ECEN474: (Analog) VLSI Circuit Design
Fall 2011

Lecture 24: Variable Gain Amplifiers (VGAs)

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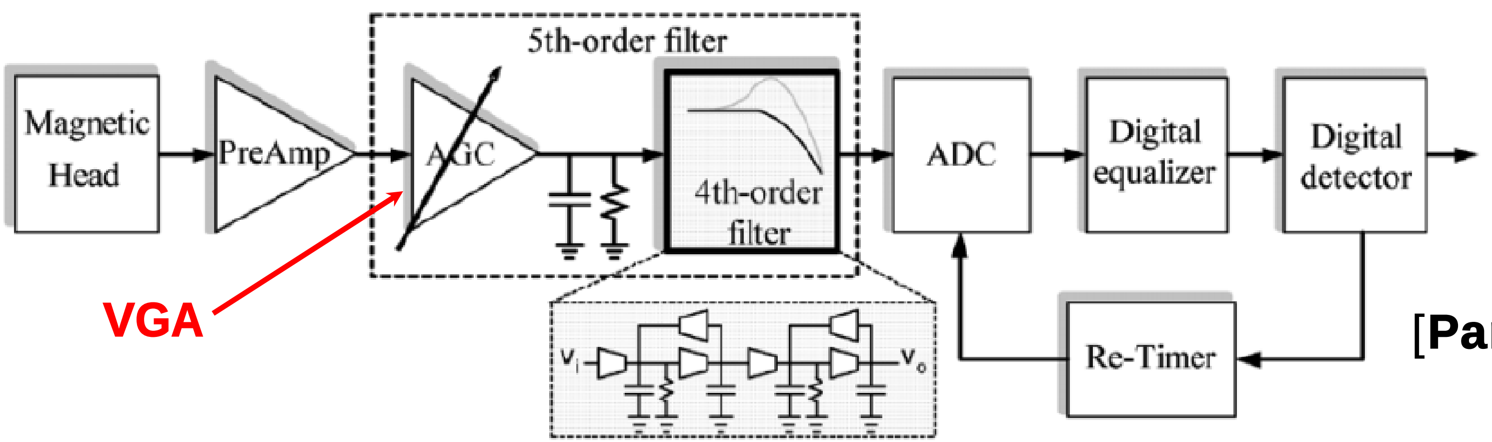
Agenda

- Variable Gain Amplifiers
- Material is related primarily to Project #4

Variable Gain Amplifier (VGA) Applications

- Variable gain amplifiers (VGAs) are employed in many applications in order to maximize the overall system dynamic range
- Critical component of automatic-gain control (AGC) systems



[Pandey]

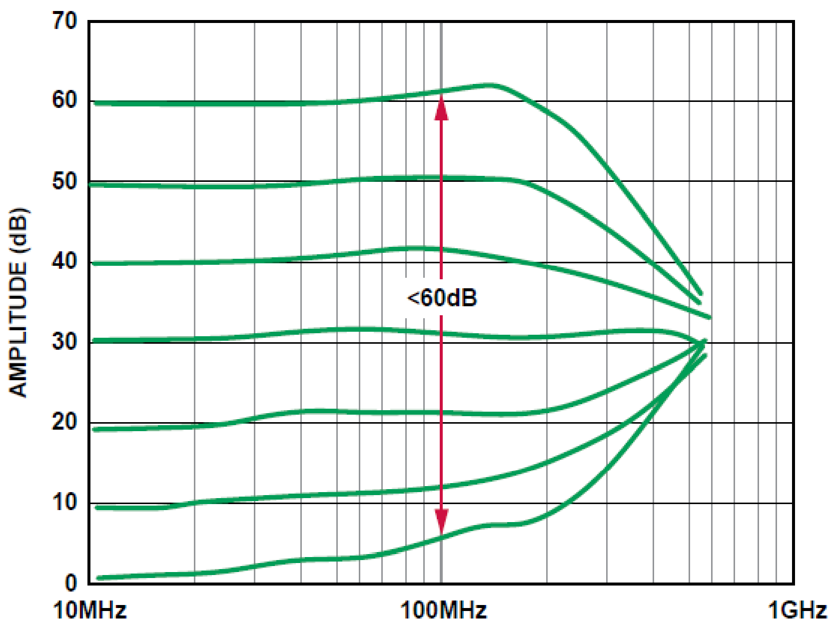
Hard-Disk Drive Receiver Front-End

Typical VGA Design Goals

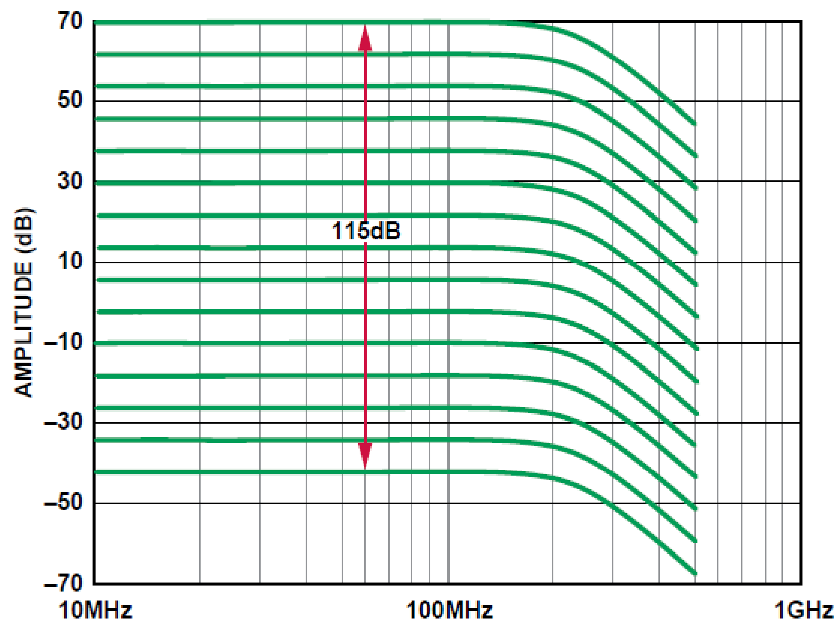
- Constant bandwidth across wide gain range
- Exponential gain control ("linear in dB") preferred in many applications
- Low noise, low distortion, low power

[**Gilbert**]

Poor Performance



Desired Performance

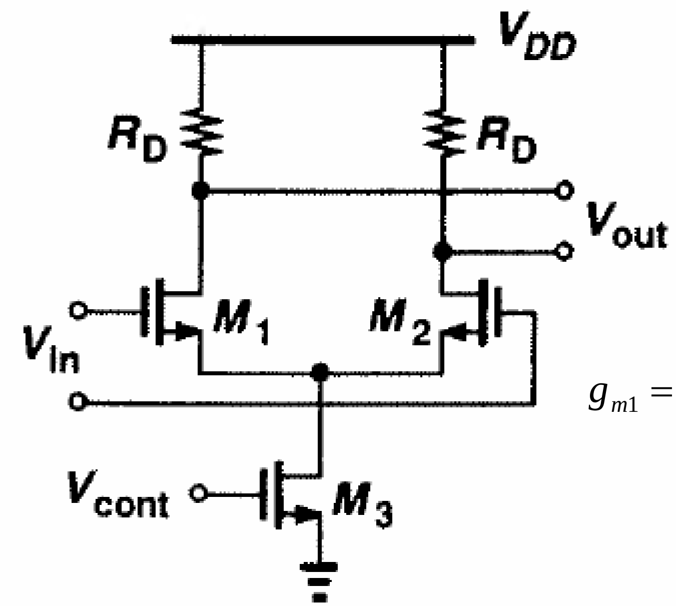


VGA Techniques

- Multipliers
- Transconductance ratio amplifiers
- Source degeneration

Multiplier-Based VGA

[**Razavi**]



$$A_v = g_{m1} R_D$$

$$g_{m1} = \sqrt{\mu C_{ox} \left(\frac{W}{L}\right)_1 I_3}$$

How is I_3 affected by V_{cont}?

