Design of Multistage Operational amplifiers

Willy Sansen

KULeuven, ESAT-MICAS

Leuven, Belgium

willy.sansen@esat.kuleuven.be

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Ref.: W. Sansen : Analog Design Essentials, Springer 2006

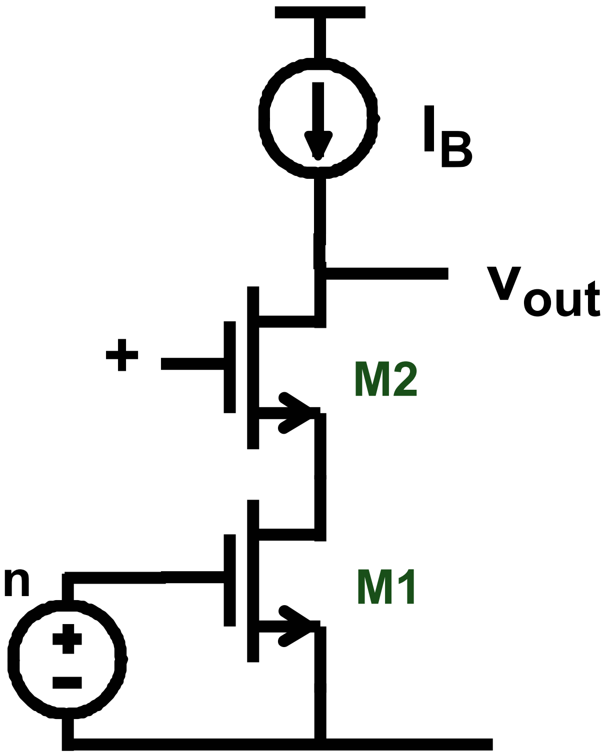
Why three-stage amplifiers ?

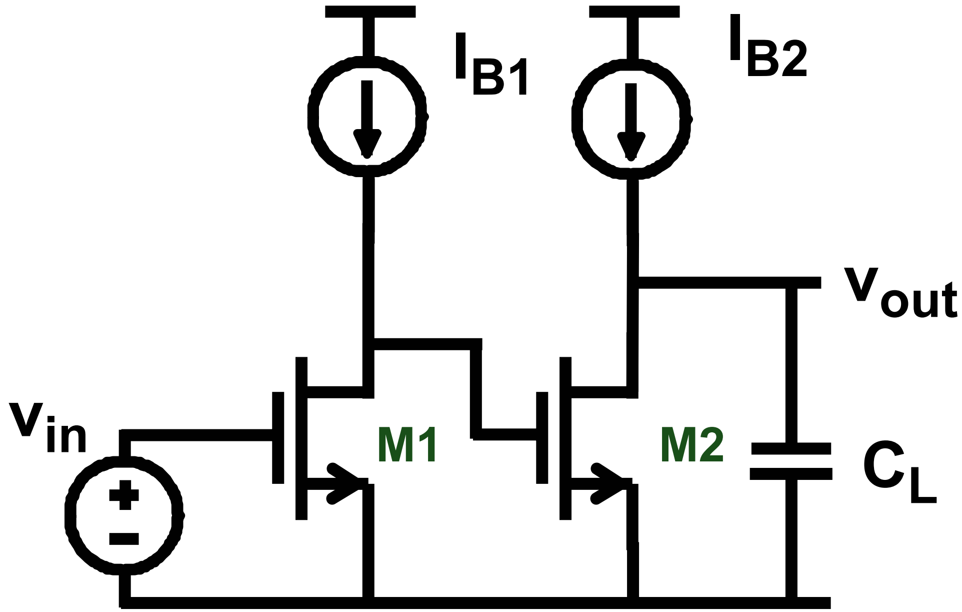
1. Each MOST only gives $g_m r_o \approx$ 15 or 24 dB :
   High gain requires three stages !

2. For drivers (small R_L) : $g_m R_L$ is very low :
   High gain requires three stages !

3. For low V_{DD}, no cascoding but cascading !
   High gain requires three stages !

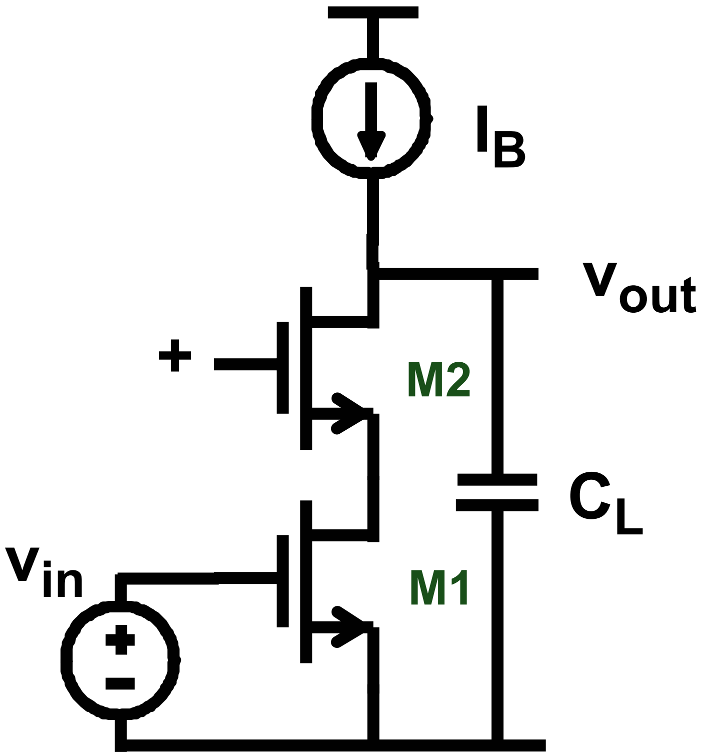
No cascoding but cascading !

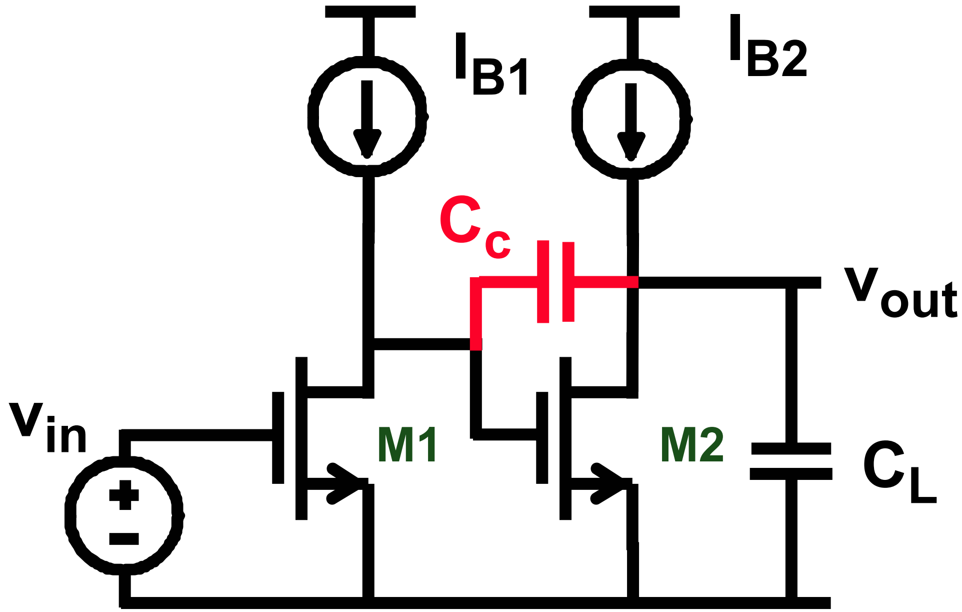




$$A_v = (g_m r_{DS})_1 (g_m r_{DS})_2 \qquad A_v = (g_m r_{DS})_1 (g_m r_{DS})_2$$

Cascode versus cascade

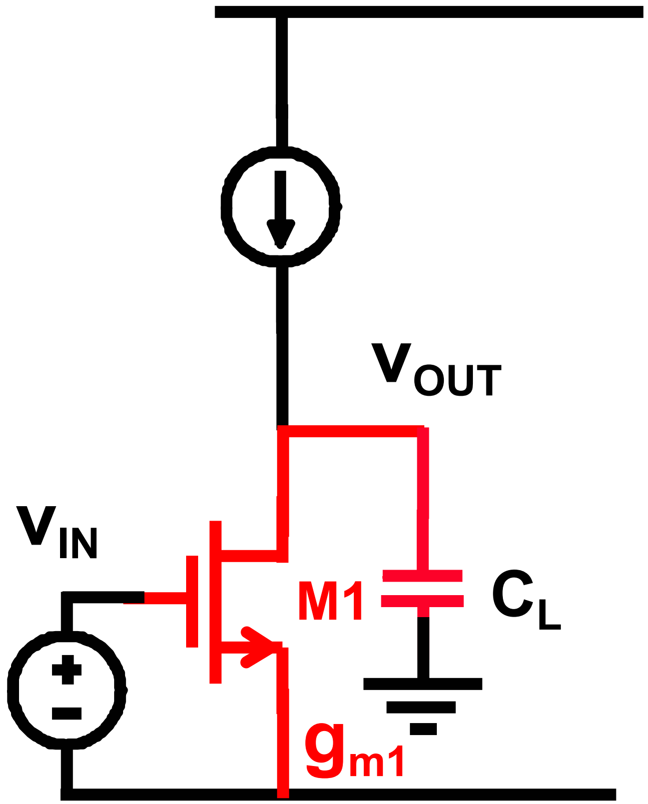




$$GBW = \frac{g_{m1}}{2\pi\, C_L}$$

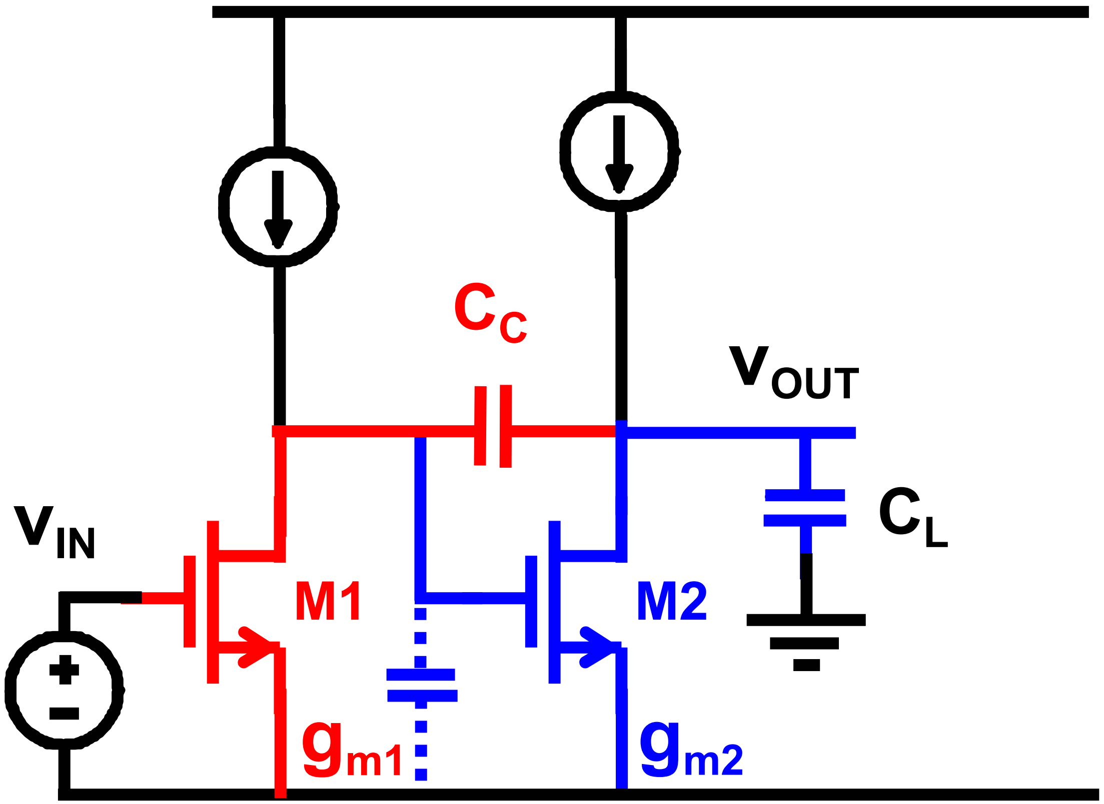
$$GBW = \frac{g_{m1}}{2\pi\, C_c} < \frac{g_{m2}}{2\pi\, C_L}$$

1-stage CMOS OTA



$$GBW = \frac{g_{m1}}{2\pi\, C_L}$$

2-stage Miller CMOS OTA

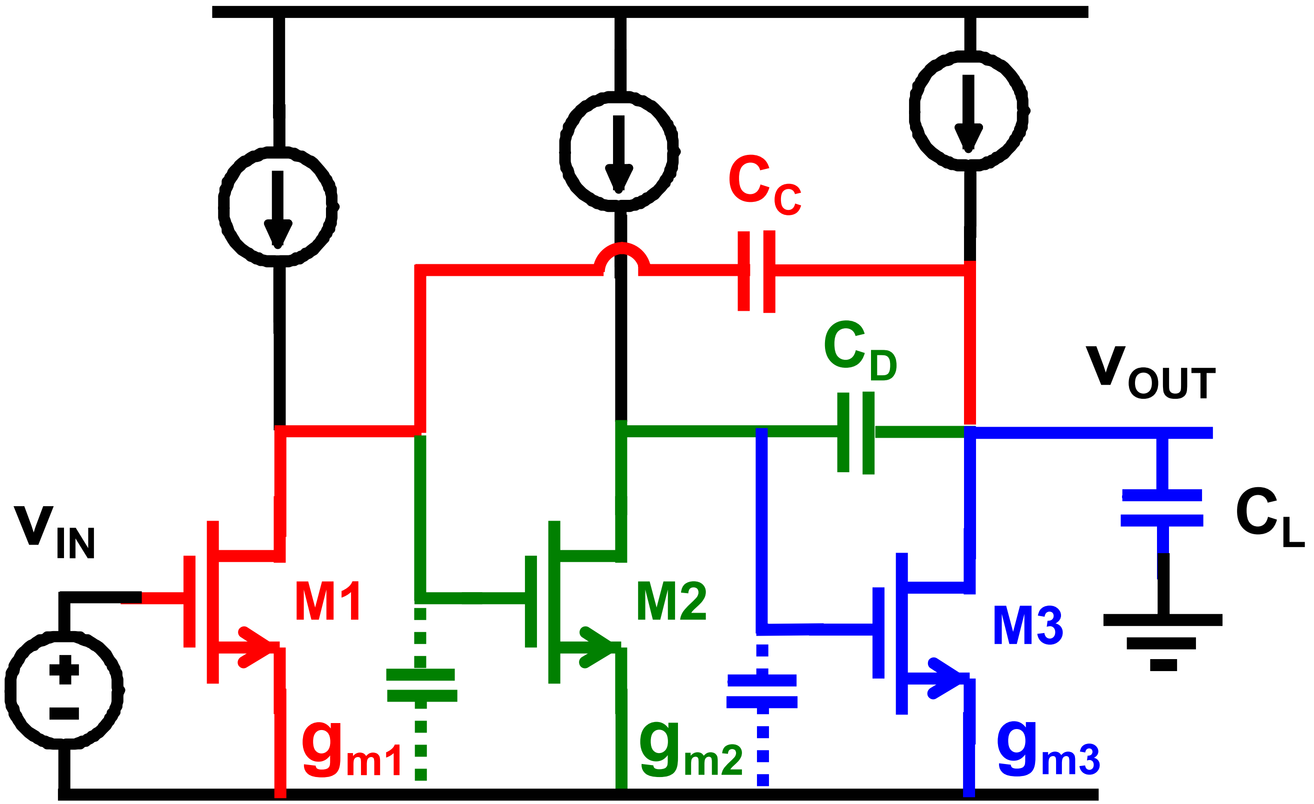


$$GBW = \frac{g_{m1}}{2\pi\, C_C}$$

$$f_{nd1} = \frac{g_{m2}}{2\pi\, C_L}$$

$$f_{nd1} = 3\ GBW$$

3-stage Nested Miller CMOS OTA



$$GBW = \frac{g_{m1}}{2\pi C_C}$$

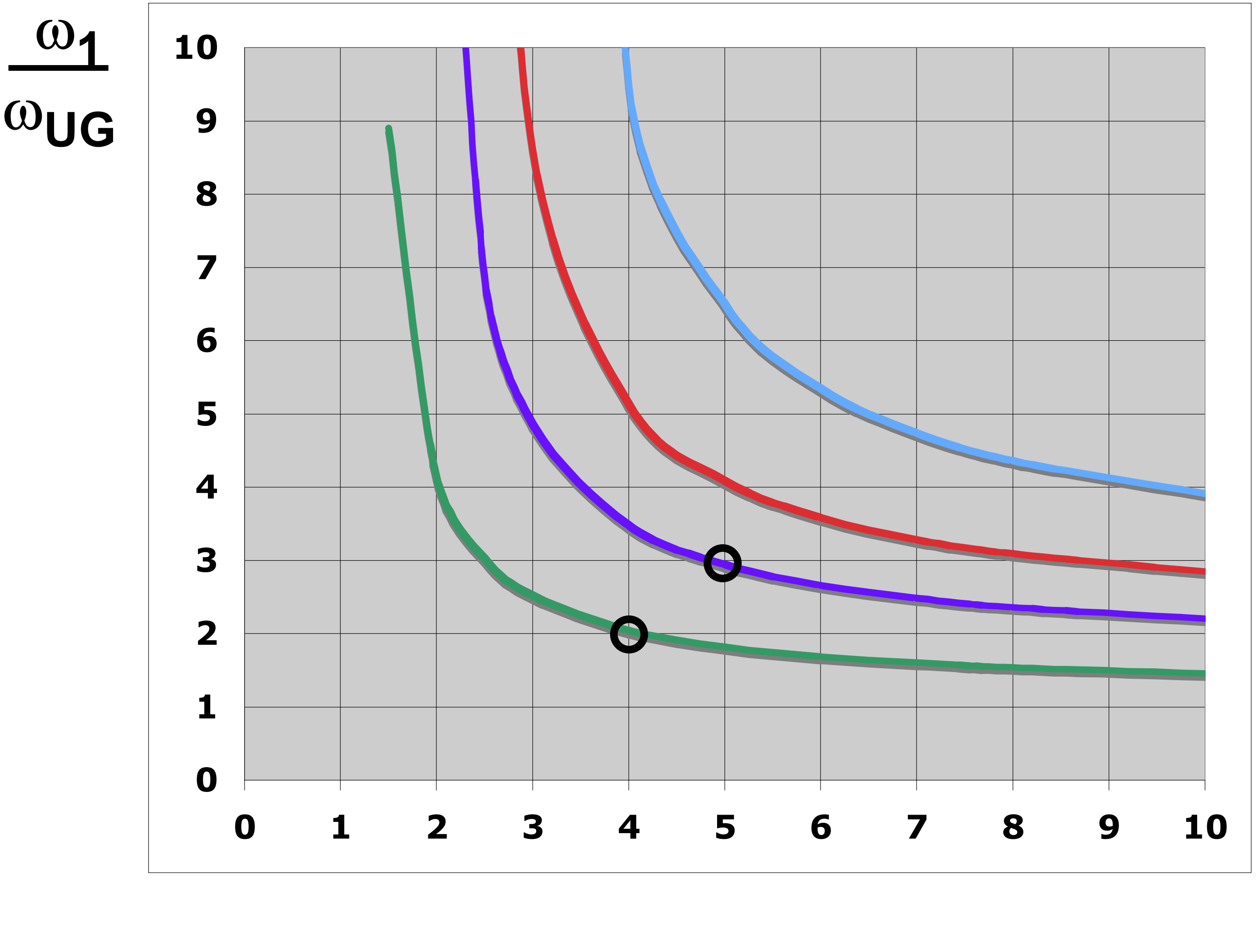
$$f_{nd1} = \frac{g_{m2}}{2\pi C_D}$$

$$f_{nd2} = \frac{g_{m3}}{2\pi C_L}$$

$$f_{nd1} = 3\ GBW$$

$$f_{nd2} = 5\ GBW$$

3-pole opamp : phase margin PM



PM ≈

$$90^{o} - \arctan\left(\frac{\omega_{UG}}{\omega_1}\right) - \arctan\left(\frac{\omega_{UG}}{\omega_2}\right)$$

