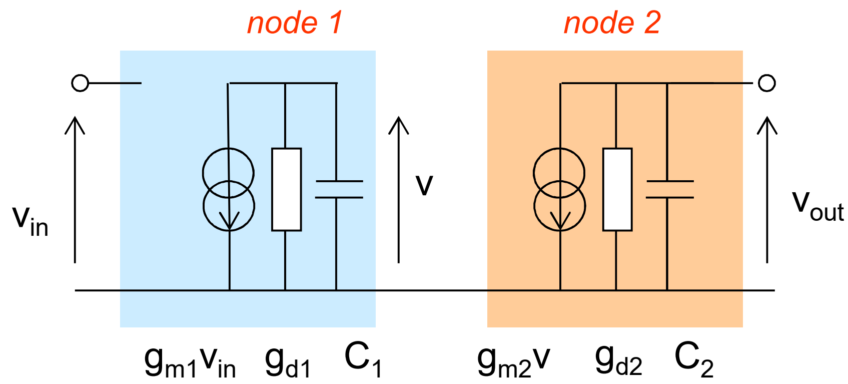
$$f_{p2} = \frac{1}{2\pi}\frac{g_{d2}}{C_2} = 531kHz$$

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

$$f_T = 14.5MHz$$



PM=2º !!!



Valores Tipicos:

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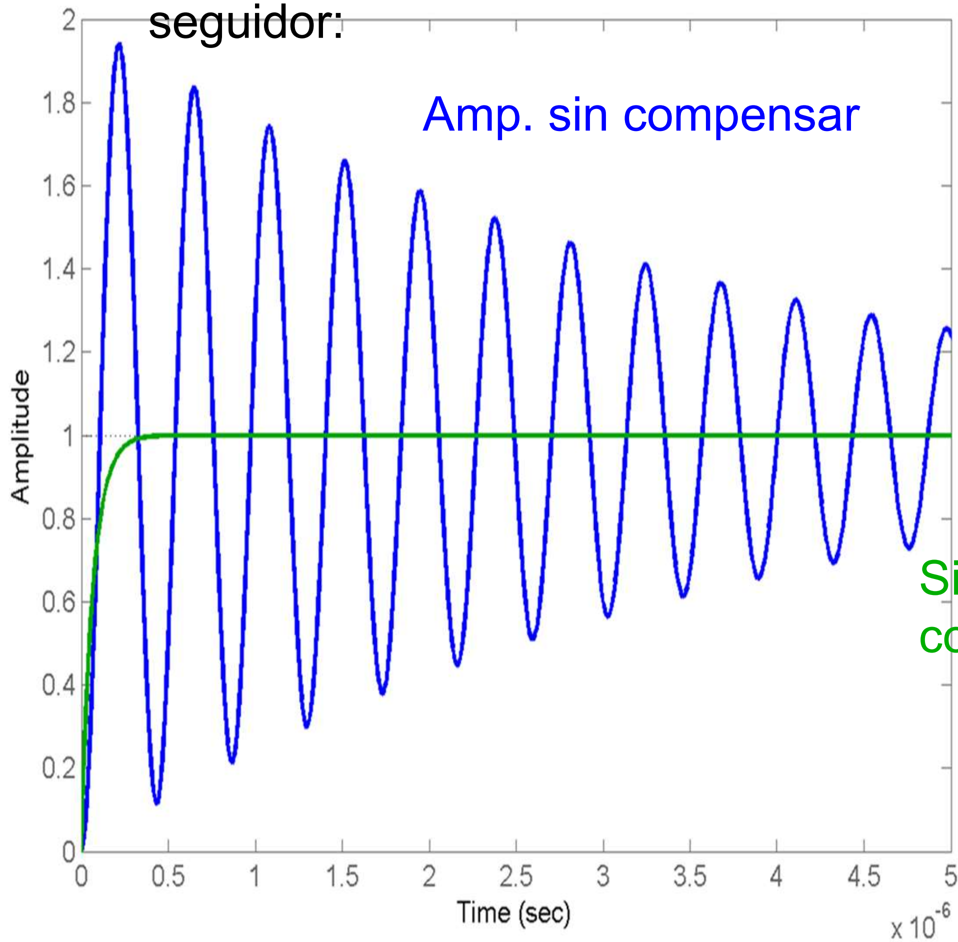
$$g_{d1} = 10^{-7}\Omega^{-1} \qquad g_{d2} = 10^{-5}\Omega^{-1}$$
$$C_1 = 1pF \qquad C_2 = 3pF$$

