

INF5490 RF MEMS

LN14: Wireless systems using RF MEMS

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INF5490: topics

- "RF MEMS"
 - → 2 parts: **RF** and **MEMS**
 - Description and modeling of MEMS components in focus
- This lecture:
 - **MEMS components used in RF systems**

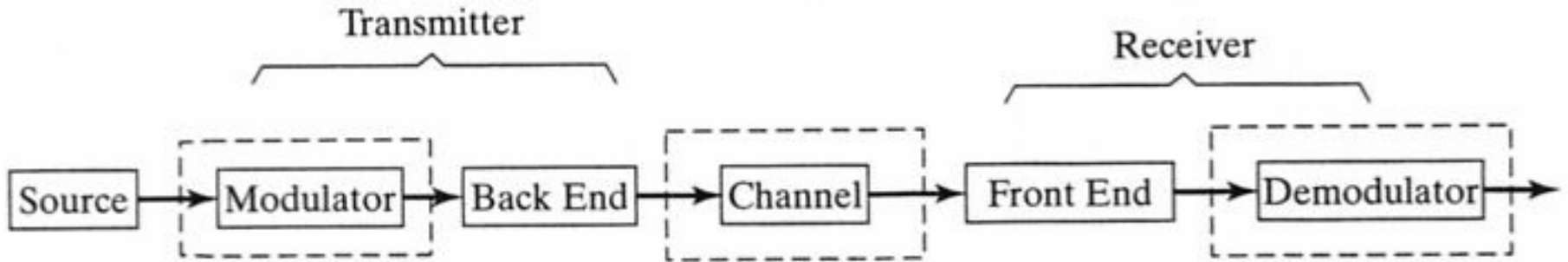
Today's lecture

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

RF-systems

- RF is essential for wireless communication
 - **Radio waves** used for transmitting/receiving
 - Electromagnetic waves (Maxwell's equations)
- 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



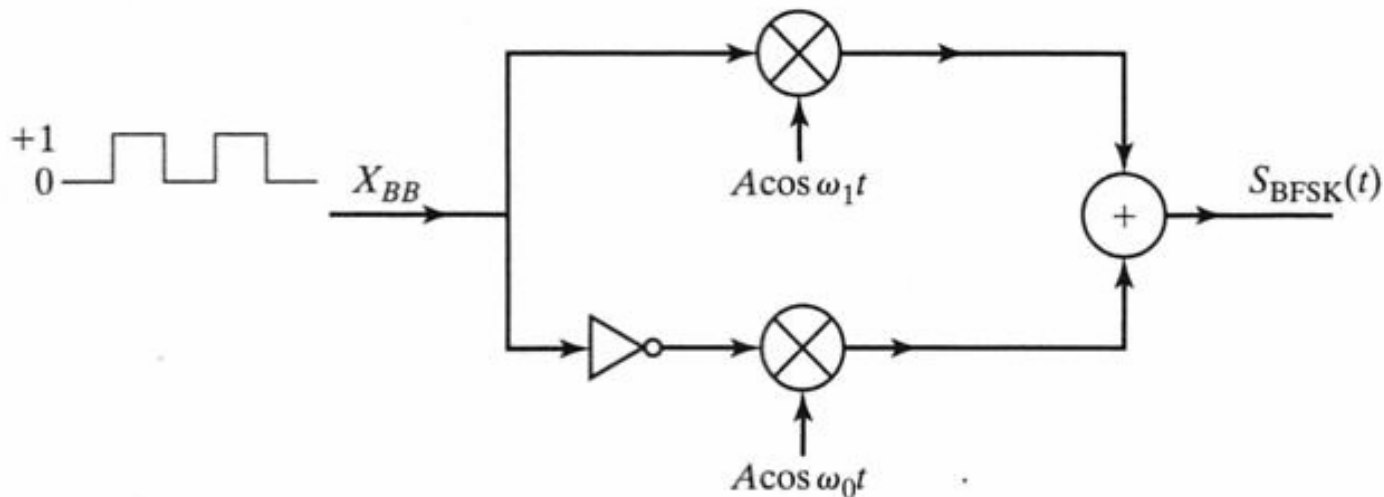
Bit streams are modulated (coded) onto a **carrier**

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**
 - Transferring digital data
 - Coding bits to 2 different frequencies (T_b is bit-duration)

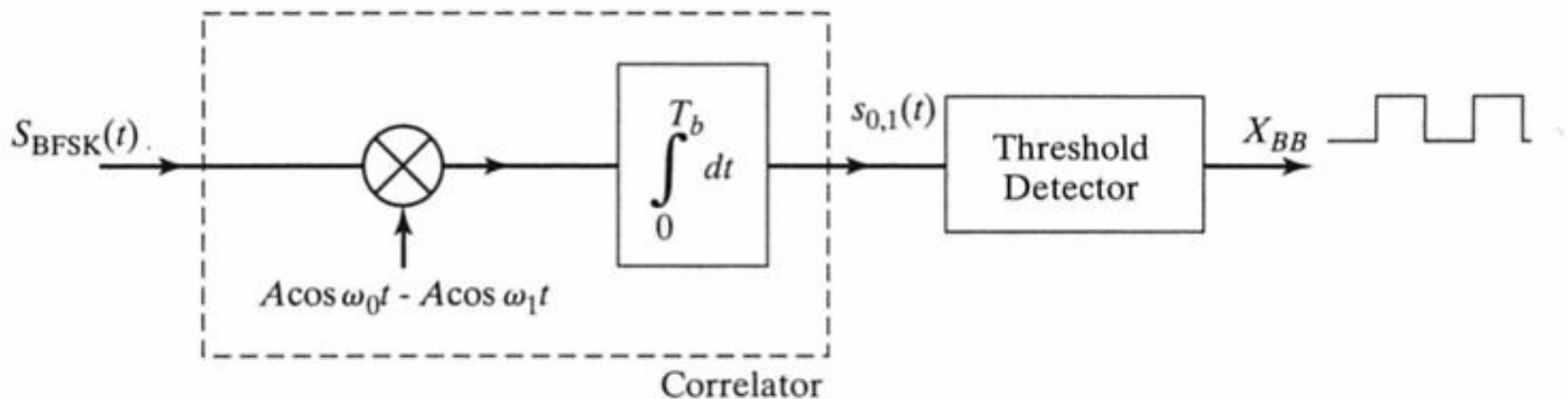


Demodulation BFSK

- Coherent demodulator

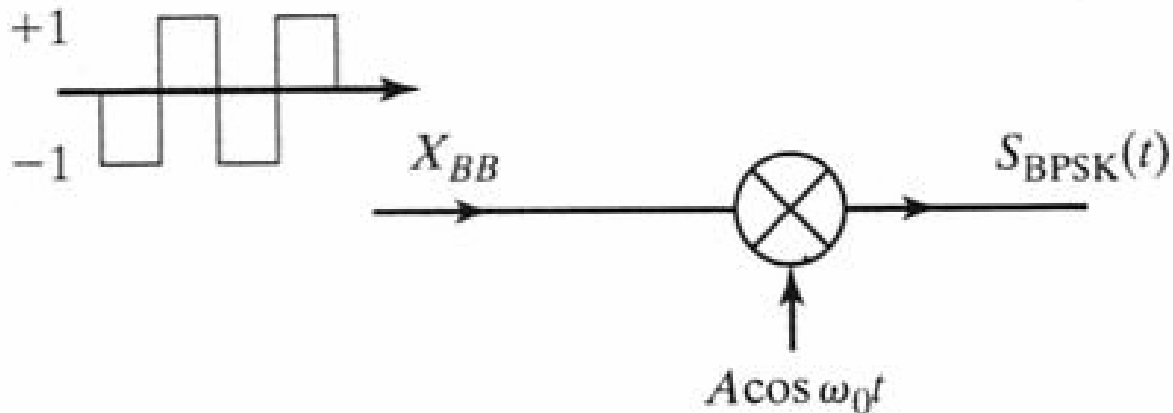
$$\text{logic 0: } s_0(t) = \int_0^{T_b} (A \cos \omega_0 t)(A \cos \omega_0 t - A \cos \omega_1 t) dt = \frac{A^2 T_b}{2}; \quad (1.1)$$

