# Architectures & RF Circuits for Miniature Wireless Transceivers


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# Outline

- ICs in Broadcast Radio Receivers
- ICs in Wireless Paging Receivers
- ICs in TV Tuners
- ICs in Cellular Telephone Transceivers
- ICs in Spread-Spectrum Wireless Transceivers
- ICs to Enable Future Transceivers

# Examples of Miniature Radios

✓ Broadcast Receivers (FM at 100 MHz RF), such as the Walkman personal entertainment device

✓ Paging Receivers (150 MHz to 900 MHz RF) such as the Motorola Bravo

✓ GPS Receivers (2 GHz RF), such as the Sony Pyxis

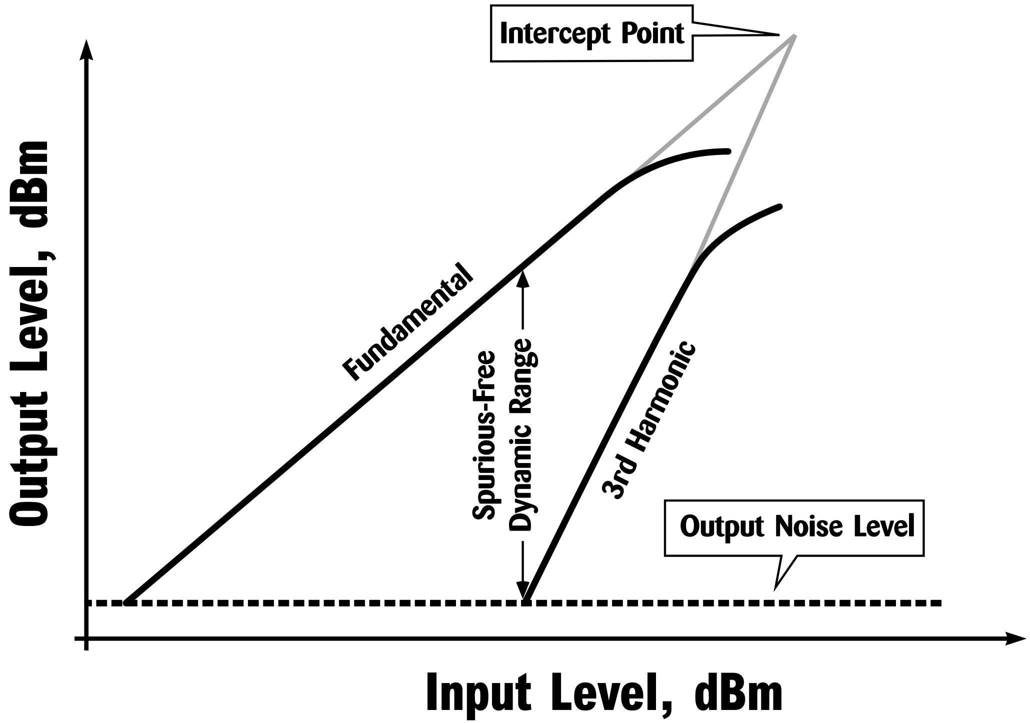
✓ Cellular Telephone Transceiver Handsets (900 MHz RF) such as the Motorola MicroTac

✓ Wireless LAN Transceivers (900 MHz or 2 GHz RF), such as the Proxim or Plessey card

# Early Preoccupations with ICs for Radio Receivers

- Potential of applying IC technology to radio receivers has occupied companies since mid-1960's
- Motorola's classic series of textbooks on IC design suggest these concerns:
  - "Integrated Circuit Design: Principles & Fabrication" (Warner & Fordemwalt, eds., 1965) discusses difficulty of making *spiral inductors* on silicon substrate.
  - "Analysis and Design of Integrated Circuits" (Meyer, Lynn, and Hamilton, eds., 1968) contains chapters on *tuned amplifiers* and *gyrator filters*
- Technology limits did not permit application of silicon ICs to RF sections until 1970s. Radios were built with discrete VHF/UHF bipolar transistors, FETs, and discrete passive components.

# Dynamic Range in a Receiver



# Early Uses of ICs in FM Receivers

Peil, McFadyen, GE, 1977

- Integration of transistors in IF amplifier strip, FM demodulator and power amp. Off-chip inductors, capacitors, ceramic resonators.
- Leads to reduction in parts count, lowered power dissipation, and miniaturization.
- Some circuits only possible in monolithic IC form:

  High gain, direct-coupled differential limiting amplifiers

  Double-balanced (analog multiplier) mixers

On-chip AM front-end

Off-chip FM RF amplifier and mixer

7 off-chip tuned circuits

1.9-V operation

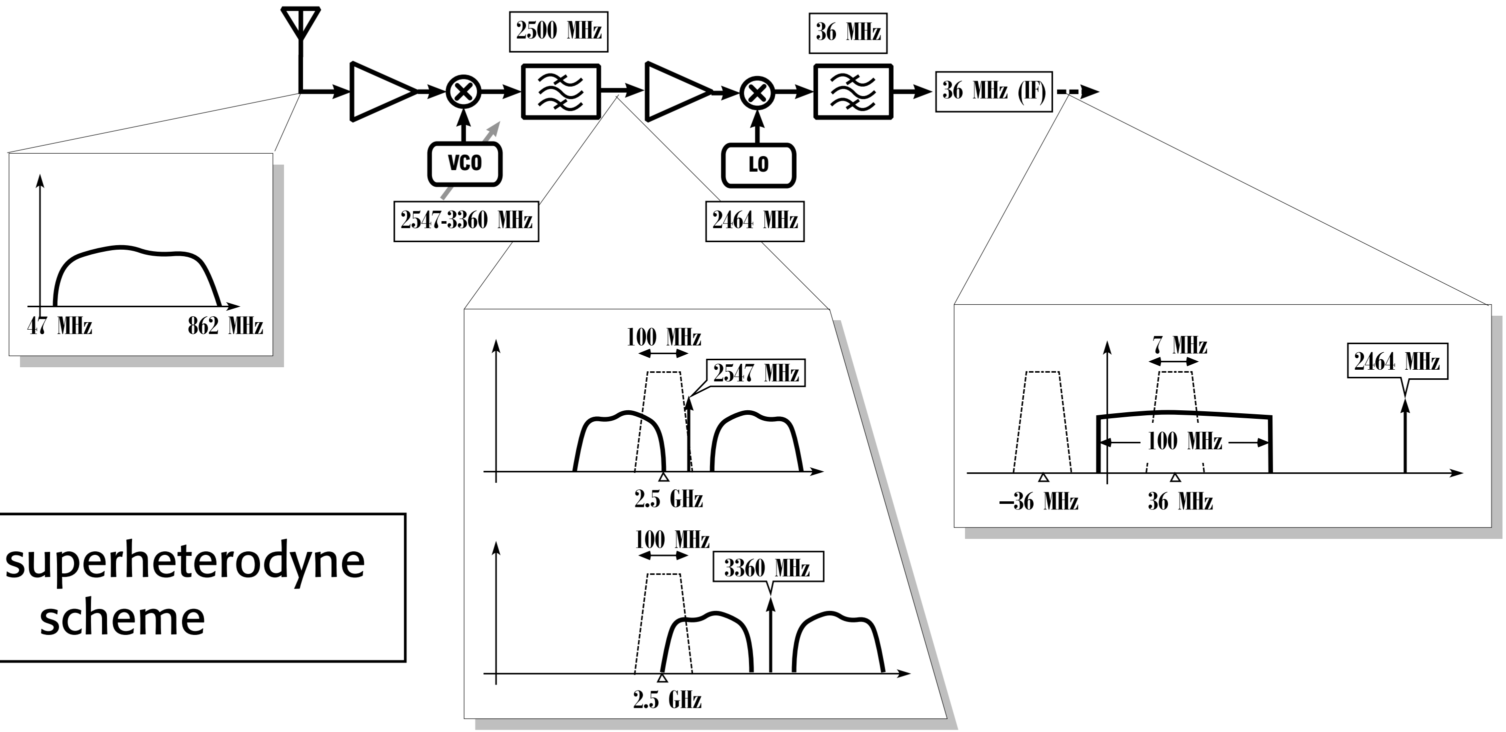
Thermal feedback on-chip

Coupling through on-chip power supplies

Parasitic coupling between IC pins at high frequencies

# Frequency Allocation Plan Example

## Siemens Wideband TV Tuner IC




Double superheterodyne scheme

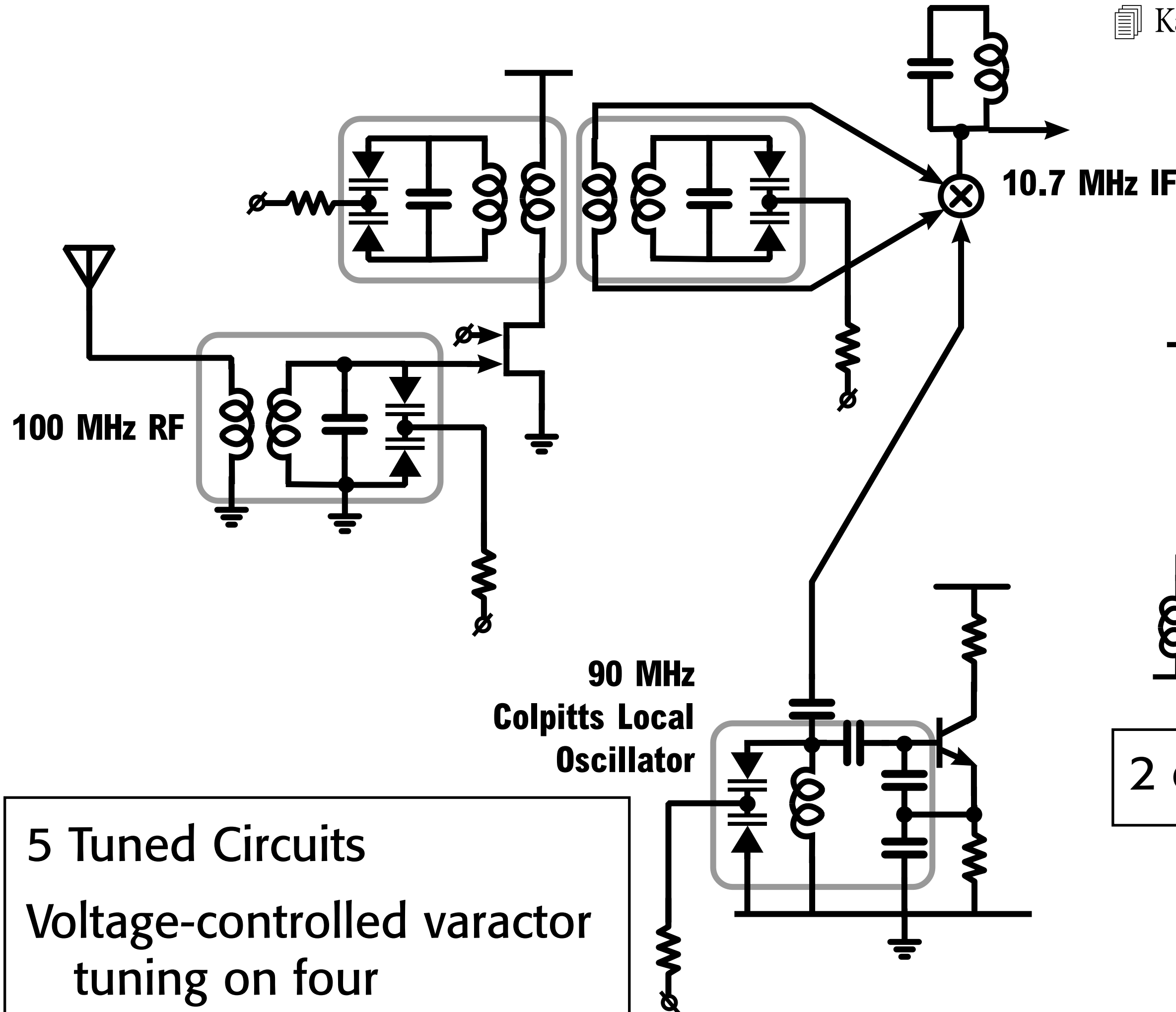
- One GaAs IC tunes all TV bands, from VHF to UHF
- Upconversion serves two functions:

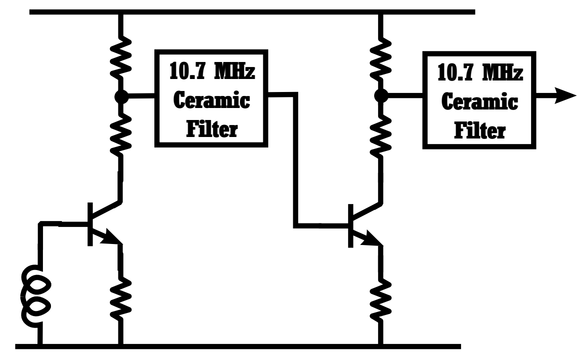
  Avoids *image frequency* reception, because antenna cannot tune 5 GHz

  Reduces *fractional tuning* range of first VCO to cover entire TV band

# Conventional FM Receiver Front-End

Kanow, Siewert, Philips, 1981



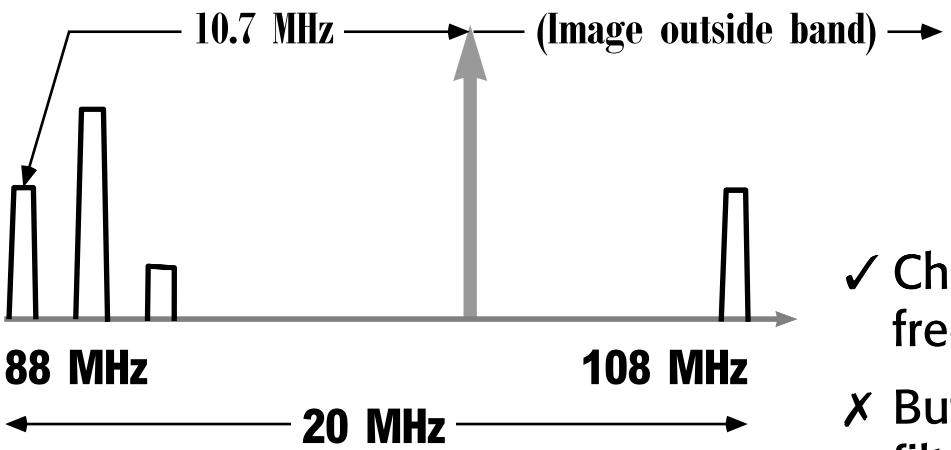

5 Tuned Circuits

Voltage-controlled varactor tuning on four

2 ceramic resonator filters

# Keys to Greater Integration

- Reduce amount of RF filtering
- Reduce number of tuned components
- Bring RF amplifier on-chip (use off-chip tuned load if necessary)
- Filters for greater selectivity and image-rejection should be on-chip

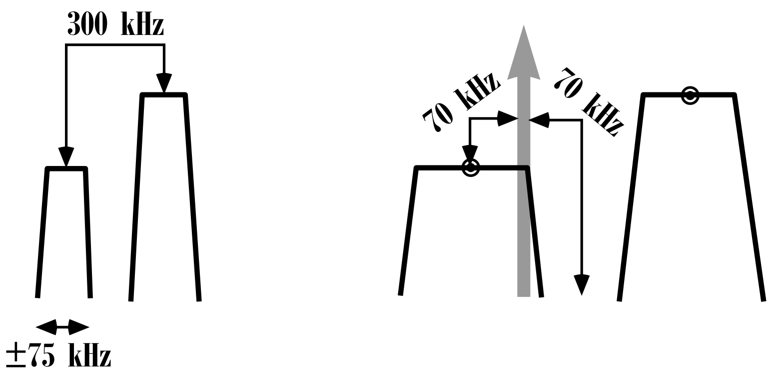


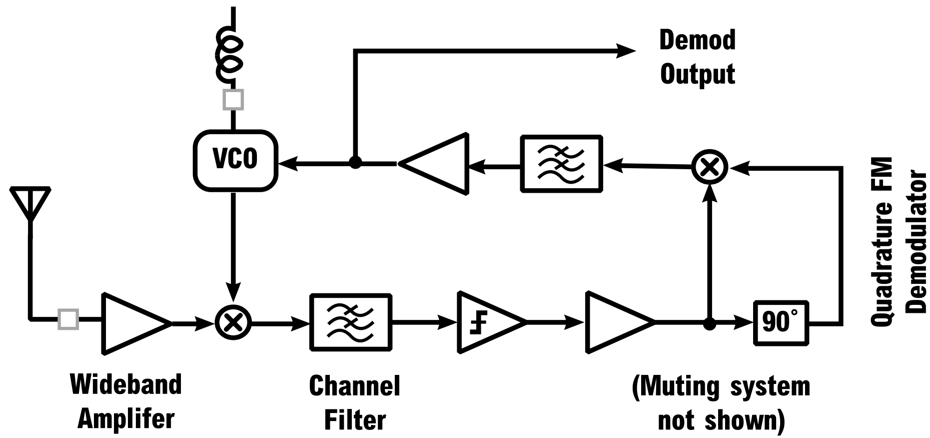

✓ Choice of high IF suppresses image frequency

✗ But, difficult to make on-chip active filters, particularly with high dynamic range and low power. Need 10.7 MHz bandpass with 150 kHz passband