$$I_3 = \frac{\mu C_{ox}}{2} \left(\frac{W}{L}\right)_3 (V_{cont} - V_T)^2$$

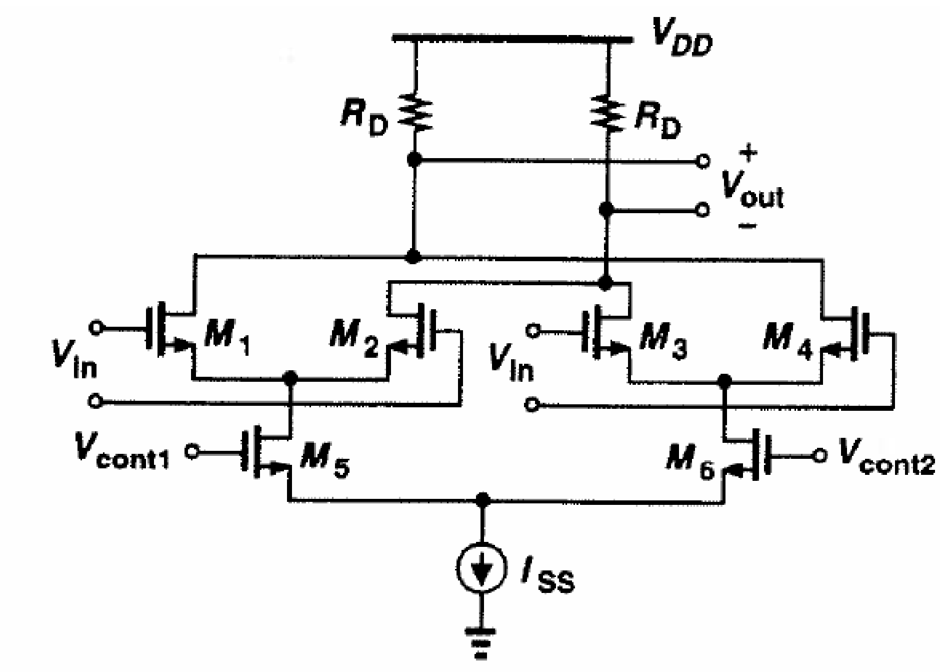
$$g_{m1} = \sqrt{\frac{(\mu C_{ox})^2}{2} \left(\frac{W}{L}\right)_1 \left(\frac{W}{L}\right)_3 (V_{cont} - V_T)^2} = \mu C_{ox} (V_{cont} - V_T) \sqrt{\frac{1}{2} \left(\frac{W}{L}\right)_1 \left(\frac{W}{L}\right)_3}$$

$$A_v = \mu C_{ox} (V_{cont} - V_T) \sqrt{\frac{1}{2} \left(\frac{W}{L}\right)_1 \left(\frac{W}{L}\right)_3} R_D$$

- Gain can be linearly controlled by V_{cont}
- Circuit only operates with positive V_{cont} (2-quadrant), which is generally OK for VGA applications

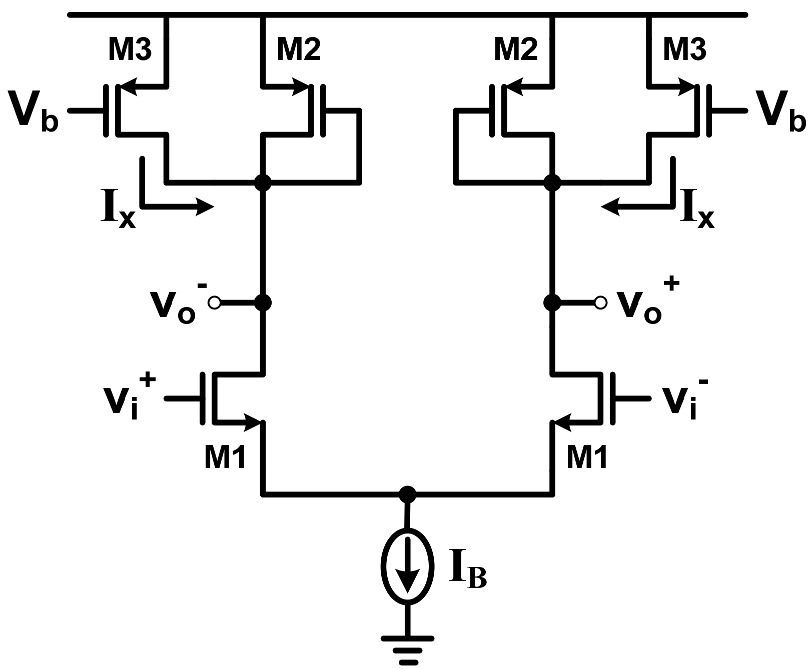
4-Quadrant Multiplier

[**Razavi**]



- Allows multiplication in all 4-quadrants
- Differential V_{cont} allows the sign of the gain to be inverted
- Can also use for VGAs, although 4-quadrant operation is not necessary
- Often used in RF transceivers as a frequency translator (mixer)
- Also called the "Gilbert Cell", after Barrie Gilbert who is the inventor of the bipolar version

Transconductance Ratio VGA #1



$$A_v \approx \frac{g_{m1}}{g_{m2}}$$

- Diode-load transconductance (g_{m2}) can be altered by stealing current with a parallel current source M3, thus altering the gain
- Issues
  - Gain is a ratio of nmos and pmos transconductance, which can be sensitive to process variations
  - Bandwidth changes with gain

Transconductance Ratio VGA #2

TP 5.1: A 2mA/3V 71MHz IF Amplifier in 0.4µm CMOS Programmable over 80dB Range

ISSCC 1997

Francesco Piazza, Paolo Orsatti, Qiuting Huang, Hiroyuki Miyakawa[1]

