INF5490 RF MEMS

LN14: Wireless systems using RF MEMS

Spring 2012, Oddvar Søråsen
Department of Informatics, UoO

INF5490: topics

- Course title: ”RF MEMS”
  - → 2 parts: **RF** and **MEMS**
  - Description and modeling of different RF MEMS components in focus

- This lecture:
  - **MEMS components used in RF systems**

Today's lecture

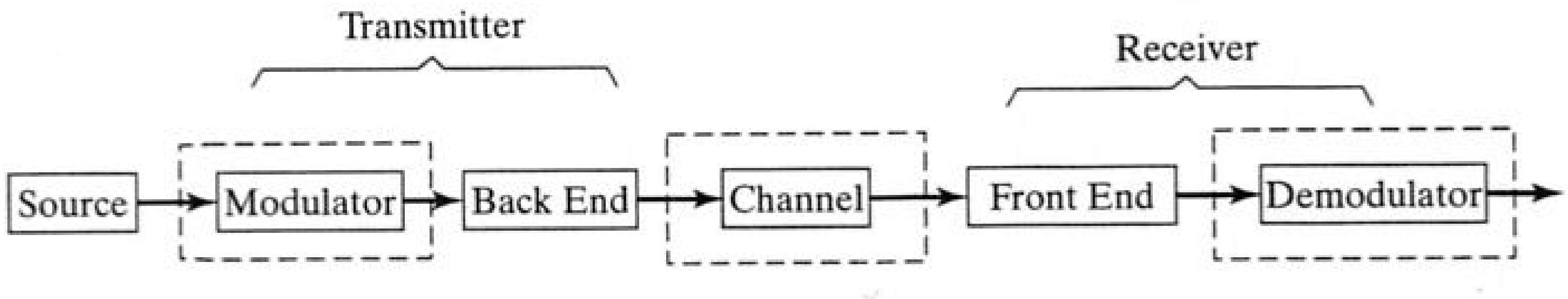
- Wireless communication
  - Different coding principles for RF transmission
- Technology and components used in RF systems
- Transceiver with RF MEMS
  - "**RF receiver** front-end" architecture
  - **Transmitter** architecture
- Relevant research topics

Wireless communication

- **Radio waves** are used for transmitting/receiving
  - Electromagnetic waves (Maxwell´s equations apply)
- Radio **”transceiver”** is a basic component
  - Transmitter + Receiver
- RF systems must
  - Transfer **power** at a specific **frequency**
  - Use a limited **bandwidth**

- **Filtering** needed to separate channels

General communication system



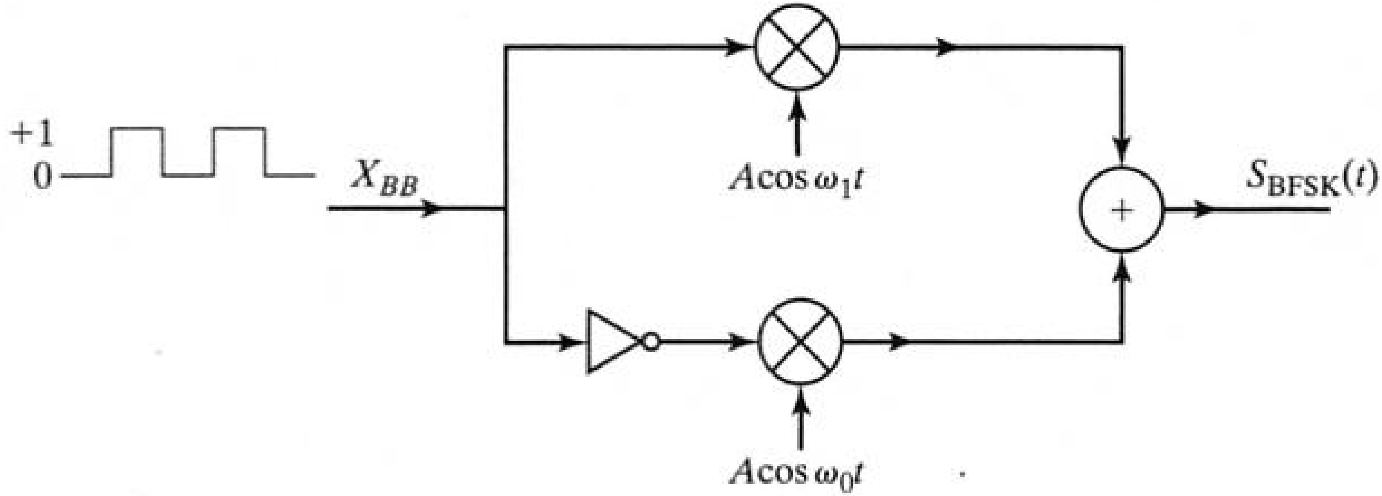
Bit streams are modulated (coded) onto a **carrier**

Radio channel introduces noise, interference, disturbances

Receiver shapes the signal for demodulation

Different coding principles

- Many different modulation schemes exist
  - F.ex. **BFSK, Binary Frequency Shift Keying**
  - Transfering digital data
  - Coding bits to 2 different frequencies (Tb is bit-duration)

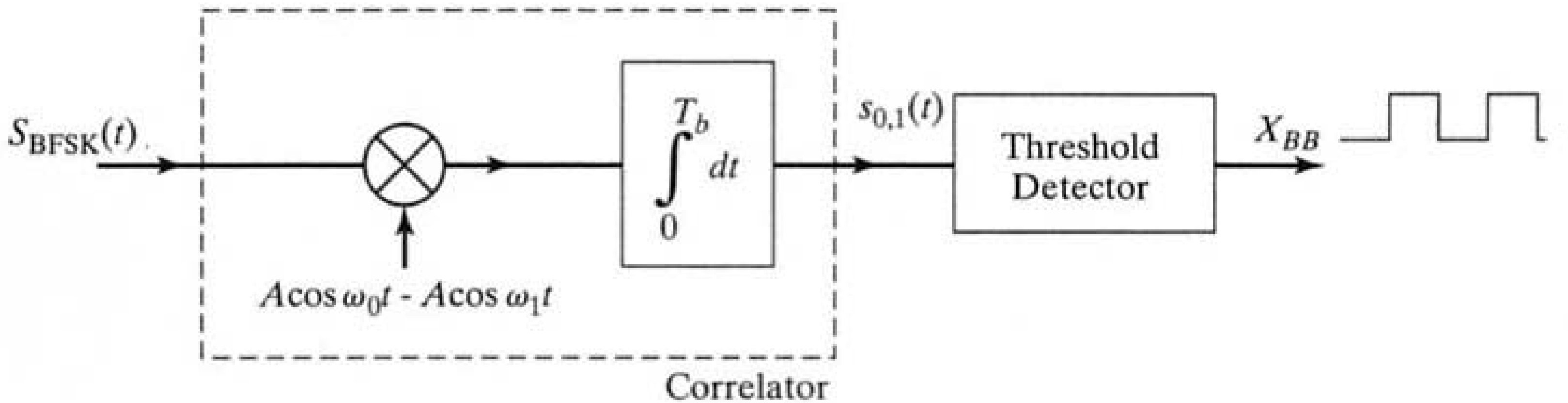


Demodulation BFSK

- Coherent demodulator

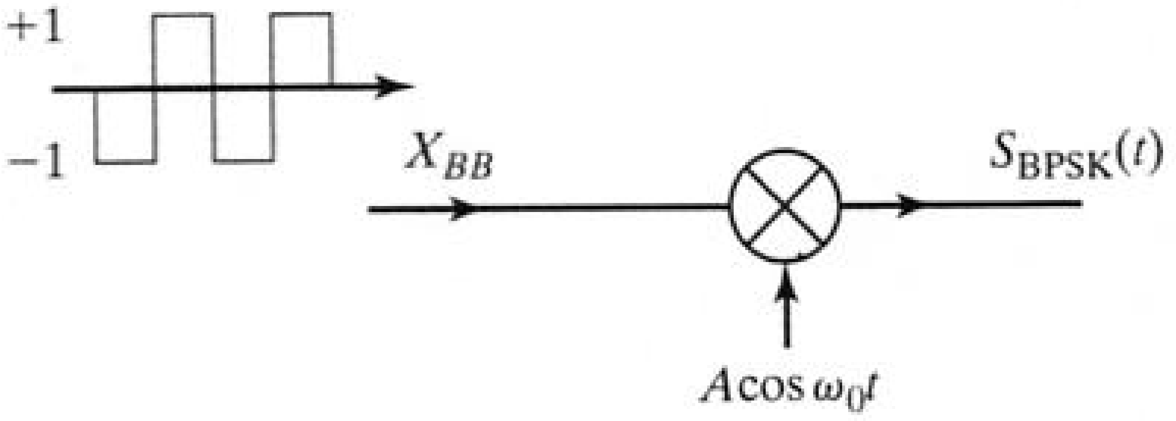
$$\text{logic } 0: \quad s_0(t) = \int_0^{T_b} (A\cos\omega_0 t)(A\cos\omega_0 t - A\cos\omega_1 t)\,dt = \frac{A^2 T_b}{2}; \qquad (1.1)$$

$$\text{logic } 1: \quad s_1(t) = \int_0^{T_b} (A\cos\omega_1 t)(A\cos\omega_0 t - A\cos\omega_1 t)\,dt = -\frac{A^2 T_b}{2}. \qquad (1.2)$$