# Low IF FM Receiver

- Kasperkovitz, Philips, 1981 & 1983
- v. Dooremolen & Hufschmidt, Philips, 1983



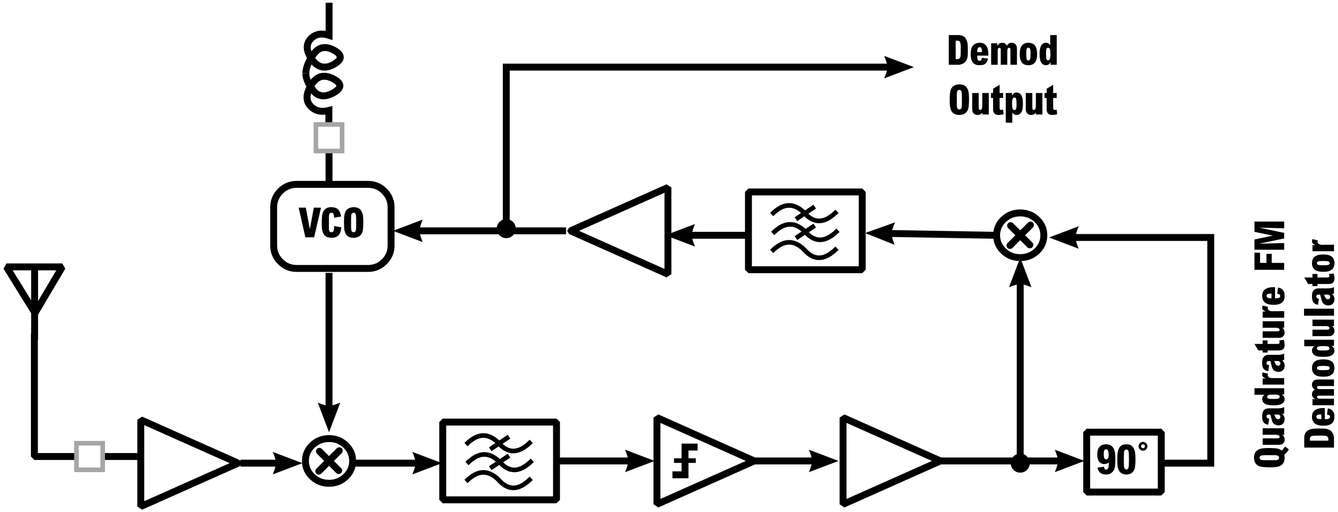

✓ Lower the IF so that on-chip lowpass filters may define channel bandwidth

✗ Zero IF has no image, but cannot use limiting amplifier to remove AM noise

✓ 70 kHz IF means that image lies in inter-channel band; only contributes extra noise!

- Negative feedback in frequency-locked loop compresses FM swing to ±15 kHz
- First LPF acts as channel filter; 4th order active-RC implementation with 100 kHz cutoff frequency
- 15 capacitors, 2 inductors, 8 mA drain from 4.5V

# Single-Chip FM Radio




- Negative feedback in frequency-locked loop compresses FM swing to ±15 kHz
- First LPF acts as channel filter; 4th order active-RC implementation with 100 kHz cutoff frequency
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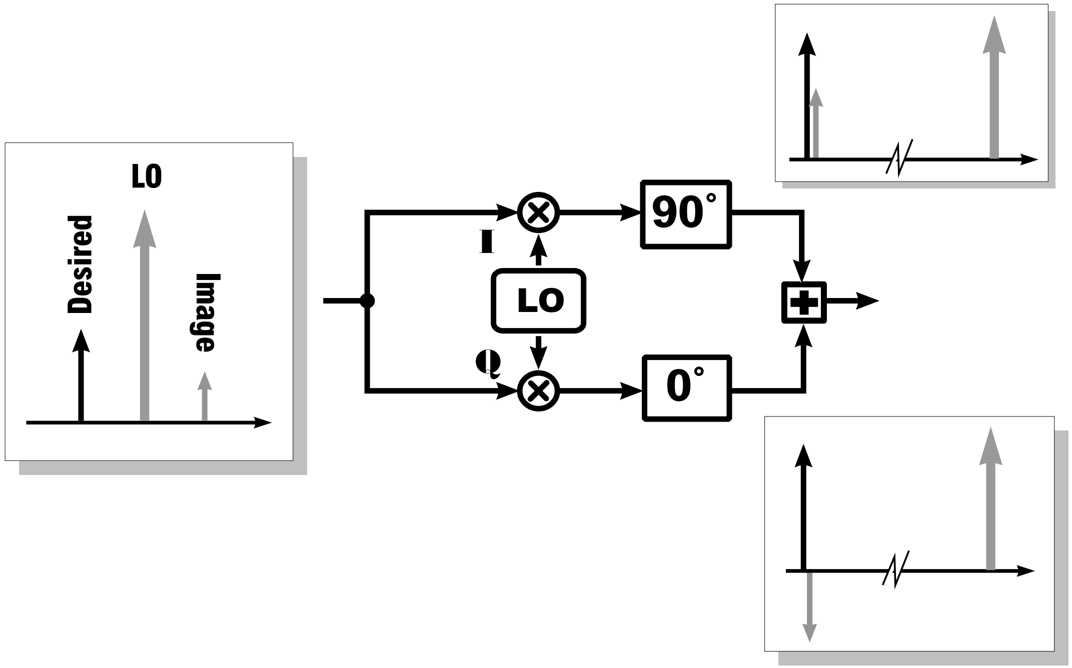
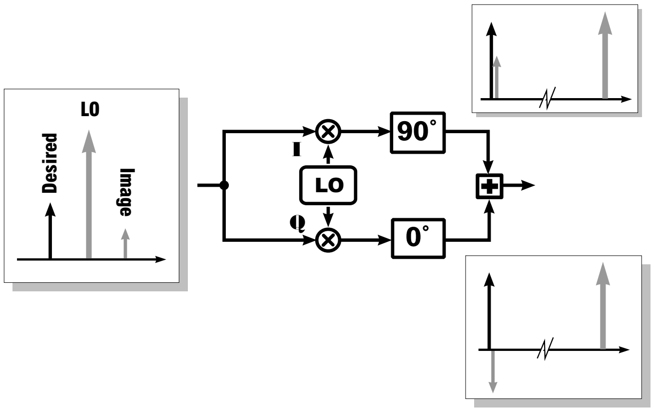
# The Image-Cancellation Mixer

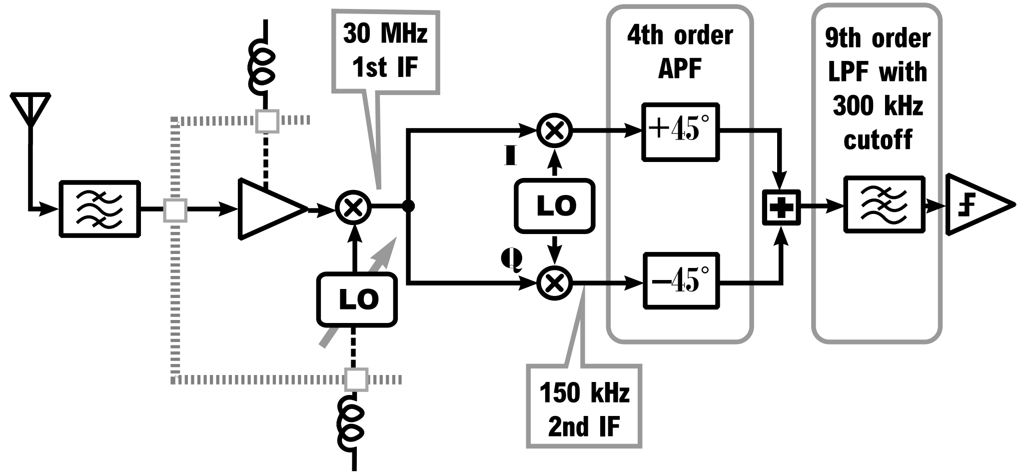



- Complex mixing eliminates need for image-cancellation filter
- Image suppression depends on exactness of quadrature; 1° error gives about 40 dB suppression
- Phase-shift in IF path usually obtained with delays or allpass filters
- Quadrature LO outputs from ÷2, *RC-CR* network, or inherently from oscillator

# Alternative Single-Chip FM Receiver

Okanobu, *et al.*, Sony, 1992



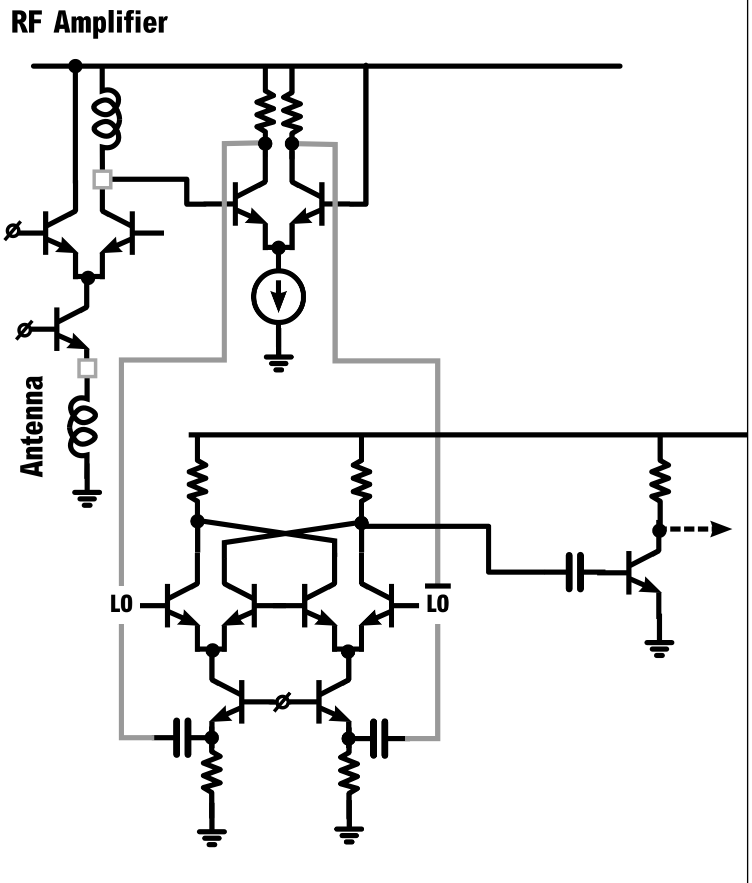




- Complex mixing eliminates need for image-cancellation filter
- Image suppression depends on exactness of quadrature; 1° error gives about 40 dB suppression
- High IF affords better image rejection
- Single off-chip BPF covering entire FM band
- Image-rejection mixer suppresses unintended channel captured by 150 kHz second IF
- Channel filter and phase-shift networks are on-chip active-*RC*

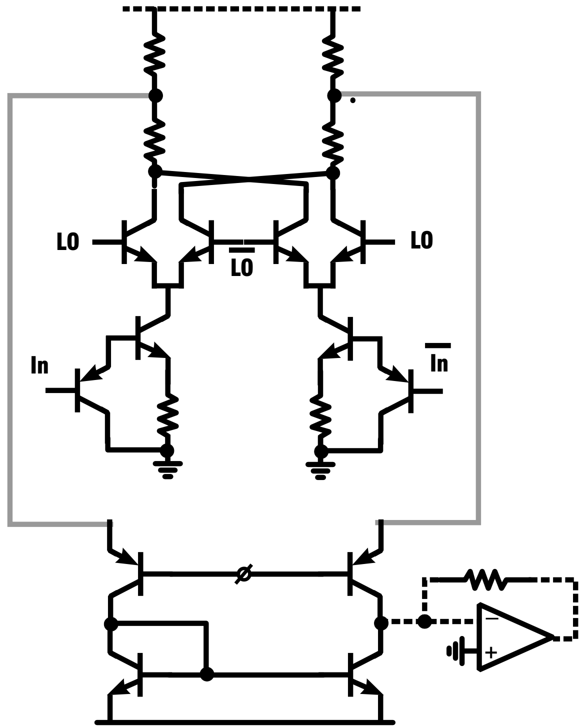
# Circuits for Low-Voltage Operation

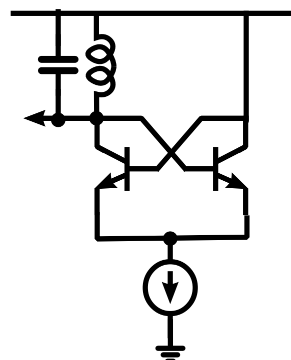
0.9V to 4.5V operation

## RF Amplifier and First Mixer



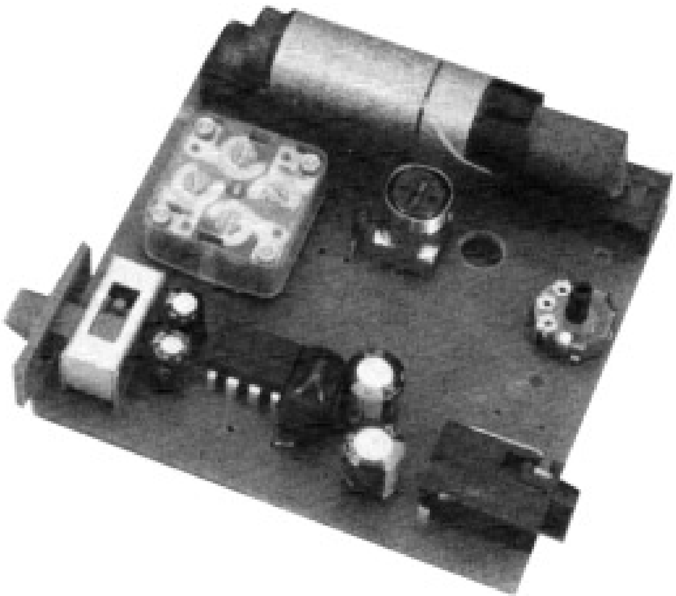

## Second Mixer



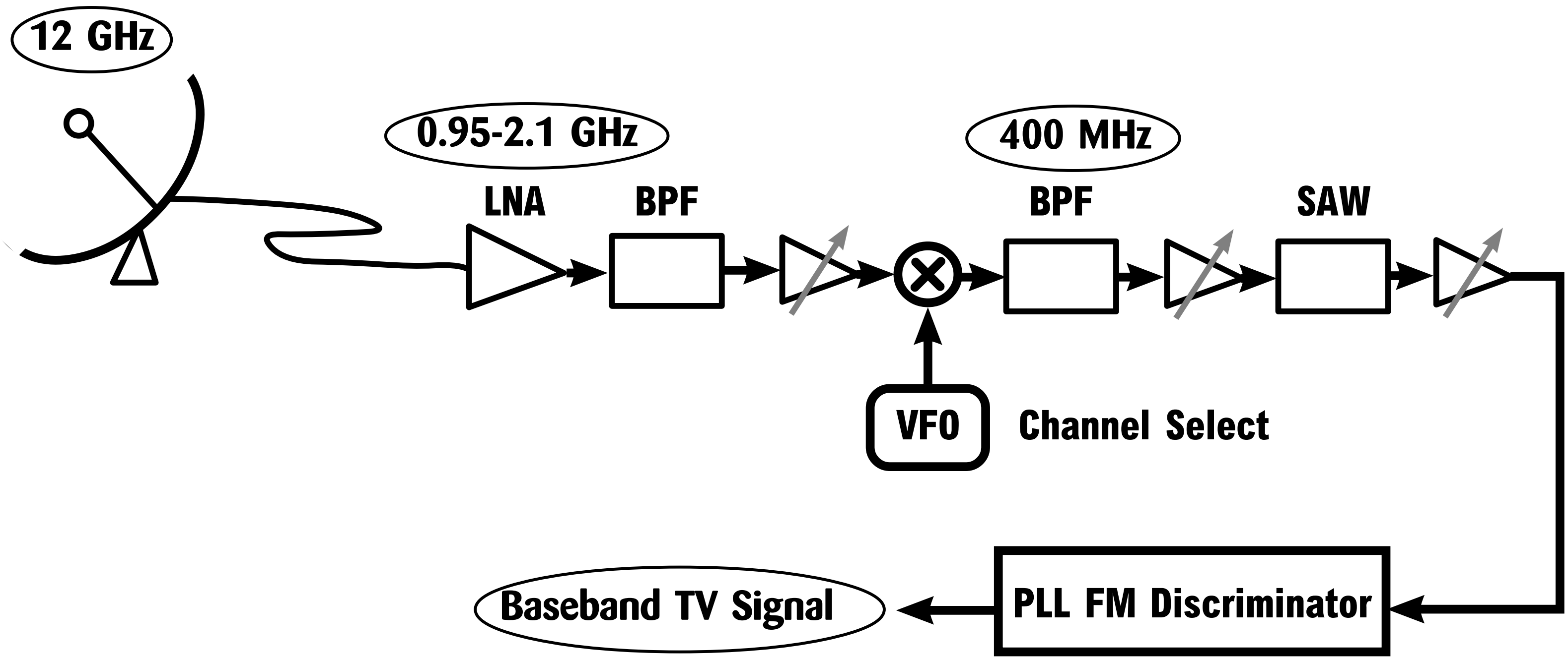
Local Oscillator

# Performance of Low-Voltage Receiver



| | |
|---|---|
| Current Drain | 16 mA |
| FM Selectivity | 40 dB at 400 kHz |
| Image Rejection | 39 dB |
| FM Max SNR | 60 dB |
| Sensitivity for quieting | 10 µV |
| THD | 0.1% |