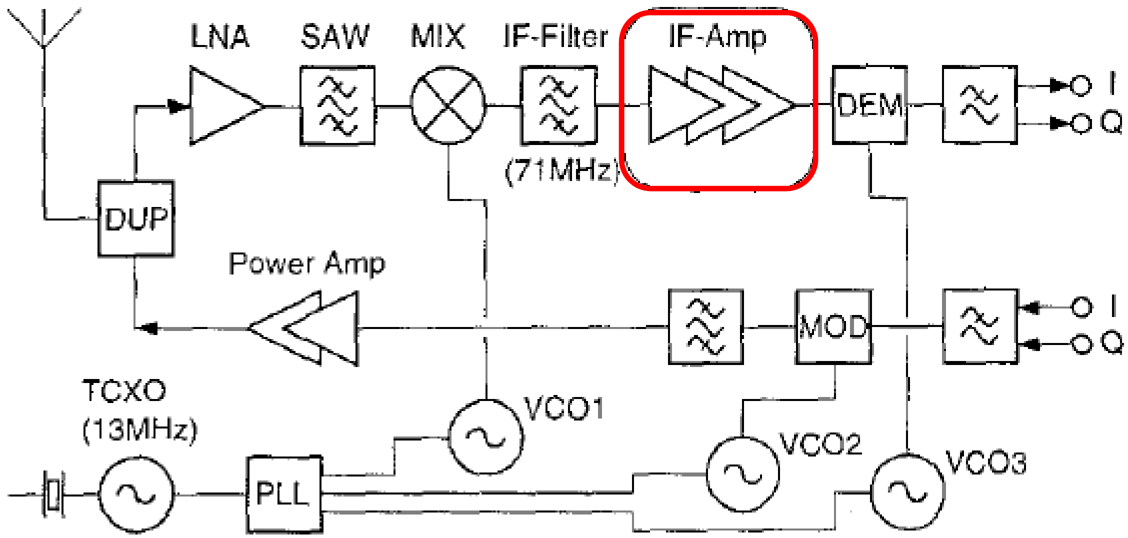
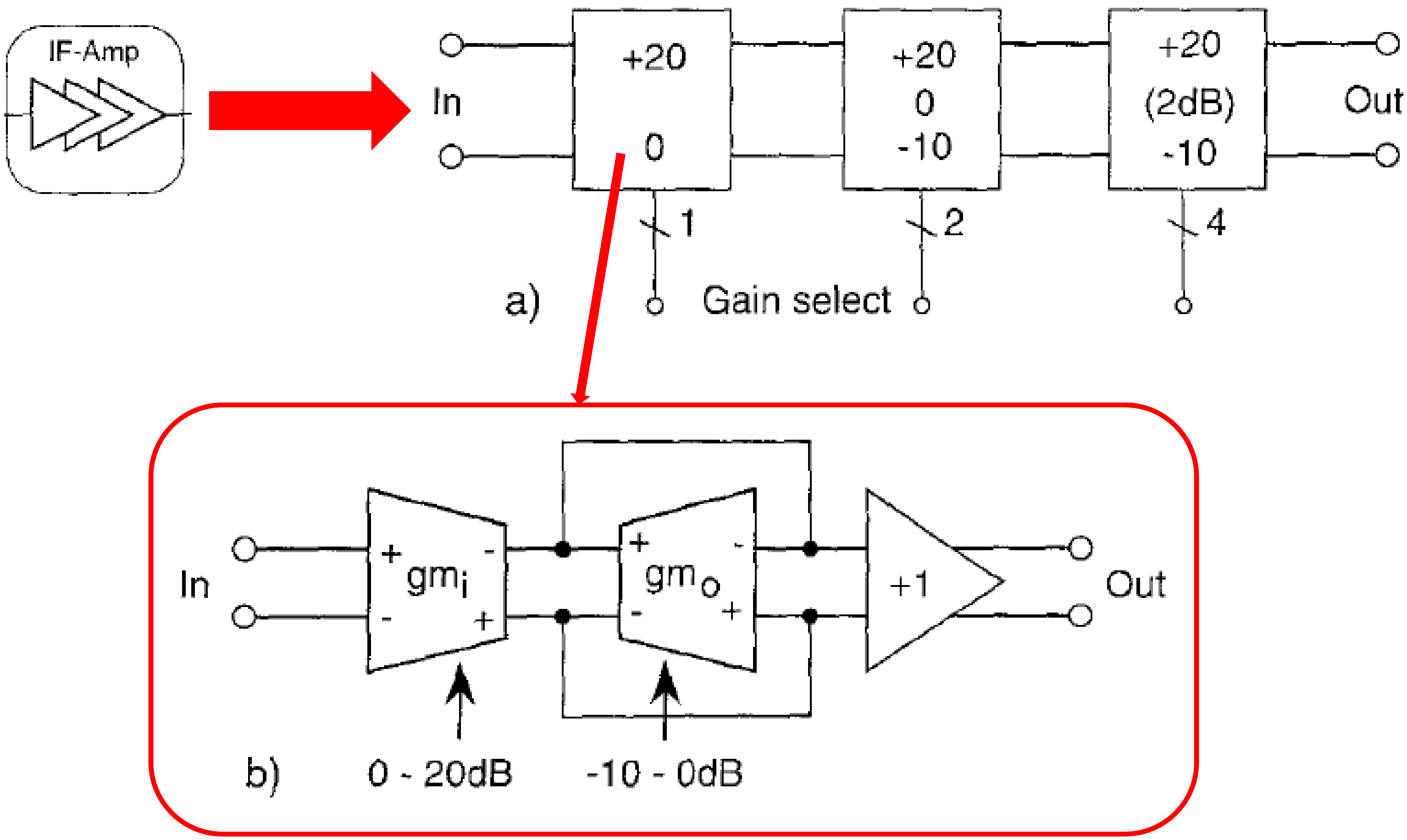


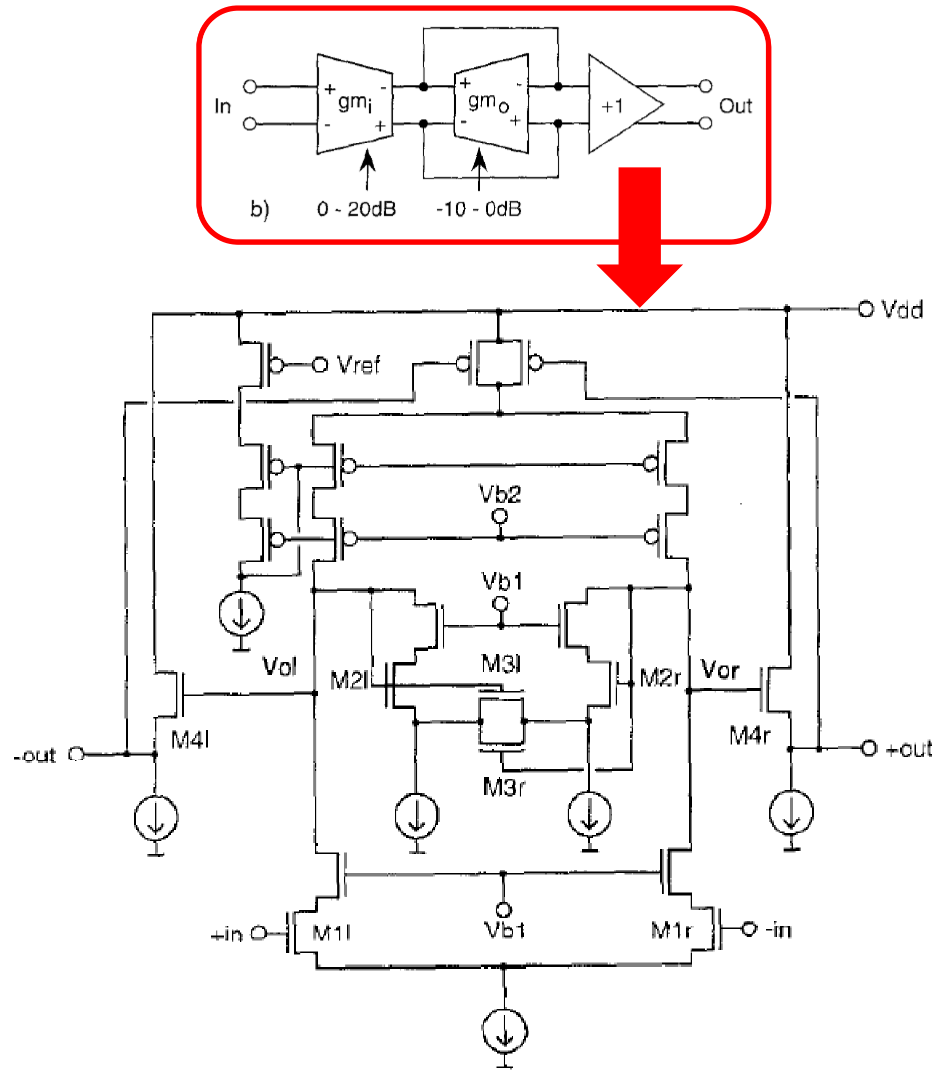
Figure 1: Block diagram of the GSM handset.

