8

RF and microwave band-pass passive filters for mobile transceivers with a focus on BAW technology

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1. Interest of RF band-pass filters in mobile communications

This chapter focuses on RF and microwave band-pass passive filters required for mobile transceiver front-ends. Band-pass filters are commonly used in wireless transceivers for communication systems such as cellular and connectivity standards or Ultra Wide Band systems. Most of the recent communications standards operate in multi-bands and have flexible frequency profiles, therefore filter banks must be implemented in order to fulfil regulation requirements in all bands.

A filter is a time-invariant linear system that can be defined by its frequency transfer function $H(f)$. It operates on an input signal $x(t)$ with respect to frequency and the resulting filtered output signal $y(t)$ has a Fourier transform equal to the product of $X(f)$ and $H(f)$: $Y(f) = H(f)X(f)$.

The ideal transfer function of a band-pass filter is equal to 1 in the pass-band and to 0 in the two stop-bands. The pass-band is defined by a range of frequencies $[f_1, f_2]$ or equivalently by its central frequency f_c and its frequency bandwidth W, with:

$$f_c = (f_1 + f_2)/2 \text{ and } W = (f_2 - f_1) \tag{1}$$

The two stop-bands are defined by the frequency ranges $[0, f_1]$ and $[f_2, +\infty]$ for the left and right stop-band respectively.

In practice, the filter transfer function is not perfect: it is not perfectly constant in the pass-band, it presents a finite attenuation (or rejection) in the stop-bands and the transitions between frequency bands are not infinitely sharp.

The different characteristics of a band-pass filter will be described in section 2. Filtering is one of the three more critical elements for the cost and size of transceivers in addition to frequency synthesizers and power amplifiers.

Many filters are present in wireless transceivers. They are distributed in the successive stages of the architectures in the baseband (BB), intermediate frequency (IF) and radiofrequency (RF) parts. This chapter focuses on RF and microwave band-pass filters.

RF band-pass filters operate on RF or microwave signals and we will use the expression RF band-pass filter to represent them regardless of whether they operate on RF or microwave signals. In the receiver, they are located just after the antenna and after the low noise amplifier (LNA). They are used to suppress out-of-band noise and blockers, to eliminate the image frequency in super-heterodyne receivers and more generally to limit the bandwidth of the received signal and the dynamic requirements of the receiver. In the transmitter, they are located before and/or after the power amplifier (PA). They are used to reject the spurious signals generated, for example by the local oscillator (LO), and to minimize power emission out of the desired frequency band that could be generated by the PA non-linearity. RF band-pass and band-reject filters are also found in the receiving and transmitting branches of duplex filters in systems using frequency division duplex (FDD) schemes. Another application of RF band-pass filters used in a filter bank is to split a large RF bandwidth into several smaller bandwidths that are easier to process. This can be useful in very wide band communications systems such as in the field of millimeter-wave 60 GHz or more generally for Ultra Wide Band (UWB) communications.

The precise role and specifications of the different filters depends on the regulation, on the standard requirements, on the architecture of the transceiver and also on the duplex scheme. Standards and regulations specify the minimum requirements for RF transceivers. They are expressed by parameters, which can take values that impose more or less stringent constraints on the RF system blocks such as filters. Among the important parameters that can influence filter (BB, IF and RF) specifications or characteristics are: frequency bands, channel and signal bandwidth, channel frequency step, duplex schemes, transmit power, output RF spectrum mask, limit on spurious emission, limit on noise, distortions, linearity, Bit Error Rate (BER), Error Vector Magnitude (EVM) and Adjacent Channel Interference expressed by the Adjacent Channel Leakage Ratio (ACLR) or the Adjacent Channel Power Ratio (ACPR).

A given standard is allocated with one or several frequency bands and these frequency bands can be split into smaller bandwidth channels allocated to different users. The RF filter is used to select the standard bands while the IF and/or BF filters select the channel bandwidths and are generally more selective than RF band-pass filters. The RF frequency bands specified by standards are usually above 50 MHz. For example, for WIMAX standards, the specified bands are between 100 and 200 MHz. Therefore, RF filters have wide pass-bands and the ratio between the bandwidth of the pass-band and the central frequency of the filter is typically of the order of a few percent.

Most mobile subscriber equipment is now multi-band, multi-mode (multi standards) and multi-radio (cellular, connectivity, FM and TV receivers, GPS, etc). They include several transmitters/receivers connected to a small number of antennas. RF low-pass, high-pass and band-pass filters are used to combine these different transceivers operating on different frequency bands that are generally quite far apart. Low-pass and high-pass filters are usually well suited for this task that most often does not necessitate very high selectivity filters with high Q resonators.

1.1 Influence of Duplex schemes on RF filter requirements

Different duplex schemes are specified in wireless communication standards to separate forward and reverse communication links in order to allow mobile equipment to share the same antenna for transmit and receive signals. These schemes are FDD (Frequency Division Duplex), TDD (Time Division Duplex), or HFDD (Half Frequency Division Duplex).

