RF Linearity of Short-Channel MOSFETs

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Outline

- ✓ Motivation
- Linearity Metrics
- Short-Channel MOSFETs
- Conclusions

Motivation

Why RF CMOS?

- Technology driven by microprocessor industry.
- Integration with digital circuits on same chip.
- Cost effective.

Issues in sub-micron RF CMOS :

- Hot electron effects, gate noise. [Shaeffer, JSSC 97]
- Linearity (nonlinearity generates undesired spectral components).

Question: How linear are short-channel CMOS devices?

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Linearity Metrics

Consider memoryless nonlinearity which can be expressed by a Taylor series as:

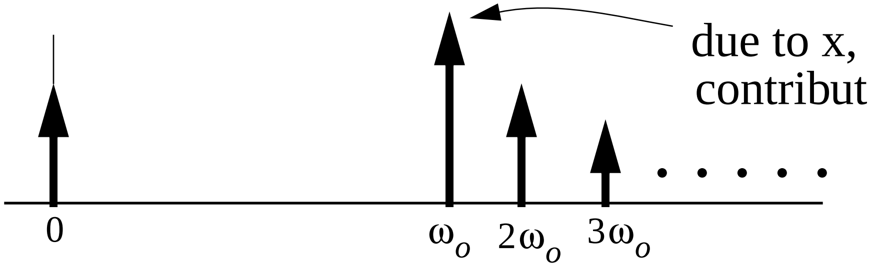
$$y = \sum_{n=0}^{\infty} c_n x^n$$

Two widely-used figures for quantifying nonlinearity :

1) 1dB compression point

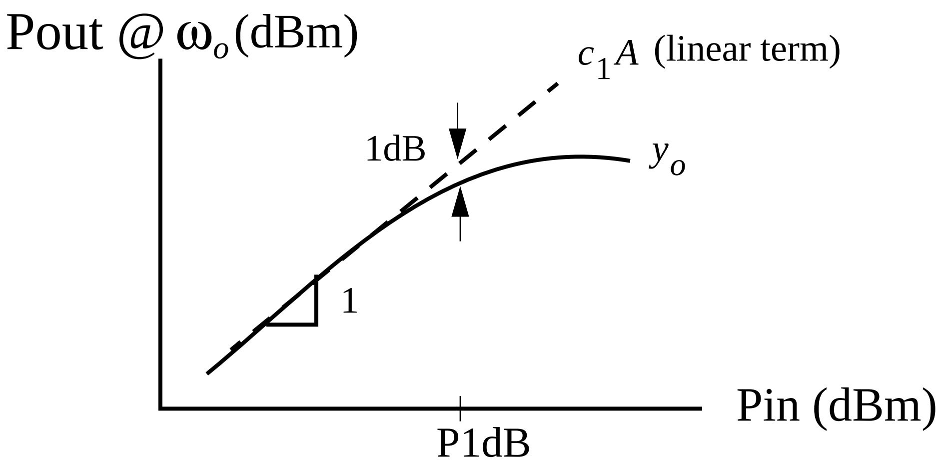
Input : $x = A\cos(\omega_o t)$

Output @ ω_o : $$y_o = \left[c_1 A + \frac{3}{4}c_3 A^3 + \ldots + \frac{c_{2k-1}}{2^{2k-2}}\binom{2k-1}{k-1}A^{2k-1}\right]\cos(\omega_o t)$$



due to x, x^3, x^5 ... only odd terms contribute to nonlinearity at ω_o

Linearity Metrics



$$\frac{c_1A}{y_o} = 1.12 \quad (=1\text{dB}) \quad ==> \quad 0.109c_1A + \sum_{k=2}^{\infty}\left[\frac{c_{2k-1}}{2^{2k-2}}\binom{2k-1}{k-1}A^{2k-1}\right] = 0$$