Transconductance Ratio VGA #2



Transconductance Ratio VGA #2

- g_{mi} is from M1
- g_{mo} is from M2
- M4 source-follower output buffers
- Both the gmi and gmo transistors are segmented into multiple parallel transistors
- Gain is controlled by switching off bias current to these segments



Transconductance Ratio VGA #2

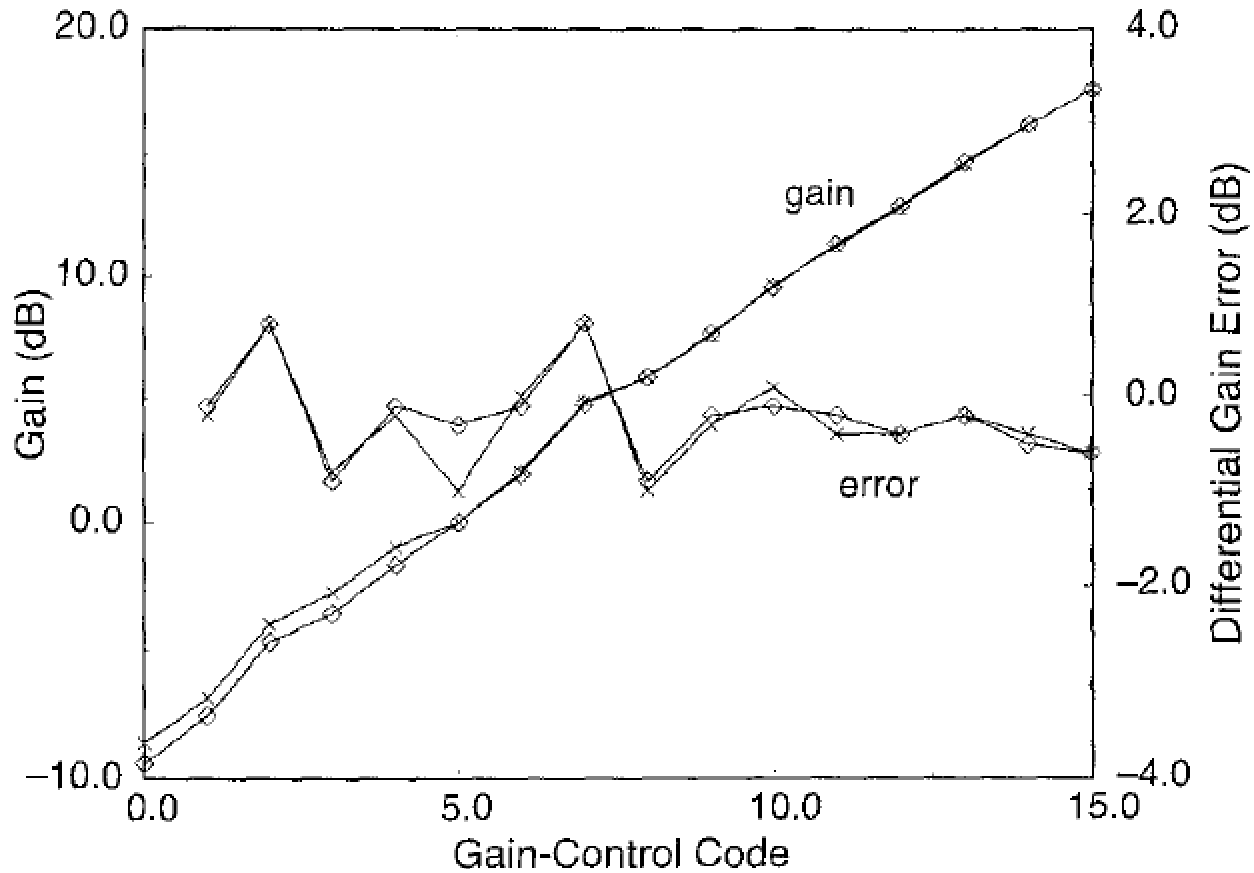


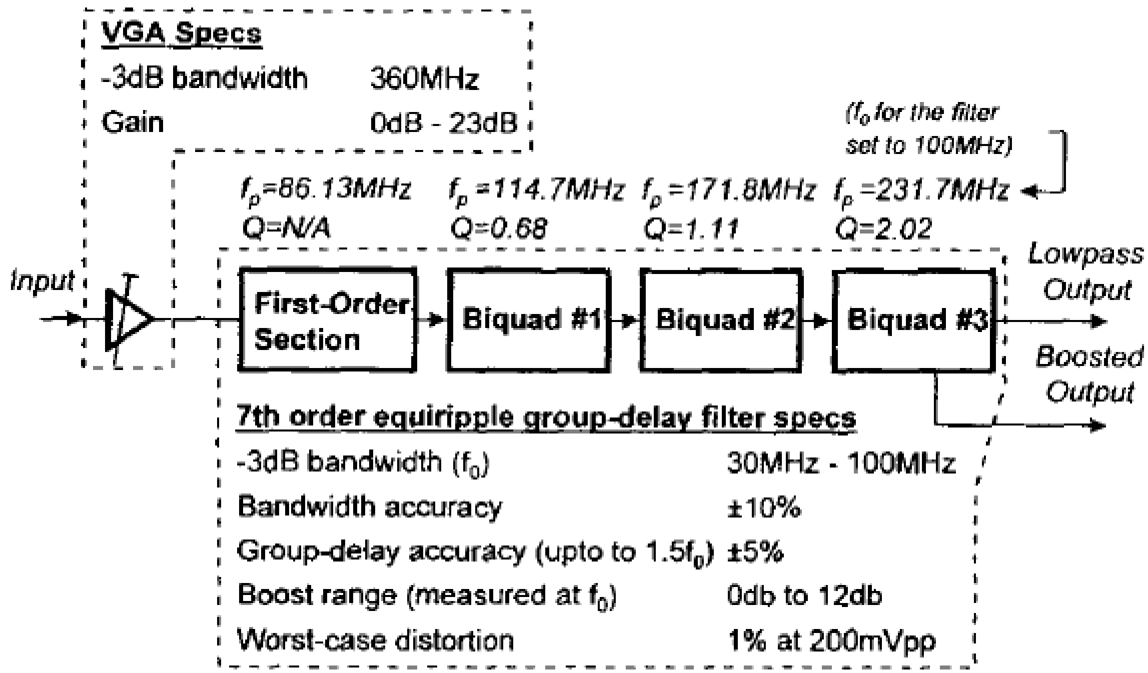
Figure 4: Amplifier gain and gain error.