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



BPSK

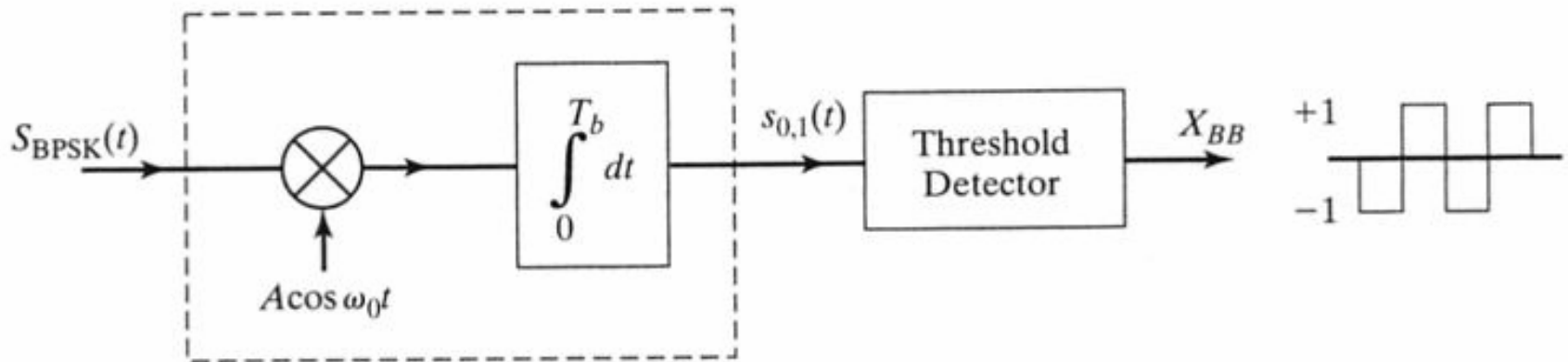
- **Binary Phase-Shift Keying**
- Modulate phase onto carrier
 - Phase changes 180 degrees from 0 to 1 ($+\pi$)



Demodulation BPSK

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

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

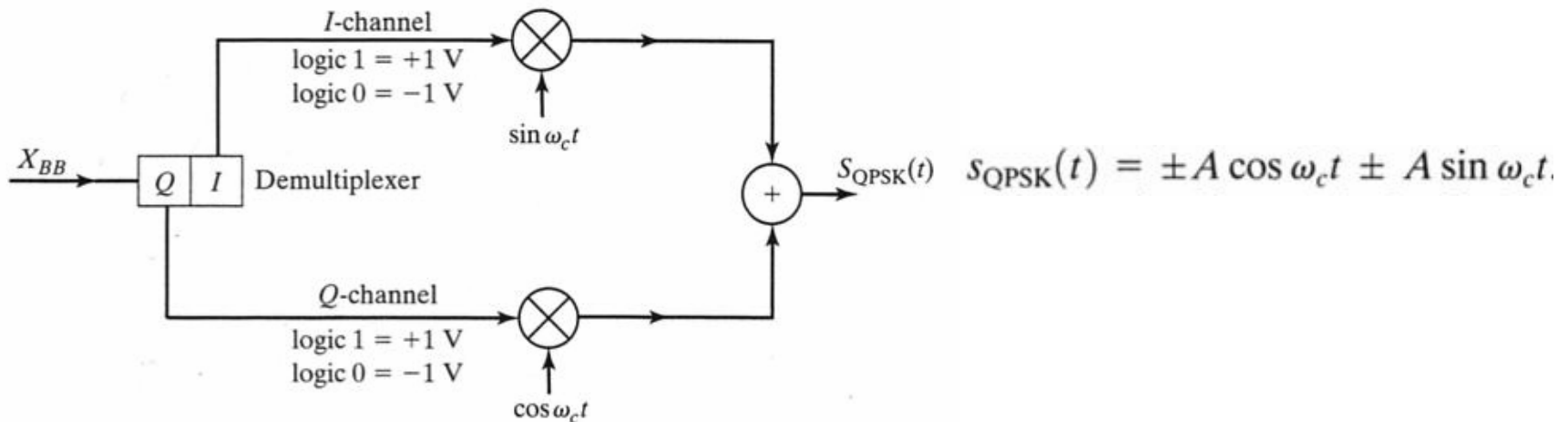


QPSK

- **Quadrature Phase-Shift Keying**

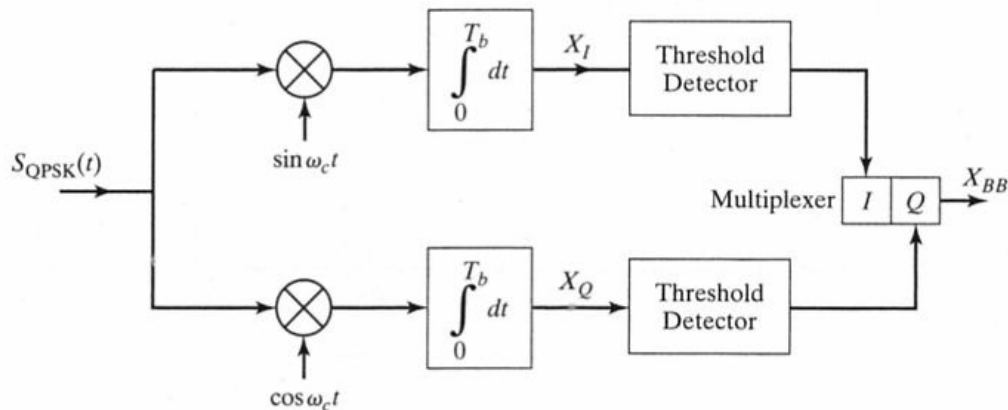
- Having more than 2 representations of input data
 - Input is combined into bit-groups 00,01,10,11

- 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



QPSK, contd.

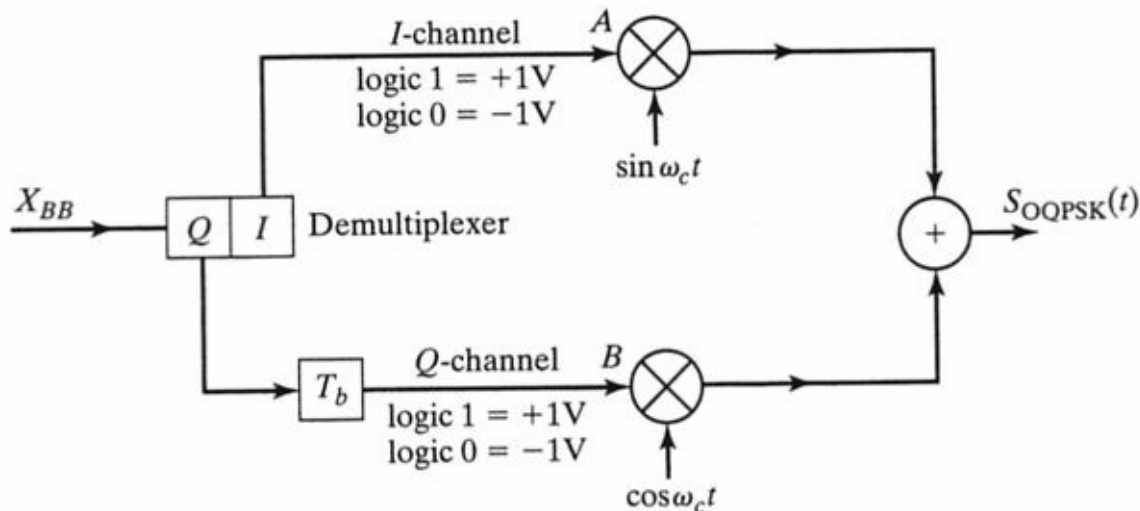
- QPSK demodulation
 - Sin and cos-signals are orthogonal
 - Each channel is demodulated independently as for BPSK