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

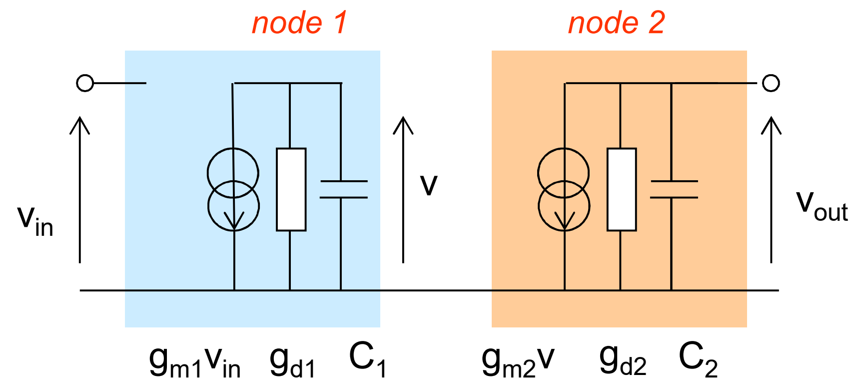
$$f_T \neq GBW\left(A_0 f_{p1} = 400MHz\right)$$

Estabilidad de un Amp. de 2 Etapas

Respuesta al escalón del amp. en configuración seguidor:



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

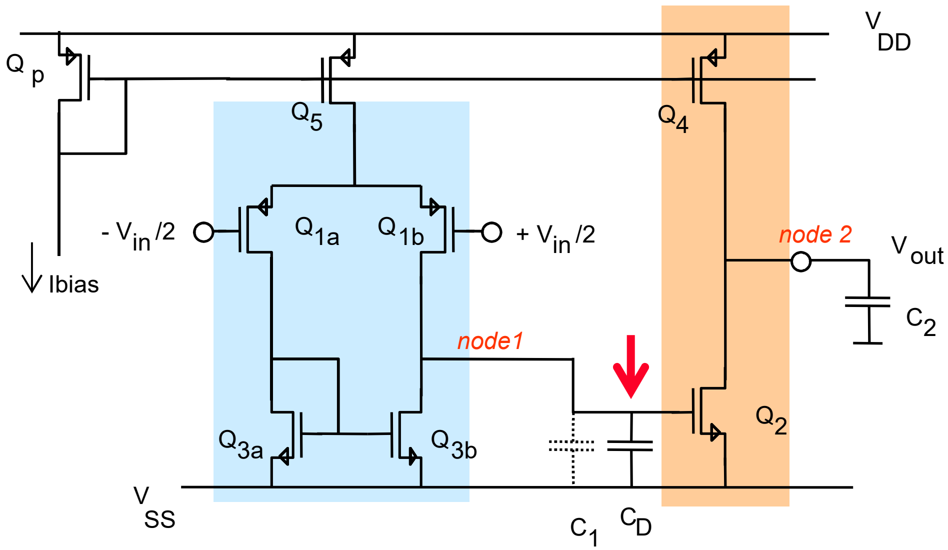


$$g_{m1} = 50\mu A/V \qquad g_{m2} = 500\mu A/V$$

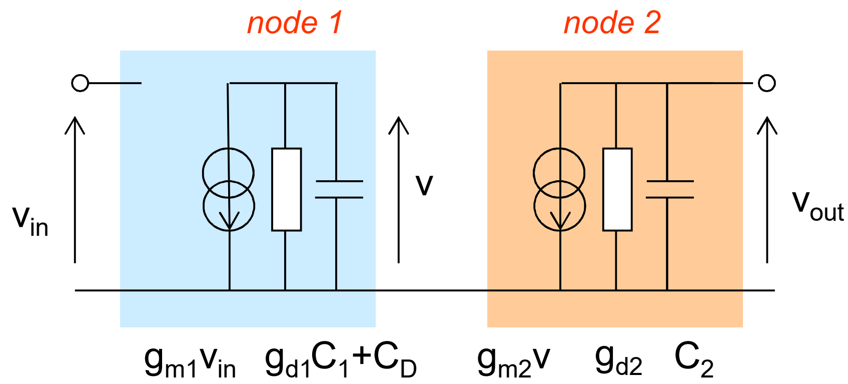
$$g_{d1} = 10^{-7}\Omega^{-1} \qquad g_{d2} = 10^{-5}\Omega^{-1}$$