BPSK

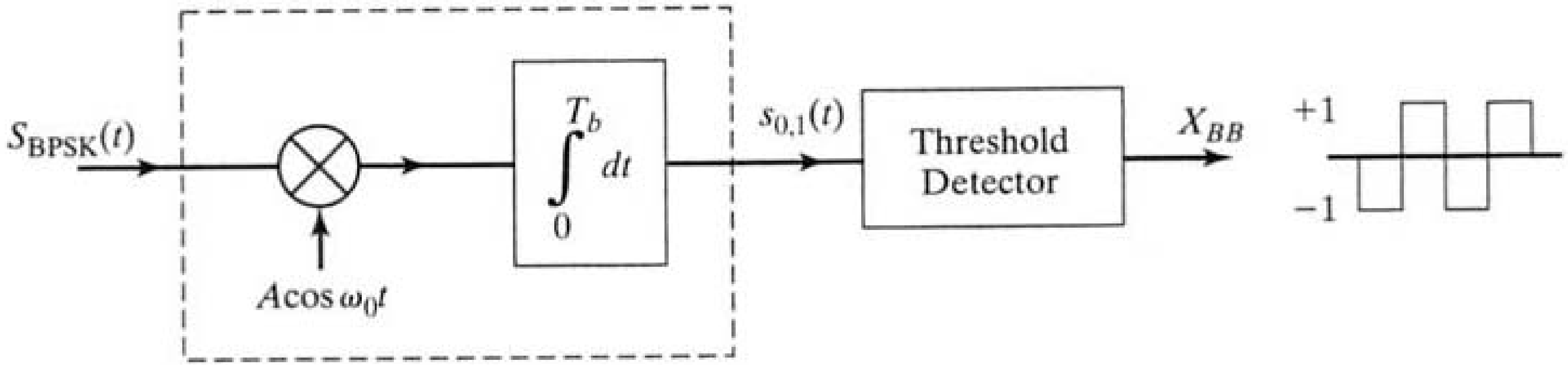
- **Binary Phase-Shift Keying**
- Modulate phase onto carrier
  – Phase changes 180 degrees from 0 to 1 (+ π)



Demodulation BPSK

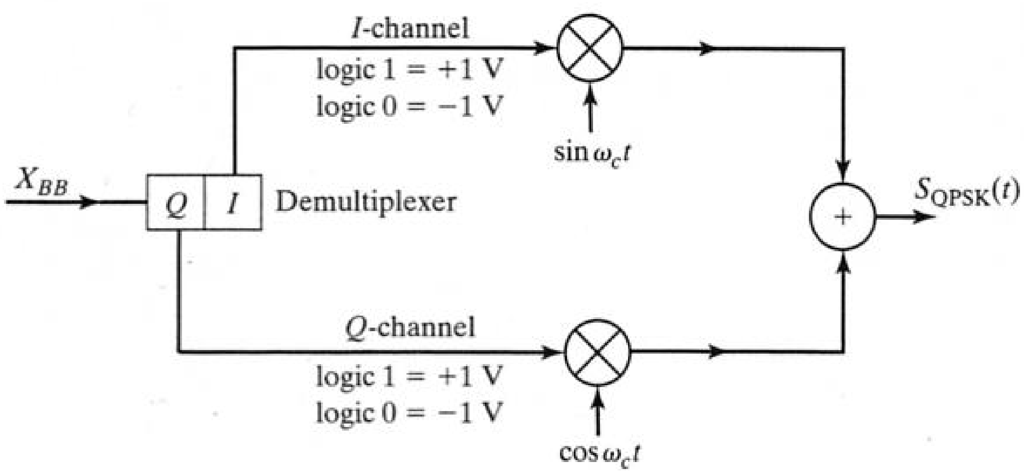
$$\text{logic 1:} \quad s_1(t) = \int_0^{T_b} (-A\cos\omega_0 t)(A\cos\omega_0 t)\,dt = -\frac{A^2T_b}{2};$$

$$\text{logic 0:} \quad s_0(t) = \int_0^{T_b} (A\cos\omega_0 t)(A\cos\omega_0 t)\,dt = \frac{A^2T_b}{2}.$$



QPSK

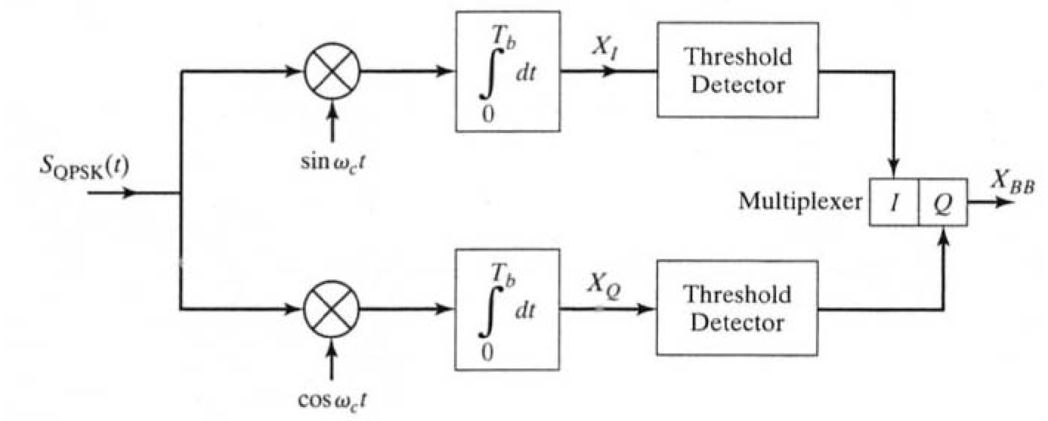
- **Quadrature Phase-Shift Keying**
- Having more than 2 representations of input data
  - Input is combined into bit-groups 00,01,10,11
- Half bit rate in each channel
- Demultiplexer sends every second bit up or down
- I and Q-channels are 90 degrees out of phase
  - **In-phase** component and **quadrature** component



$$s_{QPSK}(t) = \pm A \cos \omega_c t \pm A \sin \omega_c t.$$

QPSK, contd.

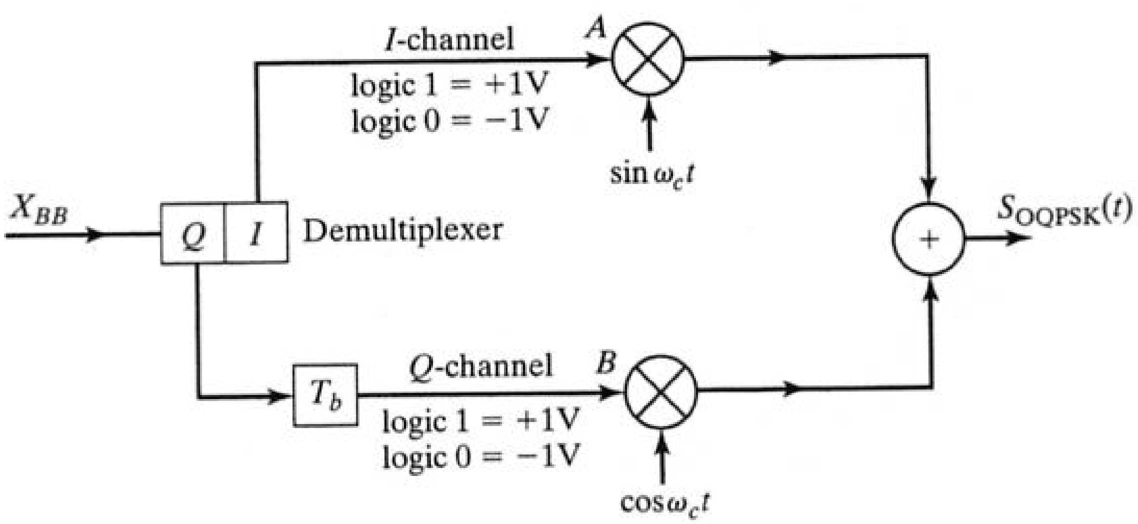
- QPSK demodulation
  - Sin and cos-signals are orthogonal
  - Each channel is demodulated independently as for BPSK



- QPSK is an ex. of **quadrature modulation** where the bit flow is split into pairs of bits (dibits)
  - Each dibit is mapped into four levels before modulation

Offset QPSK: modulator

- Each transmitting channel is non-ideal, having **finite bandwidth**:
  - → **Offset QPSK** can be used
  - Time delay Tb introduced in Q-channel
    - Offset = half the symbol period (2 Tb = period)
    - Hinders simultaneous signal transitions at A and B
    - Smaller phase shift. Lower requirements to channel bandwidth



Minimum Shift Keying

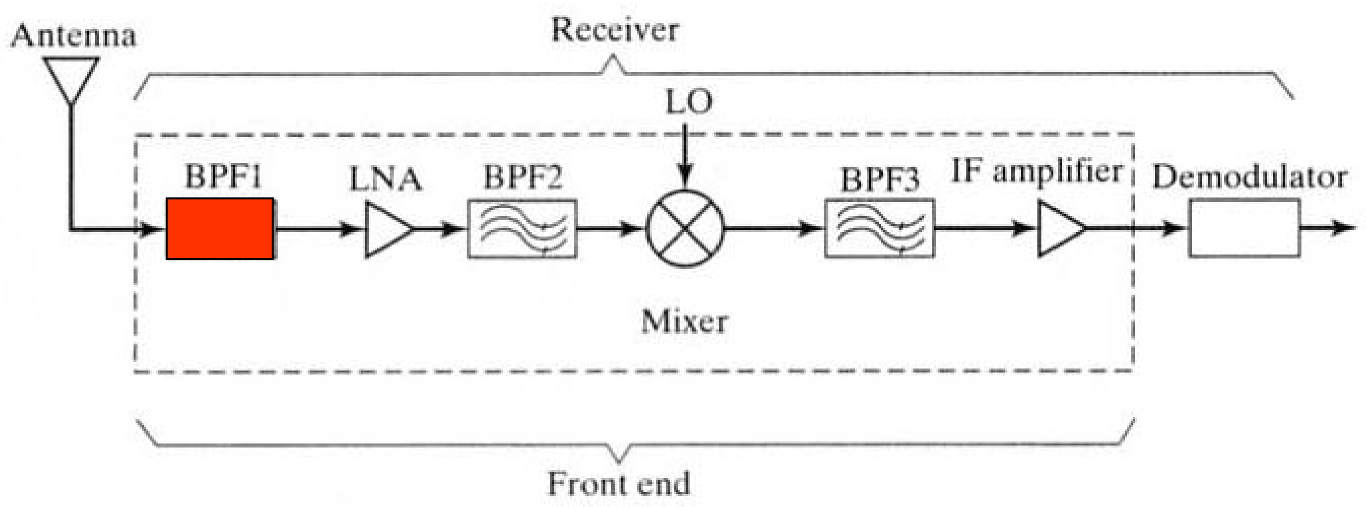
- Avoid large phase shifts at the end of each symbol!
  - Large, fast changes in phase mean large symbol bandwidth
  - Solution: **Multiply** channel signals with **half sine pulses** instead of rectangular pulses