- 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 T_b introduced in Q-channel
 - Offset = half the symbol period ($2 T_b = \text{period}$)
 - Hinders simultaneous signal transitions at A and B
 - Smaller phase shift. Lower requirements to channel bandwidth

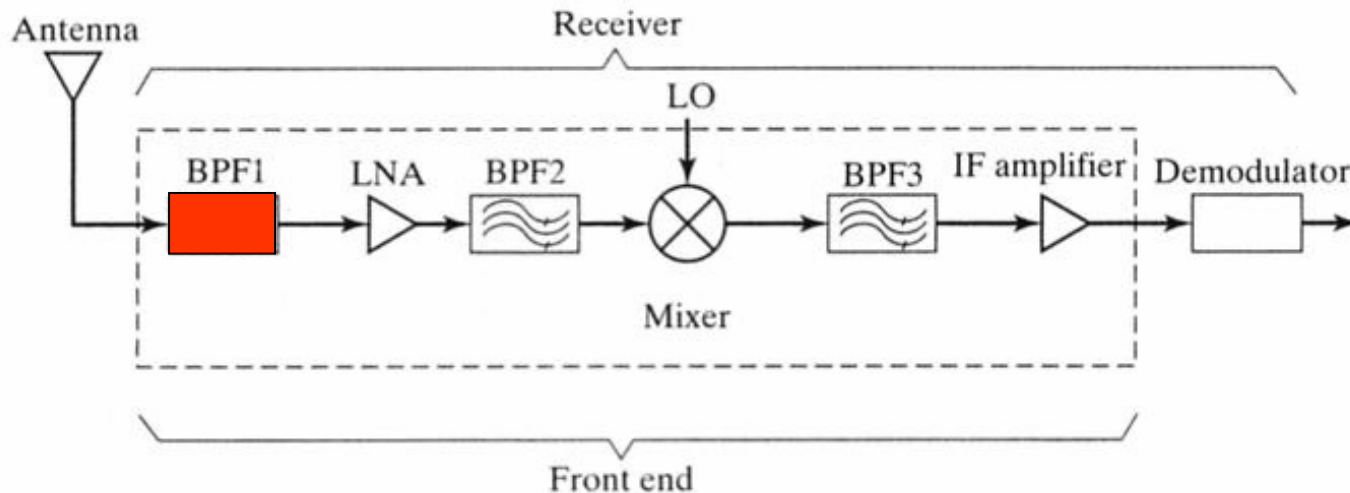


Minimum Shift Keying

- 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

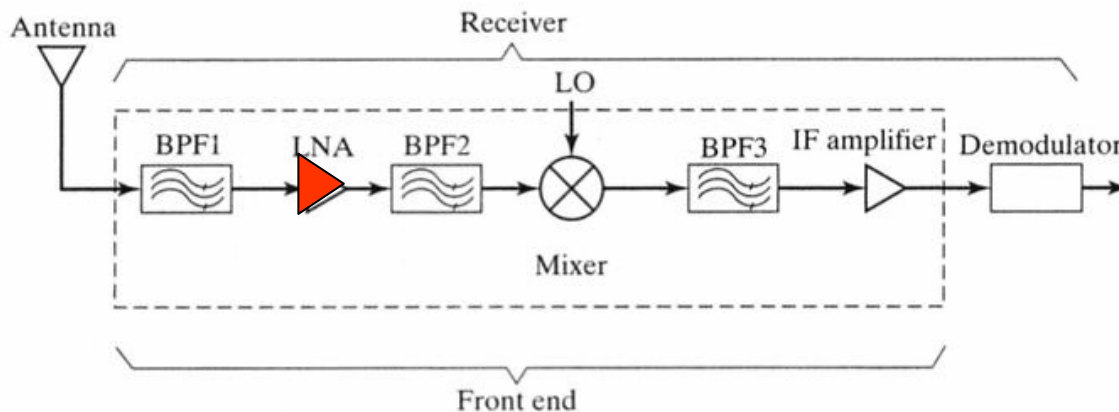
Receiver architecture

- **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 destroying



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

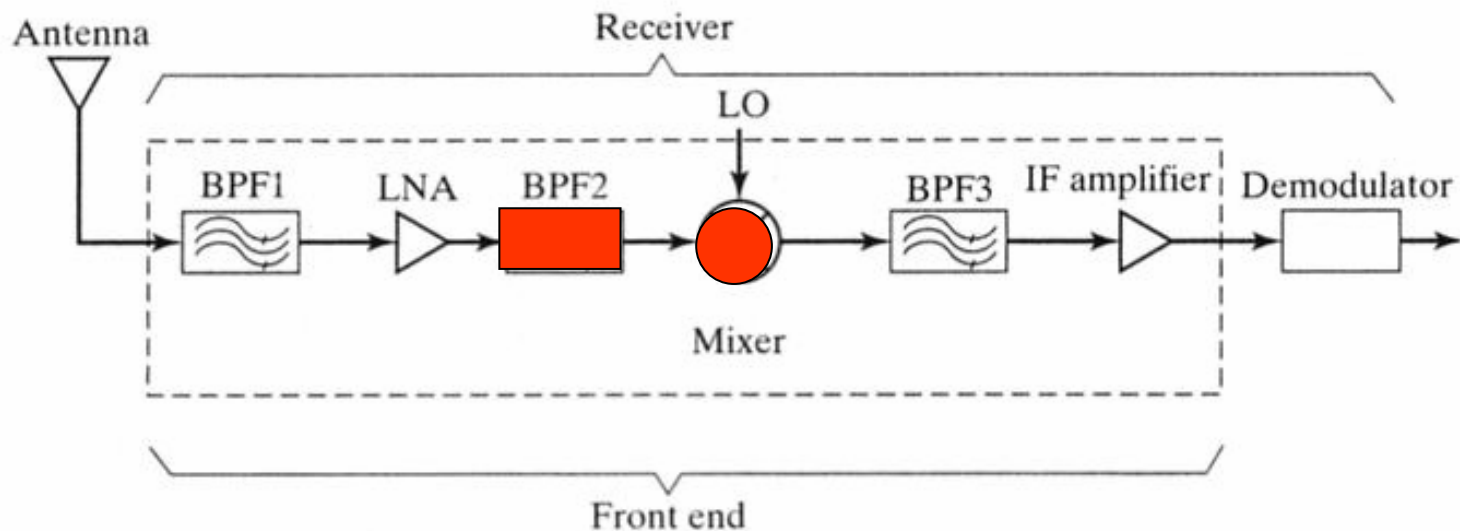
$$\begin{aligned} y(t) &= \alpha_1 A \cos \omega_0 t + \alpha_2 A^2 \cos^2 \omega_0 t + \alpha_3 A^3 \cos^3 \omega_0 t \\ &= \frac{\alpha_2 A^2}{2} + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4} \right) \cos \omega_0 t + \frac{\alpha_2 A^2}{2} \cos 2\omega_0 t + \frac{\alpha_3 A^3}{4} \cos 3\omega_0 t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

Harmonics are generated

$$\text{HD}_3 = \frac{1}{4} \frac{\alpha_3}{\alpha_1} A^2 \quad (3. \text{ harmonic})$$

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} and ω_{lo}
 - Intermediate frequency generated ω_{if} which is the difference between ω_{rf} and ω_{lo}

