Design of Linear OTA-C Filters over Wide Frequency Ranges

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Outline

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  - Motivation and objectives
  - Linearization Schemes
- Attenuation-Predistortion Linearization for Operational Transconducance Amplifiers (OTAs)
  - Proposed approach
  - Single-ended OTAs
  - Differential OTAs
- Application to OTA-C Filters
  - Low-pass filter example
  - Measurement results
  - Comparison with the state of the art
- Advanced Concepts
  - Excess phase compensation
  - Linearization without power budget increase
- Summary & Conclusions

Operational Transconductance Amplifier Linearization

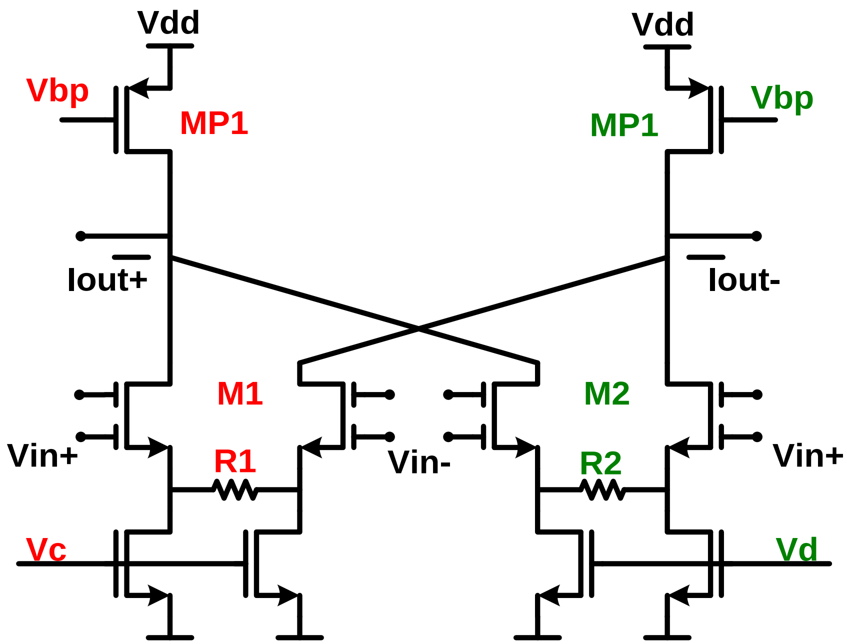
- Project objective
  - Improved cancellation of OTA non-linearities
  - Method: distortion created in an identical auxiliary path → subtracted form main signal

- Motivation
  - Robustness of linearization to process variations
  - Compensation for frequency-dependent linearity degradation

- Applications with operational transconductance amplifiers (OTAs)
  - On-chip filters in the 100-200MHz frequency range
    - In high-IF stage of wireless receivers
    - Bandpass Continuous-time ΣΔ A/D converters (SNDR > 70dB)
  - Transconductance-capacitor baseband filters
    - Third-order intermodulation distortion (IM3) < -60dB
    - f < 50MHz (ex. xDSL, WLAN, WCDMA, UMTS)

Linearization Schemes

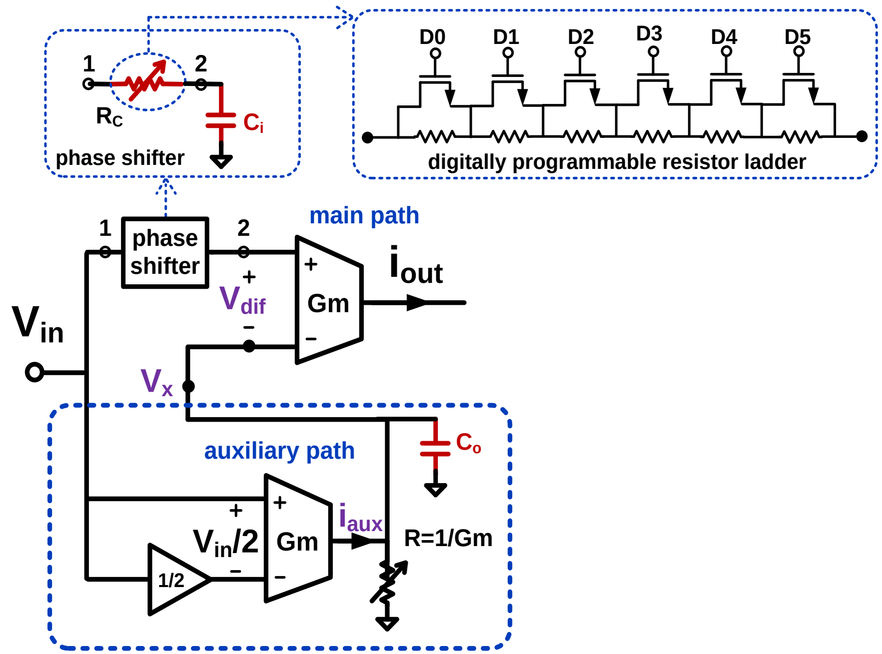
- Cross coupled differential pair
  - Sensetive to PVT variations
- Source degeneration
  - Decrease the effective transconductance and the available headroom
  - Increase the noise due to lower transconductance and addition of resistors
- Signal attenuation
  - Decrease the effective transconductance
  - Increase the input referred noise



- Combination of Cross-Coupling Cancellation, Floating-Gate Attenuation, Source Degeneration

Proposed Attenuation-Predistortion Linearization

- Single-ended OTAs
- Effective transconductance
  - Gm_{eff} = ½ Gm of non-linearized OTA with input-attenuation factor of 0.5
  - Same dimensions & bias in both paths
- Conditions for cancellation
  - Gm×R = 1 in aux. path
  - $R_c \approx R$ for optimum cancellation
  - R_c & C_i give 1st - order frequency compensation → pole frequency ≈ $1/R_cC_i$ → phase shift
- Advantages
  - Even with the presence of 10% Mismatch 20dB cancellation can be obtained
  - In the presence of 1% mismatch the cancellation can be as much as 40dB



$i_{aux} = GmV_{in}/2 + i_{non\text{-}lin}\{V_{in}/2\}$

$V_x = V_{in}/2 + i_{non\text{-}lin}\{V_{in}/2\} \times R$

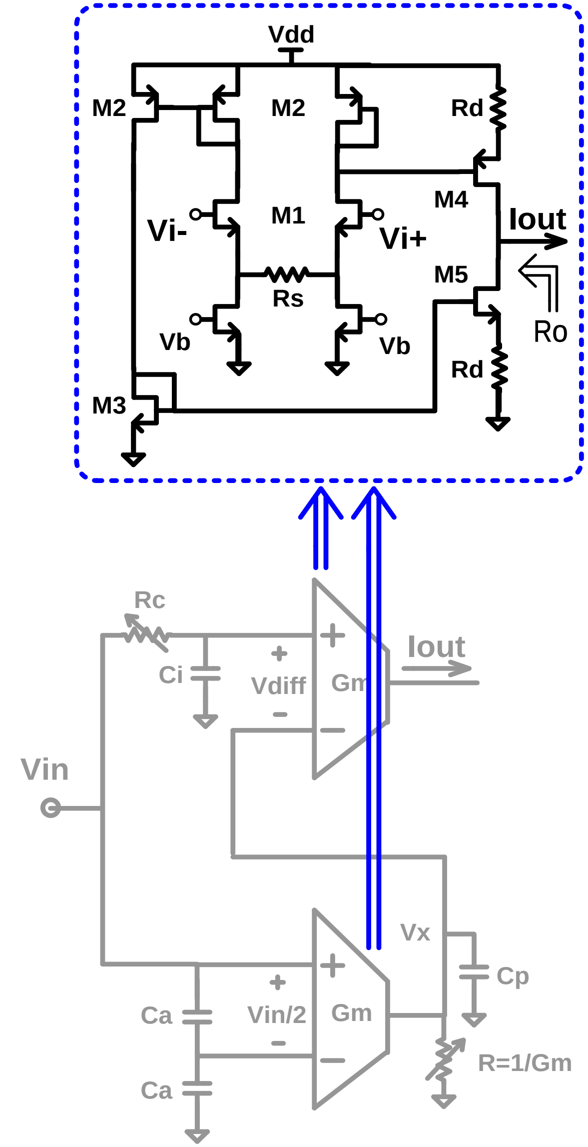
$V_{dif} = V_{in}/2 - i_{non\text{-}lin}\{V_{in}/2\} / Gm$

$i_{out} \approx GmV_{in}/2 + i_{non\text{-}lin}\{V_{in}/2\} - i_{non\text{-}lin}\{V_{in}/2\}$

* $i_{non\text{-}lin}\{V_m\}$ represents the distortion components of the current generated by Gm with input voltage amplitude V_m

Single-Ended OTA for High-Frequencies

- Topology modified from 3-current mirror OTA
  - No cascode output stage
    - Stacked devices are less effective with 1.2V supply
    - Min. lengths (min. capacitance) for 100MHz operation
      → r_{out} of transistors as low as 1.5kΩ
  - Modified OTA
    - Similar output resistance as cascode (0.13µm tech.)
    - More linear with large signal swings