- This is an example of **MSK, Minimum Shift Keying**
  - Continuous phase shift: not abrupt change of phase and no fast signal change

- MSK has a larger decrease in its spectrum than QPSK
  - Lower sidelobe signal influence

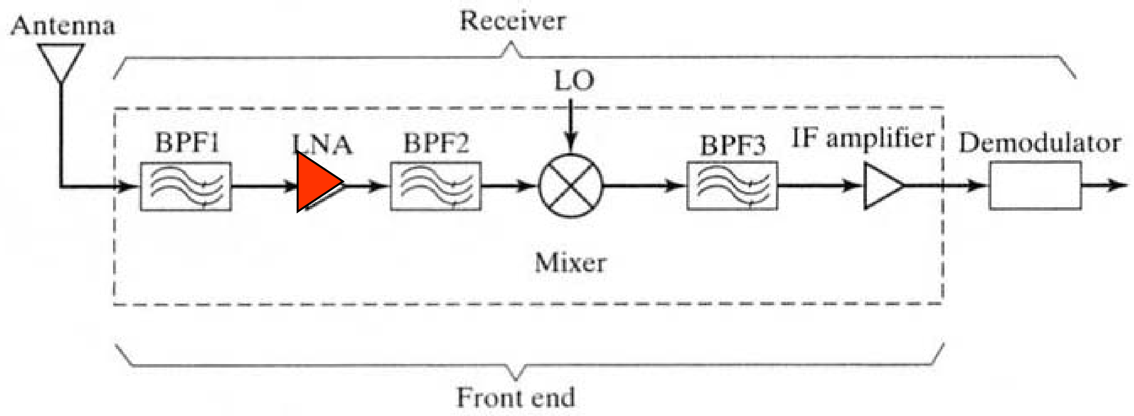
Receiver architecture

- Input filter, BPF1
  - **Band** selection filter
  - Narrow band RF filtering
  - Reduces Gauss noise and interference
  - Compromise, otherwise impractical. Good RF filtering is costly



Receiver, contd.

- **LNA**, RF amplifier **(Low Noise Amplifier)**
  - Requires high gain due to low SNR
  - LNA amplifies also **interference/noise** → Saturation can result
  - High gain means high BPF1 requirements
    - ”Compromise”: the BPF1 must be practical
  - LNA is non-linear, adds also **internal noise**
    - Generates intermodulation products from interference
    - These may have the same frequency as the signal and be destructive



LNA – Low Noise Amplifier

- Amplifier is typical **non-linear**
  - Output may be a 3rd order polynomial of the input signal

$$y(t) = \alpha_1 s(t) + \alpha_2 s^2(t) + \alpha_3 s^3(t)$$

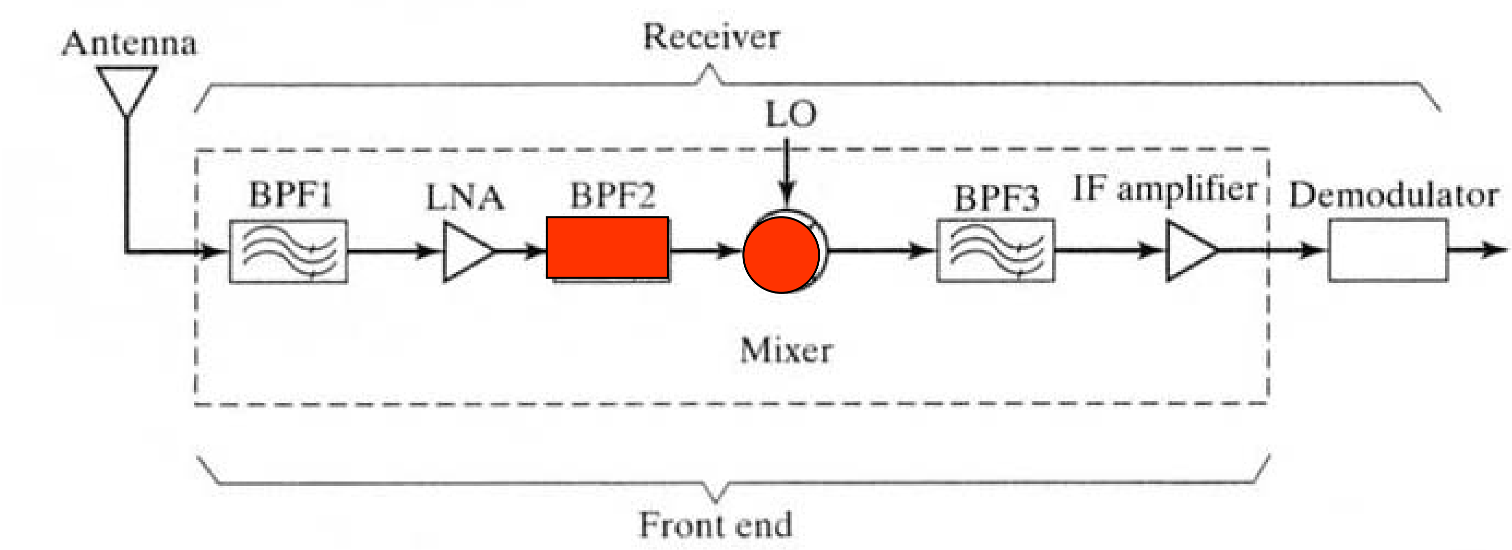
  - For a single frequency input signal, double and triple frequencies are generated

$$y(t) = \alpha_1 A \cos \omega_0 t + \alpha_2 A^2 \cos^2 \omega_0 t + \alpha_3 A^3 \cos^3 \omega_0 t$$
$$= \frac{\alpha_2 A^2}{2} + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right) \cos \omega_0 t + \frac{\alpha_2 A^2}{2} \cos 2\omega_0 t + \frac{\alpha_3 A^3}{4} \cos 3\omega_0 t$$

Harmonics are generated $\mathrm{HD}_3 = \frac{1}{4}\frac{\alpha_3}{\alpha_1}A^2$ (3. harmonic)

Architecture, contd.

- **Anti-image filter** used before mixing, BPF2
- **Mixing**
  - Frequency transformed to **Intermediate Frequency, IF**
  - Variable or fixed local oscillator (LO) -frequency



Mixing

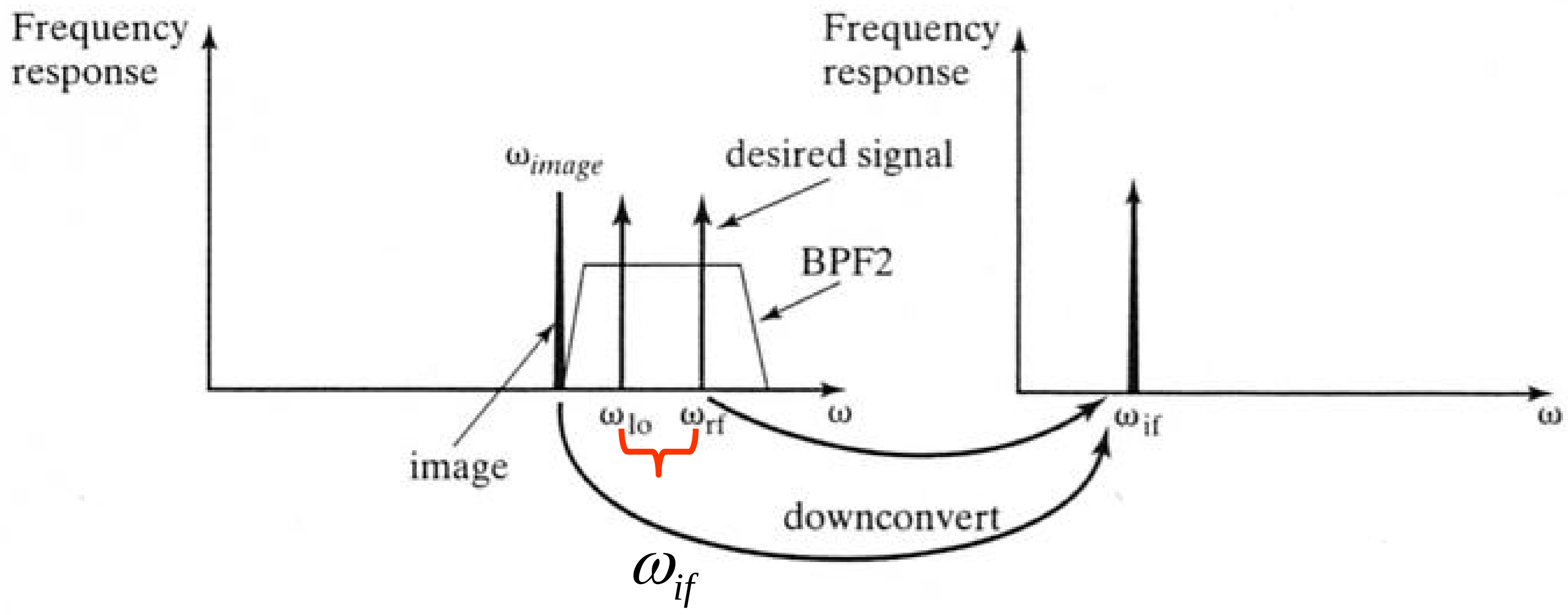
- Mixing is mathematically equivalent to multiplication
- Multiplication of 2 frequencies, ω_{rf} ω_{lo}
  - Intermediate frequency generated ω_{if} which is the difference between ω_{rf} and ω_{lo}