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

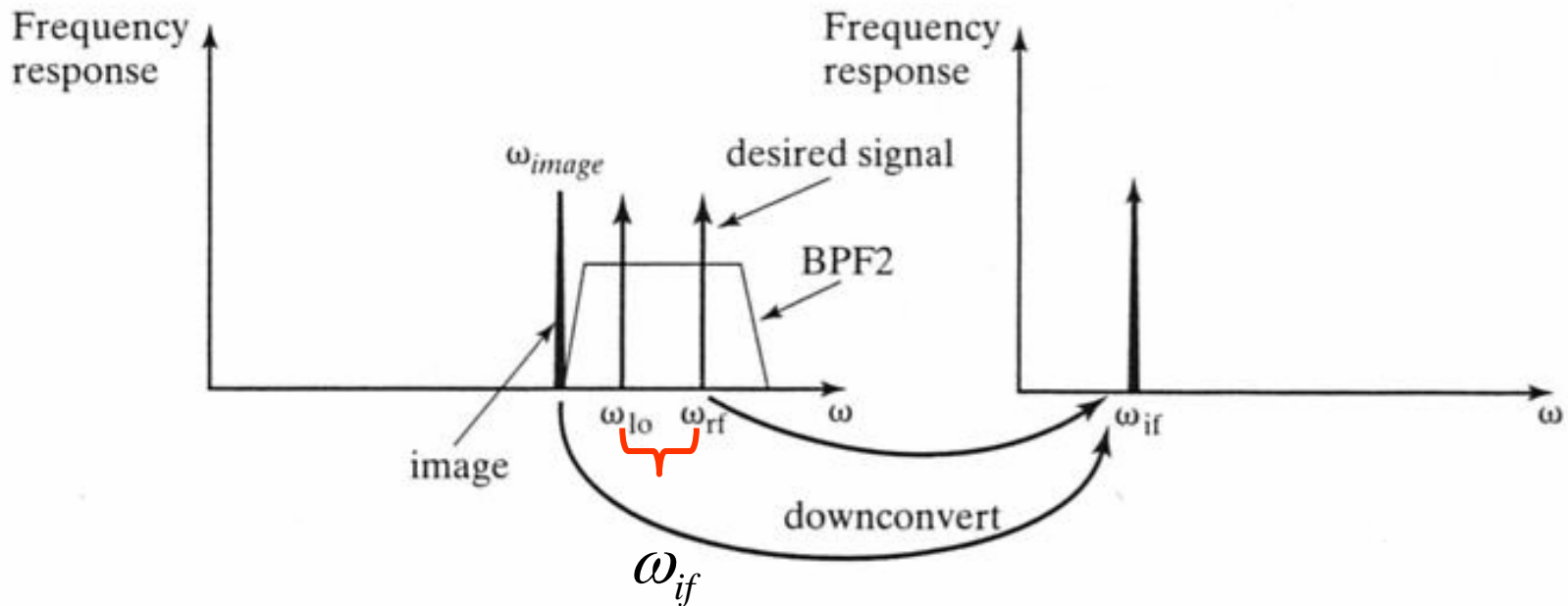
$$\begin{aligned} V_{if}(t) &= \frac{1}{2} A^2 (\cos(\omega_{rf} + \omega_{lo})t + \cos(\omega_{rf} - \omega_{lo})t) \\ &= \frac{1}{2} A^2 (\cos(\omega_{rf} + \omega_{lo})t + \cos \omega_{if}t) \end{aligned}$$

- 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 \rightarrow



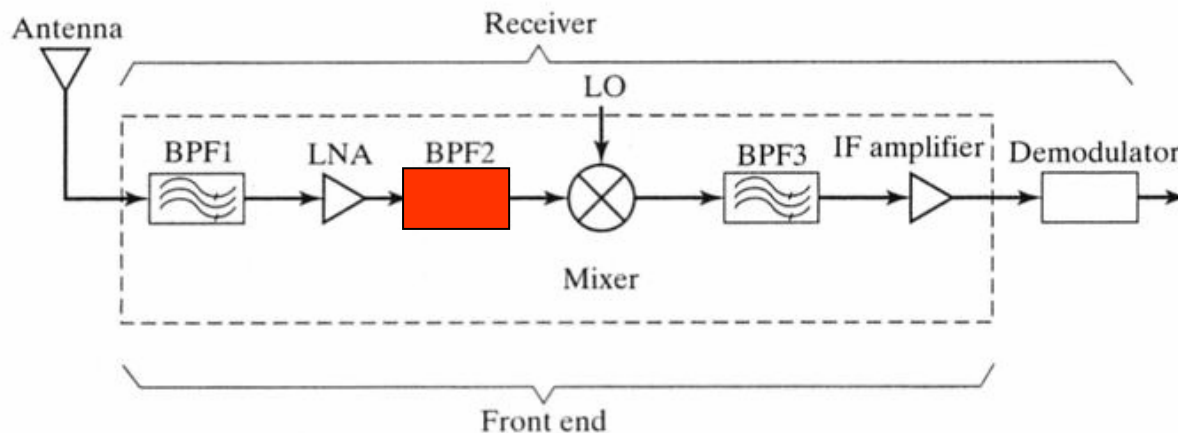
Mixing of image frequency with local oscillator frequency

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

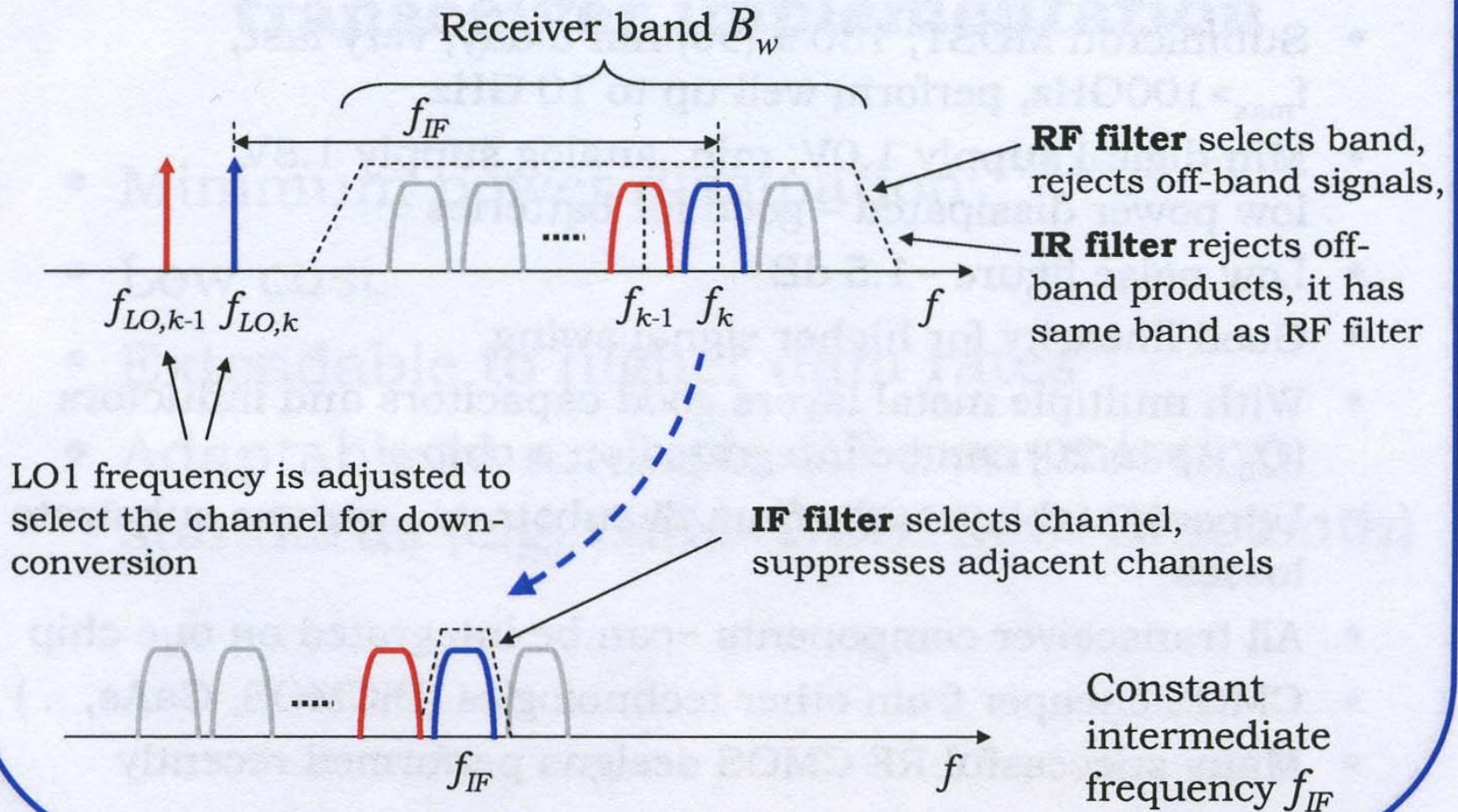
→ Same intermediate frequency generated!