Solve for A and substitute in

$$P_{1dB} = \frac{A^2}{2R_s}$$

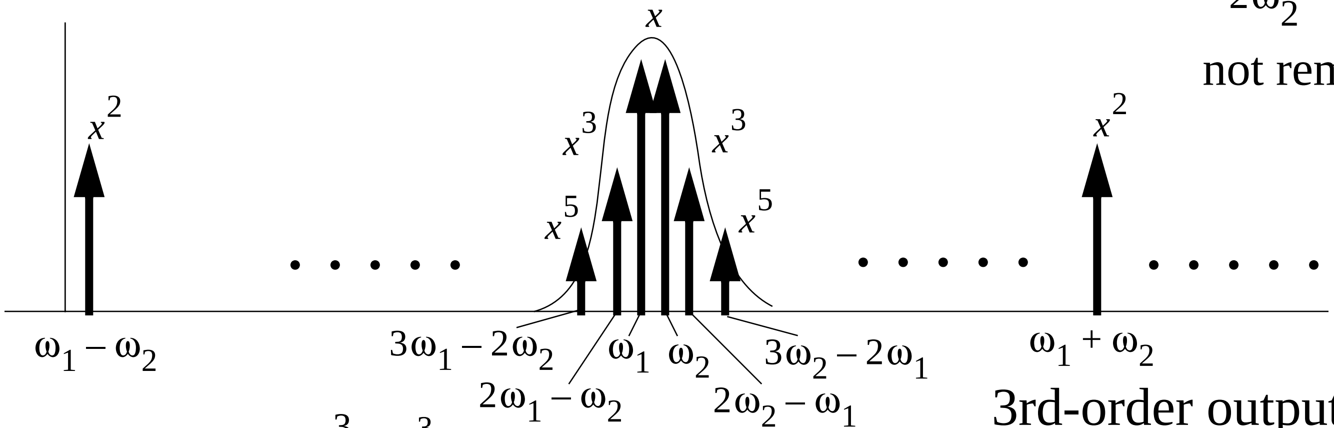
For low-order nonlinearity (e.g., n<5), solution simplifies to $P_{1dB} \approx \left|\frac{c_1}{13.8c_3R_s}\right|$

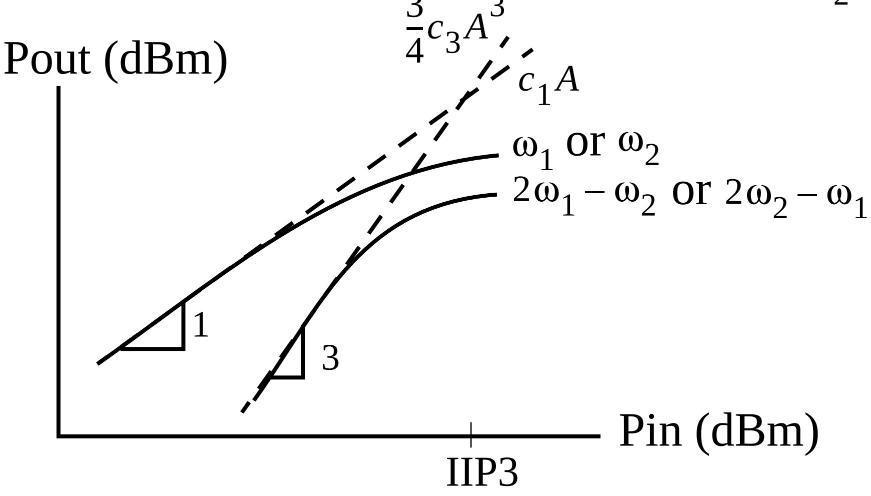
Linearity Metrics

2) IP3 (3rd-order intermodulation intercept point)