$$V_{\mathrm{if}}(t) = A\cos\omega_{\mathrm{rf}}t \times A\cos\omega_{\mathrm{lo}}t$$

$$V_{\mathrm{if}}(t) = \frac{1}{2}A^2(\cos(\omega_{\mathrm{rf}} + \omega_{\mathrm{lo}})t + \cos(\omega_{\mathrm{rf}} - \omega_{\mathrm{lo}})t)$$

$$= \frac{1}{2}A^2(\cos(\omega_{\mathrm{rf}} + \omega_{\mathrm{lo}})t + \cos\omega_{\mathrm{if}}t)$$

- Suppose a frequency
  - $\omega_{image} = \omega_{rf} - 2 \times \omega_{if}$
  - The frequency is below the oscillator frequency
  - Calculations show that this is mixed to the same IF →



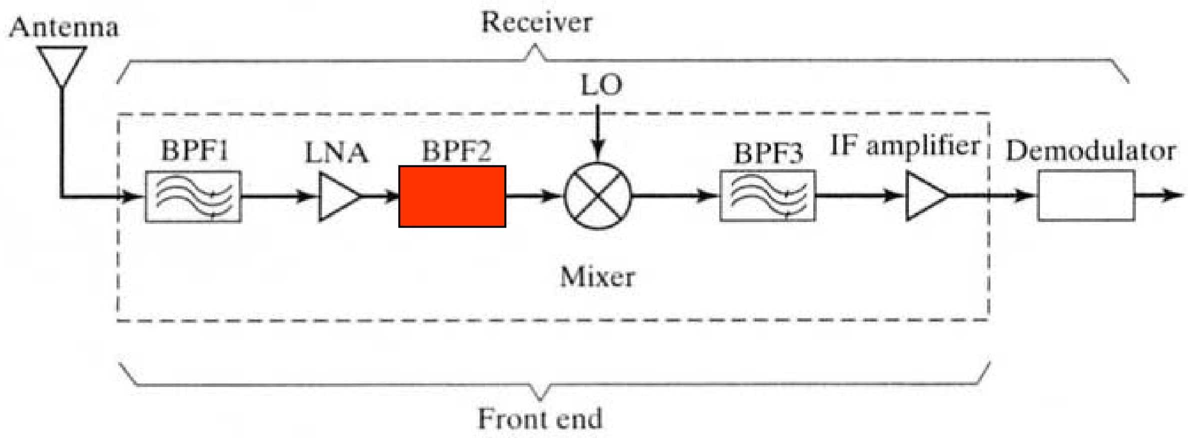
Mixing of image frequency with local oscillator frequency

$$\cos(\omega_{image} - \omega_{lo})t$$
$$= \cos(\omega_{rf} - 2\omega_{if} - \omega_{lo})$$
$$= \cos(\omega_{rf} - \omega_{lo} - 2\omega_{if})$$
$$= \cos(\omega_{if} - 2\omega_{if})$$
$$= \cos(-\omega_{if})$$
$$= \cos\omega_{if}$$

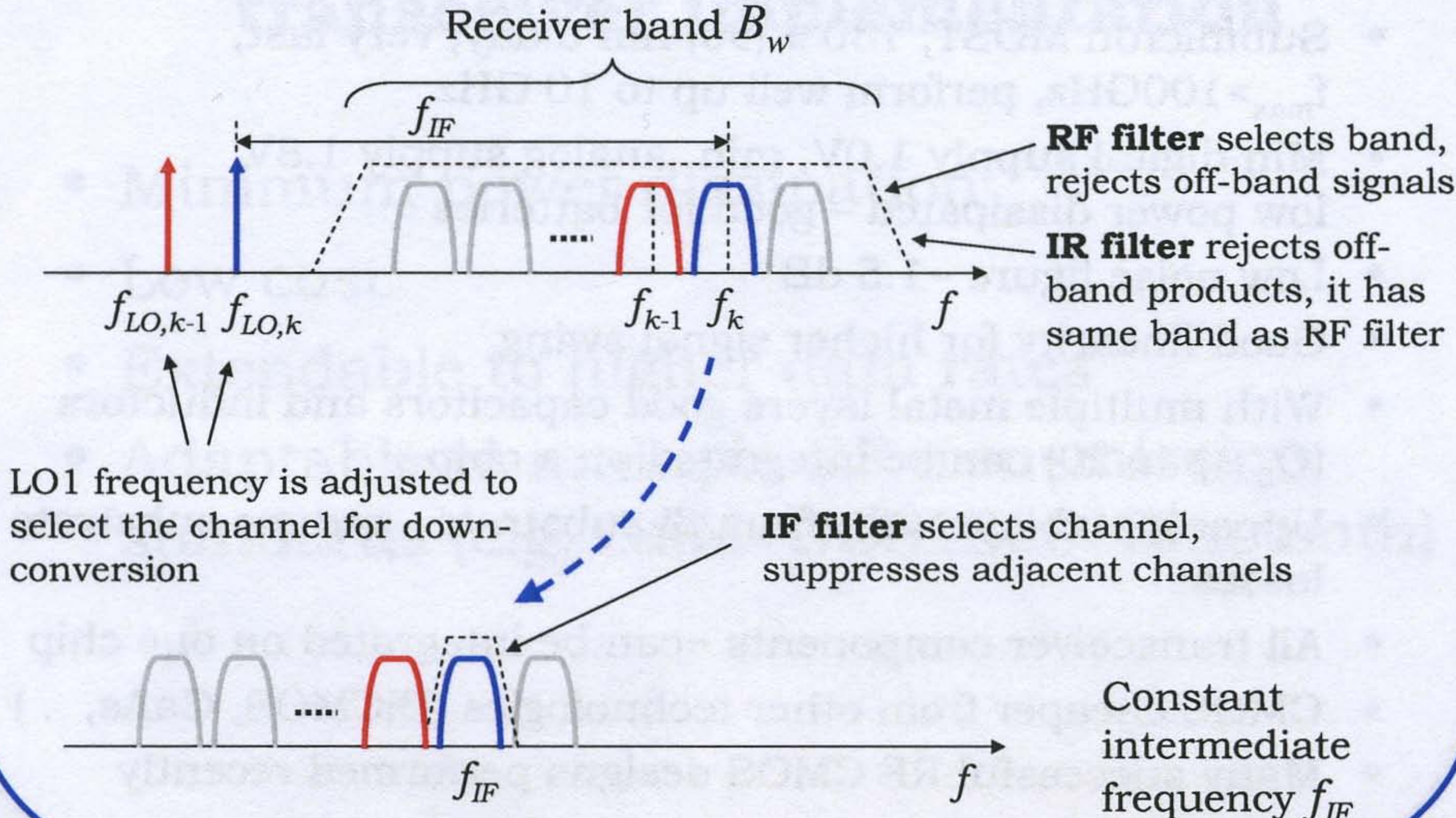
→ Same intermediate frequency generated!

BPF2 Image rejection filter

- Must remove image frequency using a filter, BPF2
  - For low IF, the difference is small, interference may come from **neighboring channels** within the transmission standard
  - For high IF, the difference is large, interference may come from signals following **other standards**
- ”Trade-offs” between the various filters
  - Must select correct channel
  - On the same time remove
    - Image-frequency
    - Other interfering frequencies

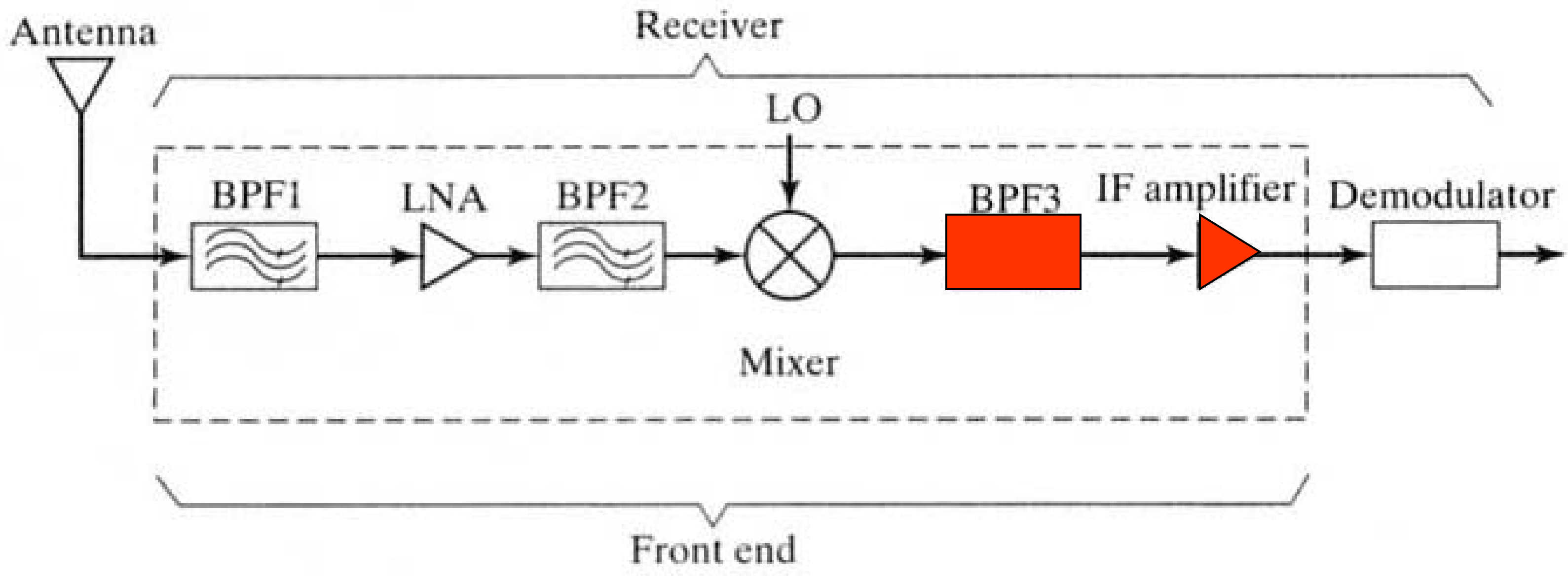


Superheterodyne receiver (cont'd)



Architecture, contd.