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

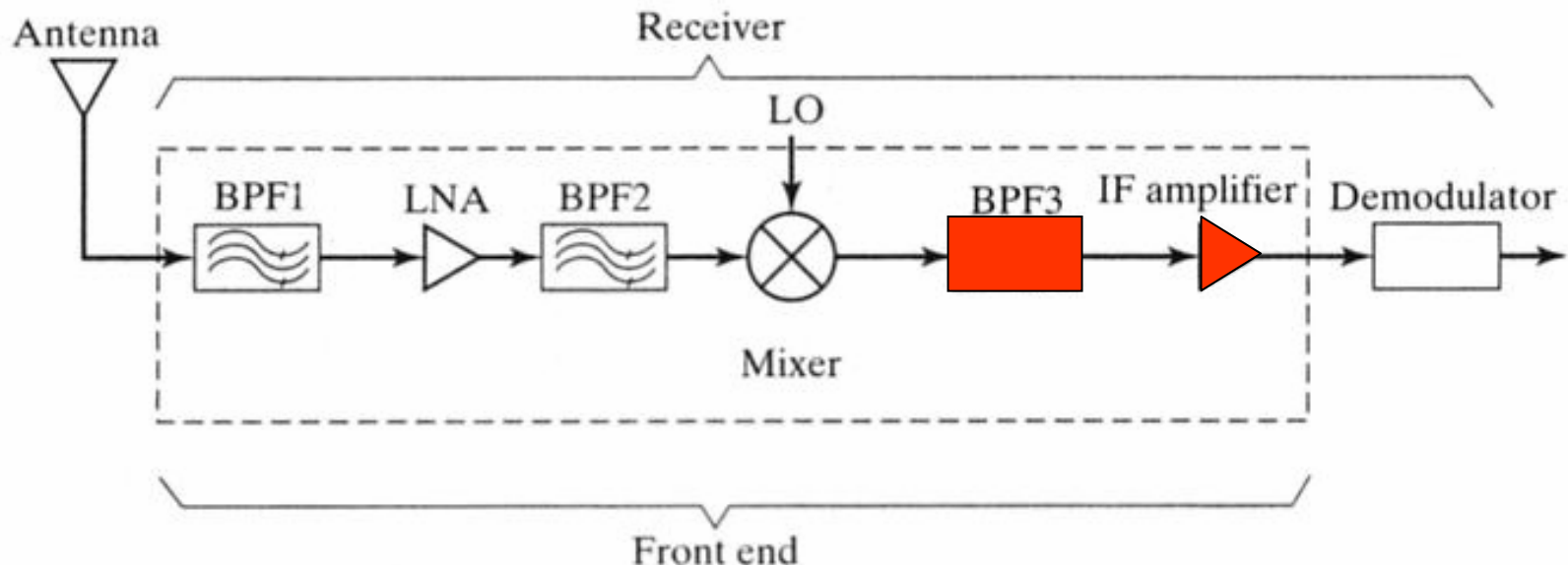


Superheterodyne receiver (cont'd)



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. crystals, inductors
 - Such components needed due to **high performance and precision requirements**
 - **Off-chip solutions** are the result
 - PCB assembly
 - 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
 - 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 cost, volume and reliability