Input : $x = A\cos(\omega_1 t) + A\cos(\omega_2 t)$; $\omega_1 \approx \omega_2 \Rightarrow \left.\begin{matrix}2\omega_1-\omega_2\\ 2\omega_2-\omega_1\end{matrix}\right\} \approx \omega_1, \omega_2$

not removed by BPF





3rd-order output @ $2\omega_1-\omega_2$

$$IM3 = \left|\frac{3}{4}c_3A^3\right|\cos[(2\omega_1-\omega_2)t]$$

At intercept point (IIP3),

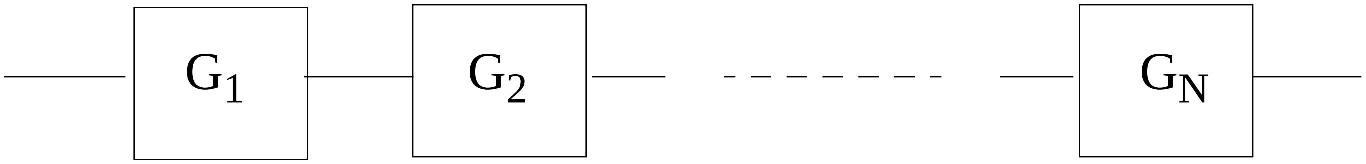
$$|IM3| = |\text{linear term}|$$

Solve for A and use $IIP3 = \frac{A^2}{2R_s} = \left|\frac{2c_1}{3c_3R_s}\right|$

Linearity Metrics

- 1dB compression point takes into account higher order terms ($n \geq 3$) and is determined with large-signal excitation.
- IP3 considers nonlinearity up to third order only and is derived from extrapolation from small-signal measurements. (Nonlinearity which lacks cubic term has infinite IP3).
- Hence, 1dB compression point is generally lower than IP3.
- For low order nonlinearity (n<5), the ratio of IP3 and 1dB compression point is a constant of 9.64 dB.

Cascaded Nonlinear Stages

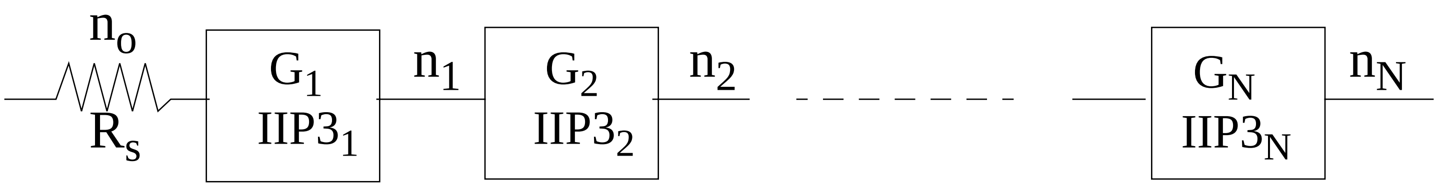


- To obtain accurate linearity figures, need to consider entire system as a single nonlinear stage and apply previous results.
- 1dB compression point => need to consider entire system as one stage since 1dB compression point is measured at large-signal level where small-signal linearization is invalid.
- IP3 => can be approximated from combination of individual IP3 values since IP3 derivation is based on small-signal extrapolation.
- Compute worst-case overall IP3 by combining IM3's of each stage in additive fashion.

$$\text{Min IIP3} = \left(\frac{1}{IIP3_1} + \sum_{i=2}^{N} \frac{\prod_{j=1}^{i-1} G_j}{IIP3_i} \right)^{-1} \quad ; \; G_i = \text{small-signal power gain}$$

Optimization of Linearity and Noise Performance

$$IP3NR = \frac{IIP3_{min}}{F}$$



$$IIP3_{min} = \left(\frac{1}{IIP3_1} + \sum_{i=2}^{N} \frac{\prod_{j=1}^{i-1} G_j}{IIP3_i} \right)^{-1}$$

$$F = 1 + \frac{1}{n_o}\left(\frac{n_1}{G_1} + \frac{n_2}{G_1 G_2} + \ldots + \frac{n_N}{G_1 \ldots G_N} \right)$$

- Maximum overall IIP3 requires maximizing individual IIP3’s (especially $IIP3_N$) and minimizing individual G’s (especially G_1).
- Minimum overall F requires minimizing individual noise power (especially n_1) and maximizing individual G’s (especially G_1).