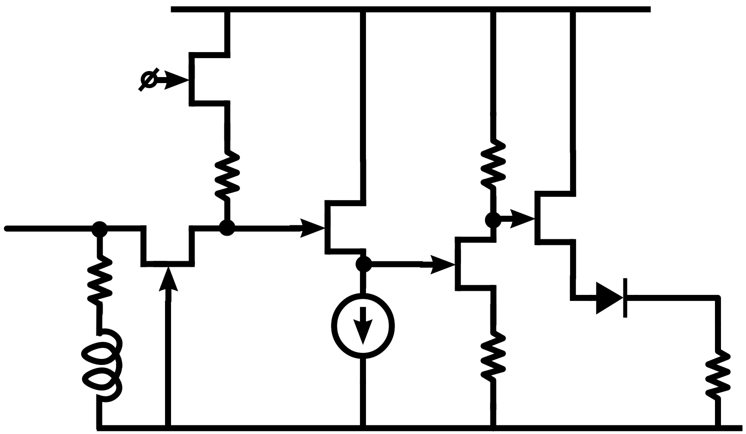
# DBS TV Receivers

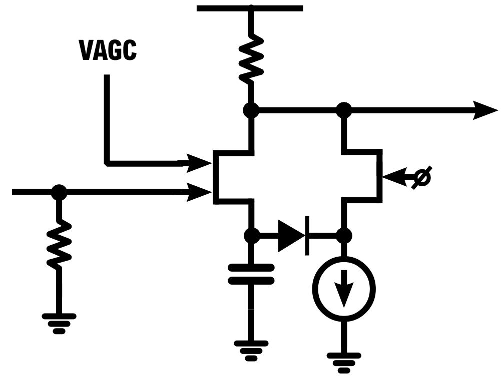



- Transmission at 12 GHz
- Conversion to first IF (900 MHz to 2 GHz) in receiver antenna
- ICs have been developed for first IF onwards -- miniature DBS receivers in TV sets and VCRs

# Front-End RF Amplifiers

- Yamamoto, *et al.*, *IEEE Trans. on CE*, Aug. 1989
- Yamamoto, *et al.*, *IEEE Trans. on CE*, Aug. 1992






| | |
|---|---|
| Gain | > 9 dB |
| Noise Figure | 8 dB |
| Input VSWR | < 2 |
| 3rd-order IM | < -58 dBc at max input |
| Reverse isolation | > 25 dB |
| Power dissipation | 120 mW from 5 V |
| Technology | 1-μm MESFET |

Receive more than 20 DBS channels, with more than 50 dB dynamic range

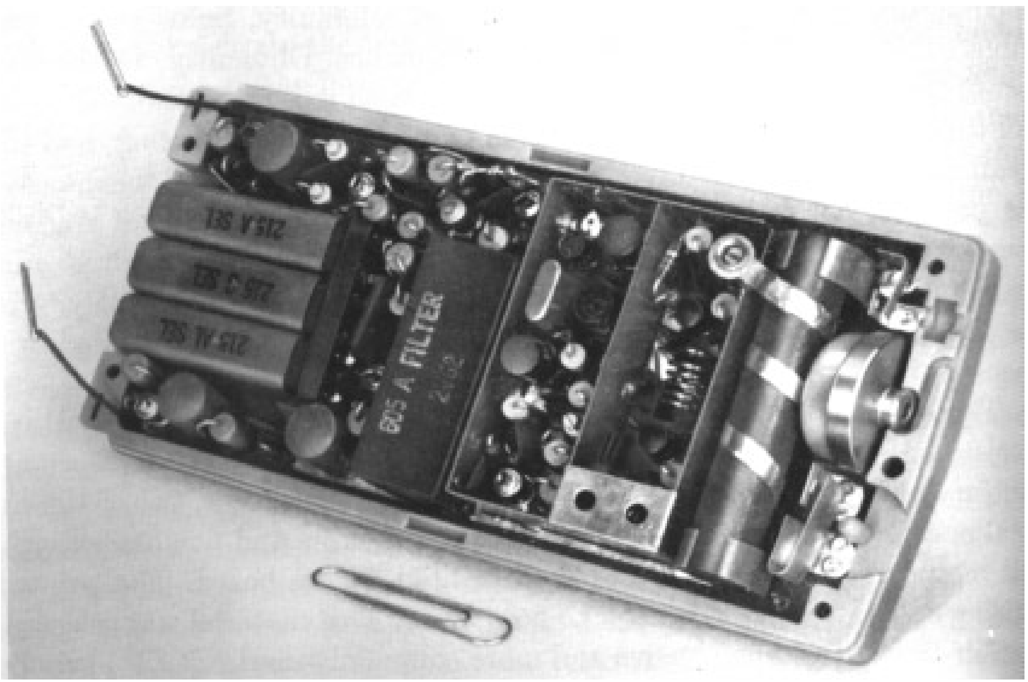
# Radio Paging Receivers

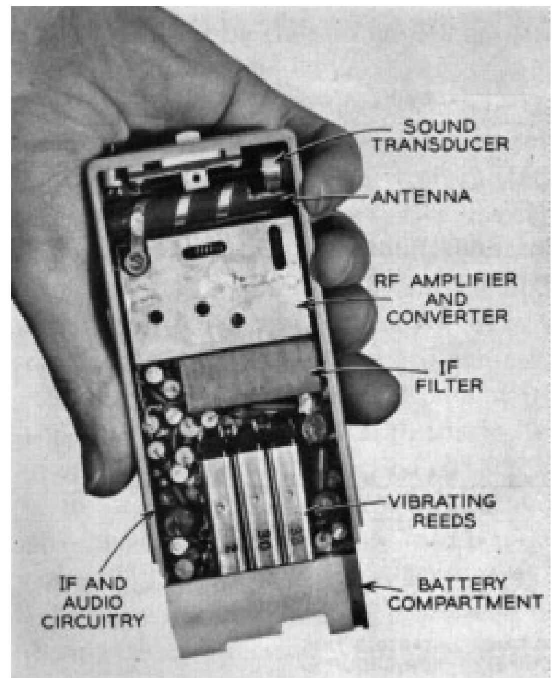
- Importance of paging people on the move with miniature radio receivers recognized in the late 1950's
- Bellboy Trials at AT&T in early 1960's. Local area paging by FM of 150 MHz with three tone set. Receiver contains vibrating reeds tuned to recognize its own code.
- Small size and long battery life recognized as keys to success
- Modern pagers use digital signalling at 500 b/s
- Paging receivers are perhaps the most highly evolved, widely used RF device. High functionality / unit volume, long battery life.

# Features of the Bellboy Receiver

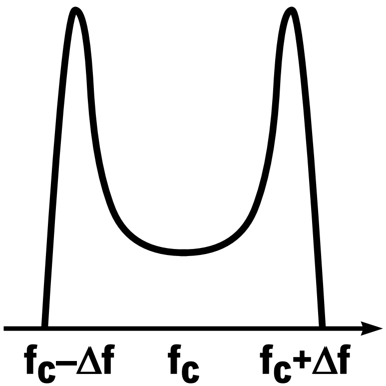
- Operates on 4-V supply
- Uses ten transistors in entire receiver
- Single-conversion superheterodyne with 6 kHz IF
  - ➪ Circuits operate at low currents
  - ➪ Capacitively-coupled 10 kHz lowpass filter for channel selection


- Mitchell & van Wynen, Bell Labs, 1961
- Kerwein & Steiff, Bell Labs, 1963

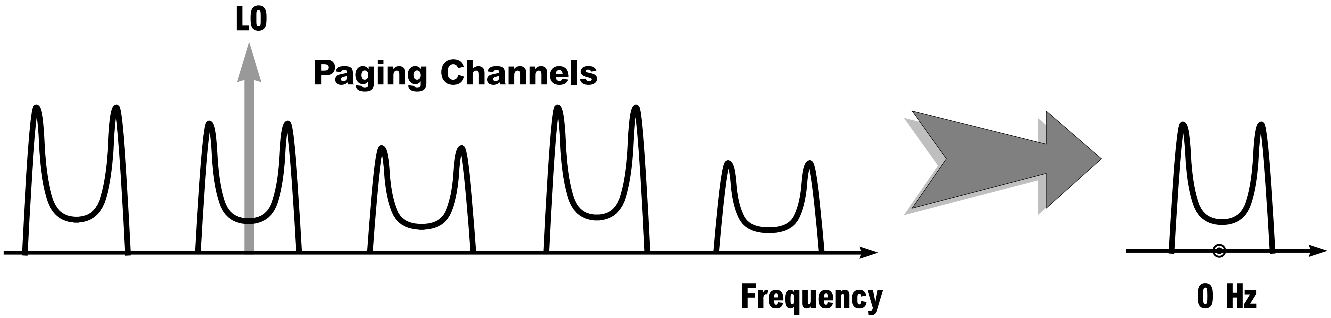
# Digital Pager Signalling




- POCSAG signalling standards used
- RF is 150 MHz in Japan, 450 MHz to 900 MHz in US and Europe
- Binary FSK suppressed-carrier spectrum contains information at ±4.5 kHz around center frequency

- Early paging receivers used conventional double-superheterodyne architectures, off-chip bandpass filters, and a frequency discriminator to detect the two tones. Too complex.
- Solution was required to radically simplify the receiver by exploiting the features of the signalling

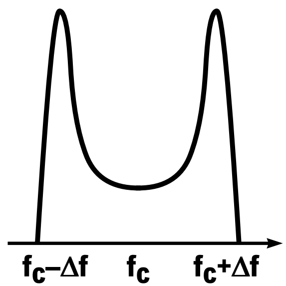
# Direct Conversion Reception

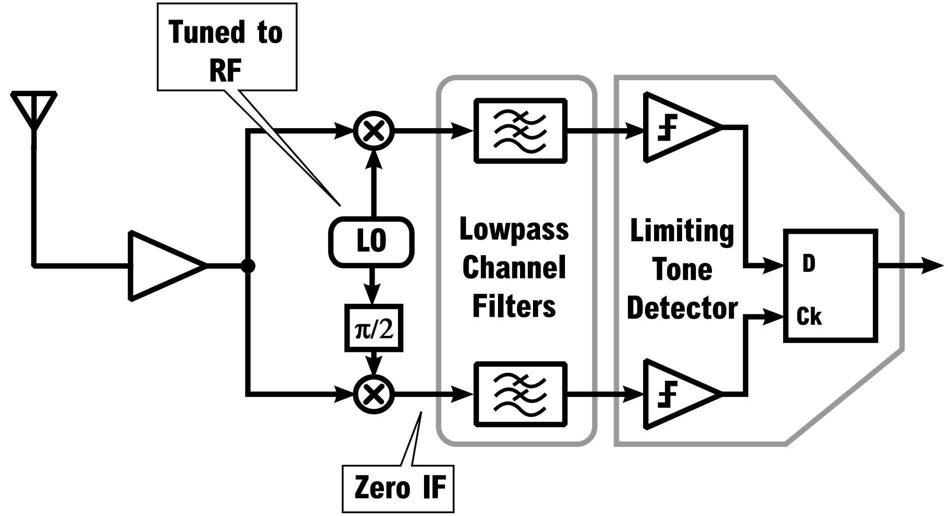



- Zero IF is the simplest possible receiver
  - ✓ Lowpass channel filters only
  - ✓ Minimum processing at high frequencies
  - ✓ No image response to worry about!
- Potential problems of Zero IF
  - ✗ DC and flicker noise add to converted signal
  - ✗ Local oscillator (at RF) can leak out of antenna

# Direct Conversion Paging Receiver

Vance, ITT Standard Telecommunications Labs, 1980, 1982

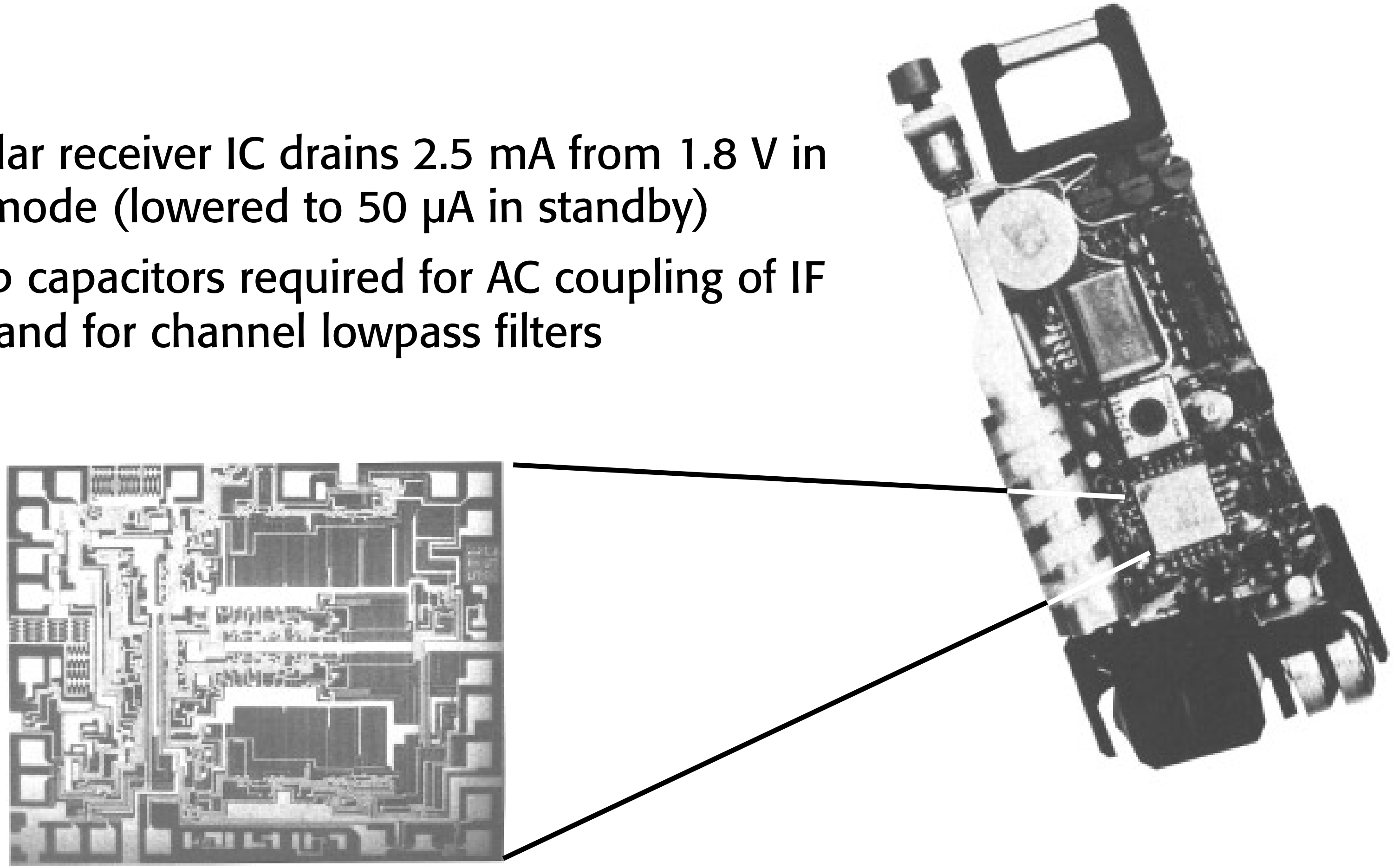



- Extremely simple receiver
- Very simple detector in principle; only a flip-flop!
- RF amp and LO are the only high frequency blocks on chip
- AC coupling eliminates DC offsets; seek energy only at ±4.5 kHz
- Naturally suggests a single-chip implementation!

