ANALOG DESIGN in the INFORMATION AGE: A Personal Overview

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ANALOG DEVICES

OUTLINE

ANALOG DEVICES

- A Little Bit of Analog History
- The View from ADI’s Ramparts
- Old and New Technology Wars
- Analog Circuits aren’t What They Seem
- Some New Developments
- Analog in the Post-Monolithic Age

ANALOG TECHNIQUES EMERGED FROM THE FIRST DAYS OF RADIO

IN THE CONTEXT OF RECORDED HISTORY, RADIO IS A “NEW” ART

We are only at the beginning of the history of “wireless” systems, which date back only to the beginning of the Twentieth Century.

THE ROOTS OF RADIO

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MY VIEWPOINT IS BASED ON WESTERN HISTORY

1774	Alessandro Volta of Como makes a chemical battery
1820's	Ampere, Oersted, Ohm, Henry .... electricity
1823	Baron Schilling perfects a signaling system using five galvanometer needles; devised a coding scheme
1831	Michael Faraday discovers electromagnetic induction
1835	Morse develops his telegraph and a new code
1858	First Atlantic cable laid
1859	First American oil-wells (Pennsylvania)

THE ROOTS OF RADIO ... cont

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1861 Johann Philipp Reis made a system to transmit tones and coined the word “telephone”

Elisha Gray becomes founder of a company that will later become Western Electric

1867 Nobel invents dynamite; later has regrets

1869 Mendeleyev makes periodic table of elements

THE ROOTS OF RADIO ... cont

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1873 Maxwell publishes his treatise on electromagnetism, a mathematical validation of Faraday's observations interrelating magnetic and electrical phenomena

1876 Bell invents the voice telephone

1877 Edison invents the phonograph

1883 Edison effect noted (a crude thermionic diode)

1884 Paul Nipkow patented first TV system

THE ROOTS OF RADIO ... cont

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1887	Hertz demonstrates electromagnetic waves in Bonn
1888	Tesla's first alternating current motors/generators
1892	Branly invents the coherer (a crude detector)
1895	Röntgen discovers X-rays
1896	Marconi demonstrates wireless telegraphy over 2km. In the same year, Popov in Russia also sent a wireless message

THE ROOTS OF RADIO ... cont

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1900	Planck proposes quantum nature of matter
1901	Marconi first transmits across the Atlantic; Bose files patent on a strange microwave detector
1902	Caruso makes first phonograph record
1903	Wright brothers make first aircraft flight
1904	Henry Ford's factory in first year of business; Fleming invents an improved thermionic diode; Bose's patent issued (March, USP 755,840)

THE ROOTS OF RADIO ... cont

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1905 Einstein proposes theory of special relativity

1906 San Francisco earthquake; Rolls-Royce founded

1907 Discovery of blood types; cubism in Paris

1908 First Model-T rolls out of Ford

1909 Blériot makes first flight over English Channel

THE FIRST BROADCAST

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On Christmas Eve, in 1906, Reginald A. Fesseden, at Brant Rock, Massachusetts, modulated the 1kW output of a 50kHz alternator, designed by Ernst Alexanderson, by putting a microphone in series with the antenna!

Electronics 50th Anniversary issue
April 17, 1980, p. 75

In this same year, Lee De Forest invented the “Audion”, the first vacuum-tube triode.

G. L. Archer, *A History of Radio to 1926*,
Stratford Press, N.Y., 1938, p. 11

WIRELESS GETS SERIOUS

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1912 Edwin Armstrong first demonstrates "regeneration"

1913 Neils Bohr writes "On the Constitution of Atoms and Molecules", *Philos. Mag*., 26, Vol. 1.

1914 Panama canal opens; World World I begins

1918 Armstrong devises the superheterodyne receiver

1920 Regular radio broadcasts begin in USA

WIRELESS GETS SERIOUS

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1925 Lilienfeld proposes a triode device incorporating a semiconductor layer (USP 1,745,175, filed 1928)

1926 Baird invents a practical TV system

1927 The word "Electronics" first appears in a paper by Grondahl & Geiger: "A New Electronic Rectifier"

1930 Sam Weber launches *Electronics* magazine (April) with contributions from Fleming, Millikan, Goldsmith.

Armstrong conceives of FM (frequency modulation)

INTERLUDE

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1935 Watson-Watt (UK) and Page (NRL) demonstrate RADAR

1938 First successful magnetron, later smuggled to MIT (1940)

1939 Haeff invents inductive output tube, a forerunner of the klystron (100W CW, 450MHz, 35%, 10dB gain) for TV

1940 Hewlett & Packard open a garage operation in Palo Alto. Later grows to HP

INTERLUDE

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1943 Kompfner invents traveling-wave tube, later perfected by Pierce and Field at BTL

1944 Analog computers important and in widespread use

1945 Arthur C. Clarke writes *"The Space Station: Its Radio Applications"*; in October, Wireless World publishes his *"Can Rocket Stations give Worldwide Radio Coverage?"*

1946 ENIAC developed by Eckert and Mauchly; no thoughts yet of combining it with a portable radio, however

THE TRANSISTOR AGE

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1947 (December 16) Brattain and Bardeen (with help) accidentally make a point-contact transistor

1950 Shockley's "Electrons and Holes in Semiconductors" published by Van Nostrand; alloy junction transistors

1951 Simulated emission in lithium fluoride using RF

1953 First JFETs (Dacey and Ross, Proc. IRE, Vol.. 41)

THE TRANSISTOR AGE

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1954 MASER invented at Columbia University; first International Solid-State Circuits Conference; first regular color TV service starts in USA

...... and I start work

1957 (May 7) First MOS patent (Ross, USP 2,791,760); models of an IC presented at RRE by Dummer; Bob Noyce joins Fairchild

1958 Jack Kilby joins TI; by September he'd fabricated a monolithic germanium oscillator and a flip-flop

1959: A TRANSITION YEAR

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Kurt Lehovec files patent describing the concept of junction isolation (USP 3,029,366, issued April 1962).

The silicon planar technology is developed by Hoerni.

Robert Noyce of Fairchild hears of Kilby's successes.

Jack Kilby files (February 6) for patent *"Miniaturized Electronic Circuits"*.

Noyce files (July 30) patent for *"Semiconductor Device-and-Lead Structure".*

Shockley having commercial difficulties with his two-terminal (pnpn) switching devices.

THE "SOARING SIXTIES"

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1960 Maiman demonstrated first LASER at Hughes Corp.

1961 (March) Fairchild announces its Micrologic family

1962 First semiconductor LASERs and red LED's arrive

1963 *Institute of Radio Engineers* merges with the *American Institute of Electrical Engineers* to become the *Institute of Electrical and Electronic Engineers (IEEE); notice that "Radio" is dropped from title*

1964 100 transistors integrated in a 5-by-3mm chip (SSI); RCA introduces first production process for MOS.

THE "SOARING SIXTIES"

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1965 Ray Warner moves from Moto to TI, joins Kilby's team; Tektronix establishes its own in-house Si IC fab. First (successful!) comms-sat (Intelsat-1) operational

1966 Monolithic active mixers, multipliers and current-mode circuits; first issue of *Journal of Solid-State Circuits*; double-implanted high-frequency pnp transistors

1967 Berkeley develops SPICE; superintegrated circuits appear, leading to invention of I^2L; Carrier Domain devices first demonstrated

THE IC COMES OF AGE

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1968 Gusev et al. in the Soviet Union fabricated the first double-implanted high-frequency pnp transistors

1969 Ion-implantation used at Mostek (by Sevin); first microwave transistors with Arsenic emitters (Toshiba); 1000-transistor logic chips (MSI) become available

1970 Boyle and Smith of Bell Labs announce CCDs; CMOS process is developed at Philips by Shappir; Jobs and Wozniak start Apple Computers

THE IC COMES OF AGE

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1974	First 8-bit microprocessor from Intel
1975	First 10,000-transistor products (VLSI) rolled out
1977	Three mass-market personal computers arrive: the Apple II; Radio Shack's TRS-80; Commodore PET
1980	Apple Macintosh; first camcorders; IBM's PS/2
1981	IBM unveils their much-awaited PC; HP goes 32-bit

Current Status

THE "PRODUCTIVITY ENGINE"

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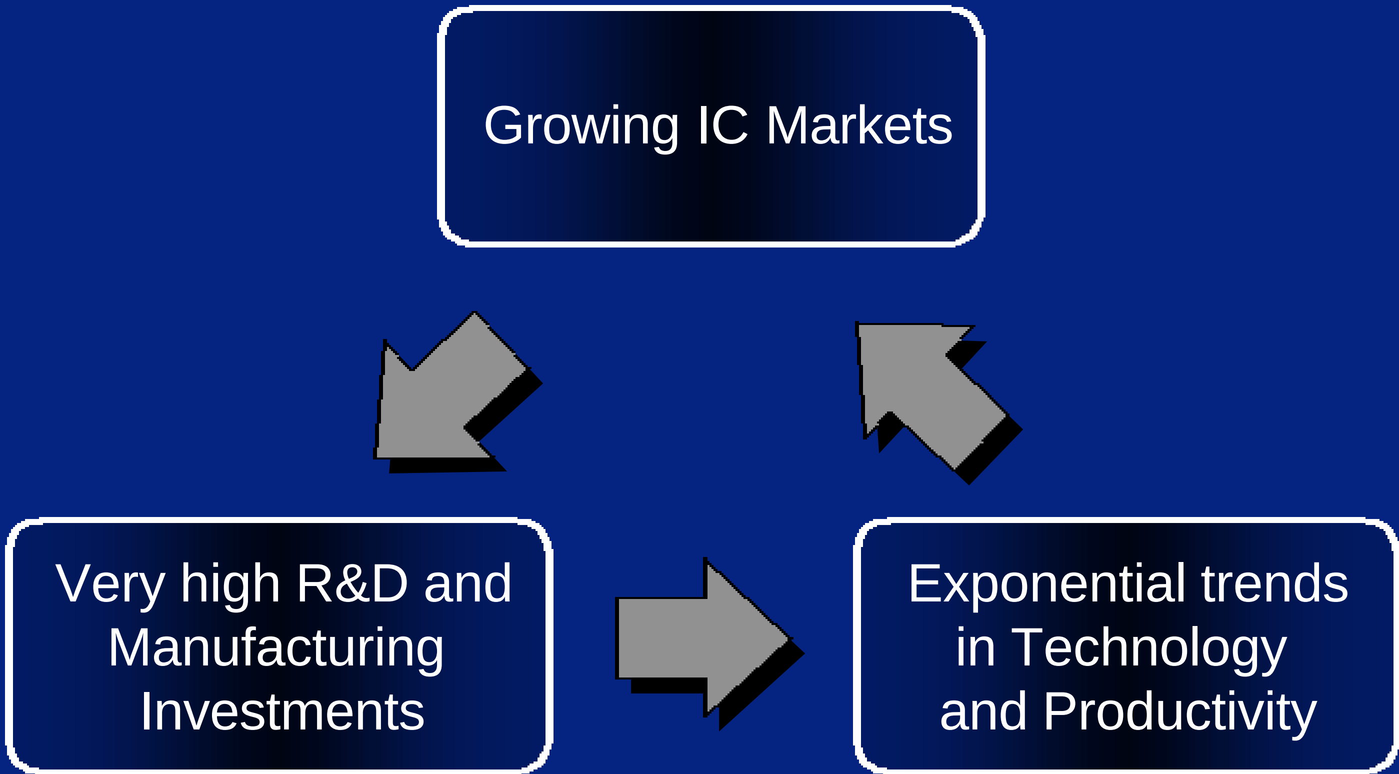

Chatterjee & Doering, Proc. IEEE, Jan 1998

THE "RADIO ROUNDABOUT"

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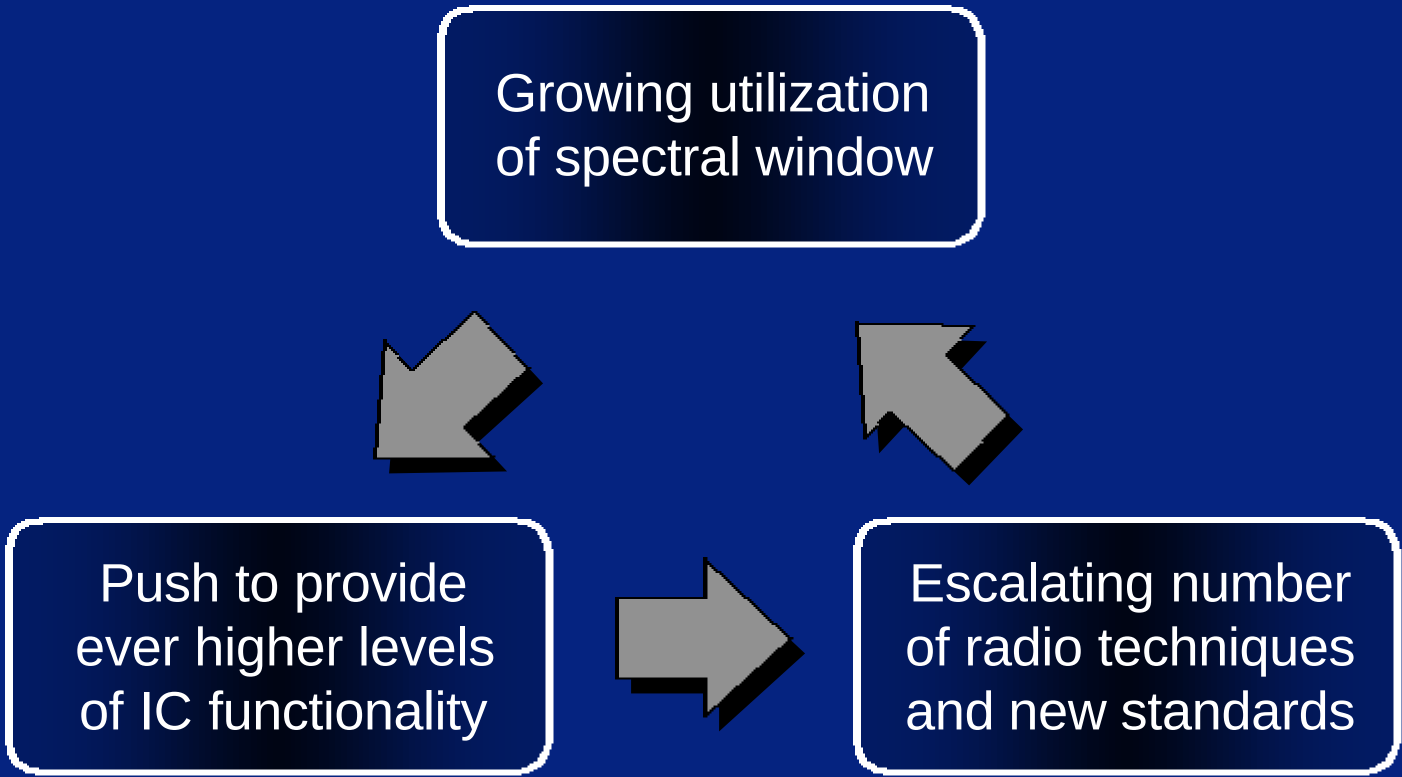
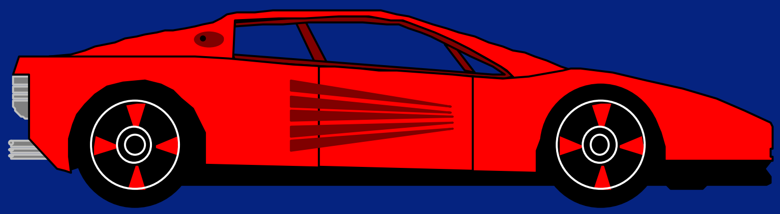


RADIOS ARE FOREVER

They have become a ubiquitous and indispensable aspect of contemporary life, but we've only just started. Much wider use of wireless communication devices is yet to come. Marriage with ENIAC appears to be consummated.



- AM/FM Radio
- Cell phone
- Pager
- Car Keys
- Radar Detector
- Watch
- Garage key
- Collision Avd.
- GPS
- TV in back

ANALOG TECHNIQUES

DEVELOPED FROM

1 TELEPHONE
2 RADIO
3 RADAR
4 INSTRUMENTS
5 FIRST COMPUTERS

ANALOG TECHNIQUES
ARE IN TRANSITION

The first one hundred years are now behind us.

The recent marriage between the radio and the computer has led to a *new view of design.*

New services for radio are in demand, with the emphasis on providing data the most prominent.

Nature's finite spectrum is now very crowded.

Integrated circuit capabilities *and their limitations* are shaping many new analog techniques.

HOW WILL THEY EVOLVE?

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Trends in wireless systems:

- Aggressive cost reduction
  -- consumable radios?
- Greater reliance on bits
- More bandwidth - megadata
  -- or maybe less: bit-dribblers
- Prompt digitization in Rx
- Total software flexibility
- Increased use of CMOS
- Spread spectrum

HOW WILL THEY EVOLVE?

Many questions remain:

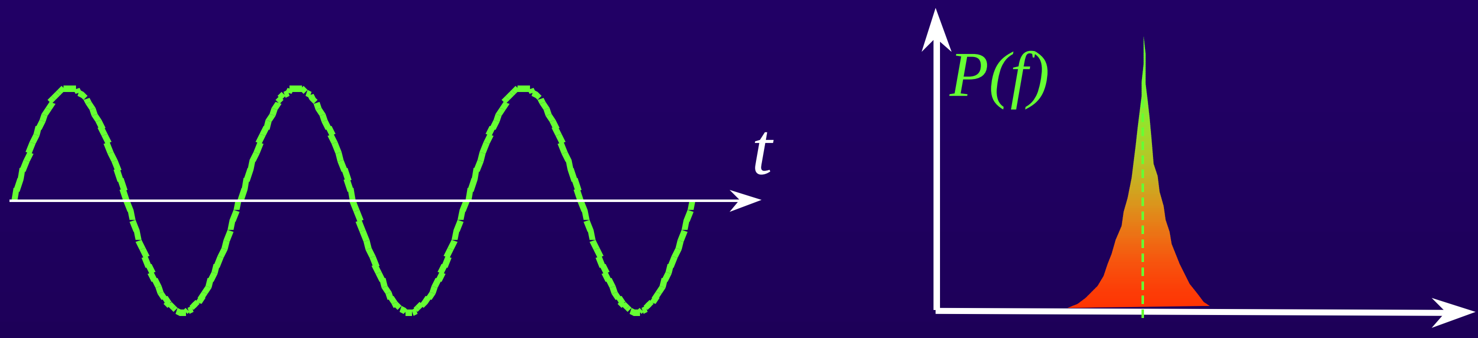
- Do large mixed-signal analog-plus-digital *monolithic* SoC's make sense?
- Is *System-in-a-Package* a better choice?
- What changes will occur in the integrated circuit industry affecting *analog design?*
- Are *bipolar transistors* still needed?
- What is the role of *Silicon-Germanium?*

  - or GaAs HBTs, MESFETs, PHEMTs, etc.?
- Spreading the spectrum further:

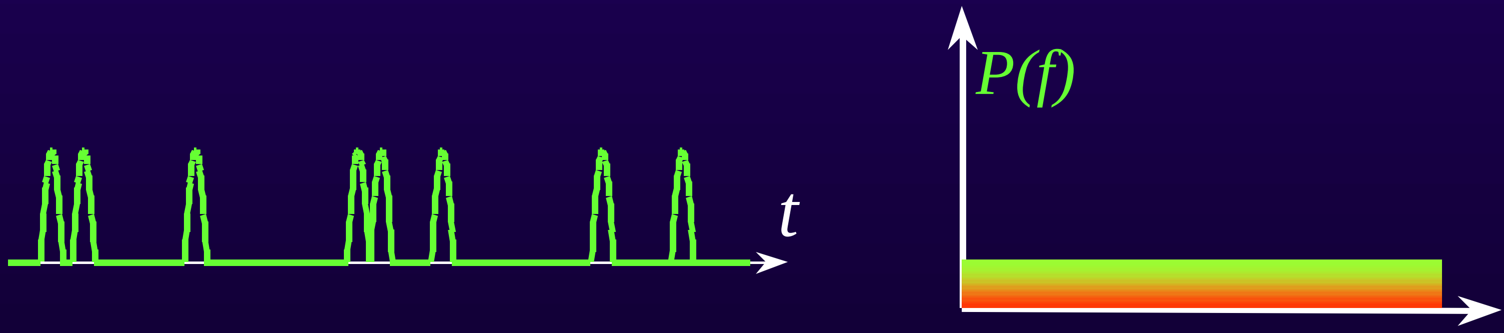
  - is operation purely in the time domain practical?

SIGNAL FORMS

Classical Radio



Time-Domain (UWB)



Is Ultra-Wide-Band radio a viable alternative to CW-based radio?
Can UWB comfortably co-exist with CW, much like CDMA does?

Analog Design at ADI

TECHNOLOGIES at ADI

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- LEADING-EDGE IN-HOUSE PROCESSES
  - *STRONG HF EMPHASIS inc SiGe*
  - *COMPLEMENTARY BIPOLAR (CB)*
  - *SILICON-ON-INSULATOR (SOI)*
  - *THIN-FILM COMPONENTS*
  - *LASER-TRIMMED CALIBRATION*
- CMOS. 0.6, 0.5. 0.35, 0.25 & 0.18μm
  - *ENHANCEMENTS FOR MIXED-SIGNAL*
- SEVERAL GENERATIONS OF BiCMOS

  and even CBCMOS

ANALOG DESIGN TOOLS

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- A FULL-TIME CAD TEAM SERVES THE SPECIAL REQUIREMENTS OF THE ANALOG DESIGN COMMUNITY
- PROPRIETARY SIMULATOR (ADICE5) INCLUDES MANY NEW FEATURES
- POWERFUL POST-PROCESSING AND PRESENTATION CAPABILITIES
- PROPRIETARY SCHEMATIC CAPTURE

  -- all programs linked synergistically

ANALOG IC DEVELOPMENTS

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- **TWO KEY THRUSTS**

MIXED-SIGNAL SYSTEMS-ON-A-CHIP

Large team efforts; strongly focused on major system initiatives; aimed at providing low-cost solutions; low-power consumption; high-volume

HIGH-PERFORMANCE COMPONENTS

Small-scale of integration; characterized by a strong innovative content; new solutions to old challenges; may use “boutique” technologies

SYSTEM-on-a-CHIP (SoC)

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The current working assumption is that the cheapest solutions to highly integrated mixed signal systems will always be fully monolithic.

This has been the most successful guiding principle of the IC business.

SYSTEM-on-a-CHIP (SoC)

ANALOG DEVICES

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This has been the most successful guiding principle of the IC business.

However, this may not always be the most efficient approach to mixed-signal products.

SYSTEM-on-a-CHIP (SoC)

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1. In radios, and other specialized systems, serious challenges stand in the way of integrating sensitive analog sections with “energetic” digital signal sections.

   Spurious signal injection; VCO phase-noise disturbances; CMOS inverter-style logic cells are especially troublesome.

SYSTEM-on-a-CHIP (SoC)

ANALOG DEVICES

2. Disparate and conflicting demands are placed on a common technology.

For example, while much has been done to utilize submicron CMOS in radio, there remain many aspects of performance that lie beyond what can sensibly be delivered by a single “one-size-fits-all” technology.

SYSTEM-on-a-CHIP (SoC)

ANALOG DEVICES

3. High integration levels -

Reduce the overall die yield

- complex chips at the mercy of a few analog cells

Greatly complicate test development and production throughput rate

Place immense demands on mixed-signal teams and therefore adversely impact time to market

SYSTEM-on-a-HEADER (SoH)

ANALOG DEVICES

An alternative path may be the use of smaller die combined into complete systems, using advanced assembly technologies. Critical to the success of this approach will be the use of highly-automated (robot) handling of bare die.

This may be called the “System-on-a-Header”, or “System-in-a-Package” concept.

This can be viewed as simply a natural extension of the manufacturing techniques already widely used in both the electronics and automobile industries.

SYSTEM-on-a-HEADER (SoH)

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SYNERGY:	Optimal IC technologies can be employed
ISOLATION:	Critical sections are more readily decoupled
FLEXIBILITY:	Systems may be easily configured on demand
VARIETY:	Diverse passive components can be included
TEST/YIELD:	The ICs are simpler, may be tested separately
TIME-to-MARKET:	Can be much quicker than VLSI development
MATERIAL RE-USE:	Numerous existing, proven die may be utilized
LOWER RISK:	Transferred from large, complex die to simple assembly; mistakes can quickly be corrected
LOWER COST:	For many systems, total development cost can be lower than that of a VLSI-SoC

SYSTEM-on-a-HEADER (SoH)

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The use of highly-automated assembly techniques, in which a broad variety of optimal technologies are synergistically combined, will herald a new phase in the evolution of mixed-signal electronics. It will soon be common to expect that *the highest performance, quickest time to market, and lowest development cost will be achieved through multi-chip methods.*

We are at the beginning of the

"POST-MONOLITHIC ERA"

But Technology Wars are Still Being Fought!

TECHNOLOGY WARS

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DIGITAL*!*

versus

ANALOG?

TECHNOLOGY WARS

ANALOG
DEVICES

New! Better! Advanced!

DIGITAL!

Superior! The Future!

versus

Tired Obsolete

ANALOG?

Stale Unstable Old

TECHNOLOGY WARS

ANALOG DEVICES

Everyone knows that analog is "old stuff". It's unreliable, prone to drift and noise, it goes out of calibration. It's where all the troubles are found in any equipment.

Communications systems will very soon be entirely digital.

TECHNOLOGY WARS

ANALOG DEVICES

Everyone knows that analog is “old stuff”. It’s unreliable, prone to drift and noise, it goes out of calibration. It’s where all the troubles are found in any equipment.

Communications systems will very soon be entirely digital.

Nothing could be farther from the truth.

BENEFITS of “DIGITAL” RADIO

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1. Digital modulation has immense advantages (data compression and spectral efficiency; use of error-correcting codes; ubiquity of digital data)
2. Digitization at the earliest point in a receiver allows the use of very powerful DSP filtering
3. Some bulky analog filters can be eliminated
4. Similar kinds of benefits arise in transmitters
5. Software control of channel frequency, gain, power control and other critical parameters makes radio a “computer peripheral”

BENEFITS of "DIGITAL" RADIO

ANALOG DEVICES

6. Leads to the development of fully-programmable transceivers (the "universal" or "software" radio)
7. Makes possible the use of sophisticated techniques such as CDMA, even pure time-domain methods, in which complex coding and decoding is needed
8. The overall management of cellular, satellite, cable and fibre networks would be impossible without complex digital supervision
9. Leads to more innovative use of deep sub-micron CMOS technologies and "digitally-friendly" circuit techniques (such as sigma-delta converters) in what were formerly strictly analog domains

NEVERTHELESS ...

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A There is little likelihood of finding ways to totally dispense with analog techniques in many areas of modern electronic systems of all kinds.

B Examples include: power sources; amplification; many kinds of HF filtering; microwave mixers and modulators; HF power generation; high-accuracy measurement devices in medical instruments as well as in radio; numerous kinds of VCOs for carrier and reference frequencies; new photonic interfaces and support of optical elements; etc.

C Analog signal processing can often provide a significant reduction in complexity (it is “elegant”).

SO.....
WHAT IS THE ROLE OF ANALOG in the INFORMATION AGE?

It is a matter of common knowledge that electronics has radically changed in character since the advent of the microprocessor.

Analog techniques *really have* become a less central aspect of modern electronics, even to the point where it is believed by many they are no longer important.

Few young people pursue analog design as a hobby; *simple, basic materials* are often hard to acquire.

A SENSIBLE SYNERGY

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DIGITAL*!*

teaming with

ANALOG*!*

Why is Analog Design "So Hard"?

QUESTIONS

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? Why is analog design so often regarded as *especially difficult* by new graduates?

? Will there be *enough* analog designers in the work force when the “first generation” (those trained during World War II years) have all gone? *Where* will they come from?

? What can be done *in universities* to ensure that classical concepts in electronics and the linear signal-processing topics are not neglected in the curriculum?

ASPECTS of ANALOG DESIGN

Analog circuits are more intimately a part of the physical world than are digital processors, since they are concerned with manipulation of signals having DIMENSION. Their physical attributes are traceable directly to fundamental quantities and constants, governing all real systems:

LENGTH:	[L]	Meter
MASS:	[M]	Kilogram
TIME:	[T]	Second
CHARGE:	[Q]	Coulomb

LENGTH:	[L]	Meter
MASS:	[M]	Kilogram
TIME:	[T]	Second
CHARGE:	[Q]	Coulomb

Dimensional signals:

VOLTAGE:	$[MLT^{2}L^{-2}Q^{-1}]$	Volt
CURRENT:	$[QT^{-1}]$	Ampere
POWER:	$[ML^{2}T^{-3}]$	Watt
FREQUENCY:	$[T^{-1}]$	Hertz

Dimensional elements:

RESISTANCE:	$[ML^{2}T^{-1}Q^{-2}]$	Ohm
CAPACITANCE:	$[M^{-1}L^{-2}T^{2}Q^{2}]$	Farad
INDUCTANCE:	$[ML^{2}Q^{-2}]$	Henry

THE "BIG DIFFERENCE"

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ANALOG DESIGN DIFFERS *FUNDAMENTALLY* FROM DIGITAL DESIGN MAINLY BECAUSE IT IS AN *INSEPARABLE PART OF THE PHYSICAL WORLD.* IT IS "NEWTONIAN".

DIGITAL LOGIC USES ELECTRONICS BECAUSE SILICON ALLOWS THE FABRICATION OF FAST AND COMPLEX ALGORITHMIC ENGINES AT VERY LOW COST. IT IS ONLY *INCIDENTALLY ELECTRONIC*. DIGITAL DESIGN IS NOT OFTEN CONCERNED WITH CRITICAL CIRCUIT ISSUES.

THE "BIG DIFFERENCE"

ANALOG DEVICES

ANALOG CIRCUIT DESIGN INVOLVES VERY FEW COMPONENTS, YET THESE CAN LEAD TO VERY COMPLEX MATHEMATICS. THIS IS ESPECIALLY TRUE WHEN ALL NONLINEAR EFFECTS ARE CORRECTLY INCLUDED.

NUMEROUS SUBTLE MECHANISMS MATTER BUT THEY ARE OFTEN NOT ADDRESSED IN TEXTBOOKS: FOR EXAMPLE, THE EFFECTS OF VARACTOR PARASITIC CAPACITANCES IN RF AMPLIFIERS.