Hence, there exists an optimal gain distribution that maximizes IP3NR.

Optimal Gain Distribution Maximizing IP3NR

$$G_1 = \sqrt{\frac{n_1 G_T\, IIP3_2}{(n_o G_T + n_N) IIP3_1}}$$

$$G_i = \sqrt{\frac{n_i\, IIP3_{i+1}}{n_{i-1}\, IIP3_i}} \quad ;\ i = 2...N\text{-}1$$

$$G_N = \sqrt{\frac{G_T (n_o G_T + n_N) IIP3_1}{n_{N-1}\, IIP3_N}}$$

Assumption:

IIP3's and G's are independent (later proven true for MOSFETs)

If n_i's and $IIP3_i$'s are identical,

$$G_1 = \sqrt{\frac{G_T}{\alpha G_T + 1}} \quad ;\ \alpha = \frac{n_o}{n_1}$$

$$G_i = 1 \quad ;\ i = 2...N\text{-}1$$

$$G_N = \sqrt{G_T(\alpha G_T + 1)}$$

- Only 2 stages needed to obtain optimal IP3NR.
- Input stage is responsible for noise performance, *i.e.*, G_1 scaled by ~ $1/\sqrt{\alpha}$ for large G_T.
- Output stage provides leftover gain.

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Short-Channel MOSFETs

(Short channel here means $E_{sat}L \ll V_{od}$)

$$I_{Dsat} = W v_{sat} C_{ox}\left(\frac{V_{od}^{2}}{V_{od} + E_{sat}L}\right) \qquad E_{sat} = \frac{2v_{sat}}{\mu_{eff}}$$

$$\mu_{eff} = \frac{\mu_o}{1 + \theta V_{od}} \qquad V_{od} = V_{gs} - V_t$$

Express I_{Dsat} with Taylor series and solve for Taylor coefficients c_n's.

$$IIP3 = \frac{8}{3}\frac{v_{sat}L}{\mu_1 R_s}V_{od}\left(1 + \frac{\mu_1 V_{od}}{4v_{sat}L}\right)\left(1 + \frac{\mu_1 V_{od}}{2v_{sat}L}\right)^{2}, \qquad P_{1dB} = \frac{\left(1 + \frac{\mu_1 V_{od}}{2v_{sat}L}\right)^{4}}{2R_s\left(\frac{\mu_1}{2v_{sat}L}\right)^{2}\left[V_{od}\left(1 + \frac{\mu_1 V_{od}}{4v_{sat}L}\right) + \frac{6.88 v_{sat}L}{\mu_1\left(1 + \frac{\mu_1 V_{od}}{2v_{sat}L}\right)^{2}}\right]}$$

$$\mu_1 = \mu_o + 2v_{sat}\theta L$$

$$IIP3\text{–}to\text{–}P_{1dB}\ \text{ratio} = 9.17\left[1 + 0.145\frac{\mu_1 V_{od}}{v_{sat}L}\left(1 + \frac{\mu_1 V_{od}}{4v_{sat}L}\right)\right]$$

- Note IIP3 and P_{1dB} are independent of W and C_{ox}.