- Basic specs → (0.13µm CMOS, 1.2V supply)

Parameter	Value
Gm	776µA/V
Excess Phase	2.6º at 100MHz
R_o	13kΩ
Gain Bandwidth Product	622MHz
Power	2.4mW

Fully-Differential OTA Linearization

- Fully differential architecture offer many advantages over single ended circuits

- Generalized conditions for attenuation-predistortion linearization

  - Non-linearity cancellation:

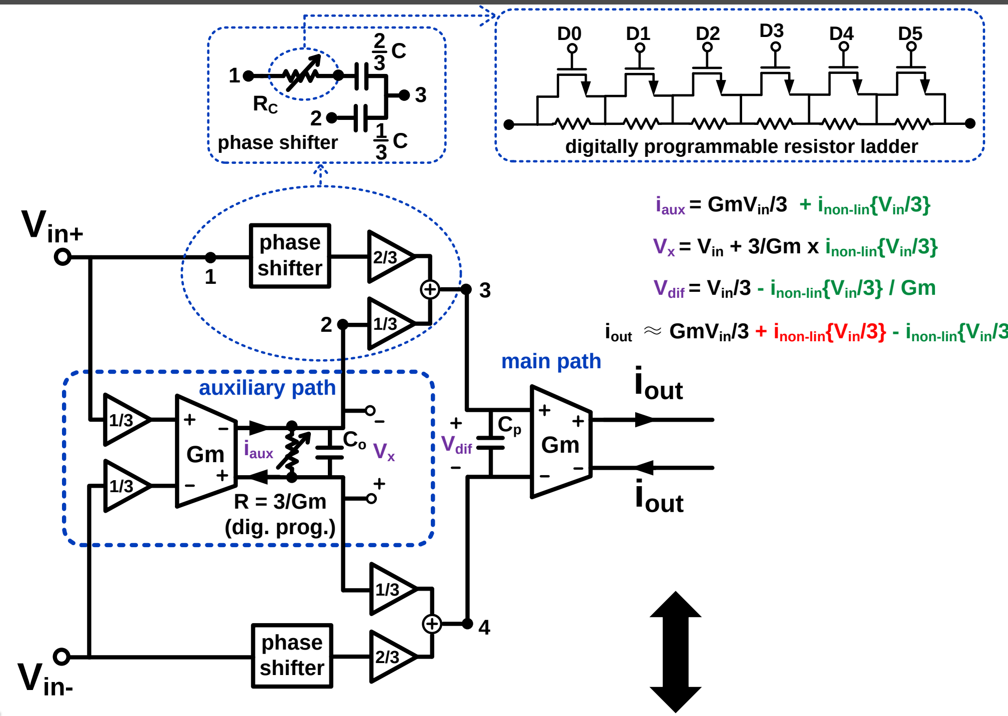
$$(1-k_1)G_m R = 1 \quad , \quad k_2 = k_1/2$$

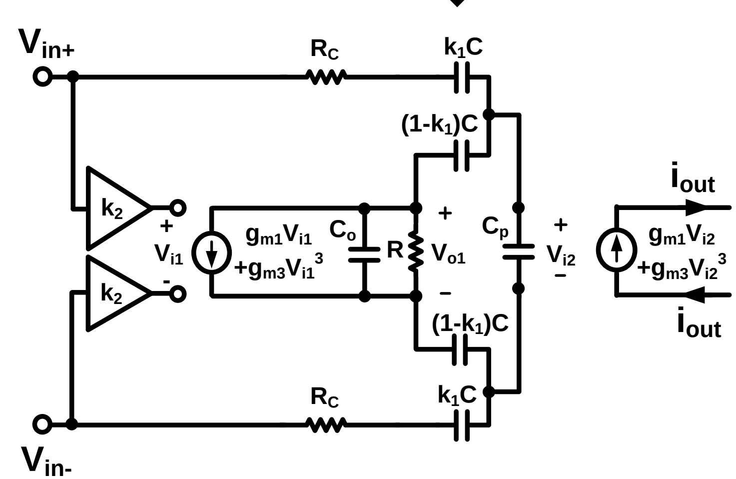
$$G_{m\_eff} = k_2 G_m \qquad k_2 G_m R \le 1$$

- To ensure IM3 ≈ 0 based on Volterra series:

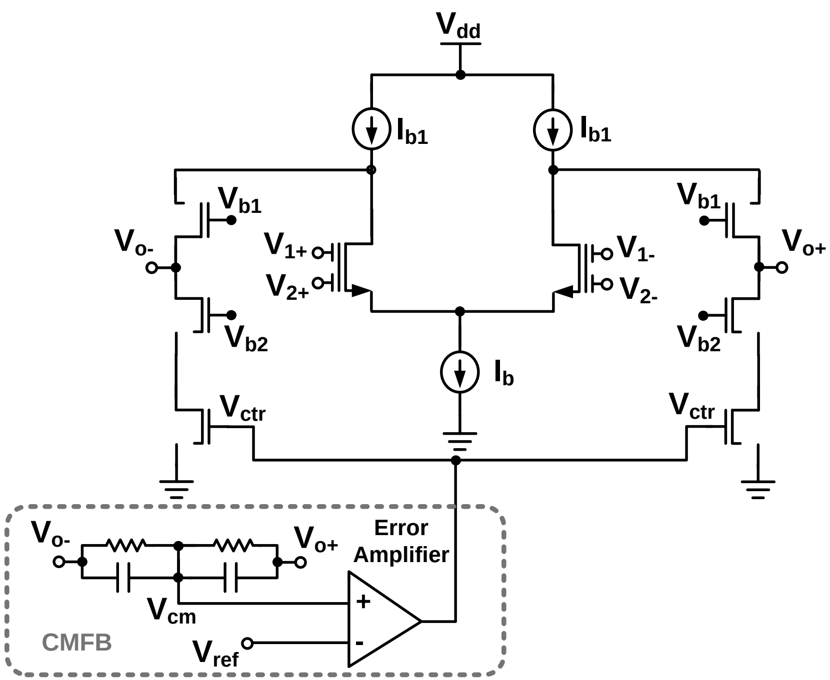
$$R_c \approx \frac{(1-k_1)+2C_o/C}{2k_1} R$$

- This design: $k_1 = 2/3$, $k_2 = 1/3$
  → $R_c=(R/4)*(1+6C_o/C)$



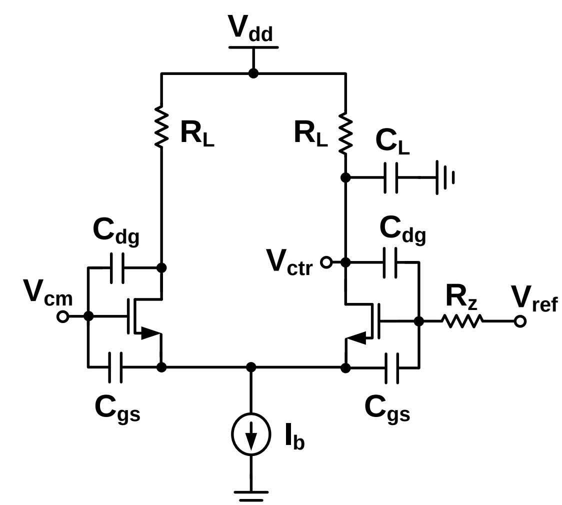


Fully-Differential OTA



Folded-cascode OTA
(implements G_m in main and auxiliary paths)

Parameter	Measurement
Transconductance (G_m)	510 µA/V
IM3 @ 50MHz (Vin = 0.2 Vp-p)	-55.3 dB
Noise (input-referred)	13.3 nV/√Hz
Power with CMFB	2.6 mW
PSRR @ 50MHz	48.9 dB
Supply	1.2 V



Error amplifier circuit in the common-mode feedback (CMFB) loop

- Error amplifier compensation with resistor R_z in CMFB improves extends the bandwidth of the common-mode rejection:

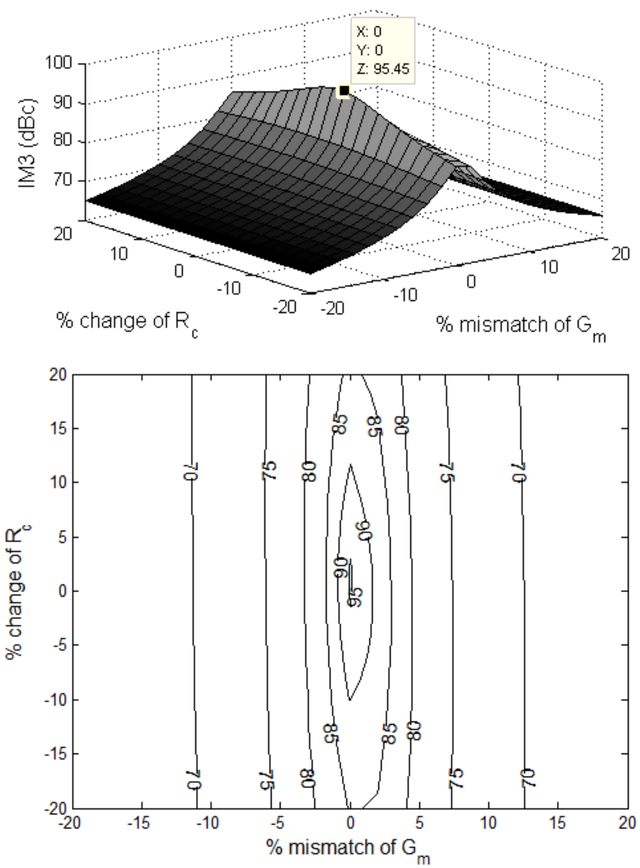
$$GBW \approx \sqrt{A_0 \cdot \omega_{p1} \cdot \omega_{p3}} \approx \sqrt{A_0 \cdot \omega_{p3} \cdot \frac{2}{R_z(C_{gs}/2 + (g_m R_L/2)C_{dg})}}$$