ANALOG ARRAY PROCESSOR

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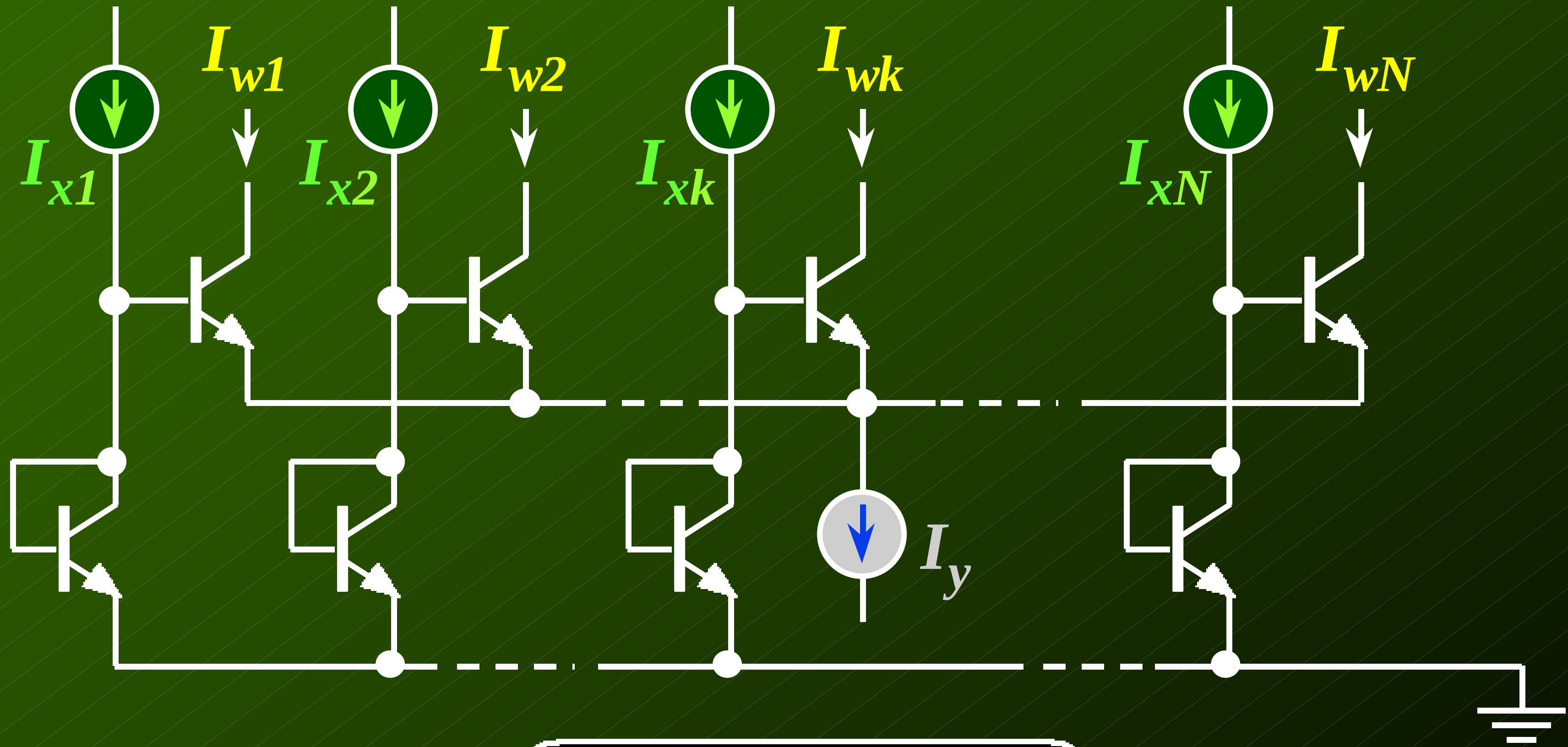

$$I_{wk} = \frac{I_{xk}}{\sum_k I_{xk}} I_y$$

VECTOR SUMMATION

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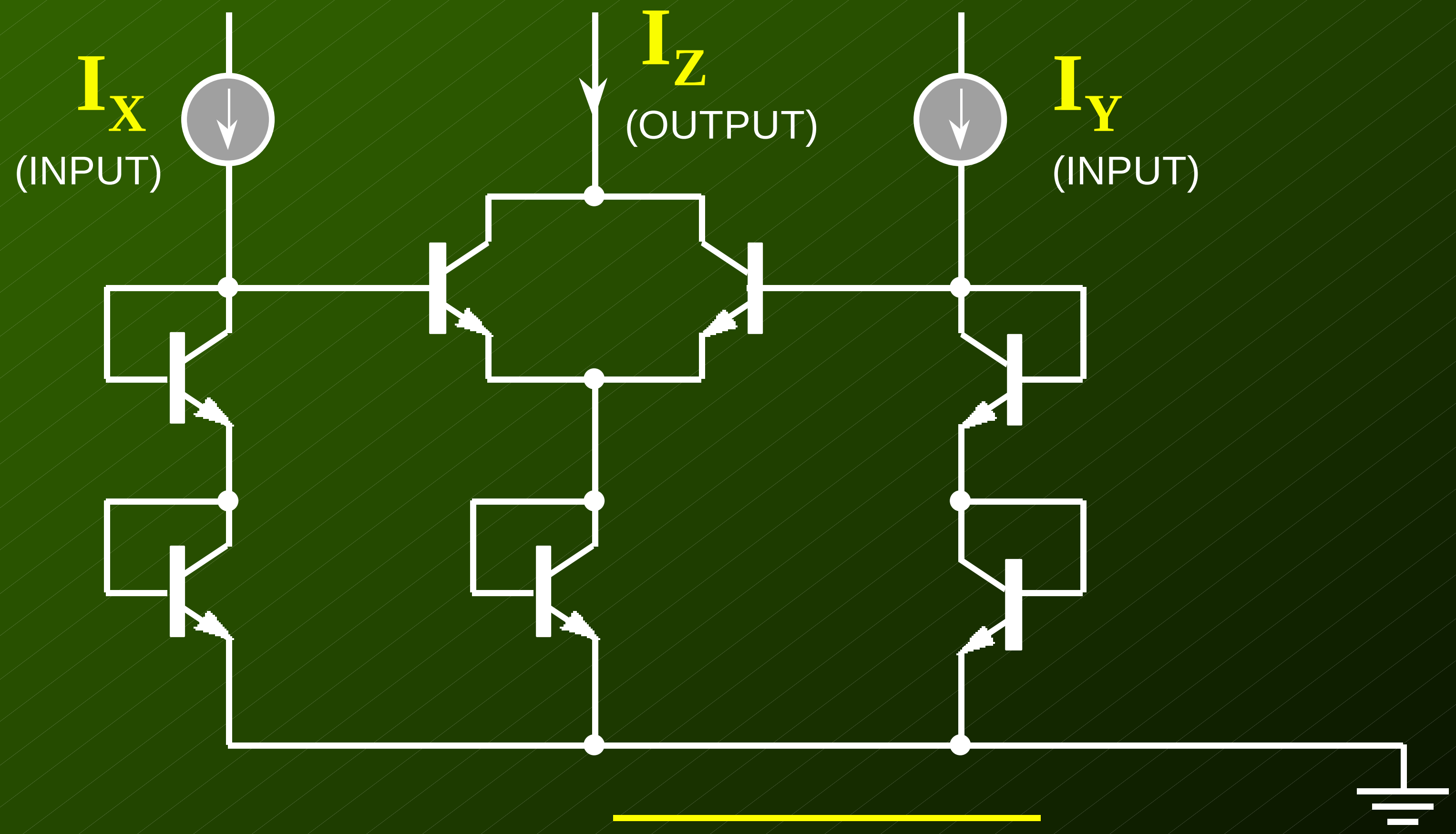

$$I_Z = \sqrt{I_X^2 + I_Y^2}$$

THE "BIG DIFFERENCE"

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TOPOLOGICAL (COMBINATORIAL) RICHNESS OF SIMPLE ANALOG CIRCUITS QUICKLY LEADS TO *EXPLOSIVE VARIETY*.

FOR EXAMPLE, THERE ARE *TWENTY-FOUR* DISTINCTLY DIFFERENT CIRCUITS THAT CAN BE DEVISED USING ONLY *TWO TRANSISTORS*!

BY THE TIME THREE OR FOUR TRANSISTORS ARE USED, THE NUMBER OF COMBINATIONS BECOMES HUNDREDS.

THE "BIG DIFFERENCE"

ANALOG DEVICES

TOPOLOGICAL (COMBINATORIAL) RICHNESS

... cont

NOT ONLY ARE THE NUMBER OF DIFFERENT CIRCUITS VERY LARGE BUT THE BEHAVIOUR QUICKLY BECOMES COMPLICATED AND MAY NOT BE READILY APPARENT BY INSPECTION

KERMIT_6

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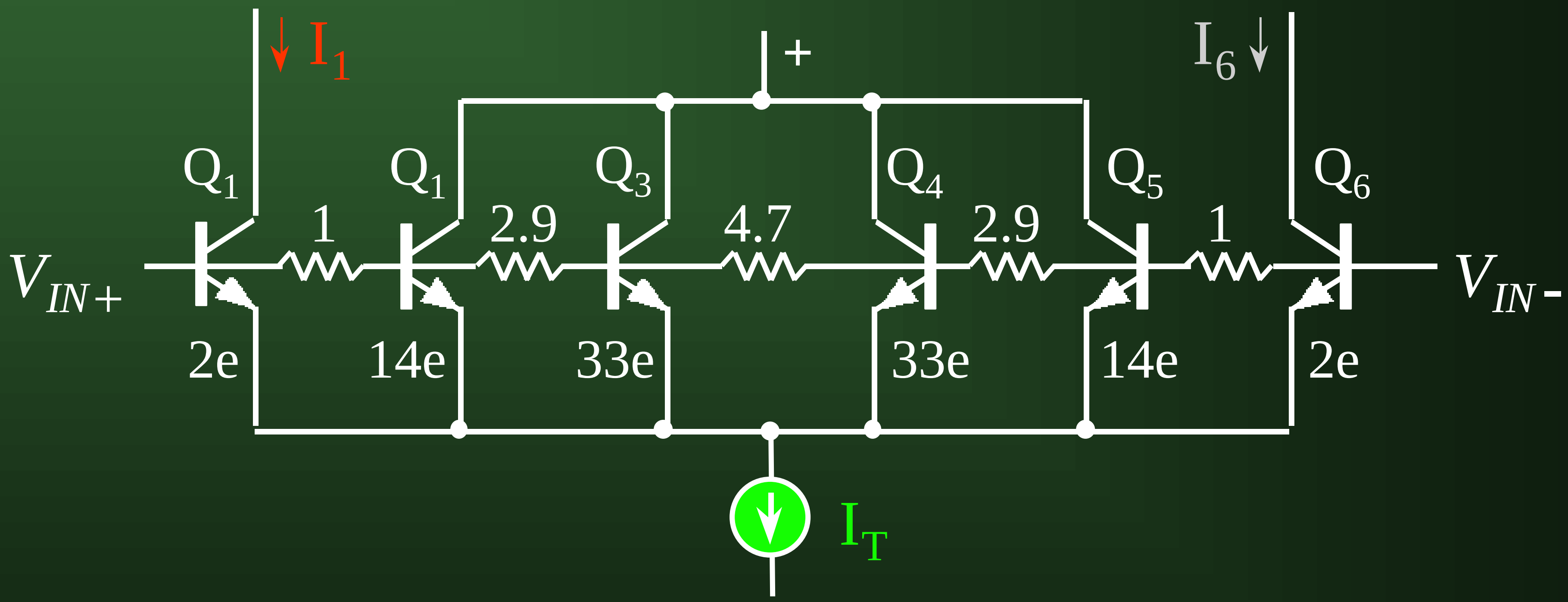
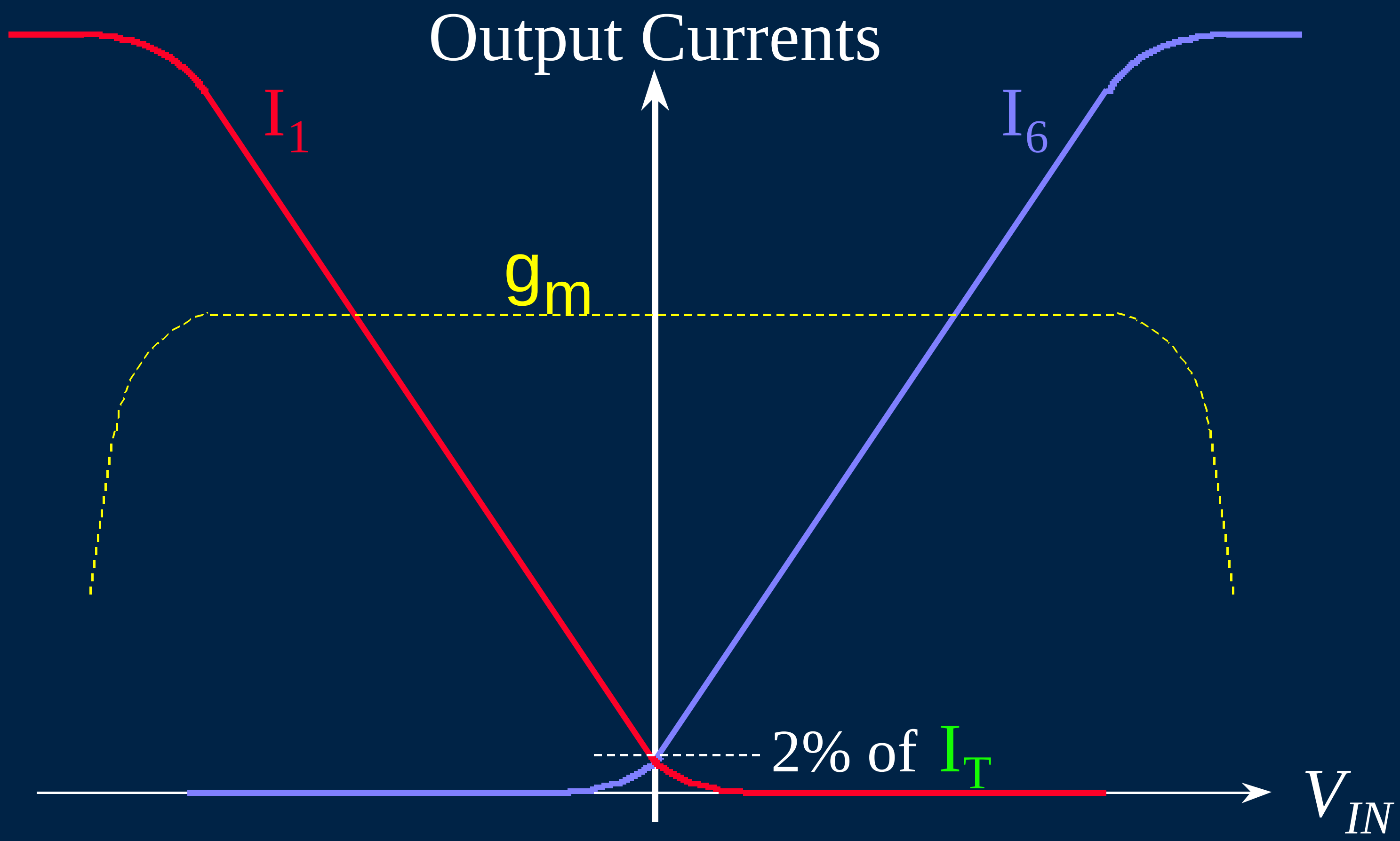
$I_{OUT} = I_1 - I_6$



This is a very linear transconductance whose magnitude is proportional to I_T



VERY LINEAR CLASS-AB BEHAVIOUR

g_m constant to within ±0.05dB to V_{IN} = ±0.65V

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PARAMETRIC SLAVERY

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The *deeply-physical* nature of analog circuits places quite different demands on a manufacturing process to those needed for the fabrication of digital circuits, primarily due to the unavoidable dependence on the absolute values of numerous parameters.

Achieving design robustness – which requires the systematic elimination (or at least, the minimization) of sensitivities to all process parameters – poses unique challenges. Design for Manufacture in the analog world demands unrelenting attention to a very large number of small details.

PARAMETRIC SLAVERY

ANALOG DEVICES

This is commonly known as the PVT challenge – Process, Voltage and Temperature must all be made to have minimum impact on performance.

Sound design practice, including careful choices of product architecture and technology, and cell topology, can lower the risk of parametric failures. But thorough simulation of the full range of PVT conditions is essential in analog practice, and invariably this work is extremely time-consuming.

It also requires excellent device modeling, to a far greater extent than needed for digital design.

PARAMETRIC SLAVERY

ANALOG DEVICES

Thus, using the CAD model libraries for the “fast”, “slow”, and “nominal” device models (of all kinds, not only transistors), and operating temperatures of, say, –60 ° C, 30 ° C and 120 ° C one generates a set of nine results; repeating at a supply voltage of, say, 2.6V, 3V and 3.6V requires twenty-seven simulation runs, for each of perhaps fifty or more key performance aspects. Any time a change is made in the design – even a small one – these must be repeated all over again.

DESIGN COMPRESSION

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The impact of this tedious and time-consuming verification work on the circuit design schedule can be catastrophic, if not fully anticipated.

This leads to the realization that the bulk of the design must be compressed into the first week or two of a development schedule.

The latter two weeks must be reserved to prepare for a Design Review and hand-over to Layout.

BACK EXTRACTION

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Only after the IC layout has been completed can the capacitances of interconnections, and some of their resistances, be extracted and added back into a new set of simulation studies, which need to be just as thorough as those during pre-layout.

These parasitics (along with others, for example, the package reactances and ESD protection) are of pivotal importance in RF-IC design. Experience teaches that the behavior of almost any circuit will be radically different when they are included. Time is thus needed to pursue further remedial action.

NEW ANALOG FRONTIERS

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Fiber systems have heralded a return to many basic *physical* principles and device development, being essentially “Newtonian”, as are RF systems:

- Dispersion compensation in optical fibers
- All-optical erbium-doped fiber amplifiers
- Multi-wavelength channel splitters
- Power-sampling partial splitters
- Laser-diode drivers and modulators
- Micromechanical (MEM) multiplexers
- Supervisory functions of many kinds

ANOTHER “WAR”

ANALOG DEVICES

squeak

BIPOLAR?

fizz

versus

CMOS!

XFCB BIPOLAR TECHNOLOGIES

ANALOG DEVICES

HIGH-PERFORMANCE COMPLEMENTARY BIPOLAR

- Ultra-Low Inertia:
  - Small transit time and low capacitances
  - Substrate capacitance not a varactor
- Trench-Isolated; Bonded Wafers (SOI)
- Three processes in full production
- Laser-trimmable thin-film resistors
- High-quality metal-plate capacitors
- Excellent device modeling

WHY CONTINUE TO BE CONCERNED WITH BJT'S - WHEN AN INCREASING NUMBER OF MODERN SYSTEMS ARE TURNING TO CMOS TECHNOLOGIES FOR RF SIGNAL PROCESSING ?

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Highest Performance Devices will Continue to use BJT Technologies

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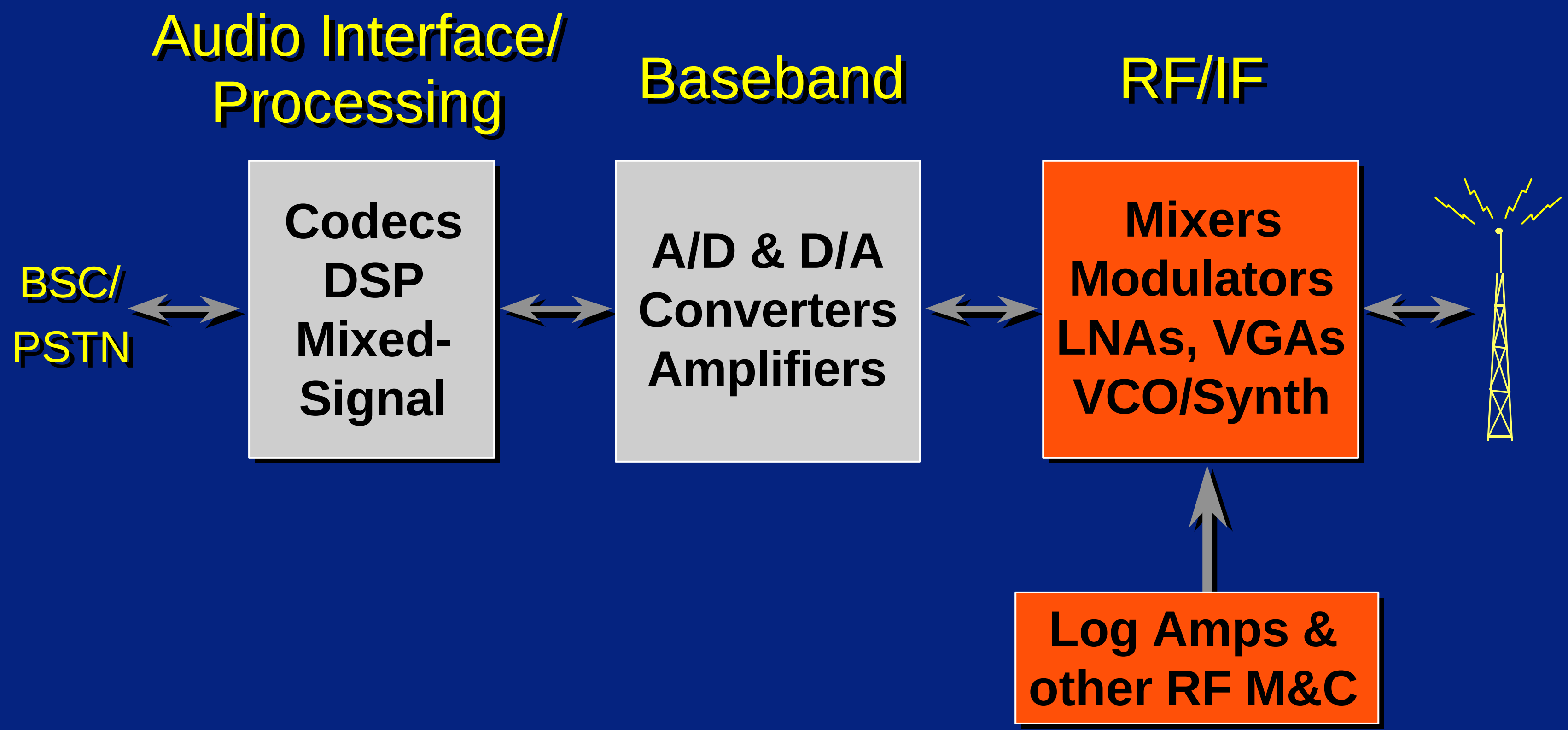

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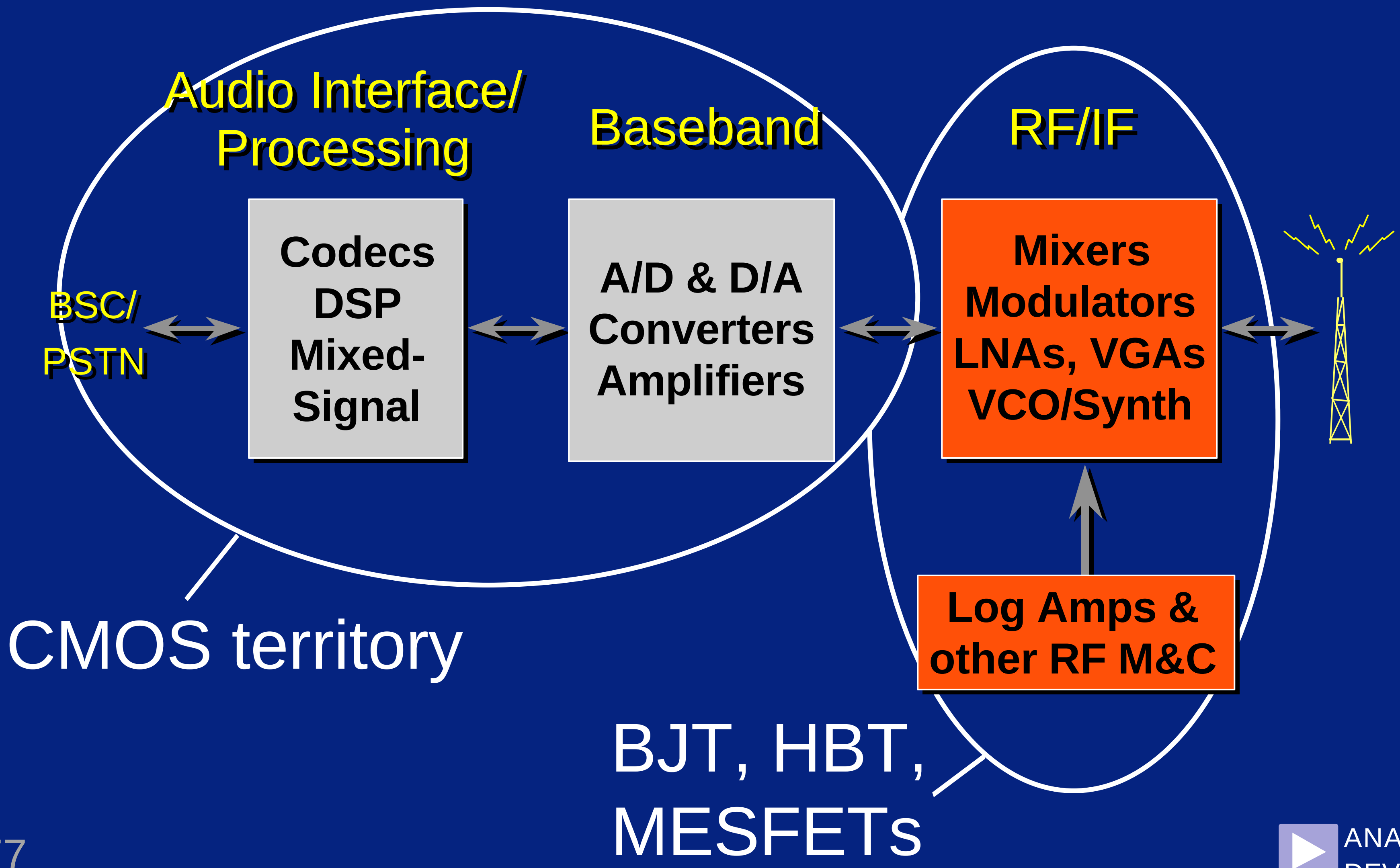

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Highest Performance Devices will Continue to use BJT Technologies

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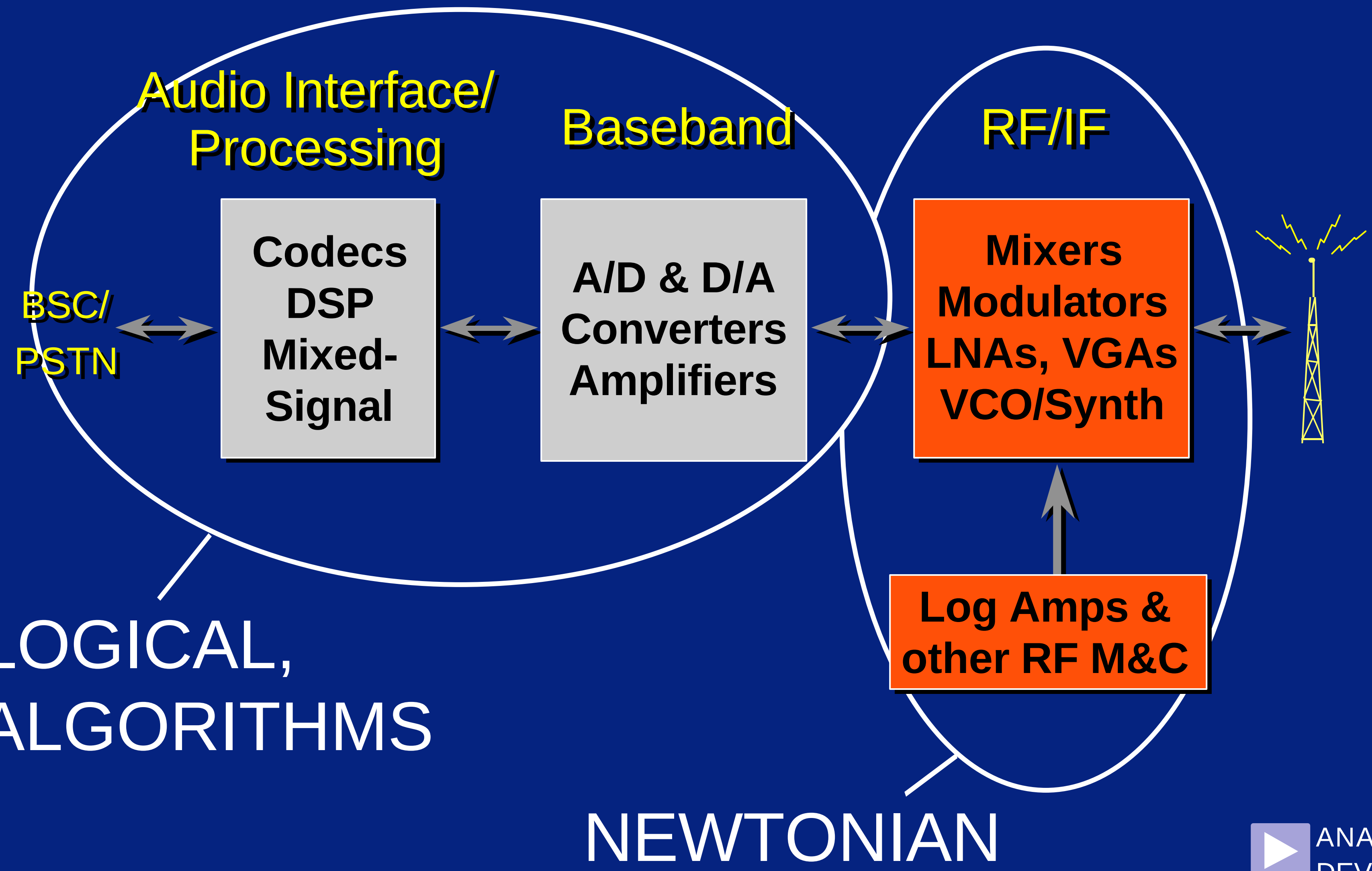


ANALOG DEVICES

BJT MODELING

CONTRARY TO SOME VIEWPOINTS, THE BJT IS FAR EASIER TO DESCRIBE IN MODELING EQUATIONS, COMPARED TO CMOS. WHILE THE EQUATIONS ARE STILL COMPLEX, THEY ARE *FUNDAMENTALLY SOUND*, OVER A VERY WIDE RANGE. USING SOI SUBSTRATES, THE BJT IS *A PURE, THREE-TERMINAL DEVICE*; ITS TINY COLLECTOR-SUBSTRATE CAPACITANCE IS NOT VOLTAGE-DEPENDENT. THERE ARE NO OTHER SUBSTRATE SENSITIVITIES.

ANALOG DEVICES

ADVANCED MODELS

FOR MANY MICROWAVE APPLICATIONS IT IS NECESSARY TO INCLUDE SPECIAL ASPECTS OF BJT DEVICE BEHAVIOR. EXCELLENCE IN THIS ARENA, CENTERED ON *IN-HOUSE CAD TEAMS,* PROVIDES A MAJOR COMPETITIVE ADVANTAGE. FOR EXAMPLE, THE BJT SUPER-MODELS INCLUDE *DISTRIBUTED* ASPECTS OF DEVICE BEHAVIOR. NUMEROUS OTHER SUBTLE DETAILS ARE GENERALLY NOT OF IMPORTANCE AT LOWER FREQUENCIES.

ANALOG DEVICES

HOWEVER . .

DEEP SUB-MICRON CMOS PROMISES TO PROVIDE SOME PERFORMANCE ADVANTAGES (BETTER LINEARITY, ABSENCE OF SHOT NOISE) THOUGH NOT YET FULLY PROVEN; DIE COST IS RARELY OF MATERIAL CONCERN IN SSI AND EVEN LSI RF PRODUCTS

ANALOG DEVICES

HOWEVER . .

MANY OF THESE BJT CELL DESIGNS HAVE ALREADY BEEN ADAPTED TO CMOS FORM, AND IN GENERAL THE THEORY IS DIRECTLY APPLICABLE; THE “GAP” BETWEEN BJT AND CMOS DESIGN PARADIGMS IS NARROWING

ANALOG DEVICES

HOWEVER . .