- Following band-pass filter, BPF3
  - Operates at **intermediate frequency**, IF
  - Not so high Q-factor requirement, - more practical to implement
- Amplifier at IF



Transition to RF results in

- Increased frequency:
  - → Shorter wavelength
    - in vacuum:

$$\lambda \cdot f = c$$

  - → Signals vary over short distances
    - voltage V, current I
  - → Smaller component dimensions required
    - High precision fabrication required
    - **→ micro machining**

Present technology

- Technology and components used today
  - **Discrete**, **passive** components with good properties
    - R, C, L
    - Ex. Crystal oscillators, inductors
  - Such components needed due to **high performance and precision requirements**
  - **Off-chip solutions** are the result
    - PCB assembly of discrete components
    - Systems take a lot of space
    - Integrated solutions not possible

  - **Active** components
    - Amplifiers, switches
    - GaAs, bipolar Si, CMOS Si, PIN-diodes

Present RF technology has limitations

- The discrete components have **limited performance**
  - Conventional PIN-diodes are inefficient for high frequencies
- High performance **RF filters** are especially difficult to implement
  - High Q-factor is difficult to achieve
  - Costly
- **Systems may not be fully integrated**
  - PCB implementations
  - → Efficient integration is important for reducing cost, volume and increasing reliability

Transceivers using RF MEMS

- How micromechanical circuits can be used in **communication systems**
- Ex.: **”RF receiver front-end”-architecture**
  – A. **Direct substitution** of off-chip passive components
  – B. Special **RF MEMS blocks**
  – C. RF front-end with **only mechanical** components
- Architectures are somewhat ”speculative”
  – We are not there yet!
  – **Gives motivation for further progress!**

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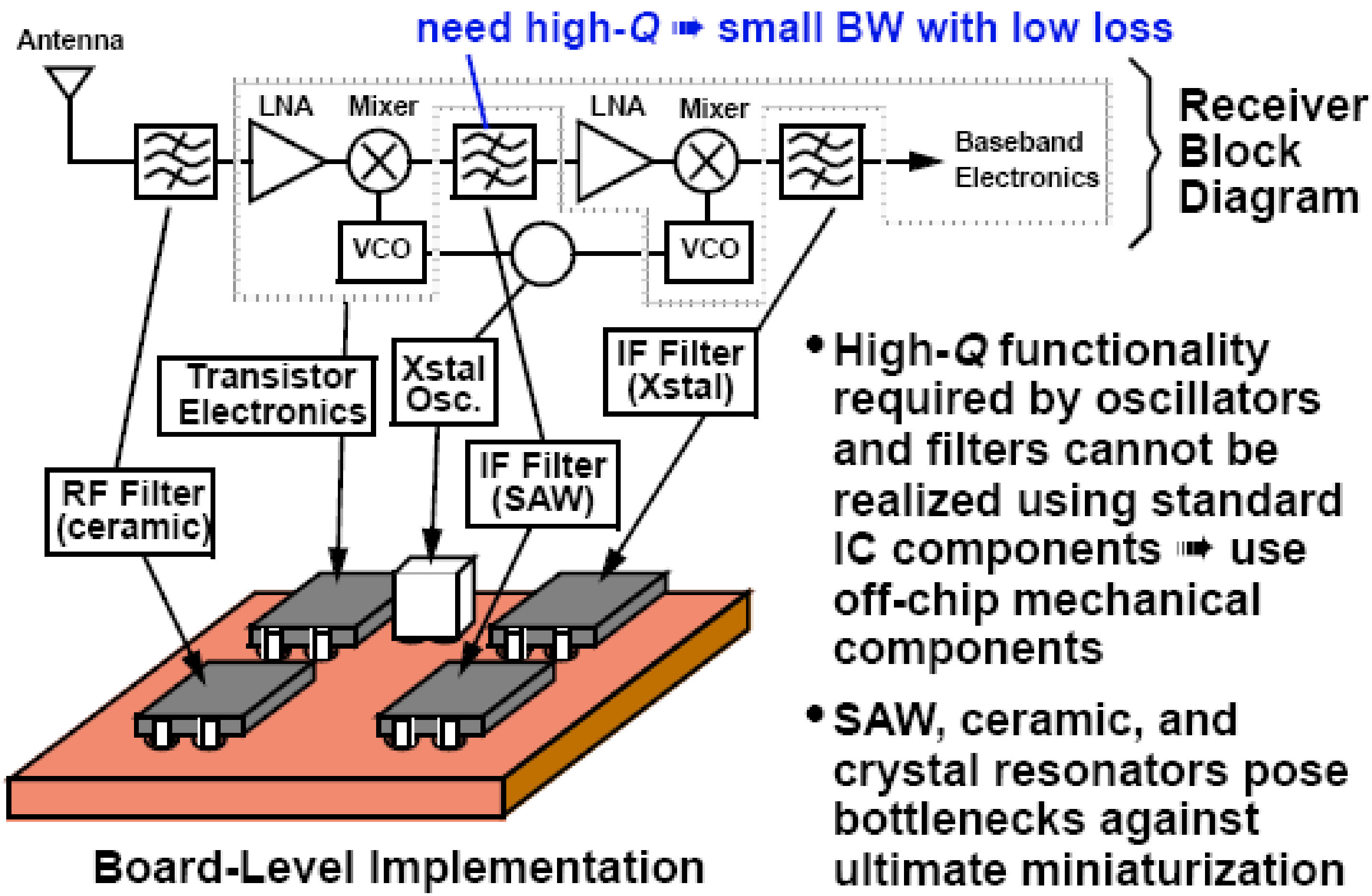
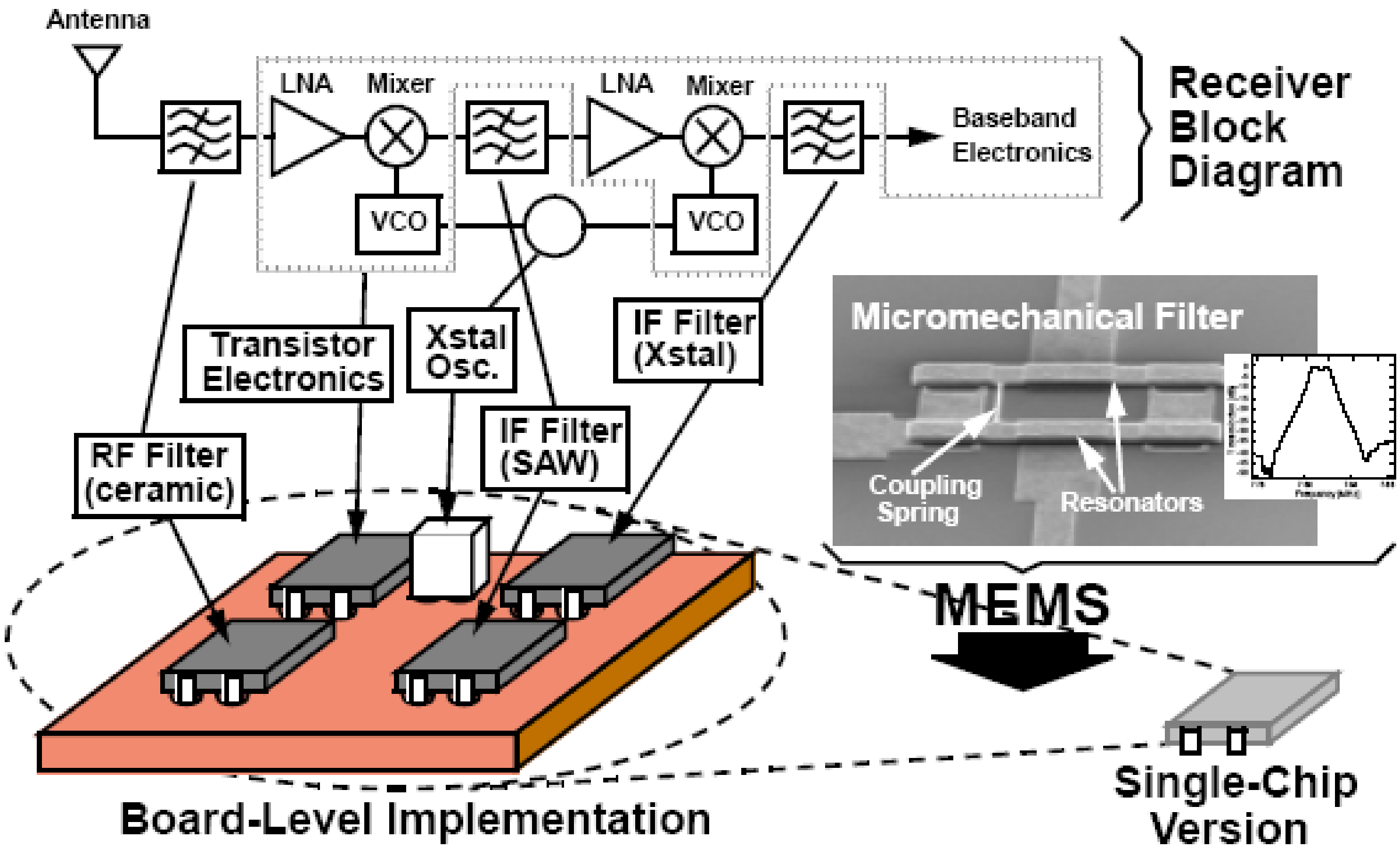
Miniaturization of Transceivers