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

Met. de Compensación: Compensación Directa



Ejemplo Amp. MOS



Valores Tipicos:

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

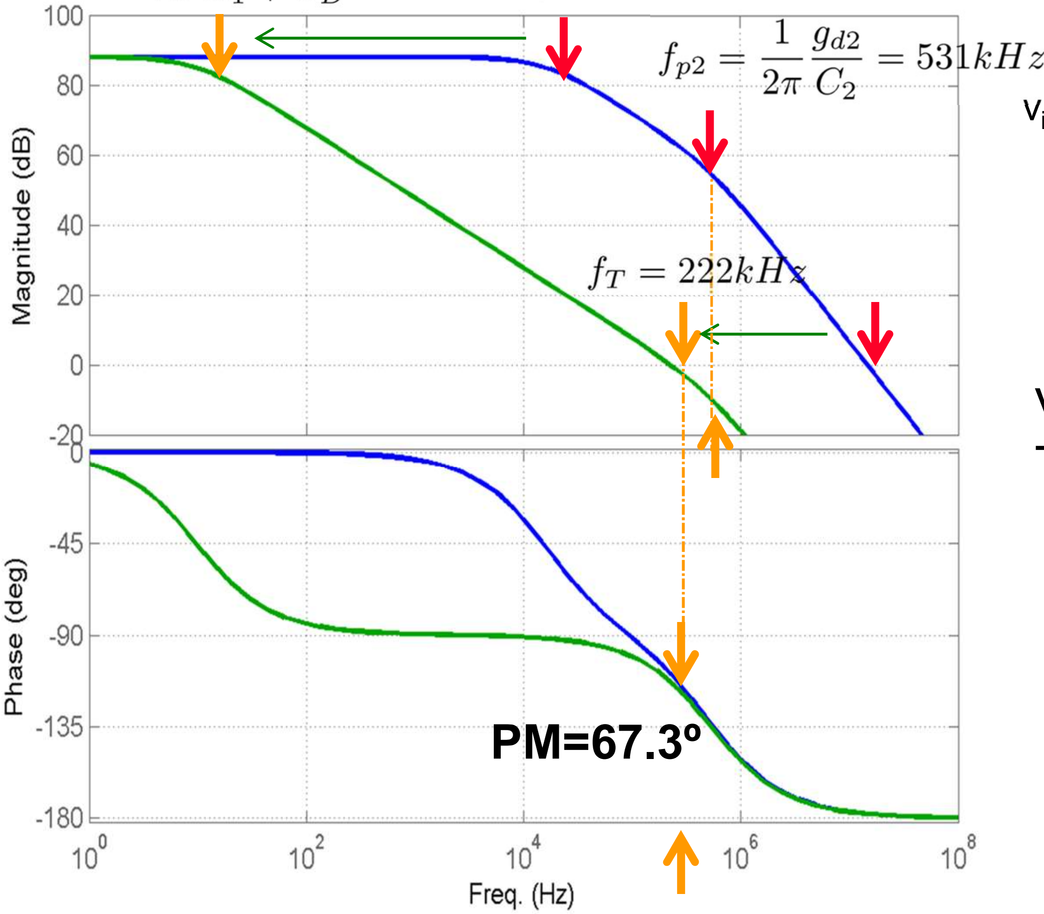
$g_{d1} = 10^{-7}\Omega^{-1}$ $\quad g_{d2} = 10^{-5}\Omega^{-1}$