IN ULTRA-SHORT-CHANNEL CMOS TRANSISTORS (BELOW 0.2μm) THE SUBTHRESHOLD REGION EXTENDS UP TO CURRENTS AT WHICH QUITE HIGH f_T's ARE POSSIBLE, WHEN

CMOS ➡ BJT

ANALOG DEVICES

CMOS SHORTFALL

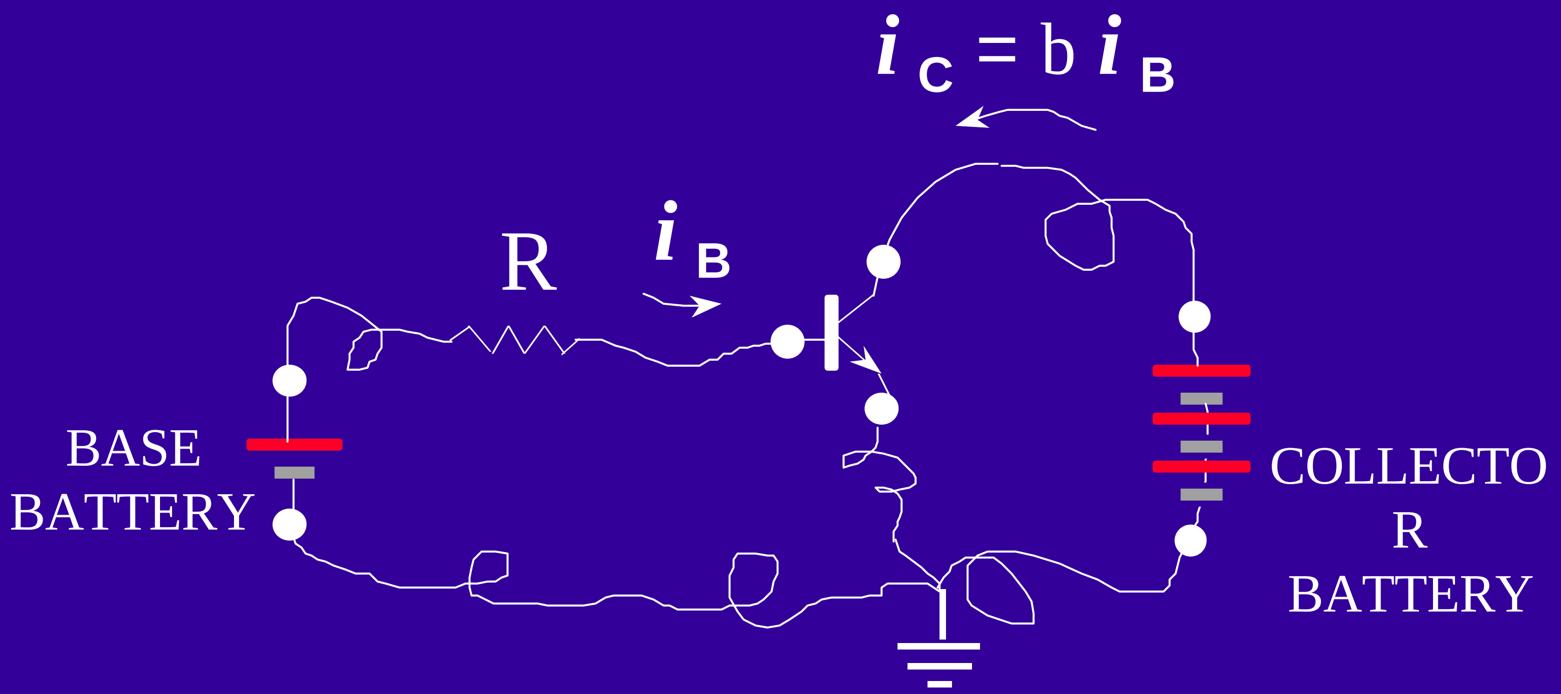
- PRESENT-DAY (0.35-0.18μm) CMOS DEVICES STILL HAVE LOWER gm/C RATIOS THAN COMPARABLE BJTs
- LOW-FREQUENCY NOISE AN ISSUE
- NONLINEAR OUTPUT CONDUCTANCE
  - can quickly lose that nice *gm* linearity at the load
- MANY SUBSTRATE SENSITIVITIES
- EXTREMELY COMPLEX BEHAVIOUR
- CONSEQUENTLY, POOR MODELING

ANALOG DEVICES

A BIT About the BJT

50 YEARS AGO

... this was the commonplace view of how the transistor worl



ANALOG
DEVICES

50 YEARS AGO

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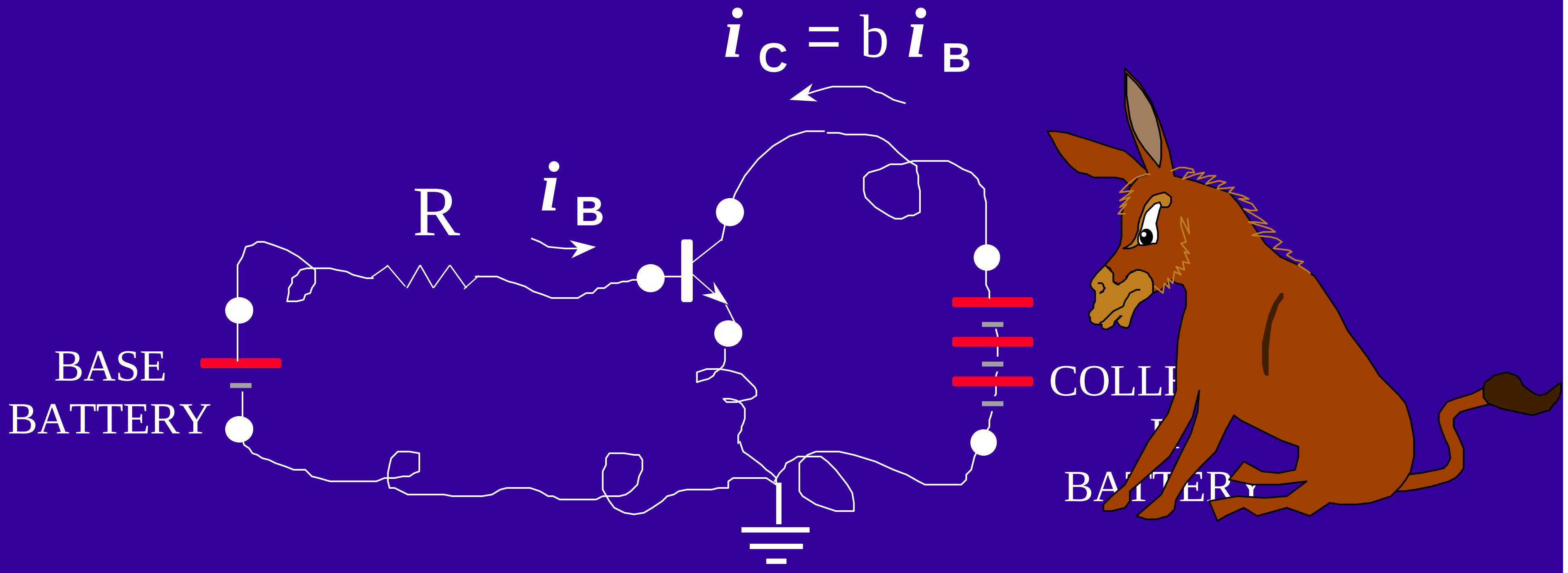
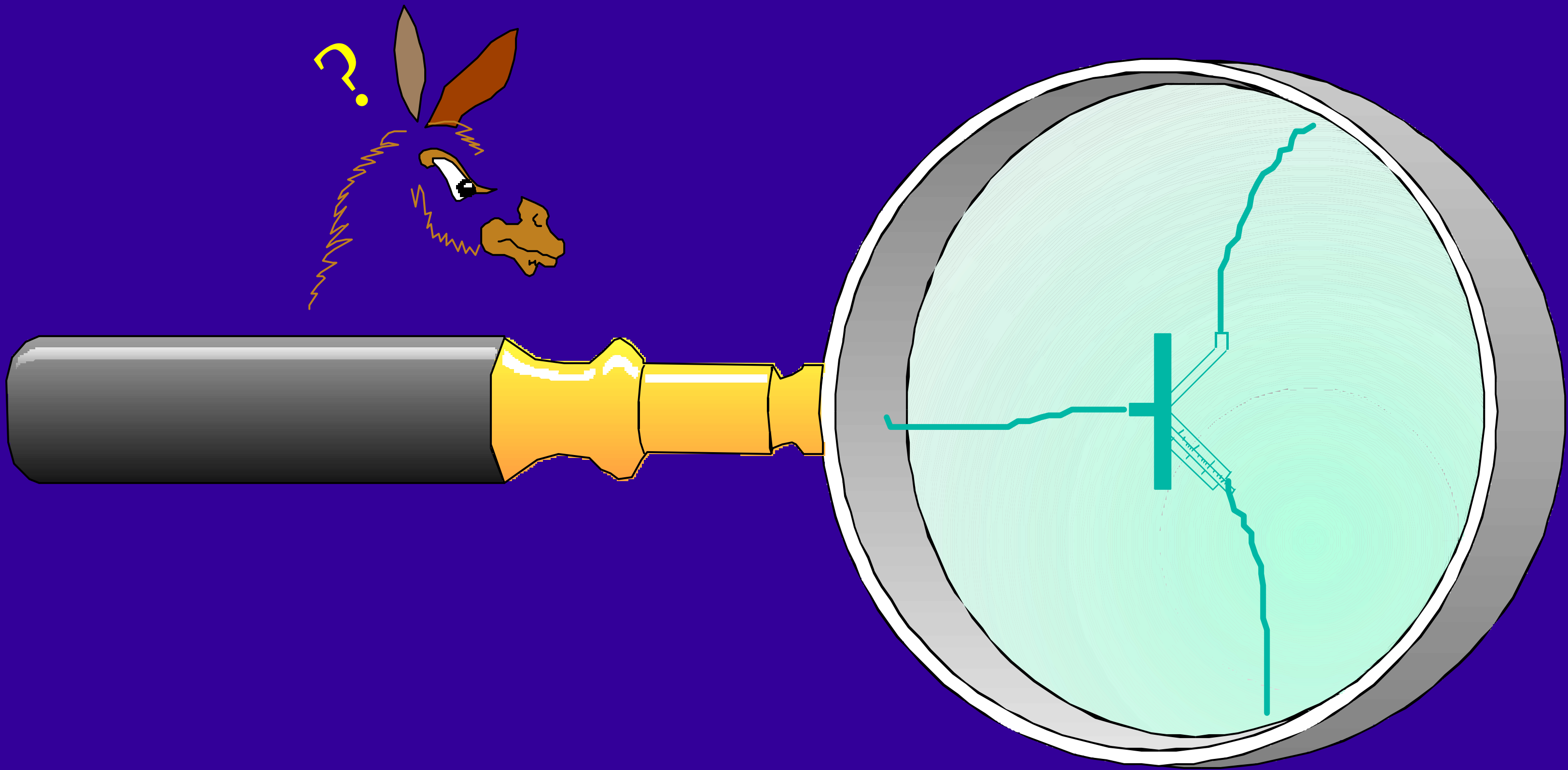


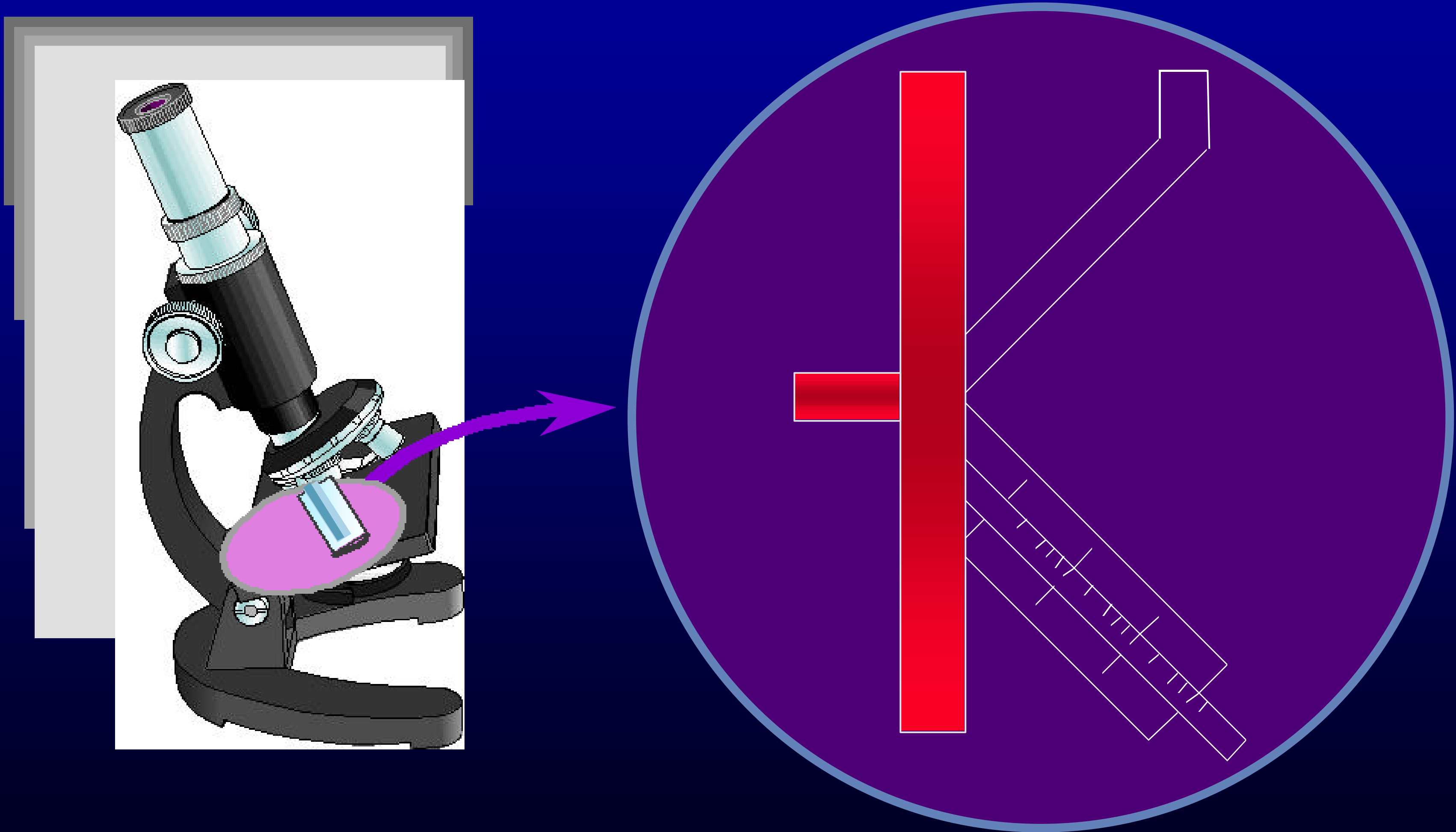
The Beta View

BUT LOOK CLOSER ....



ANALOG DEVICES

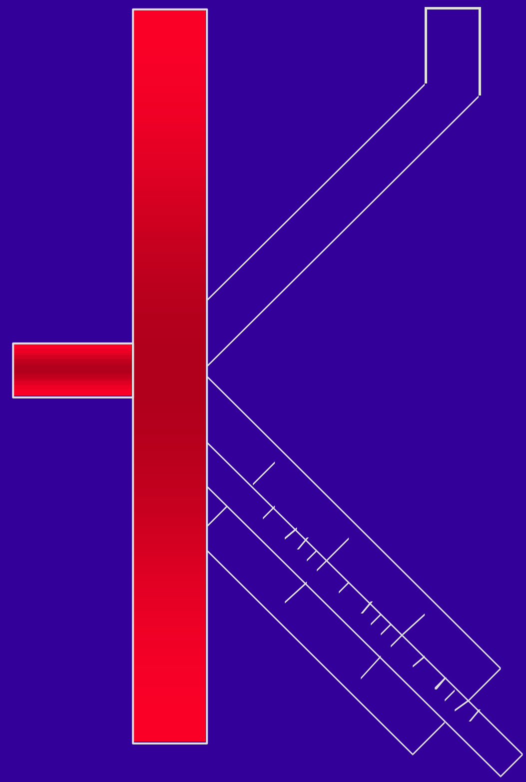
THE BJT AT HIGH MAGNIFICATION



ANALOG DEVICES

THE HEART OF THE BJT

- $I_C = I_S(T) \exp V_{BE} / V_T$
- $V_{BE} = V_T \log I_C / I_S(T)$
- ONE EQUATION; TWO FORMS



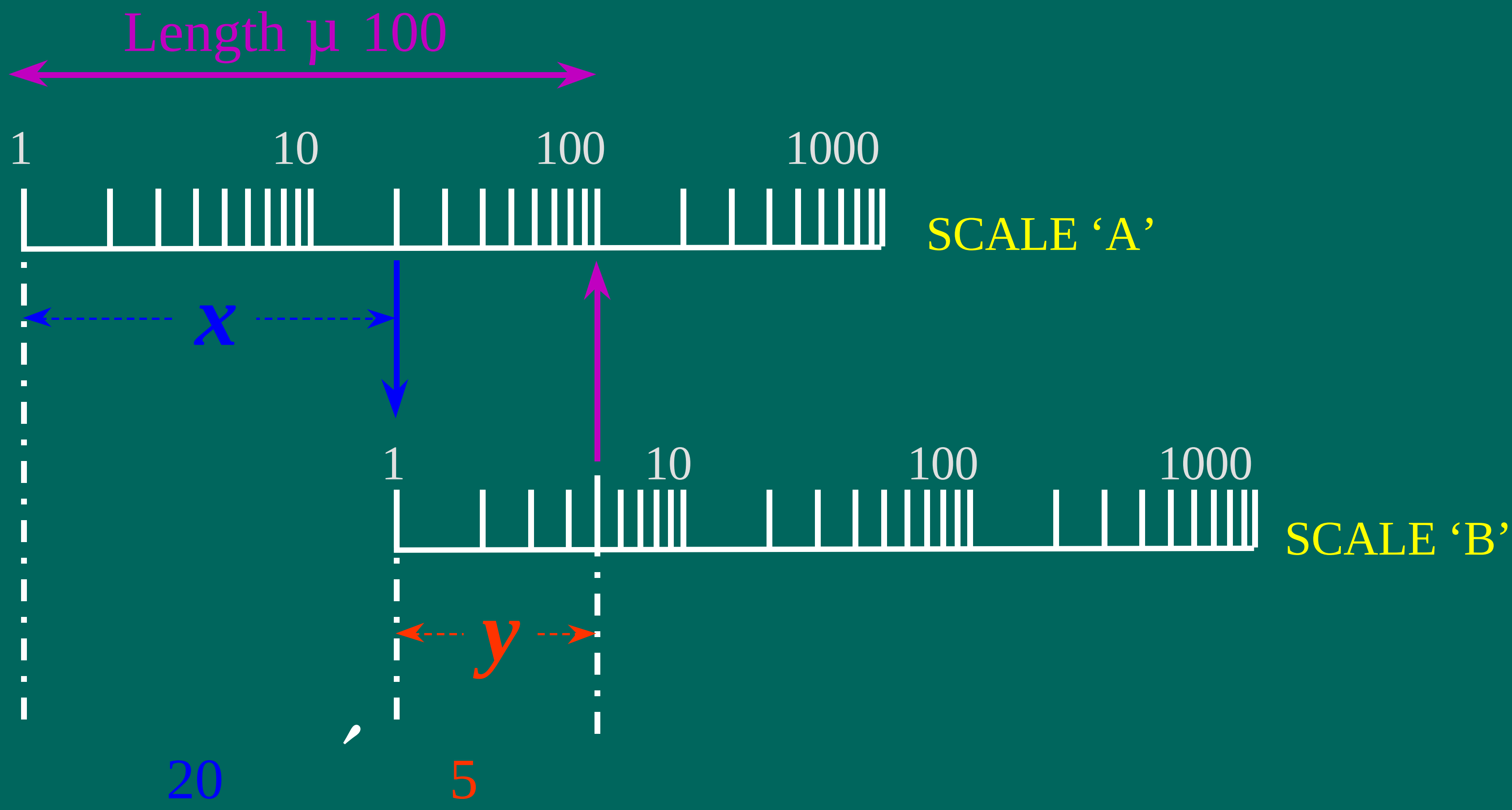
ANALOG DEVICES

TRANSCONDUCTANCE

- $I_C = I_S(T) \exp V_{BE} / V_T$
- $dI_C / dV_{BE} = \{ I_S(T) \exp V_{BE} / V_T \} / V_T$
- $gm = I_C / V_T$
- **WHICH IS LITTLE SHORT OF MIRACULOUS !**

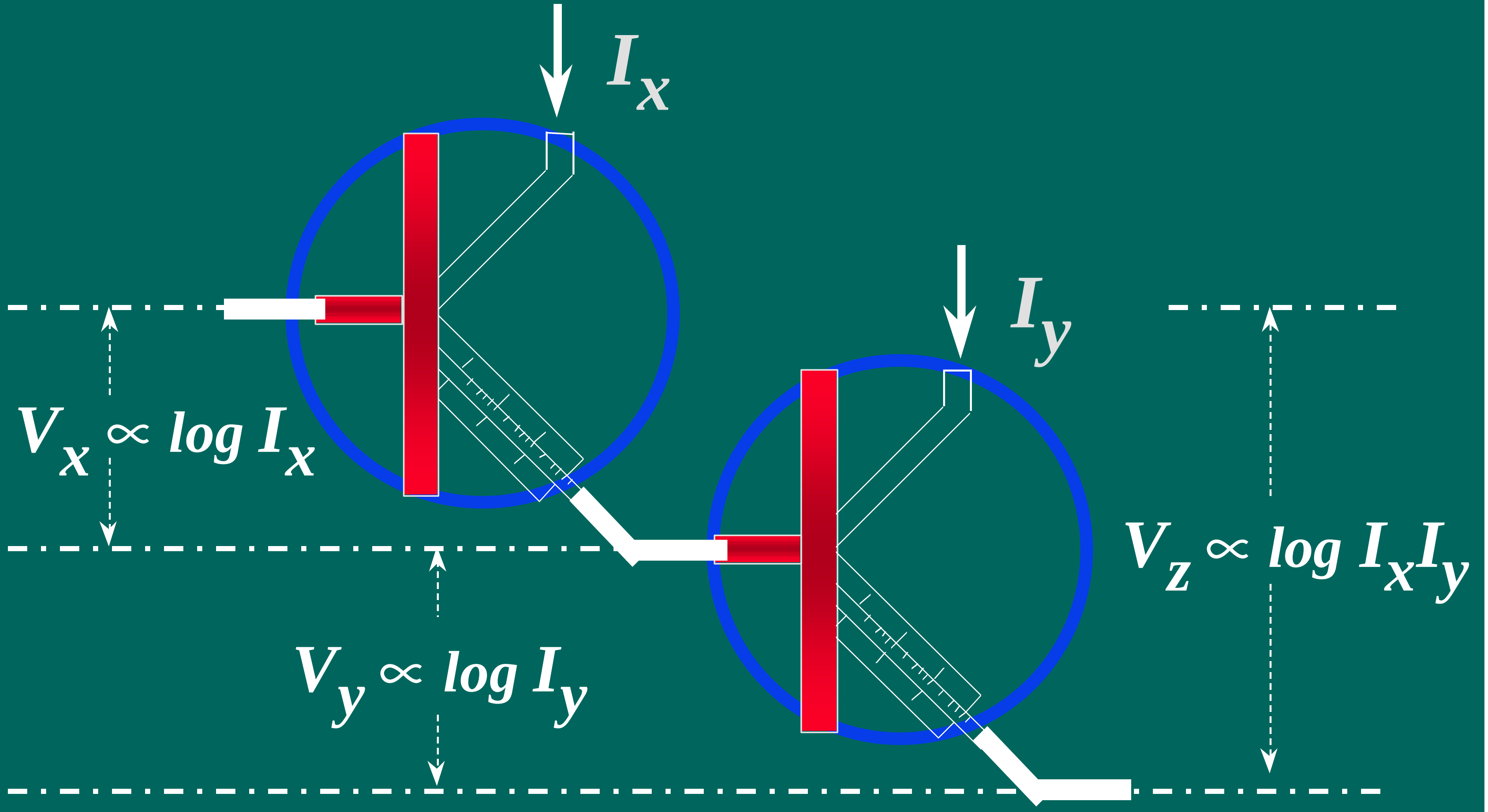
ANALOG DEVICES

MULTIPLICATION USING A SLIDE-RULE



ANALOG DEVICES

MULTIPLICATION USING TRANSISTORS



ANALOG DEVICES

THE 'BAND-GAP' EQUATION FOR $V_F(I_F,T)$

$$V_F = E_{GE} - \mathbf{H}\left\{V_{EN} - V_{TN}\left(\log\frac{I_F}{I_N} - h\ \log \mathbf{H}\right)\right\}$$

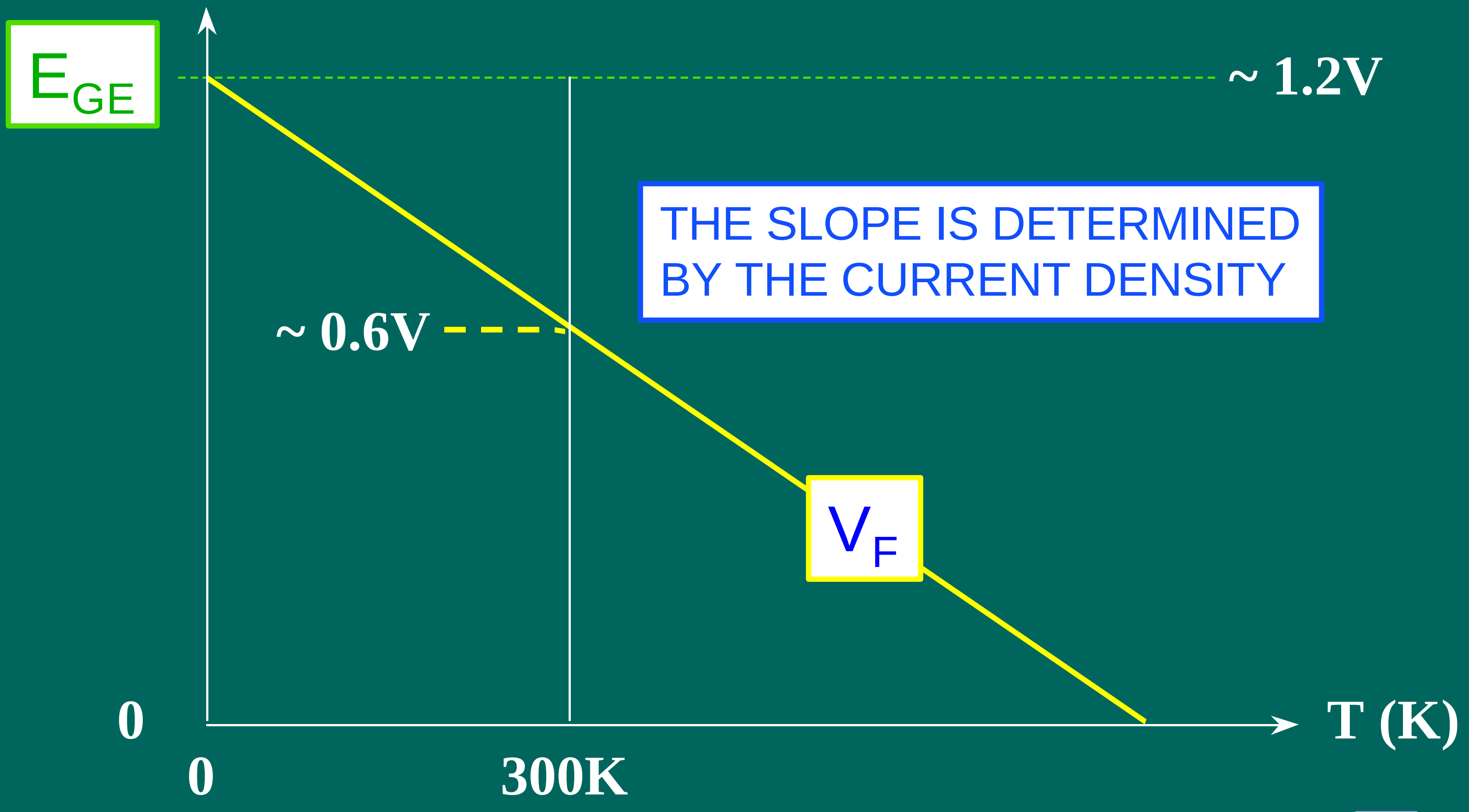
where $\mathbf{H}$ is the 'Hotness factor T/T_N

$$V_{EN} = \underbrace{E_{GE} - V_N}_{}$$

a temperature-independent constant for a given device

ANALOG DEVICES

V_F versus TEMPERATURE



ANALOG DEVICES

TRANSLINEAR DESIGN

ANALOG DEVICES

> Exploits a fundamental and unique property of the bipolar transistor ¾
>
> Transconductance (g_m) is reliably a linear function of collector current:

$$g_m = I_C / V_T$$

where $V_T = kT/q$

> The basis of almost all analog multipliers and numerous VGAs since the late ’60’s

> *Current-mode* signal processing is often used

ANALOG DEVICES

TRANSLINEAR DESIGN

ANALOG DEVICES

> In short, the bipolar transistor retains certain unique properties not matched by any CMOS technology, in particular, the remarkable benefits of "translinearity".

> In many difficult areas of wireless systems, the BJT (or its more sophisticated cousin, the HBT) provides significant performance advantages over CMOS, for example, in low-noise amplifiers and power amplifiers (where GaAs HBTs are proving valuable).

> The highly predictable and mathematical nature of the bipolar transistor can be relied on to provide very high levels of accuracy and temperature stability.