- Affect of R_z on stability according to phase margin (PM):

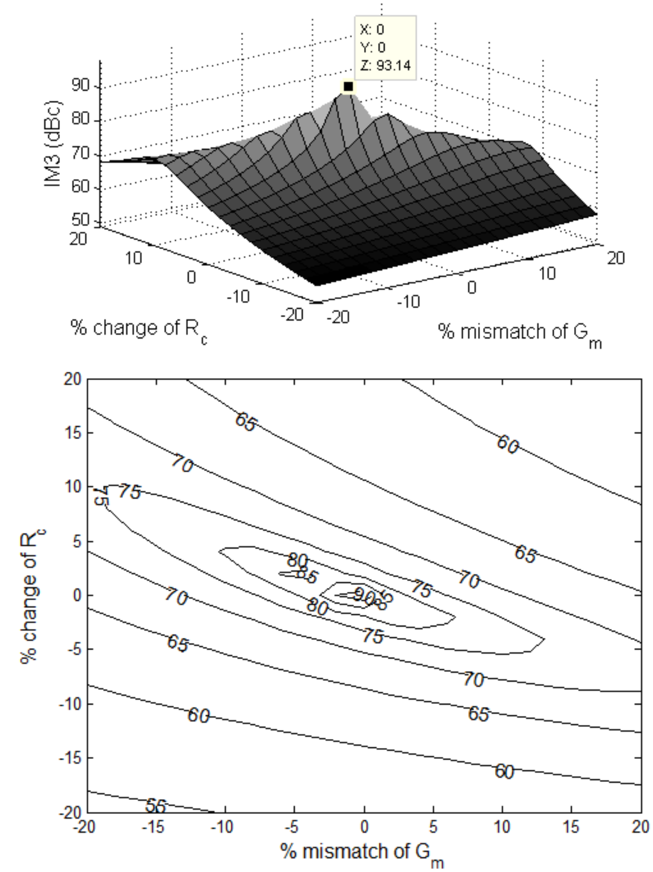
$$PM \approx \tan^{-1}\left(\sqrt{A_0 \cdot \omega_{p3} \cdot \frac{2R_z C_{dg}^2}{(C_{gs}/2 + (g_m R_L/2)C_{dg})}}\right)$$

High-Frequency Effects & Process Variation

- Theoretical IM3 higher than 70dBc with up to ±10% variation of Gm and ±5% of R_c
  - Can be ensured by matching devices in the layout
  - Robustness verified with schematic corner and component mismatch simulations
- Sensitivity of IM3 (in dBc) to component mismatches:



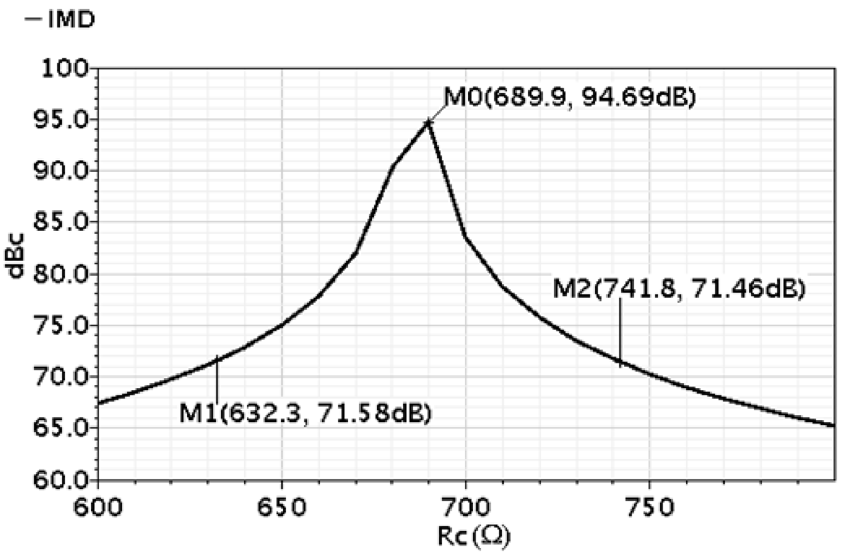
10MHz signal frequency



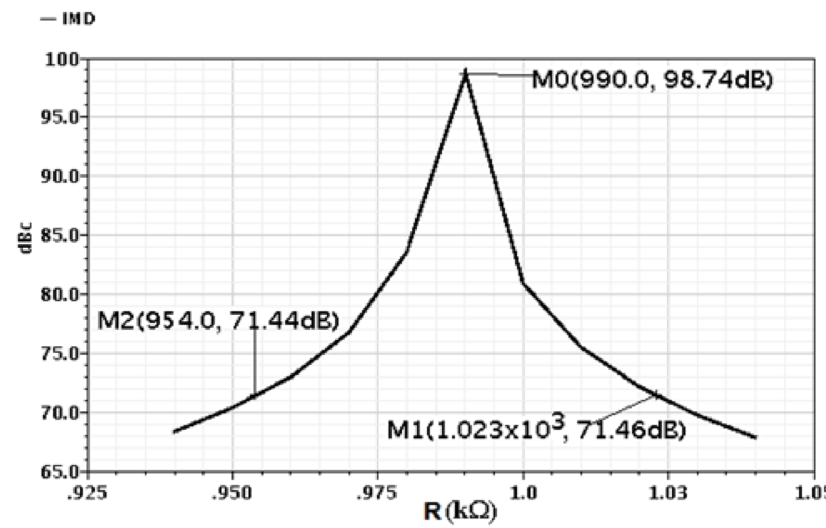
200MHz signal frequency

Simulated Fully-Diff. OTA: Mismatch of Critical Components

- IM3 better than 71dBc for ±7.5% Rc-variation
- IM3 better than 71dBc for ±3.3% R-variation in the presence of 10% Gm-mismatch
- Reference OTA has IM3 of 51dBc



IM3 vs. change in R_c at 350MHz



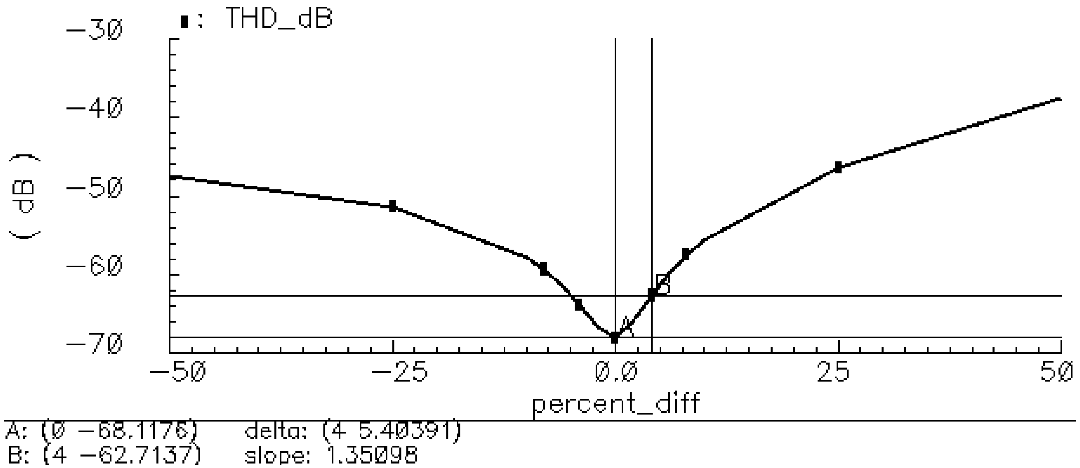
IM3 vs. R with 10% transconductance mismatch between main OTA and auxiliary OTA at 350MHz

Theoretical IM3:

$$i_{IM3} \approx g_{m3}\left(\frac{k_1/2}{1+2C_p/C}\right)^3 \left(3V_{in1}^2 V_{in2}/4\right)\left(\frac{1+j\omega_1 C\left((1-k_1)R - k_1 R_c\right) + 2j\omega_1 C_o R}{1+j\omega_1 b - c\omega_1^2}\right)^2 \left(\frac{1-j\omega_1 C\left((1-k_1)R - k_1 R_c\right) - 2j\omega_1 C_o R}{1-j\omega_1 b - c\omega_1^2}\right)$$