Source Degeneration VGA

WA 23.2 A 2.5V, 30MHz-100MHz, 7th-Order, Equiripple Group-Delay Continuous-Time Filter and Variable-Gain Amplifier Implemented in 0.25µm CMOS

ISSCC 1999

Venu Gopinathan[1], Maurice Tarsia[1], Davy Choi



Source Degeneration VGA

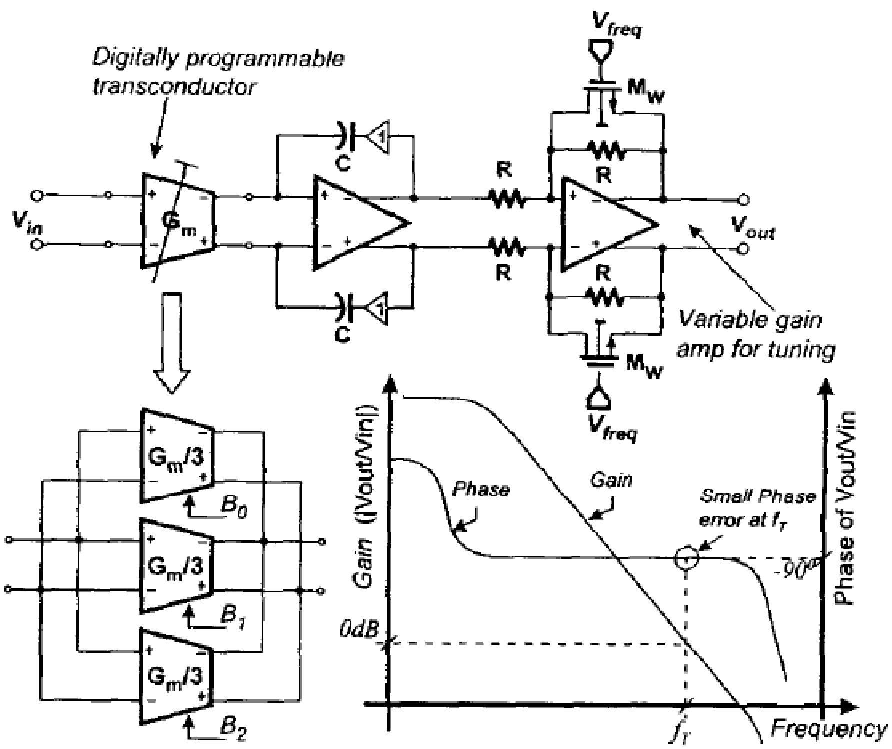


Figure 23.2.2: Programmable integrator.

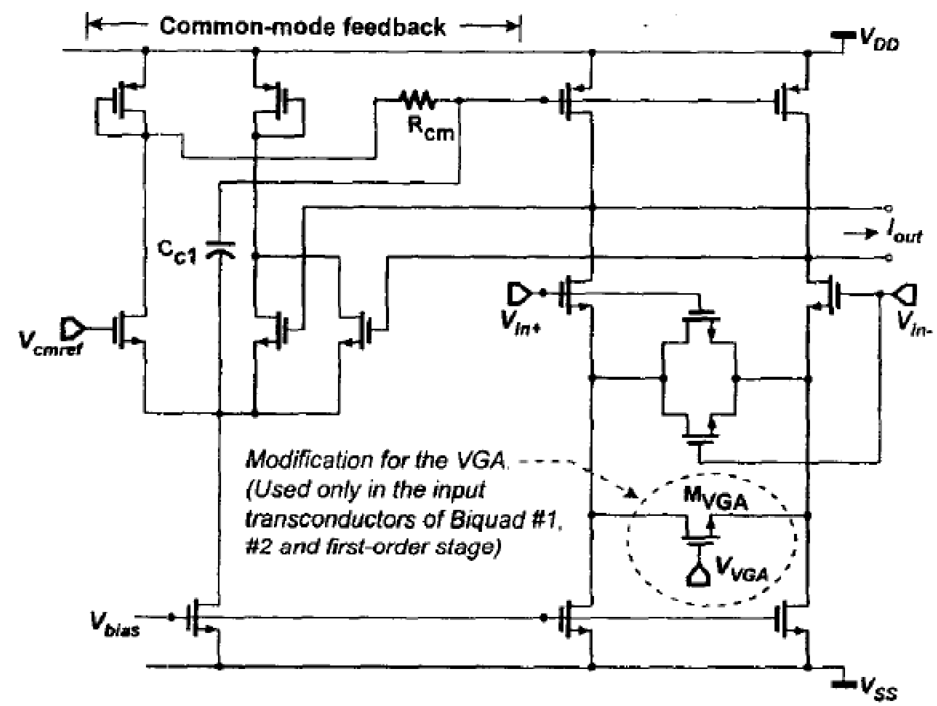


Figure 23.2.3: Complete transconductor.

Gm-OpAmp-C Integrator

Source Degeneration VGA

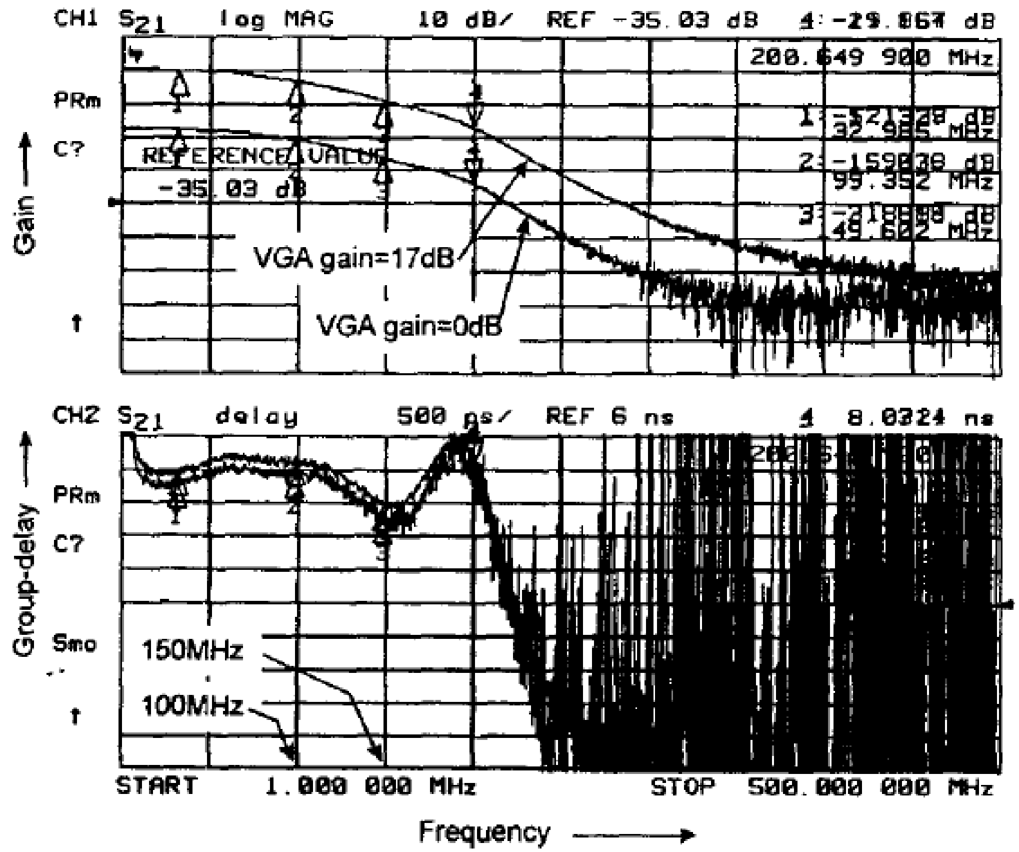


Figure 23.2.5: VGA operation.