ANALOG DEVICES

ANALOG DESIGN in the INFORMATION AGE must use PARTNERSHIPS of TECHNOLOGY

ANALOG *teaming* with DIGITAL

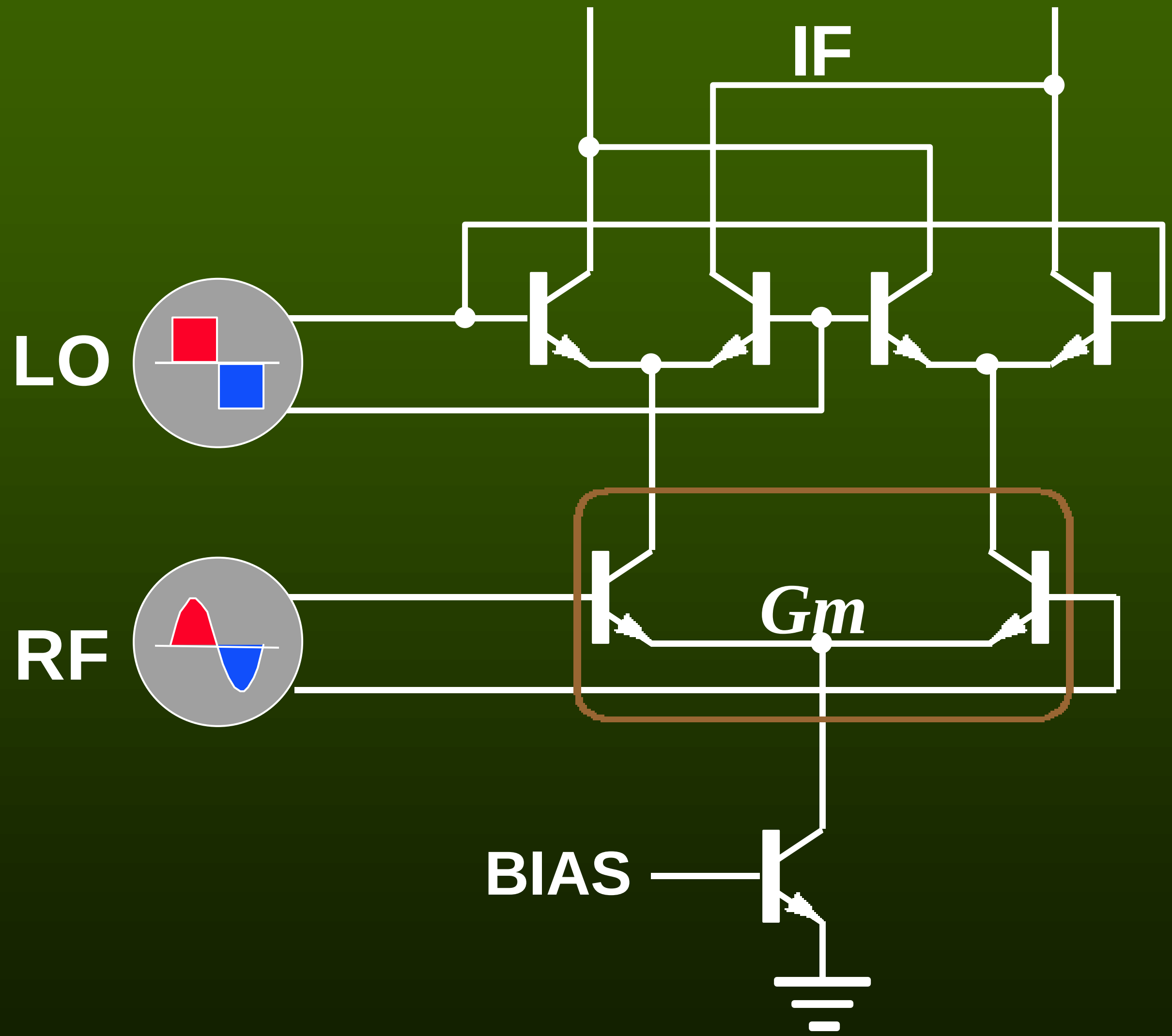
BIPOLAR *teaming* with CMOS

SOC's *teaming* with SOH's

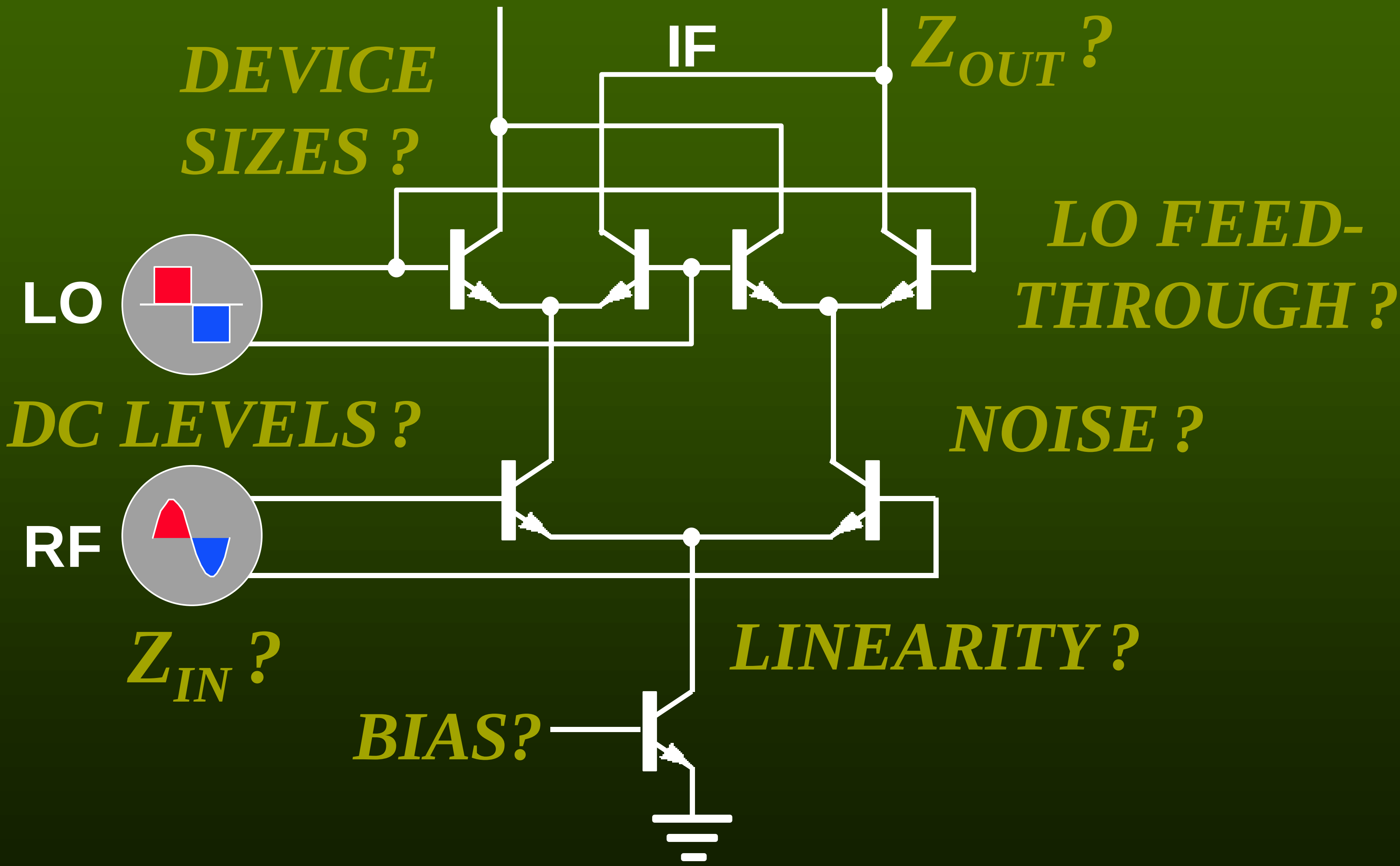
ANALOG DEVICES

Some BJT
“Tricks”

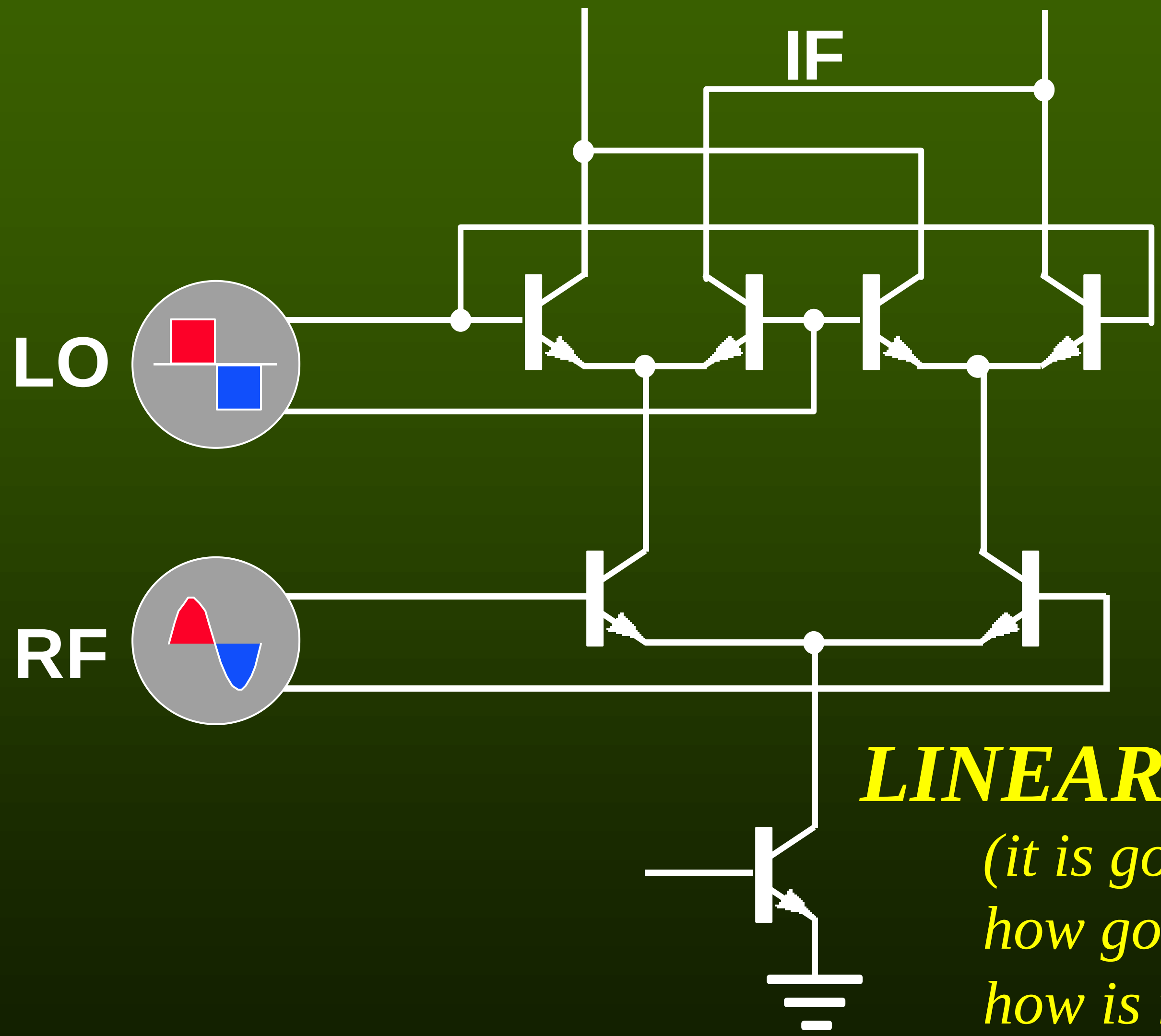
CLASSIC MIXER



CLASSIC MIXER



CLASSIC MIXER



LINEARITY?

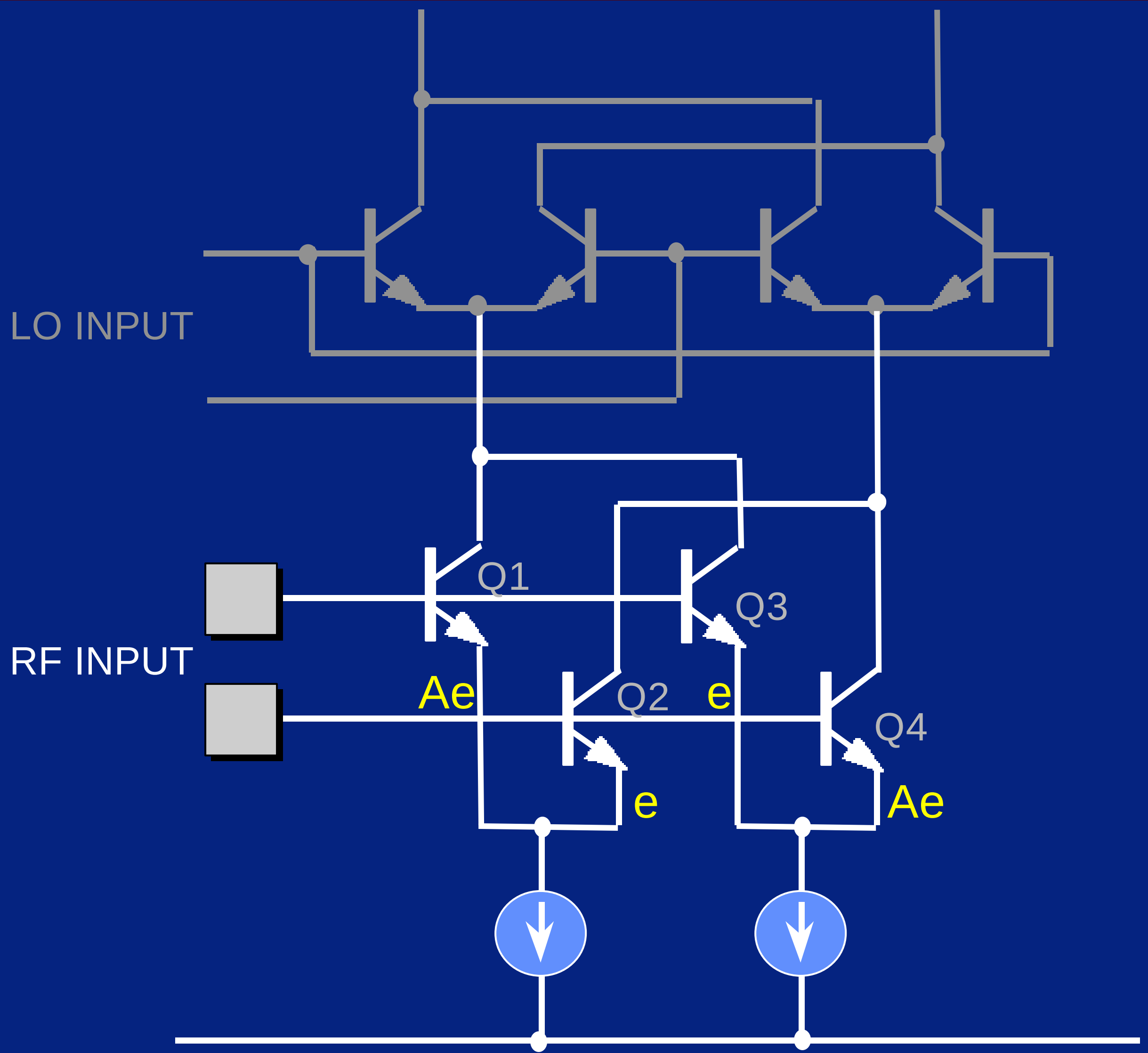
(it is good enough?
how good is good enough?
how is it improved?)

The ‘MULTI-tanh’ TECHNIQUE

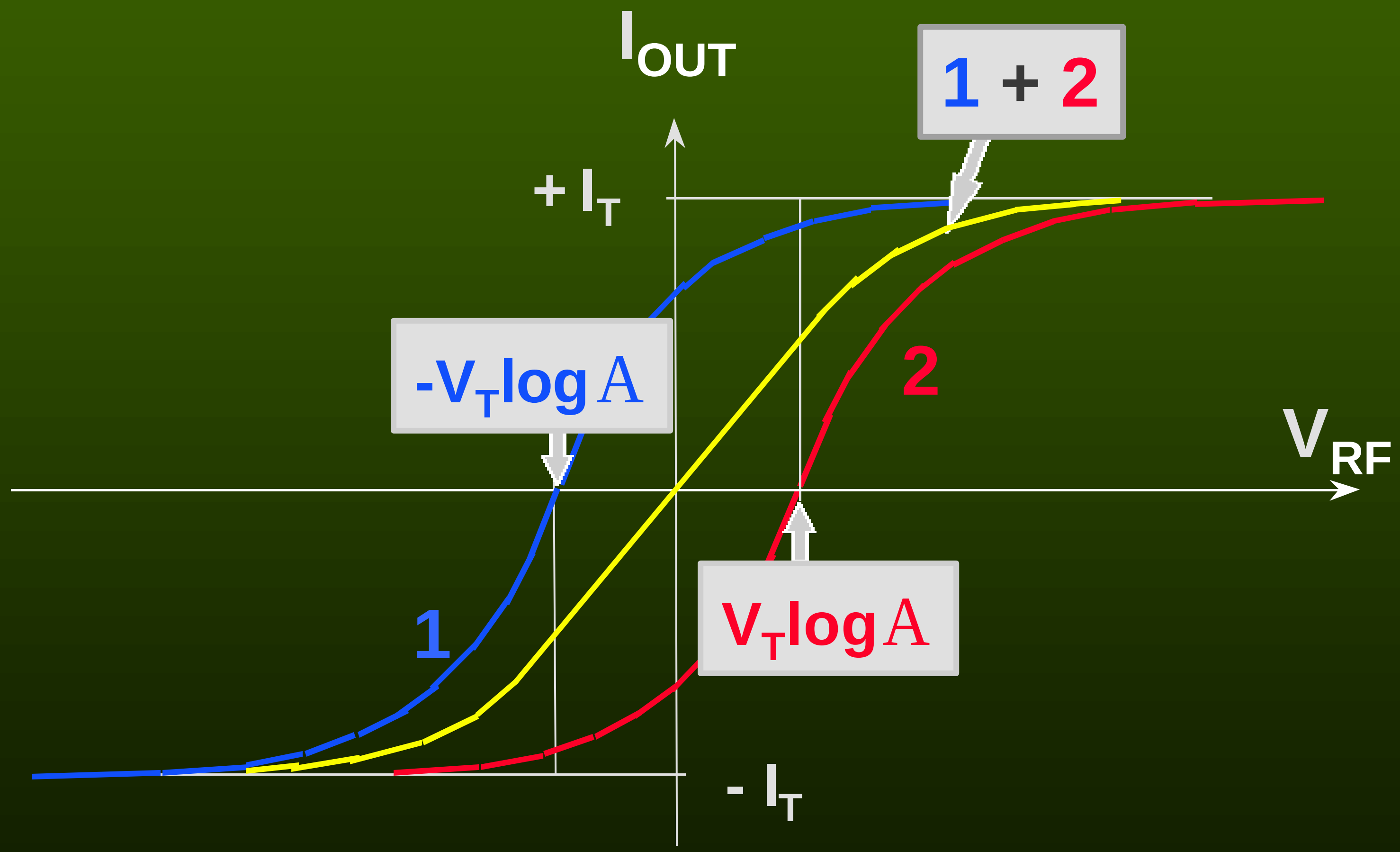
ANALOG DEVICES

- A special class of translinear circuit, which does not invoke current-mode techniques
- Achieves reductions in distortion through the use of a *multi*plicity of *tanh* functions
- Very effective in certain circumstances
- Once an academic curiosity, multi-tanh cells are now widely used