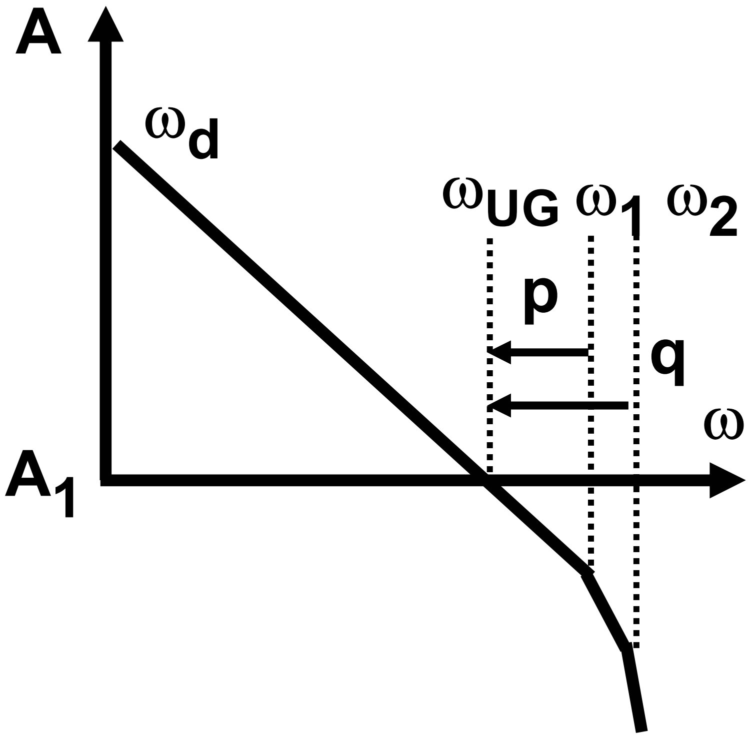
70°

65°

60°

50° PM

Three-pole opamp



$p = \omega_1 / \omega_{UG}$

$q = \omega_2 / \omega_{UG}$

Open loop gain

$$A = \frac{\omega_{UG}}{s} \frac{1}{\left(1 + \frac{s}{\omega_1}\right)\left(1 + \frac{s}{\omega_2}\right)}$$

Closed loop gain (Unity gain)

$$A_1 = \frac{A}{1+A} \approx$$

$$\frac{1}{1 + \frac{s}{\omega_{UG}} + \left(\frac{1}{p} + \frac{1}{q}\right)\left(\frac{s}{\omega_{UG}}\right)^2 + \frac{1}{pq}\left(\frac{s}{\omega_{UG}}\right)^3}$$

3-pole opamp: $\omega_1 = 3\ \omega_{UG}$ $\omega_2 = 5\ \omega_{UG}$

Open loop

Three poles:

ω_d

ω_1 3x

ω_2 5x

Unity gain

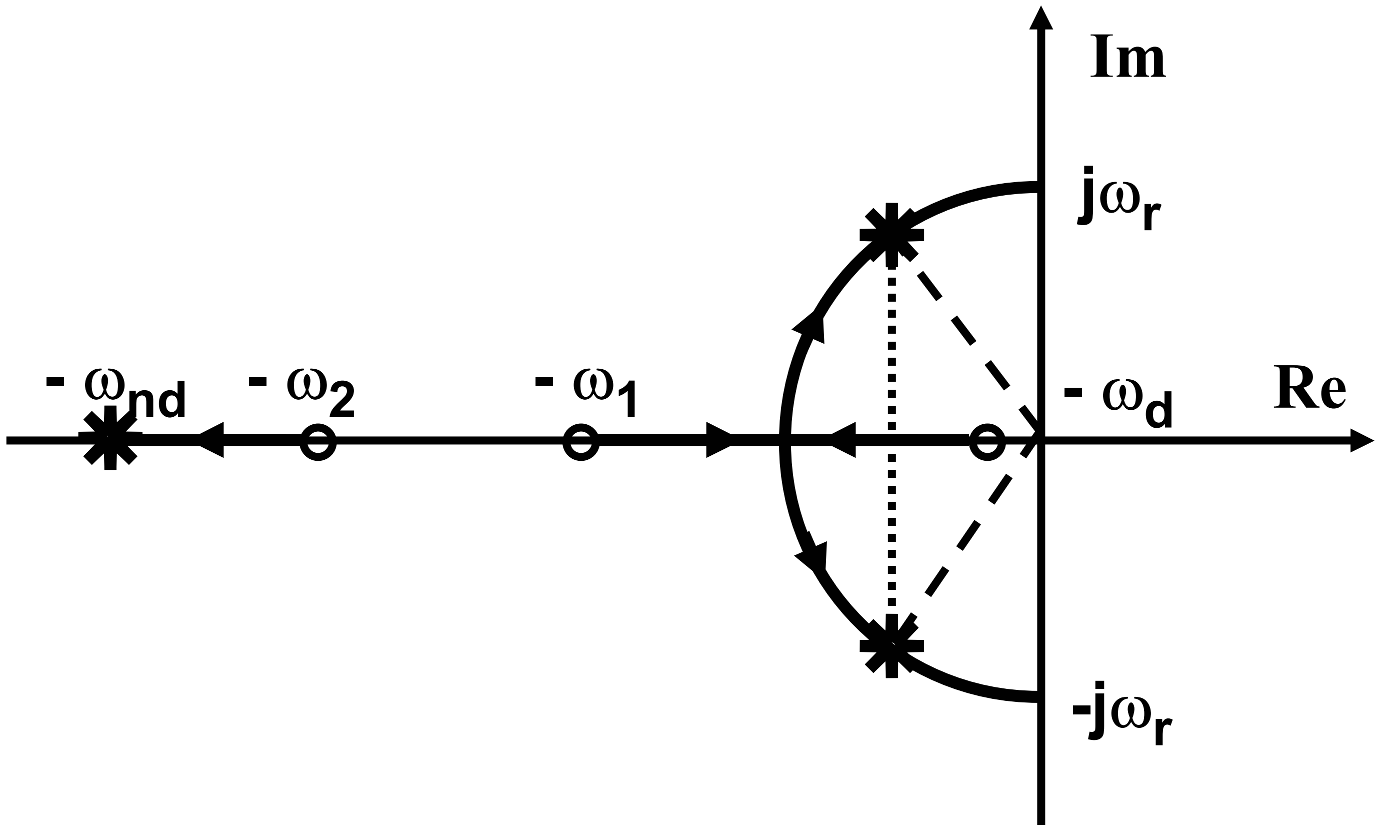
Three poles:

ω_d

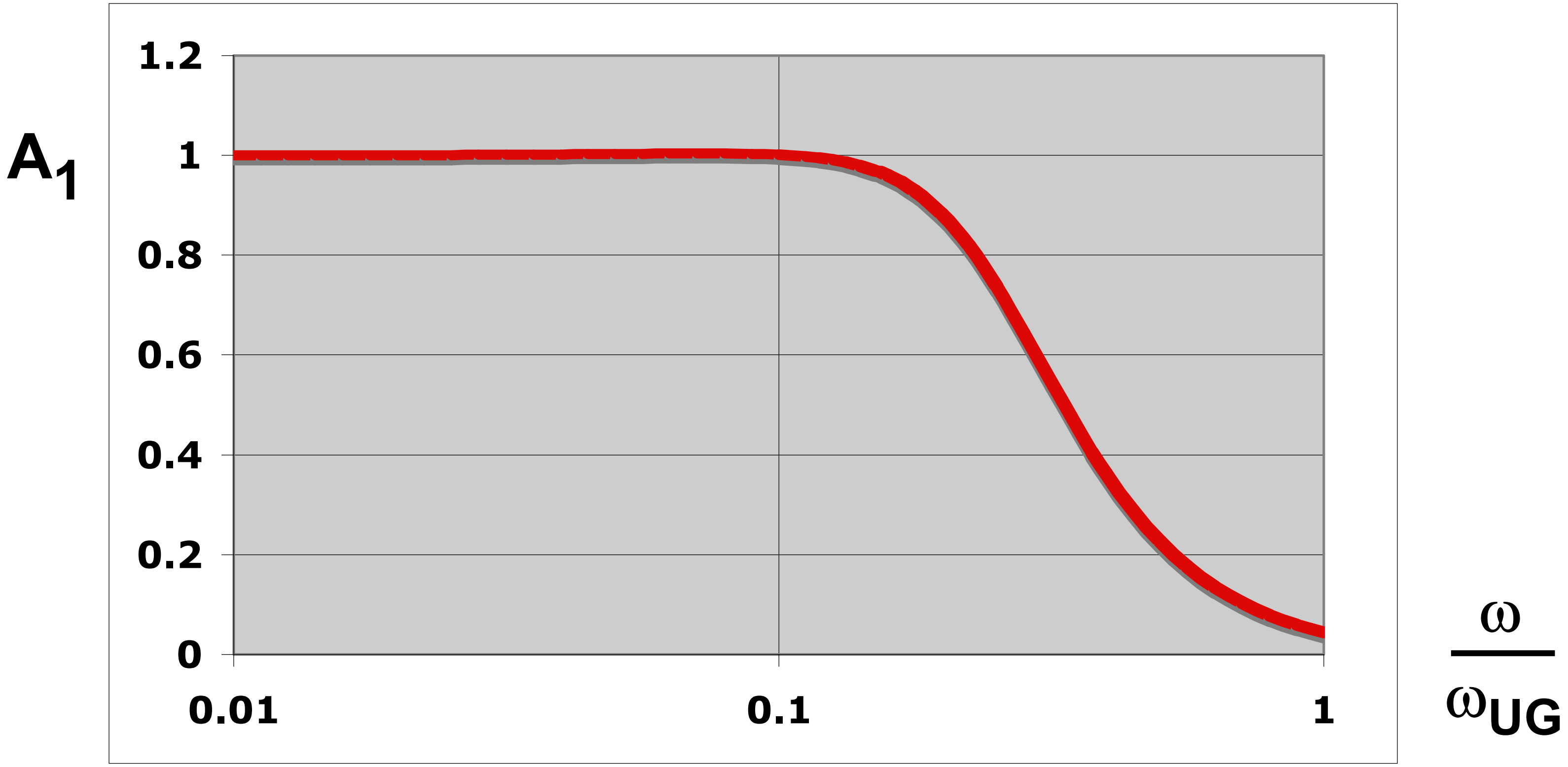
ω_{nd} 6x

ω_r 1± j1.2 x

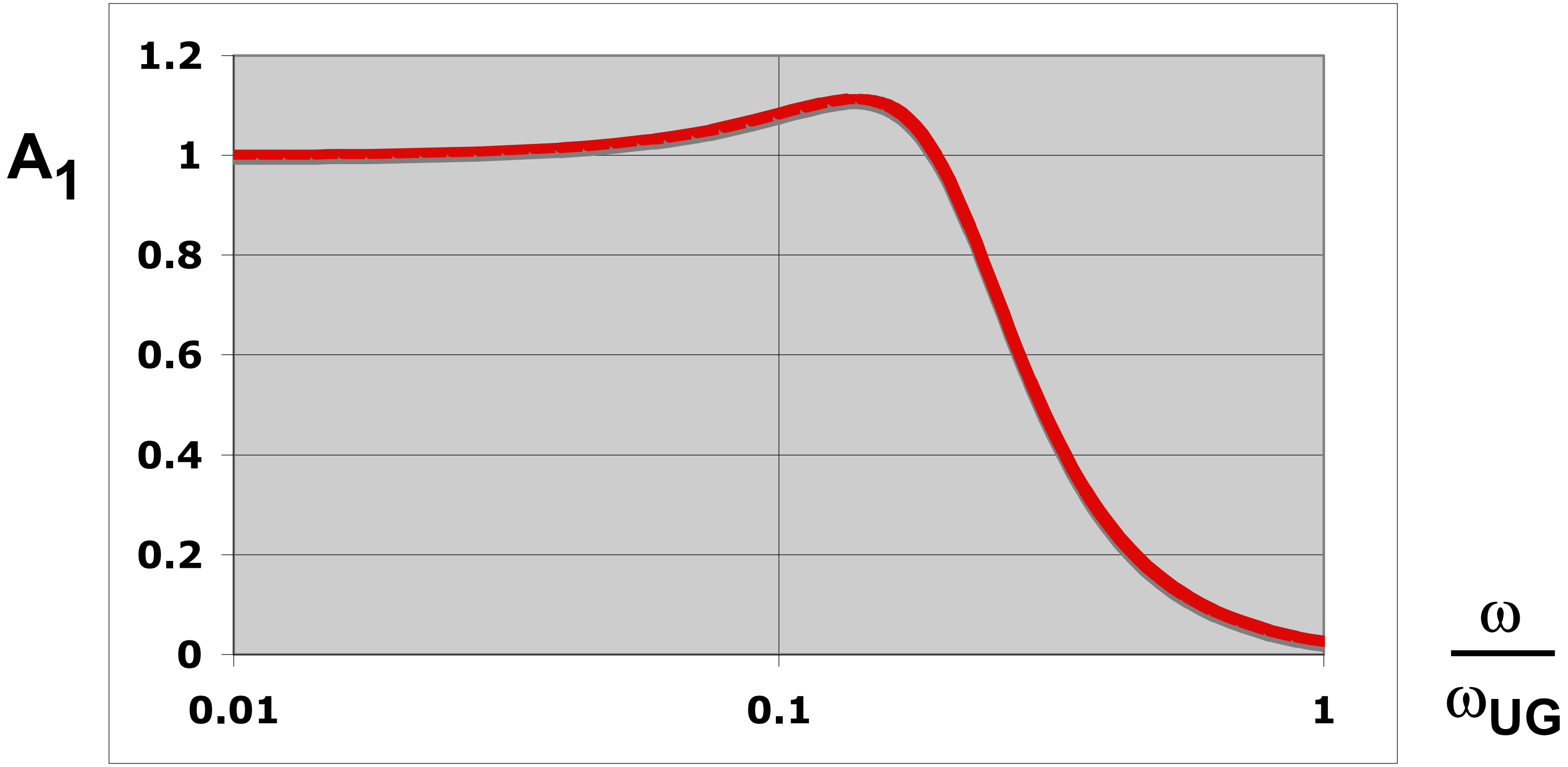
1.6 50°



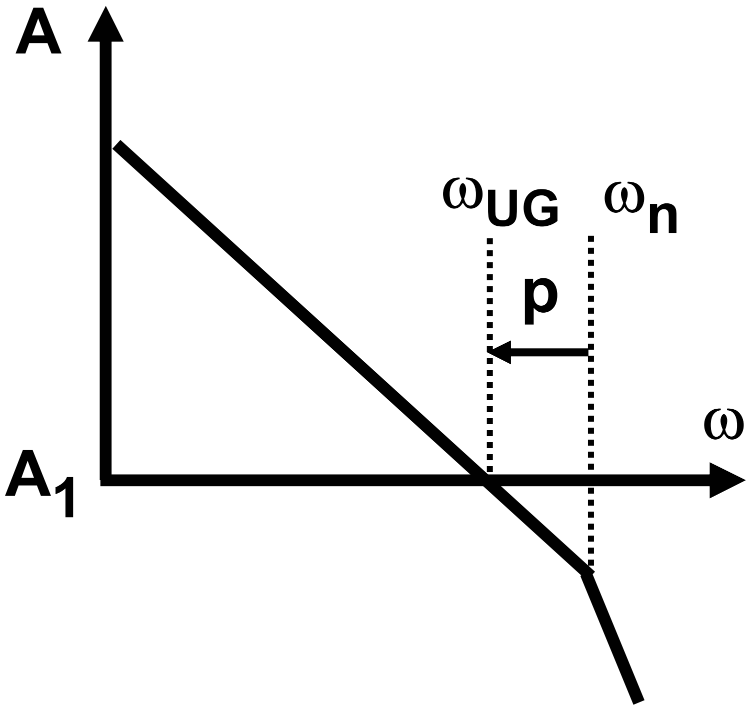
Three-stage with 3/5 on 60º PM with unity gain