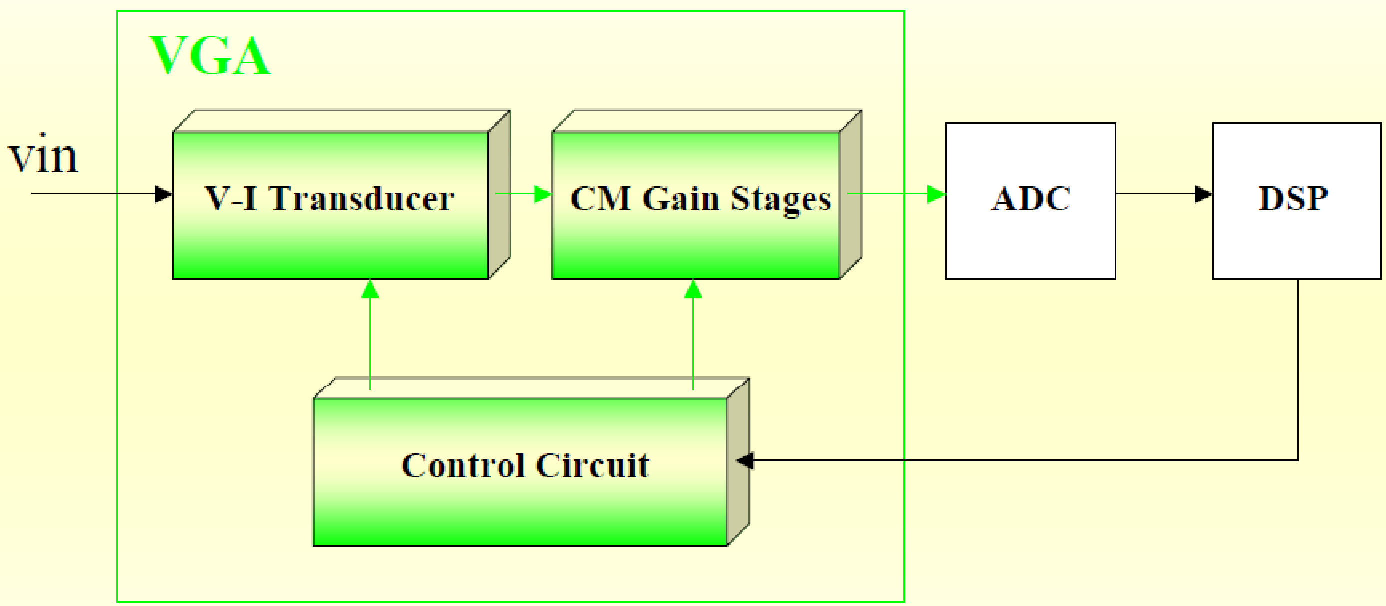
- Bandwidth and group delay display consistent performance over gain range

Digitally Controlled VGA

Analog Integrated Circuits and Signal Processing, 38, 149–160, 2004

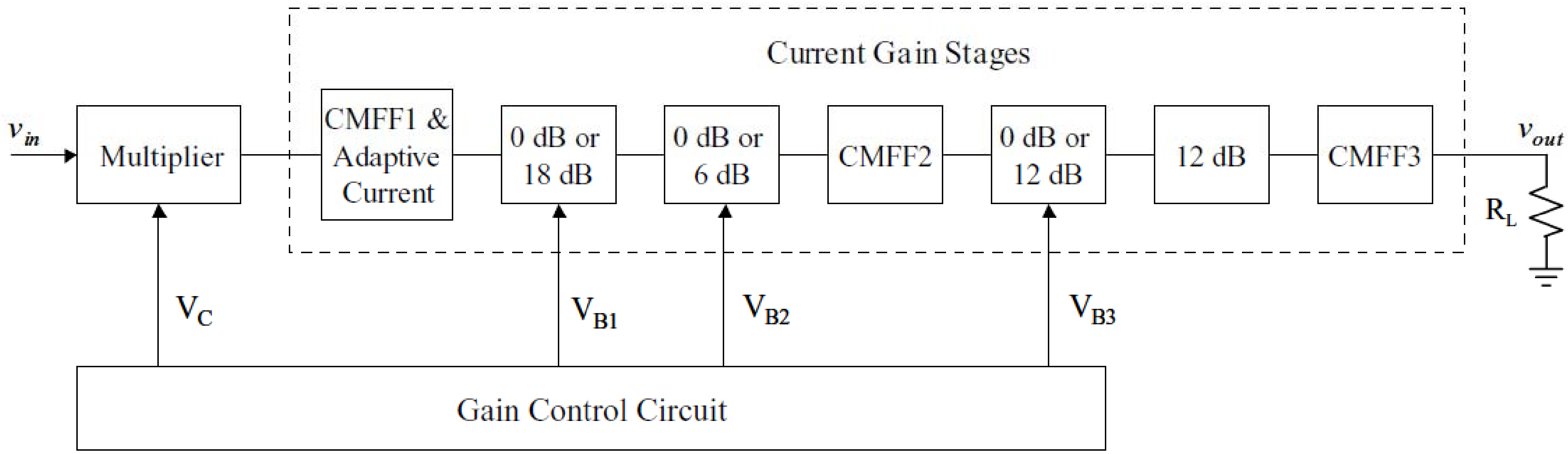
A 270 MHz, 1 $V_{pk\text{-}pk}$, Low-Distortion Variable Gain Amplifier in a 0.35 μm CMOS Process

SIANG TONG TAN* AND JOSÉ SILVA-MARTÍNEZ



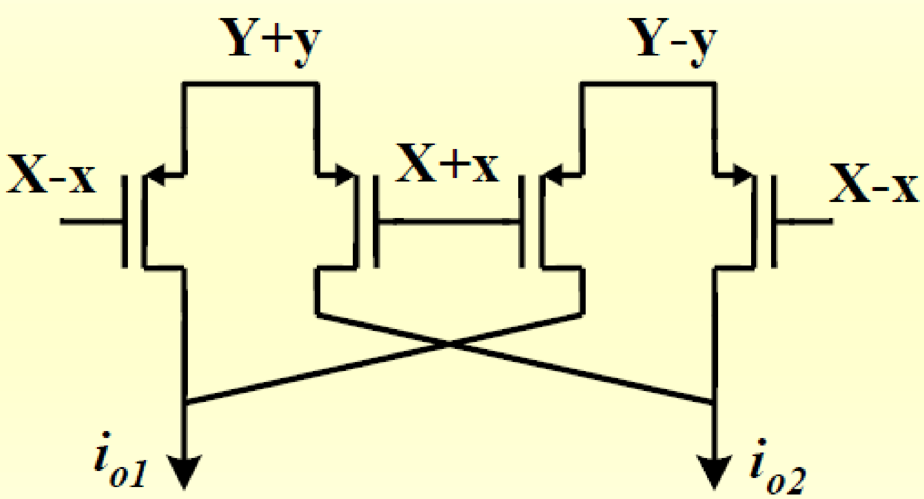
Scheme based on OTAs and/or multipliers and current mirrors