MT-DOUBLET in a MIXER

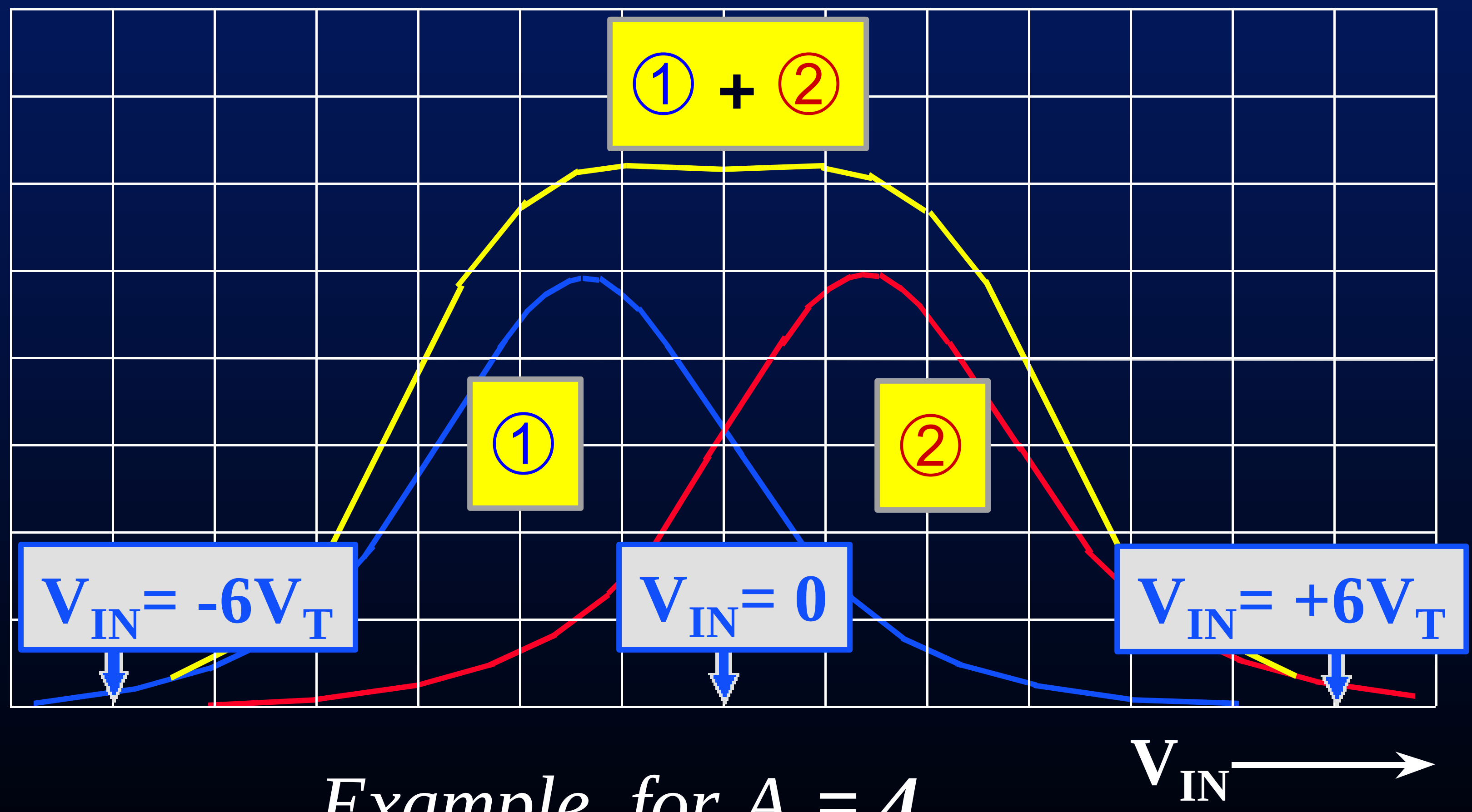


SUMMATION OF THE TWO tanh SECTIONS



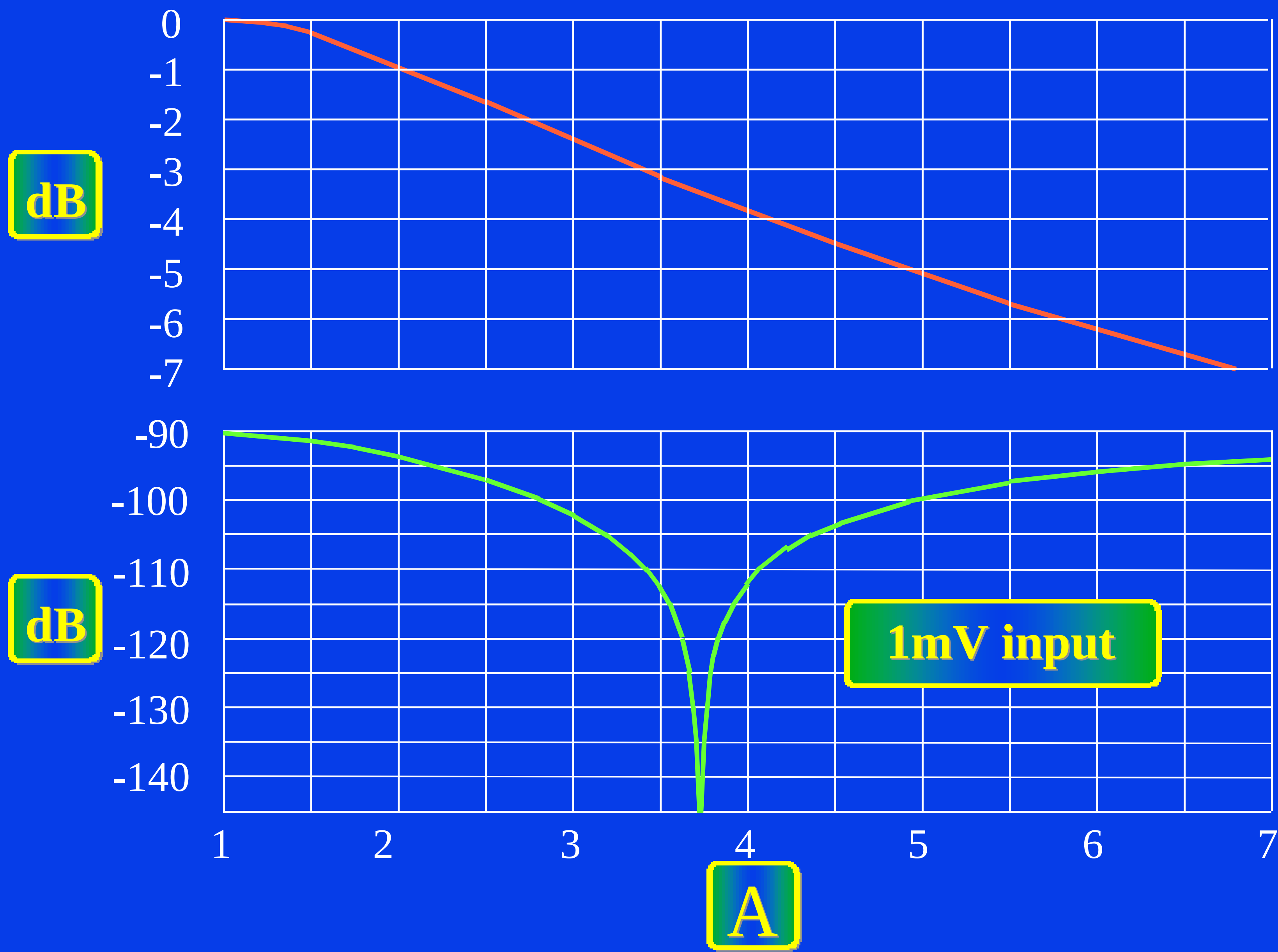
INCREMENTAL GAIN of DOUBLET

ANALOG DEVICES

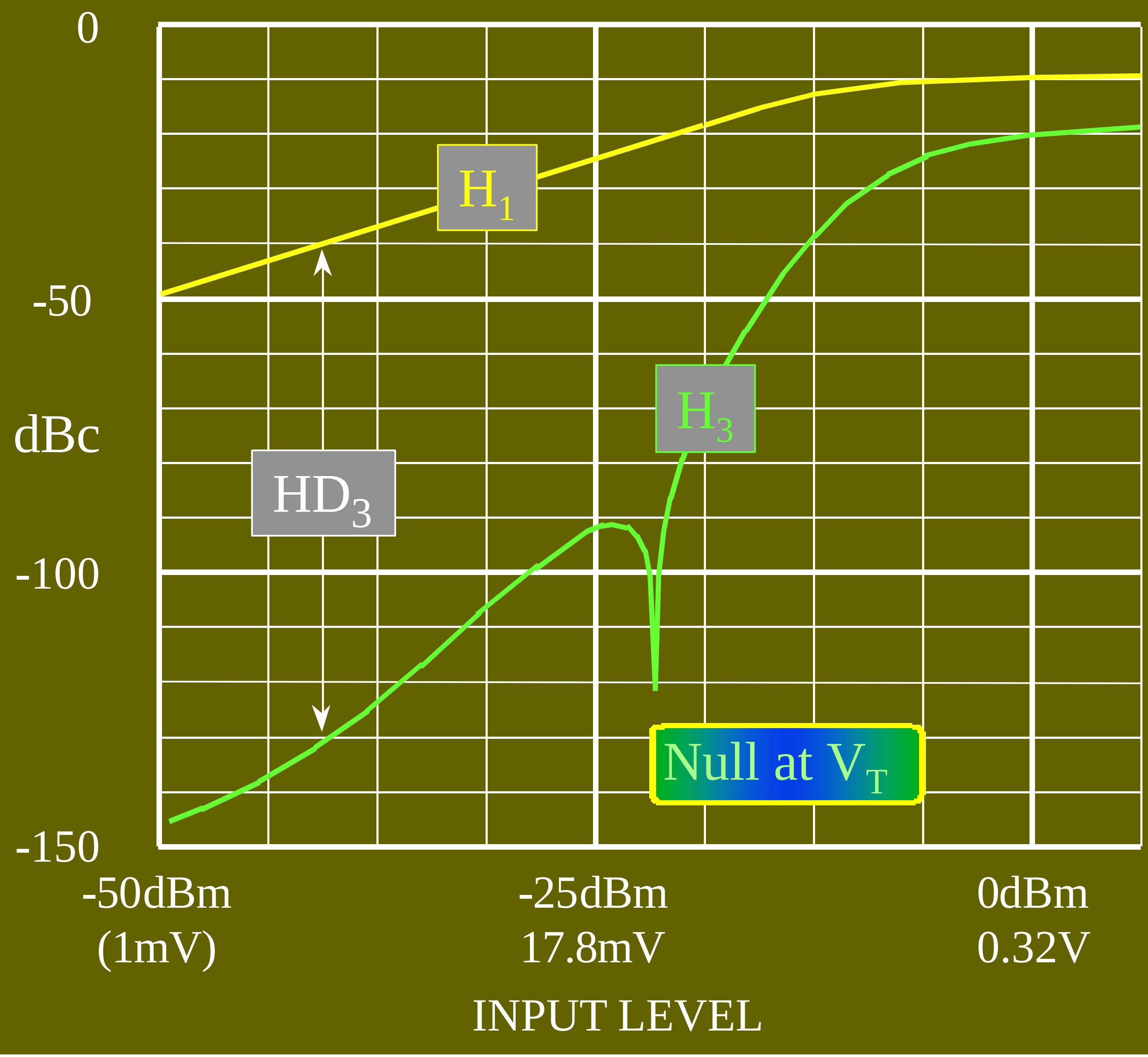


Example, for A = 4

Doublet: Relative Gain and HD3 vs. A

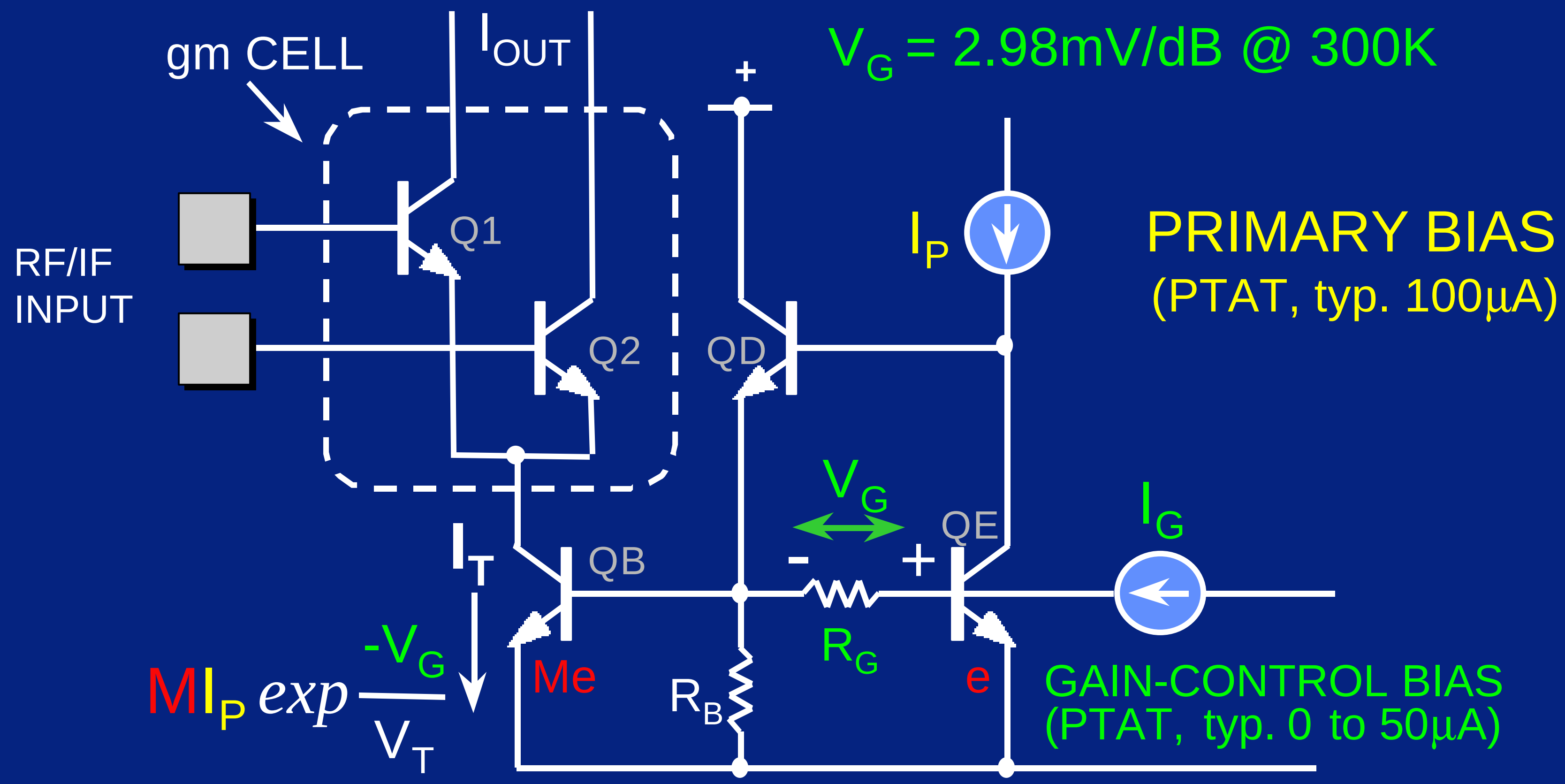


Harmonic Signature for Doublet, A = 4

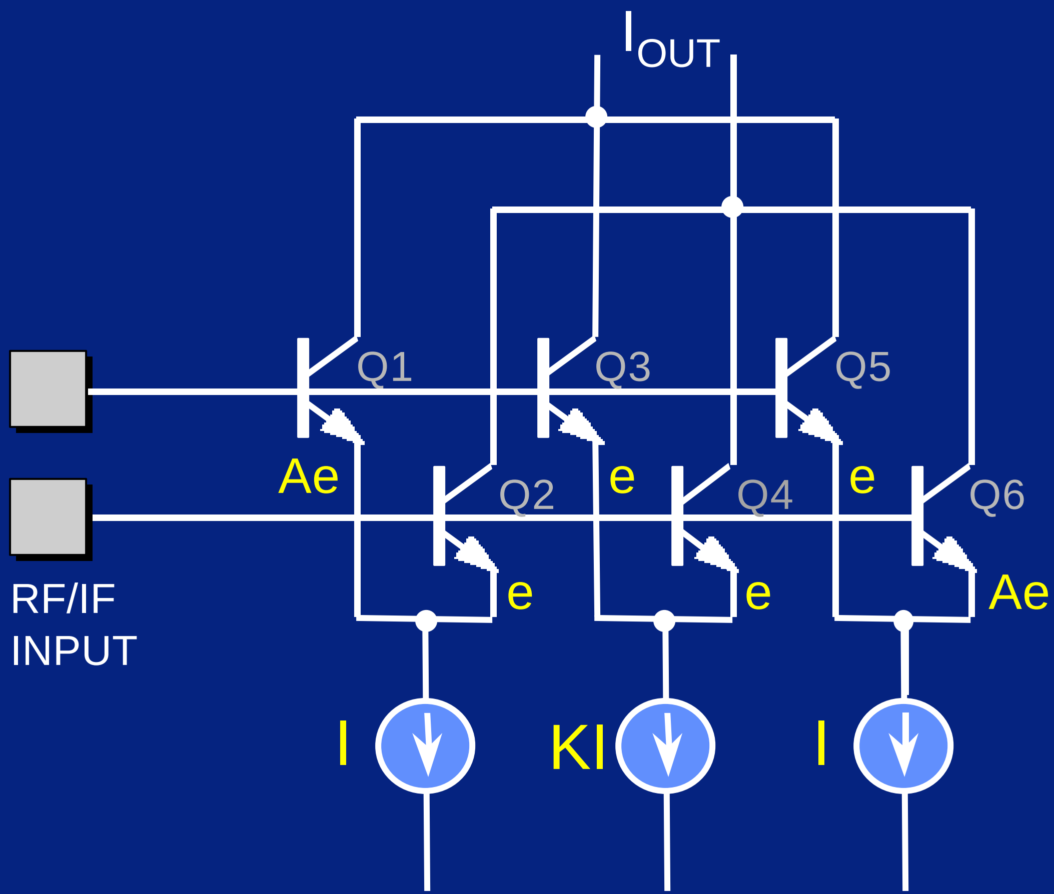


ACHIEVING LINEAR-in-dB GAIN

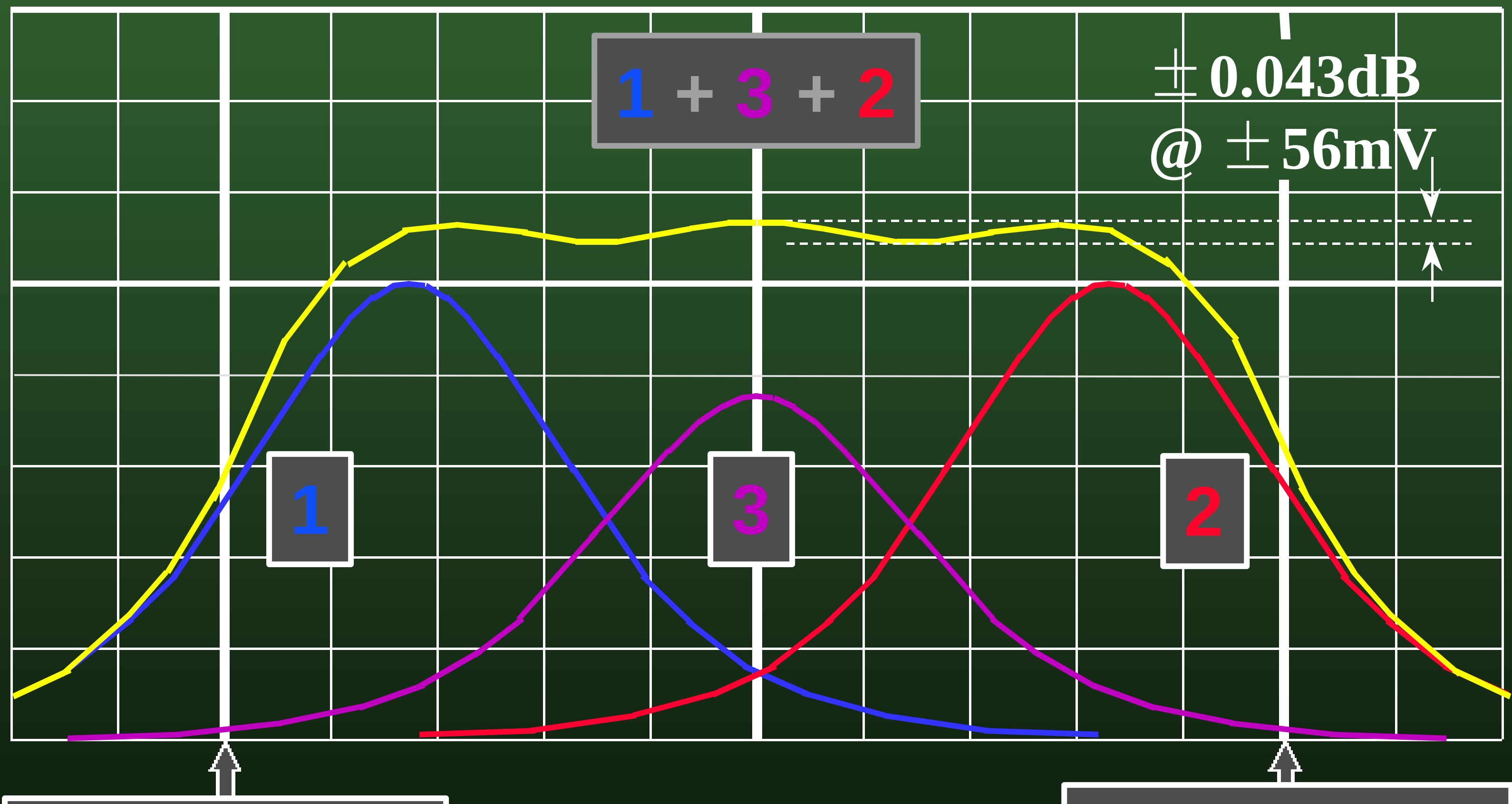
ANALOG DEVICES



MULTI-tanh TRIPLET



INCREMENTAL g_m of a typical TRIPLET

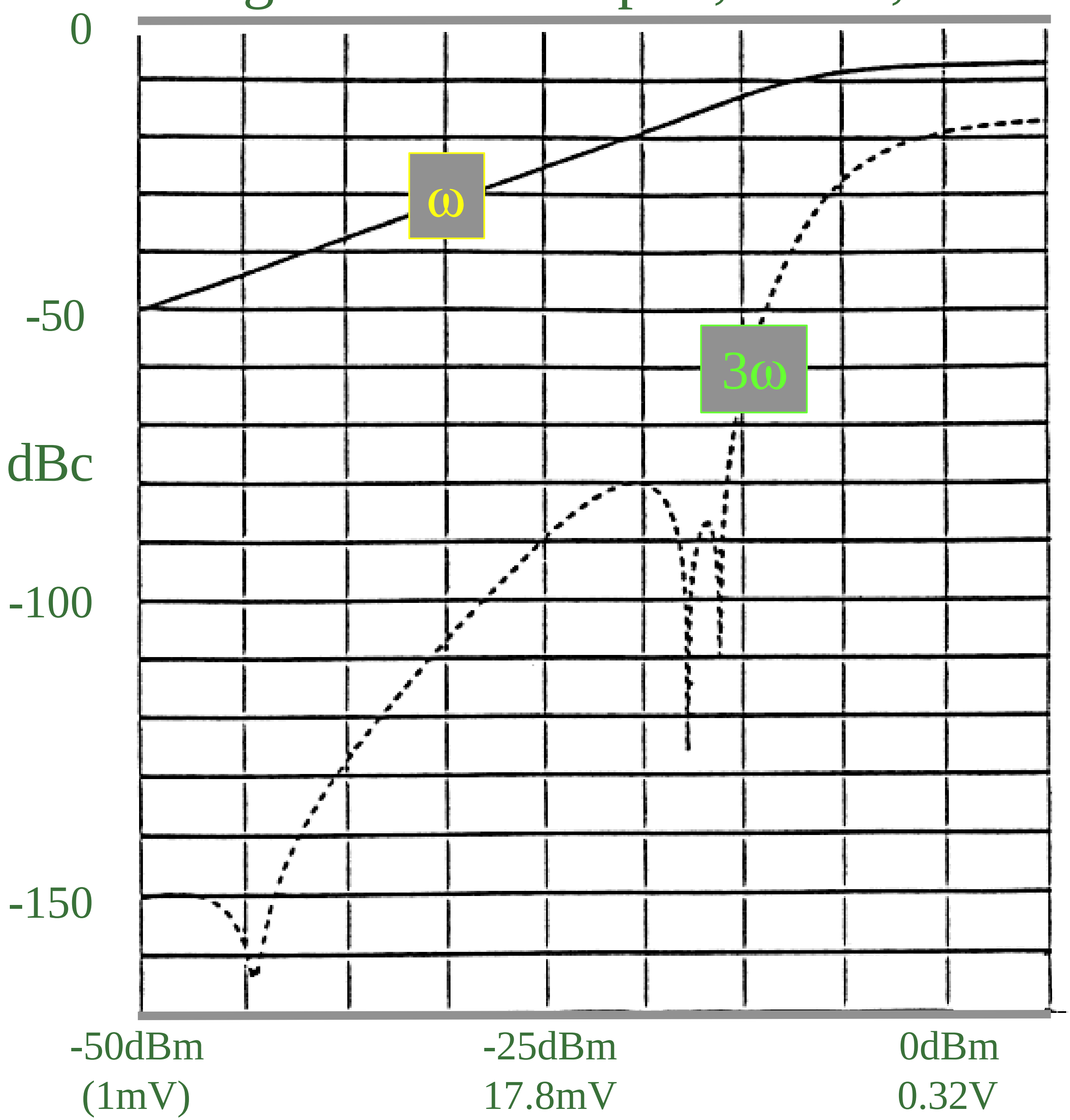


V_X= -100mV

A = 13, K = 3/4

V_X= +100mV

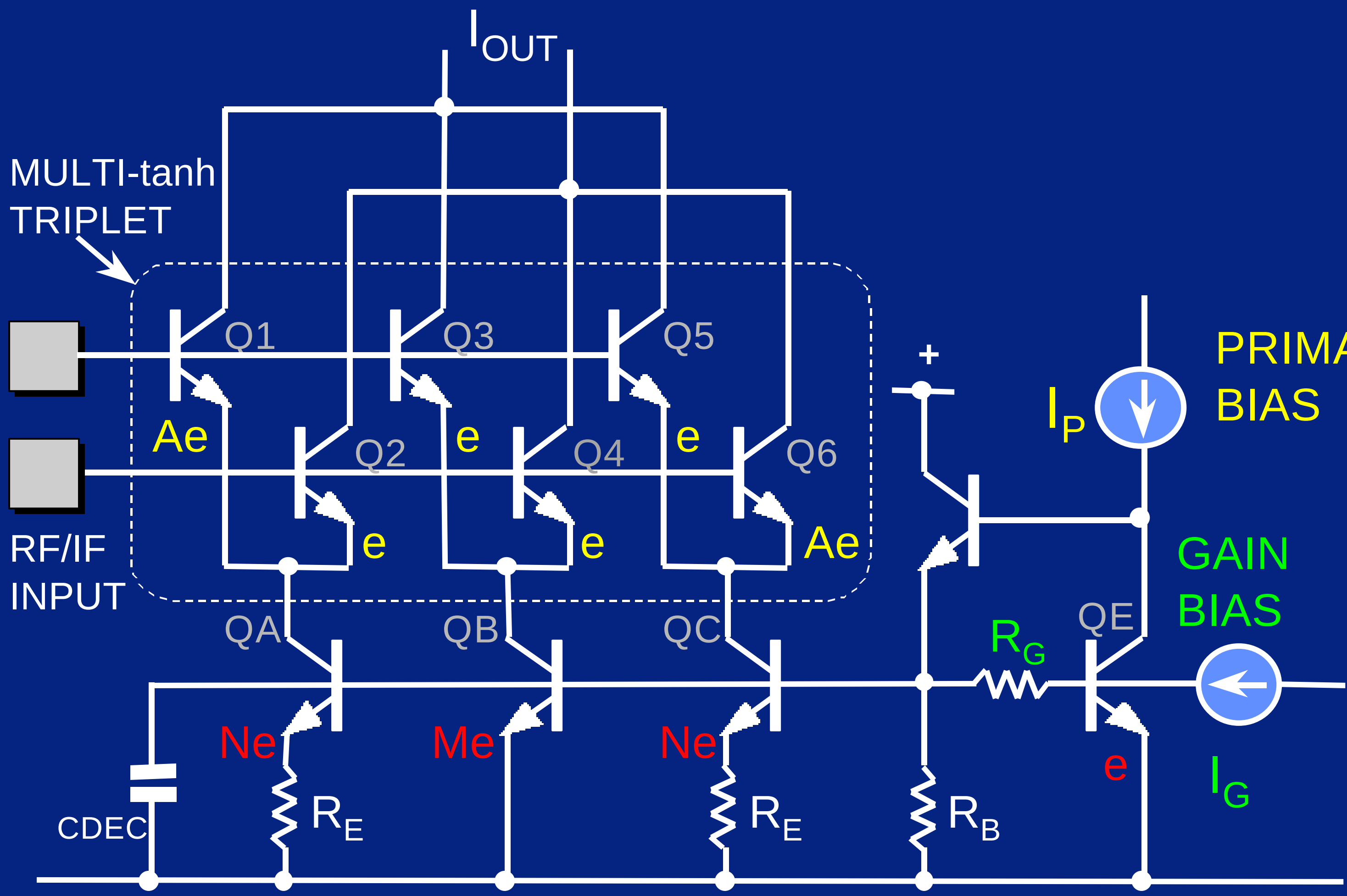
Harmonic Signature for Triplet, A=13, K=3/4



ANALOG DEVICES

TRIPLUS: MULTI-tanh TRIPLET+

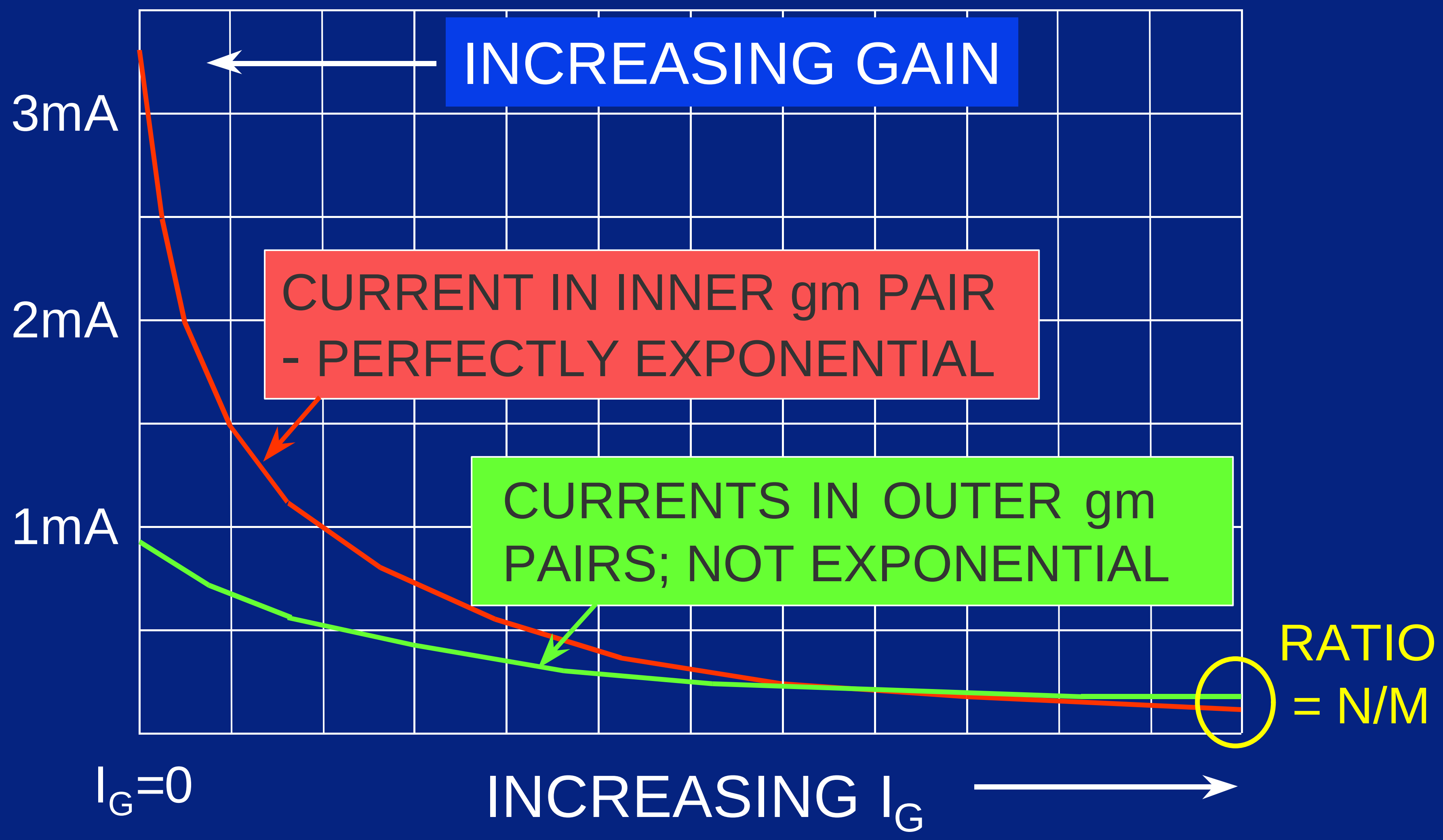
ANALOG DEVICES



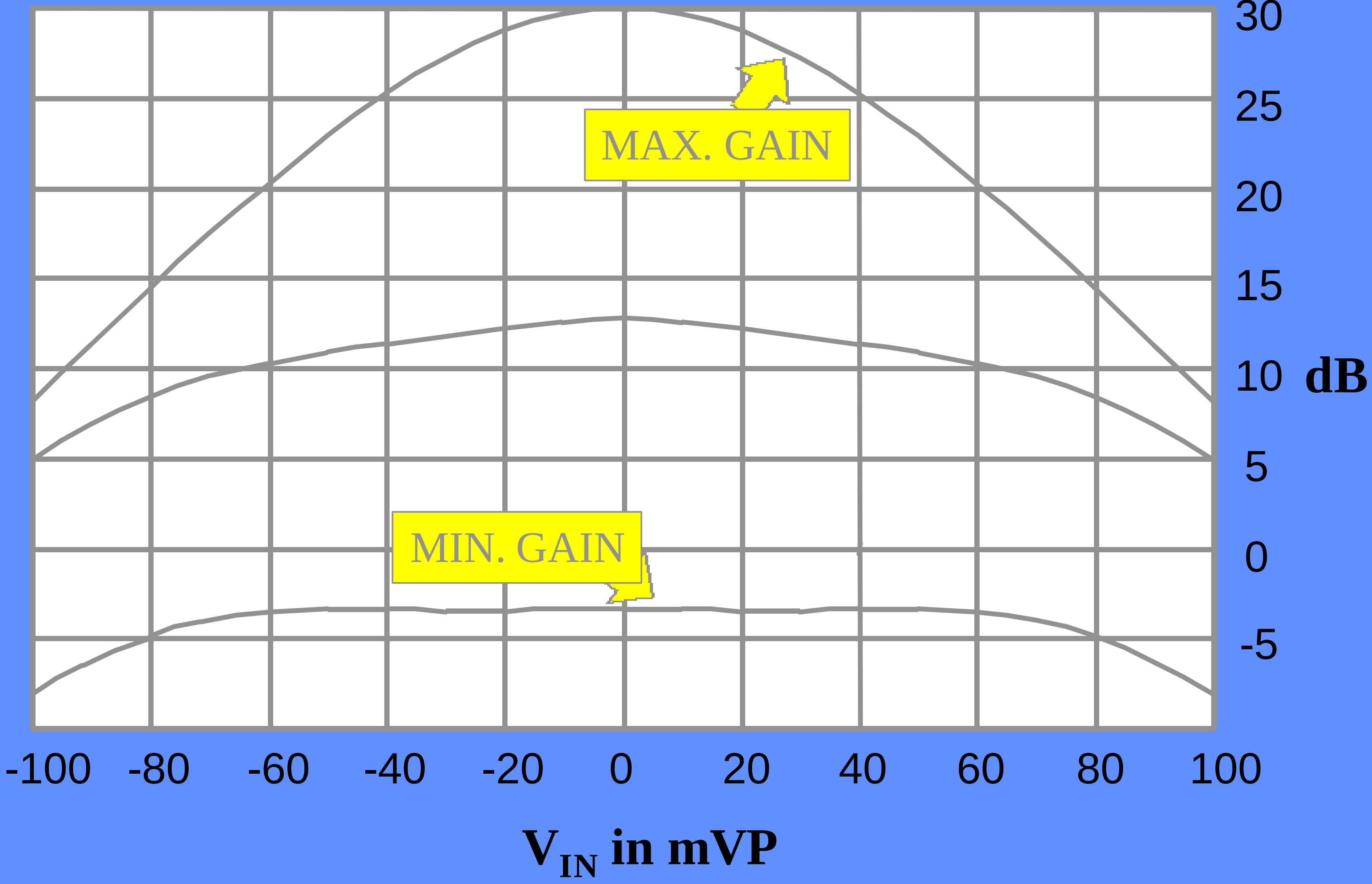
THIS SPECIAL BIASING SCHEME EXTENDS DYNAMIC RANGE

