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
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

[Diagrams showing poor and desired performance]
VGA Techniques

• Multipliers

• Transconductance ratio amplifiers

• Source degeneration
Multiplier-Based VGA

\[ A_v = g_{m1} R_D \]
\[ g_{m1} = \sqrt{\mu C_{ox}} \left( \frac{W}{L} \right)_1 \]

How is \( I_3 \) affected by \( V_{\text{cont}} \)?
\[ I_3 = \frac{\mu C_{ox}}{2} \left( \frac{W}{L} \right)_3 (V_{\text{cont}} - V_T)^2 \]

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

- 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
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, Qiuting Huang, Hiroyuki Miyakawa

ISSCC 1997

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

a) Gain select

b) 0 - 20dB  -10 - 0dB
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

ISSCC 1999

Venu Gopinathan¹, Maurice Tarsia¹, Davy Choi

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

First-Order Section
Biquad #1
Biquad #2
Biquad #3

7th order equiripple group-delay filter specs
-3dB bandwidth \( f_0 \) 30MHz - 100MHz
Bandwidth accuracy ±10%
Group-delay accuracy (upto to 1.5\( f_0 \)) ±5%
Boost range (measured at \( f_0 \)) 0db to 12db
Worst-case distortion 1% at 200mVpp

(f₀ for the filter set to 100MHz)
Q=0.68
Q=1.11
Q=2.02

Input

Lowpass Output
Boosted Output
Source Degeneration VGA

Figure 23.2.2: Programmable integrator.

Gm-OpAmp-C Integrator

Figure 23.2.3: Complete transconductor.
Source Degeneration VGA

Figure 23.2.5: VGA operation.

- Bandwidth and group delay display consistent performance over gain range
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

Diagram:
- \( v_{in} \) input
- Multiplier
- \( v_C \)
- Current Gain Stages:
  - CMFF1 & Adaptive Current
  - 0 dB or 18 dB
  - 0 dB or 6 dB
  - CMFF2
  - 0 dB or 12 dB
  - 12 dB
  - CMFF3
- \( v_{B1} \), \( v_{B2} \), \( v_{B3} \)
- Gain Control Circuit
- \( v_{out} \) output
- \( R_L \) load resistance
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

\[ \frac{i_{\text{out}}}{i_{\text{in}}} = \frac{N g_{m1} g_{m2}}{(N+1) C_1 C_2} \left( s^2 + \frac{g_{m2}}{C_2} s + \frac{g_{m1} g_{m2}}{(N+1) C_1 C_2} \right) \]

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

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

Best bandwidth for \( N \sim 2 - 3 \)

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