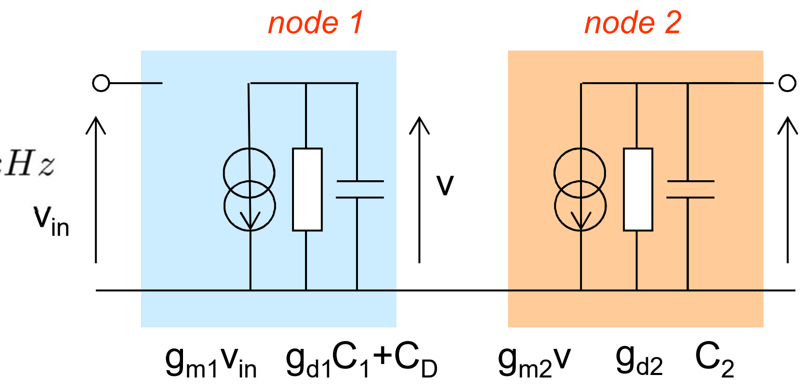
$C_1 = 1pF$ $\quad C_2 = 3pF$

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

Met. de Compensación: Compensación Directa

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





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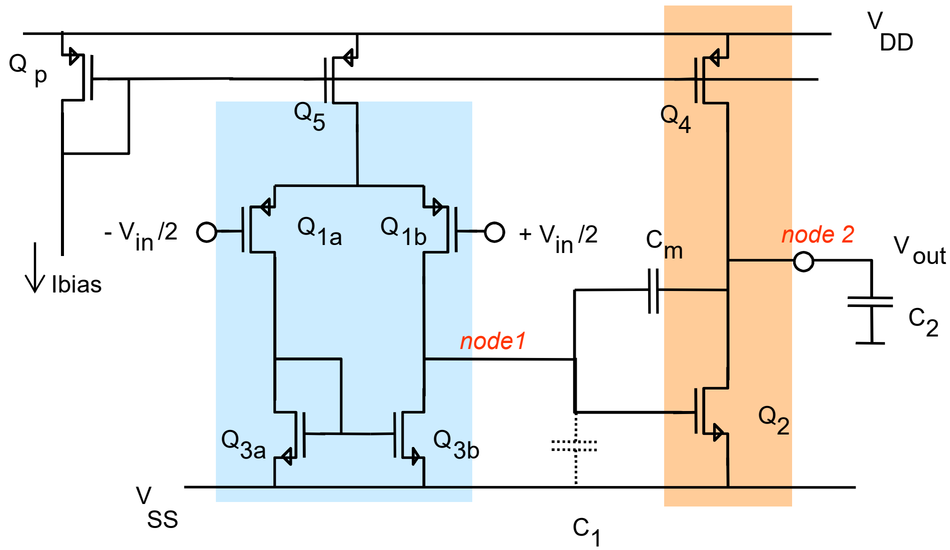
$$g_{d1} = 10^{-7}\Omega^{-1} \qquad g_{d2} = 10^{-5}\Omega^{-1}$$
$$C_1 = 1pF \qquad C_2 = 3pF$$

Criterio usual: NDP=2.2

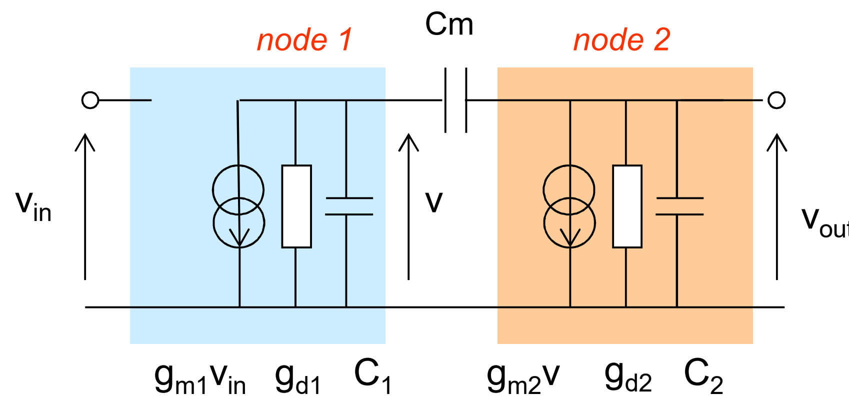
$$f_{p2} = 2.2 f_T$$
$$\Rightarrow f_{p2} = 2.2 A_0 f_{p1}$$
$$\Rightarrow \frac{g_{d2}}{C_2} = 2.2\frac{g_{m1}g_{m2}}{g_{d1}g_{d2}}\frac{g_{d1}}{C_1 + C_D}$$