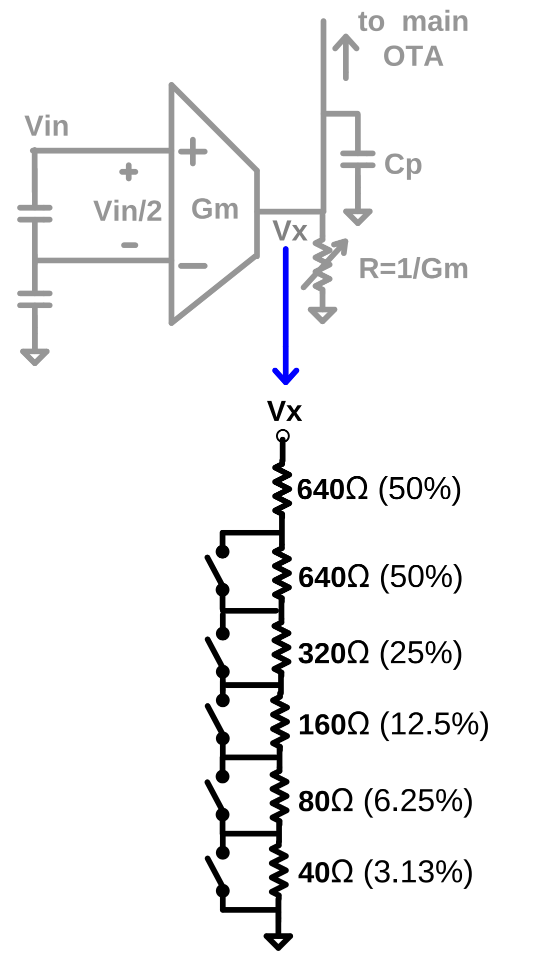
$$- g_{m3}\left(\frac{k_1/2}{1+2C_p/C}\right)^3 \left(3V_{in1}^2 V_{in2}/4\right)\frac{1+j\omega_1 C k_1 R_c}{1+j\omega_1 b - c\omega_1^2}$$

Variation of Resistor R & Calibration



THD vs. %-variation of resistor R

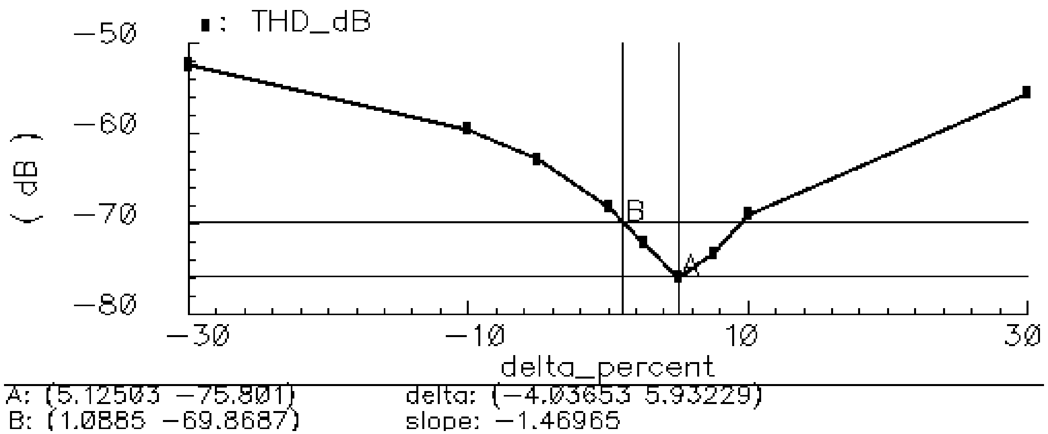
Auxiliary OTA:



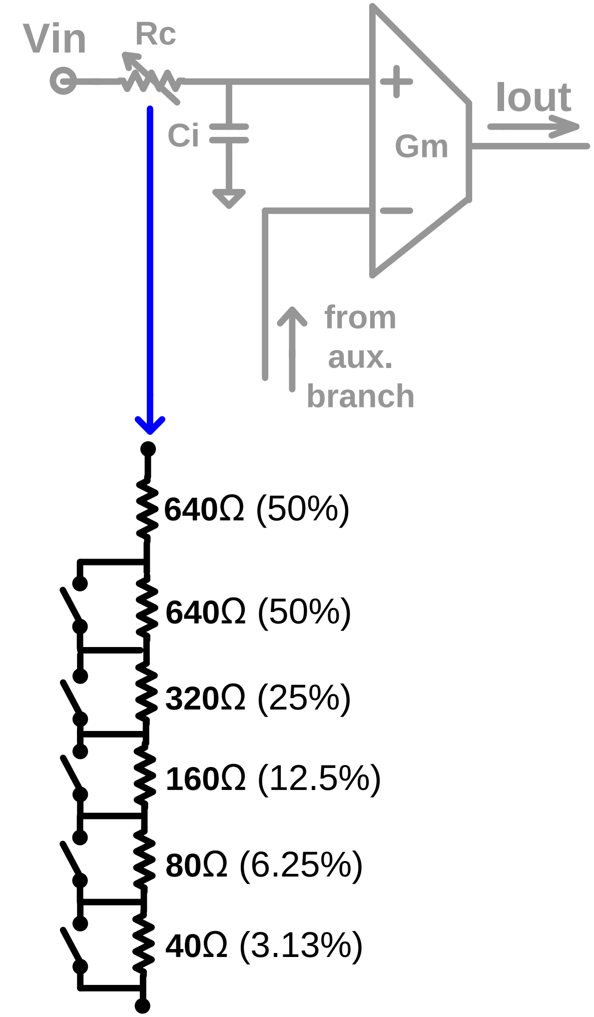
- ΔTHD < 5.4dB requires accuracy of R within 4%
- Some form of calibration is necessary
  - Digital (implemented): R can be adjusted with discrete steps until Gm×R = 1
  - Analog tuning also a possibility: comparison of Vin and Vx with an error amplifier (Vpeak, Vrms, etc. should be identical), automatic adjustment of R (transistor biased in triode region)

Total Rc = 1.28kΩ in this design

Variation of Resistor Rc & Calibration



THD vs. %-variation of resistor Rc



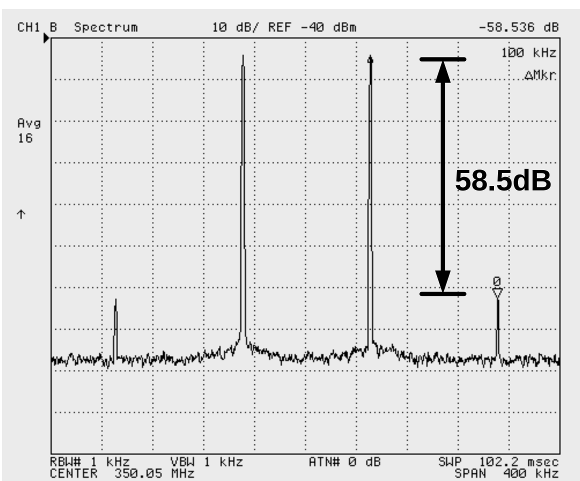
Total Rc = 1.28kΩ in this design

- ΔTHD < 6dB requires accuracy of Rc within 4%
- Requires same calibration approach as for resistor R
  - Simplest: cycling through switch combinations until optimum linearity
  - Options to assess performance in the digital domain:
    - Monitor HD3 or THD (if A/D, DSP are available)
    - In receivers: monitor bit error rate

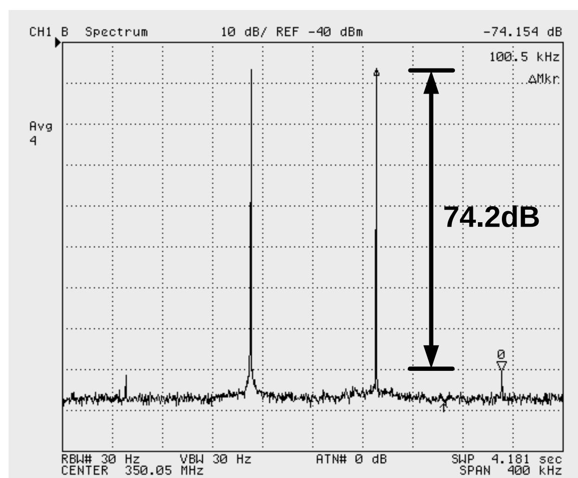
Measurements: Fully-Differential OTA

- 0.13μm CMOS Testchip
- Fully-differential reference OTAs & linearized fully-differential OTAs
  - 2nd-order low-pass filter with linearized OTAs

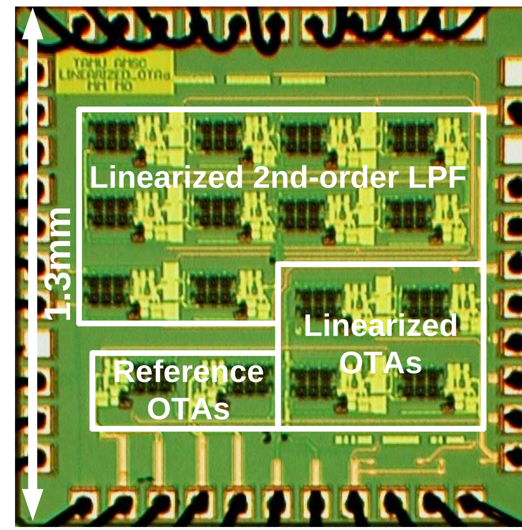
OTA type	Input-referred Noise	IM3 (V_{in} = 0.2 $V_{p\text{-}p}$)		
		50 MHz	150 MHz	350 MHz
Reference (input attenuation = 1/3)	13.3 nV/√Hz	-55.3 dB	-60.0 dB	-58.5 dB
Linearized (attenuation = 1/3 & compensation)	21.8 nV/√Hz	-77.3 dB	-77.7 dB	-74.2 dB