BIAS CURRENTS in INNER/OUTER gm CELLS

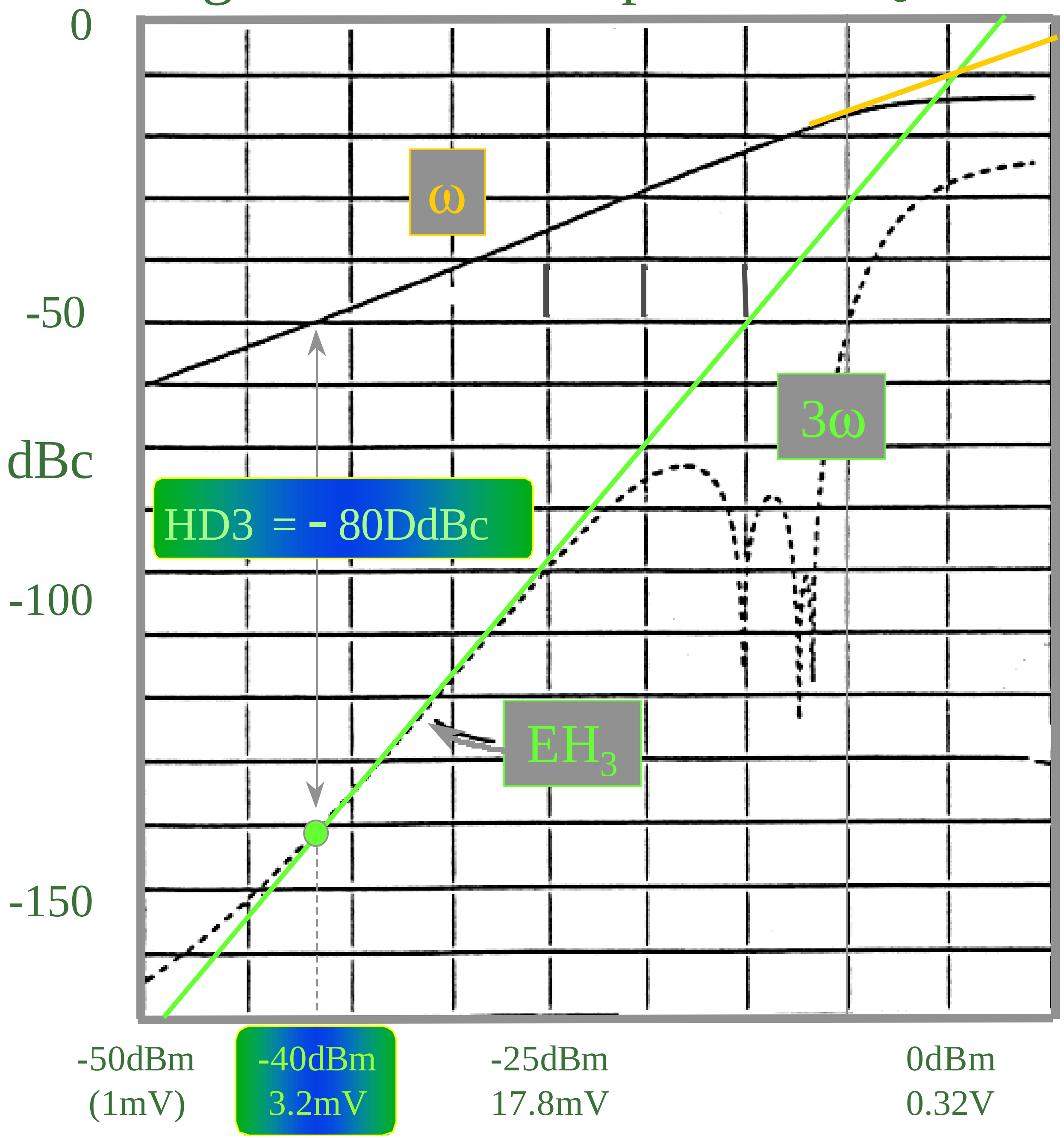
ANALOG DEVICES



TRIPLUS Incremental Gain vs. Instantaneous V_{IN}

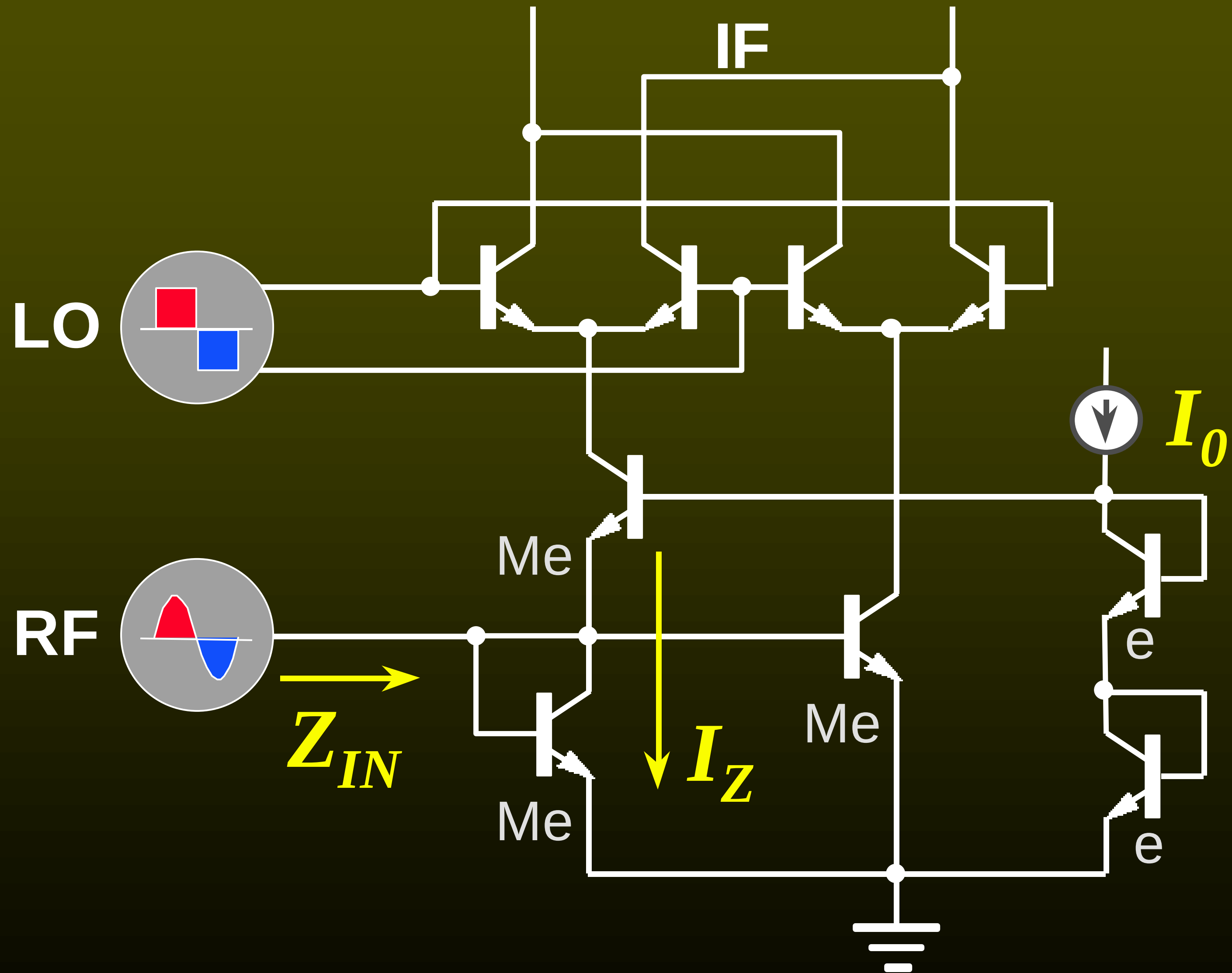


Harmonic Signature for an Optimized Quadlet

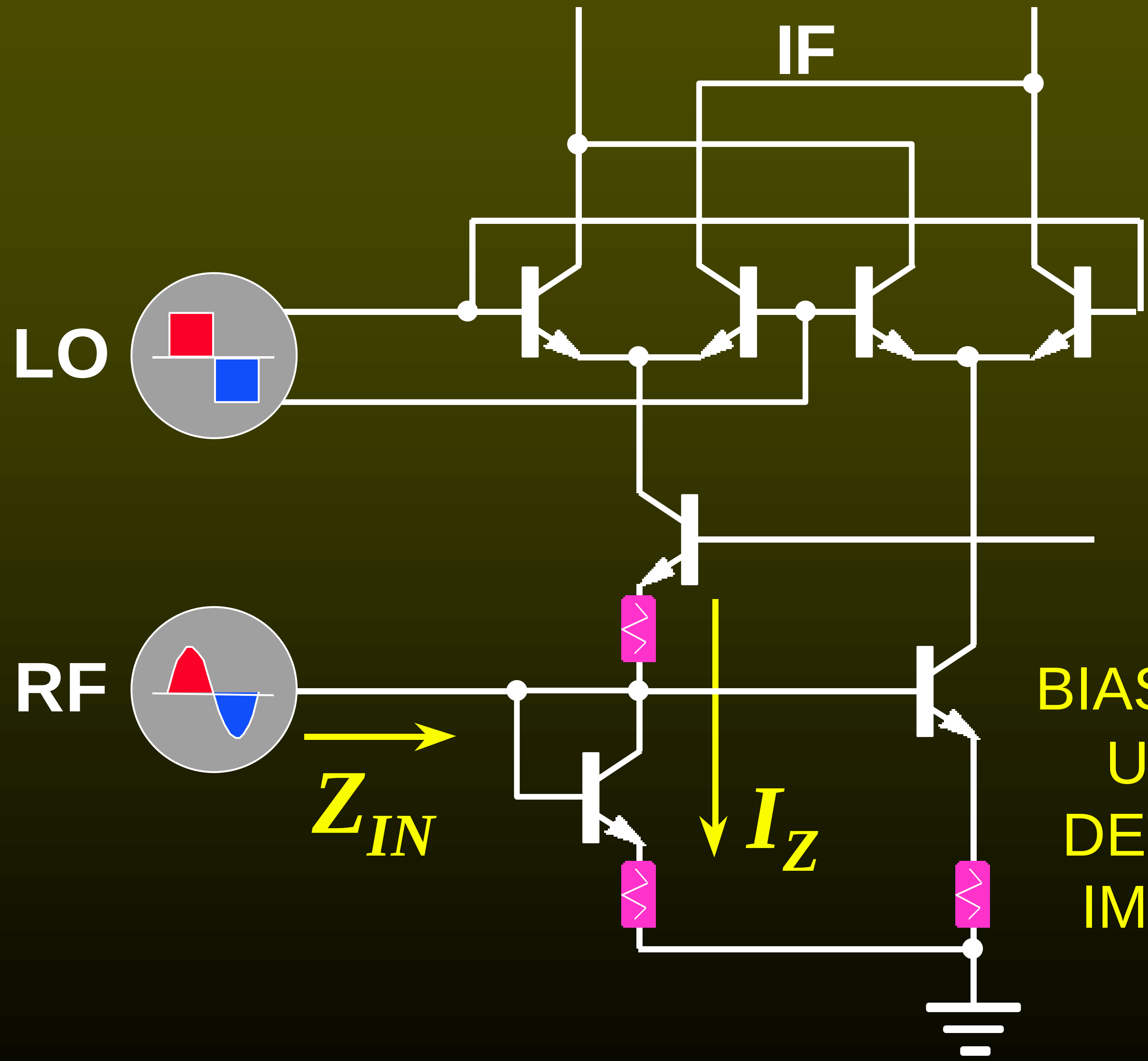


ANALOG DEVICES

MicroMixer

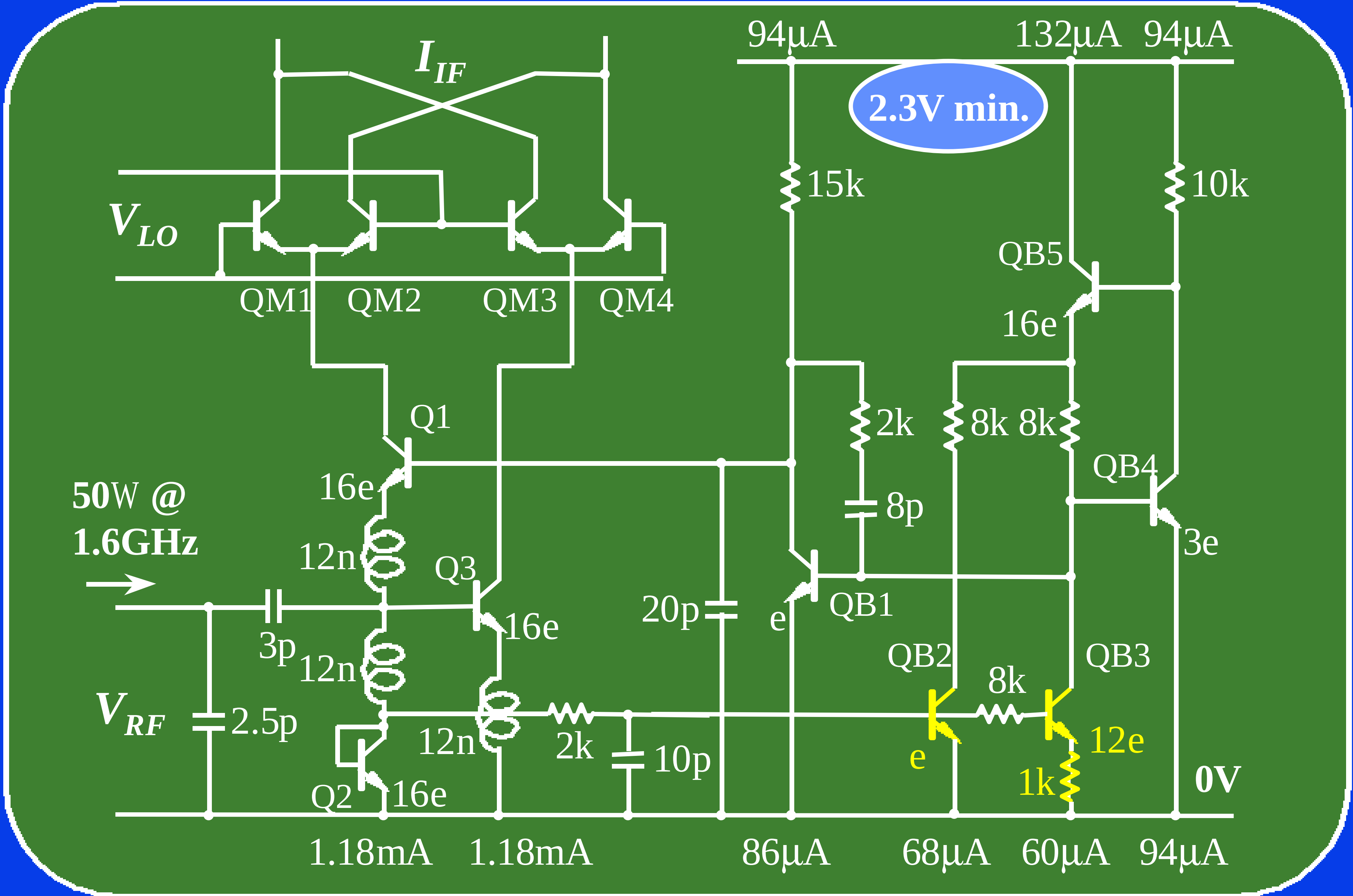


MicroMixer



BIAS CURRENT UNIQUELY DETERMINES IMPEDANCE

L-BAND MICROMIXER



Log-Amps

LOGARITHMIC AMPLIFIERS

ANALOG DEVICES

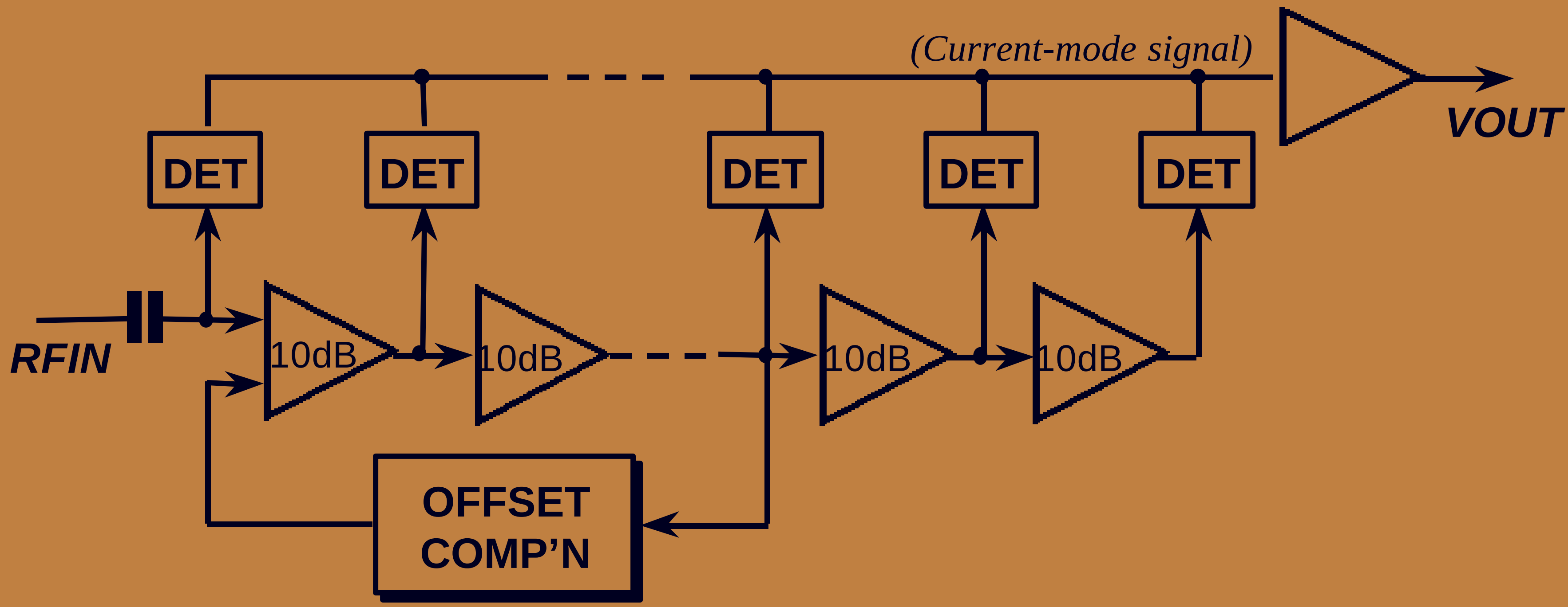
"LOG-AMPS" ARE NONLINEAR CIRCUITS WHICH CONVERT A WIDE-DYNAMIC RANGE SIGNAL ON A DECIBEL SCALE TO A QUASI-DC VOLTAGE OF SMALL RANGE: -70dB to 0dB becomes 0 to 1.4V.

WHEN DESIGNED WITH SUFFICIENT CARE TO PROVIDE CALIBRATED OPERATION, THEY ARE HIGHLY VALUABLE MEASUREMENT DEVICES.

LOGARITHMIC AMPLIFIERS

ANALOG DEVICES

N stages (typically 5-10)



Log-Amp based on Progressive-Compression

LOGARITHMIC AMPLIFIERS

ANALOG DEVICES

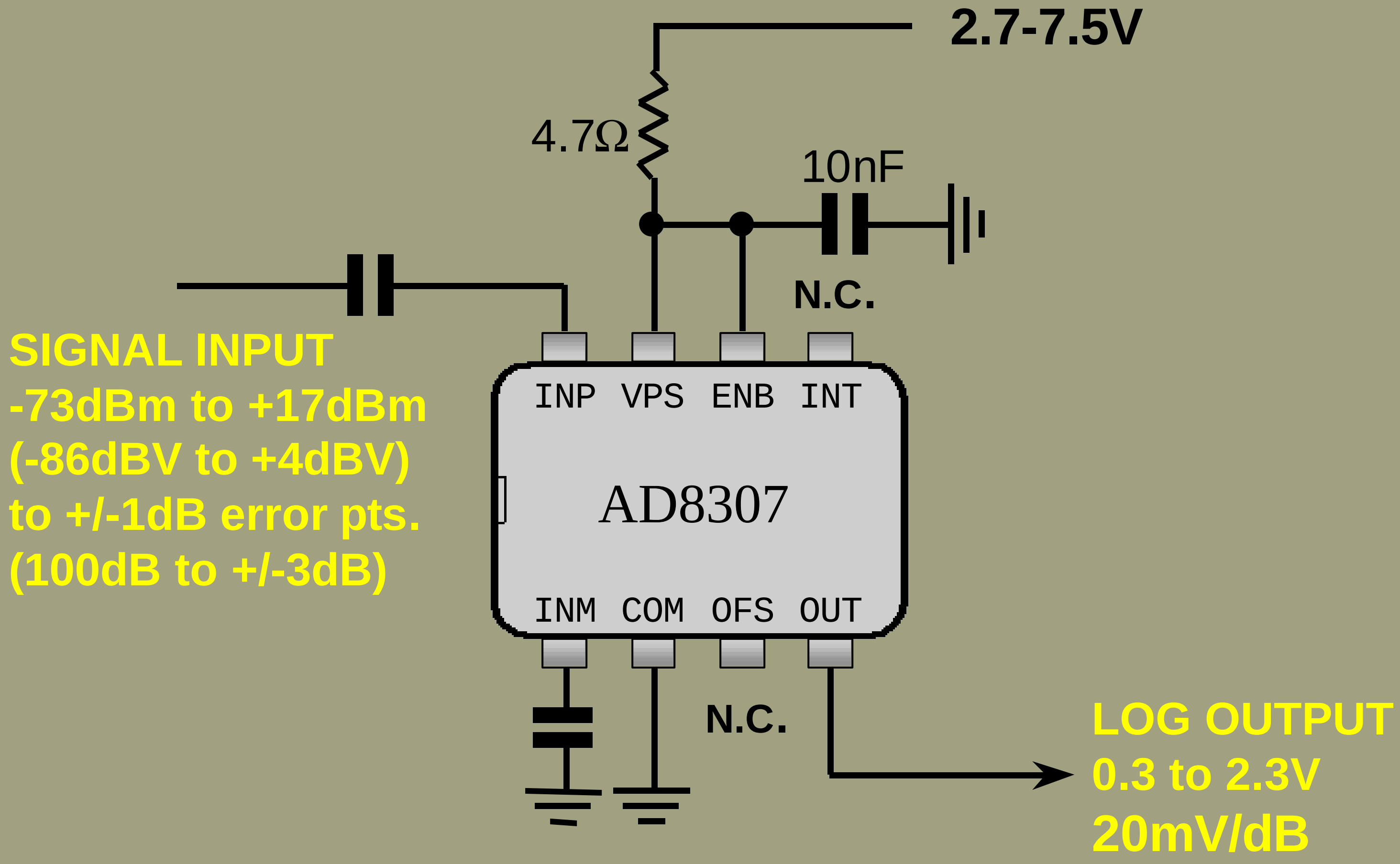
- Unique Nonlinear Function
- Integrated Multistage Systems
- Calibrated Slope and Intercept
- Provide Complete Solutions

  -- easy to use
- Up to 100 dB Dynamic Range
- Covering DC - 3500 MHz
- Limiter Versions for PSK, FSK
- Low Cost, Small Packages

AD606
AD608
AD640
AD641
AD8302
AD8306
AD8307
AD8309
AD8310
AD8313
AD8314
AD8315
AD8316

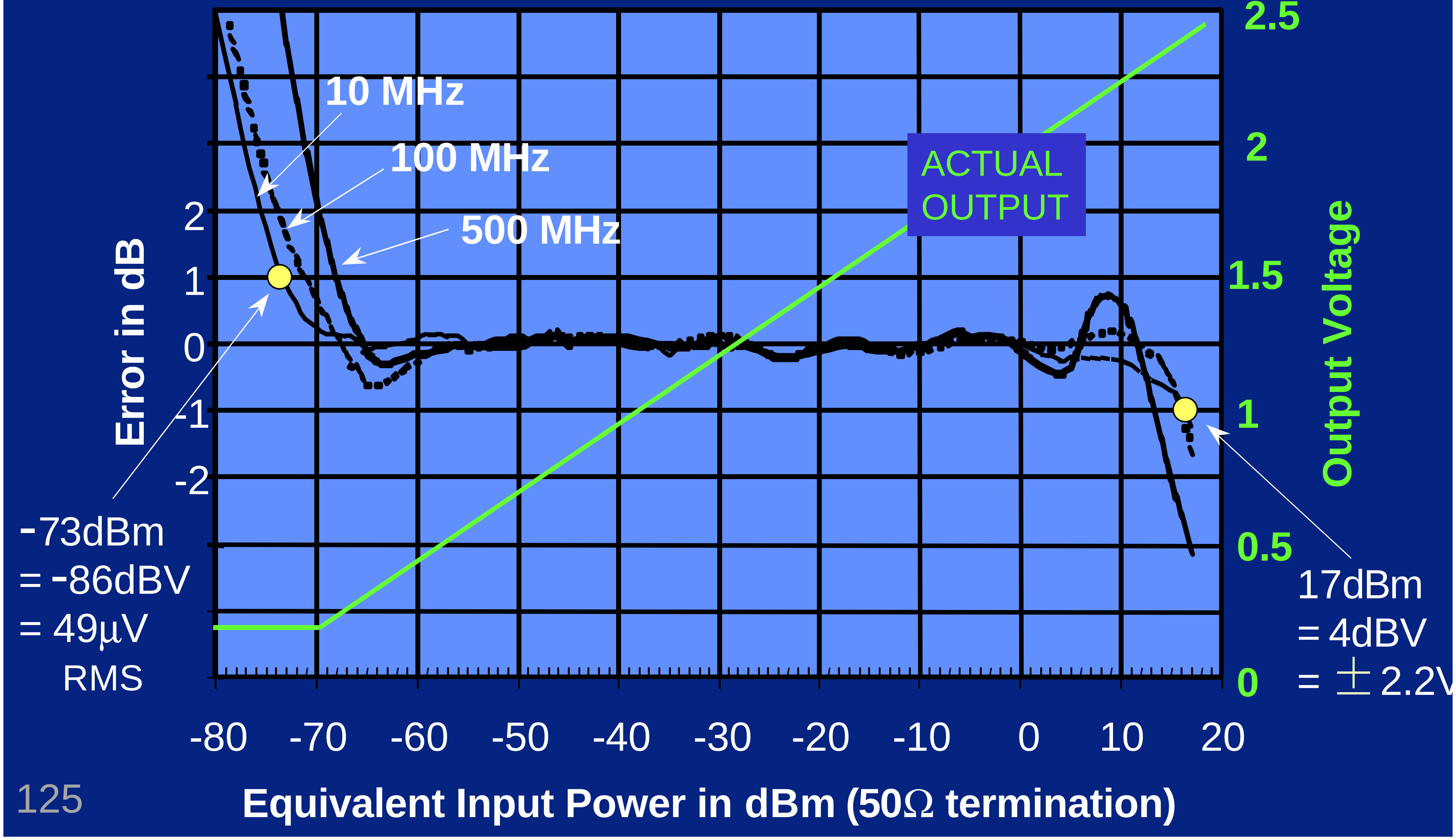
A Personal Goal: Make Log Amps as Cheap, and Easy to Use, as Op Amps

ANALOG DEVICES

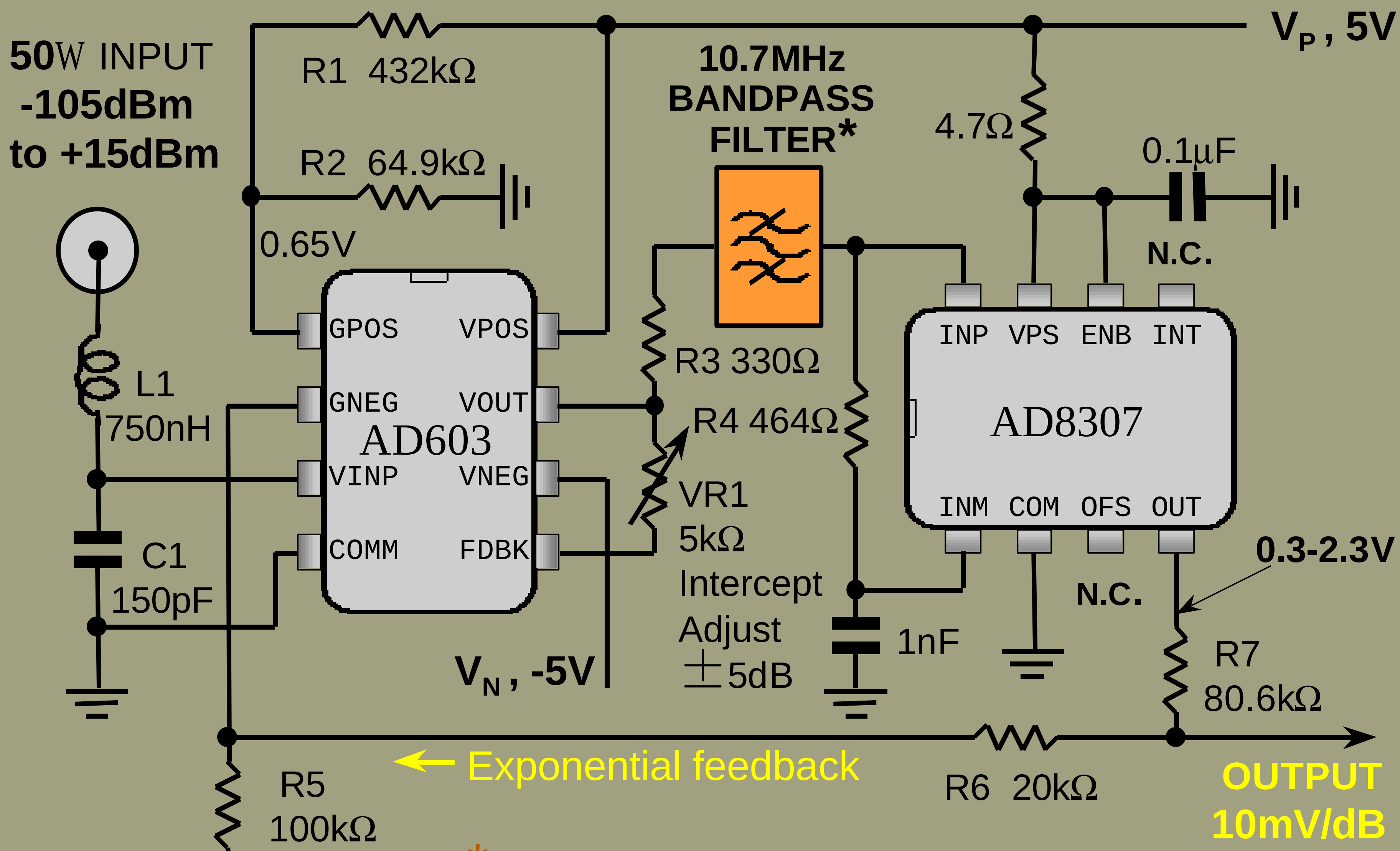


Logarithmic Conformance of AD8307 (AD8310 is similar)

ANALOG DEVICES



120+ dB MEASUREMENT SYSTEM



* E.g., Murata SFE10.7MS2G-A

ANALOG DEVICES

RF Power Detectors

TRUE POWER MEASUREMENT

ANALOG DEVICES

LOGARITHMIC AMPLIFIERS MAY BE USED TO ACCURATELY INDICATE EQUIVALENT POWER IN A CERTAIN SYSTEM IMPEDANCE BUT THEY

DO NOT MEASURE TRUE POWER.

THAT IS, THEY DO NOT RESPOND TO THE

TRUE MEAN-SQUARE

VALUE OF SIGNALS OF ARBITRARY WAVEFORM

TRUE POWER MEASUREMENT

ANALOG DEVICES

A COMPLEX RF SIGNAL

Q: What is the true power

TRUE POWER MEASUREMENT

ANALOG DEVICES

THE ACCURATE MEASUREMENT OF THE

ROOT-MEAN-SQUARE (RMS)

VALUE OF SIGNAL OF ARBITRARY WAVEFORM CAN BE ACHIEVED IN TWO WAYS:

- THERMAL DETECTORS
- ANALOG COMPUTATION

TRUE POWER MEASUREMENT

ANALOG DEVICES

- THERMAL DETECTORS
  - Fundamentally correct
  - Very slow - milliseconds
  - Small dynamic range
  - Difficult to integrate
    - need MEM structures

TRUE POWER MEASUREMENT

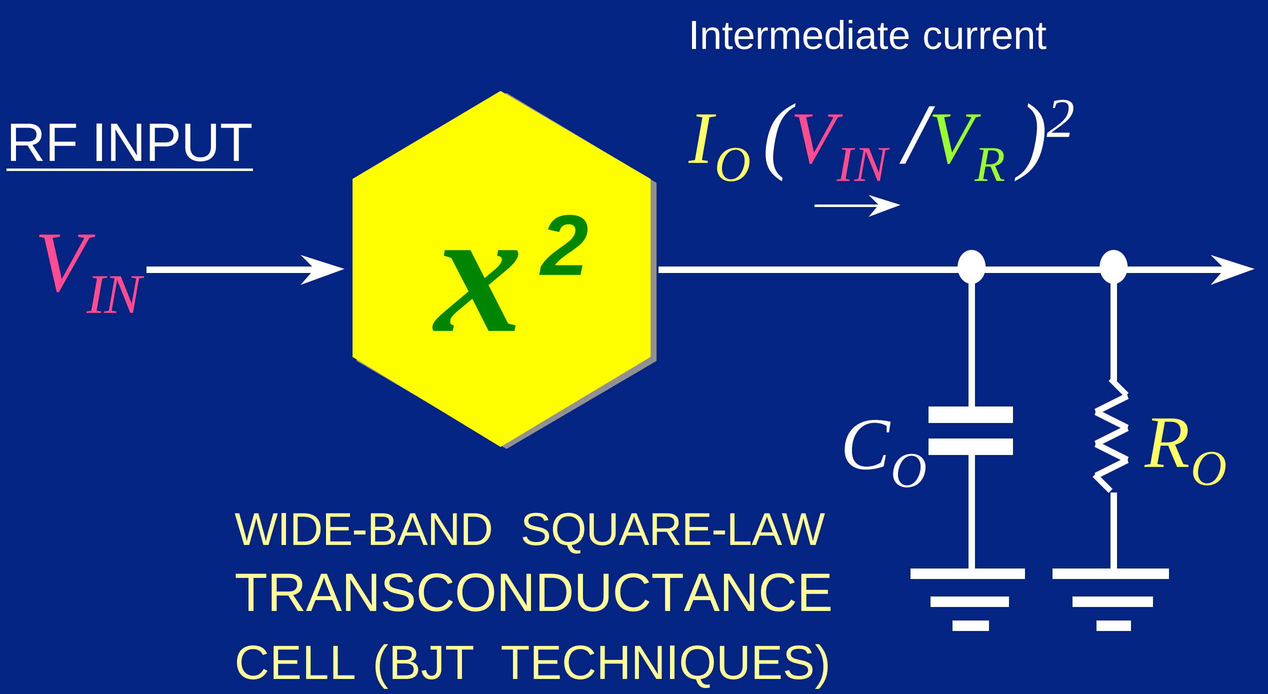
ANALOG DEVICES

ANALOG COMPUTATION

- Very accurate with good design
- Can have large dynamic range
  - 30dB for direct squaring
  - up to 100dB using new methods
- Output can be linear-in-dB
- Low Voltage and Power (<10mW)
  - with chip enable

A BASIC METHOD

ANALOG DEVICES



$$V_{OUT} = \text{AVE}\left[\frac{\{V_{IN}\}^2}{V_O}\right]$$

where

$$V_O = V_R^2/I_O R_O$$

This simple structure produces the Mean-Square of V_{IN} with an averaging time determined by the product $C_O R_O$

A BASIC METHOD

ANALOG DEVICES

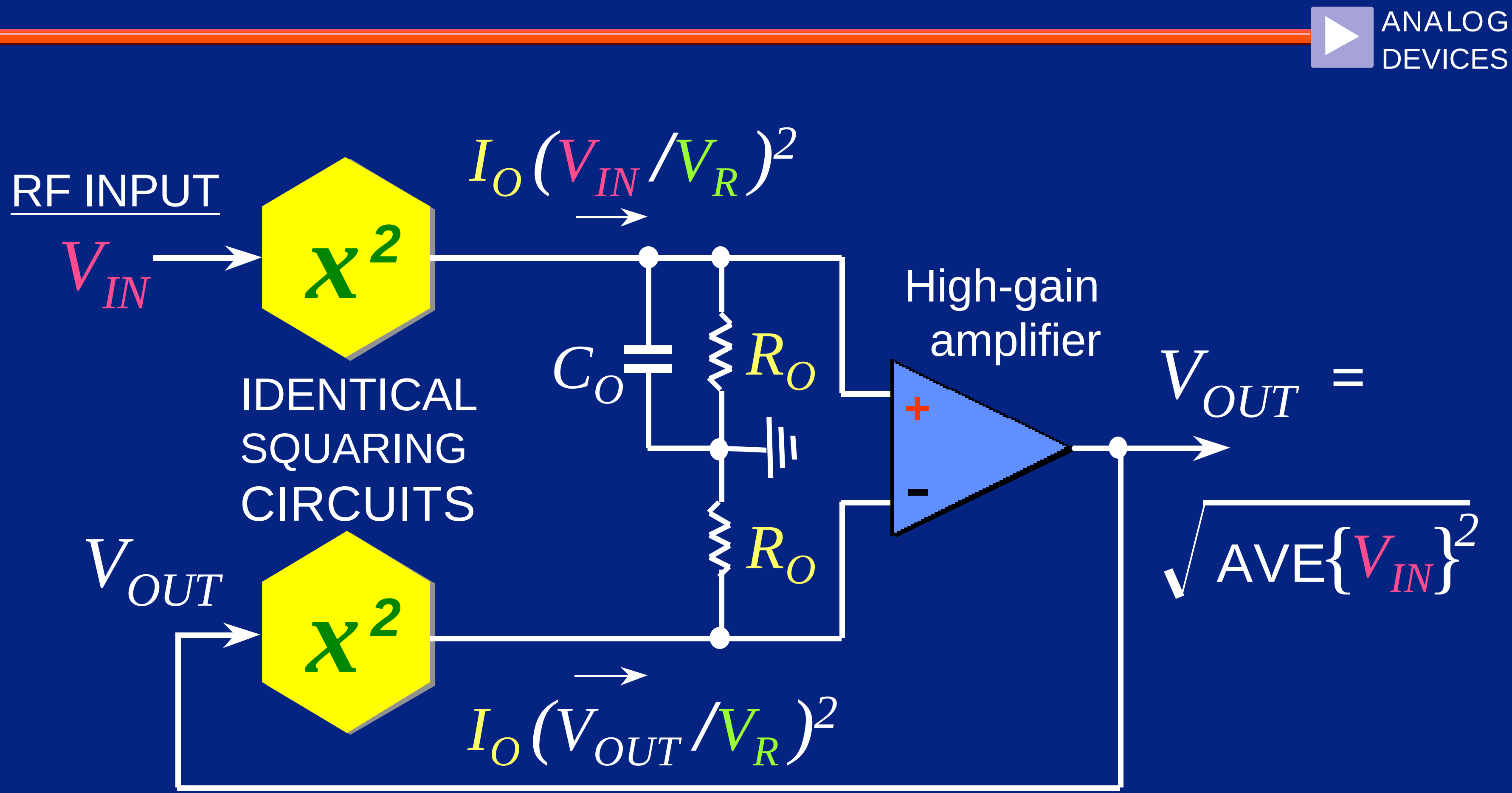
ADVANTAGES

- Very simple cell design
- Can fit into a 1.5V supply
- Wideband -- to >6GHz

DISADVANTAGES

- Low dynamic range capacity
- Higher dynamic range of output
- Complicated scaling mechanisms

DIFFERENCE-OF-SQUARES



Directly produces the Root-Mean-Square of V_{IN} with an averaging time determined by the product $C_O R_O$

DIFFERENCE-OF-SQUARES

ANALOG DEVICES

- ADVANTAGES
  - Still a very simple design
  - No change in bandwidth
  - Computes RMS directly
    -- scaling of cells cancel
  - High output drive capacity

- DISADVANTAGE
  - Still a low dynamic range capacity

AD8361

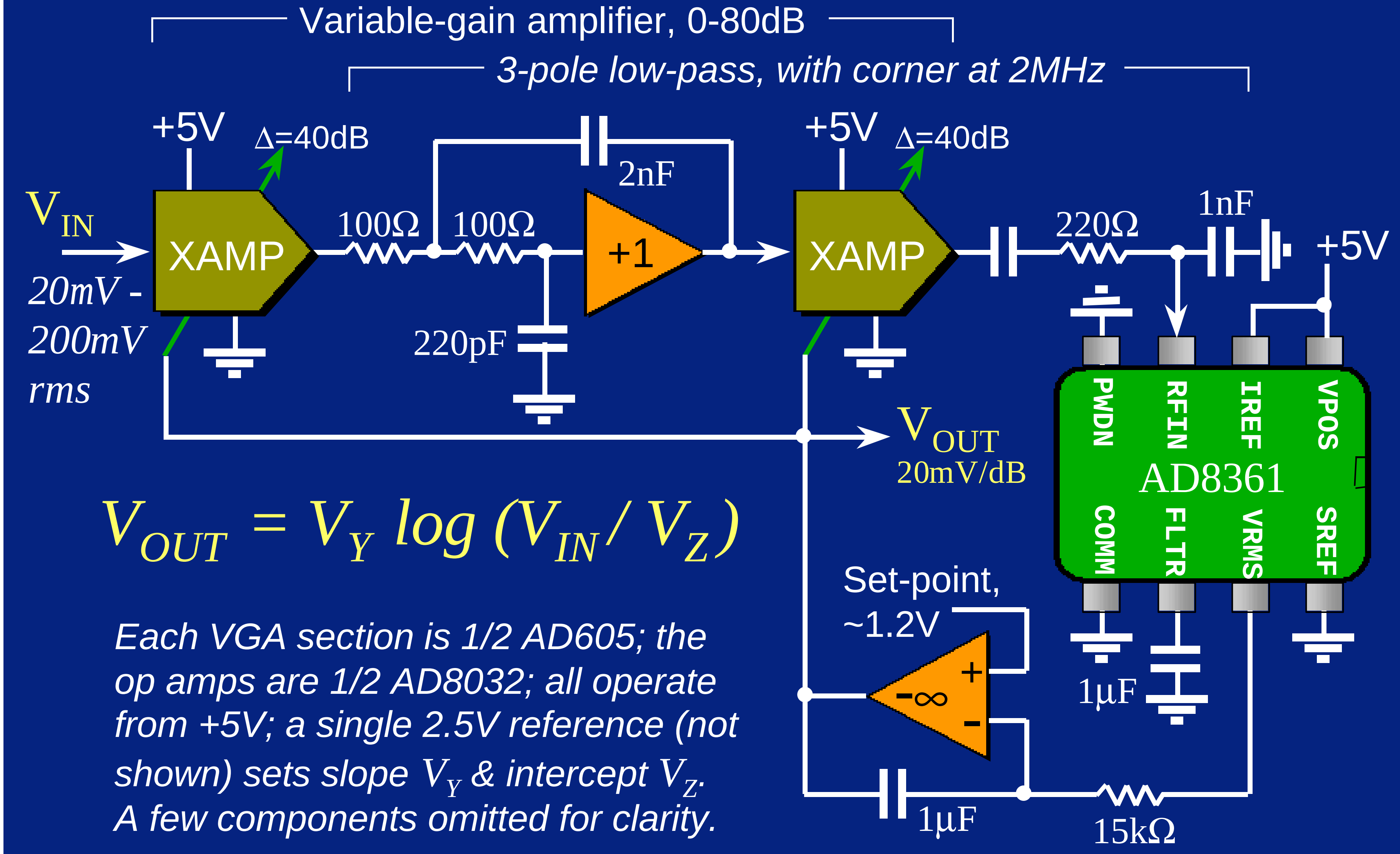
ANALOG DEVICES

A COMPLETE IC POWER DETECTOR

- Uses a different squaring cell design
- About the same bandwidth (>3GHz)
  - -- limited mostly by package
- Basically unlimited signal range
  - -- due to Class AB operation
- Precisely-defined input impedance
- Can provide over 30dB dynamic range
- Only 6mW quiescent consumption

80dB Log-RMS Voltmeter

ANALOG DEVICES



$$V_{OUT} = V_Y \log (V_{IN} / V_Z)$$

Each VGA section is 1/2 AD605; the op amps are 1/2 AD8032; all operate from +5V; a single 2.5V reference (not shown) sets slope V_Y & intercept V_Z. A few components omitted for clarity.