# Paging Receiver Prototype

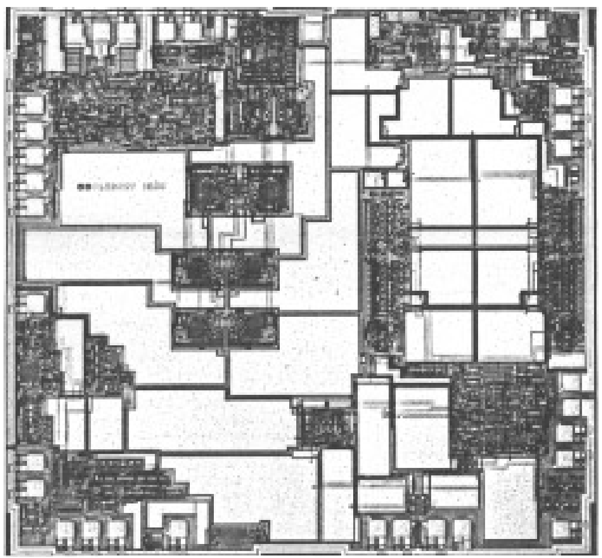
- Si Bipolar receiver IC drains 2.5 mA from 1.8 V in active mode (lowered to 50 μA in standby)
- Off-chip capacitors required for AC coupling of IF signal, and for channel lowpass filters



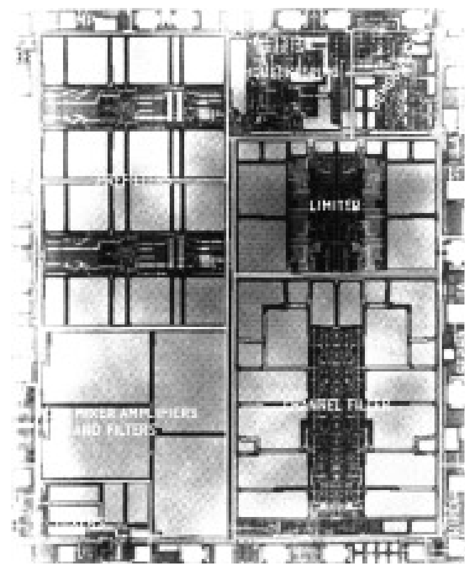
# Single-Chip Paging Receivers

- Two-chip pagers are now standard. One IC for receiver, one for user interface.
- Only off-chip components are inductor load for RF tuned amplifier, quadrature phase-shift network, and crystal
- Low-frequency active filters (e.g 7th order lowpass filter with 15 kHz cutoff) require large on-chip capacitance

Burt, GEC-Plessey, 1992



Wilson, Philips, 1991

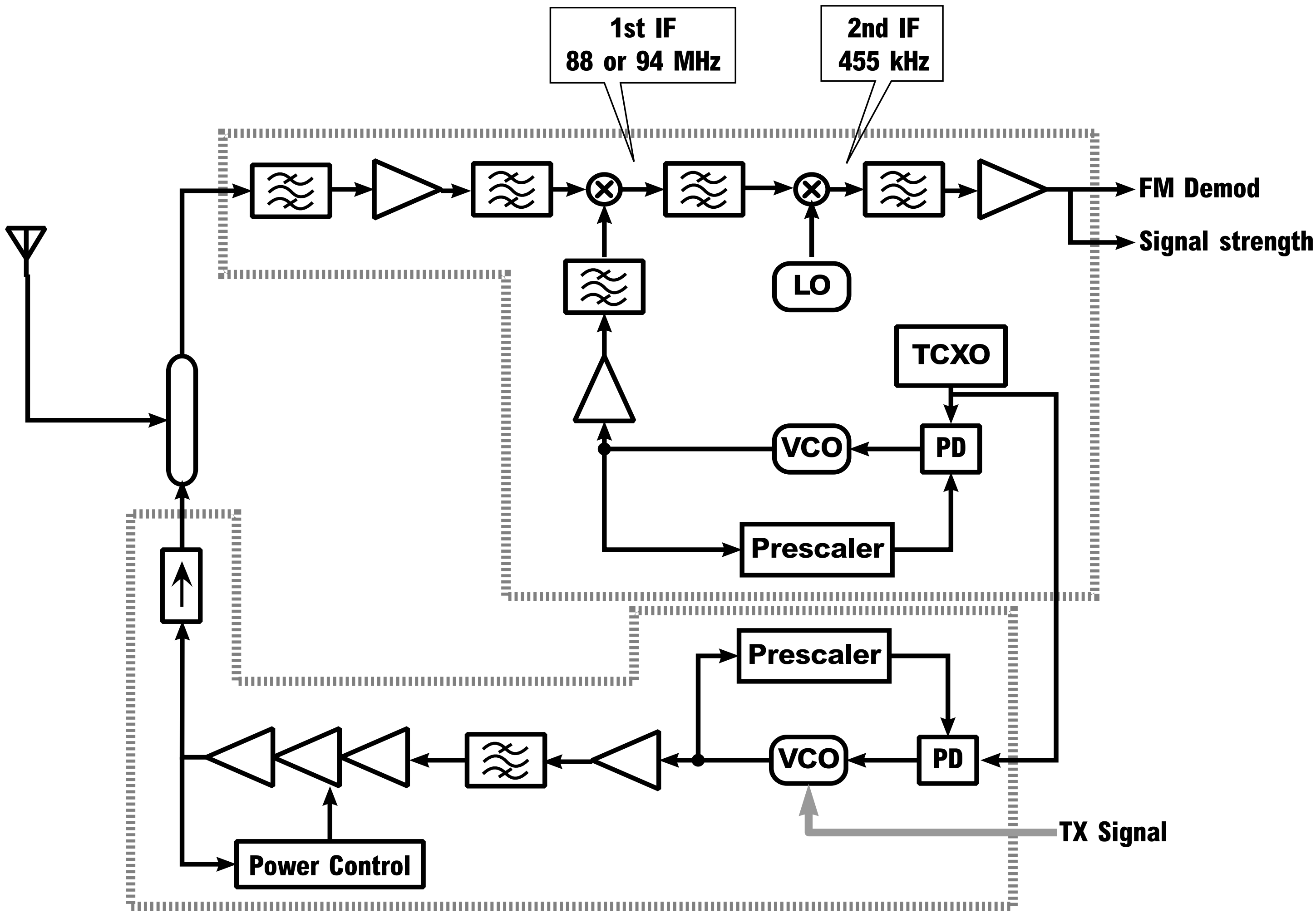


# Cellular Telephones

- The first widespread *two-way* wireless communications devices
- Success in the market depends on small volume handset, long battery life

  ⇨ Integration is the key!
- Most cellular telephones today are double superheterodyne transceivers, receiving and transmitting in separate frequency bands
- High frequency ICs used therein are building blocks. Relatively small levels of integration in RF portions.

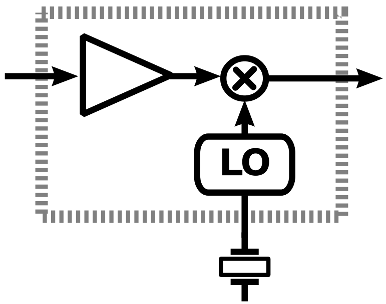
# Analog FM Cellular Phone Front-End



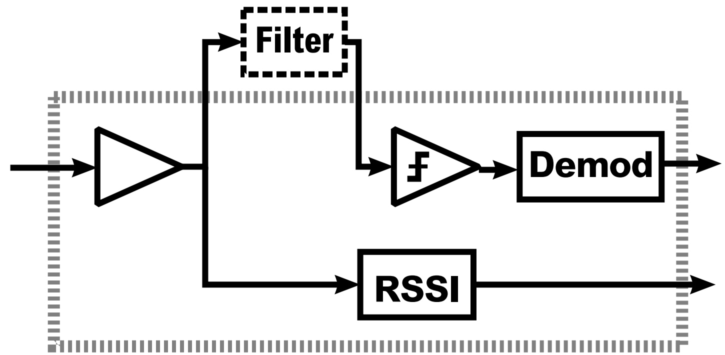
# IF ICs in Cellular Telephones

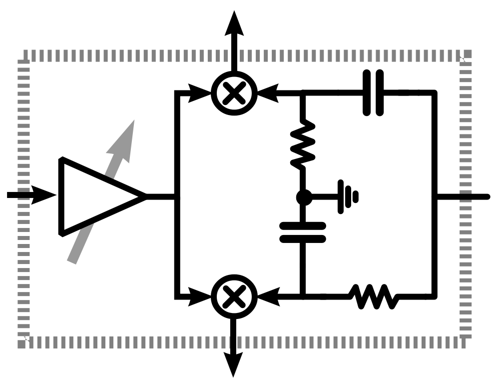
- Medium-scale integration used in 100 MHz first IF blocks (typically silicon bipolar)

  Include mixers, IF amplifier chain, signal strength indicators




Anderson & Zavrel, Philips/Signetics, 1985



Koullias, *et al.*, AT&T, 1990

# RF ICs in Cellular Telephones

- Small-scale integration, predominantly as GaAs MESFET ICs, for operation at 900 MHz to 2 GHz. This is the “low-end” of the economically feasible frequency range for this technology.
- Effort in recent years to reduce current drain of these ICs, and to increase power conversion efficiency
- Scaled discrete transistors in miniature packages continue to compete, although at disadvantage of higher assembly costs

Typical SSI RF-ICs

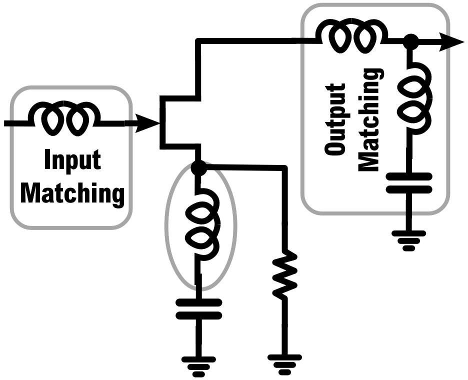
**LNA (Low Noise Amplifier) ICs**

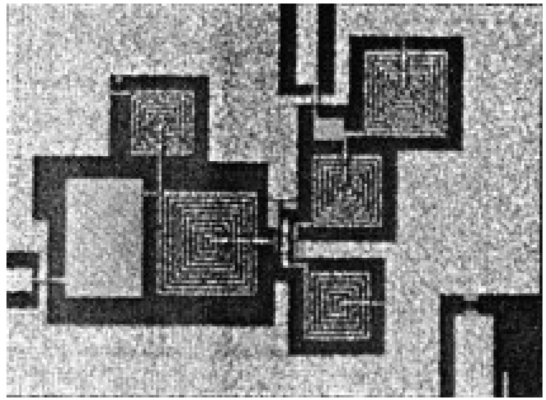
**LNA-Mixer Pairs**

**Power Amplifier Modules**

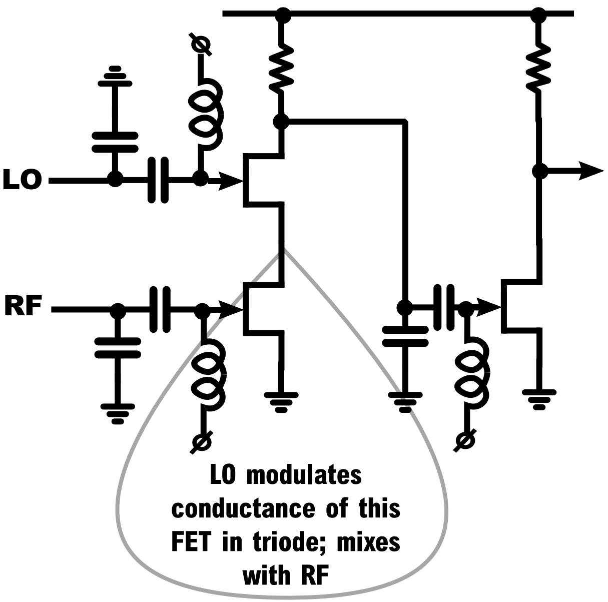
# GaAs ICs for Receiver Front End

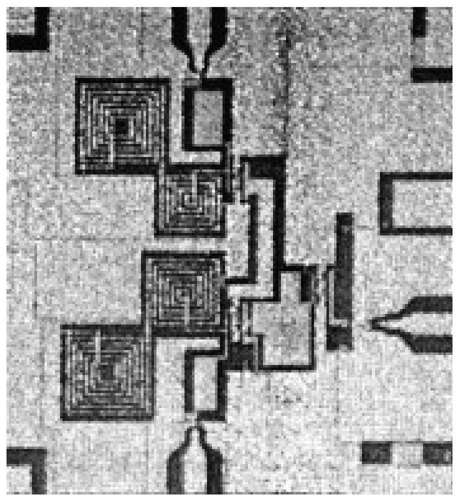
Imai, *et al.*, NTT, 1991



| | |
|---|---|
| Gain | 11.5-13 dB |
| Noise Figure | 2.5-3 dB |
| 3rd-order IM | -60 dBc at -30 dBm input |
| Frequency Band | 1.5-1.7 GHz |
| Power dissipation | 10 mW from 3 V |
| Technology | 0.3-µm SA MESFET |

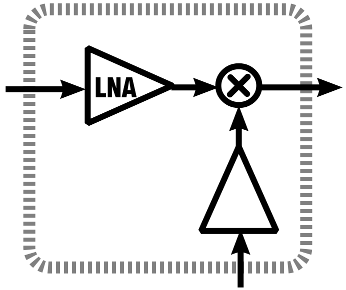


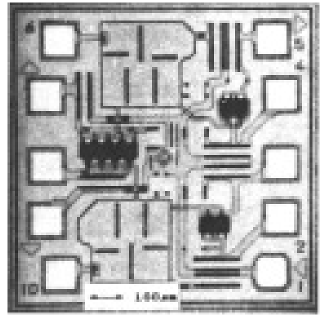



| | |
|---|---|
| Conversion Gain | 12.5 dB |
| Noise Figure | 12.6 dB |
| Intercept Point | -7 dBm |
| Frequency Band | 1.5-1.7 GHz |
| Power Dissipation | 10 mW from 3-V |
| Technology | 0.3-µm SA MESFET |

# GaAs ICs for Transceiver

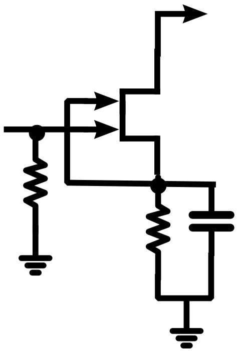
Sakai, *et al.*, Matsushita, 1992



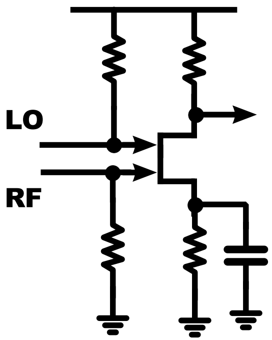



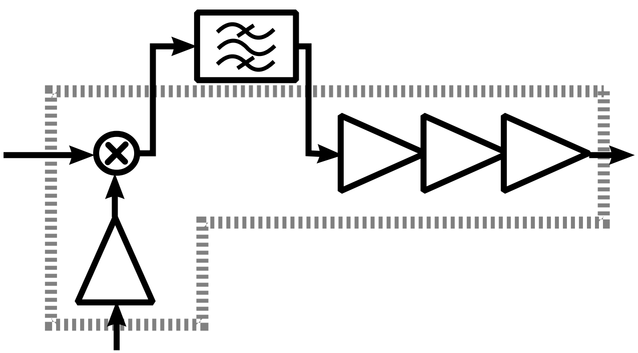
| | |
|---|---|
| Gain | 21 dB |
| Noise Figure | 3.5 dB |
| 3rd-order IM | -30 dBc at -30 dBm input |
| Frequency Band | 0.9 GHz |
| Power dissipation | 15 mW from 3 V |
| Technology | 1-µm Dual-Gate MESFET |

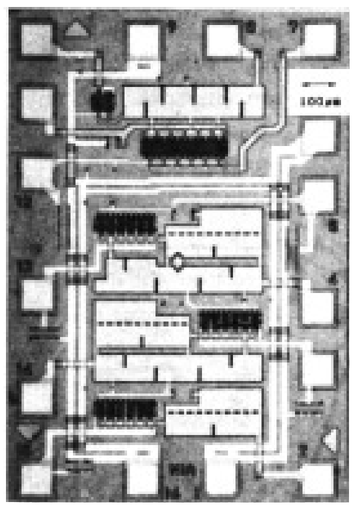
**Amplifier**



**Mixer**



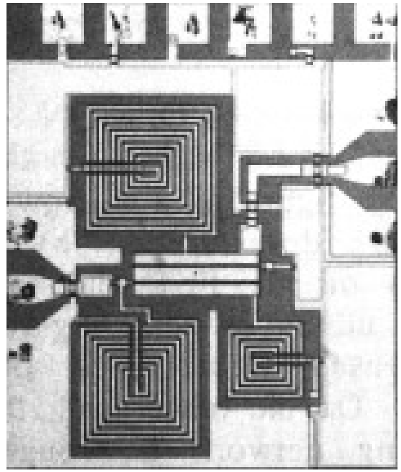





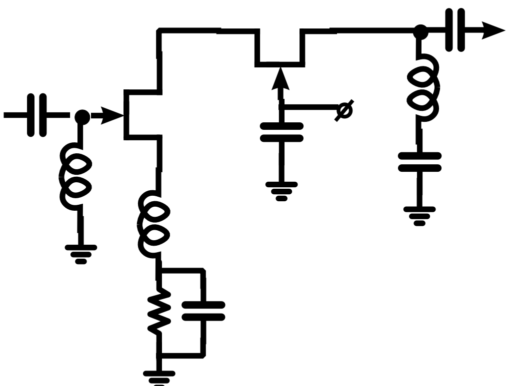
| | |
|---|---|
| Conversion Gain | 13 dB |
| Spurious Level | -80 dBc |
| Frequency Band | 0.9 GHz |
| Power dissipation | 27 mA from 3 V |
| Technology | 1-µm Dual-Gate MESFET |