Three-stage with 2/4 on 50º PM with unity gain



Three-pole opamp with complex poles



Open loop gain

$$A = \frac{\omega_{UG}}{s} \frac{1}{1 + 2\zeta \frac{s}{\omega_n} + \left(\frac{s}{\omega_n}\right)^2}$$

Closed loop gain (Unity gain)

$$A_1 = \frac{A}{1+A} \approx$$

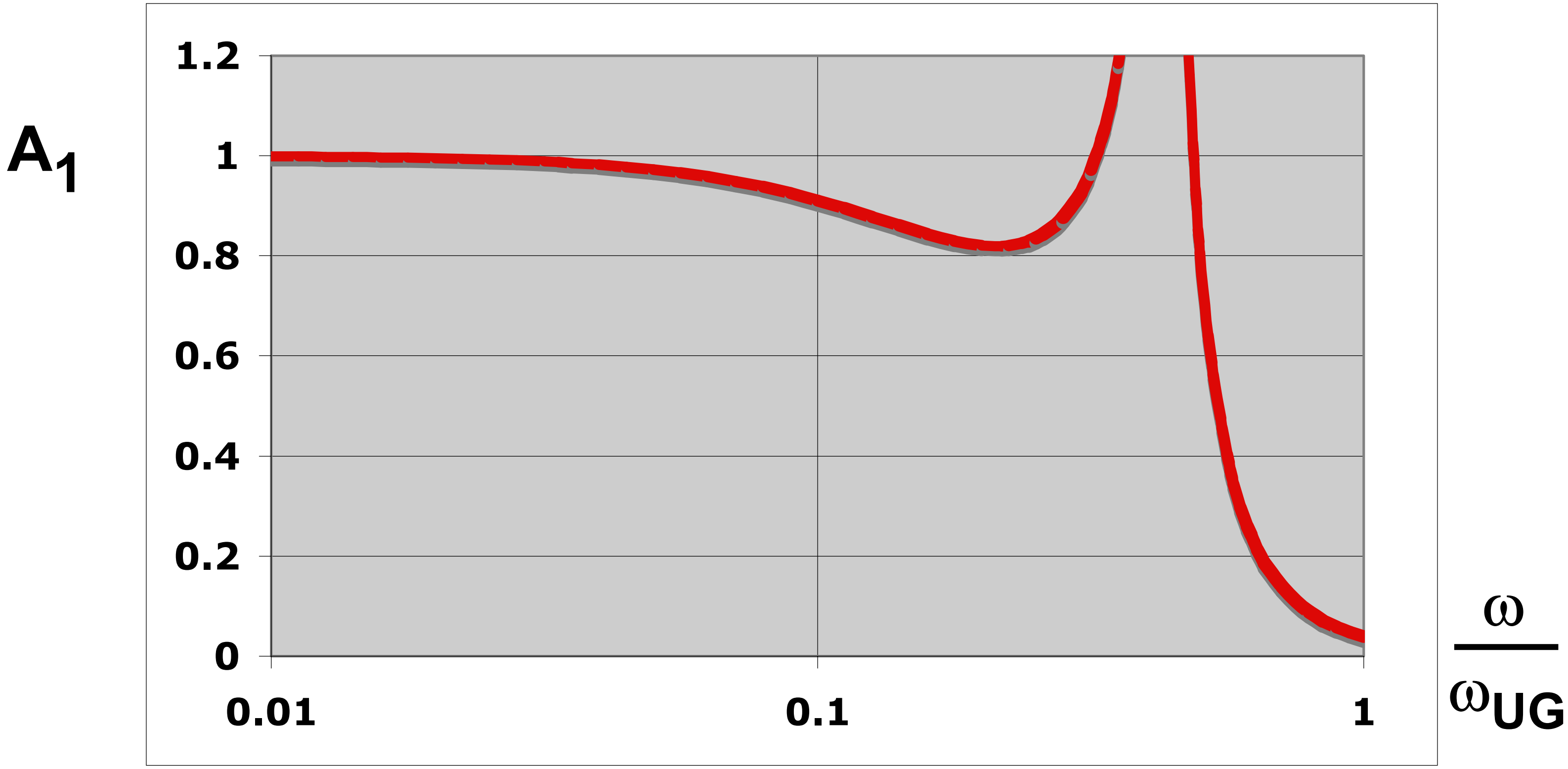
$$\frac{1}{1 + \frac{s}{\omega_{UG}} + \frac{2\zeta}{p}\left(\frac{s}{\omega_{UG}}\right)^2 + \frac{1}{p^2}\left(\frac{s}{\omega_{UG}}\right)^3}$$

Two parameters:

ζ damping (=1/2Q)

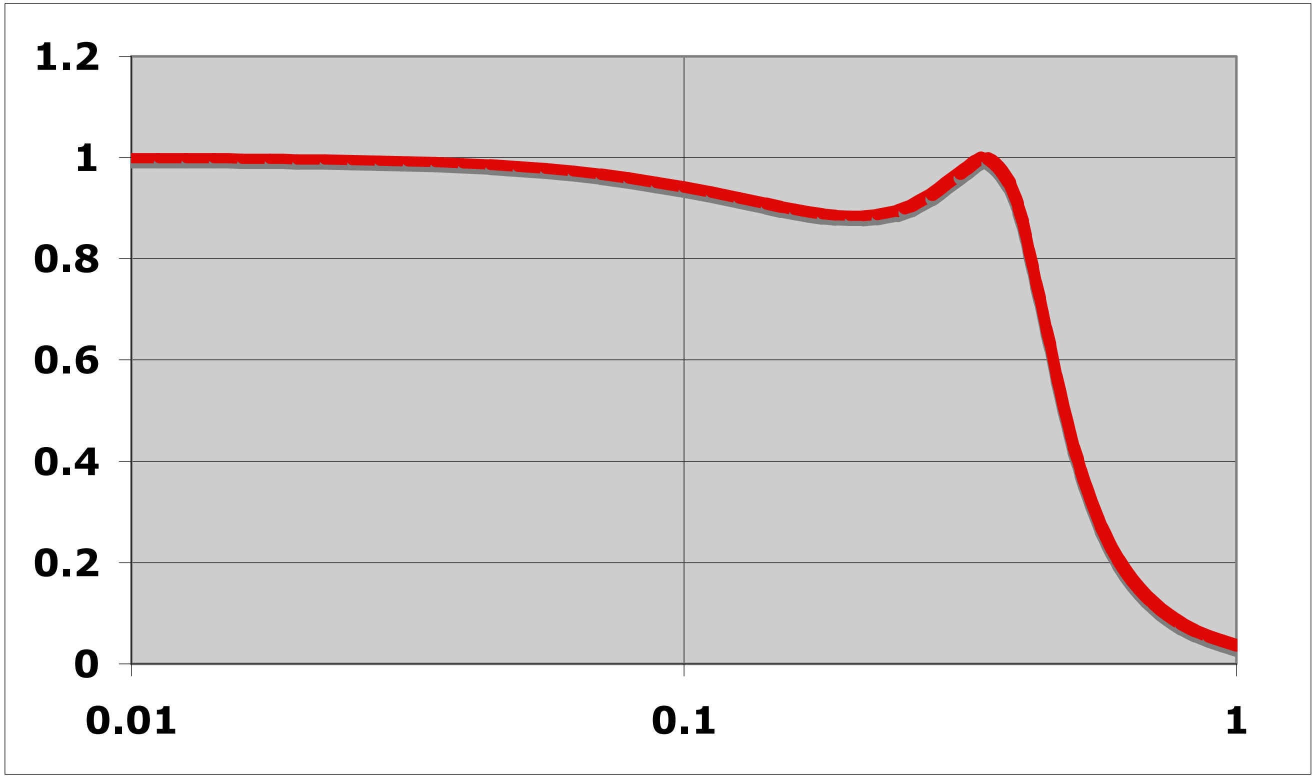
$p = \omega_n / \omega_{UG}$

Unity-gain 3-pole opamp: $\zeta = 0.28$ $p = 2.828$



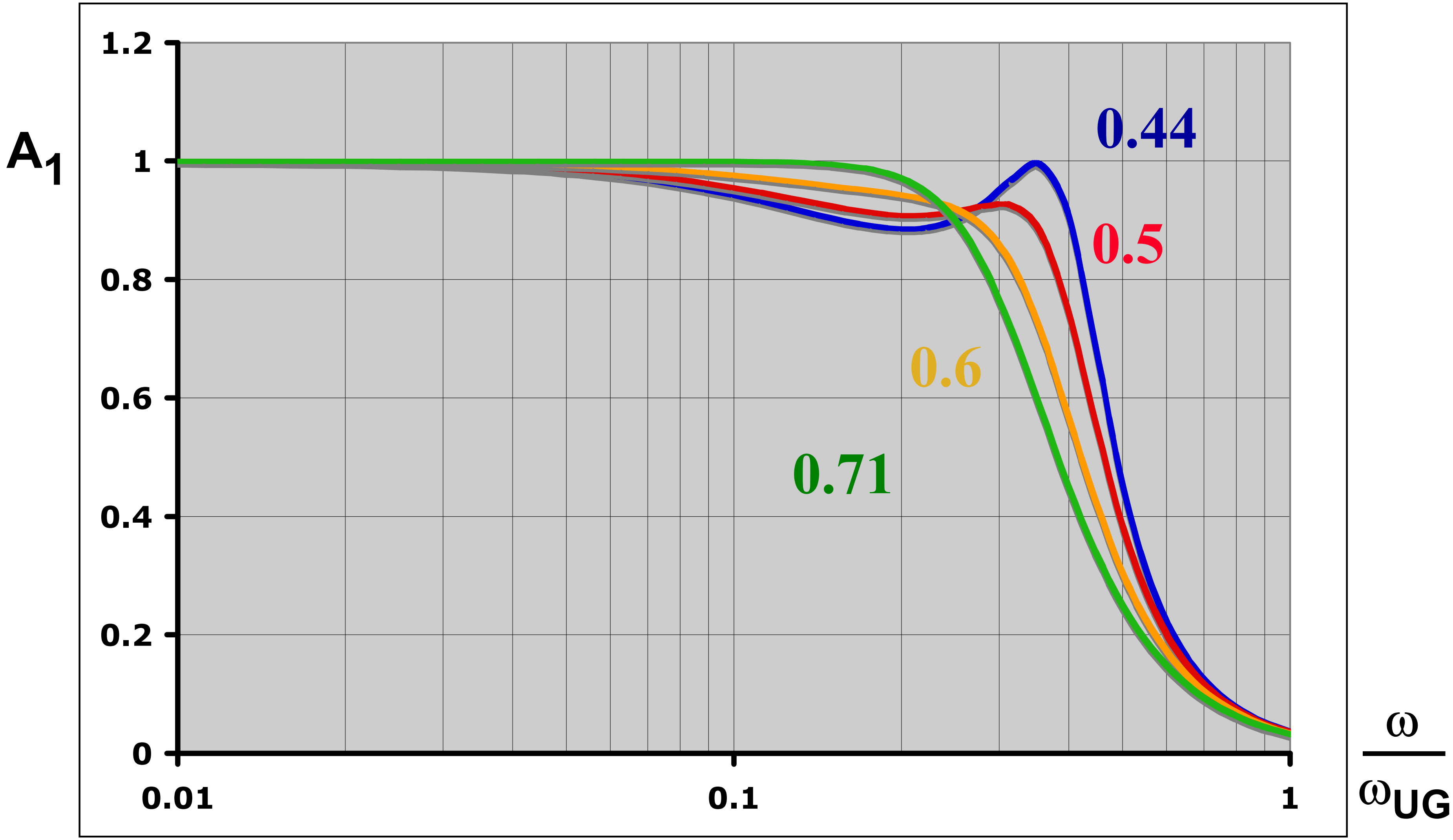
Unity-gain 3-pole opamp: $\zeta = 0.44$ p = 2.828

A_1



$\frac{\omega}{\omega_{UG}}$

Unity-gain 3-pole opamp : ζ = … p = 2.828

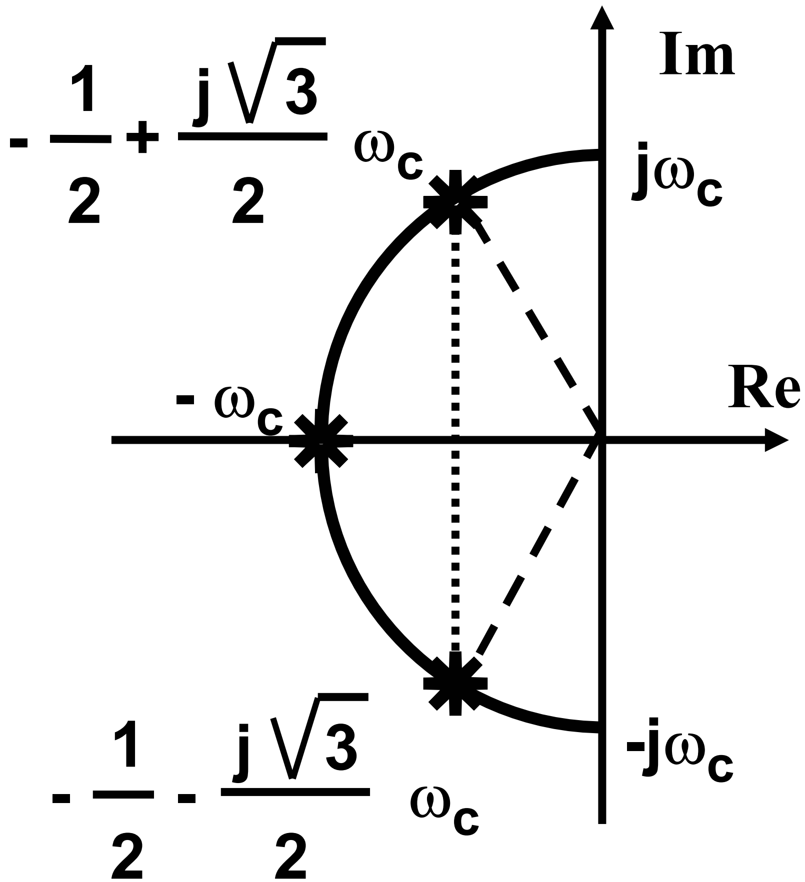


Unity-gain 3-pole opamp: $\zeta = 0.71 \quad p = 2.828$

Closed loop

Butterworth response :

maximally flat



Poles :