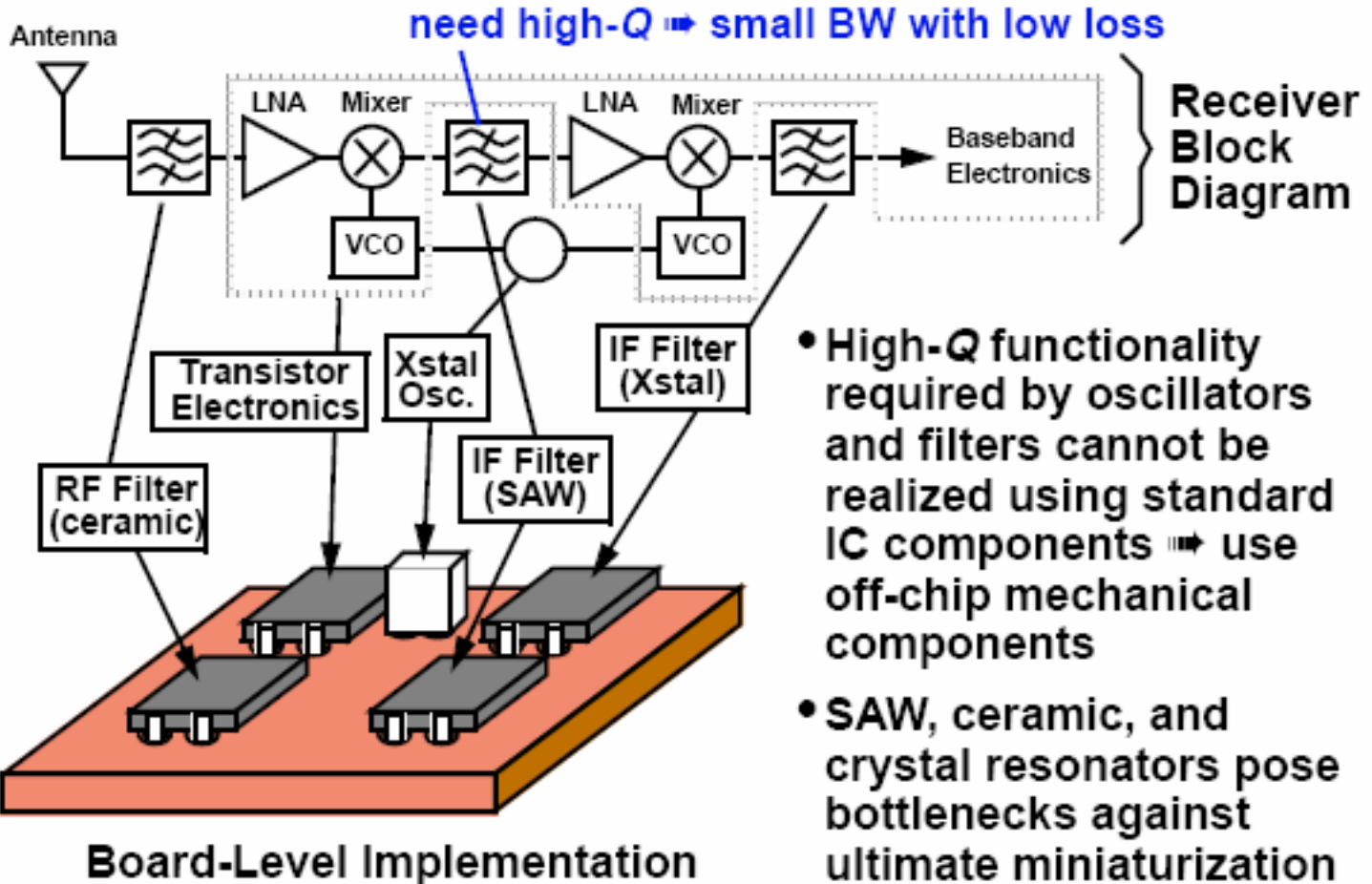
Transceivers using RF MEMS

- 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!**

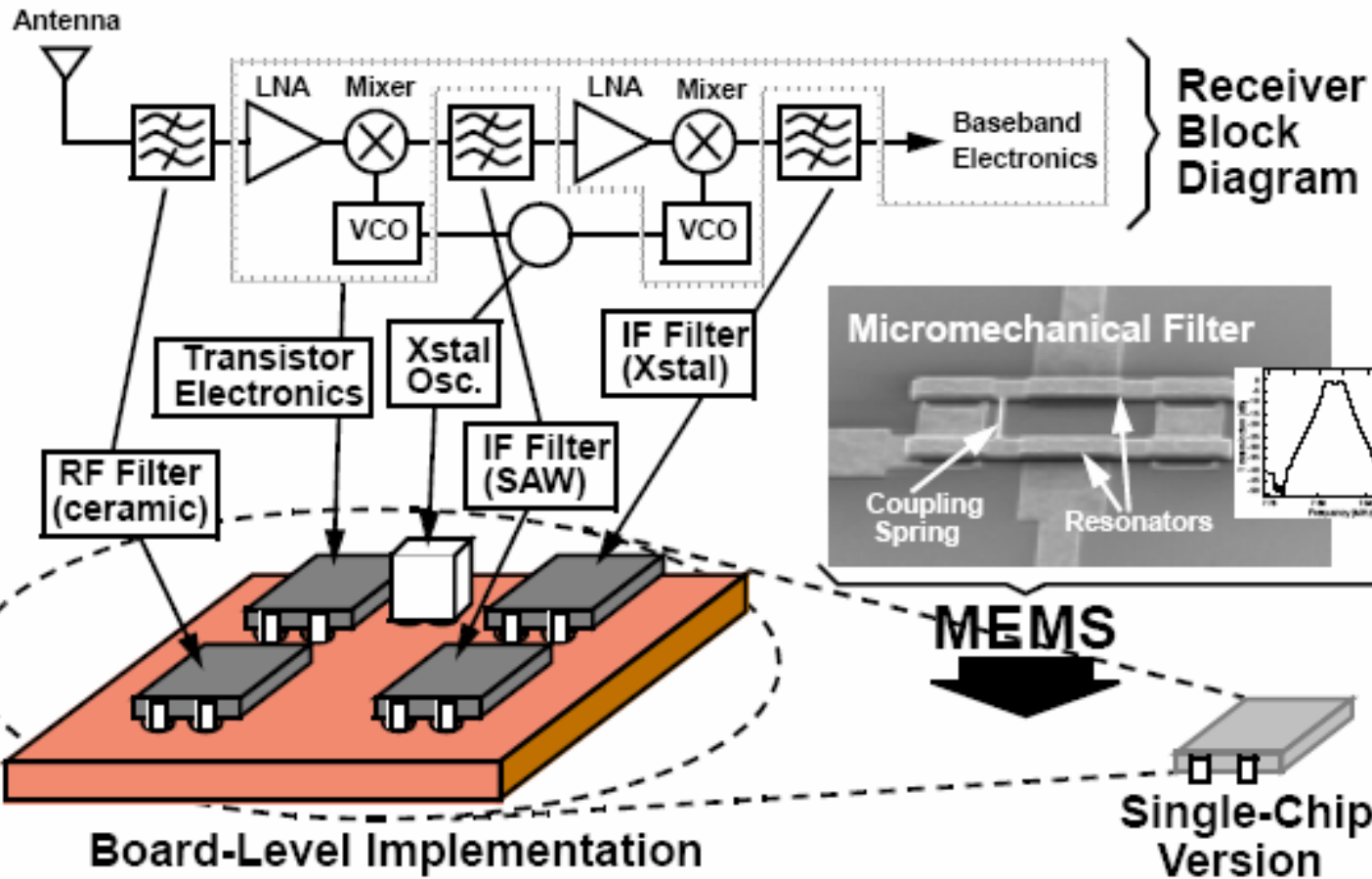
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Miniaturization of Transceivers



Target Application: Integrated Transceivers

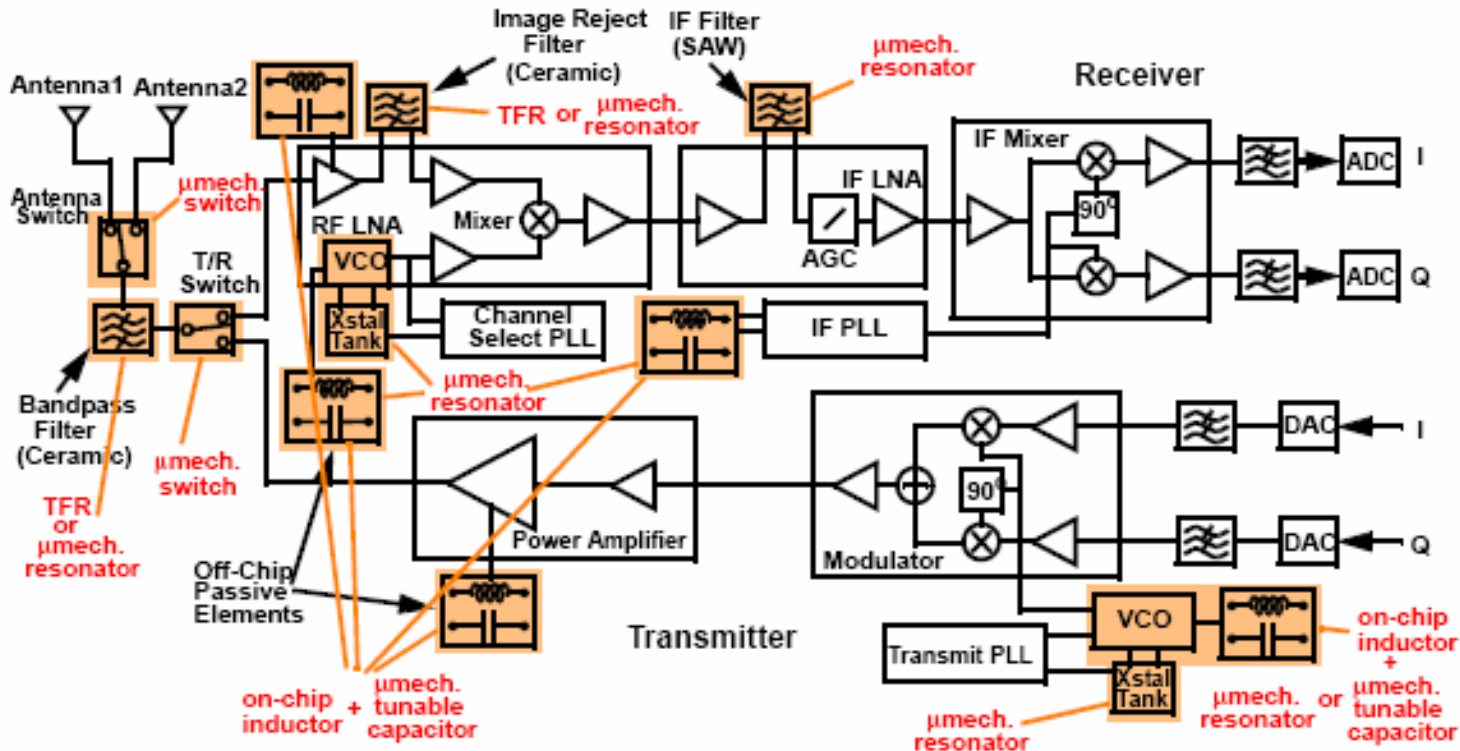


- Off-chip high-Q mechanical components present bottlenecks to miniaturization \Rightarrow replace them with μ mechanical versions