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

Met. de Compensación: Compensación Miller

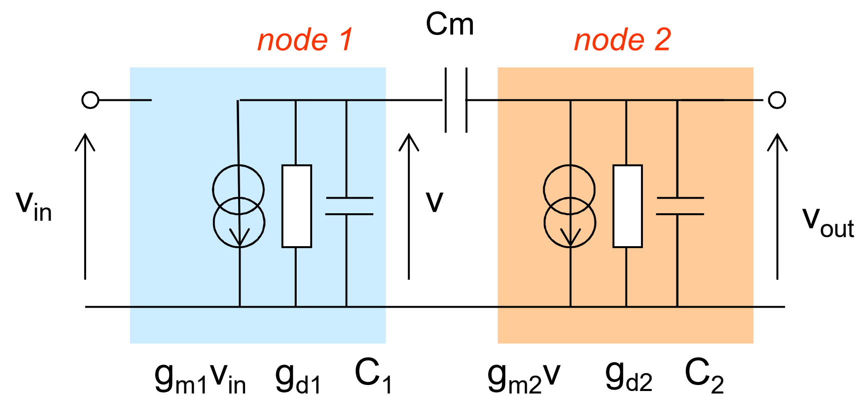


Ejemplo Amp. MOS



Met. de Compensación: Compensación Miller

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



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

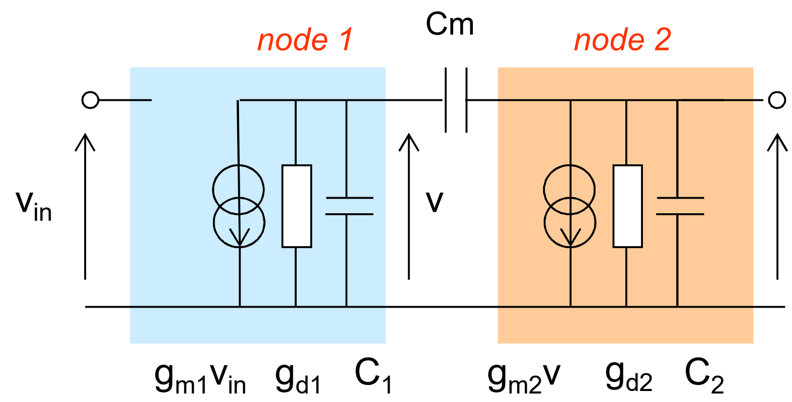
Hipotesis :

•Polo dominante

•Efecto Miller domina

Met. de Compensación: Compensación Miller

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



zero RHP : $\omega_z = \frac{g_{m2}}{C_m}$
(resta fase)

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

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

Hipotesis :
- Polo dominante
- Efecto Miller domina

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

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

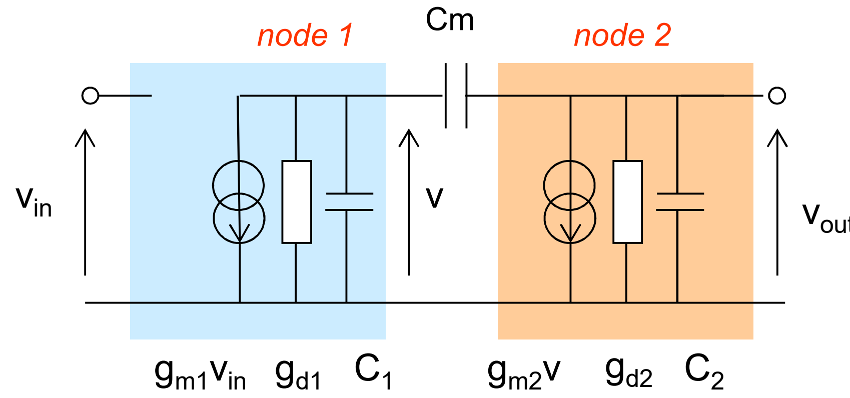
"pole splitting"