VGA Based on Analog Multiplier & Current Mirror Amplifiers



Analog Multiplier

Transistors operate in saturation region: Linearized



$$i_{out} = 4\mu C_{ox}\frac{W}{L}v_y v_x$$

Advantages:

⇨Very fast

⇨Relative good linearity

⇨Easy to program

Drawbacks:

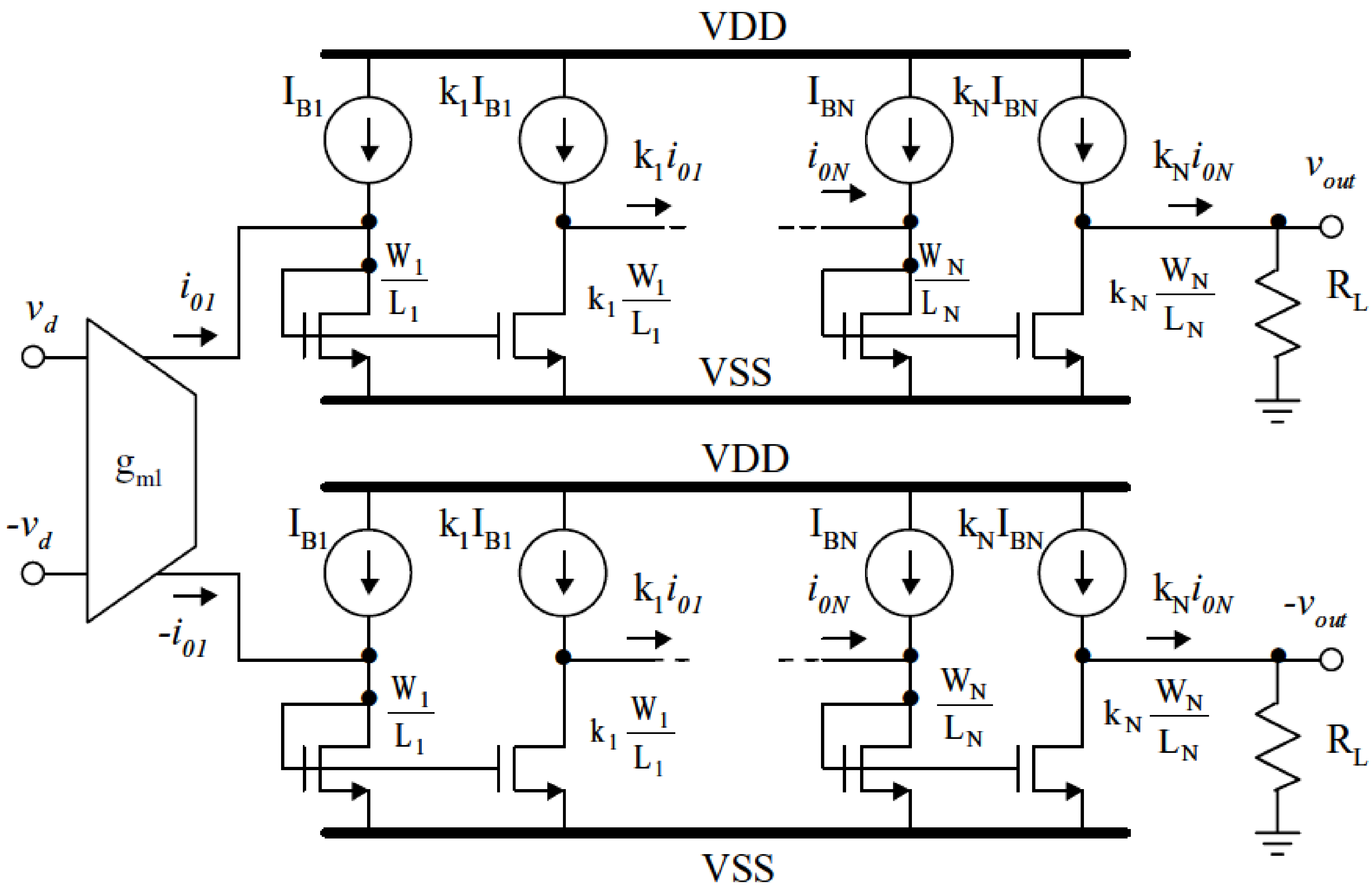
Requires low impedance Y drivers

Large swing requires large X and Y

Mobility degradation effects

Poor accuracy (calibration is required)

VGA Based on Analog Multiplier & Current Mirror Amplifiers

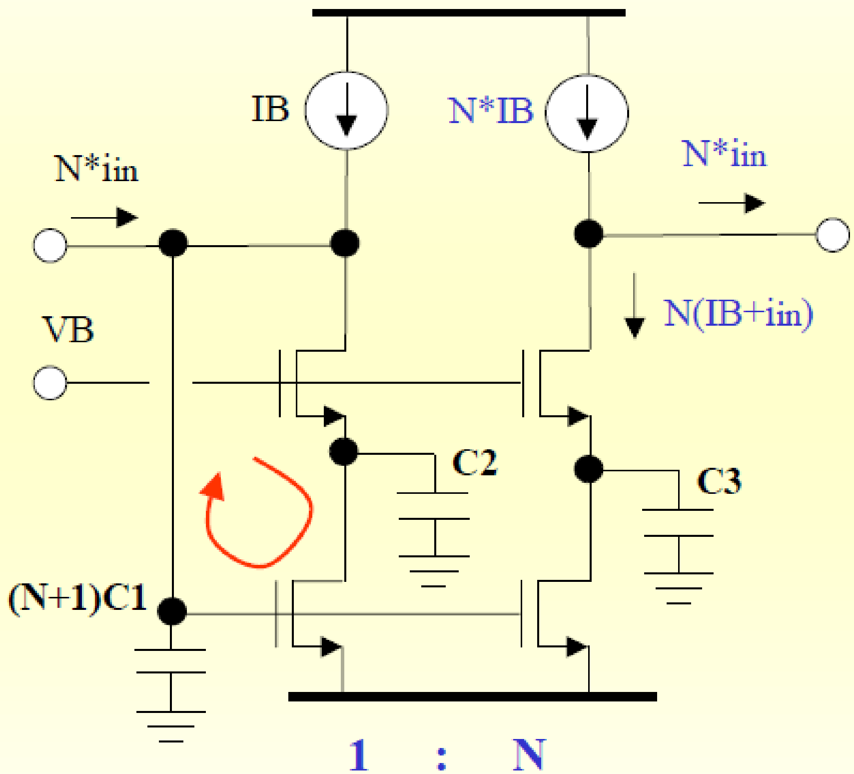


Low-Voltage Cascode Current Mirrors

Cascode Current Mirrors are used

- High bandwidth
- High output impedance and low input impedance
- More accurate, because Vds are always fixed
- Low voltage headroom
- 2nd order loop,   bandwidth can be improved