$$\omega_{-3dB} = \frac{\omega_c}{2}$$

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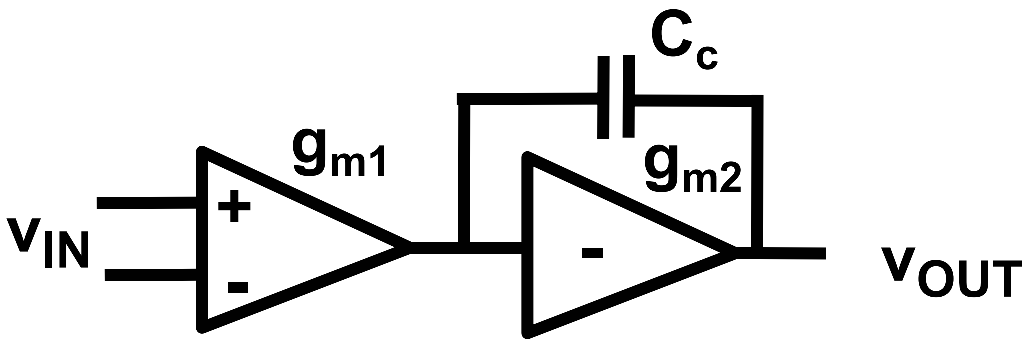
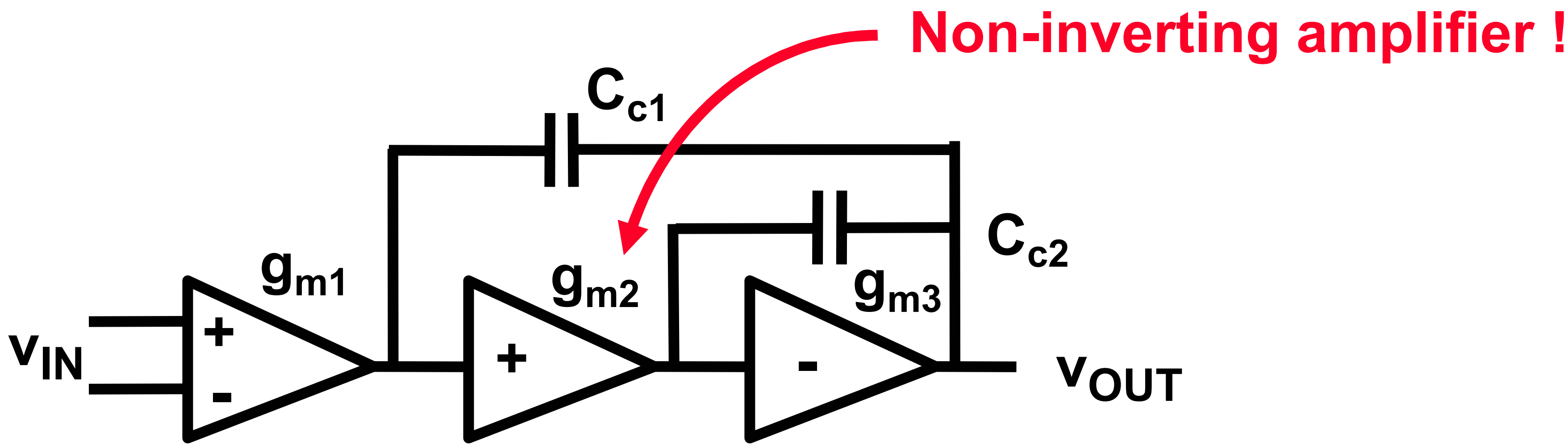
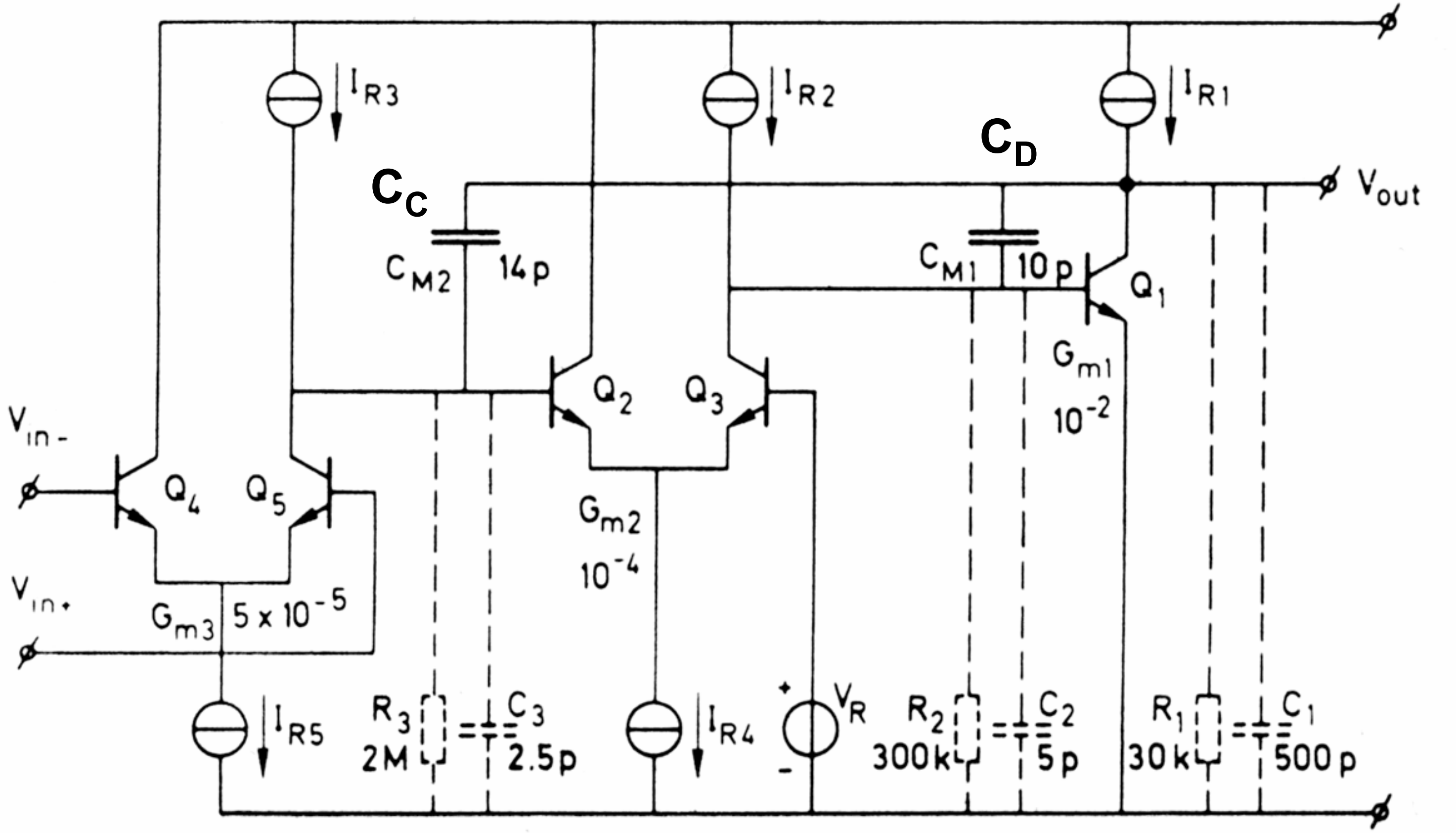
Three-stage configuration





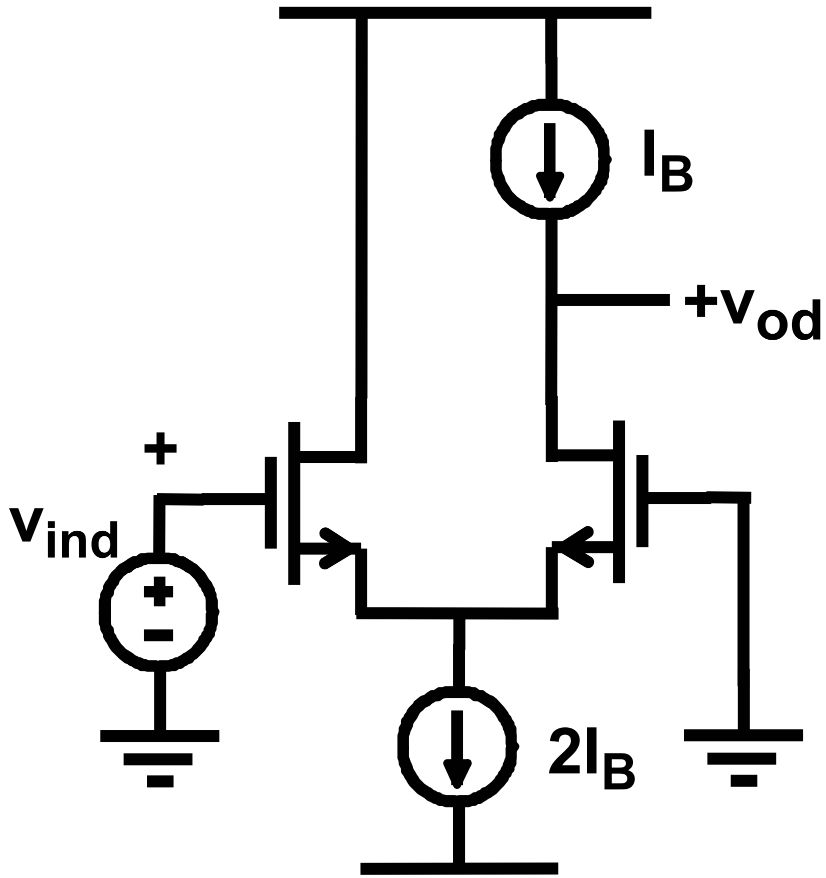
Nested Miller with differential pair as 2nd stage



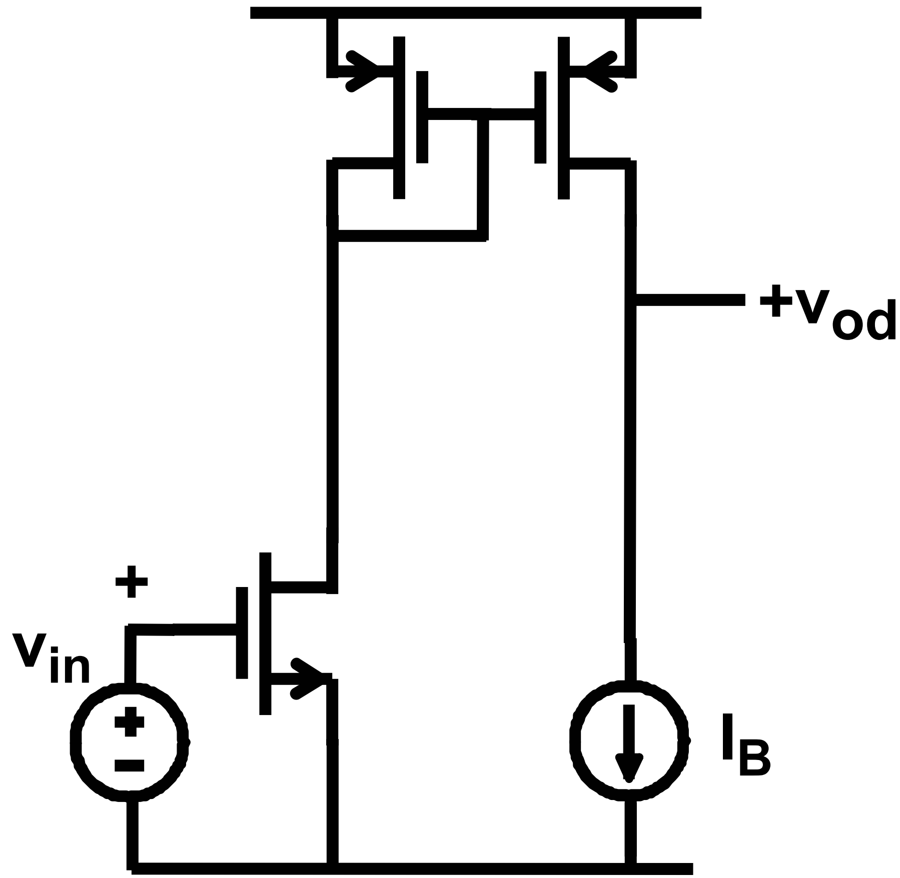
$$GBW = \frac{g_{m4}}{2\pi\ C_C}$$

Huijsing, JSSC Dec.85, pp.1144-1150

Two ways to non-inverting gain

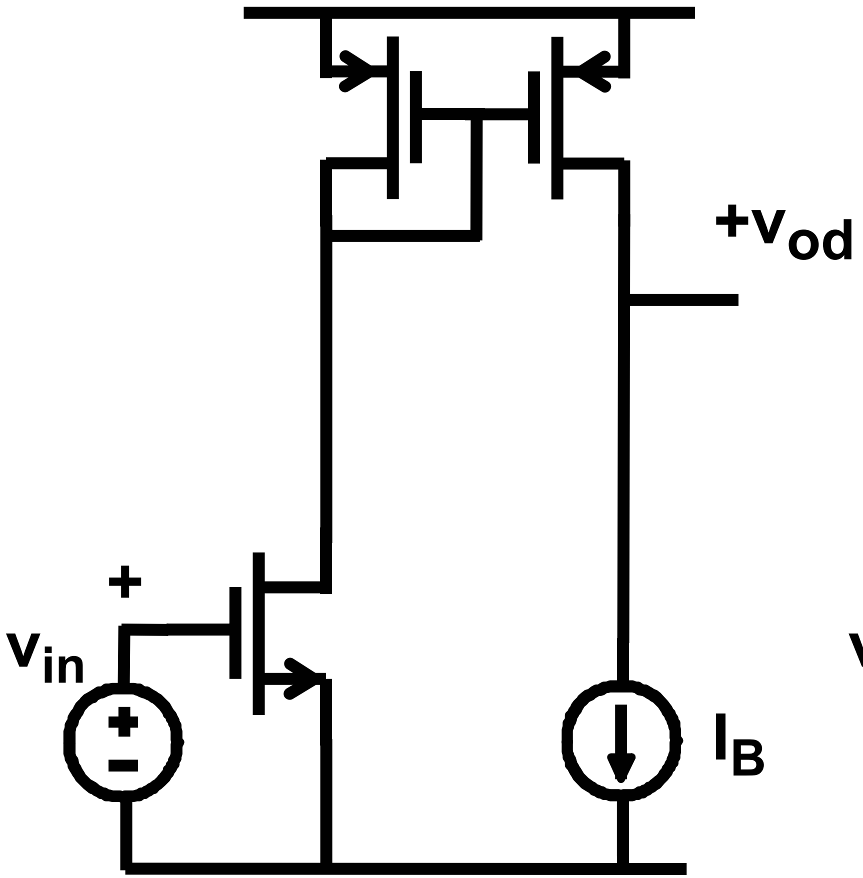


Differential pair

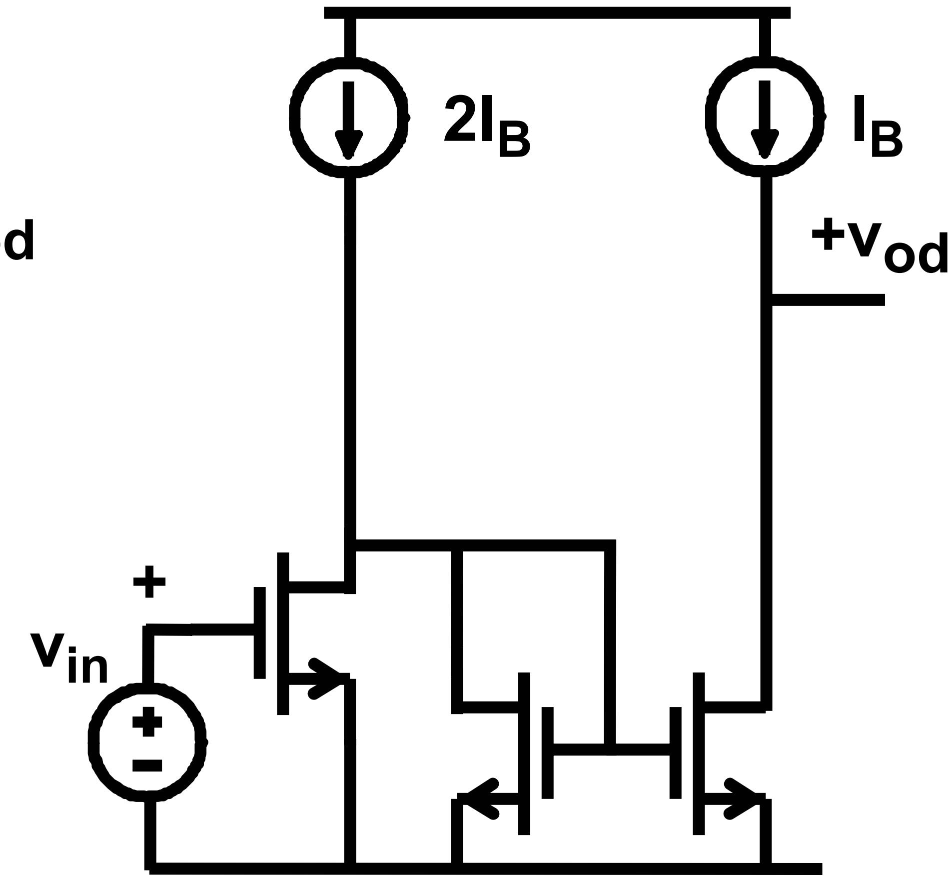


Current mirror

Two types of current mirroring

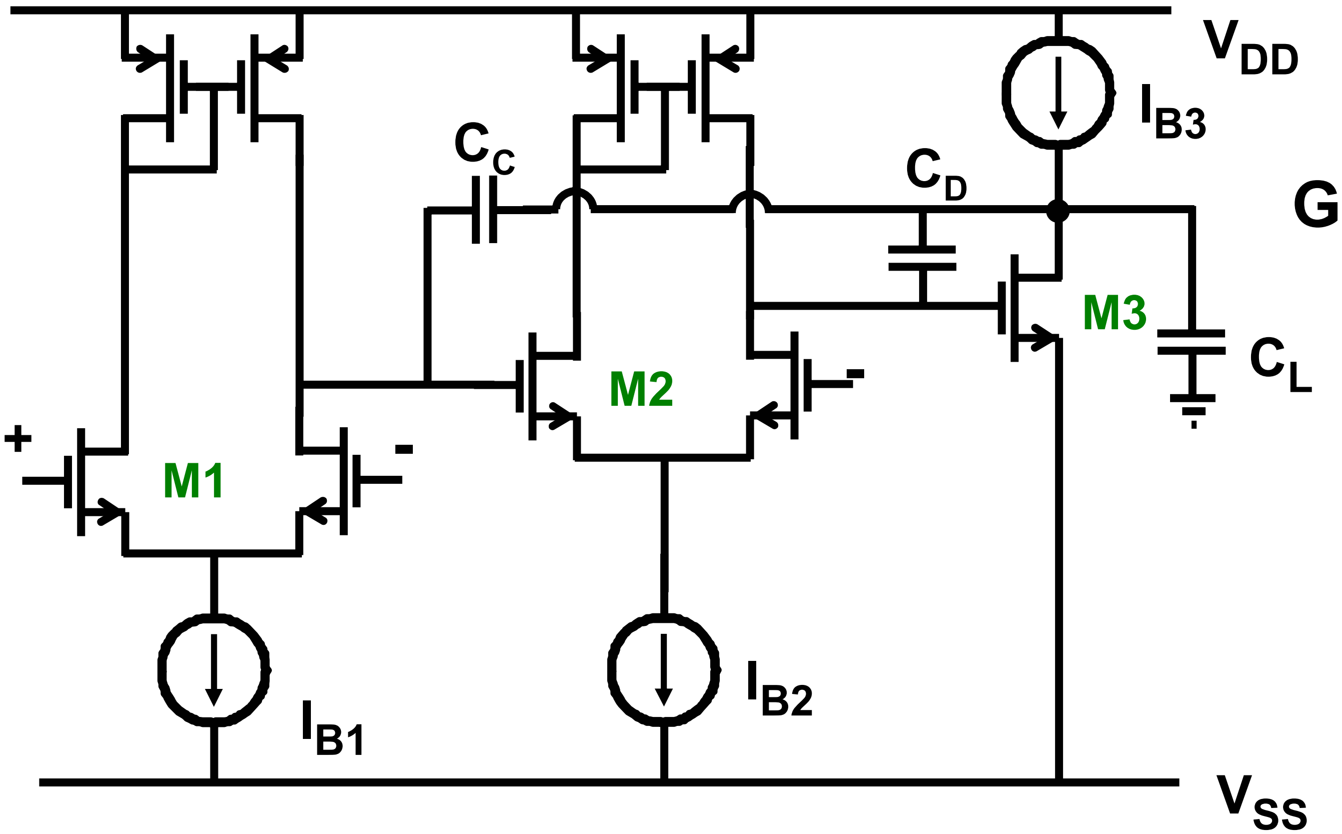


Current mirror 1



Current mirror 2 (only nMOST)