A Network Analyzer on a Chip

GAIN-PHASE DETECTOR

ANALOG DEVICES

- A Network Analyzer on a Chip! - Almost!

$$\mathbf{V_{GAIN} = V_G}\ \boldsymbol{log}\ \mathbf{(V_A/V_B)} \qquad V_G = 30\text{mV/dB}$$

$$\mathbf{V_{PHS} = V_P\,(\mathit{f}_1 - \mathit{f}_2)} \qquad V_P = 10\text{mV/}\mathit{deg}$$

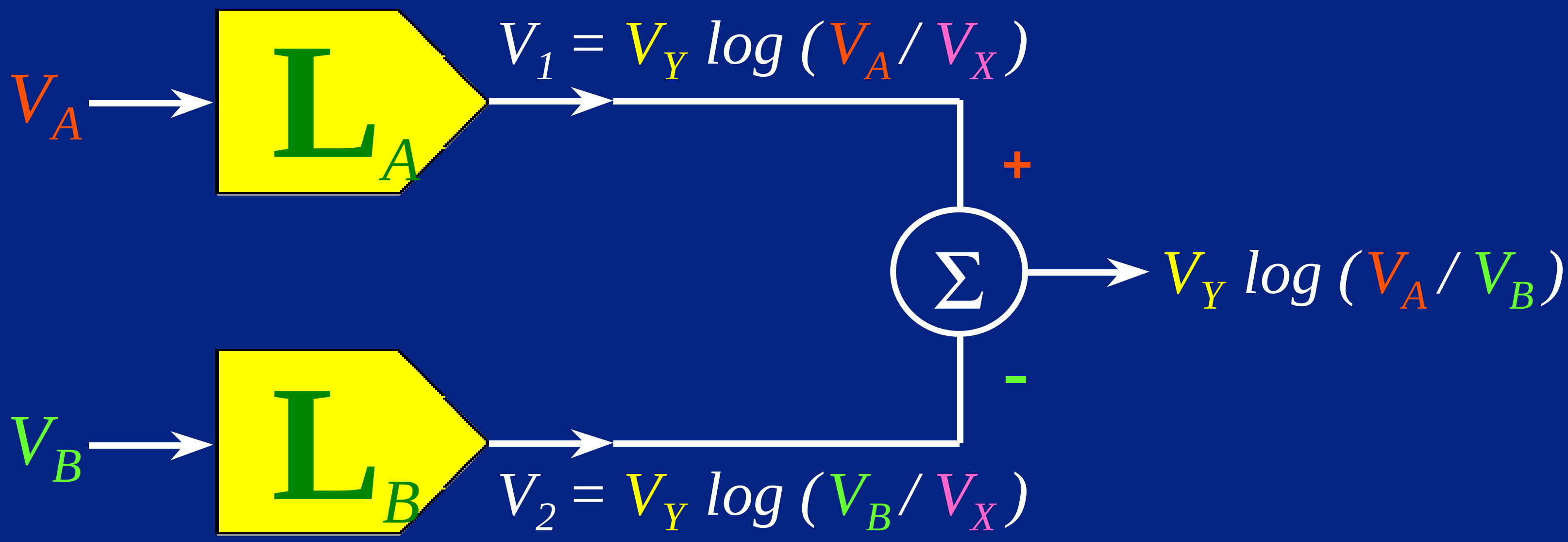
- Operates from LF to >3 GHz

Applications

- Power Amplifier Phase/Gain Control
  .... independent of actual power level
- Monitoring of System Gain/Loss (e.g. Return Loss)
- System Diagnostics
- Linear Phase Demodulator

TRUE GAIN MEASUREMENT

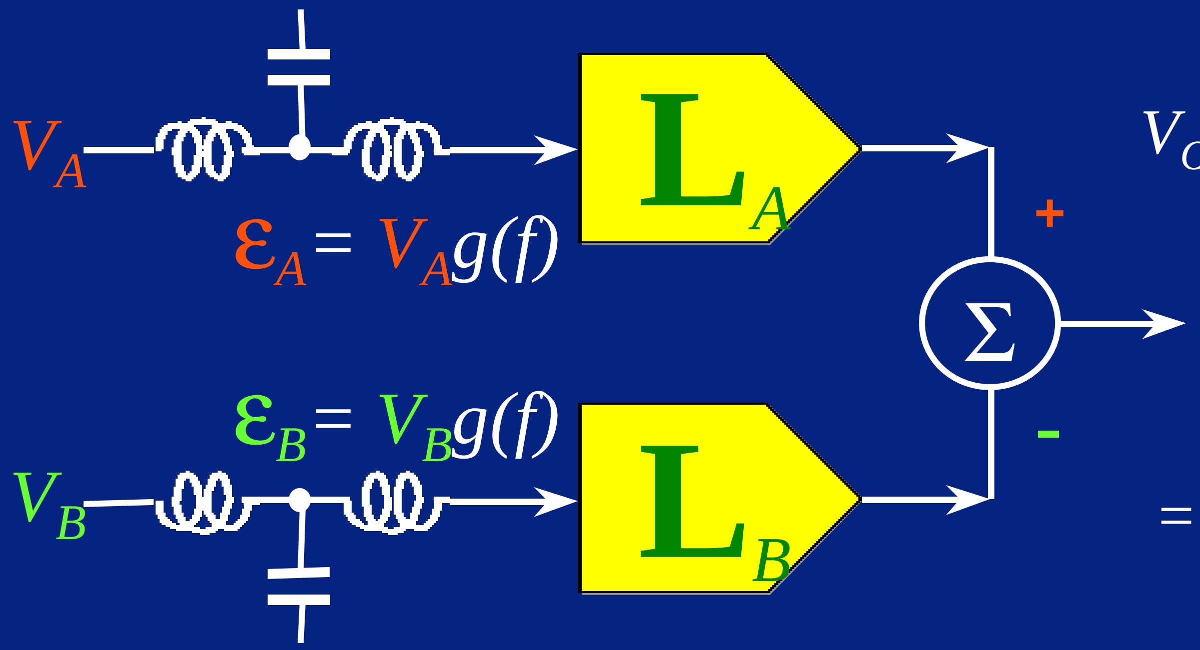
ANALOG DEVICES



By subtracting the output of the B-channel log-amp from that of the A-channel log-amp, the intercept V_X is eliminated and the resulting difference is a measure of the RATIO of V_A / V_B

CANCELS PACKAGE RESONANCES

ANALOG DEVICES



$$V_{OUT} = V_Y \log \frac{\varepsilon_A}{\varepsilon_B}$$

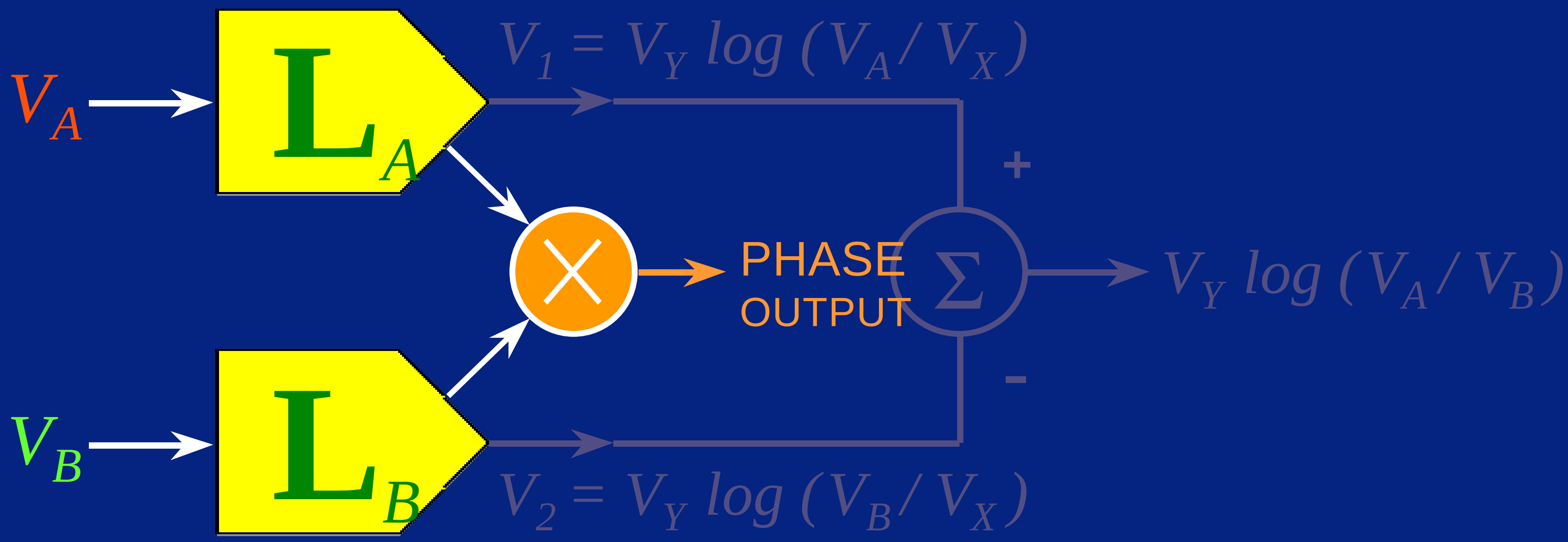
$$= V_Y \log \frac{V_A g(f)}{V_B g(f)}$$

$$= V_Y \log \frac{V_A}{V_B}$$

Both channels have the same HF resonances and other HF transmission effects g(f), but these are canceled in taking the difference which remains a measure of the RATIO of V_A / V_B

PHASE MEASUREMENT at 2.5GHz

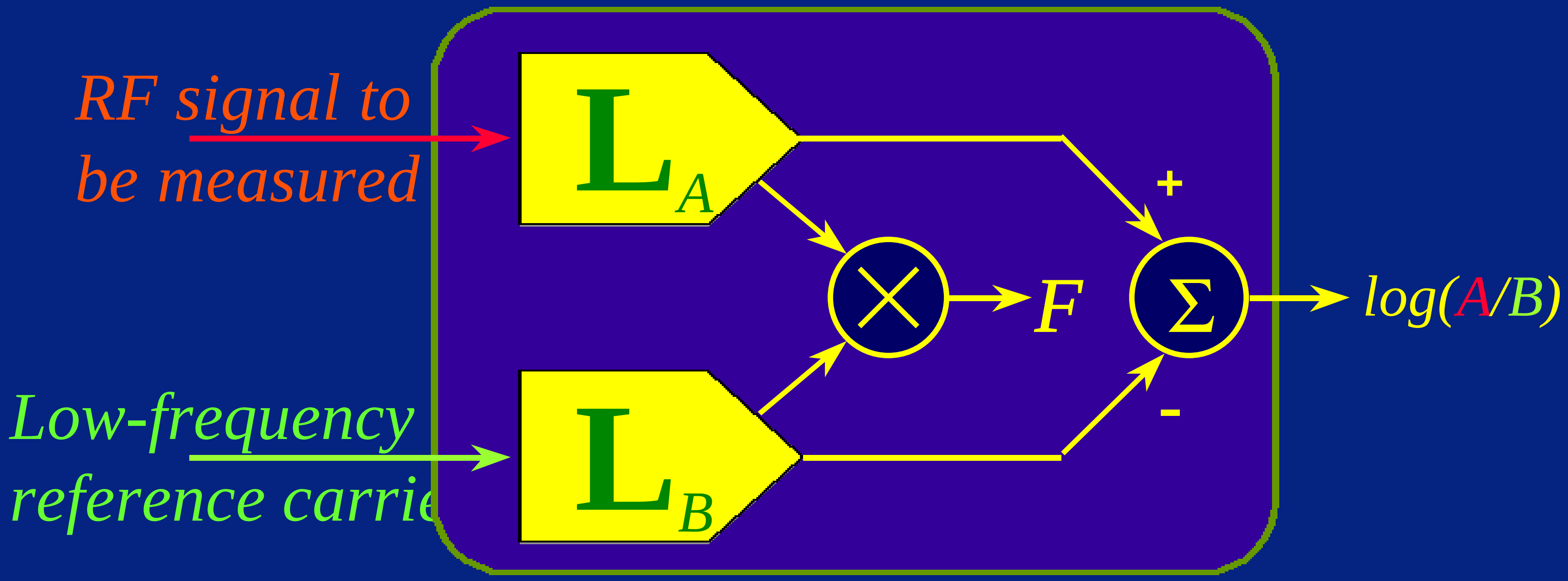
ANALOG DEVICES



Logarithmic amplifiers also provide very high gain and limiting action: using a special type of analog multiplier between the limiter outputs, phase measurements can be made at 3GHz

APPLICATIONS

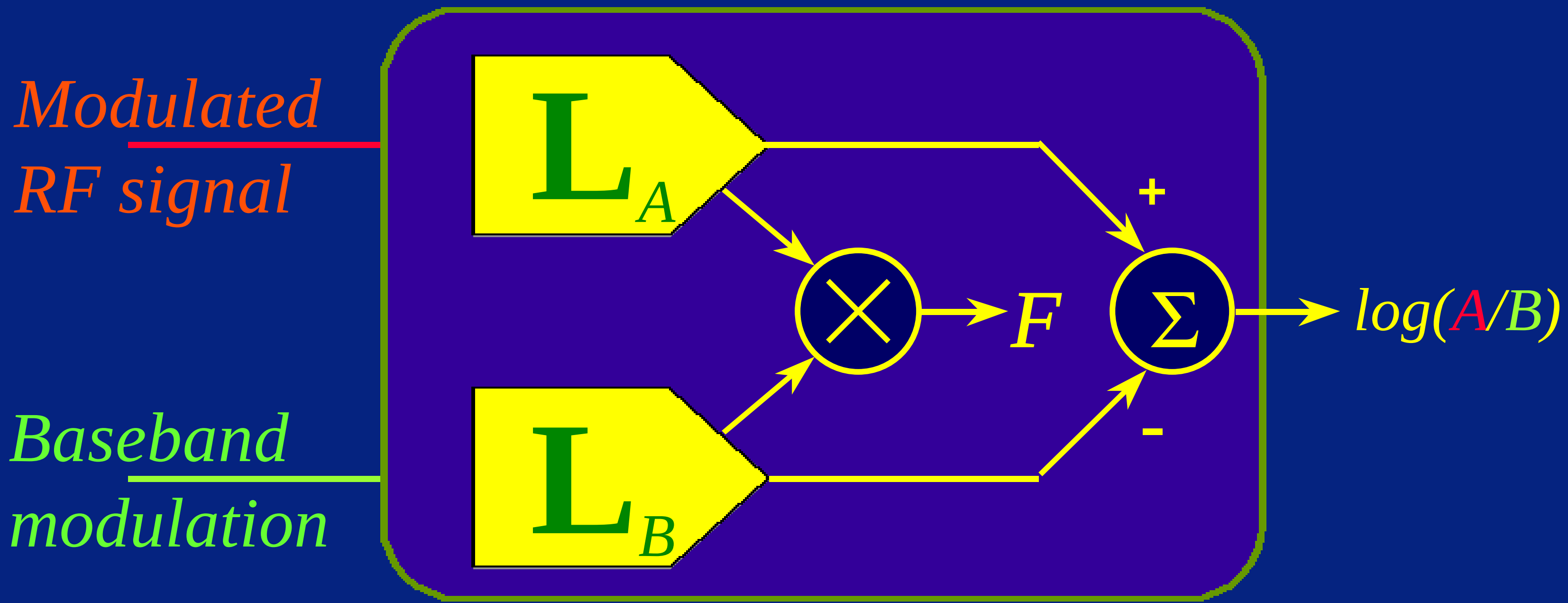
ANALOG DEVICES



In this case, a low-frequency carrier provides a very high calibration reference for the intercept

APPLICATIONS

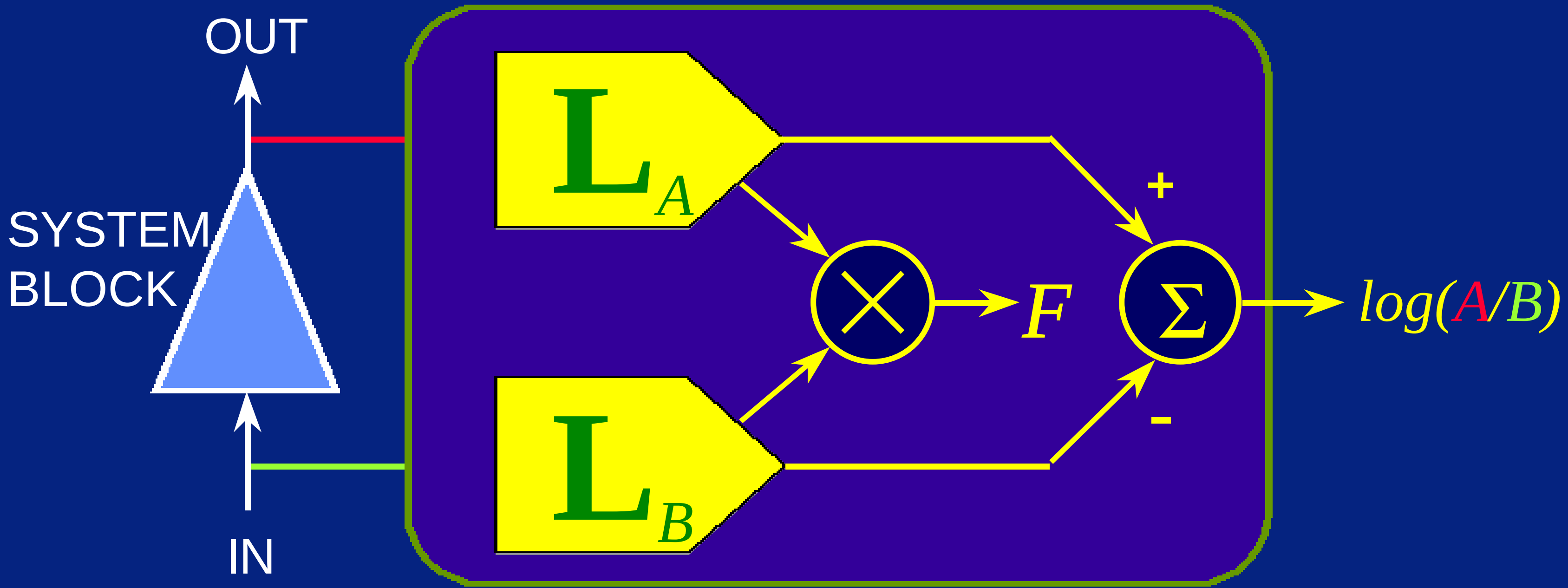
ANALOG DEVICES



Here, the reference is provided by the baseband modulation & system measures conversion gain

APPLICATIONS

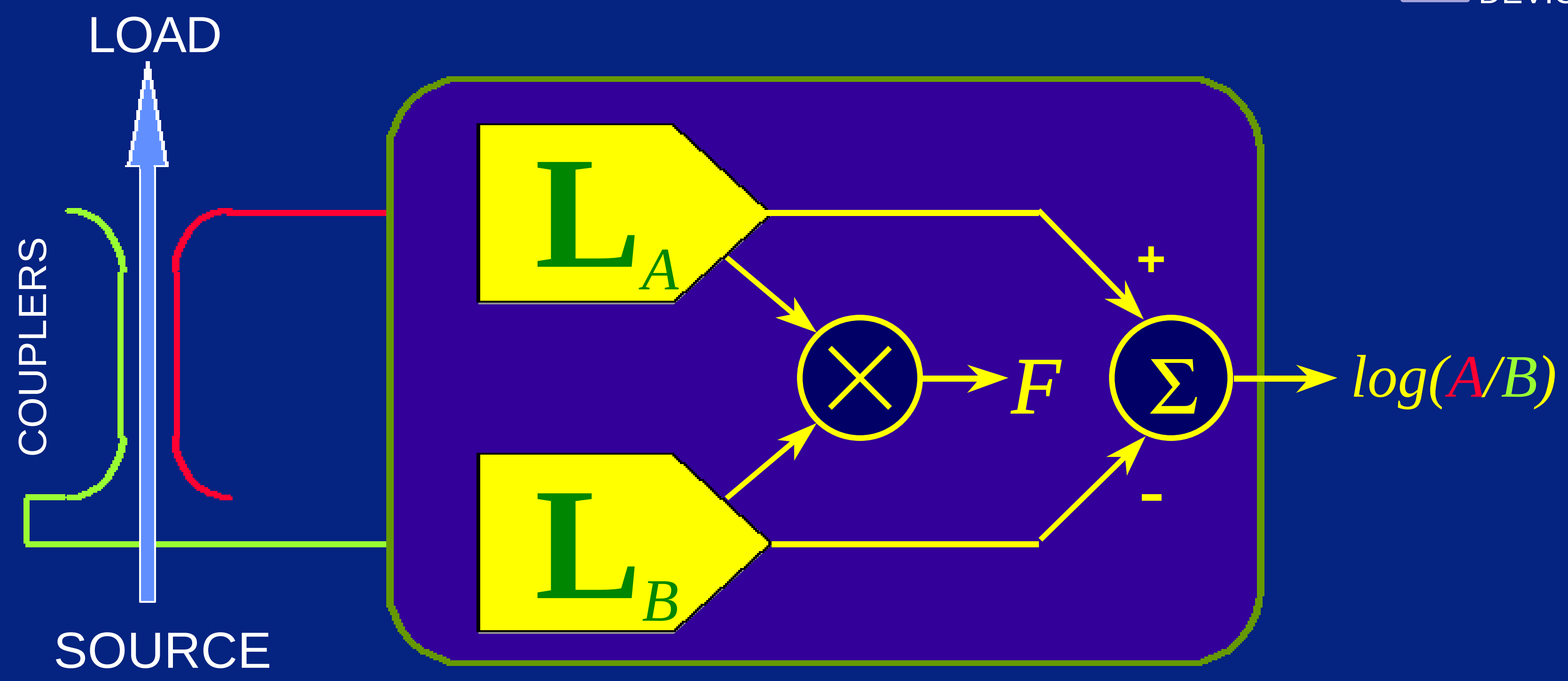
ANALOG DEVICES



True gain of system block is measured independent of the actual power levels

APPLICATIONS

ANALOG DEVICES



Measurement of return loss
independent of power level

The X-AMP

The X-AMP™

ANALOG DEVICES

- A PROPRIETARY VGA PRINCIPLE
- FUNDAMENTALLY “LINEAR-in-dB”
- USES FEEDBACK IN ORDER TO:

  ACCURATELY DETERMINE GAIN

  MINIMIZE HF NONLINEARITIES
- GUARANTEES ULTRA-LOW NOISE
- EXHIBITS WIDE DYNAMIC RANGE

  FROM NOISE FLOOR (0.7mV RMS)

  TO TYPICALLY 1.4V RMS (106dB)

X-AMP PRODUCTS

ANALOG DEVICES

- AD600 & AD602 (BOTH DUAL-VGAs)
  DEVELOPED FOR ULTRASOUND

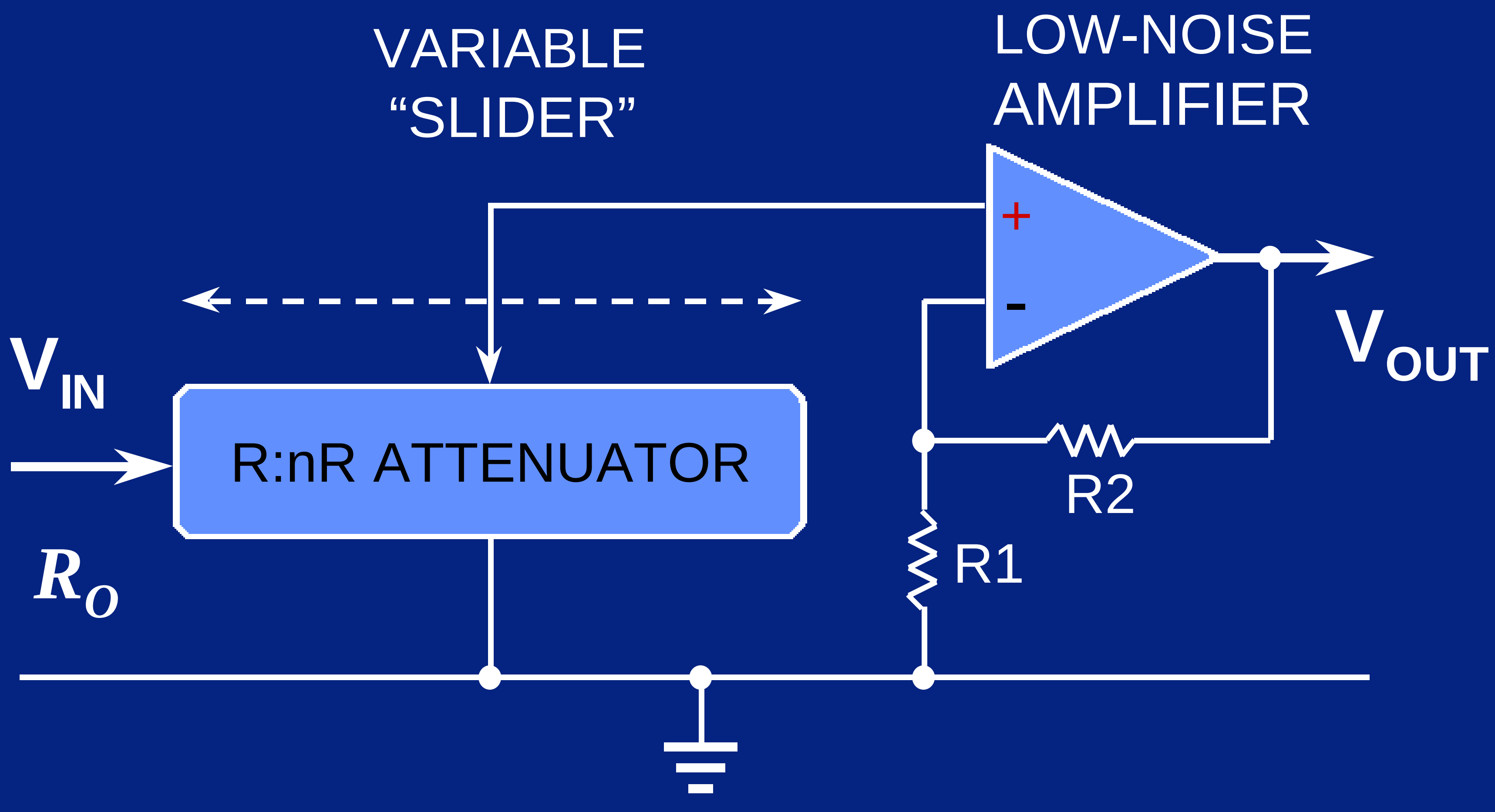
- AD603 (8-PIN, SINGLE)
  -10/30dB AND 20/50dB RANGES
  BEING WIDELY USED IN IF STRIPS