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

Gracias a efecto Miller, Cm es integrable

Met. de Compensación: Compensación Miller

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



$$A_0 = \frac{g_{m1}g_{m2}}{g_{d1}g_{d2}}$$

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

$$GBW = \frac{g_{m1}}{C_m}$$

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

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

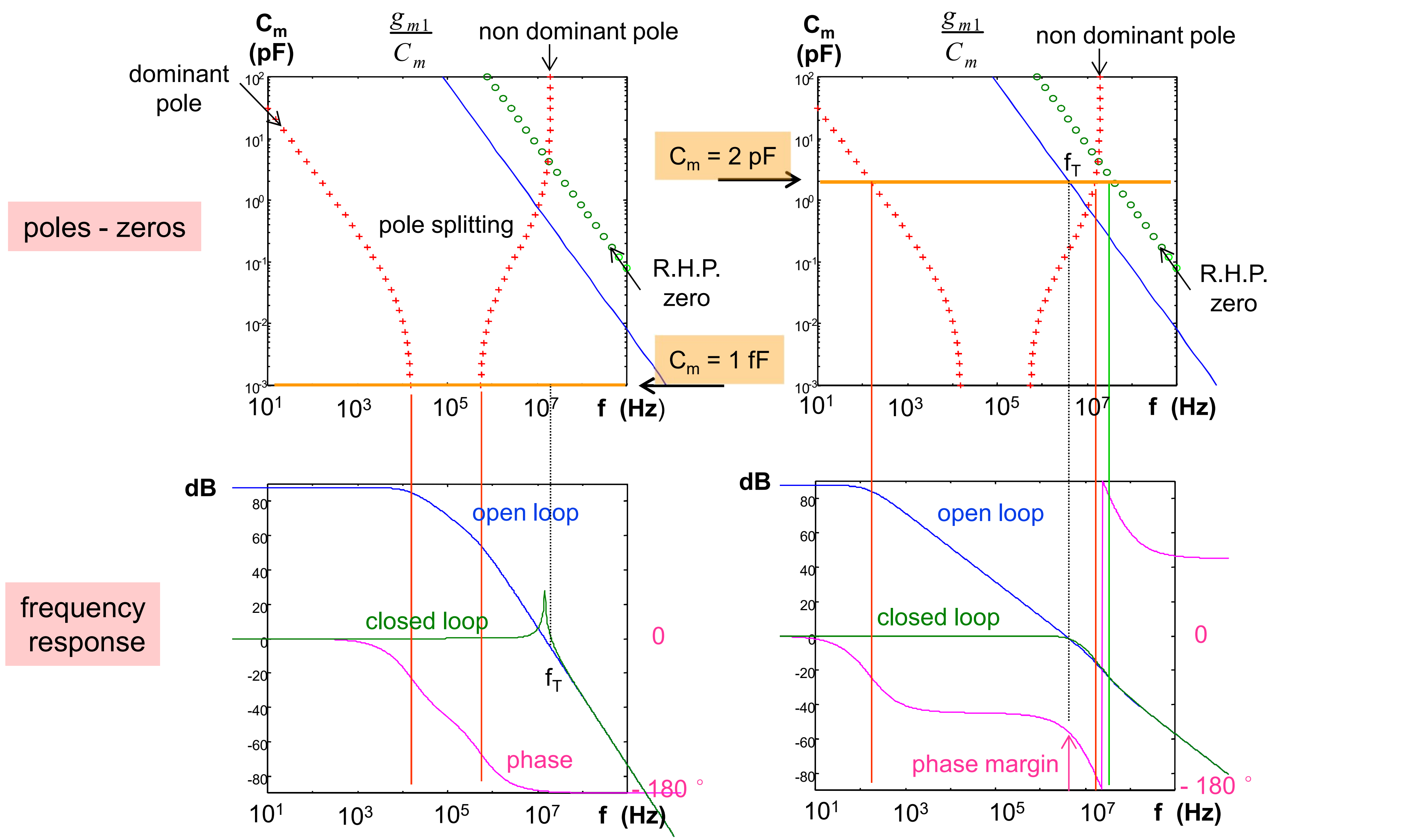
$$NDP = \frac{g_{m2}}{g_{m1}}\frac{C_m^2}{C_1C_2 + C_m(C_1+C_2)}$$