# GaAs ICs for Receiver Front-Ends

Hara, *et al.*, Sharp, 1993



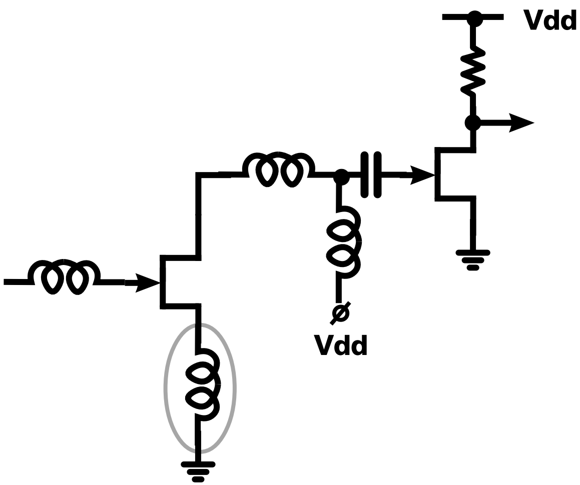
| | |
|---|---|
| Gain | 15 to 3 dB (controllable) |
| Noise Figure | 3 dB |
| 3rd-order Intercept | 6.5 dBm |
| Frequency Band | 1.5-1.7 GHz |
| Power dissipation | 1.8 mA from 3 V |
| Technology | 0.6-µm MESFET |



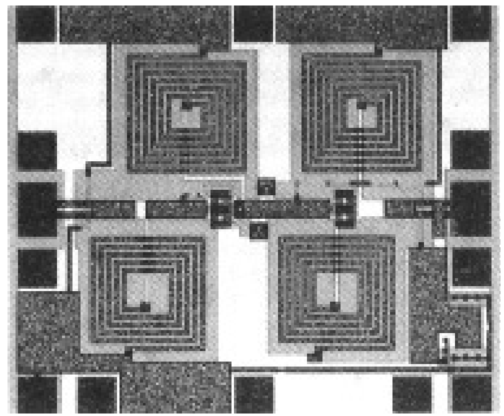
Kermarrec, *et al.*, M/A-Com, 1992

| | |
|---|---|
| Gain | 14.5 dB |
| Noise Figure | 1.7 dB |
| 3rd-order IM | -55 dBc at -30 dBm input |
| Frequency Band | 1.9 GHz |
| Power dissipation | 3.2 mA from 4 V |
| Technology | 1-µm E/D MESFET |

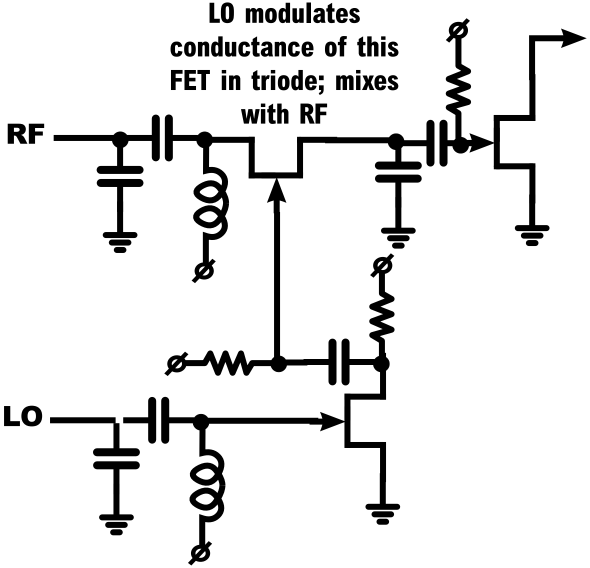
# GaAs ICs for Receiver Front-Ends

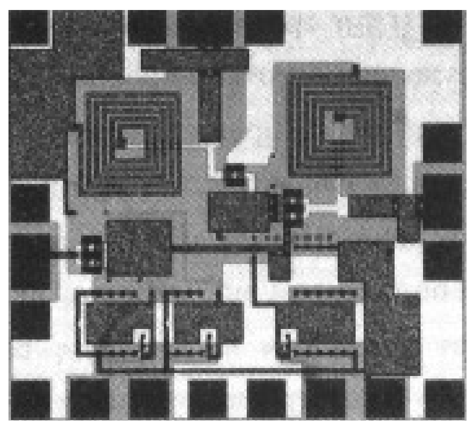



Ohgihara, *et al.*, Sony, 1993



| | |
|---|---|
| Gain | 18 dB |
| Noise Figure | 2.8 dB |
| Intercept Point | 7 dBm (output) |
| Frequency Band | 2 GHz |
| Reverse Isolation | 21 dB |
| Power Dissipation | 4 mA from 3 V |
| Technology | 0.5-µm GaAs JFET |



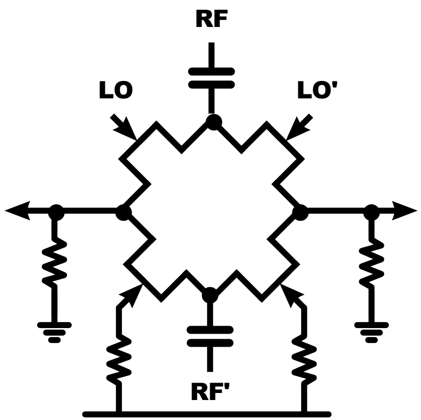



| | |
|---|---|
| Conversion Gain | 5.7 dB |
| Noise Figure | 10.8 dB |
| Intercept Point | 8 dBm (output) |
| Frequency Band | 2 GHz |
| LO-RF Isolation | 13 dB |
| Power Dissipation | 4 mA from 3 V |
| Technology | 0.5-µm GaAs JFET |

# Key Components in Cellular Telephone

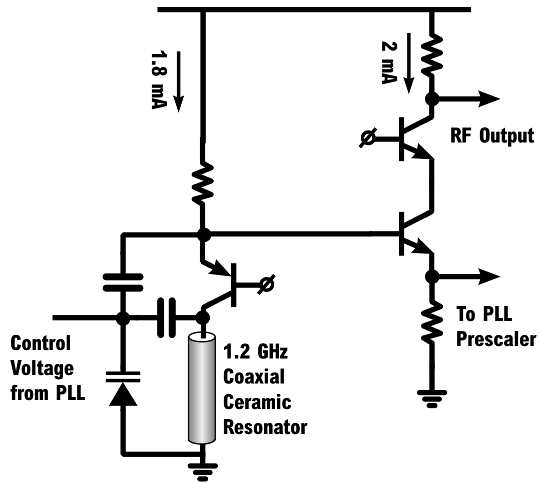
### Upconversion Mixer

Woo, *et al.*, Pacific Monolithics, 1992



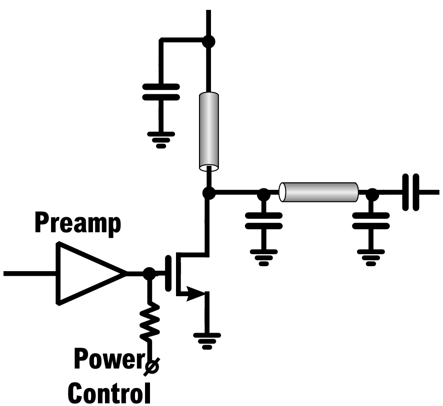

### Transmitter VCO

Beyer & Lipperer, Siemens, 1992




- VCO usually discrete, tuned by ceramic resonator for high Q ⇨ low phase noise
- Varactor adjusts oscillation frequency

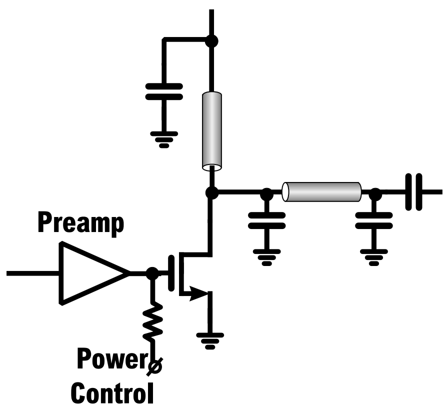
### Power Amplifier



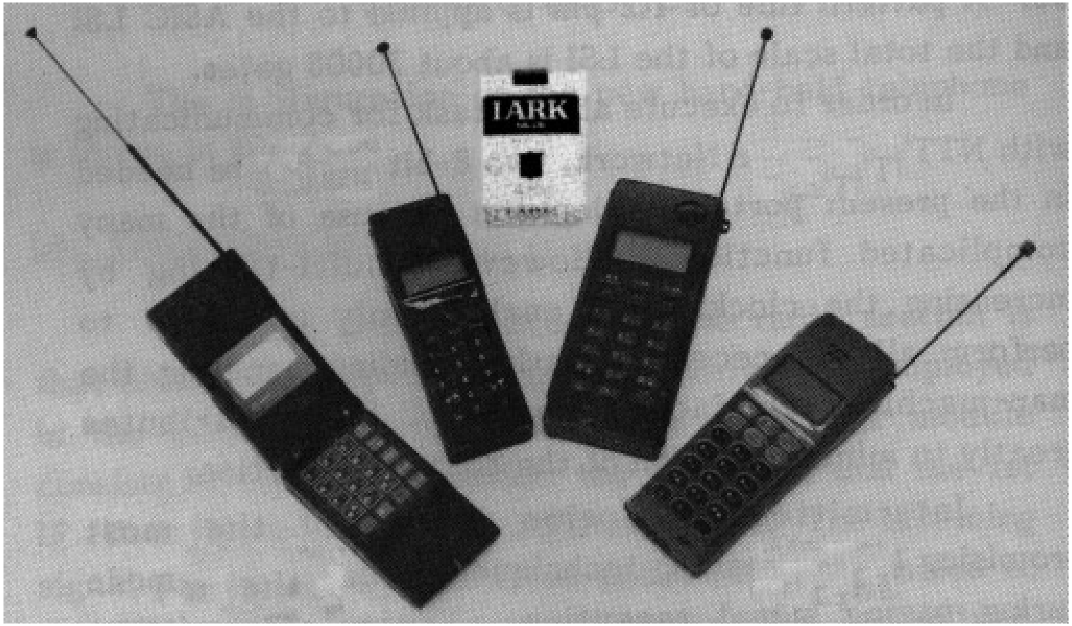

- Almost always a separate module with heat-sink package
- Designed for high power conversion efficiency
- Class-C operation, followed by impedance-matching circuits and filter to remove harmonics
- Typically a cascade of single FET stages, appropriately biased

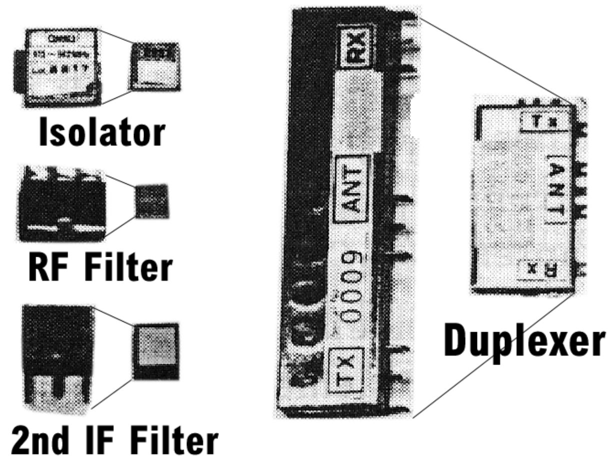
# Power Amplifier

- Almost always a separate GaAs module with heat-sink package
- Designed for high power conversion efficiency
- Class-C operation, followed by impedance-matching circuits and filter to remove harmonics
- Typically a cascade of single FET stages, appropriately biased



# Smaller Telephone Handsets

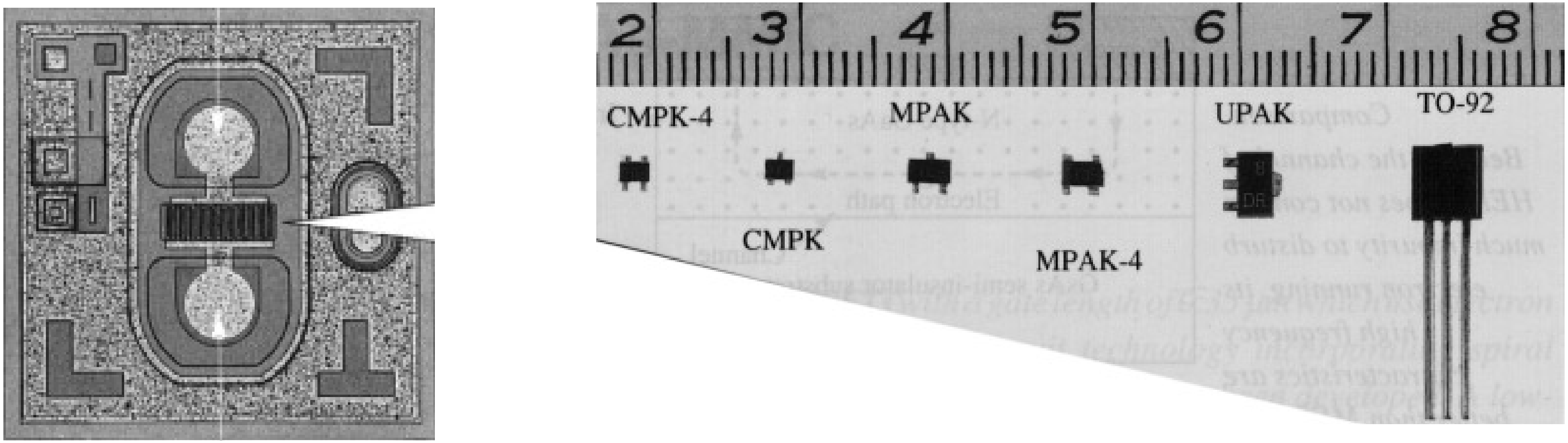


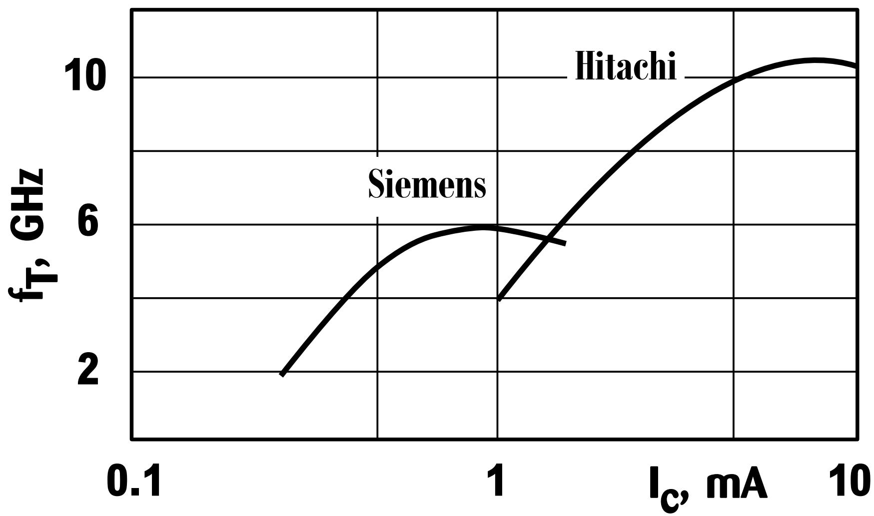




Shimizu, *et al.*, NTT, 1991

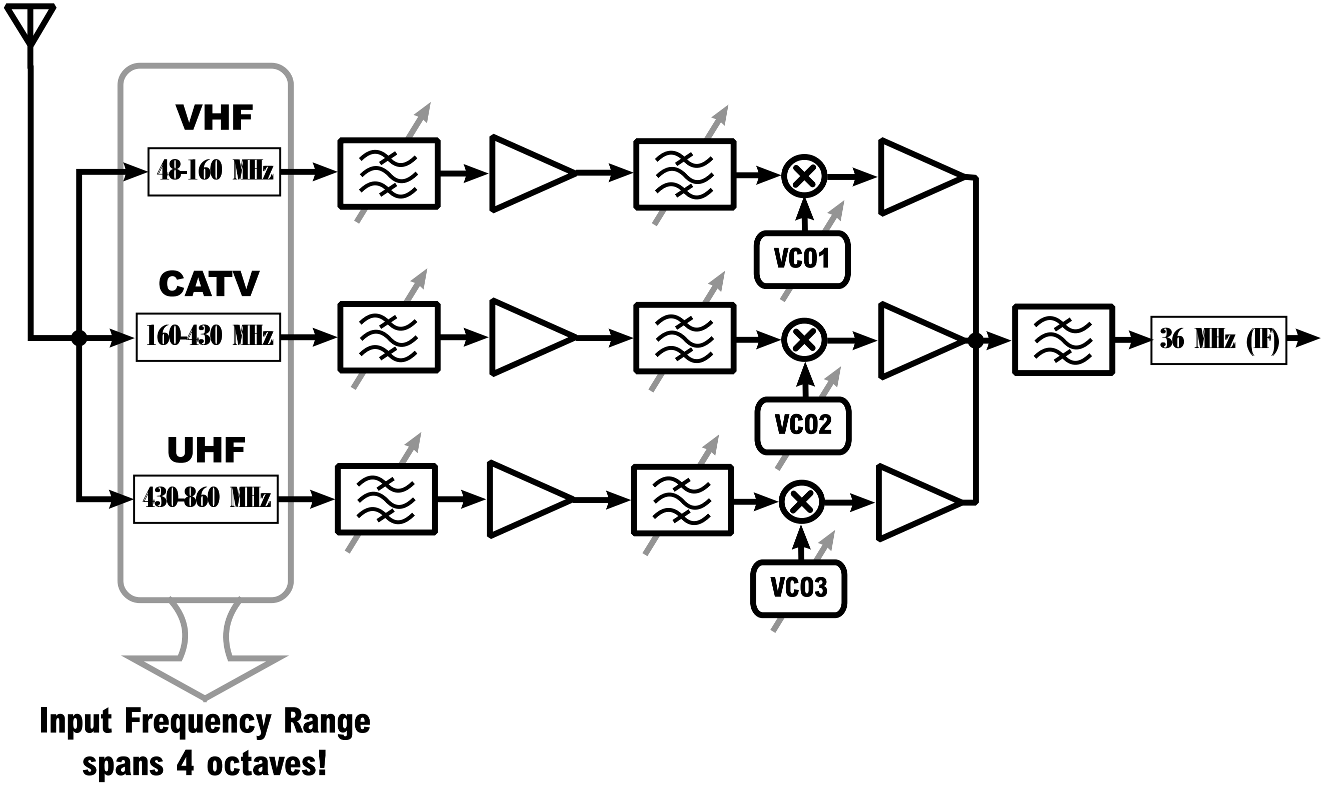
- Handsets are attaining smallest practical size: 150 cc, 230 g, distance between human mouth and ear
- Miniaturization comes from reduction in size of *passive components* and their *packages*, not from greater integration of the electronics!