Uncompensated OTA IM3 (input: 0.2$V_{p\text{-}p}$@350MHz)



Compensated OTA IM3 (input: 0.2$V_{p\text{-}p}$@350MHz)



Die micrograph
Reference OTA area: 0.033mm^2
Linearized OTA area: 0.090mm^2

Fully-Differential OTA Comparison With Previous Works

- Figure of Merit [1]:
  - FOM = NSNR + 10log(f/1MHz)   where:
    - NSNR = $SNR_{(dB)}$ + 10log[($IM3_N$ / IM3)(BW / BW_N)(P_N / P_{dis})] from [11]
    - Normalizations: SNR integrated over 1MHz, $IM3_N$ = 1%, bandwidth BW_N = 1Hz , power P_N = 1mW
- Competitive performance with respect to the state of the art
  - Effective trade-offs between linearity, power, noise
  - Proposed method can also be applied to low-frequency OTAs optimized for low power consumption

	[2]* TCAS I	[3]* JSSC 2006	[4] TCAS I 2006	[5] ISSCC 2001	[6]* ISSCC 2005	This work
IM3	-	-47 dB	-70 dB	-60 dB	-	-74.2 dB
IIP3	-12.5 dBV	-	-	-	7 dBV	14.1 dBV
f	275 MHz	10 MHz	20 MHz	40 MHz	184 MHz	350 MHz
Input voltage	-	0.2 V_{p-p}	1.0 V_{p-p}	0.9 V_{p-p}	-	0.2 V_{p-p}
Power / transconductor	4.5 mW	1.0 mW	4 mW	9.5 mW	1.26 mW	5.2 mW
Input-referred noise	7.8 nV/√Hz	7.5 nV/√Hz	70.0 nV/√Hz	23.0 nV/√Hz	53.7 nV/√Hz	21.8 nV/√Hz
Supply voltage	1.2 V	1.8 V	3.3 V	1.5 V	1.8 V	1.2 V
Technology	65 nm CMOS	0.18 µm CMOS	0.5 µm CMOS	0.18 µm CMOS	0.18 µm CMOS	0.13 µm CMOS
$FOM_{(dB)}$	87.5	92.9	96.1	99.1	100	105.6
Normalized |FOM|**	1.0	3.4	7.1	14.3	17.8	64.3

* Power/transconductor calculated from filter power. Individual OTA characterization results not reported in full.

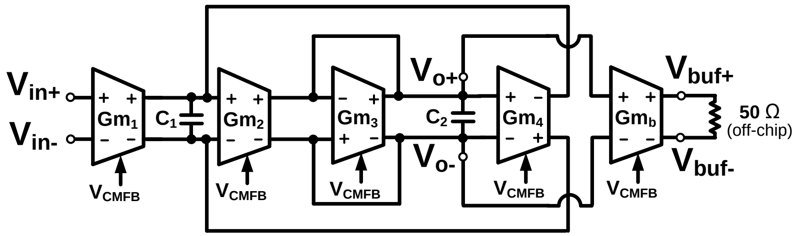
** Normalized FOM magnitude relative to [12]: Normalized |FOM| = 10^($FOM_{(dB)}$/10) / (10^($FOM_{(dB)}$/10) of [12])

Measurements: Filter with Linearized OTAs

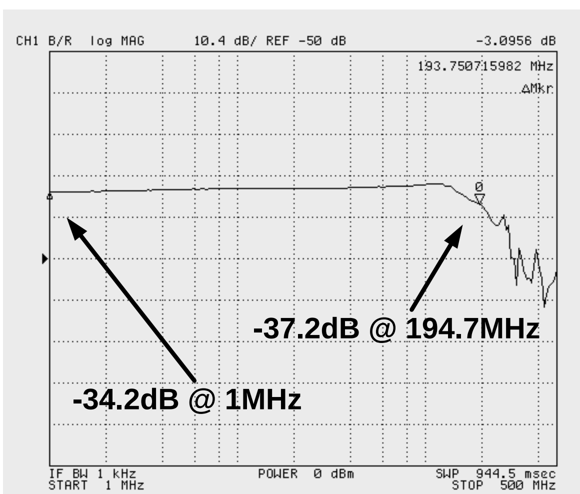
- IM3 is degraded 2-3dB due to non-linearity of output buffer
- IM3 ≈ -70dB up to 150MHz for a $0.2V_{p\text{-}p}$ two-tone input
- Broadband linearization due to compensation with phase shifter (IM3 of -66.1dB at 200MHz, with f_c = 194.7MHz)

	IM3 (V_{in} = 0.2 $V_{p\text{-}p}$)			
Linearized Filter	**50 MHz**	**100 MHz**	**150 MHz**	**200 MHz**
	-73.9 dB	**-69.6 dB**	**-69.7 dB**	**-66.1 dB**

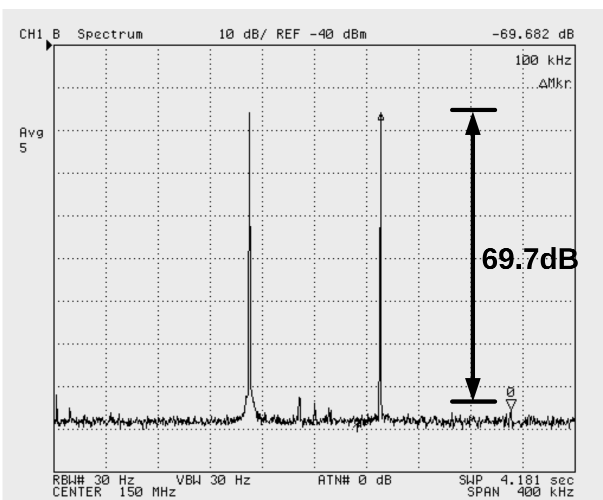
Parameter	Value
Corner frequency (f_{3db})	194.7 MHz
Passband gain	0 dB
Gain of output buffer (Gm_b x 50 Ω)	-34.2 dB
$Gm_{1,2,3,4}$	510 μA/V



2nd-order low-pass filter diagram & design parameters

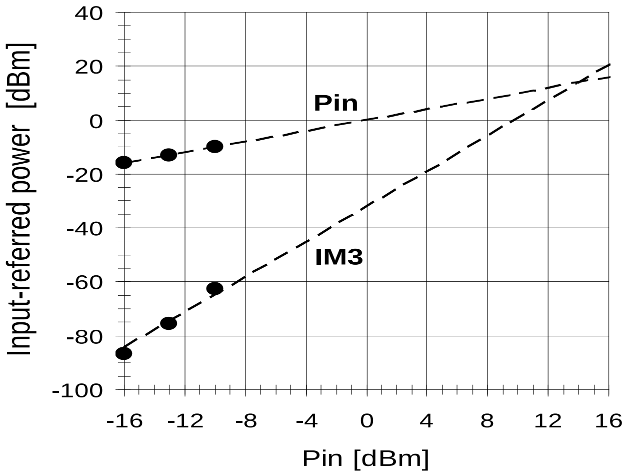


Frequency response of the 2nd - order low-pass filter

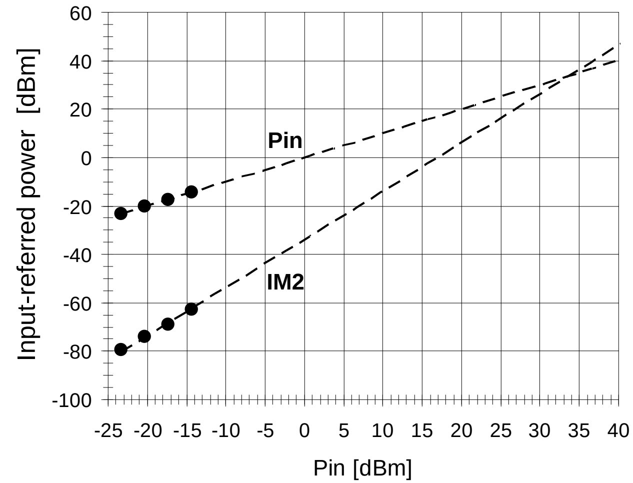


IM3 with compensated OTAs (input: $0.2V_{p\text{-}p}$@150MHz)