- AD604 & AD605 (SINGLE-SUPPLY DUALS)
  PRE-AMP PROVIDES A HIGH Z_{IN}

- NEW X-AMPs IN DEVELOPMENT

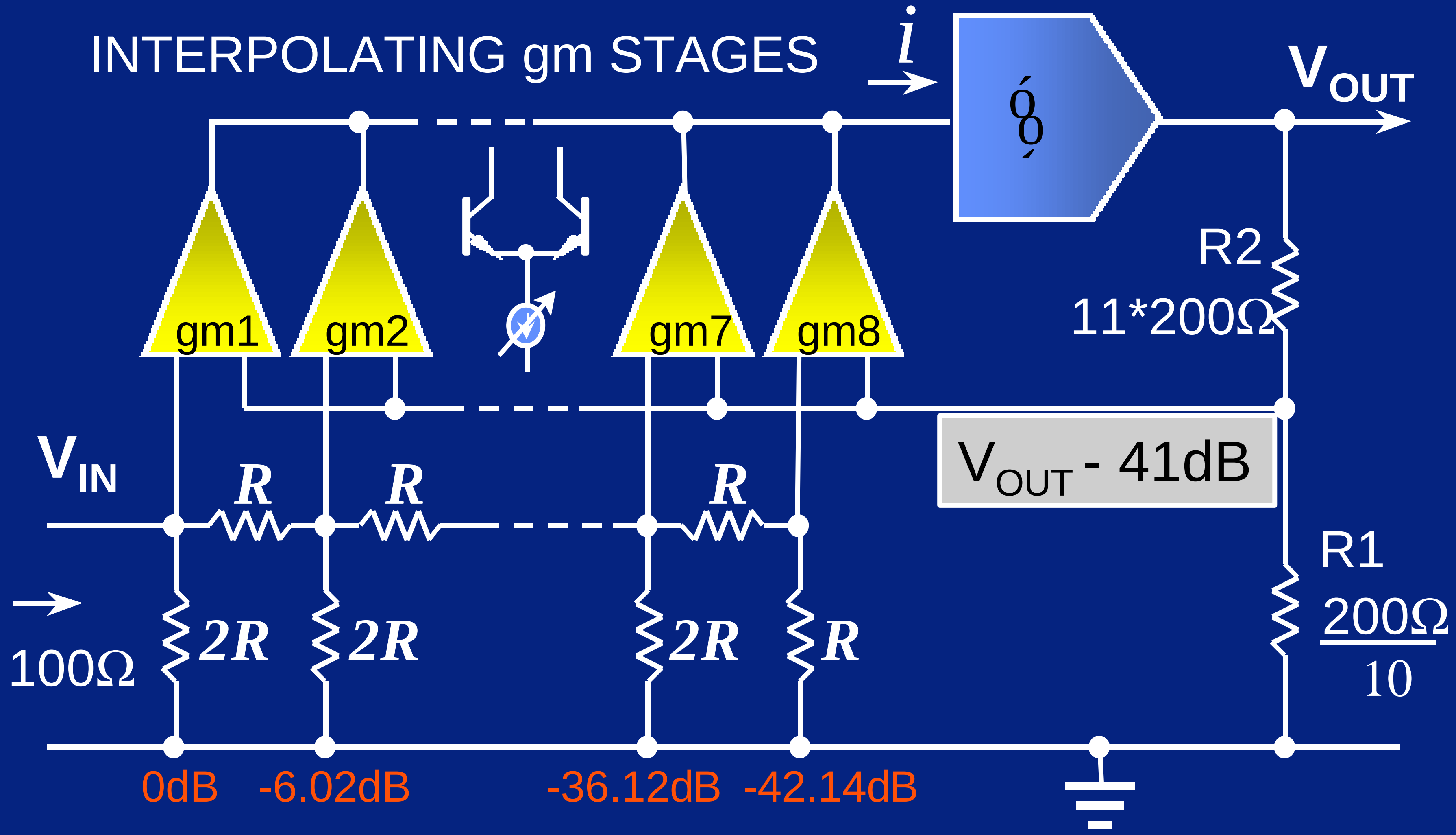
THE BASIC X-AMP

ANALOG DEVICES

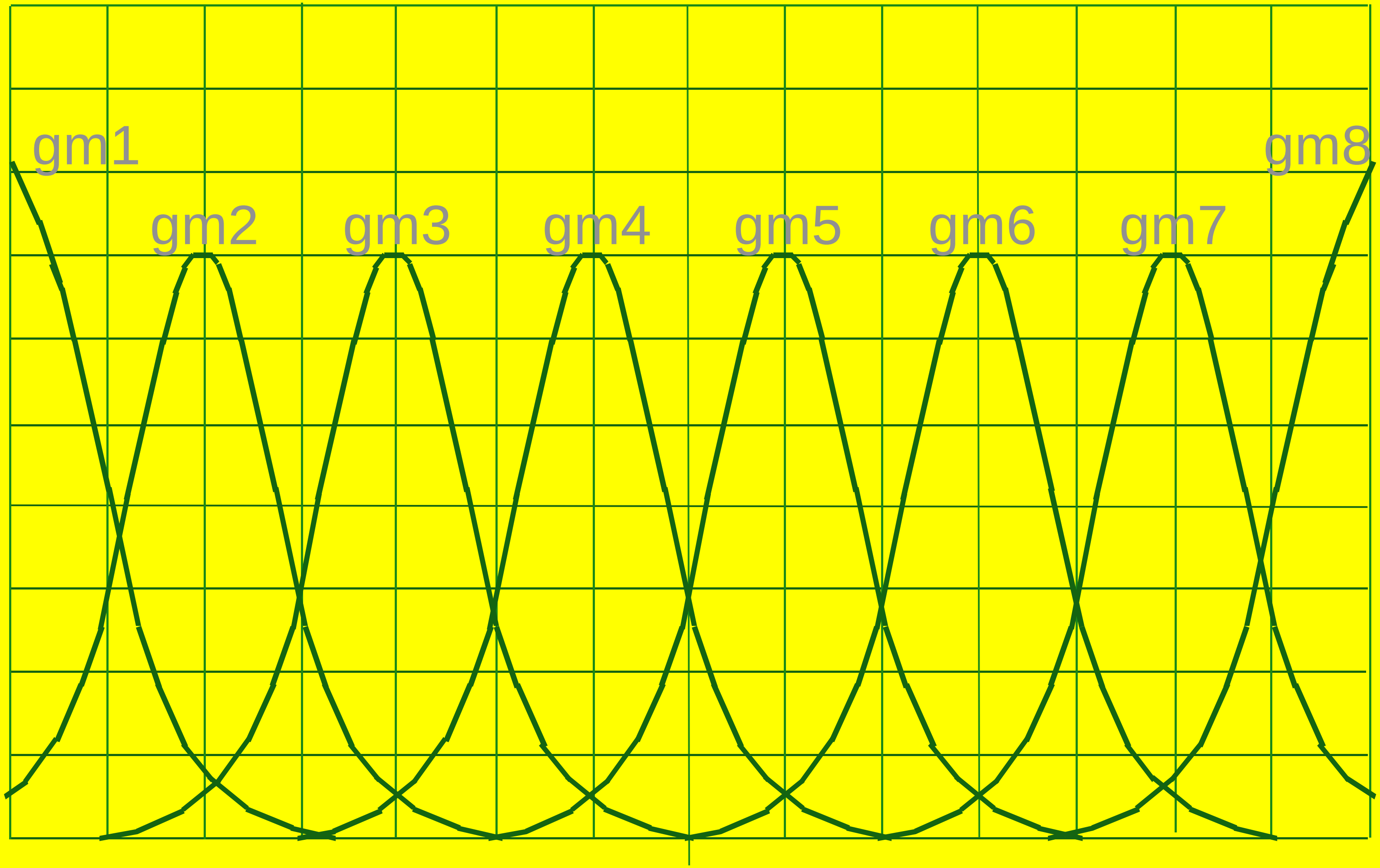


TYPICAL 8-STAGE X-AMP

ANALOG DEVICES



CURRENTS IN THE gm STAGES



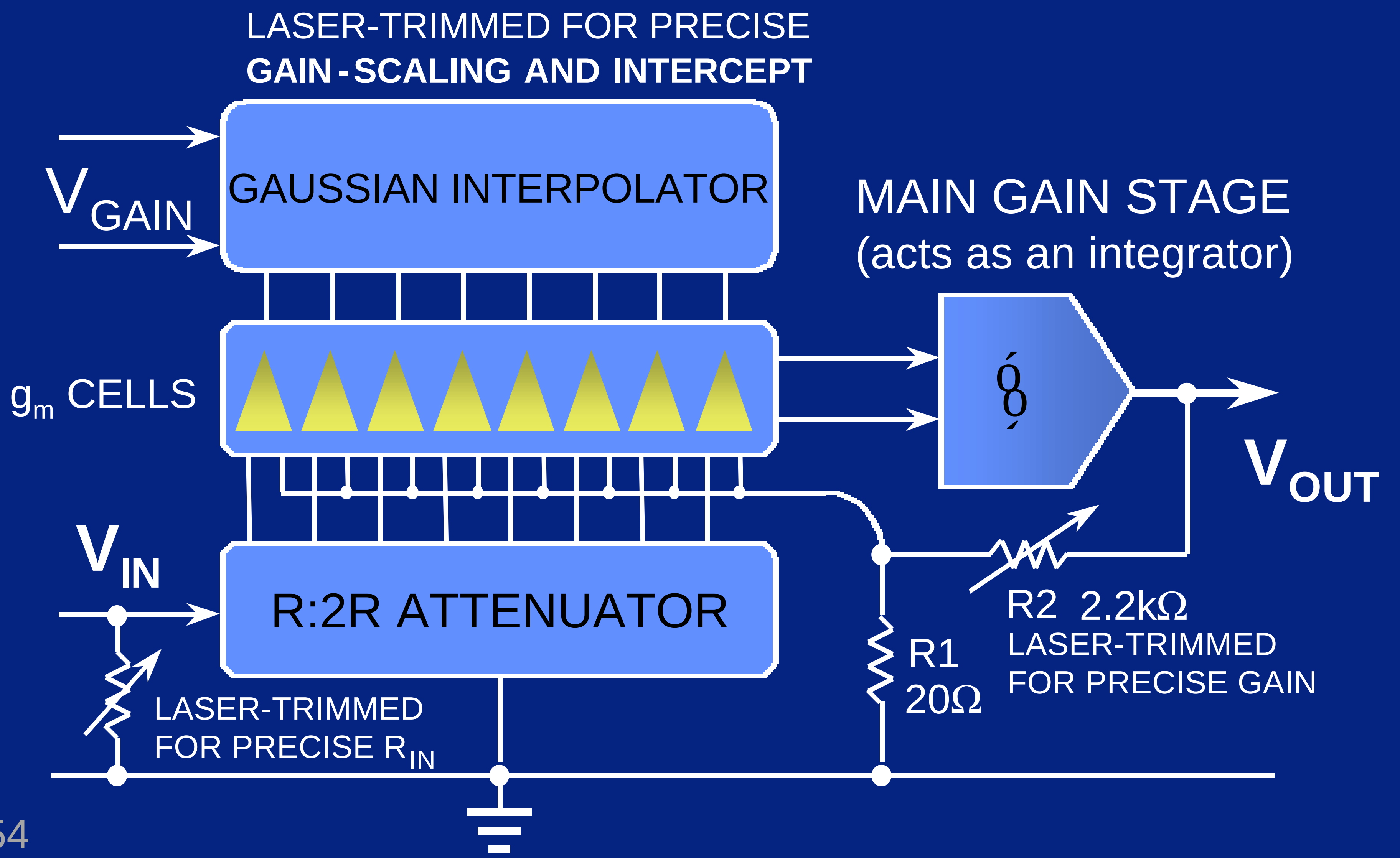
INCREASING GAIN

(MOVES ACTION TOWARDS FRONT)

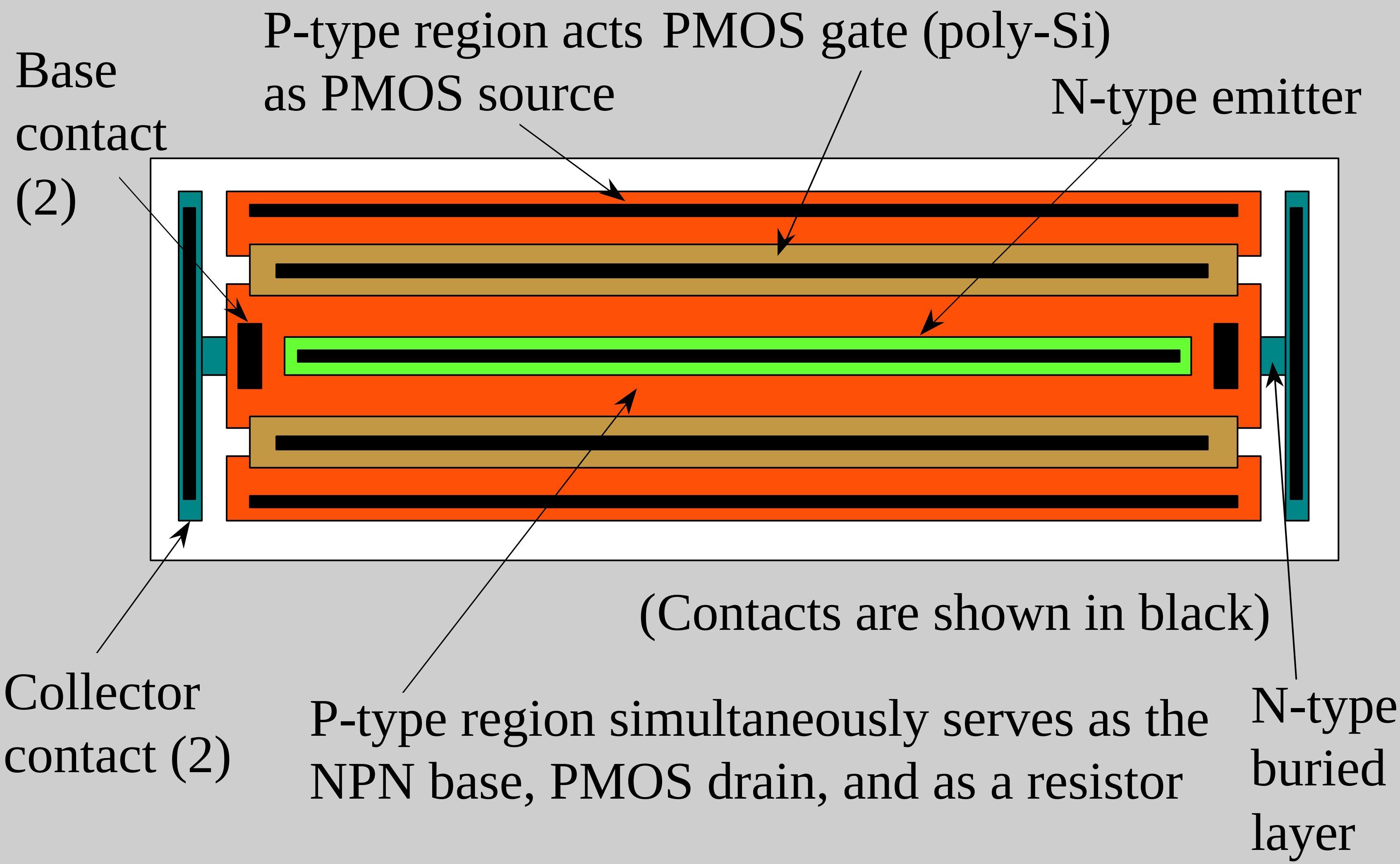
ANALOG DEVICES

MORE COMPLETE X-AMP

ANALOG DEVICES

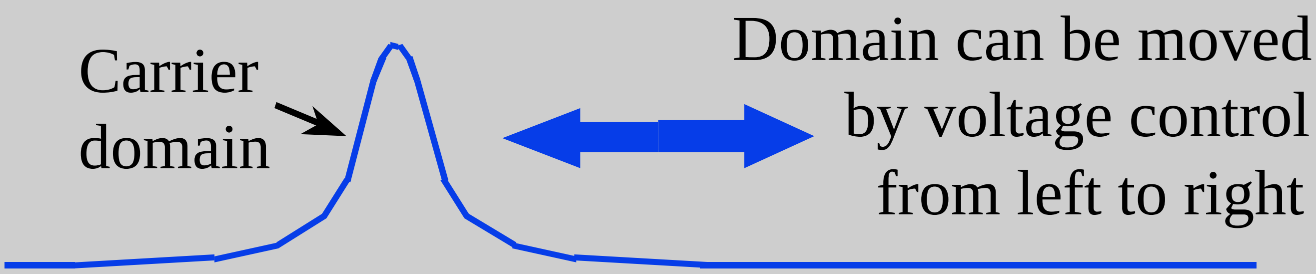


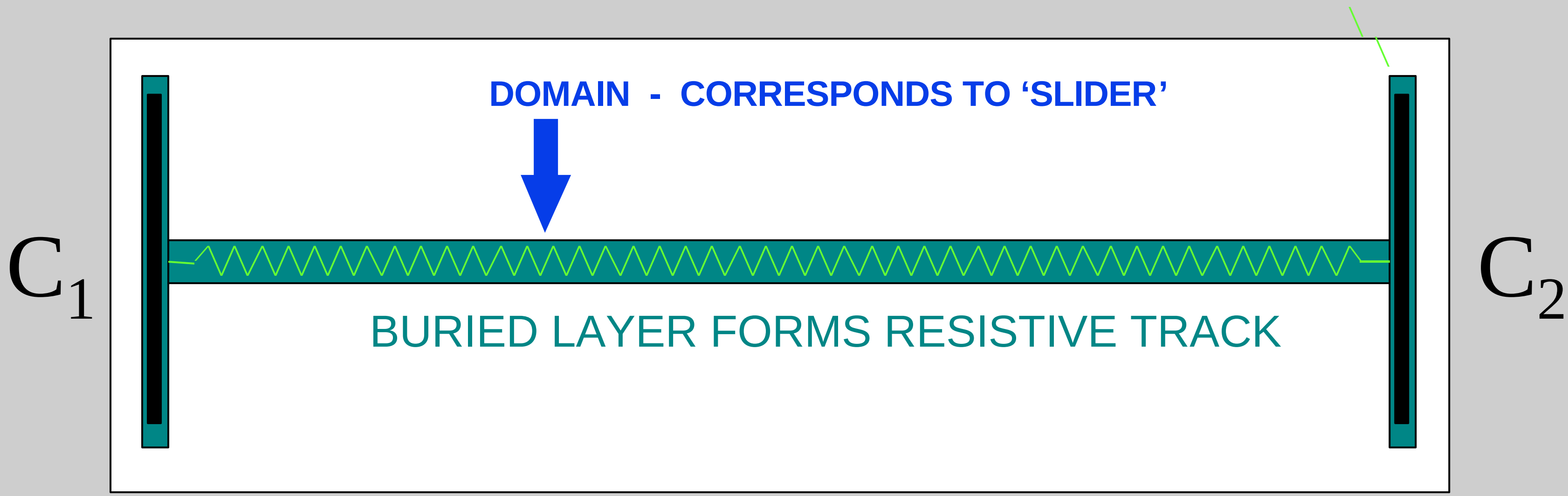
SOLID-STATE POTENTIOMETER



SOLID-STATE POTENTIOMETER

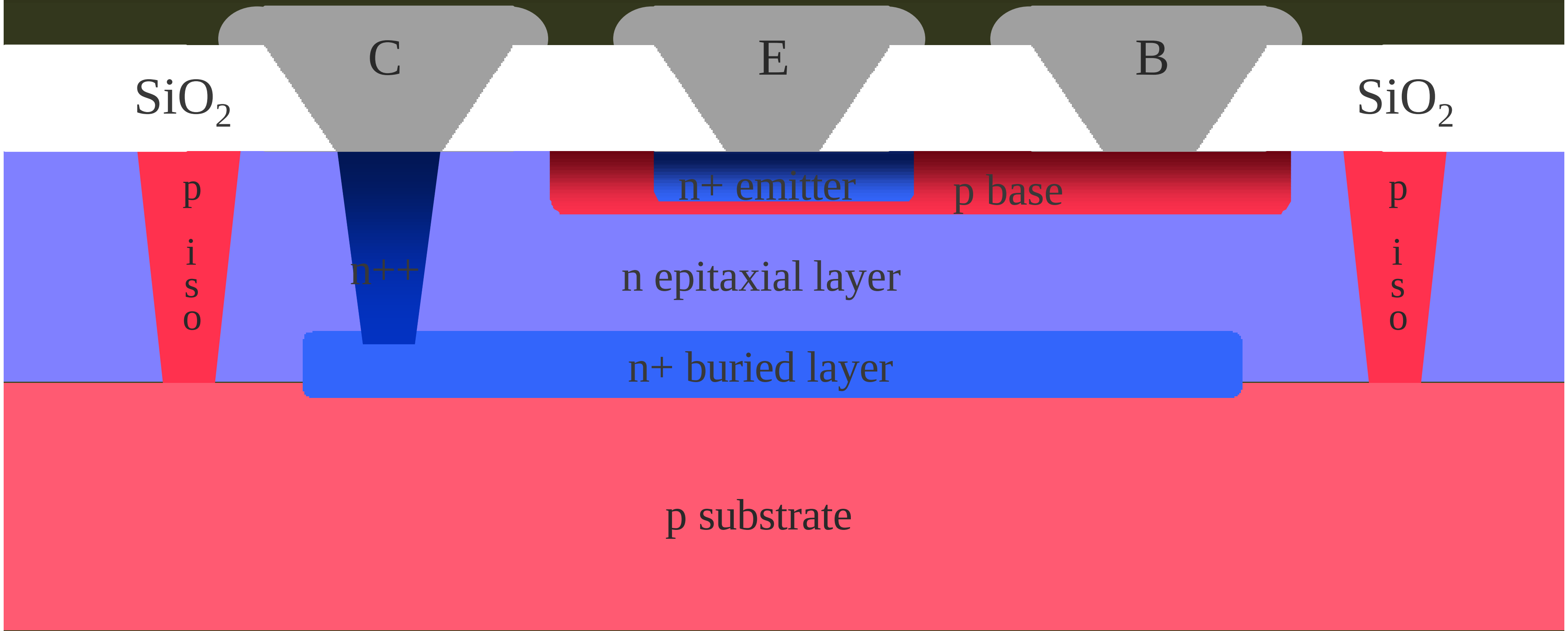
ANALOG DEVICES





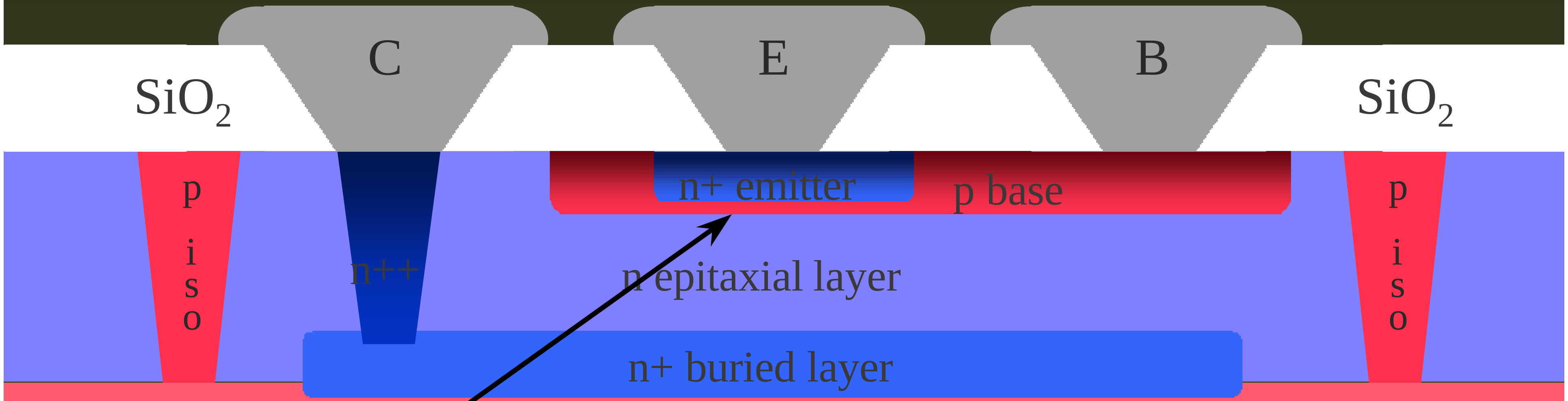
Why SiGe?

PLANAR NPN TRANSISTOR



ANALOG DEVICES

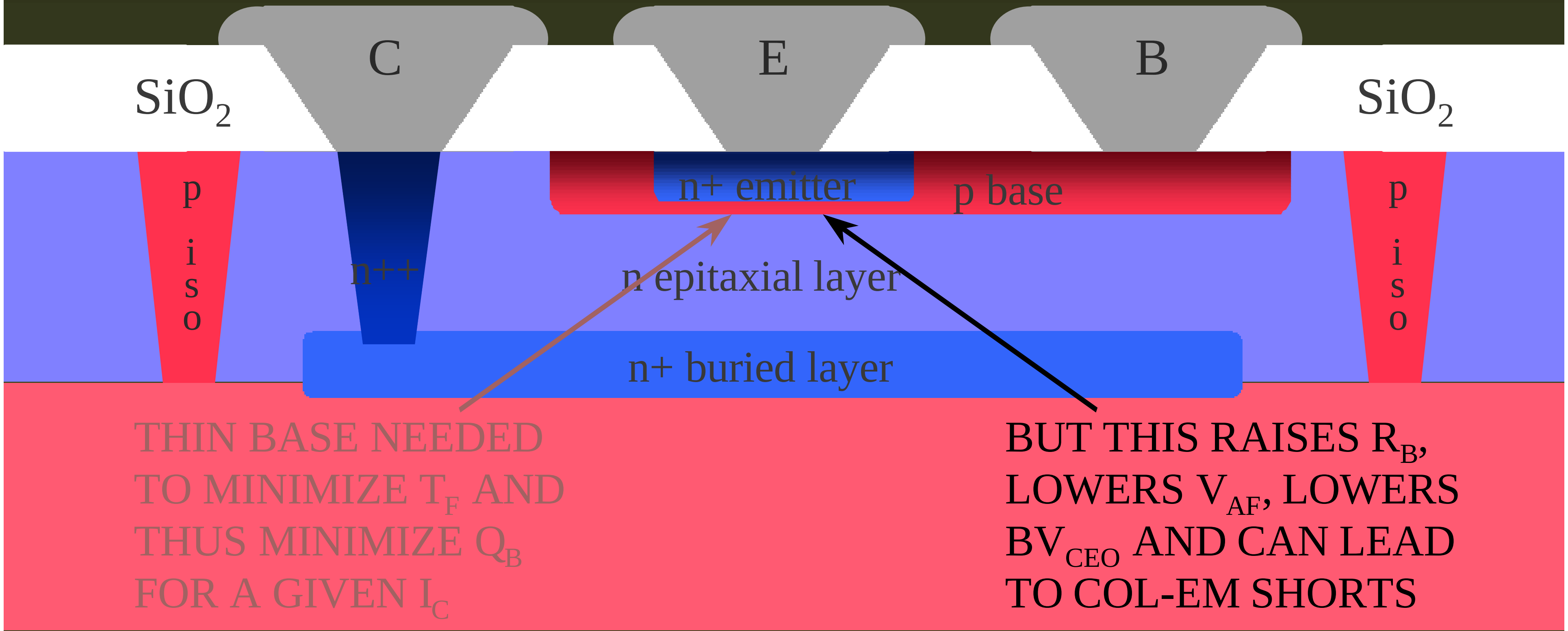
PLANAR NPN TRANSISTOR



THIN BASE NEEDED TO MINIMIZE T_F AND THUS MINIMIZE Q_B FOR A GIVEN I_C

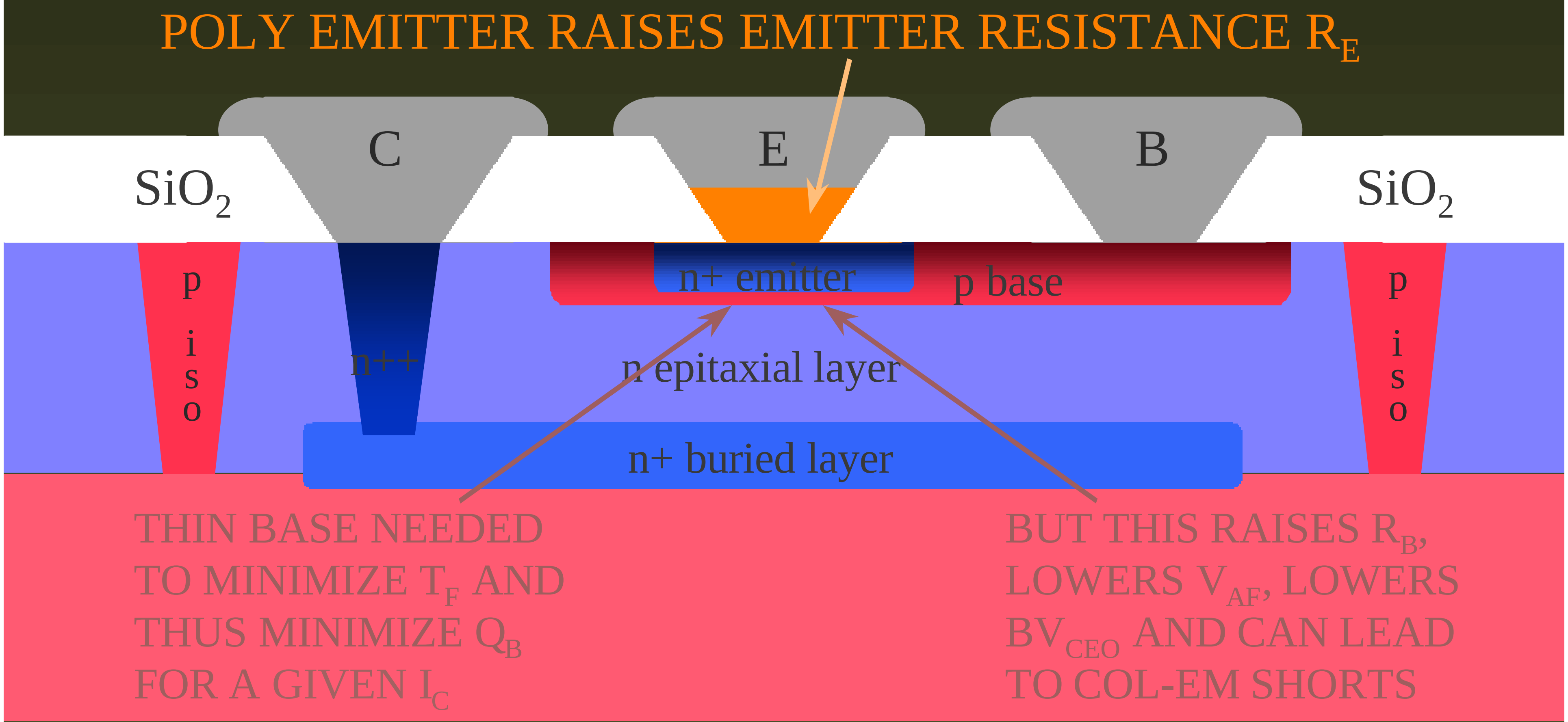
ANALOG DEVICES

PLANAR NPN TRANSISTOR



ANALOG DEVICES

PLANAR NPN TRANSISTOR



ANALOG DEVICES

KEY IDEAS ABOUT SiGe

- BEGIN BY USING AN EPITAXIALLY-GROWN BASE FILM RATHER THAN AN ION-IMPLANTED LAYER
- DURING BASE-FILM DEPOSITION ADD A SMALL PERCENTAGE OF GERMANIUM
- GRADE THE Ge CONCENTRATION; THIS WILL INTRODUCE A FIELD IN THE BASE
- ALSO, INCREASE THE CONCENTRATION OF THE NORMAL BASE DOPANT (BORON)

ANALOG DEVICES

THIS BUYS YOU:

- A BASE FILM OF VERY PRECISELY CONTROLLED COMPOSITION, WITH A THICKNESS ACCURATE TO WITHIN A FEW ATOMIC LAYERS
- A MUCH LOWER BASE RESISTANCE, DUE TO USE OF HIGHER BASE DOPING CONCENTRATION
- A MUCH HIGHER EARLY VOLTAGE, SINCE THE DEPLETION LAYER WIDTH IS SMALLER
- HIGH BETA IS ACHIEVED BECAUSE OF HIGHER EMITTER EFFICIENCY DUE TO REDUCTION OF BAND-GAP ENERGY AT EMITTER EDGE

TRANSLATED:

- SUPER-ACCURATE BASE-WIDTH OF ABOUT 0.1µm MEANS THAT TRANSIT TIME IS VERY SMALL AND VERY WELL CONTROLLED
- LOW BASE RESISTANCE ALSO INCREASES SPEED AND LOWERS JOHNSON NOISE
- HIGH EARLY VOLTAGE RAISES AVAILABLE GAIN & LOWERS COLLECTOR DISTORTION
- HIGH DC BETA SIMPLIFIES BIASING

ANALOG DEVICES

SIMILARITY TO A GaAs MESFET?

THEY ARE BOTH VERY FAST SEMICONDUCTOR DEVICES

but

A SiGe HBT USES STANDARD SILICON WAFERS

IT DOES NOT HAVE ANY STRANGE SUBSTRATE EFFECTS (e.g. SLOW STATES) THAT PLAGUE GaAs

IT CAN BE INTEGRATED INTO VLSI USING BiCMOS

ANALOG DEVICES

IN SHORT....

THE BENEFITS OF SiGe, THOUGH MODEST, ARE REAL ENOUGH TO GUARANTEE WIDESPREAD ADOPTION IN STATE-OF-THE-ART IC PROCESS TECHNOLOGIES.

THE COMBINATION OF A 50GHz HBT WITH A 0.25mm CMOS PROCESS WILL BECOME STANDARD FOR USE IN MIXED-SIGNAL RF & IF SIGNAL-PROCESSING ICs. IN THESE PRODUCTS, WAFER COST IS NOT CRITICAL.

THIS PROCESS WILL BE VERY DURABLE, AND WILL NOT READILY BE OBSOLETED IN THIS PARTICULAR CLASS OF APPLICATIONS FOR MANY YEARS.

What's

Ahead?

RADIO IN THE INFORMATION AGE

The challenges facing designers of analog radio systems, now inextricably interwoven with the integrated circuit and the exclusive use of digital modulation, are considerable.

The economics of the mass market affect every aspect of system development, and dictate the use of ultra-low-cost processes, assembly, and testing techniques.

The Newtonian nature of radio remains an inescapable factor in approaching design.

FUTURE TRENDS

ANALOG DEVICES

PARTNERSHIPS IN TECHNOLOGY

- ANALOG *teaming* with DIGITAL
- BIPOLAR *teaming* with CMOS
- SOC's *teaming* with SOH's
- CONTAINED PROPAGATION (e.g fiber) *teaming* with BROADCAST MODES

FUTURE TRENDS

ANALOG DEVICES

GREATER INTERCONNECTIVITY

- Demand for access will increase
- Bandwidth will become more affordable
- Home networks will become common
- Many data links will be radio-based, and use both microwave and long-wave
- Distinction between “TV” and “PC” presentation of images will disappear
- Un-self-conscious use of facial images in day-to-day communications
- Wearable computers and communications

FUTURE TRENDS

ANALOG DEVICES

NEW PARADIGMS for DESIGN

- The present approaches to the design of integrated circuits and systems must be supplanted by more efficient ones, as systems become more complex
- This will entail greater re-use of proven cells, and of less time for highly-specific customization
- Increased use of advanced hybrid assembly techniques will generate a demand for a new kind of IC designer
- Fundamental analog design principles must be restored to curricula and mixed-signal techniques emphasized
- Today’s IC designers increasingly need to diversify
- Need to focus more strongly on the crucial issue of Design for Manufacture

FUTURE TRENDS

ANALOG DEVICES

INCREASING ELECTRONICS IN MEDICINE

- Already used in many investigative and diagnostic tools
- Small swallowable radio pills can report on temperature, digestive chemistry, pressure, etc. Cheap transponders can be given to a patient to connect to a PC or PDA
- An increasing use of prosthetic devices can be foreseen, some of which may rely on ultra-short-range radio links
- Further advances in affordable ultra-fast computers will facilitate the modeling of molecules and the development of more effective disease-specific drugs

FUTURE TRENDS

ANALOG DEVICES

INCREASING DEPENDENCE ON GPS

- GPS is already finding a host of unexpected uses: in Paris, buses are equipped; in Amsterdam, Berlin and Singapore, taxi-cab are tracked by GPS; as are trucks in the USA: farmers guide their tractors and other equipment by GPS
- Next step: universal use in automobiles, and other personal transportation systems; these have numerous applications
- Wrist-watch GPS facilitates the location of key personnel
- Later: fully automated, GPS-guided transport systems

(Knowing the “where” will be as important knowing the “time”)

FUTURE TRENDS

ANALOG DEVICES

NEW PARADIGMS FOR COMPUTING?

- When will neural networks provide useful adjuncts to serial, algorithmic machines? Perhaps by 2015
- Still at the fringes of practical utilization, quantum computers approach problem solving in an entirely novel manner, stressing the holistic physical aspects of a system model, again in contrast to a reliance on binary representations and serial algorithms
- Employing nuclear magnetic resonance (NMR) to excite and then “listen to” molecular signatures, the need for RF transceiver techniques is central

SUMMARY

- ANALOG IS NOT OBSOLETE !
- DESIGN CHALLENGES ABOUND
- BIPOLAR REMAINS IMPORTANT
- SYSTEM-on-a-HEADER may be a good alternative to SoC VLSI

ANALOG DEVICES