# Discrete Bipolar Transistors in Low-Power RF Applications



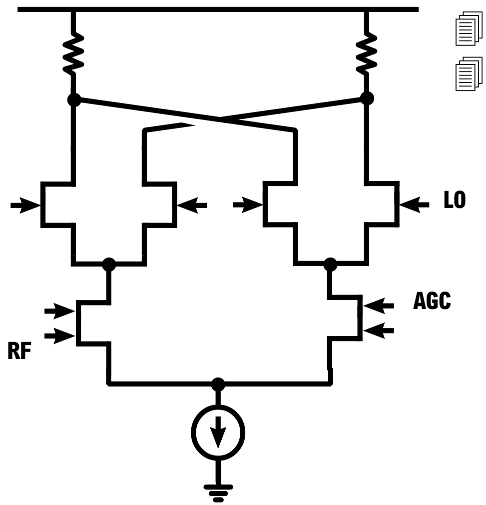



# ICs in Television Tuners




- ✓ Mixers
- ✓ LNA and Variable Gain Amplifier
- ✓ Local Oscillator

# Mixers and LO for Upconversion TV Tune




Ablassmeier, *et al.*, Siemens, 1980

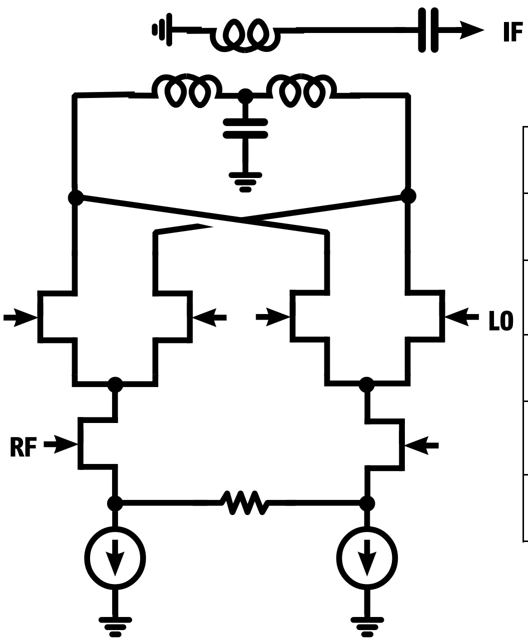
Müller, *et al.*, Siemens, 1984

Off-chip oscillator

| | |
|---|---|
| RF Range | 40-900 MHz |
| IF | 2500 MHz / 36 MHz |
| Conversion Gain | 20 dB |
| Noise Figure | 6-8 dB |
| In-channel signal causing 1% cross-modulation | 20 mV |

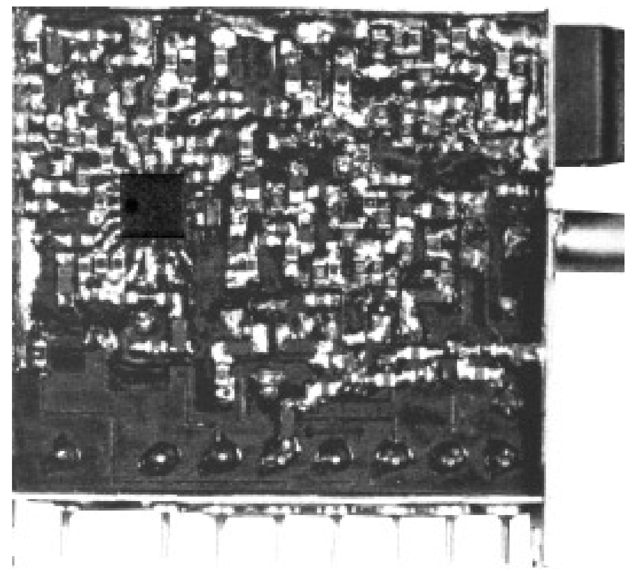
# Low-Voltage TV Tuner

- Mizukami, *et al.*, Hitachi, 1988
- Mizukami, *et al.*, Hitachi, 1992

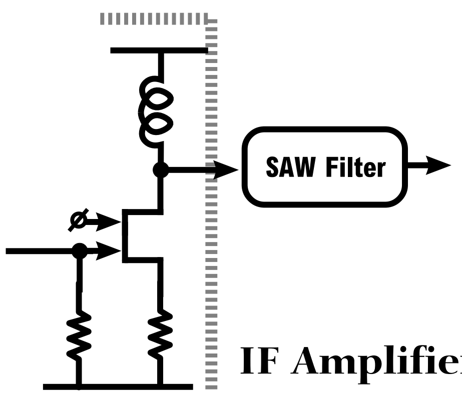



**Mixer**

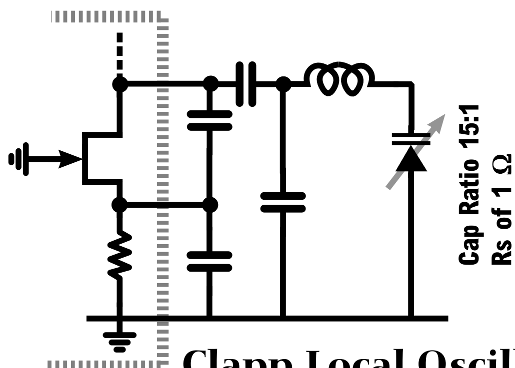
| | |
|---|---|
| RF Range | 48-860 MHz |
| Conversion Gain | 20-23 dB |
| Noise Figure | 11-13 dB |
| 3rd Order IM | -50 dB at -30 dBm inputs |
| Power Dissipation | 225 mW from 5-V<br>135 mW from 3.3-V |
| Technology | 1-µm GaAs MESFET |



**Tuner Assembly**



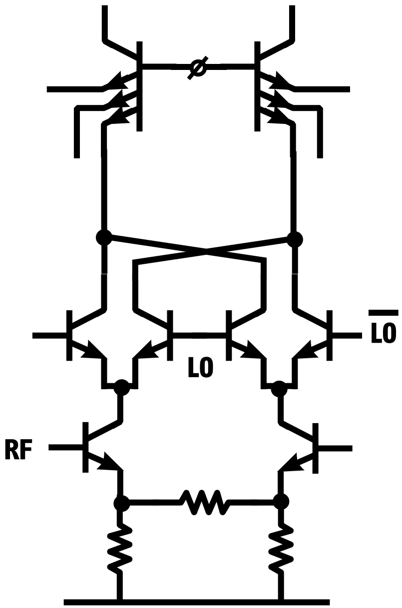

**IF Amplifier**



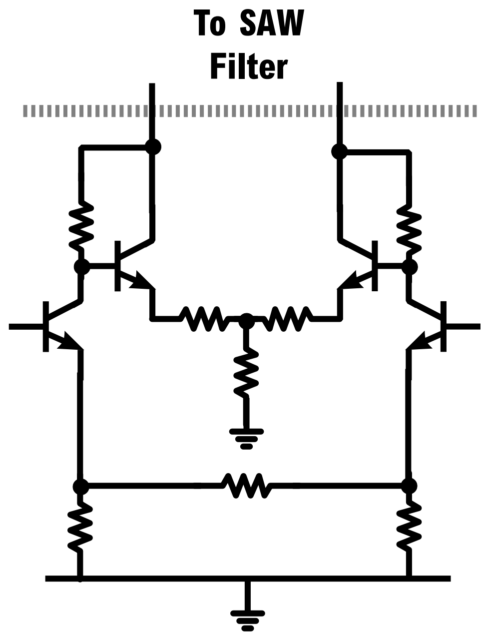

**Clapp Local Oscillator**

# Silicon TV Tuner ICs

🗐 Fenk & Tauber, Siemens, 1986




**RF Amplifier & Mixer**




**SAW Filter Driver**

- Conventional single-conversion frequency plan
- Covers 54 MHz to 438 MHz (5 GHz bipolar process) in two separate sub-sections of IC

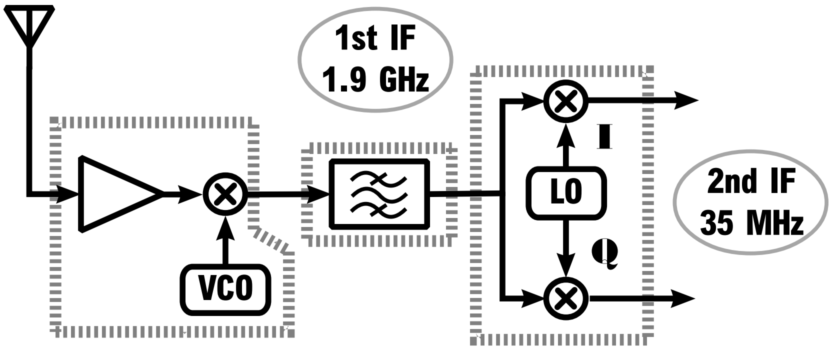
| | |
|---|---|
| RF Range | 175-462 MHz |
| IF | 60 MHz |
| Conversion Gain | 34 dB |
| Noise Figure | 8.3-9 dB |
| In-channel signal causing 1% modulation | 70 mV |

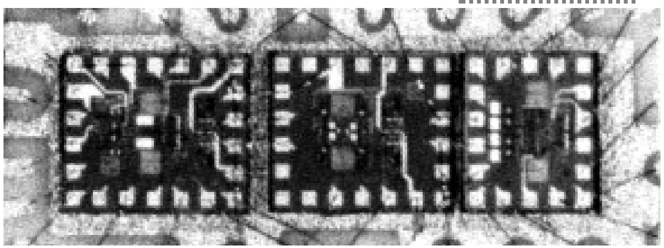
🗐 van Glabbeek, *et al.*, Philips, 1987

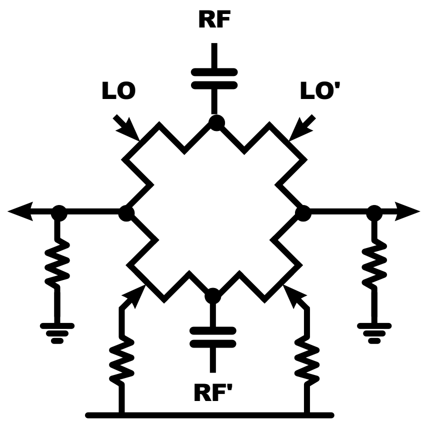
Includes UHF input (up to 900 MHz)

# Highly Integrated TV Tuner

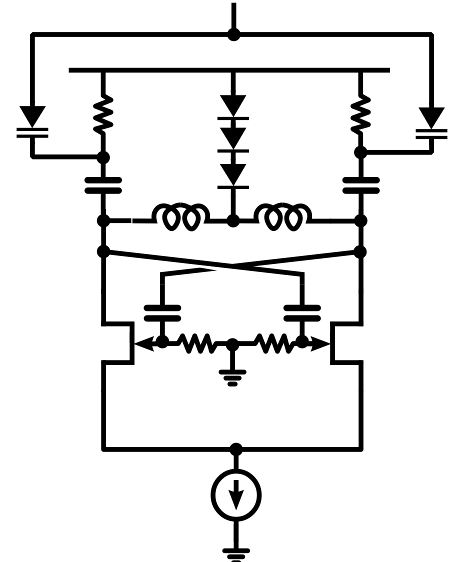
Ducourant, *et al.*, LEP/Philips, 1989






FET Switch Mixer



LC Tuned Multivibrator VCO

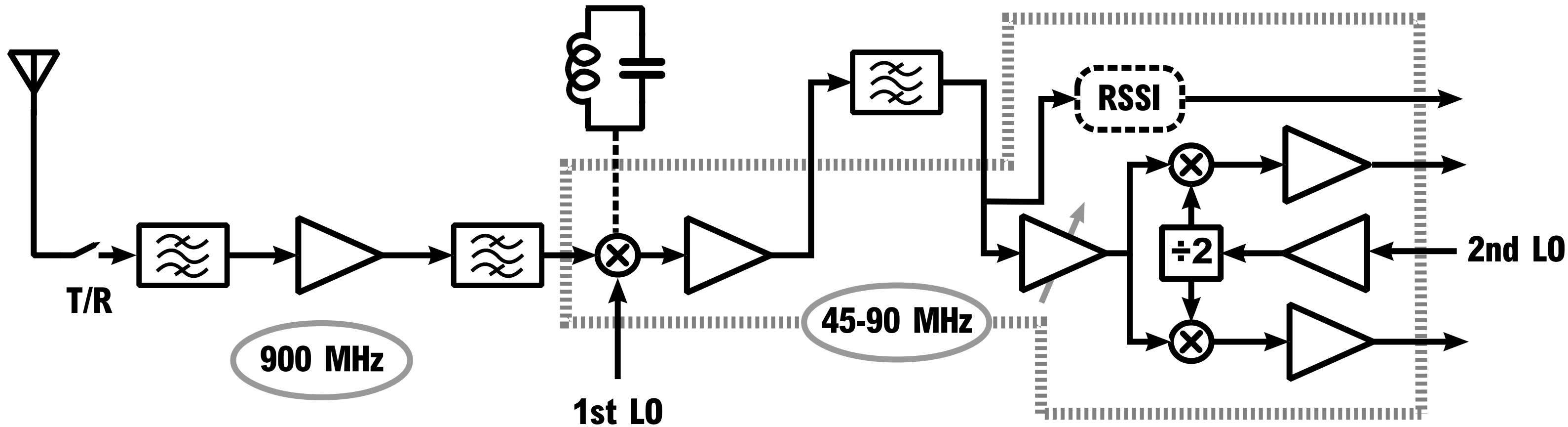
| | |
|---|---|
| RF Range | 48-860 MHz |
| Conversion Gain | 18 dB |
| Noise Figure | 12 dB |
| Input signal level for 1% cross-modulation | 5.6 mV |
| Technology | 0.7-µm GaAs MESFET |

- Eliminates *all* RF passive components!
- 1st IF filter is a GaAs tuned amplifier (4 dB down at Δf=70 MHz)
- On-chip *RC-CR* network to generate quadrature LO gives 60 dB image rejection, 70 dB after trim (channel independent)

# RF ICs in Digital Cellular Telephones

Fenk, *et al.*, Siemens, 1990
Badura, Siemens, 1991

**Receiver IC**

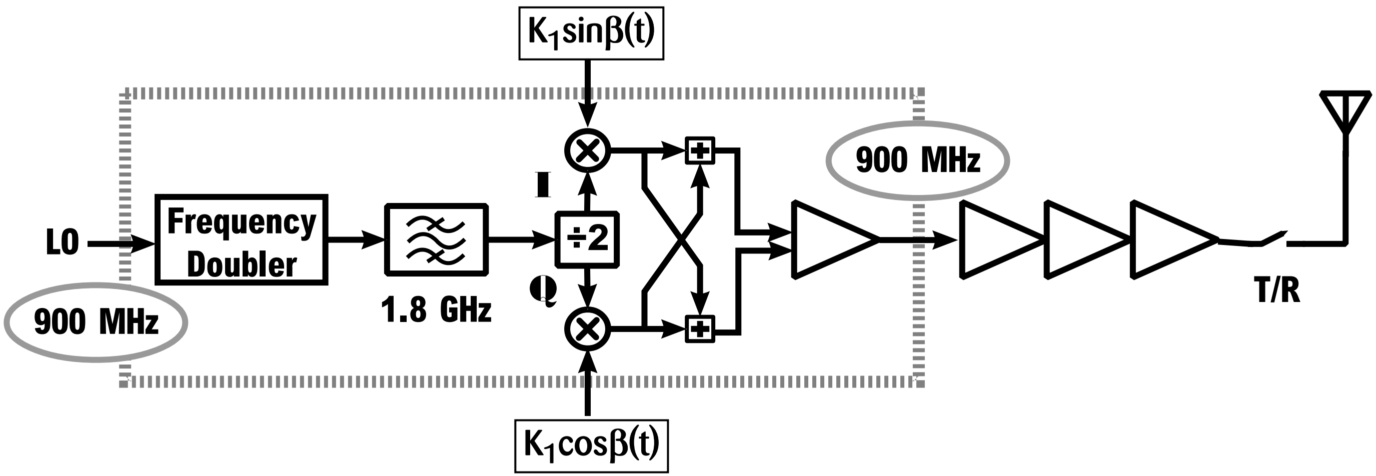



- Implemented in 7.5 GHz silicon bipolar technology
- Fully balanced signal path on IC
- 15 dB mixer conversion gain + 70 dB AGC range (implemented by cascade of four amplifiers with controlled degeneration resistance)
- 7 dB Noise Figure
- 27 mA drain from 4.5 to 5.5 V; 10 μA in standby