Basic Current Amplifier Frequency Response



C1 ~ CGS1

$$\frac{i_{out}}{i_{in}} \cong -\frac{\dfrac{N g_{m1} g_{m2}}{(N+1) C_1 C_2}}{s^2 + \dfrac{g_{m2}}{C_2} s + \dfrac{g_{m1} g_{m2}}{(N+1) C_1 C_2}}$$

$$\omega_0 = \sqrt{\frac{g_{m1} g_{m2}}{(N+1) C_1 C_2}}$$

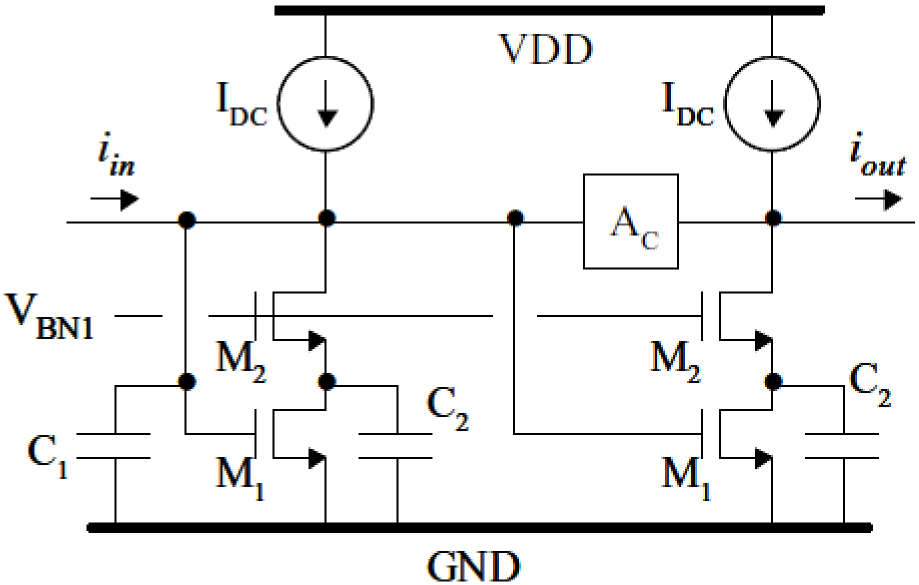
$$Q = \sqrt{\frac{g_{m1}}{g_{m2}}} \sqrt{\frac{C_2}{(N+1) C_1}}$$

Peaking?

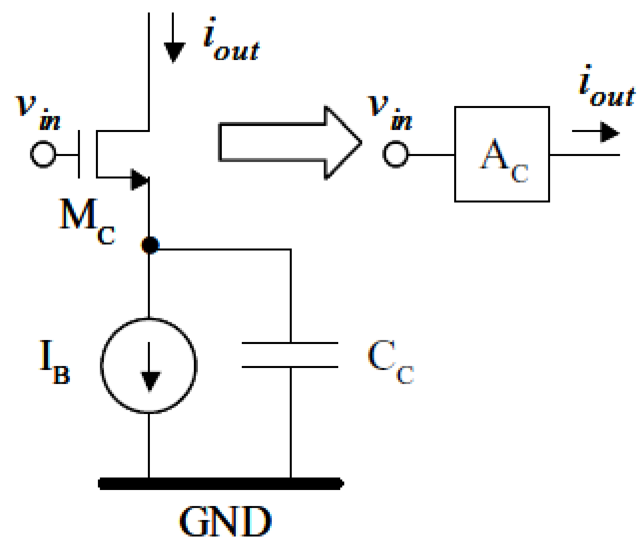
Best bandwidth for N ~ 2 - 3

C3 introduces an additional pole

Frequency Compensation Scheme



- Parallel transconductance transistor MC with capacitive degeneration introduces a zero which provides frequency compensation



Measurement Results

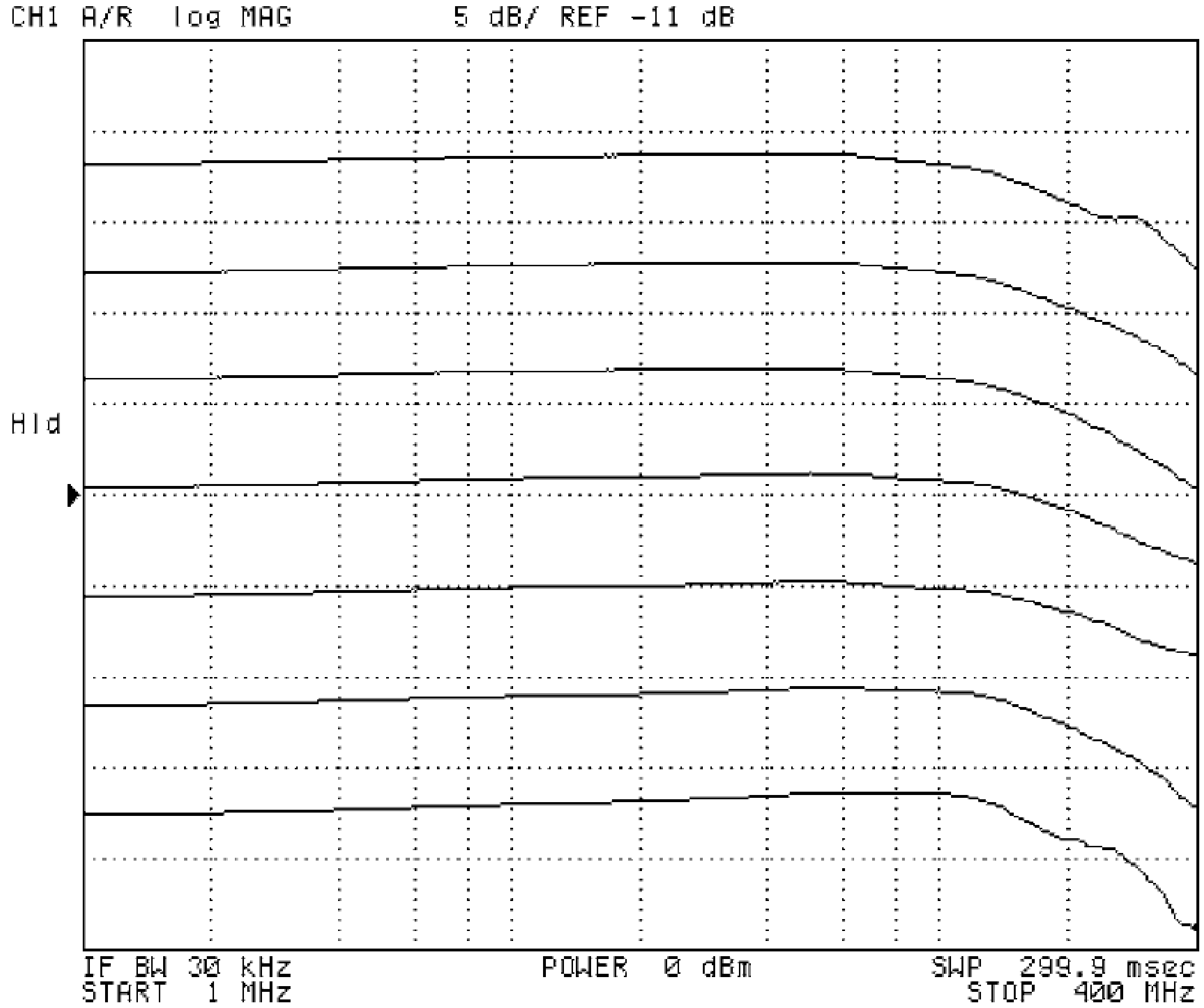


Fig. 10. Experimental frequency response of the VGA for several gain settings.

Next Time

- Analog Applications
  - Switch-Cap Filters, Broadband Amplifiers
- Bandgap Reference Circuits
- Distortion