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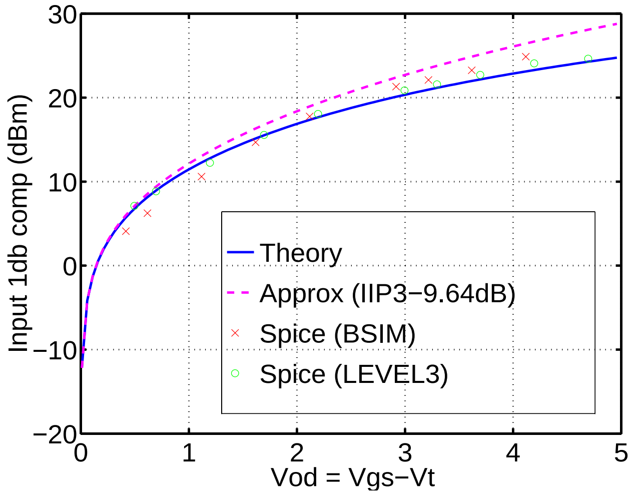
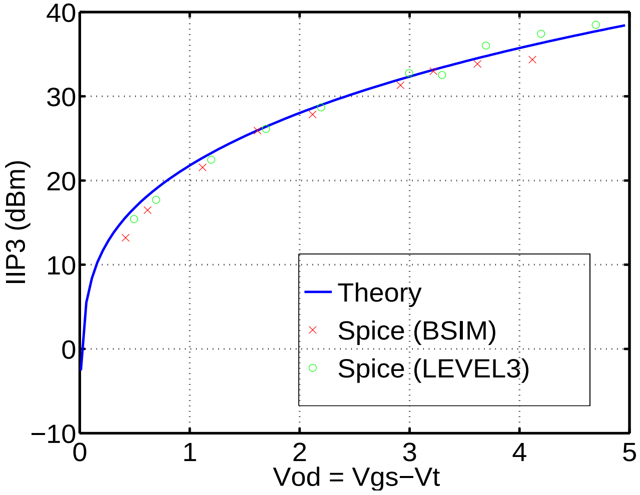
Short-Channel MOSFETs



Input P_{1dB} vs V_{od}



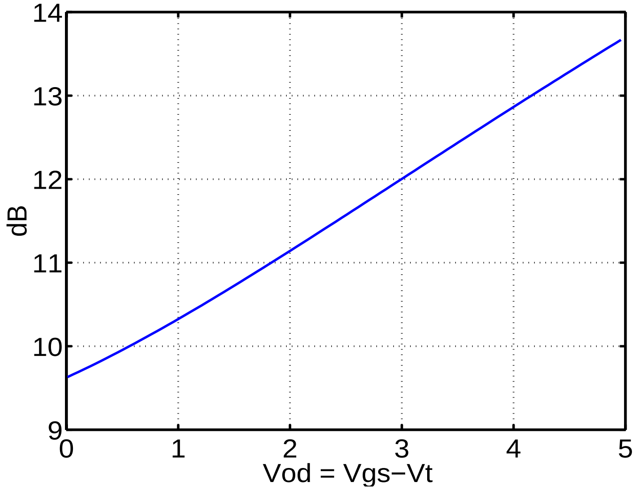
IIP3 vs V_{od}

For comparison, BJT has

$$IIP3 = \frac{4}{R_S}\left(\frac{kT}{q}\right)^2$$

$$= -12.7 \text{ dBm}$$

for $R_s = 50$, $T = 300$.



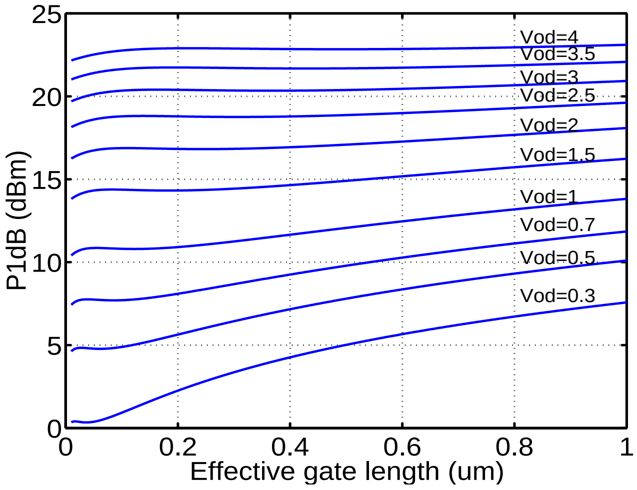
IIP3-to-P_{1dB} ratio vs V_{od}

Assumptions:

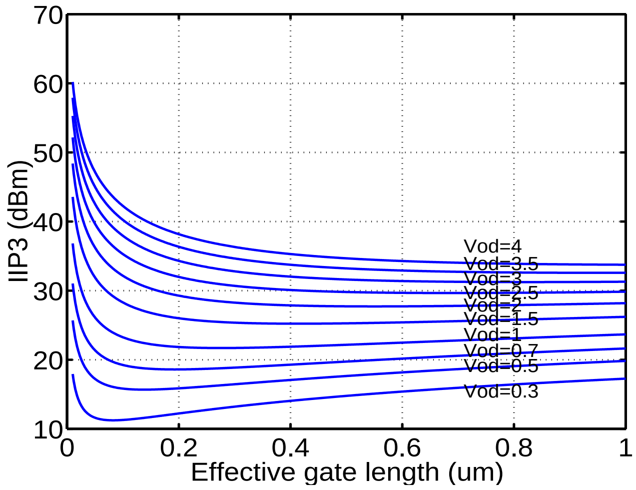
- Memoryless (valid when ω is well below ω_T).
- Impedance matched to 50 Ω.
- 0.35 μm L_{eff} , 9.7 nm t_{ox} , μ_o = 495 cm^2/V-sec, v_{sat} = 2.4x10^7 cm/s.
- Spice simulations based on MOSIS HP 0.5 μm CMOS Model.

Impact of Technology Scaling on Linearity

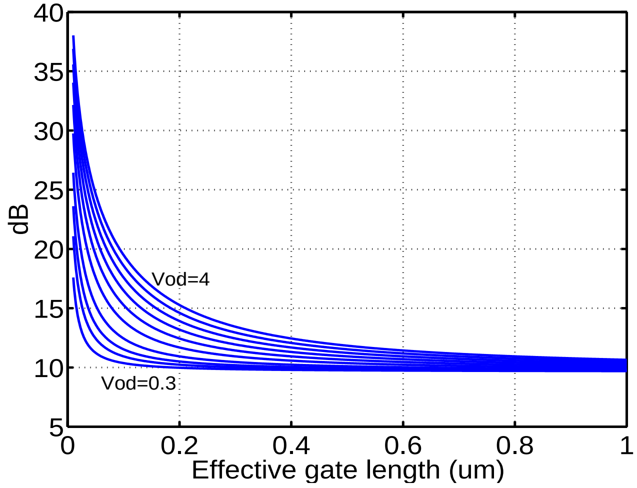
Input P1dB vs L



IIP3 vs L



IIP3-to-P1dB ratio vs L



For Vod < 1 (typical values for low power applications),

- IP3 varies slightly for L_{eff} above 0.6 μm. As L_{eff} decreases below 0.6 μm, IP3 starts decreasing slowly and eventually rises above the long channel value.
- 1dB compression point decreases as L_{eff} reduces and eventually flattens out.
- IP3-to-P1dB ratio increases from the approximate 10dB constant as technology scales.

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IP3 Specification of Mobile Communication Standards

Standard	IIP3 (dBm)
GSM	- 18
DCS	- 19
CDMA	- 13
AMPS	- 5
DECT	- 23
PWT	- 29.5

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Conclusions

- For “smooth”, memoryless nonlinearity, 1dB compression point and IP3 can be written in terms of Taylor coefficients of nonlinear transfer characteristics.
- In cascaded nonlinear gain stages, there exists an optimal gain distribution that maximizes overall IP3NR.
- For short-channel MOSFETs, 1dB compression point and IP3 increase as V_{od} increases and are independent of W and C_{ox}.
- As technology scales, IP3 improves whereas P_{1dB} stays relatively invariant (for $V_{od} > 2$) or even decreases (for $V_{od} < 2$). Hence, the IP3-to-P1dB ratio increases from the ~10dB long channel value as L decreases.
- The results of this work verify that CMOS is promising for RF designs.