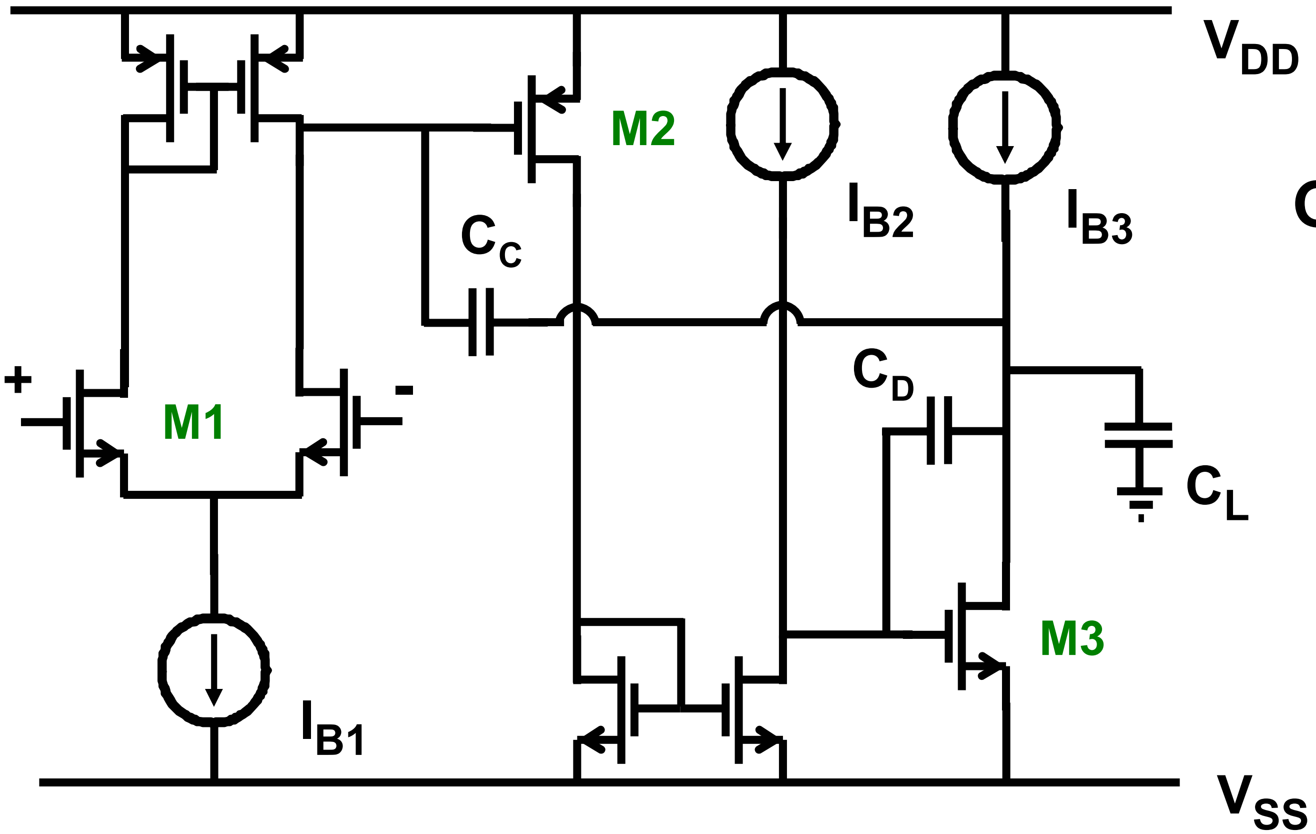
Nested Miller with differential pair as 2nd stage



$$GBW = \frac{g_{m1}}{2\pi\, C_C}$$

"Huijsing"

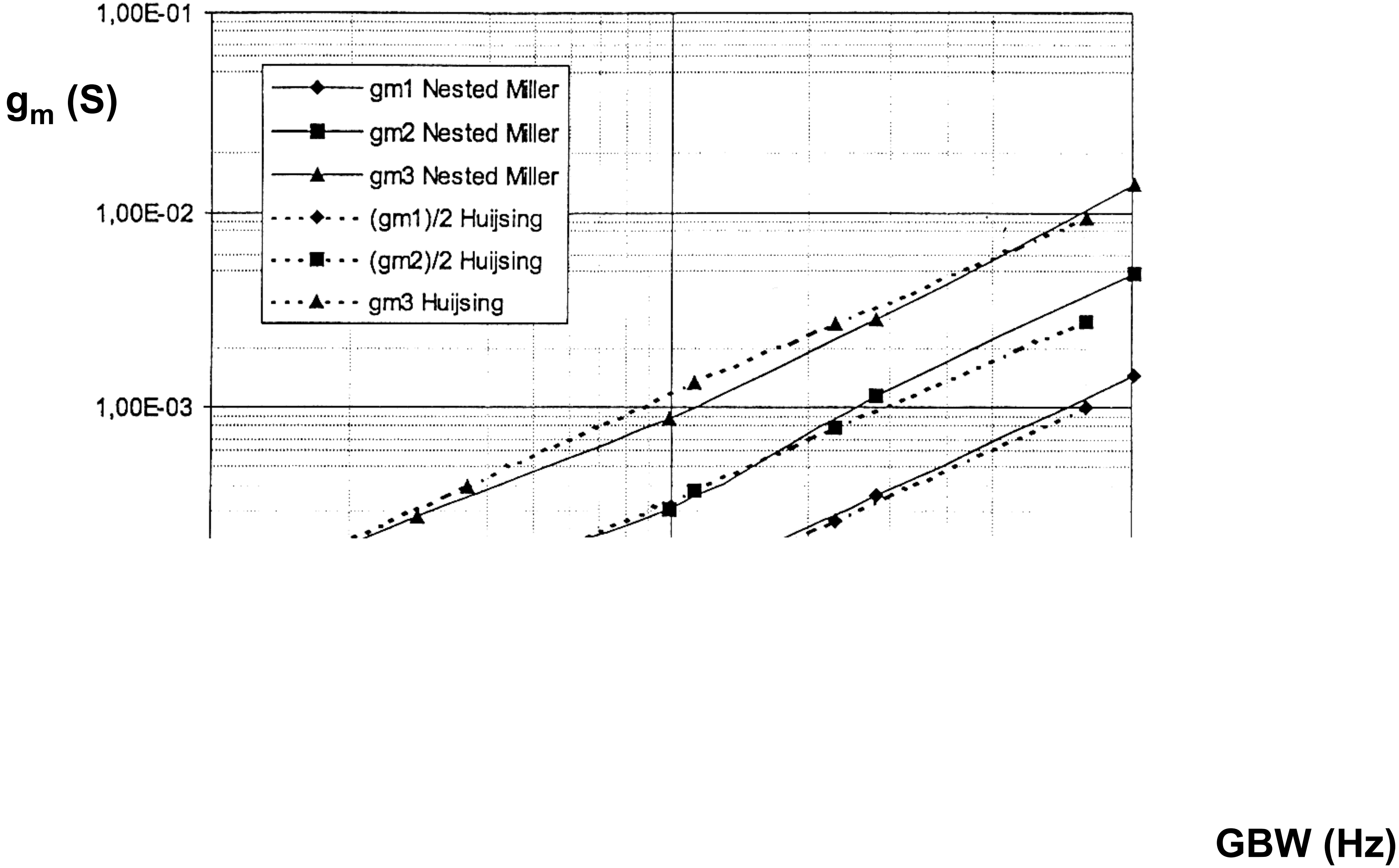
Nested Miller with current mirror as 2nd stage



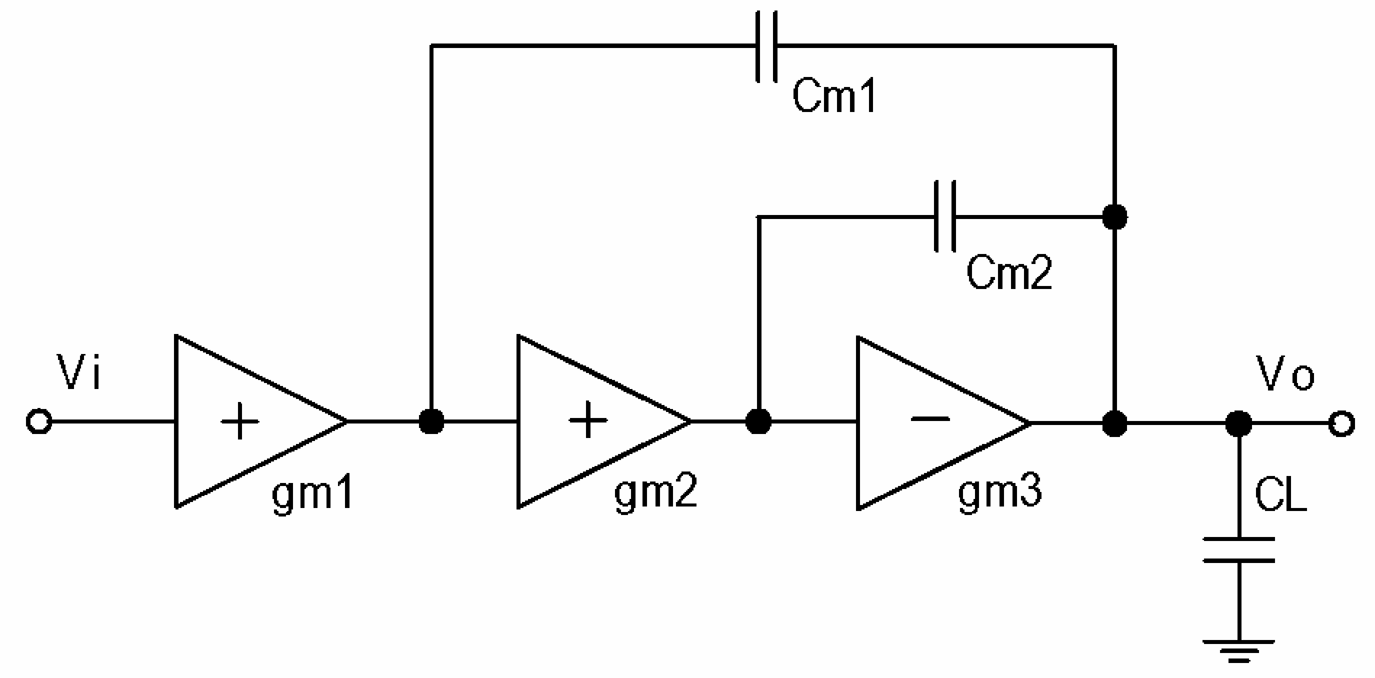
$$GBW = \frac{g_{m1}}{2\pi\, C_C}$$

"Nested Miller"

Comparison of power consumption



Nested-Miller Frequency compensation - NMC



Huijsing, JSSC Dec.85, pp.1144-1150

NMC equations in open loop

$$A_v(s) = \frac{A_{dc}\left(1 + \frac{s}{\omega_3} + \frac{s^2}{\omega_3\omega_4}\right)}{\left(1 + \frac{s}{\omega_d}\right)\left(1 + \frac{s}{\omega_1} + \frac{s^2}{\omega_1\omega_2}\right)}$$

$$\omega_1 = \frac{g_{m2}}{C_{m2}}$$

$$\omega_2 = \frac{g_{m3}}{C_L}$$

$$A_{dc} = g_{m1}g_{m2}g_{m3}R_1R_2R_3$$

$$\omega_3 = -\frac{g_{m3}}{C_{m2}}$$

$$\omega_d = -\frac{1}{C_{m1}g_{m2}g_{m3}R_1R_2R_3}$$

$$\omega_4 = \frac{g_{m2}}{C_{m1}}$$

$$\omega_{UG} = \frac{g_{m1}}{C_{m1}}$$

NMC stability

$$A_v(s) = \frac{A_{dc}\left(1 + \frac{s}{\omega_3} + \frac{s^2}{\omega_3\omega_4}\right)}{\left(1 + \frac{s}{\omega_d}\right)\left(1 + \frac{s}{\omega_1} + \frac{s^2}{\omega_1\omega_2}\right)}$$