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

$$Z = \frac{\omega_z}{GBW}$$

$$Z = \frac{g_{m2}}{g_{m1}}$$

Met. de Compensación: Compensación Miller



Tomado de P.Jespers – "Interfacing Microsystems" IWS 2001

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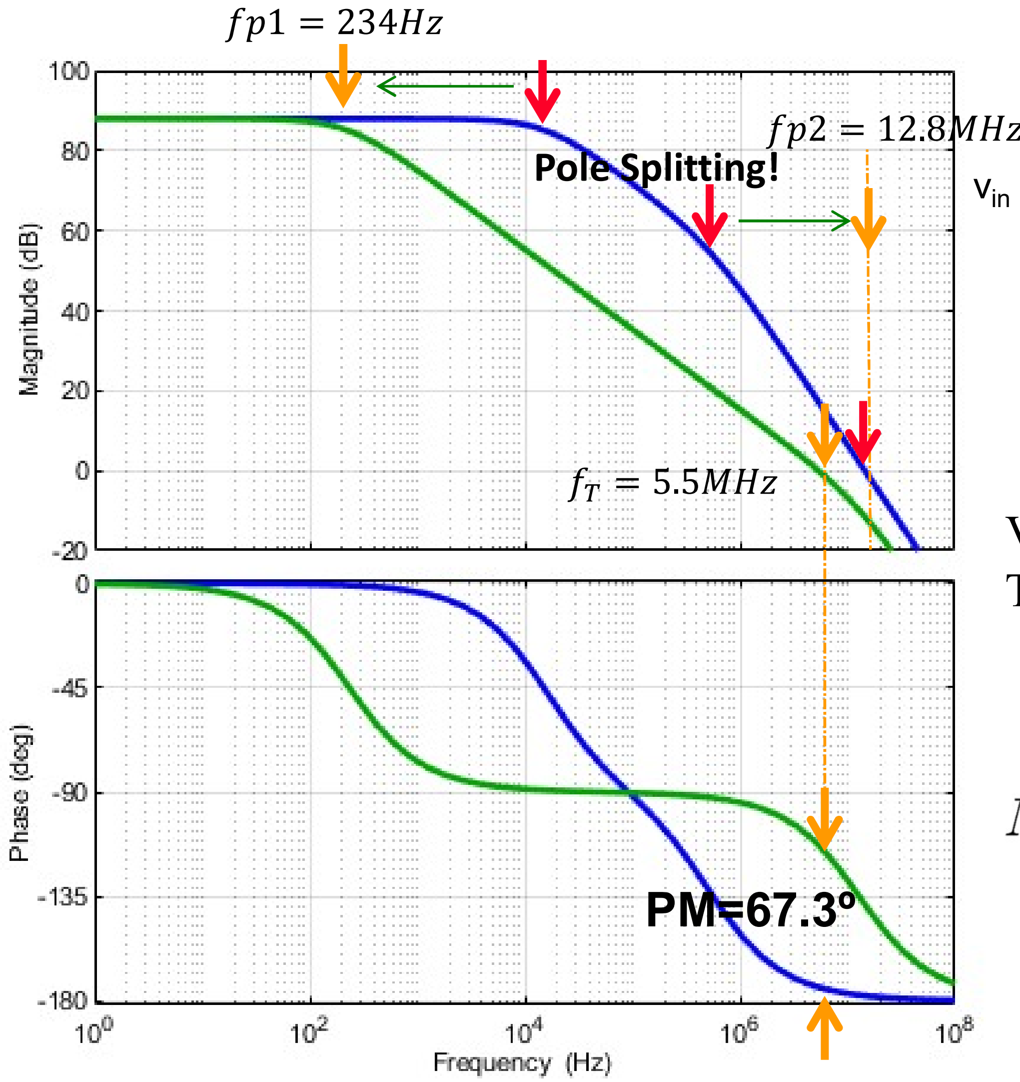

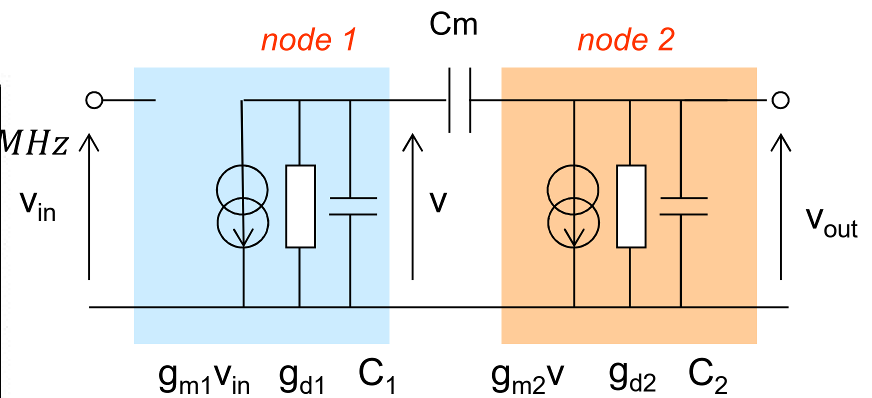

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$C_1 = 1pF$ $\quad C_2 = 3pF$

