Lecture 25: Variable Gain Amplifiers (VGAs)
Announcements

• Project
  • Preliminary report due Nov 19

• No Class on Monday 11/15
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

Hard-Disk Drive Receiver Front-End

[Image of diagram showing the VGA and other components]
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

![Graphs showing Poor and Desired Performance](image)
VGA Techniques

• Multipliers

• Transconductance ratio amplifiers

• Source degeneration
Multiplier-Based VGA

Gain can be linearly controlled by $V_{\text{cont}}$

- Circuit only operates with positive $V_{\text{cont}}$ (2-quadrant), which is generally OK for VGA applications

$A_v = g_{m1} R_D$

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

How is $I_3$ affected by $V_{\text{cont}}$?

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

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

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

- Allows multiplication in all 4-quadrants
- Differential $V_{\text{cont}}$ 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

- 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

Francesco Piazza, Paolo Orsatti, Qiuling Huang, Hiroyuki Miyakawa

ISSCC 1997

Figure 1: Block diagram of the GSM handset.
Transconductance Ratio VGA #2

**Diagram:***
- **IF-Amp:**
- **Gain Select:**
  - 0 dB
  - 10 dB
  - 20 dB

**Gain Range:**
- **0 - 20 dB**
- **-10 - 0 dB**
Transconductance Ratio VGA #2

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

Venu Gopinathan¹, Maurice Tarsia¹, Davy Choi

ISSCC 1999

VGA Specs
- 3dB bandwidth: 360MHz
- Gain: 0dB - 23dB

7th order equiripple group-delay filter specs
- 3dB bandwidth ($f_o$): 30MHz - 100MHz
- Bandwidth accuracy: ±10%
- Group-delay accuracy (upto $1.5f_o$): ±5%
- Boost range (measured at $f_o$): 0db to 12db
- Worst-case distortion: 1% at 200mVpp

(f_o for the filter set to 100MHz)
Source Degeneration VGA

Figure 23.2.2: Programmable integrator.

Gm-OpAmp-C Integrator

Figure 23.2.3: Complete transconductor.

Modification for the VGA (Used only in the input transconductors of Biquad #1, #2 and first-order stage)
• Bandwidth and group delay display consistent performance over gain range

Figure 23.2.5: VGA operation.
Digitally Controlled VGA

A 270 MHz, 1 V_{pk-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

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)

\[ i_{out} = 4\mu C_{ox} \frac{W}{L} v_y v_x \]
VGA Based on Analog Multiplier & Current Mirror Amplifiers
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

\[
\frac{i_{\text{out}}}{i_{\text{in}}} \approx \frac{N_{g_{m1}}g_{m2}}{(N+1)C_1C_2} \frac{\frac{g_{m1}g_{m2}}{C_2}}{s^2 + \frac{g_{m2}}{C_2}s + \frac{g_{m1}g_{m2}}{(N+1)C_1C_2}}
\]

\[
\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{(N+1)C_1C_2}}
\]

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

Best bandwidth for N ~ 2 - 3

C3 introduces an additional pole

C1 ~ CGS1
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