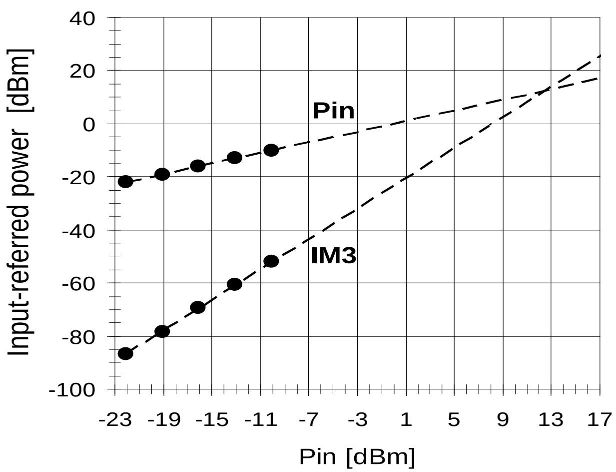
Measurements: Filter with Linearized OTAs



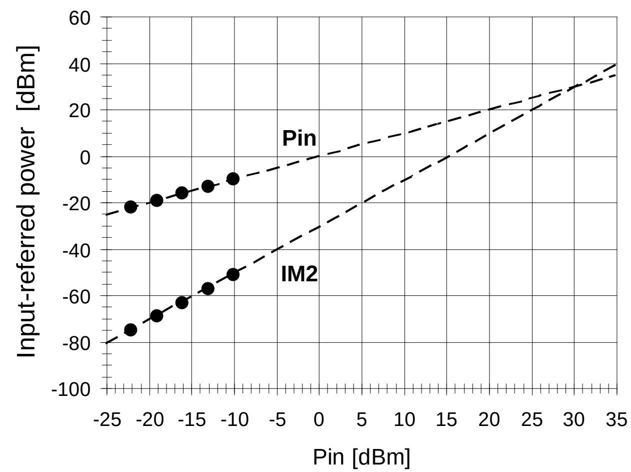
In-band IIP3 (14 dBm)



In-band IIP2 (33.7 dBm)



Out-of-band IIP3 (12.4 dBm)



Out-of-band IIP2 (30.4 dBm)

Comparison of wideband Gm-C lowpass filters

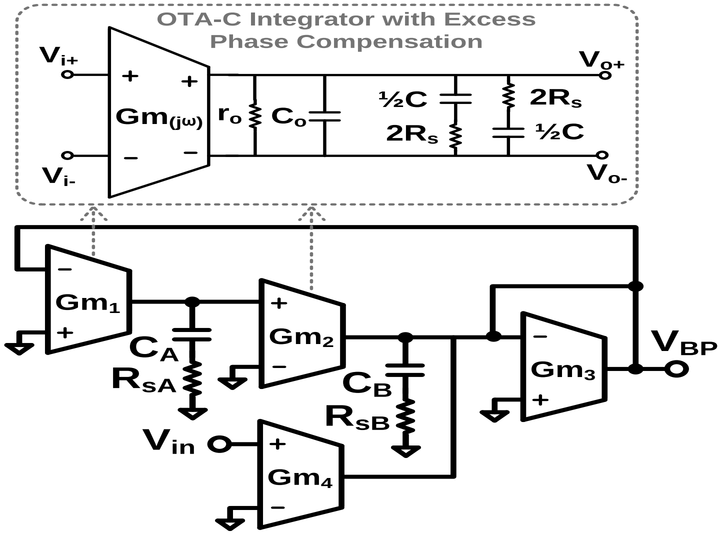
	[2]	[6]	[26]	[27]	[28]	[29]	[30]	This work
Filter order	5	5	8	4	7	5	3	2
f_c (max.)	275 MHz	184 MHz	120 MHz	200 MHz	200 MHz	500 MHz	300 MHz	200 MHz
Signal swing	-	0.30 V_{p-p}	0.20 V_{p-p}	0.88 V_{p-p}	0.80 V_{p-p}	0.50 V_{p-p}	-	0.75 V_{p-p}
Linearity with max. Vin_{p-p}	-	HD3, HD5: < -45dB	THD: -50dB @ 120MHz	THD: -40dB @ 20MHz	THD: -42dB @ 200MHz	THD: < -40dB @ 70MHz	-	IM3: -31dB **** @ 150MHz
In-band IIP3	-12.5 dBV (0.5 dBm)	7dBV (20dBm)	-	-	-	-	3.9 dBV (16.9 dBm)	1.0 dBV (14.0 dBm)
In-band IIP2	-	-	-	-	-	-	19 dBV (32 dBm)	20.7 dBV (33.7 dBm)
Out-of-band IIP3	-8 dBV (5 dBm)	-	-	-	-	-	-	-0.6 dBV (12.4 dBm)
Out-of-band IIP2	15 dBV (28 dBm)	-	-	-	-	-	-	17.4 dBV (30.4 dBm)
Power	36 mW	12.6 mW	120 mW	48 mW	210 mW	100 mW	72 mW	20.8 mW
Power per pole	7.2 mW	2.5 mW	15 mW	12 mW	30 mW	20 mW	24 mW	10.4 mW
Input-referred noise	7.8 nV/√Hz	53.7 nV/√Hz**	-	-	-	-	5 nV/√Hz	35.4 nV/√Hz
Dynamic range	44 dB*	43.3 dB***	45 dB	58 dB	-	52 dB	-	54.5 dB***
Supply voltage	1.2 V	1.8 V	2.5 V	2 V	3 V	3.3 V	1.8 V	1.2 V
Technology	65 nm CMOS	0.18 µm CMOS	0.25 µm CMOS	0.35 µm CMOS	0.25 µm CMOS	0.35 µm CMOS	0.18 µm CMOS	0.13 µm CMOS

•Reported spurious-free dynamic range. ** Calculated from 9.3µV_{RMS} in 30kHz BW.

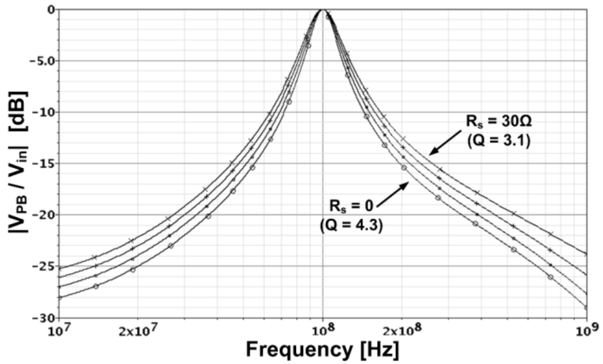
• *** Calculated from max. V_{p-p}, f_c, and input-referred noise density. **** IM3 of -31dB measured close to f_c ensures THD < -40dB.

Excess phase compensation

- Linearization introduces a pole that can cause stability problems
- The effect of the pole can be cancelled by adding a series resistance with integrating capacitors
- Poles effect can be partially cancelled in nodes where multiple OTAs are connected together



Single-ended equivalent block diagram of a bandpass biquad



Filter simulations with different Rs values for excess phase compensation

Linearization without power budget increase

- Linearized OTA consumes twice the power of non-linearized OTA

- Linearization can be done while keeping the power the same by dividing the power budget between the main and auxiliary OTA

OTA type	V_{DSAT} of input diff. pair (M_c)	f_{3db} with 50Ω load	Input-referred noise	Power	IM3 (V_{in} = 0.2 V_{p-p})	Normalized |FOM|* (at f_{max})
Reference (input attenuation = 1/3)	90 mV	2.49 GHz	9.7 nV/√Hz	2.6 mW	-53.1 dB at f_{max} = 350MHz (-53.2 dB at 100MHz)	57.2
Linearized (attenuation = 1/3 & compensation)	54 mV	1.09 GHz	14.3 nV/√Hz	2.6 mW	-77.1 dB at f_{max} = 100MHz	119.2

Simulated comparison: OTA linearization without power consumption increase

Summary & Conclusions

- Proposed attenuation-predistortion technique
  - Effective over a wide frequency band and across PVT variations
  - Independent of OTA circuit topology
  - Allows linearity, noise, power design trade-offs with state of the art performance
  - Compensation for PVT variations are based on digital adjustment of resistors
- Measured performance
  - IM3 improvement of up to 22dB compared to identical reference OTA w/o linearization
  - IM3 as low as -74dB with $Vin_{p\text{-}p}$ = 0.2V at 350MHz
  - Suitable for filter applications requiring an overall IM3 ≤ -70dB up to the cutoff frequency

References

[1] A. Lewinski and J. Silva-Martinez, “A high-frequency transconductor using a robust nonlinearity cancellation,” *IEEE Trans. Circuits and Systems II: Express Briefs*, vol. 53, no. 9, pp. 896-900, Sept. 2006.

[2] V. Saari, M. Kaltiokallio, S. Lindfors, J. Ryynänen, and K. A. I. Halonen, “A 240-MHz low-pass filter with variable gain in 65-nm CMOS for a UWB radio receiver,” *IEEE Trans. Circuits and Systems I: Regular Papers*, vol. 56, no. 7, pp. 1488-1499, July 2009

[3] S. D'Amico, M. Conta, and A. Baschirotto, "A 4.1-mW 10-MHz fourth-order source-follower-based continuous-time filter with 79-dB DR," *IEEE J. Solid-State Circuits*, vol. 41, no. 12, pp. 2713-2719, Dec. 2006.

[4] J. Chen, E. Sánchez-Sinencio, and J. Silva-Martinez, “Frequency-dependent harmonic-distortion analysis of a linearized cross-coupled CMOS OTA and its application to OTA-C filters,” *IEEE Trans. Circuits and Systems I: Regular Papers*, vol. 53, no. 3, pp. 499-510, March 2006.