- High-Q functionality required by oscillators and filters cannot be realized using standard IC components ➠ use off-chip mechanical components
- SAW, ceramic, and crystal resonators pose bottlenecks against ultimate miniaturization

Target Application: Integrated Transceivers



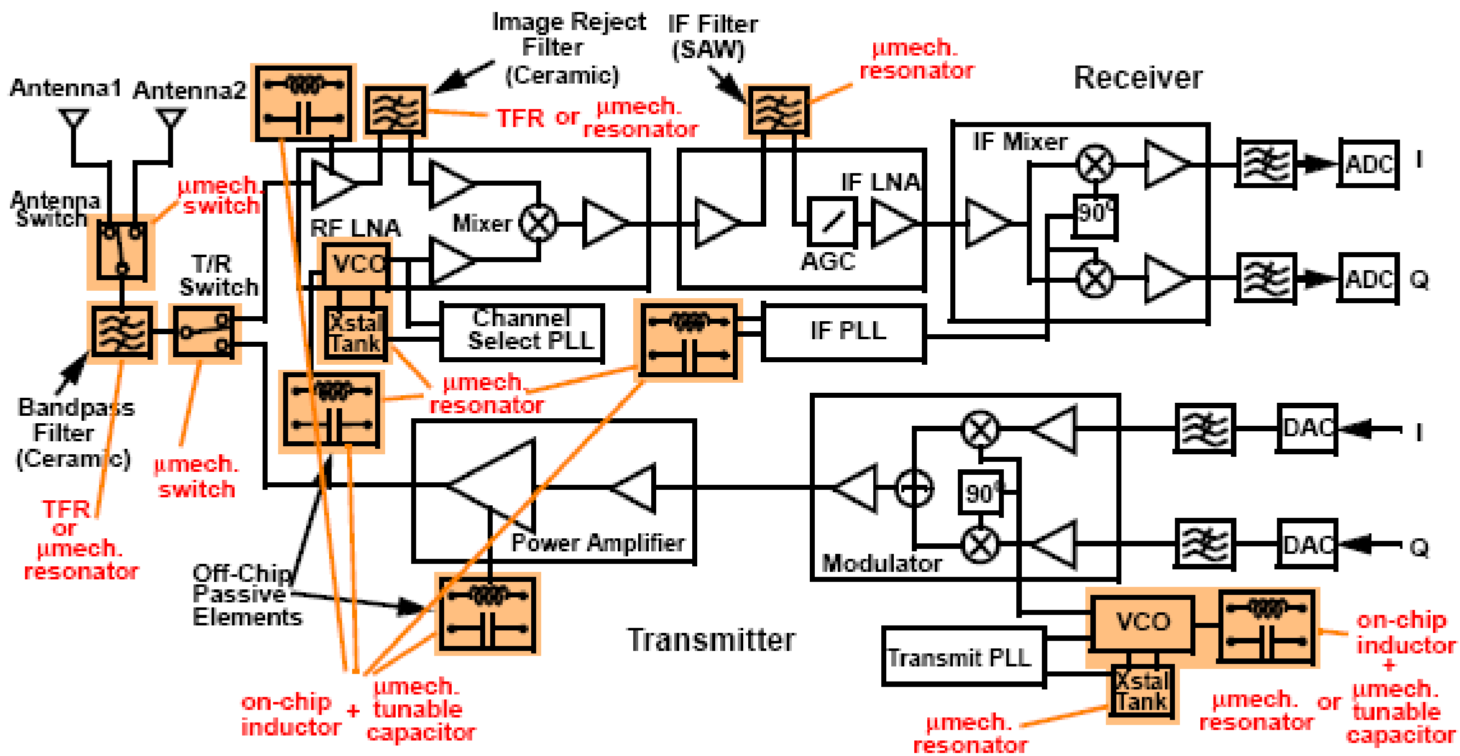
- Off-chip high-Q mechanical components present bottlenecks to miniaturization ➠ replace them with µmechanical versions

A. Direct substitution

- Different types of MEMS-based components
  - Inductors with medium Q-value
  - Tunable capacitors (varactors)
    - Used in VCO and matching networks
  - Low loss MEMS switches (~0.1 dB)
    - Increases flexibility of antenna
  - Resonators

- Used for
  - RF-filters (replace ceramic filters)
    - ”preselect filter”, ”image-reject filter”
  - IF-filters (replace SAW filters)
    - ”channel-select filter”
  - Crystal reference oscillator

MEMS-Replaceable Transceiver Components



- A large number of off-chip high-Q components replaceable with μmachined versions; e.g., using μmachined resonators, switches, capacitors, and inductors

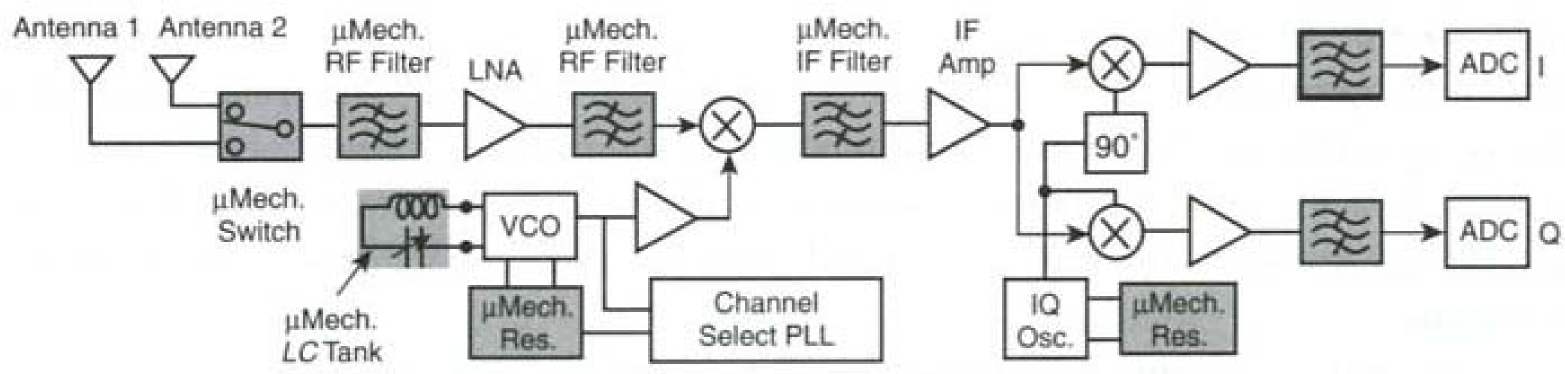
C. T.-C. Nguyen *Univ. of Michigan*

Itoh et al, fig 12.1

Benefits of MEMS substitutes

- Reduction of **dimensions**
- Possible **integration**
  - Multi-chip
  - Monolithic
- **Power reduction**
- More flexibility for **impedance matching** of MEMS filters

- **Termination impedance** matched to the following LNA (Low Noise Amplifier)
  - ”Higher” (than 50 Ω) LNA input impedance can be used → power reduction and reduced noise



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- How micromechanical circuits can be used in **communication systems**
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- Architectures are somewhat ”speculative”
  - We are not there yet!
  - **Gives motivation for further progress!**

B. Special RF MEMS blocks

- Figure shows 3 basic blocks that are substituted by RF MEMS
  - **B1.** Switchable RF **channel-select filter bank**
  - **B2.** Switchable micromechanical **frequency synthesizer**
  - **B3.** Micromechanical **mixer-filter** block