$$\omega_1 = \frac{g_{m2}}{C_{m2}}$$

$$\omega_2 = \frac{g_{m3}}{C_L}$$

$$\omega_3 = -\frac{g_{m3}}{C_{m2}}$$

$$\omega_4 = \frac{g_{m2}}{C_{m1}}$$

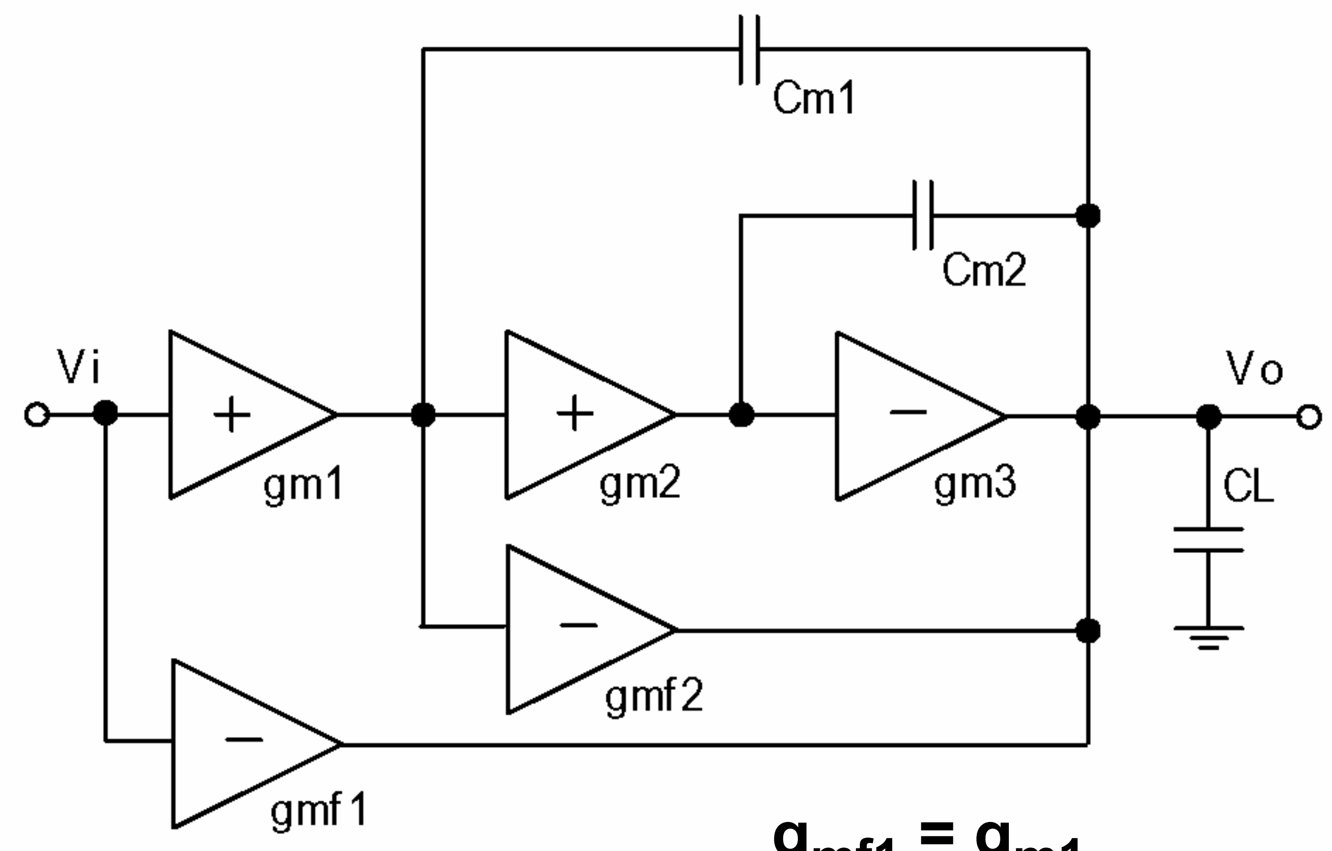
$g_{m1} < g_{m2} < g_{m3}$

Butterworth 3rd order : $\zeta = 0.7$; $p = 2.8$

$$\omega_2 = 2\,\omega_1 = 4\,\omega_{UG}$$

Zero's negligible

Nested Gm-C compensation NGCC



$$\omega_1 \approx \frac{g_{m2}}{C_{m2}}$$

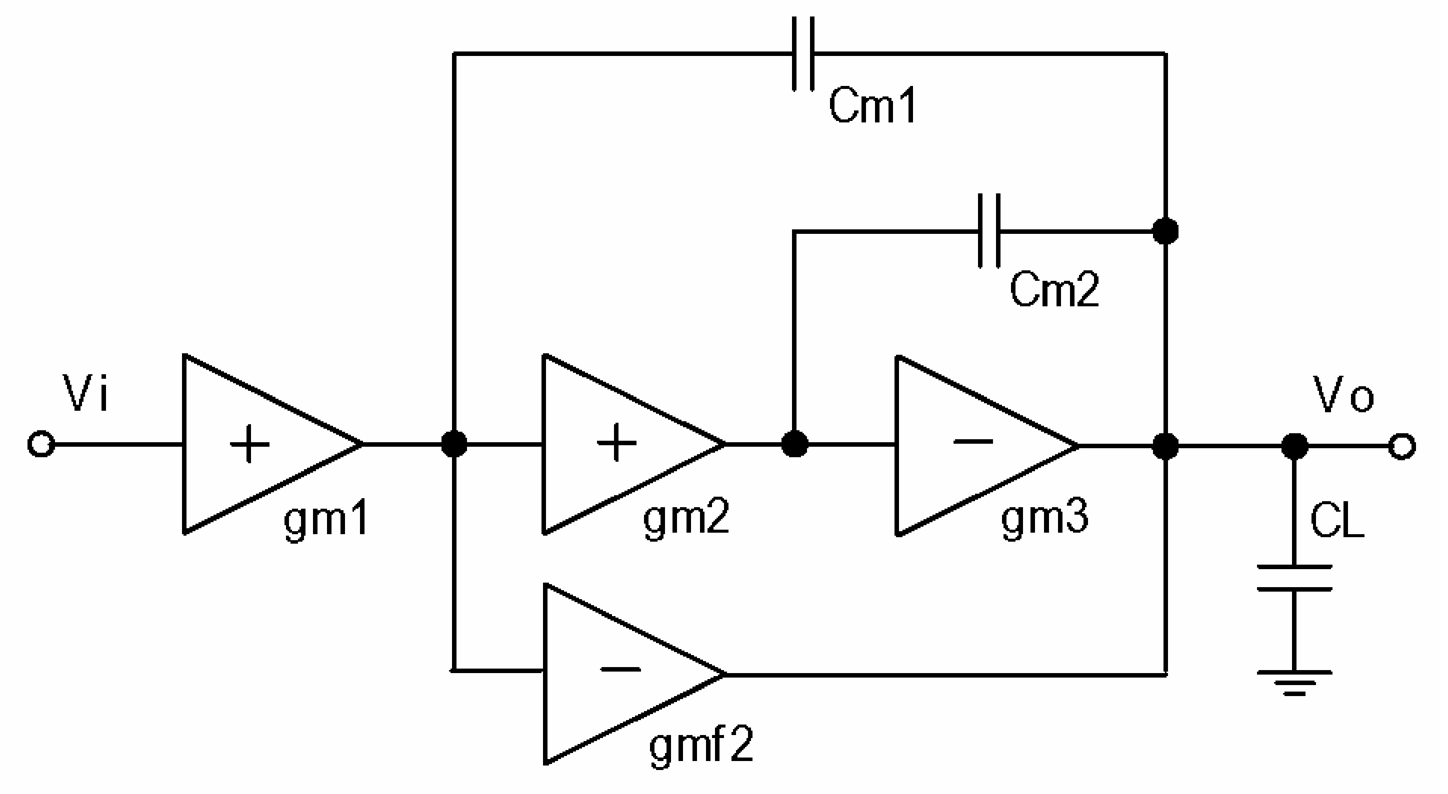
$$\omega_2 \approx \frac{g_{m3}}{C_L}$$

$$g_{mf1} = g_{m1}$$

$$g_{mf2} = g_{m2}$$

You, JSSC Dec.97, 2000-2011

Nested-Miller with single Feedforward - NMCF



$$g_{mf2} = g_{m3}$$

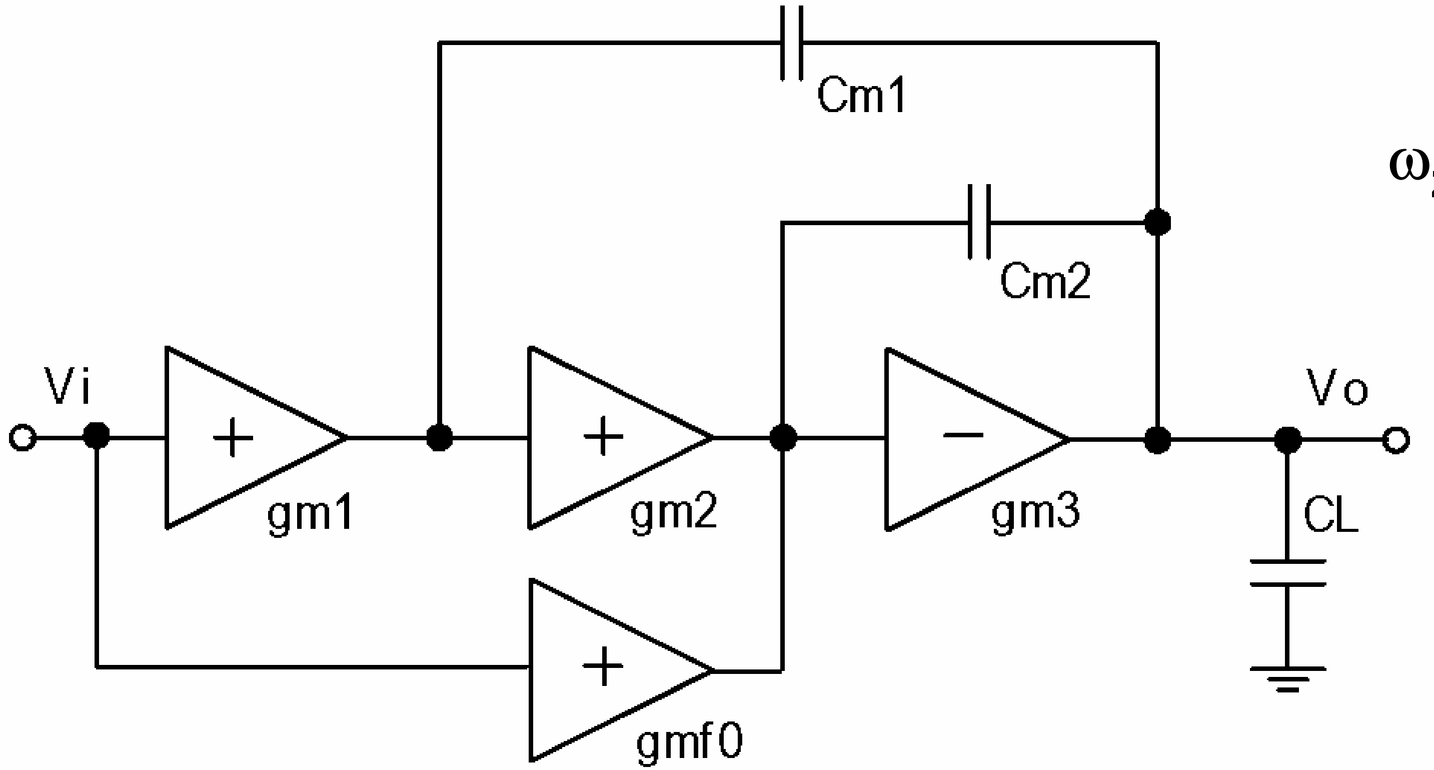
$$\omega_z \approx \frac{g_{m2}}{C_{m2}}$$

$$\omega_1 \approx \frac{g_{m2}}{2C_{m2}}$$

$$\omega_2 \approx \frac{2g_{m3}}{C_L}$$

Leung, CAS April 01, 388-394

Multipath Nested-Miller - MNMC



$$\omega_z \approx \frac{g_{m1}\, g_{m2}}{g_{mf0}\, C_{m1}}$$

$$\omega_1 \approx \frac{g_{m2}}{C_{m2}}$$

$$\omega_2 \approx \frac{g_{m3}}{C_L}$$

Eschauzier, JSSC Dec.92, pp.1709-1717

Comparison Nested-Miller solutions

Topology	Stages	PM	GB=2πGBW	T_{eL}	T_{eL} / $T_{eL\,(NMC)}$
Single	One	$<90°$	(g_m/C_L)	1.0	4.0
SMC	Two	$<63°$	$0.5(g_{m2}/C_L)$	0.5	2.0
NMC	Three	$\approx 60°$	$0.25(g_{m3}/C_L)$	0.25	1.0
NGCC	Three	$\approx 60°$	$0.25(g_{m3}/C_L)$	0.25	1.0
NMCF	Three	$>60°$	$<0.5(g_{m3}/C_L)$	<0.5	<2.0
MNMC	Three	$\approx 63°$	$\approx 0.5(g_{m3}/C_L)$	≈ 0.5	≈ 2.0

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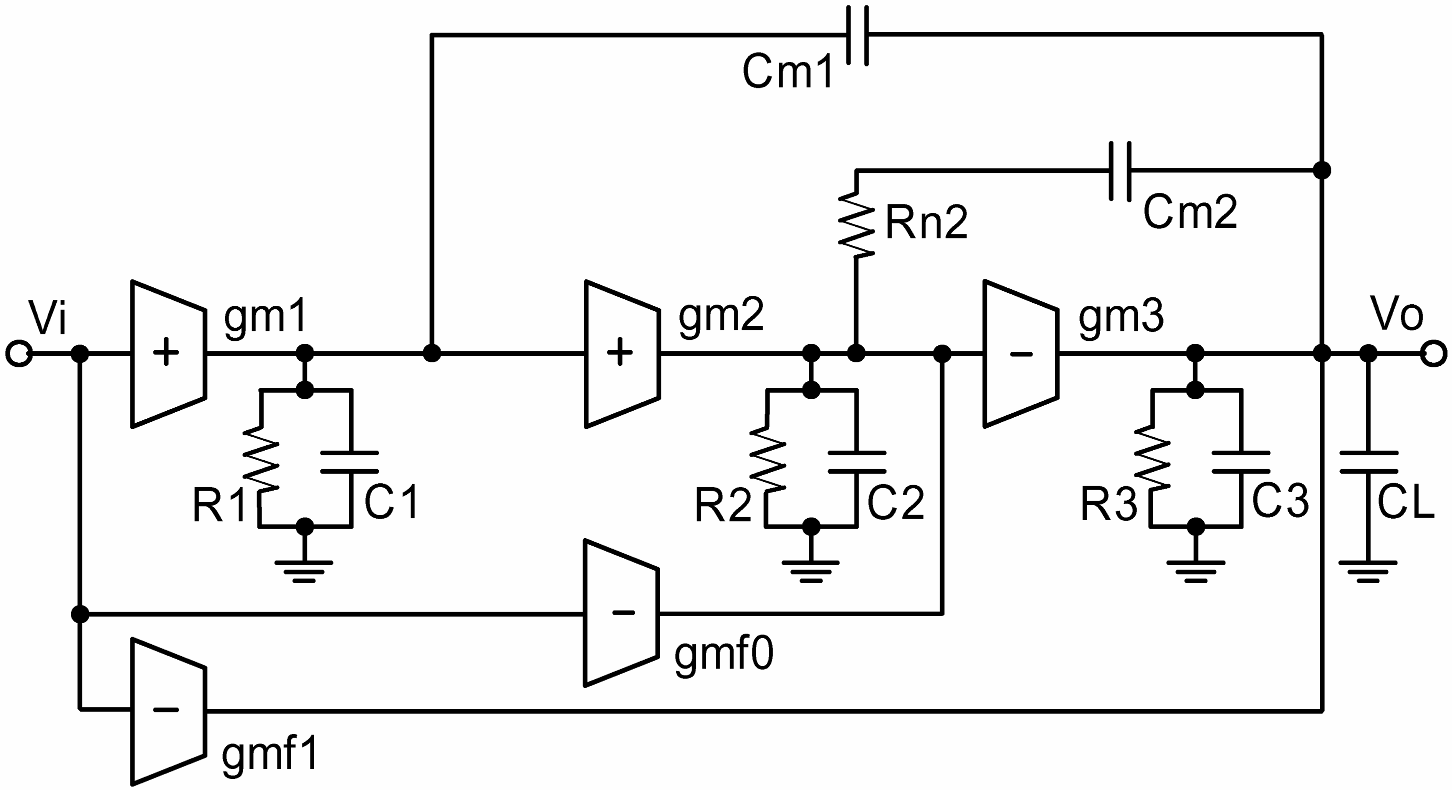
Nested Gm and nulling Res. NMC - NGRNMC



$$\omega_1 \approx \frac{1}{R_{n2}C_{m2}}$$

$$\omega_2 \approx \frac{g_{m2}g_{m3}R_{n2}}{C_L}$$

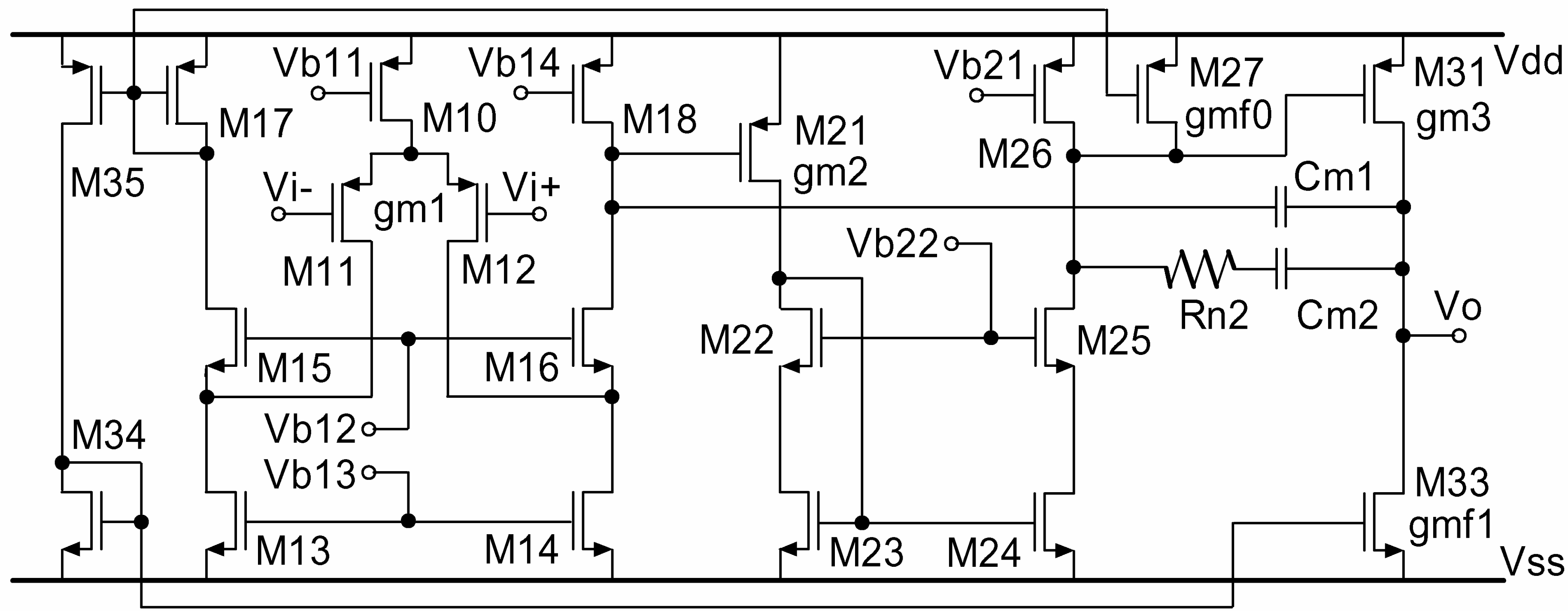
$g_{mf1} = g_{m1}$

$g_{mf0} = \cdots$

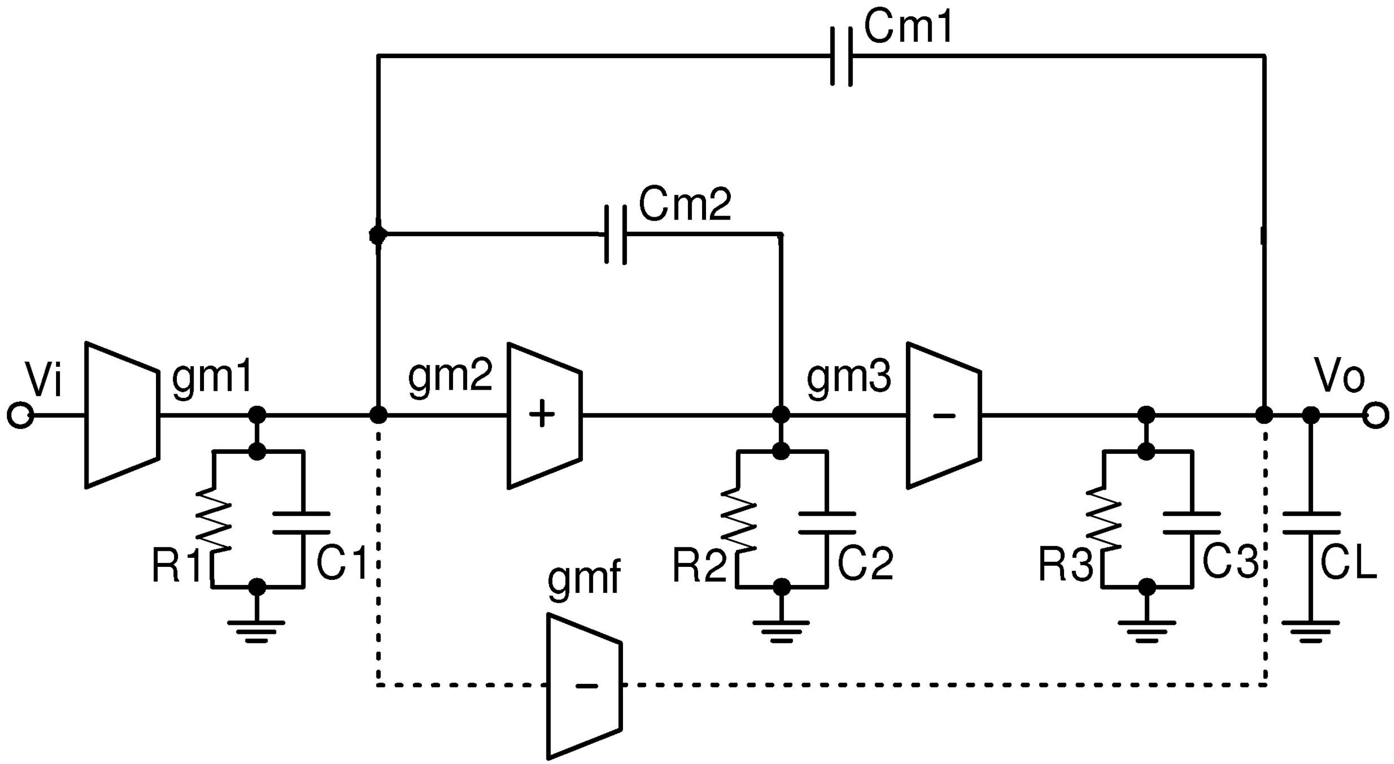
$GBW / GBW_{NMC} \approx 6.8$

Peng, CICC 2002, 329-332

NGRNMC schematic



Positive Feedback Compensation - PFC



$GBW / GBW_{NMC} \approx 6$

Ramos, CICC 2002, 333-336

PFC Equations

$$A_v(s) = \frac{A_{dc}\left(1 + \frac{s}{\omega_1} + \frac{s^2}{\omega_1\omega_3}\right)}{\left(1 + \frac{s}{\omega_d}\right)\left(1 + \frac{s}{\omega_1} + \frac{s^2}{\omega_1\omega_2}\right)}$$