# RF ICs in Digital Cellular Telephones

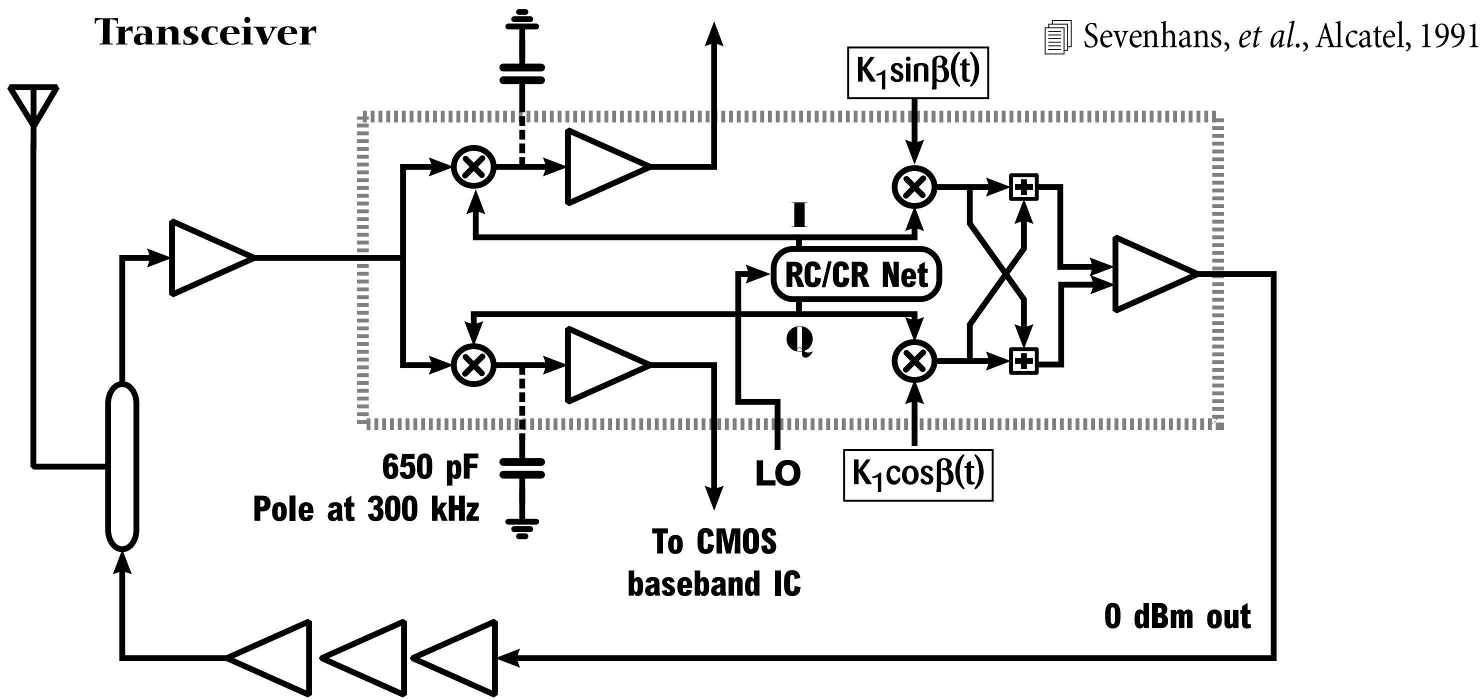
Fenk, *et al.*, Siemens, 1990
Badura, Siemens, 1991

**Transmitter IC**




- One-step upconversion of complex baseband signal GSM ➪ phase-shift modulation (GSM)
- I-Q matching on-chip good enough (<2° error) for:
  Carrier suppression of 45 dB
  SSB rejection of 45 dB
  Intermod products less than 42 dB
- 40 mA drain from 4.5 to 5.8 V; 10 µA standby
- 0 dBm drive into power amplifier
- Good isolation at 900 MHz on-chip; small leakage of intended sideband remodulates carrier to produce -57 dBc spur

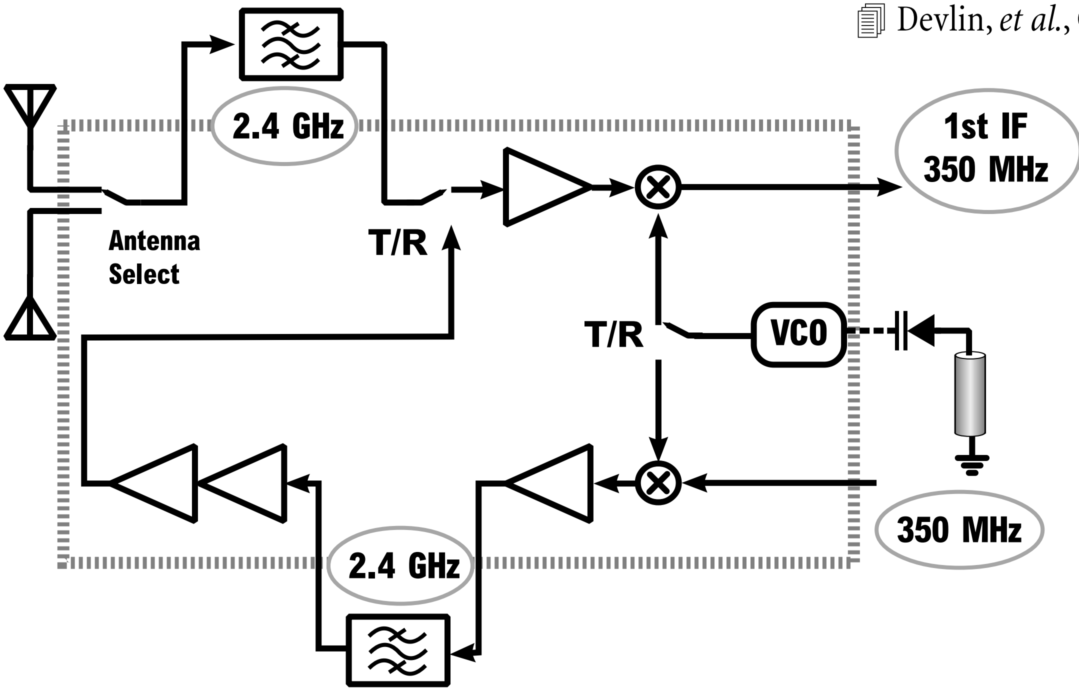
# RF ICs in Digital Cellular Telephones




- *Zero IF* eliminates bandpass filters
- LNA has 17 dB gain, 3 dB NF
- Rcv mixer must withstand large (-6 dBm) blocking signals 6 MHz away from carrier
- Degenerated Gilbert cell used ⇨ 14 dB NF + 3 dB due to image noise in SSB rcvd signal
- Quadrature LO generated with RC/CR to reduce power dissipation; this needs adjustment to meet specs
- 9 GHz silicon bipolar IC (2.5 mm sq)
- Drains 25 mA in RX, 45 mA in TX from 5V supply
- Image suppression of 40 dB

# RF IC for a Spread-Spectrum Radio

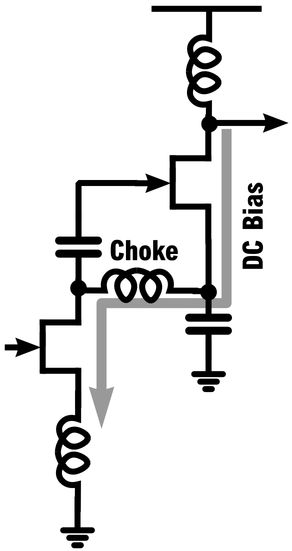
Devlin, *et al.*, GEC-Marconi, 1993

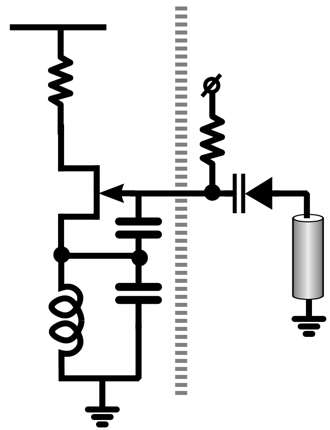


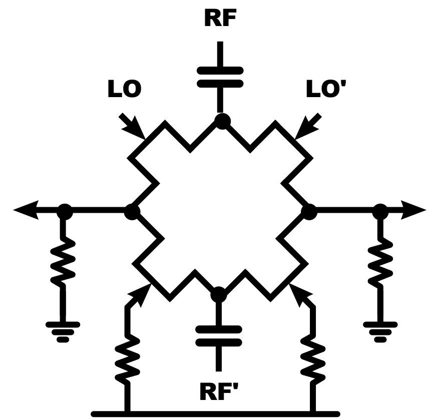

To silicon bipolar IC for IF signal processing and frequency de-spreading

- Monolithic GaAs transceiver IC for operation in the 2.4 - 2.48 GHz band
- For use in double-conversion architecture (thus 350 MHz first IF to reject image)
- Requires off-chip (dielectric resonator) passive bandpass filters
- On-chip switching for two-antenna diversity

# Details of Spread-Spectrum IC






**Low–Noise RF Amplifier**

- Noise matching with series feedback inductor
- Two cascaded gain stages share bias current

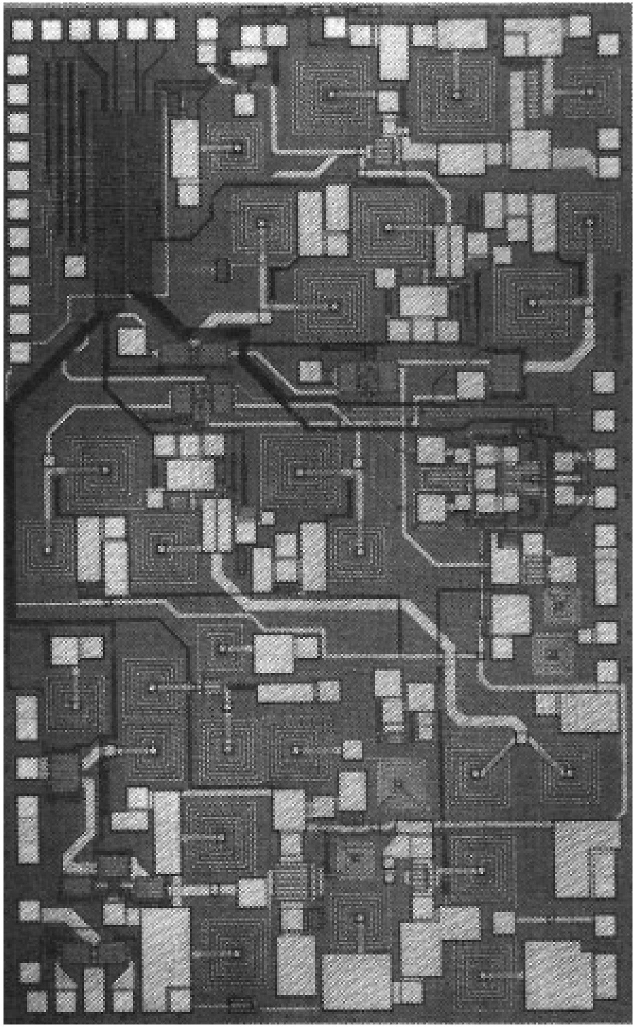
**Voltage–Controlled Clapp Oscillator**

- Varactor affords tuning range of 150 MHz
- Phase noise is -122 dBc/Hz at a 1 MHz offset from carrier

**Mixer in TX and RX**

- High Linearity
- 6 dB conversion loss

# Chip Performance

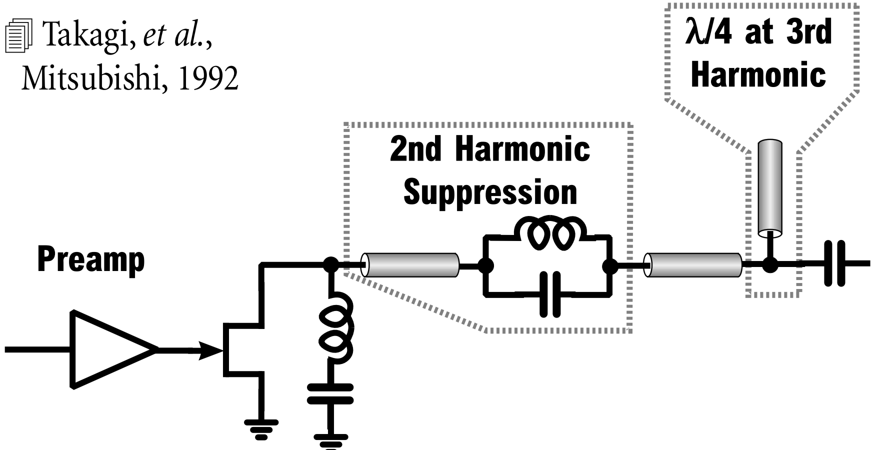


| | |
|---|---|
| Transmit Level | Up to 21 dBm |
| Transmitter Gain | 38 dB |
| Phase noise | -122 dBc/Hz at 1 MHz off carrier |
| Current Drain | 220 mA from 5 V in transmit mode<br>30 mA in receive mode<br>0.5 mA in standby |
| Receiver Gain | 14 dB |
| Net Noise Figure | 4 dB (DSB) |

More than 20 spiral inductors on-chip!

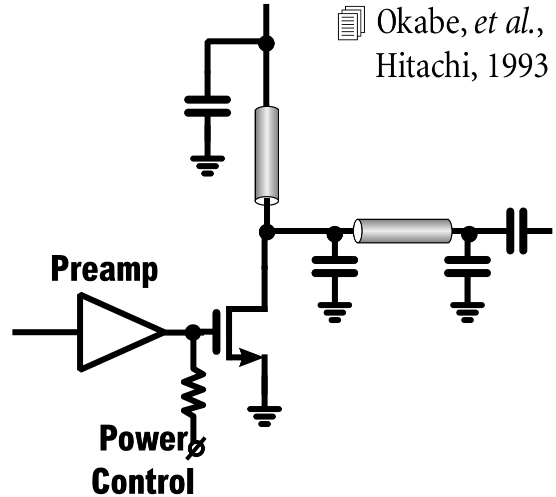
# Power Amplifiers

Takagi, *et al.*,
Mitsubishi, 1992




| | |
|---|---|
| Peak Output Power | 1.3 W from 5.5 V supply |
| Efficiency | 0.63 |
| 2nd & 3rd Harmonics | -50 dBc and -40 dBc |
| Frequency Band | 900 MHz |

Okabe, *et al.*,
Hitachi, 1993

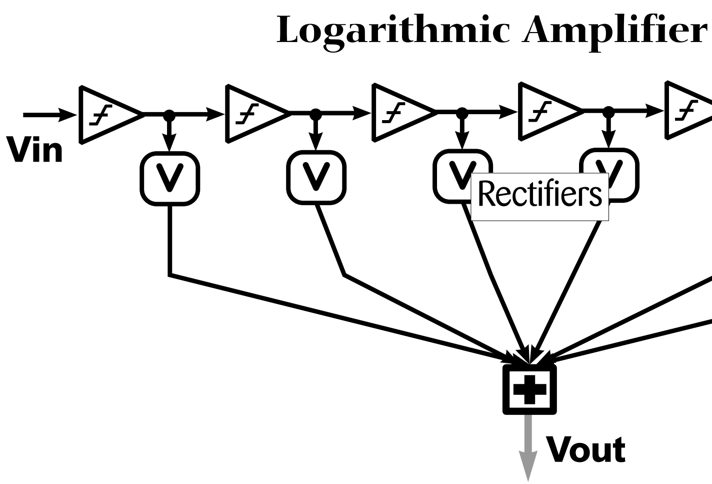


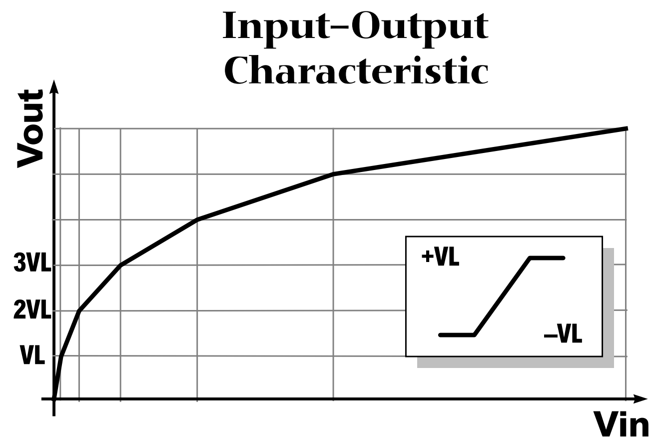

| | |
|---|---|
| Peak Output Power | 3.6 W from 6 V supply |
| Efficiency | 35% |
| 2nd & 3rd Harmonics | -45 dBc |
| Frequency Band | 900 MHz |