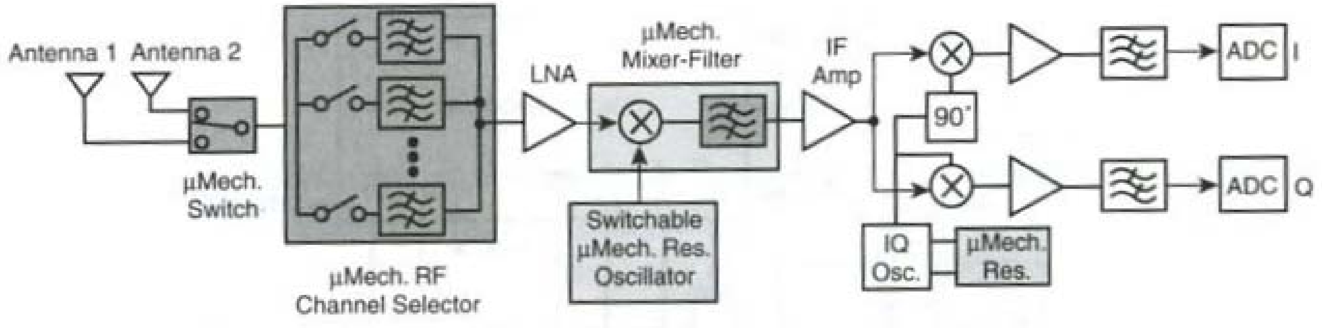
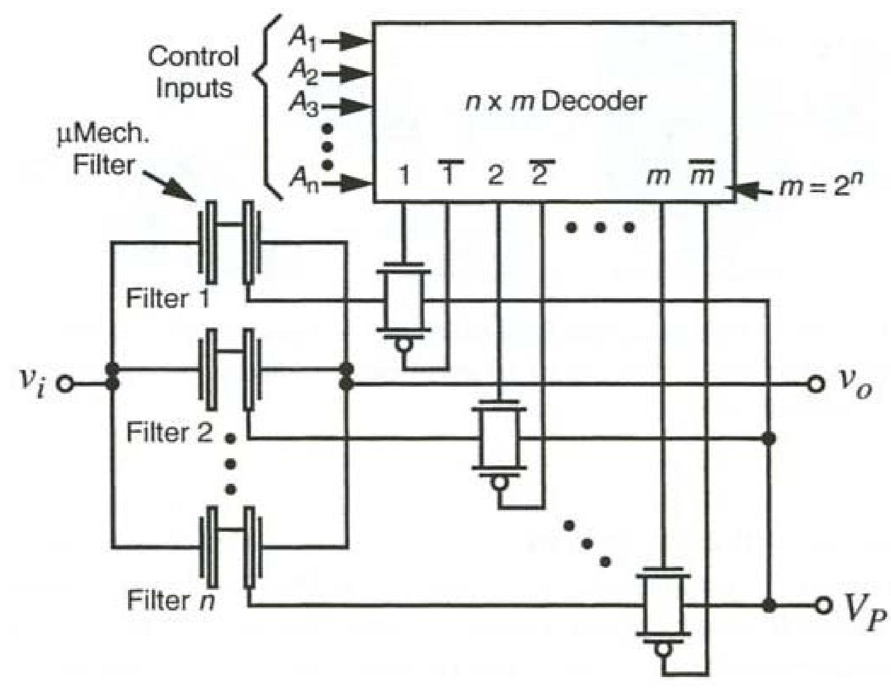


Figure 12.21. System block diagram for an RF channel-select receiver architecture utilizing large numbers of micromechanical resonators in banks to trade Q for power consumption. (On-chip μmechanics are shaded.)

B1. Switchable RF channel-select filter bank

- Idea
  - Use **many, simple,** non-tunable filters with high Q
  - One for each channel, - switched on command
  - A communication standard needs 100 – 1000 of filters



- Block diagram
  - Common input and output
  - Controlled by Vp from decoder
    - With no Vp the outputs are effectively ”open-circuited”

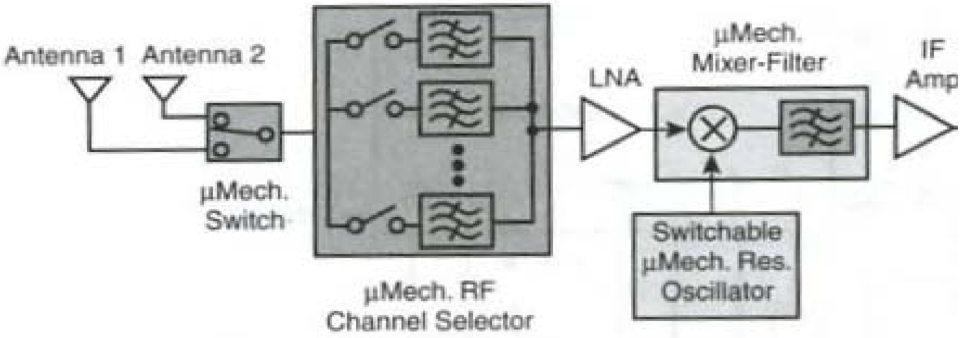
Use of RF filter bank

- **Narrow RF channel** can be selected directly
  - Signal will not be influenced by adjacent channels
  - A succeeding electronic block can be **simplified!**

- LNA can be simplified!
  - **Dynamic range** can be reduced, meaning reduced power consumption
  - Less stringent requirements to **IIP3** (intermodulation product 3) gives an order of magnitude reduction in LNA power consumption:
    - *Ex.* ***CDMA*** *cell phone, test results:*
    - *Single tone signal 900 kHz outside of centre frequency*
    - *LNA IIP3 > + 7.6 dBm by conventional implementation* ***(intermodulation!)***
    - *By using a filter bank the tone is damped 40 dB → IIP3 < -29.3 dBm*
  - Requirements to LNA **linearity** is reduced
    - Then LNA gain can be increased → improving SNR for the following blocks
  - Reduced **phase noise** requirements for LO (Local Oscillator)
    - → also power reduction
    - On-chip implementation of LO might be possible

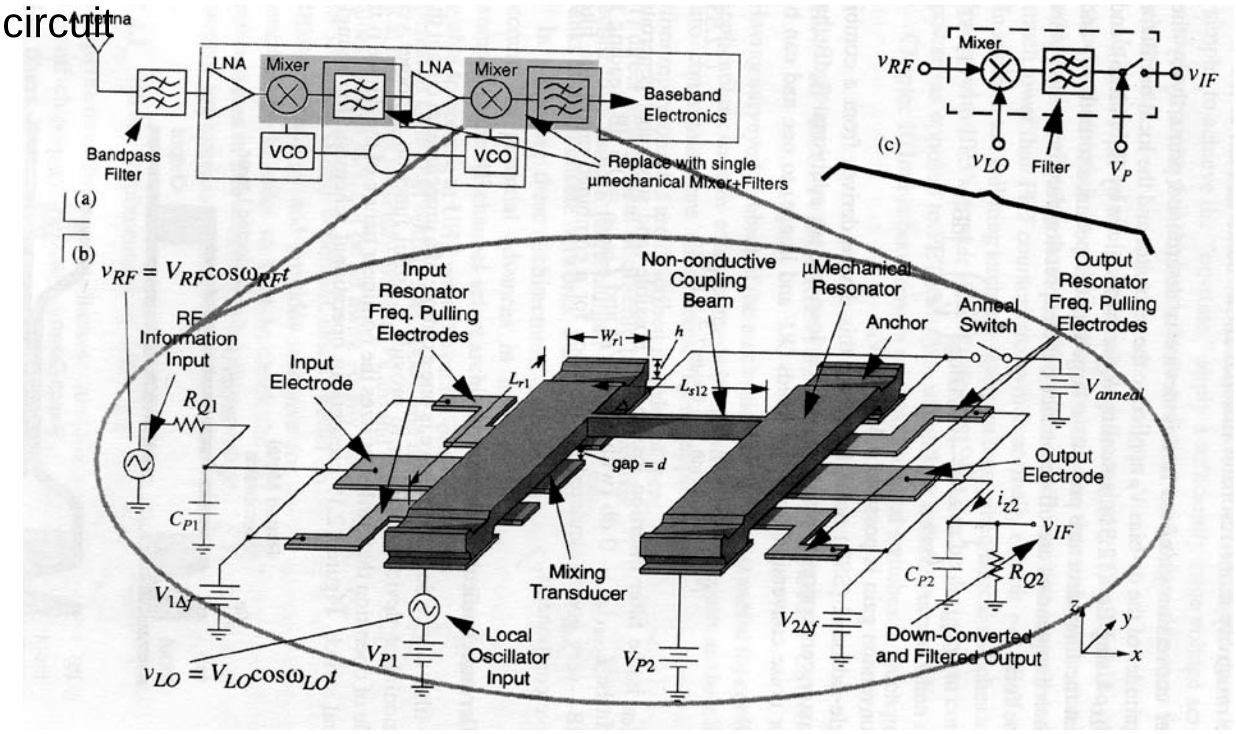
B2. Switchable MEMS frequency synthesizer

- Implementing VCO with MEMS resonators
  - Oscillator can be implemented using a **switchable resonator bank**
  - Resonators oscillate with the frequencies needed for the given standard
  - Resonators must have high Q and should be **thermally stabilized** (mechanically or by electronic compensation)
    - **Might allow the VCO to operate without crystal reference**
    - → significant power reduction, f.ex. 90 nW versus 1-4 mW



B3. Micromechanical mixer-filter

- Use of a micro-machined mixer-filter eliminates the DC power consumption compared to what present commercial mixers need
- Two input ports used in the mixer-filter: one for RF, one for LO
  - RF-input port can be made capacitive
  - Output port can be tailored to a specific **impedance level**
  - → LNA can be simplified and does not need a separate impedance matching circuit



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C. RF front-end with RF MEMS only

- Do we need LNA for RF?
  - Use of relatively broadbanded **”image-reject”** MEMS RF filter followed by a narrowband **IF-mixer-filter**
    - The only active RF-component are then the LO
    - → This gives low power consumption

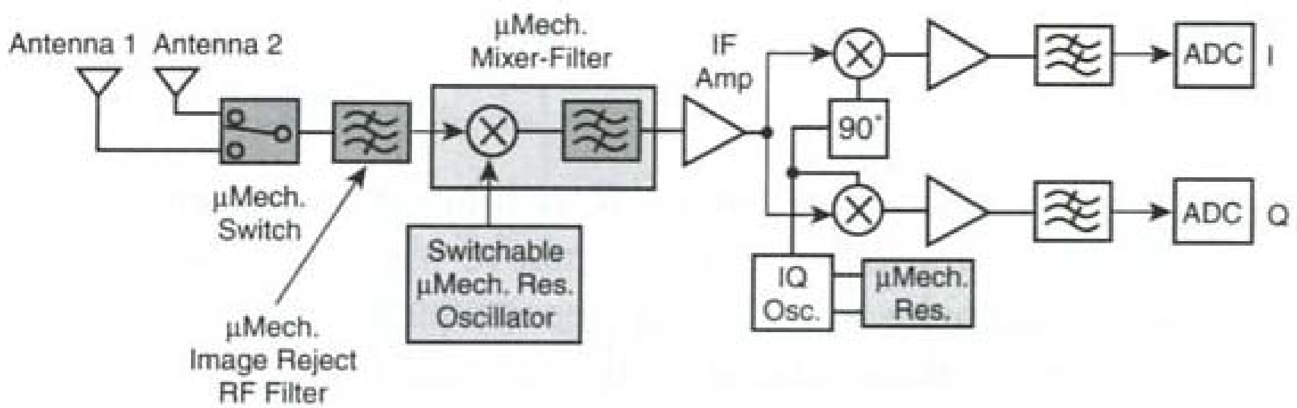


Figure 12.23. System block diagram for an all-MEMS RF front-end receiver architecture. (On-chip µmechanics are shaded.)