$$\omega_1 = \frac{g_{m2}}{2C_{m2}}$$

$$\omega_2 = \frac{2g_{m3}}{C_L}$$

$$A_{dc} = g_{m1}g_{m2}g_{m3}R_1R_2R_3$$

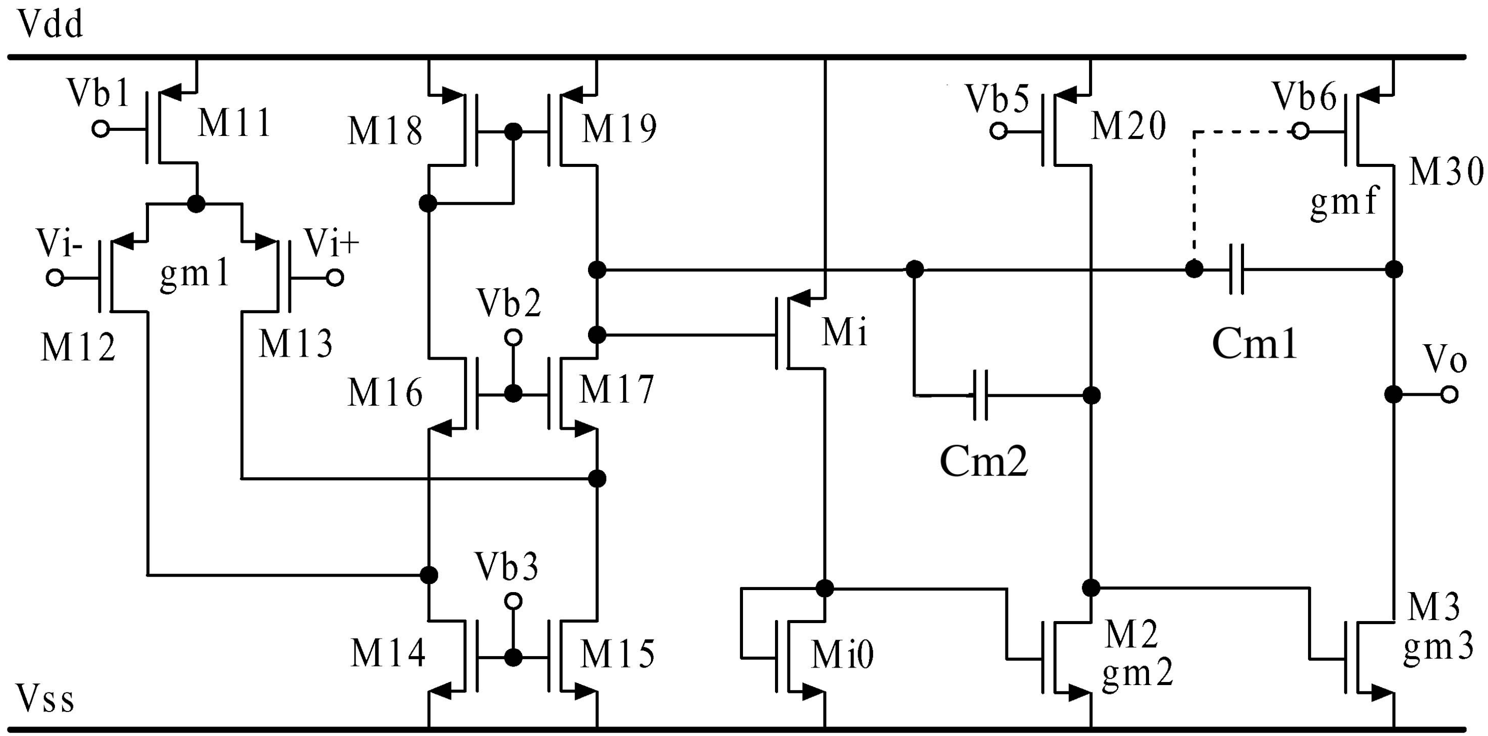
$$\omega_3 = -\frac{2g_{m3}}{C_{m1}}$$

$$\omega_d = -\frac{1}{C_{m1}g_{m2}g_{m3}R_1R_2R_3}$$

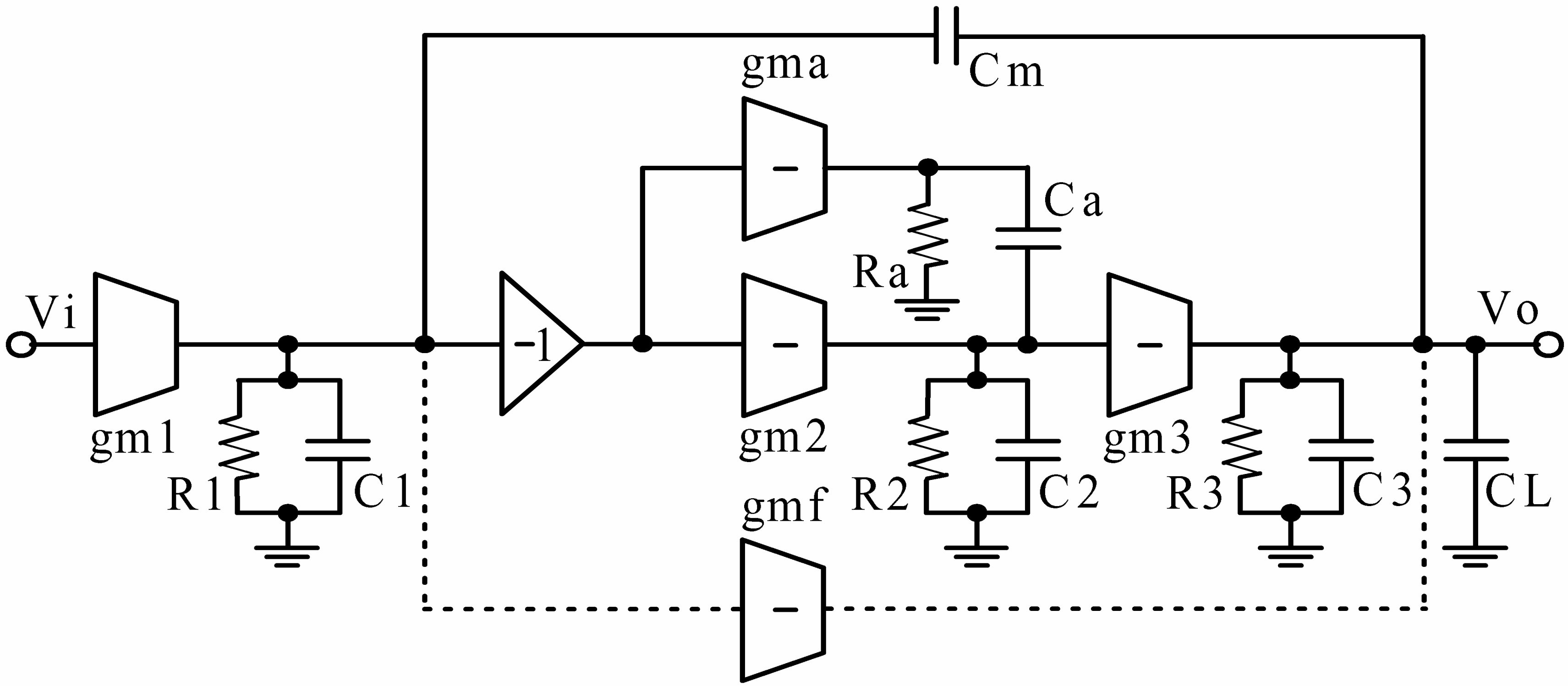
$$\omega_{UG} = \frac{g_{m1}}{C_{m1}}$$

Stability : $\frac{2g_{m3}}{C_L} > \frac{g_{m2}}{C_{m1}}$

PFC schematic



AC Boosting Compensation - ACBC



$$A_{2h} = (g_{m2} + g_{ma})\, R_a$$

Peng, JSSC Nov.04, 2074-2079

ACBC equations

$$A_v(s) = \frac{A_{dc}\left(1 + \frac{s}{\omega_1} + \frac{s^2}{\omega_1\omega_4} + \frac{s^3}{\omega_1\omega_3\omega_4}\right)}{\left(1 + \frac{s}{\omega_d}\right)\left(1 + \frac{s}{\omega_1} + \frac{s^2}{\omega_1\omega_2} + \frac{s^3}{\omega_1\omega_2\omega_3}\right)}$$

$$\omega_1 = \frac{1}{A_{2h}} \frac{g_{m2}}{C_a}$$

$$\omega_2 = A_{2h} \frac{g_{m3}}{C_L}$$

$$A_{dc} = g_{m1}g_{m2}g_{m3}R_1R_2R_3$$

$$\omega_3 = \frac{1}{R_aC_2}$$

$$\omega_d = - \frac{1}{C_{m1}g_{m2}g_{m3}R_1R_2R_3}$$

$$\omega_4 = - A_{2h} \frac{g_{m3}}{C_m}$$

$$\omega_{UG} = \frac{g_{m1}}{C_{m1}}$$

$$A_{2h} = (g_{m2} + g_{ma})\, R_a$$

ACBC stability

$$A_v(s) = \frac{A_{dc}\left(1 + \frac{s}{\omega_1} + \frac{s^2}{\omega_1\omega_4} + \frac{s^3}{\omega_1\omega_4\omega_3}\right)}{\left(1+\frac{s}{\omega_d}\right)\left(1+\frac{s}{\omega_1}\right)\left(1+\frac{s}{\omega_2}\right)\left(1+\frac{s}{\omega_3}\right)}$$