Criterio usual: NDP=2.2

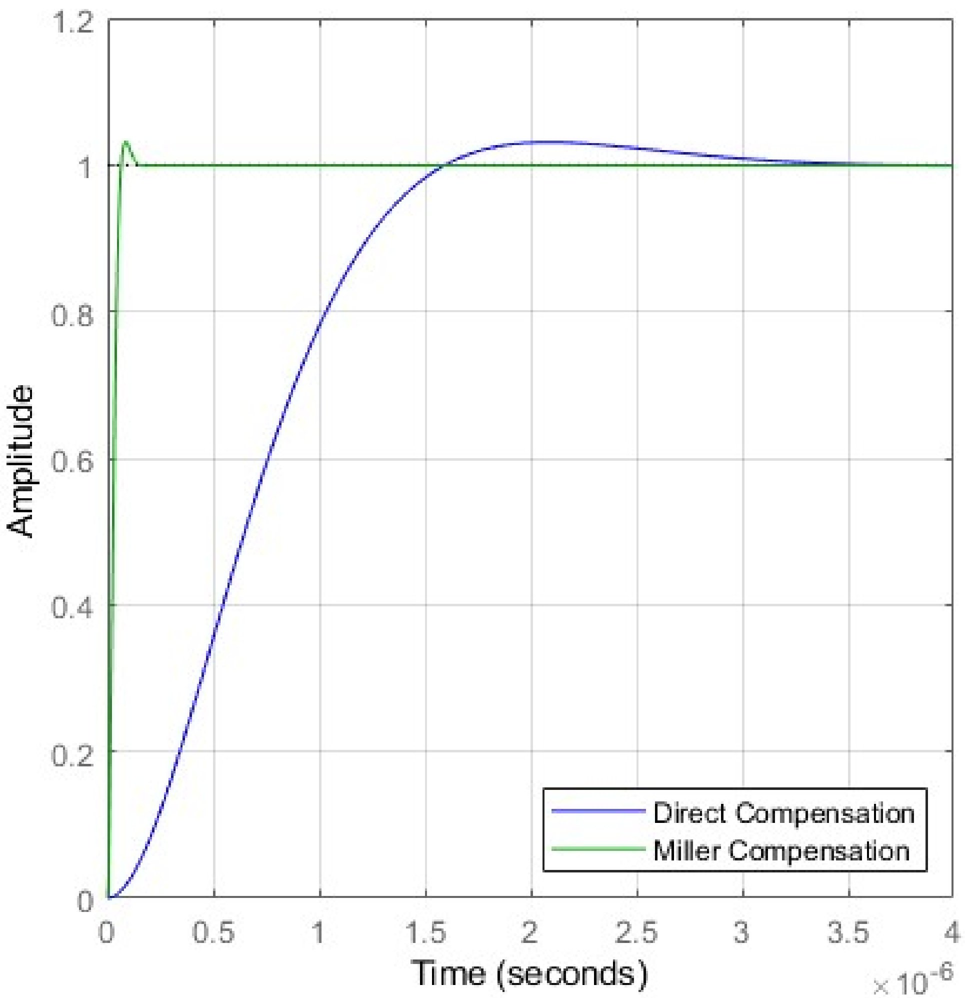
$$NDP = \frac{g_{m2}}{g_{m1}} \frac{C_m^2}{C_1C_2 + C_m(C_1 + C_2)}$$

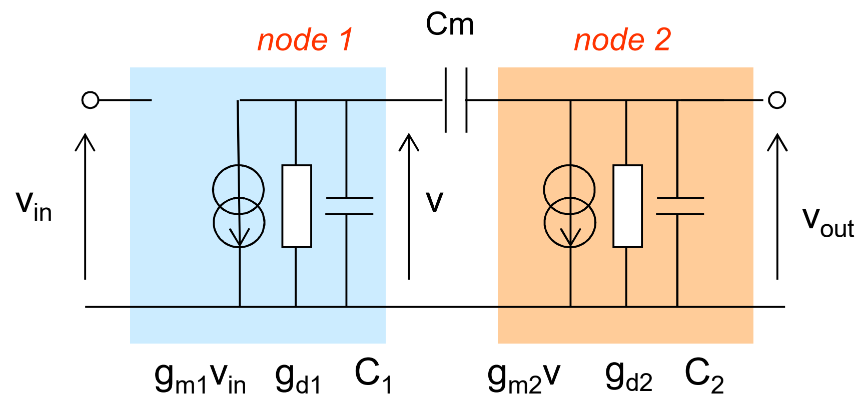
Resuelvo eq. de 2do orden en Cm:

$$C_m = 1.36pF$$

Fácil de integrar ✓

Met. de Compensación: Compensación Miller





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Resuelvo eq. de 2do orden en Cm:

$$C_m = 1.36pF$$

Fácil de integrar ✔

Resumen: Estabilidad en Amps. de 2 Etapas

Compensación	fp1	fp2	fz	fT	PM
Sin compensar	16 kHz	531 kHz	-	14.5 MHz	2º
Directa $C_D = 1650pF$	9.6 Hz	531 kHz	-	222 kHz	67.3º
Miller $C_m = 1.36pF$	228 Hz	20 MHz	58 MHz	5.5 MHz	69.2º

- 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)