[5] T. Y. Lo and C.-C. Hung, "A 40-MHz double differential-pair CMOS OTA with -60dB IM3," *IEEE Trans. Circuits and Systems I: Regular Papers*, vol.55, no.1, pp. 258-265, Feb. 2008.

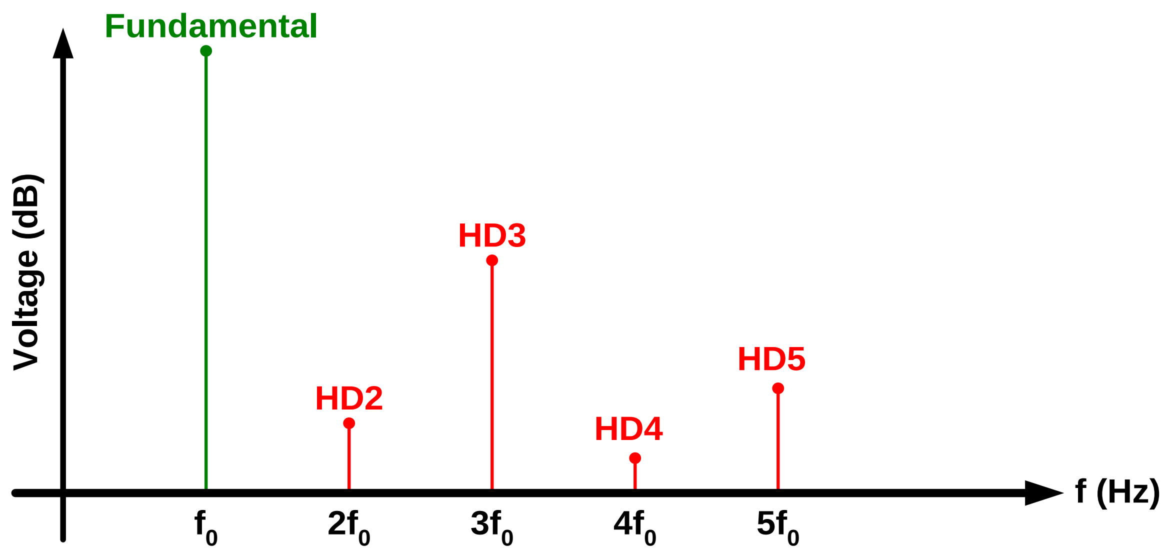
[6] J. C. Rudell, O. E. Erdogan, D. G. Yee, R. Brockenbrough, C. S. G. Conroy, and B. Kim, "A 5th-order continuous-time harmonic-rejection GmC filter with in-situ calibration for use in transmitter applications," in *ISSCC Dig. Tech. Papers*, pp. 322-323, Feb. 2005.

References (Continued)

- [7] G. Bollati, S. Marchese, M. Demicheli, and R. Castello, "An eighth-order CMOS low-pass filter with 30-120 MHz tuning range and programmable boost," *IEEE J. Solid-State Circuits*, vol. 36, no. 7, pp. 1056-1066, July 2001.
- [8] A. Otin, S. Celma, and C. Aldea, "A 40–200 MHz programmable 4th-order Gm-C filter with auto-tuning system," in *Proc. 33rd Eur. Solid-State Circuits Conf. (ESSCIRC)*, pp. 214-217, Sept. 2007.
- [9] S. Dosho, T. Morie, and H. Fujiyama, "A 200-MHz seventh-order equiripple continuous-time filter by design of nonlinearity suppression in 0.25-μm CMOS process," *IEEE J. Solid-State Circuits*, vol. 37, no. 5, pp. 559-565, May 2002.
- [10] S. Pavan and T. Laxminidhi, "A 70-500MHz programmable CMOS filter compensated for MOS nonquasistatic effects," in *Proc. 32nd Eur. Solid-State Circuits Conf. (ESSCIRC)*, pp. 328-331, Sept. 2006.
- [11] K. Kwon, H.-T. Kim, and K. Lee, "A 50–300-MHz highly linear and low-noise CMOS Gm-C filter adopting multiple gated transistors for digital TV tuner ICs," IEEE Trans. Microwave Theory and Techniques, vol. 57, no. 2, pp. 306-313, Feb. 2009.

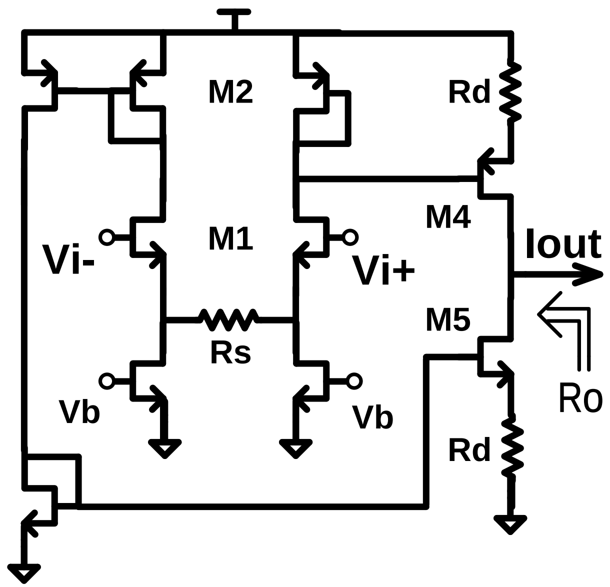
Linearization Basics

- Linearity Improvement Concepts
  - Effect of odd-order harmonics can be reduced by:
    - Signal attenuation
    - Cancellation
    - Feedback
  - Even-order harmonics are suppressed in fully-differential circuits



Spectrum for a fully-differential OTA without odd-order cancellation

Single-Ended OTA: Device Dimensions



Component	Design (W/L in µm)
$(W/L)_{M1}$	43.2 / 0.12
$(W/L)_{M2}$	38.4 / 0.24
$(W/L)_{M3}$	11.04 / 0.24
$(W/L)_{M4}$	153.6 / 0.24
$(W/L)_{M5}$	44.16 / 0.24
Rs	250Ω
Rd	700Ω
Vdd	1.2V

Single-Ended OTA: Schematic Simulations

Comparison with $Vin_{p\text{-}p}$ = 200mV @ 100MHz:

Parameter	Reference OTA	Linearized OTA
$Gm_{effective}$	Gm/2	Gm/2
THD	1.32% (-37.6dB)	0.048% (-66.8dB)
HD2 (below fundamental)	37.68dB	66.68dB
HD3 (below fundamental)	54.35dB	84.26dB
IM3, Δf=5MHz (below fundamental)	42.8dB	61.9dB
Input-referred noise	17.3nV/√Hz	27.7nV/√Hz

Comparison with $Vin_{p\text{-}p}$ = 200mV @ 10MHz:

Parameter	Reference OTA	Linearized OTA
$Gm_{effective}$	Gm/2	Gm/2
THD	1.31% (-37.7dB)	0.021% (-73.6dB)
HD2 (below fundamental)	37.78dB	73.49dB
HD3 (below fundamental)	53.88dB	93.03dB
IM3, Δf=0.5MHz (below fundamental)	42.8dB	67.2dB
Input-referred noise	18.7nV/√Hz	29.1nV/√Hz

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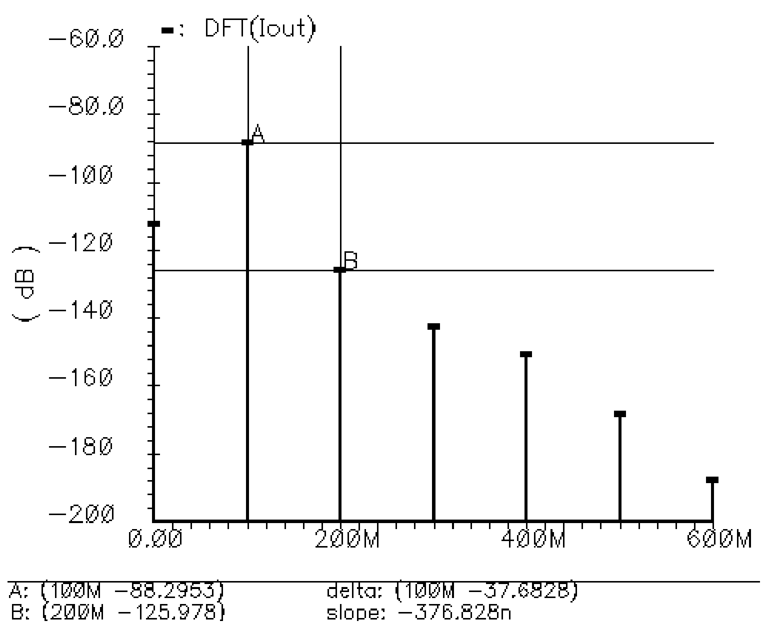
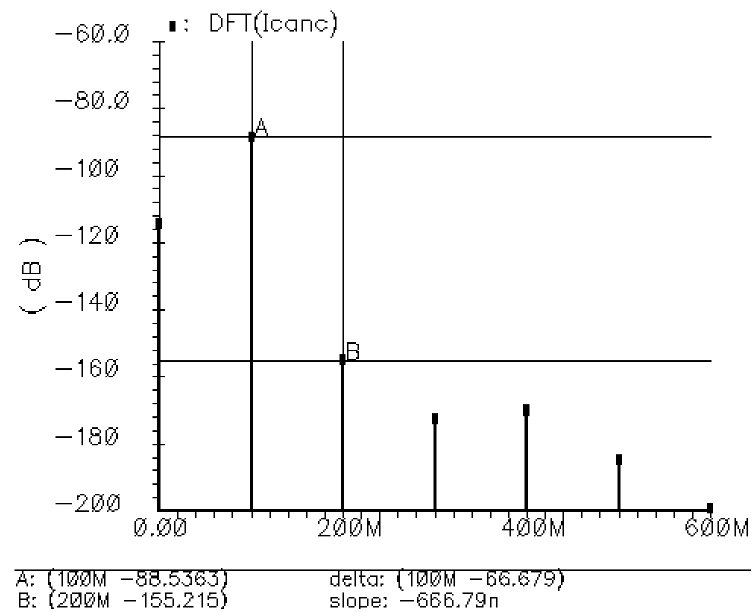
Single-Ended OTA: HD3 Simulations