$$\omega_1 = \frac{1}{A_{2h}}\frac{g_{m2}}{C_a}$$

$$\omega_2 = A_{2h}\frac{g_{m3}}{C_L}$$

$$\omega_3 = \frac{1}{R_aC_2}$$

$$\omega_4 = -A_{2h}\frac{g_{m3}}{C_m}$$

Stability : $\omega_3 > \omega_2 > \omega_1$

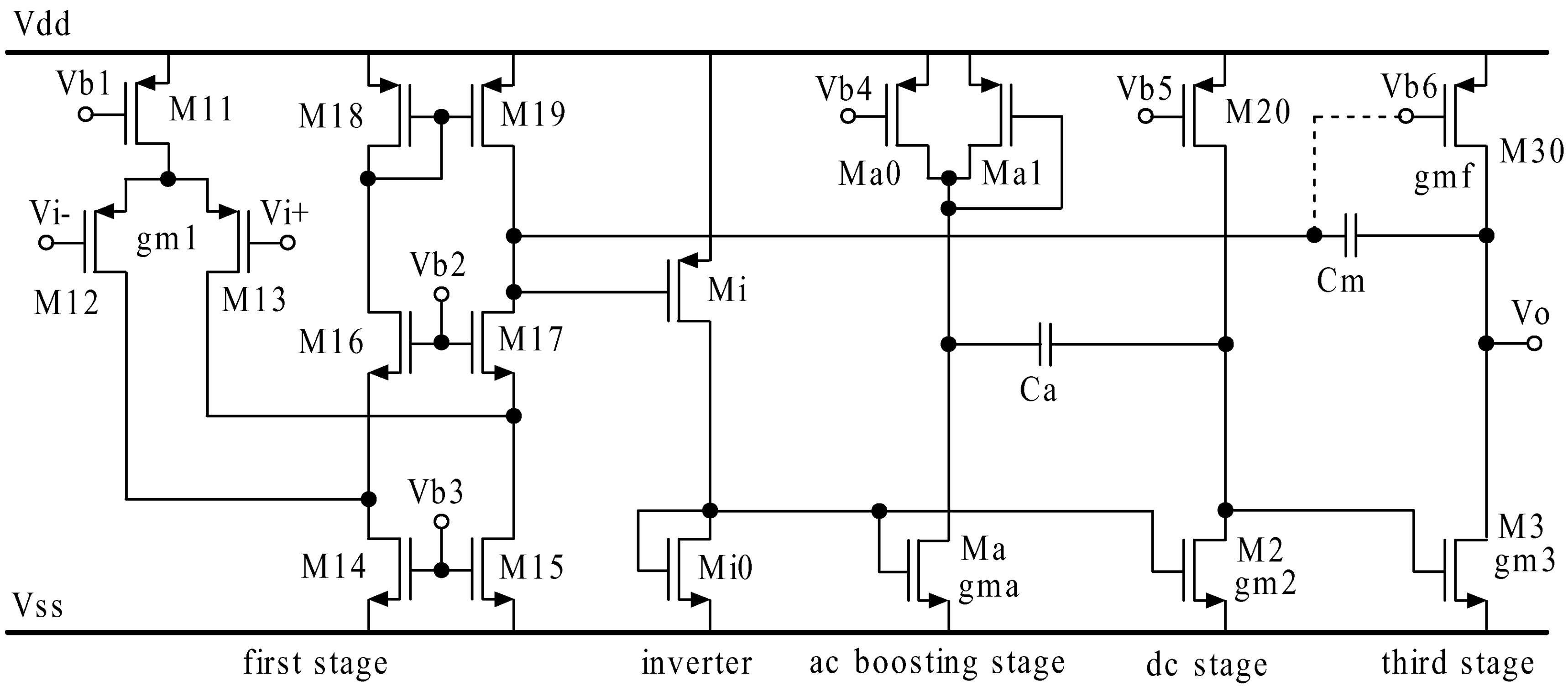
Pole and zero at ω_1 cancel

Design : $\omega_2 \approx 2\,\omega_{UG}$ **for 60° PM**

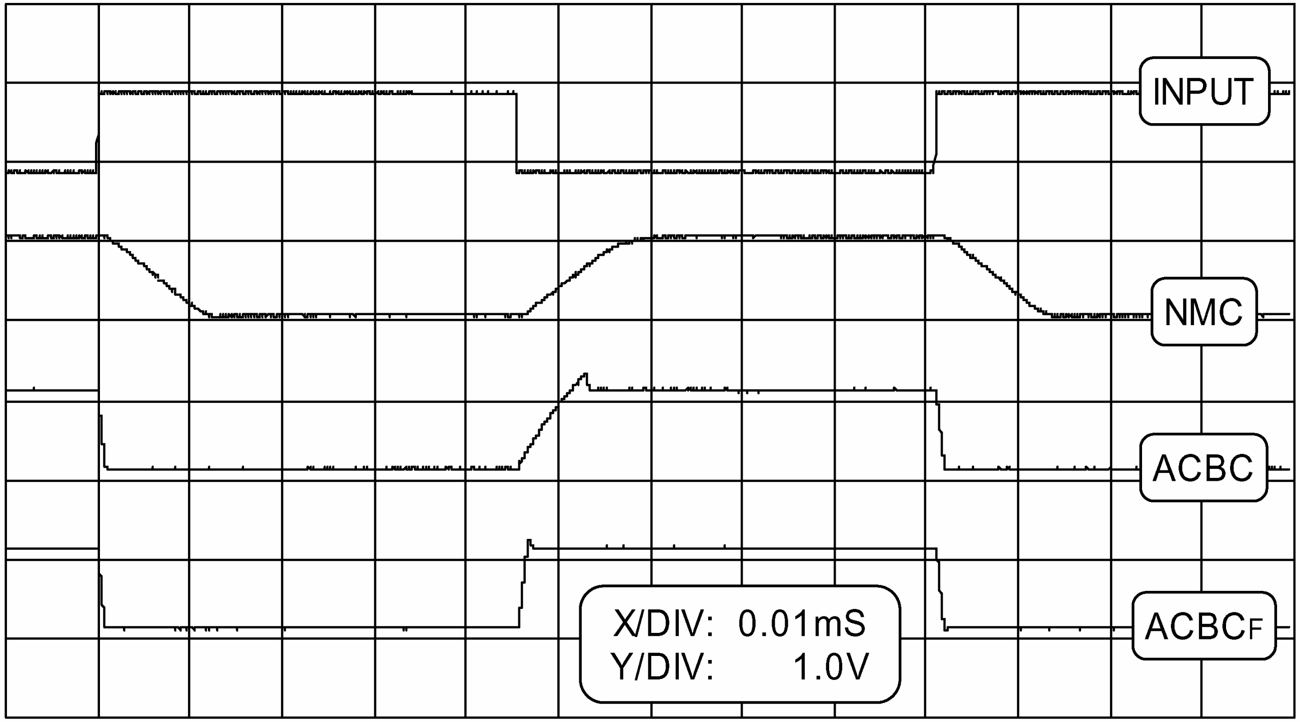
$GBW / GBW_{NMC} \approx 17$

$$A_{2h} = (g_{m2} + g_{ma})\,R_a$$

ACBC schematic



ACBC results



2 MHz

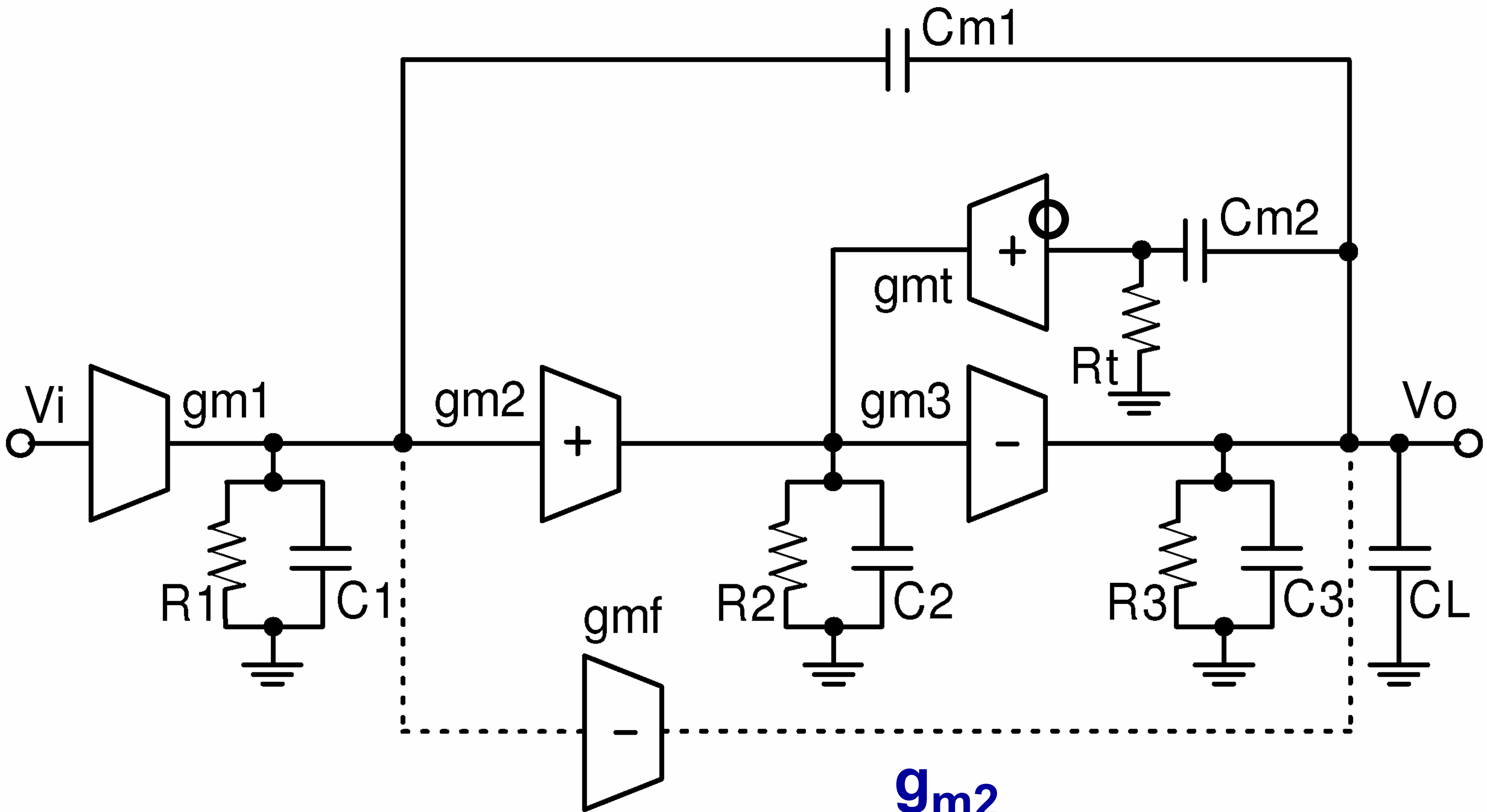
500 pF

0.16 mA

0.2 V/μs

1.2 V/μs$_F$

Transcond. with Cap. Feedback Comp.- TCFC



$$k_t = \frac{g_{m2}}{g_{mt}}$$

Peng, JSSC July 05,1514-1520

TCFC equations

$$A_v(s) = \frac{A_{dc}\left(1 + \frac{s}{\omega_2} + \frac{s^2}{\omega_2{}^2} + \frac{s^3}{\omega_2{}^2\omega_4}\right)}{\left(1 + \frac{s}{\omega_d}\right)\left(1 + \frac{s}{\omega_1} + \frac{s^2}{\omega_1\omega_2} + \frac{s^3}{\omega_1\omega_2\omega_3}\right)}$$

$$\omega_1 = \frac{1}{1+k_t}\frac{g_{m2}}{C_{m2}}$$

$$\omega_2 = \frac{1}{k_t}\frac{g_{m2}}{C_{m2}}$$

$$A_{dc} = g_{m1}g_{m2}g_{m3}R_1R_2R_3$$

$$\omega_d = -\frac{1}{C_{m1}g_{m2}g_{m3}R_1R_2R_3}$$

$$\omega_3 = (1+k_t)\frac{C_{m2}}{C_2}\frac{g_{m3}}{C_L}$$

$$\omega_{UG} = \frac{g_{m1}}{C_{m1}}$$

$$k_t = \frac{g_{m2}}{g_{mt}}$$

$$\omega_4 = -k_t\frac{C_{m2}}{C_2}\frac{g_{m3}}{g_{m1}}\omega_{UG}$$

TCFC stability

Stability ($k_t = 2$):

$$\frac{C_{m2}}{C_2}\frac{g_{m3}}{C_L} > \omega_{UG} \quad \text{since } C_{m2} > C_2$$

$$\omega_1 = \frac{1}{1+k_t}\frac{g_{m2}}{C_{m2}}$$

Design :

$$\omega_2 = \frac{1}{k_t}\frac{g_{m2}}{C_{m2}}$$

$\omega_3 > \omega_1$ since $C_{m2} > C_2$; then $p_{nd} = -\,\omega_1$

set $\omega_1 \approx 2\,\omega_{UG}$ for 60° PM

$$\omega_3 = (1+k_t)\frac{C_{m2}}{C_2}\frac{g_{m3}}{C_L}$$

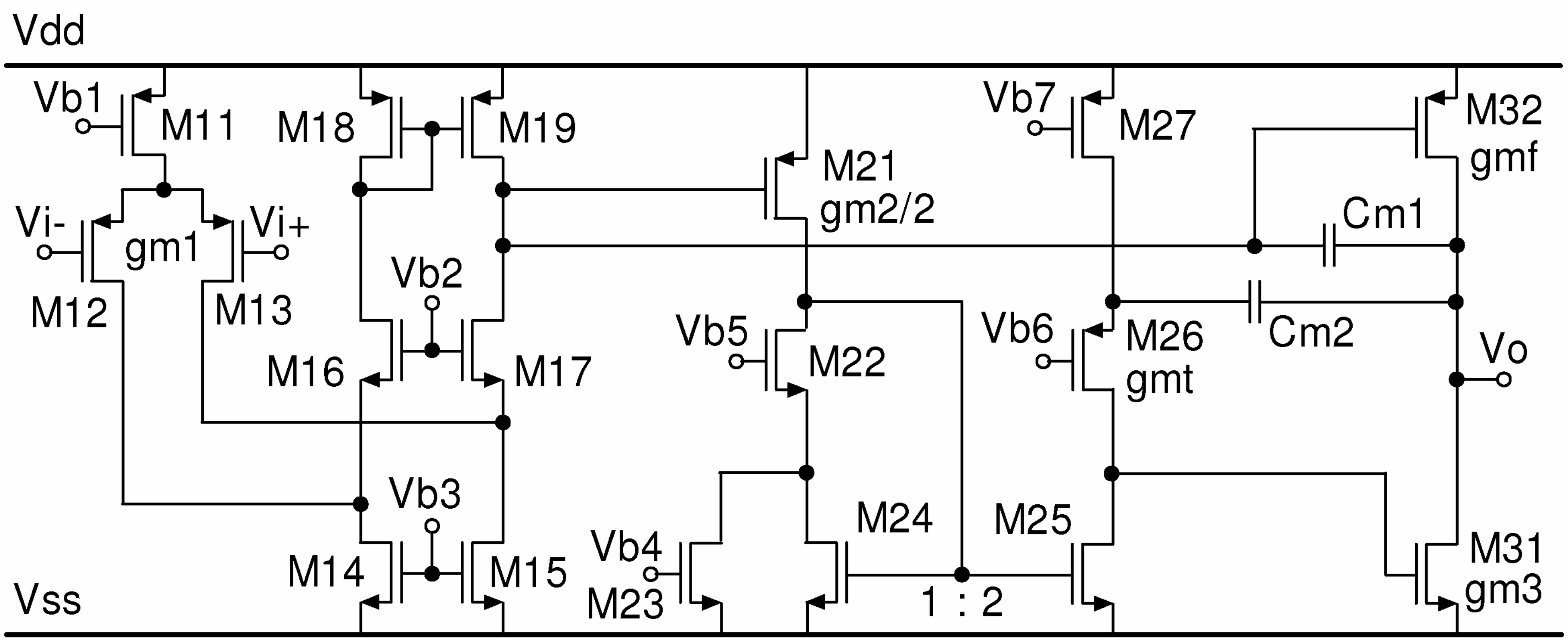
$\omega_4 > \omega_{UG}$; then $z_{nd} = -\,\omega_2$

is $(1+k_t)/k_t$ larger than ω_1

$$\omega_4 = -\,k_t\frac{C_{m2}}{C_2}\frac{g_{m3}}{g_{m1}}\,\omega_{UG}$$

$GBW / GBW_{NMC} \approx 41$

TCFC schematic



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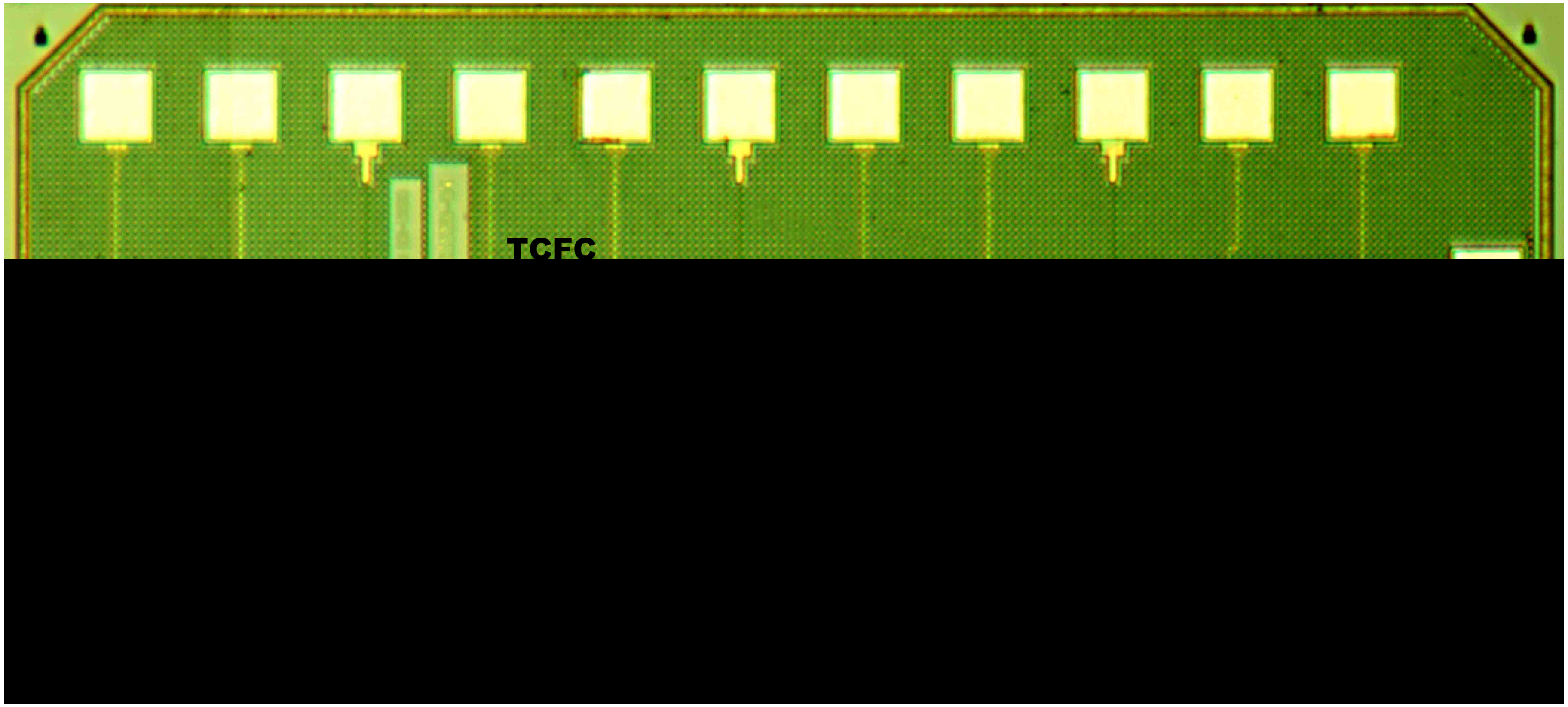
TCFC and other 3-stage opamps



Comparison

No Capacitance

Nested Miller comp.

NMC with nulling R

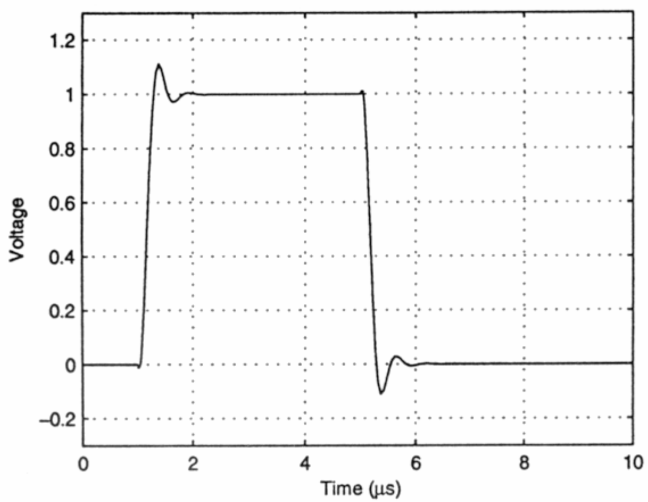
Miller C Substitutions

AC Boosting comp.

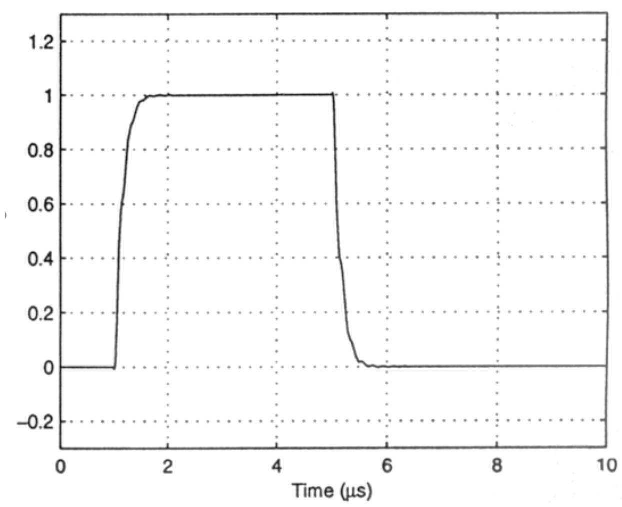
Transconductance Capacitance FC

		IFOMS $\frac{MHz \cdot pF}{mA}$	IFOML $\frac{V/\mu S \cdot pF}{mA}$	FOMS $\frac{MHz \cdot pF}{mW}$	FOML $\frac{V/\mu S \cdot pF}{mW}$	Tech.
			NCs			
NCFF	[Tha03]	536	-	214	-	$\frac{0.5\mu m}{CMOS}$
			NMs			
NMC	[Esc92]	632	211	79	26	$\frac{3GHz\, f_t}{BJT}$
MNMC	[Esc92]	1053	368	132	46	$\frac{3GHz\, f_t}{BJT}$
NMCF	[Leu01a]	600	246	300	123	$\frac{0.8\mu m}{CMOS}$
NGCC	[You97]	36	148	18	74	$\frac{2\mu m}{CMOS}$
HNMC	[Esc94]	134	134	89	89	$\frac{0.8\mu m}{CMOS}$
MHNMC	[Esc94]	401	467	267	311	$\frac{0.8\mu m}{CMOS}$
DNMC	[Per93]	250	188	50	38	$\frac{1.5\mu m}{CMOS}$
			MRs			
NMCNR	[Leu01a]	410	168	205	84	$\frac{0.8\mu m}{CMOS}$
IRNMC	[Ho03]	626	444	209	148	$\frac{0.6\mu m}{CMOS}$
EFC	[Ng99]	817	1200	272	400	$\frac{0.6\mu m}{CMOS}$
NGRNMC	[Peng03]	700	490	280	196	$\frac{0.35\mu m}{CMOS}$
			MSs			
PFC	[Ram03b]	1915	709	1276	473	$\frac{0.35\mu m}{CMOS}$
DFCFC	[Leu01a]	1238	628	619	314	$\frac{0.8\mu m}{CMOS}$
			ACBs			
ACBC	[Peng04]	5981	2215	2991	1108	$\frac{0.35\mu m}{CMOS}$
$ACBC_F$	[Peng04]	5864	3086	2932	1543	$\frac{0.35\mu m}{CMOS}$
			TCFs			
AFC	[Ahu83]	326	-	33	-	$\frac{4\mu m}{CMOS}$
AFFC	[Lee03b]	2700	894	1350	447	$\frac{0.8\mu m}{CMOS}$
DLPC	[Lee03a]	3818	1800	2545	1200	$\frac{0.6\mu m}{CMOS}$
TCFC	[Peng05]	14250	5175	9500	3450	$\frac{0.35\mu m}{CMOS}$

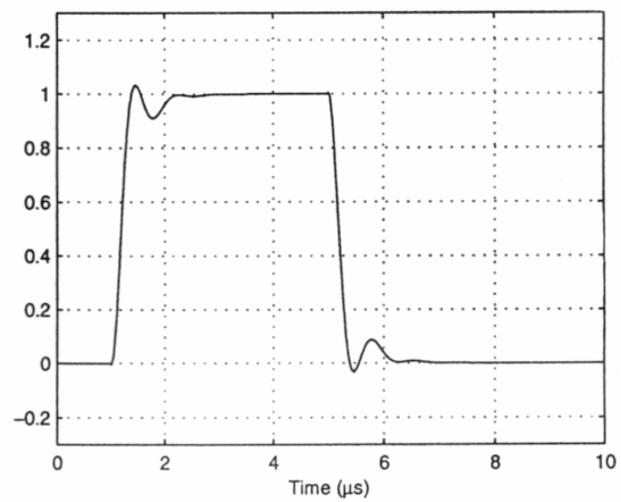
Transient responses in unity gain



NMC



TCFC



PFC

All GBW ≈ 1 MHz and C_L = 100 pF

Same C_{m1} = 18 pF ; C_{m2} = 3 pF; minimum currents.

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