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

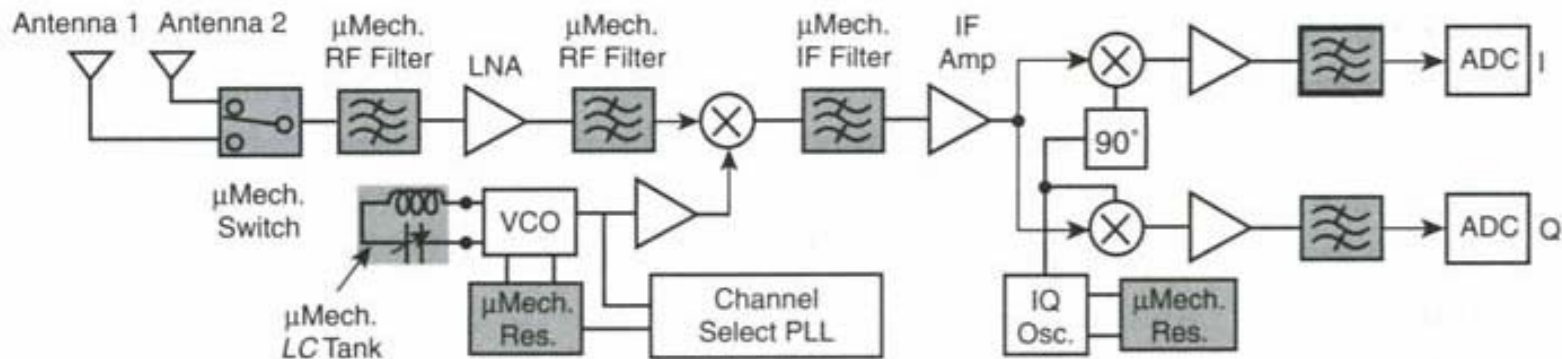
MEMS-Replaceable Transceiver Components



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

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 $50\ \Omega$) LNA input impedance can be used \rightarrow power reduction and reduced noise



Transceivers using RF MEMS

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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

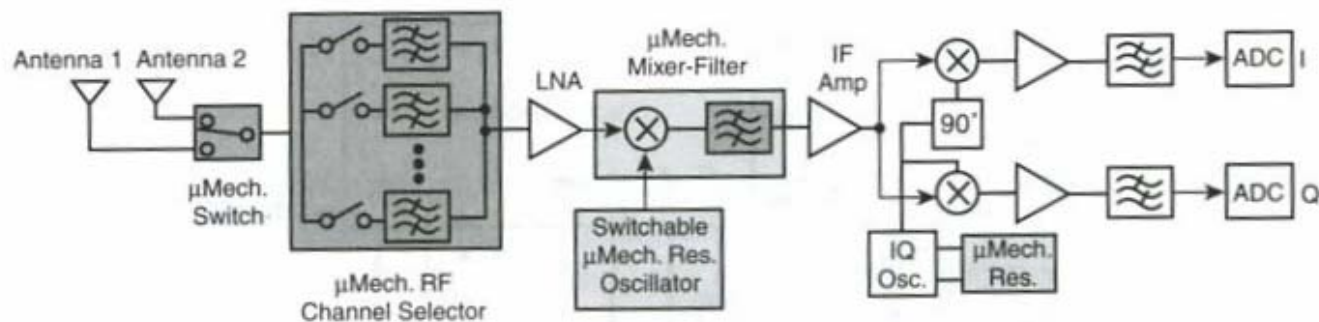


Figure 12.21. System block diagram for an RF channel-select receiver architecture utilizing large numbers of micromechanical resonators in banks to trade Q for power consumption. (On-chip μ mechanics are shaded.)

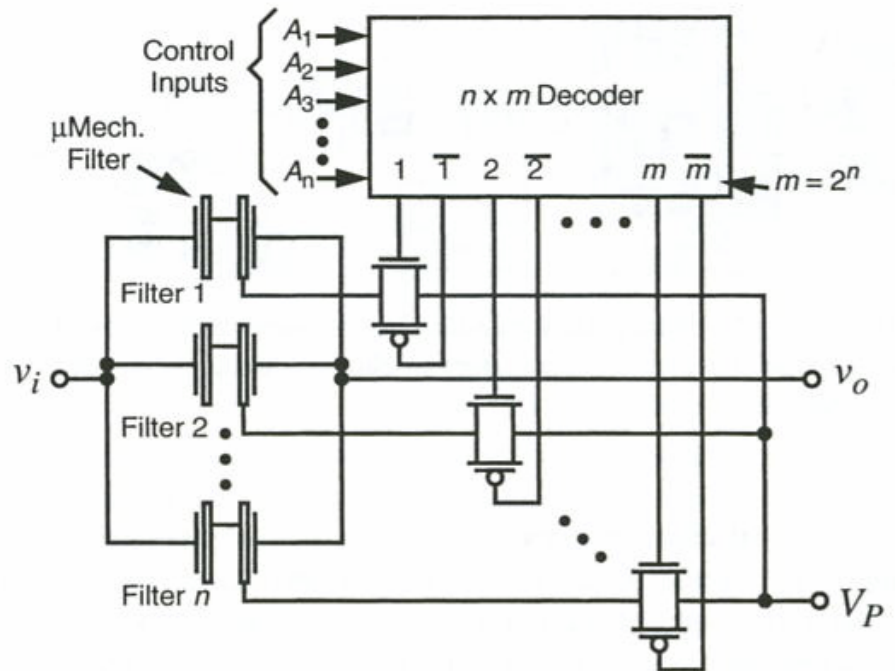
B1. Switchable RF channel-select filter bank

- 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 V_p from decoder
 - With no V_p the outputs are effectively "open-circuited"

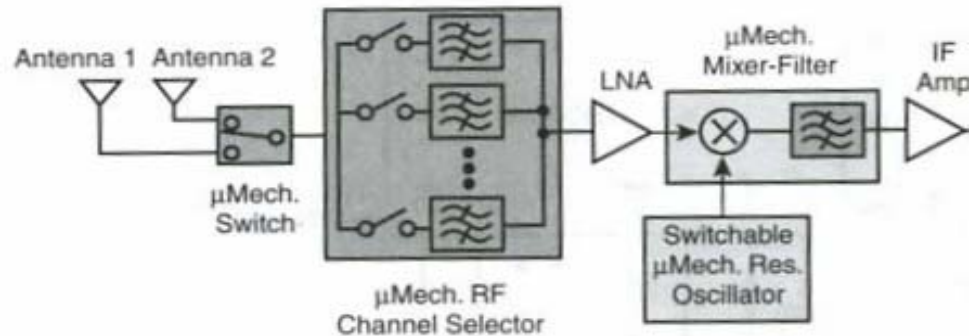


Use of RF filter bank

- **Narrow RF channel** can be selected directly
 - A succeeding electronic block can be **simplified!**
 - Signal will not be influenced by adjacent channels
- LNA can be simplified
 - Dynamic range can be reduced, meaning reduced power consumption
 - **Less stringent requirements to IIP3 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 of LNA linearity is reduced**
 - Then LNA gain can be increased → improving SNR for the following blocks
 - Reduced phase noise requirements for LO
 - → also power reduction
 - On-chip implementation of LO might be possible