- Output current spectra from HD3 tests
  - $Vin_{peak\text{-}peak} = 200mV$



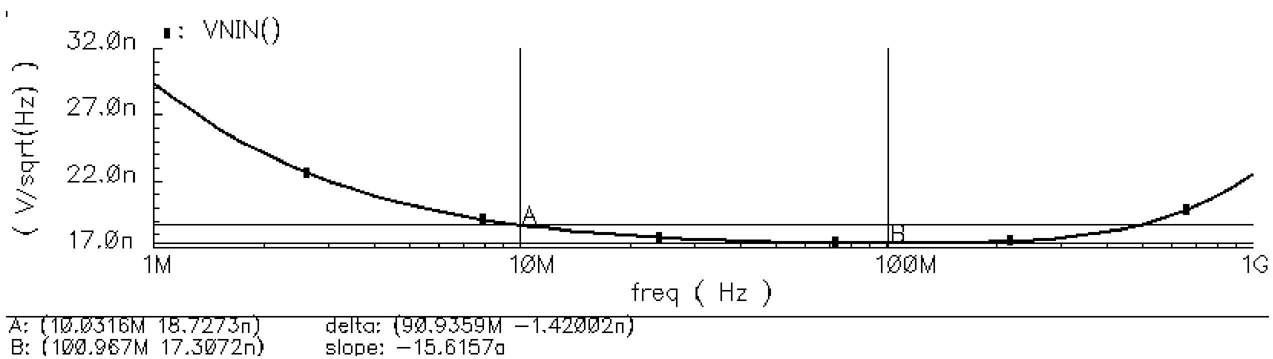
OTA with input-attenuation factor of 0.5



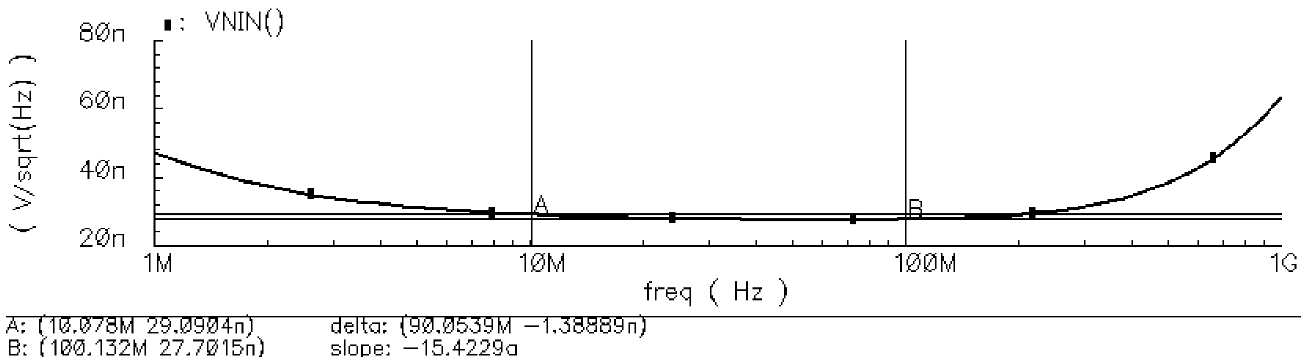
Linearized OTA

Single-Ended OTA: Noise Simulations

- Input-referred noise of linearized OTA is larger by a factor of ~1.6

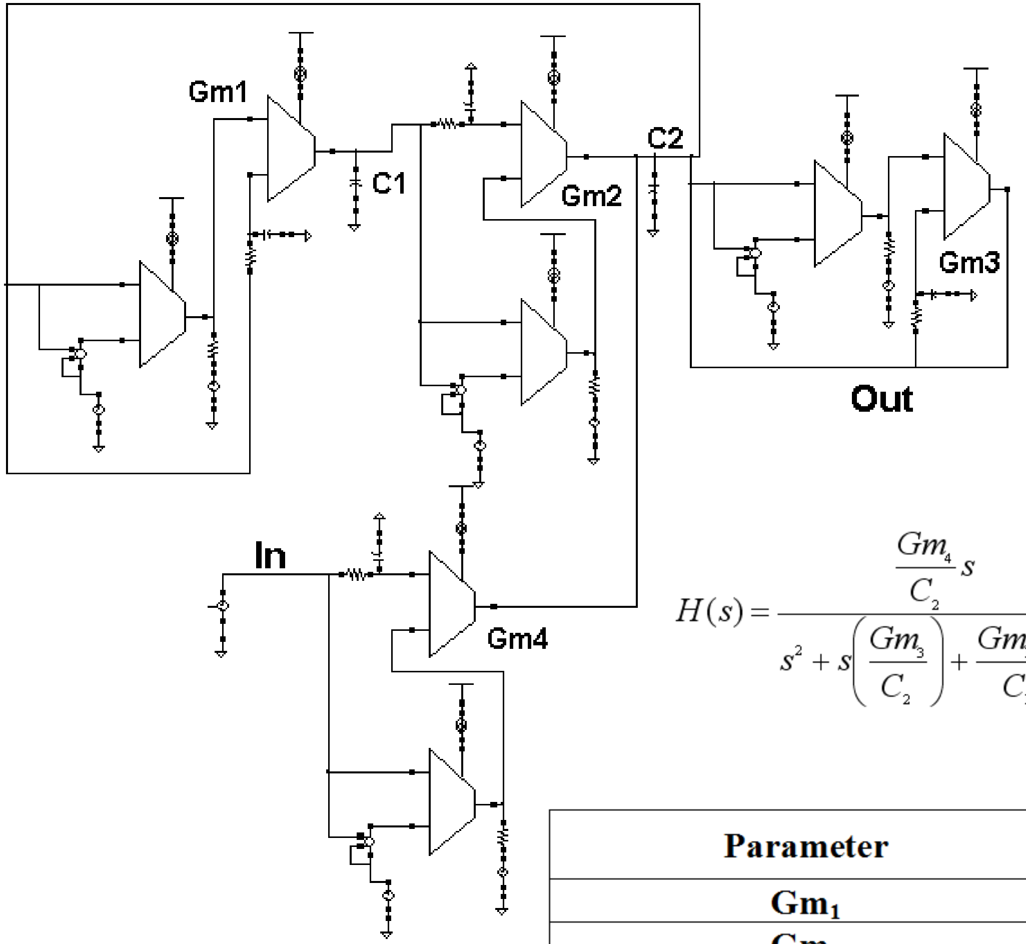


OTA with input-attenuation factor of 0.5



Linearized OTA

Biquad with Single-Ended OTAs



$$H(s)=\frac{\frac{Gm_4}{C_2}s}{s^2+s\left(\frac{Gm_3}{C_2}\right)+\frac{Gm_1Gm_2}{C_1C_2}}$$

$$\omega_0=\sqrt{\frac{Gm_1Gm_2}{C_1C_2}}$$

$$Q=\frac{C_2}{Gm_3}\sqrt{\frac{Gm_1Gm_2}{C_1C_2}}$$

Parameter	Reference Filter	Linearized Filter
Gm_1	760µA/V	760µA/V
Gm_2	760µA/V	760µA/V
Gm_3	204µA/V	435µA/V
Gm_4	760µA/V	760µA/V
C_1	140fF	~117fF (more parasitics)
C_2	400fF	~271fF (more parasitics)

Biquad Simulations with Single-Ended OTAs

Comparison with $Vin_{p\text{-}p}$ = 200mV at 100MHz:

Parameter	Reference OTA	Linearized OTA
$Gm_{effective}$ (OTAs)	Gm/2	Gm/2
f_o	100MHz	100MHz
Q	2	~2
$Av_{passband}$	1.91dB	1.77dB
$Vo_{p\text{-}p}$	232mV	241mV
THD	**3.144% (-30.1dB)**	**0.212% (-53.5dB)**
HD2 (below fundamental)	30.08dB	53.85dB
HD3 (below fundamental)	53.45dB	64.57dB

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