Benefits of using RF MEMS only

- System is power efficient
  - Power consumption of LNA and mixer eliminated
  - Can increase standby-time for cell phones significantly!
- Some of the actual components have already been demonstrated
  - Filter and mixer circuits
  - Ex. image-reject filters at UHF with 3 dB insertion loss has been demonstrated
- A promising implementation technology is to use high Q **f-f- beams**
  - Higher frequencies than c-c beam

RF MEMS transmitter architecture

- Little done in using RF MEMS in transmitters
  - Due to lack of **high power capability**
    - Transmitting power is a significant parameter
- Active research being performed on this matter

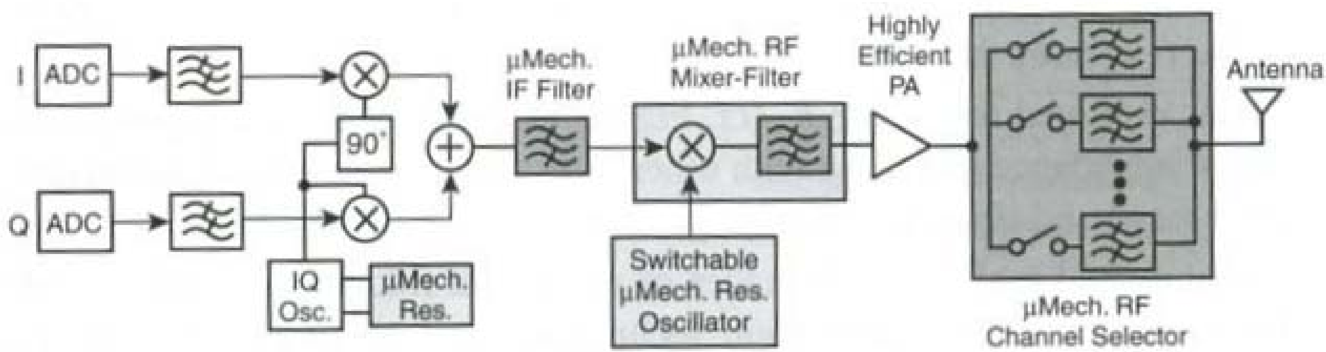
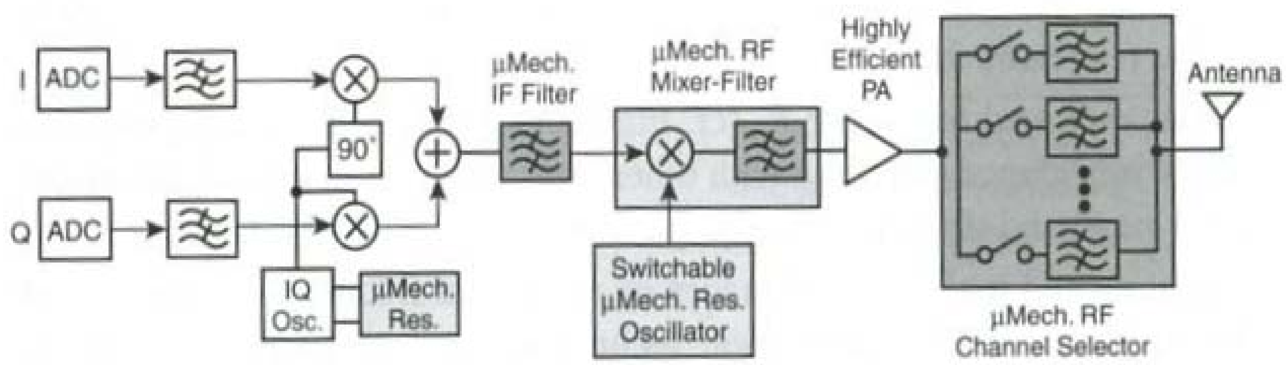


Figure 12.24. RF channel-select transmitter architecture, possible only if high-power µmechanical resonators can be achieved. Here, on-chip µmechanical blocks are shaded, and the PA is not necessarily implemented on-chip.

RF MEMS transmitter architecture

- RF MEMS **channel selector** can be placed **after PA** (”power amplifier”)
  - Use MEMS filter bank
  - MEMS resonators should sustain high power, have high Q and low ”insertion loss” (<1 dB)
  - ”Pure signals” are sent out
  - **+ PA requirements may be reduced**, since all spectral noise due to non-linearity in the PA is filtered out after the PA!
- Architecture may give significant reduction of power consumption
- ”Up-converter” can be realized using MEMS mixer-filter structure



Relevant research topics

- Remember: *The architectures shown are to some extent based on resonators with performance not yet achieved*

- Research topics
  - **1.** Obtain required **high Q at UHF**
  - **2.** Set specific **impedance levels**
  - **3.** Good enough **linearity** and capability to sustain **power**
  - **4.** Efficient **integration methods**

1. Frequency and Q-value

- **Frequency**
  - What frequency range can be covered?
  - Structures/ geometry are critical issues
    - Research shows that 10 MHz – 2.5 GHz can be achieved by using realistic element dimensions
    - Today components exist that have Q ~ 1000 at 3 GHz
  - Absolute value and tolerances in resonance frequency
    - Depends on fabrication, trimming and tuning
  - Stability of resonator frequency
    - Dependent on temperature variations and aging
- Competing resonator types for high frequency and Q
  - ”Thin-film **Bulk Acoustic Resonators**”
    - High frequencies (UHF and over), Q > 1000
  - Use of piezolectric materials

Frequency and Q-value, contd.

- **Q-factor**
  - Energy loss in material influences Q value
- Q-factor depends on
  - Material type
  - Fabrication process
    - Surface cleanness
    - Doping: diffusion and implantation give different properties
  - Damping
  - Loss via anchors
    - ”Anchor-less” structures: f-f beam is beneficial
    - Balanced tuning fork structure
    - Disk resonators

2. Custom-set impedance level

- Serial ”motional resistance” R_Q is often high
- Value of resistance should be matched directly to other transceiver components
  - Components before and after resonator
- Should be ~ minimized
  - Realistic requirements: some hundred Ω´s
  - Value depends on how small the gap, d, can be made

Resonator impedance

- ”Motional” impedance and gap for 2-resonator structures
  - Ex. By reducing gap (ca. 140 → 70 Å) the resonance impedance will be **reduced** from 5000 Ω → 300 Ω (870 MHz)
  - BUT this will also **degrade linearity!**
  - **→ important to balance linearity requirements to impedance requirements**

TABLE 12.3. Two-Resonator μMechanical Filter Electrode-to-Resonator Gap Spacing Design[a]

	Gap Spacing, d, for R_Q of:				
Frequency	300 Ω	500 Ω	1000 Ω	2000 Ω	5000 Ω
70 MHz[b]	160 Å	178 Å	207 Å	243 Å	301 Å
870 MHz[c]	68 Å	77 Å	92 Å	109 Å	137 Å

[a] Determined with $Q = 10{,}000$, $W_e = 0.54$, $V_P = 10$ V, using Timoshenko methods and ignoring beam topography.
[b] CCBeam, polysilicon, $L_r = 14.92$ μm, $W_r = 8$ μm, $h = 2$ μm, BW = 200 kHz
[c] CCBeam, diamond, $L_r = 5.97$ μm, $W_r = 8$ μm, $h = 2$ μm, BW = 1.25 MHz.

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Example of compromise

- If impedance matching means that a smaller gap has to be used than linearity requirements allow:
  - Eg. d_{min} for desired impedance matching $<$ d_{min} for desired linearity
- Solution: **use several micromachined parallel filters**
  - With identical frequency response
  - F.ex. 10 filters in parallel with $R_Q = 2000\ \Omega$ give $R_{Q\_total} = 2000\ \Omega / 10 = 200\ \Omega$
- Parallel filters also increase **power capability! →**
  - 10 filters in parallel with 10 mW each, give totally 100 mW

3. Linearity and power capability

- Linearity and power capability are reduced when dimensions get smaller
  - Present ceramic or SAW filters have very high linearity
- MEMS structures based on c-c beams have OK linearity
  - Good enough, except for some standards allowing **simultaneous** transmit and receive
    - Ex. CDMA needs transmit-reject filter in front of the receiver filter bank
- Increased power capability
  - Use alternative geometries
  - Use alternative transduction
    - Piezoelectric
    - Magnetostrictive
  - Parallel units

4. Efficient integration methods

- Critical research topics
  - Combination of MEMS with transistors on-chip
    - Monolithic integration!
    - CMOS-MEMS
  - Jmfr. Lecture on integration and packaging
    - LN13

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