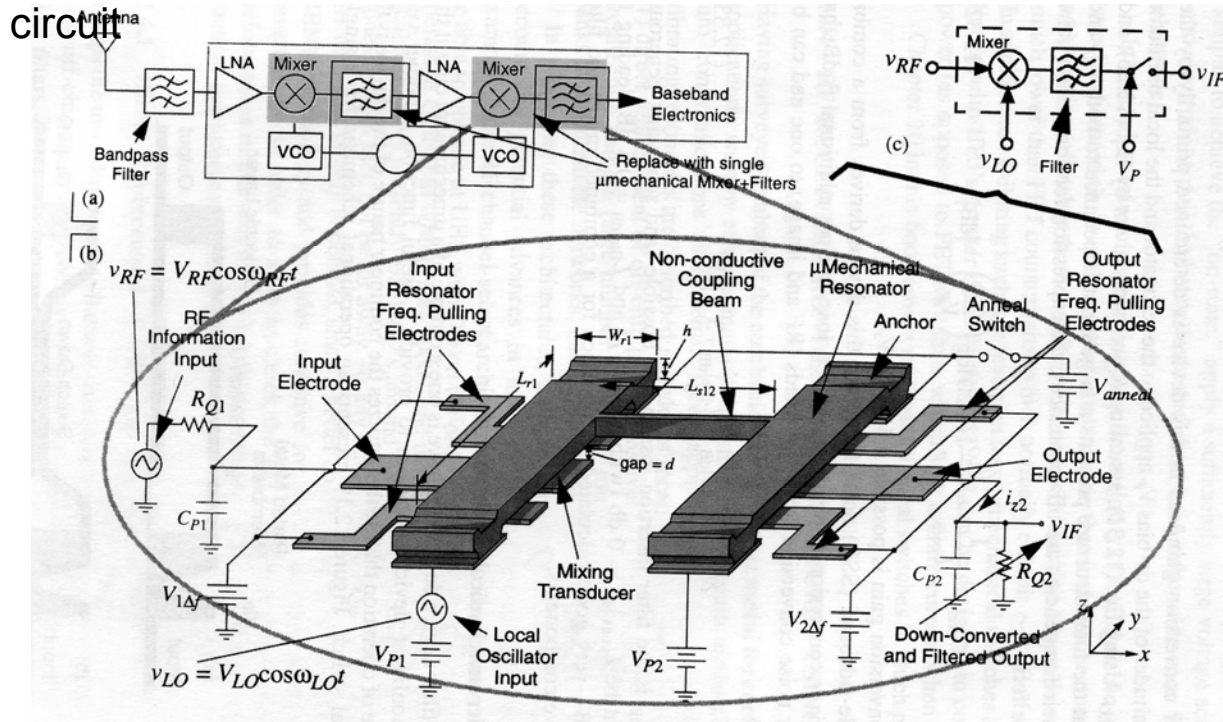
B2. Switchable MEMS frequency synthesizer

- 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**
 - → LNA can be simplified and does not need a separate impedance matching circuit



Transceivers using RF MEMS

- How micromechanical circuits can be used in **communication systems**
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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

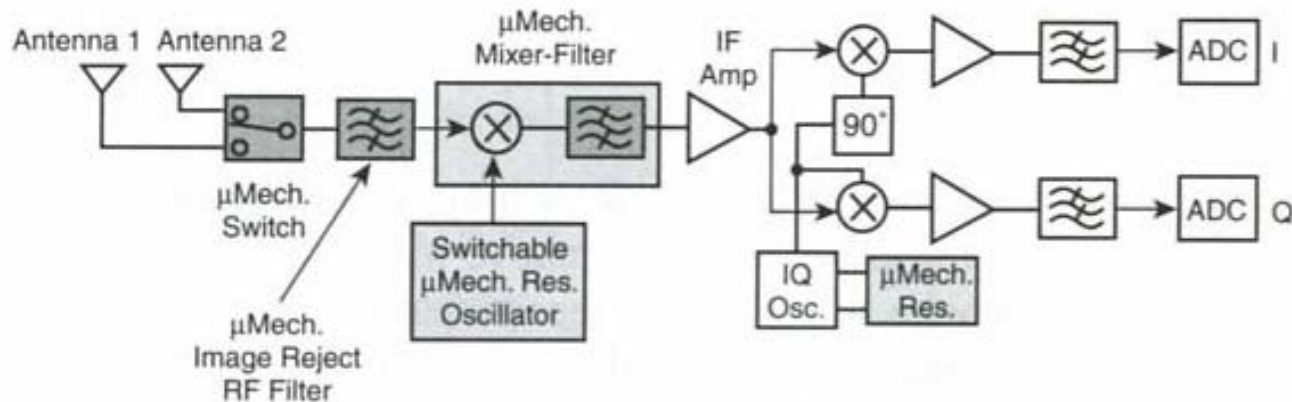


Figure 12.23. System block diagram for an all-MEMS RF front-end receiver architecture. (On-chip μ mechanics are shaded.)

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 on this matter

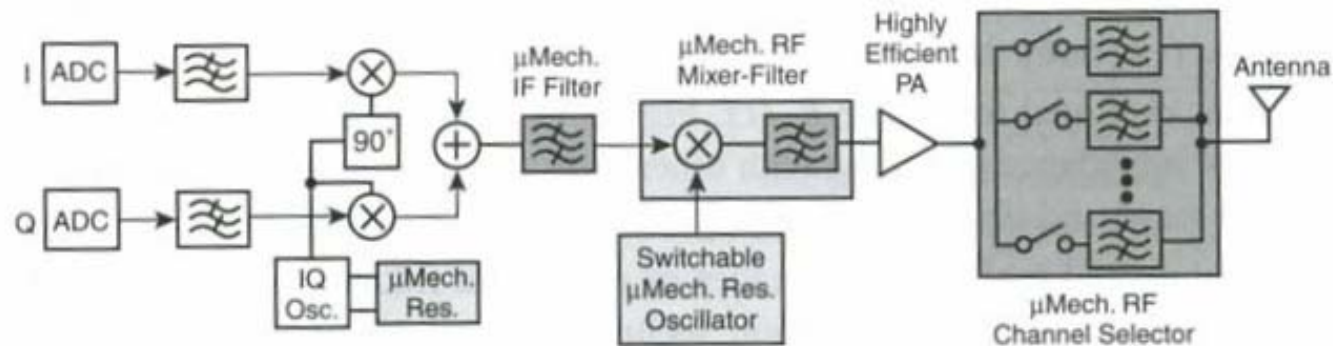
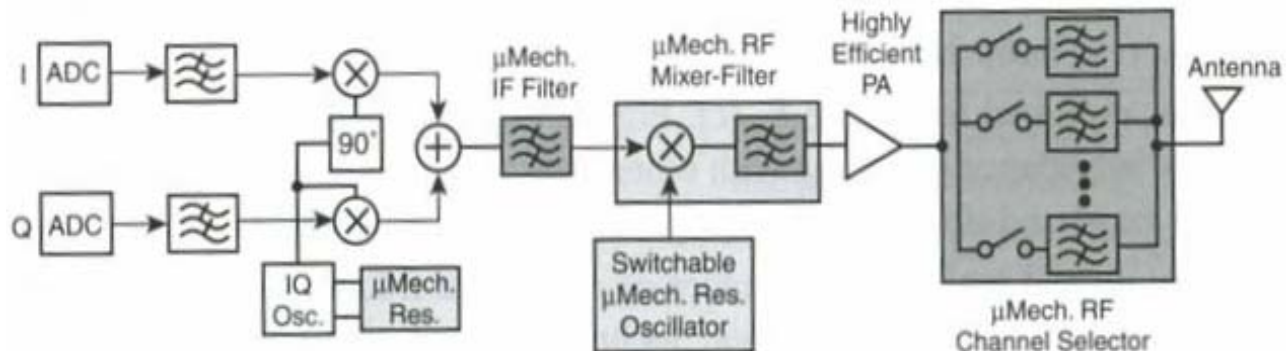


Figure 12.24. RF channel-select transmitter architecture, possible only if high-power μ mechanical resonators can be achieved. Here, on-chip μ mechanical blocks are shaded, and the PA is not necessarily implemented on-chip.

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 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 $Q \sim 1000$ at 3 GHz
 - Absolute value and tolerances in resonance frequency
 - Depends on fabrication, trimming and tuning
 - Stability of resonator frequency
 - Wrt. 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 piezoelectric materials

Frequency and Q-value, contd.

- **Q-factor**
 - **Energy loss** in material influences Q value
 - Q-factor depends on **material type**
 - Q-factor dependence of **fabrication**
 - Surface cleanness
 - Doping: diffusion and implantation give different properties
 - **Loss** via anchors reduce Q
 - "anchor-less" structures: f-f beam is beneficial
 - Balanced tuning fork structure
 - Circular resonator

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 \sim 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 \rightarrow 70 \AA) the resonance impedance will be **reduced** from 5000 Ω \rightarrow 300 Ω (870 MHz)
 - BUT this will also **degrade linearity**
 - **\rightarrow important to balance linearity requirements to impedance requirements**

TABLE 12.3. Two-Resonator μ Mechanical Filter Electrode-to-Resonator Gap Spacing Design^a

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

^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.

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

Thanks to Ulrik Hanke, HVE, for his help with translation of RF MEMS slides from Norwegian to English in 2008!