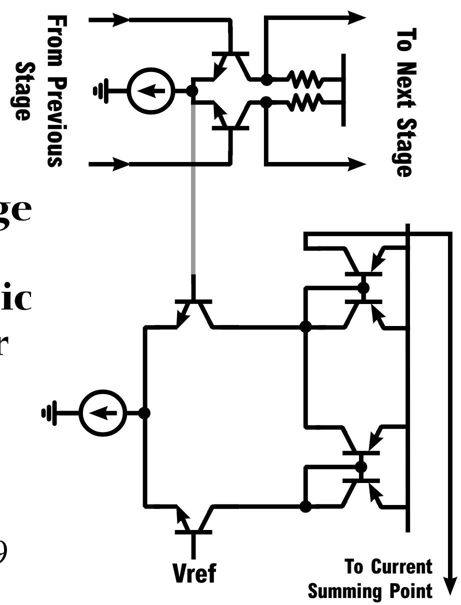
- Narrowband power amplifiers:
  Usually single transistors biased close to cutoff (for high power-conversion efficiency)
  Followed by filters to remove harmonics

- Efficiency at high frequencies determined by transistor $f_T$ and parasitic capacitances

# Signal Strength Indication Circuits



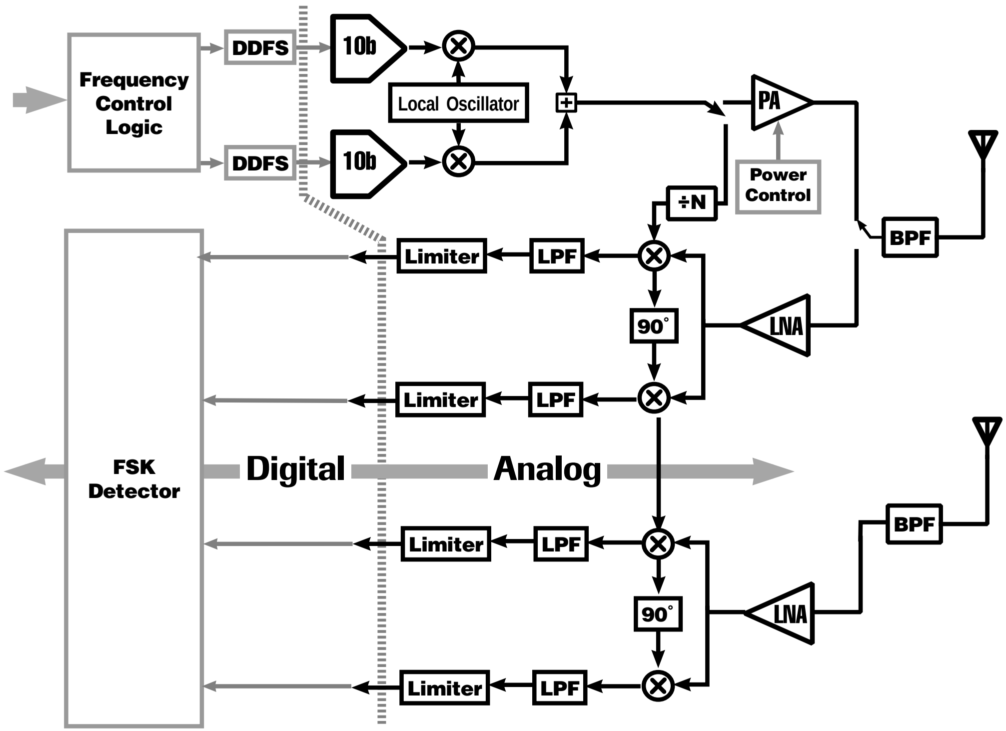




Single Stage in Logarithmic Amplifier

Fenk, *et al.*, Siemens, 1989

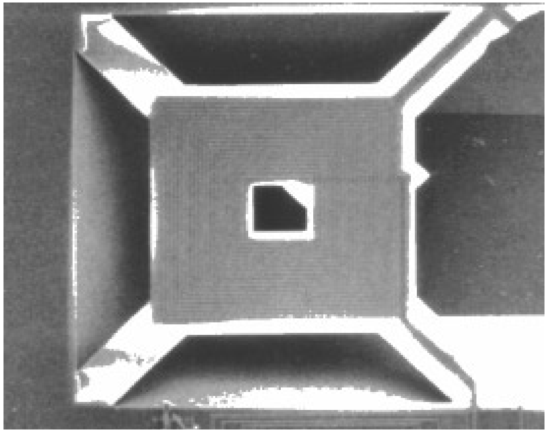
- Received signal-strength indication (RSSI) required for AGC and transmitted power control
- Logarithmic amplifiers with full IF bandwidth provide RSSI over 70 dB or more
- Approximate logarithm with cascade of AC coupled high-speed limiting amplifiers

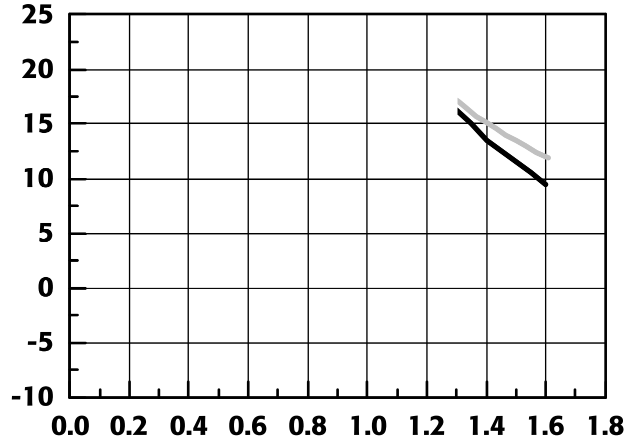
# The UCLA CMOS Frequency-Hopped Spread-Spectrum Transceiver

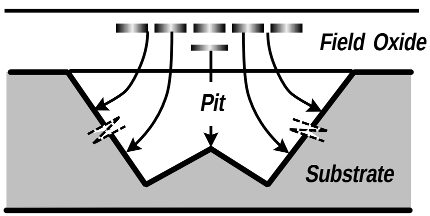


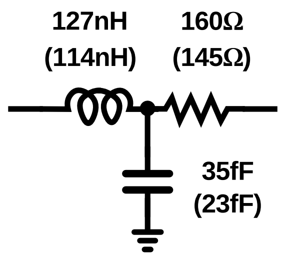

- Mixed analog-digital design, appropriate for CMOS
- Direct-conversion receiver eliminates off-chip filtering
- Binary FSK modulation may be detected with limiting, no AGC
- No high-speed equalization
- No high chip rate

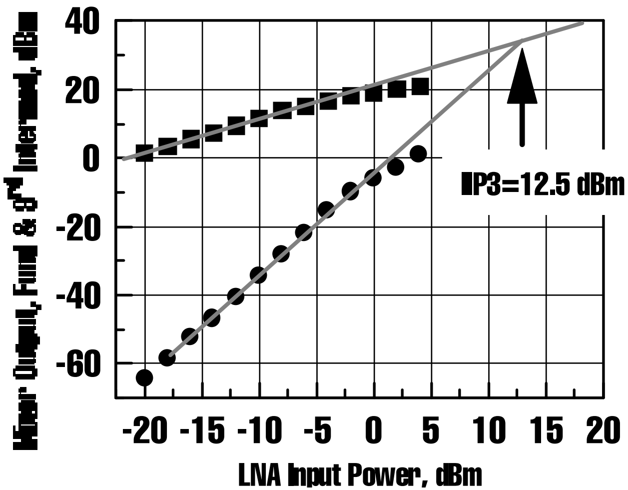
# On-Chip CMOS Tuned Amplifiers





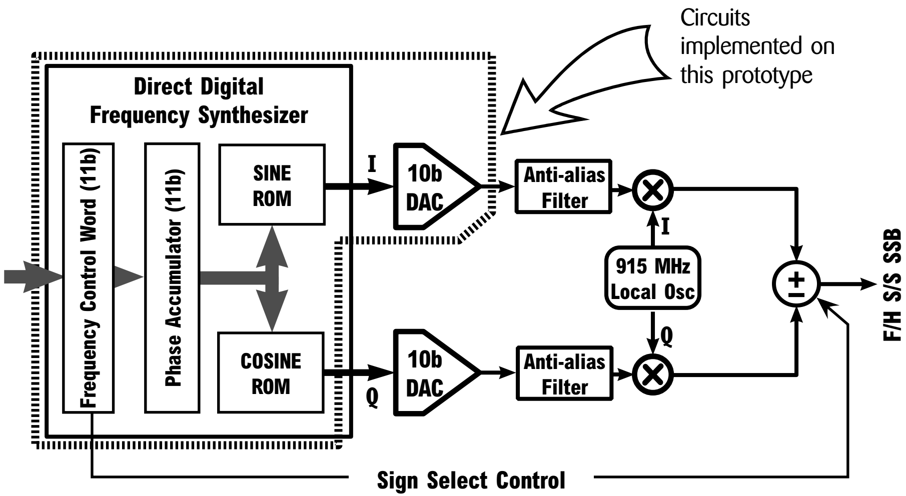



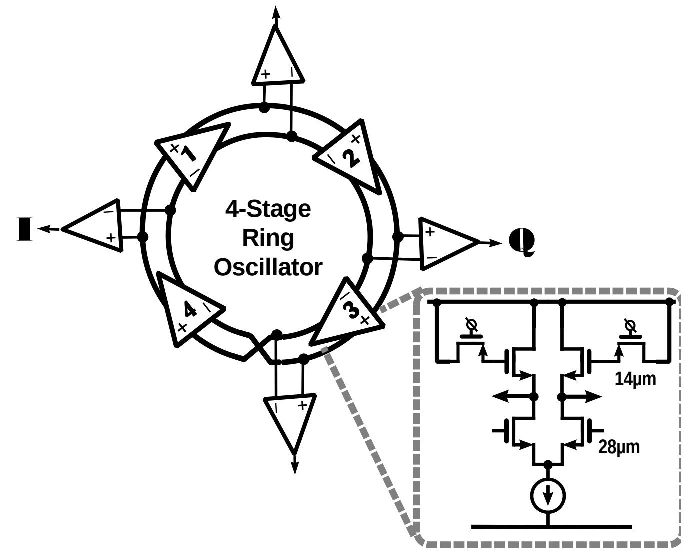



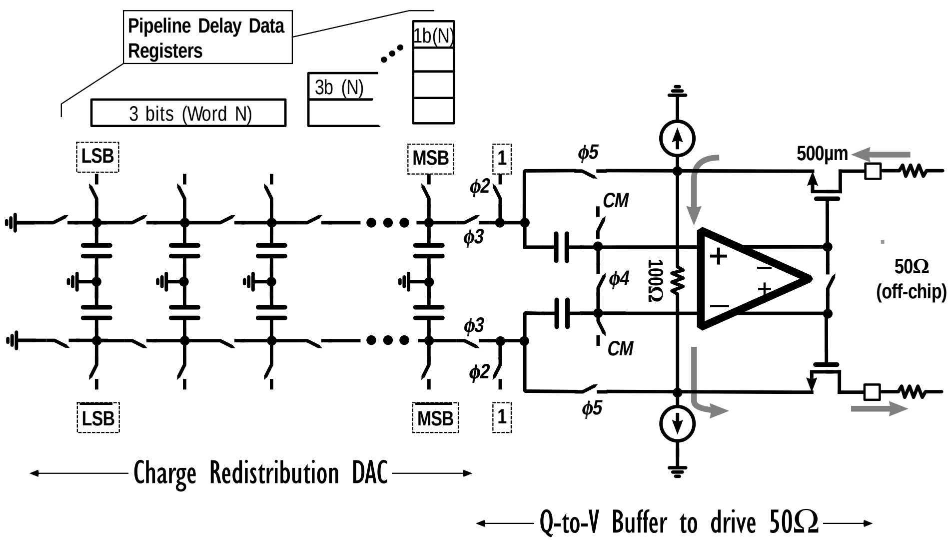




- 1 GHz front-end possible in 1-μm CMOS!
- High linearity, low noise (3 dB NF), low current drain (~8mA) from 3-V
- Suspended inductor requires no extra masks

# Frequency Synthesizer

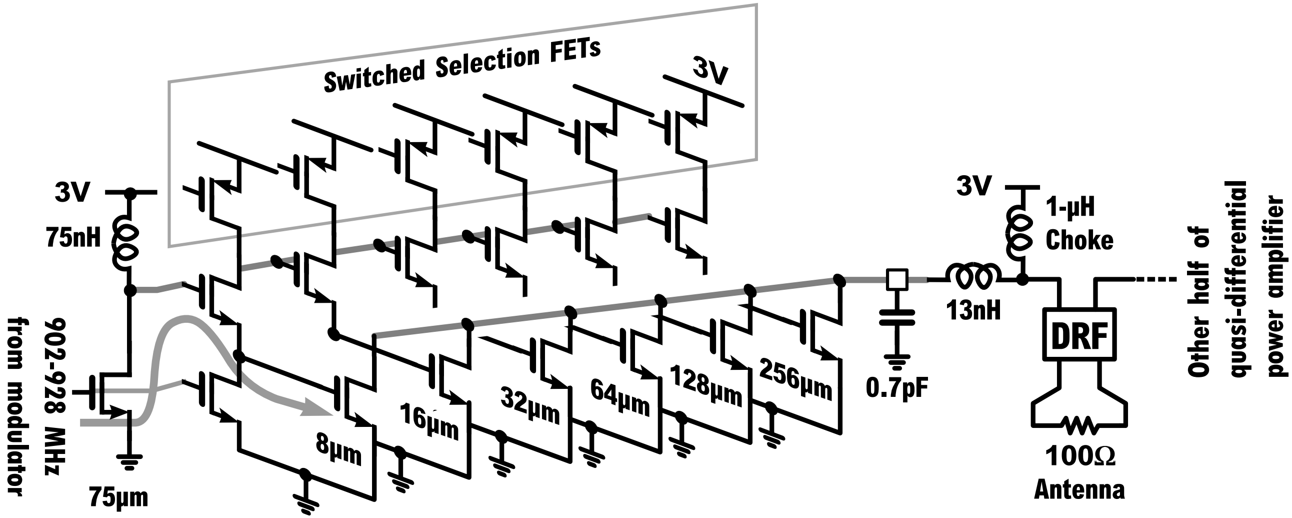


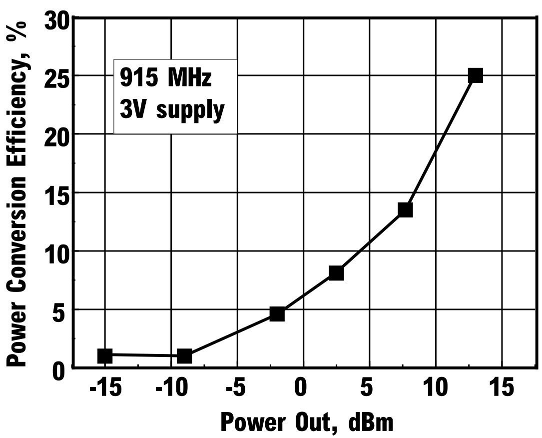




- DDFS-DAC shows worst-case –58 dBc spectral impurity, while dissipating 40 mW
- Fixed-frequency LO locked to 20 MHz crystal has –82 dBc/Hz phase noise at 100 kHz offset (10 mW)

# Power Amplifier

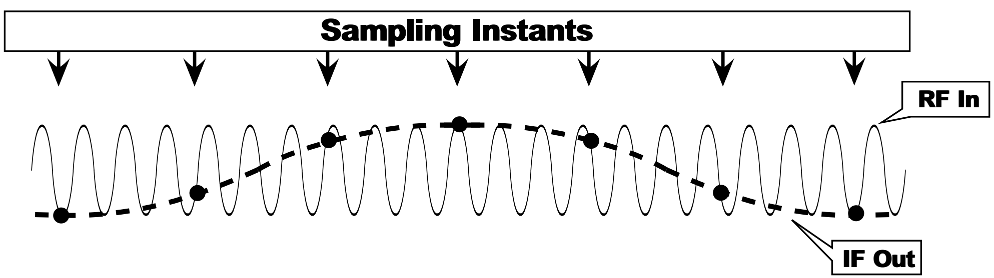


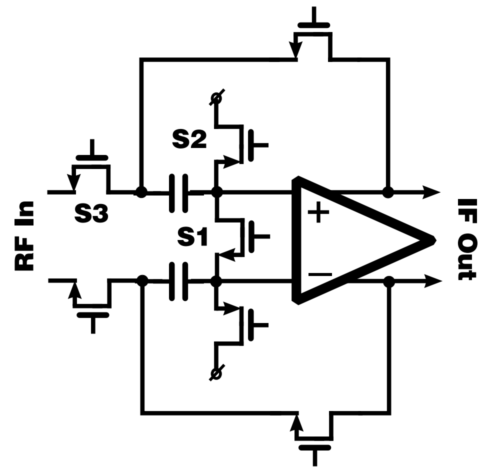




- Unique CMOS method to digitally select transmitted power level
- Good efficiency for low transmitted power levels
- Preamp with inductor load swings above power supply

# Frequency Mixers

- MOSFETs are much better suited to linear, continuous-time commutating mixers than BJTs!
- Alternative approach: Downconversion by direct sub-sampling of RF carrier (very high linearity, high NF)
- Subsampling mixer well-suited to direct-conversion receiver
- IIP3 of >20 dBm routinely possible, at typically10 mW dissipation, in 1-μm CMOS




- Four-FET commutating switch well-suited to upconversion mixers