1.1.1 FDD

In the FDD method, the forward and reverse communications use different carrier frequencies separated by a frequency offset. With the FDD method, a real full duplex communication is possible, but it requires a complex RF front-end since it uses separate receiving and transmitting synthesizers. Besides, it requires two different RF filters for transmitting and receiving. The transmission must not degrade the simultaneous reception. Therefore, on the one hand, the attenuation of the transmit filter must be high enough in the receiver frequency band so that the noise introduced by the transmitter on the receiver is kept low in comparison to the noise floor of the receiver. On the other hand, the receiver RF filter must sufficiently reject the transmitter frequency band so that the transmitter does not overload the receiver. The constraints on RF filters used in duplex filters in FDD modes are usually quite stringent: The larger the frequency offset, the easier these filters. Typical values of frequency offset are 50 to 100MHz.

For example, in GSM 900 standard, the transmitter uses the uplink frequency sub-band Tx: 890-915 MHz and the receiver uses the downlink frequency sub-band Rx: 935-960 MHz.

The GSM sub-bands are separated by a frequency offset equal to 45 MHz. And each sub-band has a 25 MHz bandwidth, while the channel spacing is equal to 200 KHz. For the DCS 1800 standard, the frequency offset is 95 MHz and each sub-band has a 75 MHz bandwidth, Tx: 1710-1785 MHz and a Rx: 1805-1880 MHz.

The GSM standard (ETSI, 1999) specifies the output RF spectrum of the modulated signal for the transmitter. The spectrum mask for a class 4 mobile GSM transmitter is given in Fig. 1.

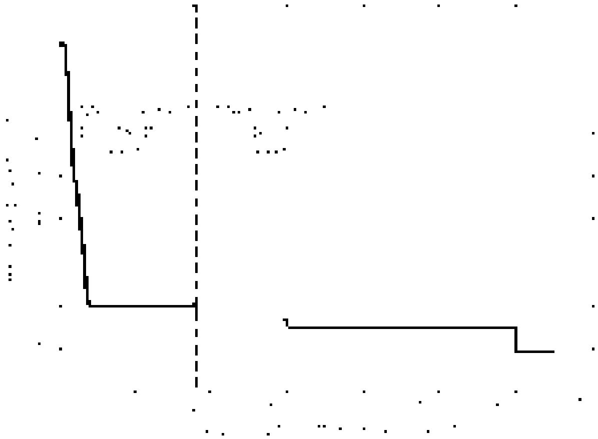


Fig. 1. GSM 900 spectrum mask of modulated signal.

Using these specifications, we can calculate the required filter attenuation (rejection) in the receive band for the GSM duplex scheme. Let's suppose that we require a transmit noise 10 dB below the noise floor of the receiver, for a receiver noise figure of 6 dB. Noting P_{out} the transmitted power in dBm, the output power spectral density in dBm/Hz for a channel bandwidth W_{ch} is:

$$PSD = P_{out} - 10\log(W_{ch})\ [dBm/Hz] \tag{2}$$

Filter attenuation at the receive frequency must be greater than:

$$\begin{aligned} Att_{dB} &\geq P_{out} - 10\log(W_{ch}) - Mask - (-174 + NF - 10) \\ Att_{dB} &\geq 33 - 53 - 71 - (-174 + 6 - 10) = 87dB \end{aligned} \tag{3}$$

Therefore, the filter attenuation must be 87dB at 45 MHz from the carrier frequency which is a rather stringent requirement for RF filters.

The insertion losses of the filters have not been taken into account in this calculation.

The transmit/receive duplexer filters for mobile terminals must have high-performance with high out-of-band attenuation and a low in-band transmit/receive distortion and insertion loss. It is sometimes necessary to use cavity filters to fulfill the severe filter requirements of the FDD method.

1.1.2 TDD

For the TDD method, the antenna is switched alternatively between the transmitter and the receiver. The same frequency band is used for transmission and reception. The transceiver can be simplified because, even if it looks like a full duplex system for the user, the transceiver actually operates in a single mode at a time. The transmitted signal does not interfere with the received signal since transmission and reception are done at different periods of time. Therefore, the RF filter requirements are relaxed. Besides, since the transmission and reception use the same carrier frequency, a single RF filter can be used. However there are some drawbacks in TDD, e.g. the adjacent channel interference is higher than in a FDD scheme.

1.1.3 HFDD

In some standards, such as WiMAX, a Half Frequency Division Duplex is possible in order to reduce the cost and size of mobile stations. HFDD systems operate in half-duplex; the transmission and reception are done in separate bands and at separate time periods. This approach allows a single frequency synthesizer to be used and relaxes the constraints on the RF filters.

1.2 Filtering of out-of-band blockers and image frequency

RF filters are also used in the receiver to remove the RF band blockers and image frequency.

1.2.1 Blocking signals

The blocking characteristics of the receiver are specified separately for in-band and out-of-band performance. For example, for the GSM 900 standard, these bands are defined by the following frequency ranges for the mobile station: In-band: 915 MHz -980 MHz and Out-of-band: > 980 MHz-12 750 MHz.

For a small mobile station, the reference sensitivity should be met when different signals are simultaneously input to the receiver:

- a useful signal, modulated at frequency f_o, 3 dB above the reference sensitivity level or input level for reference performance,
- a continuous, static sine wave signal at a frequency f which is an integer multiple of 200 kHz and at a level of 0 dBm out-of-band and -43 dBm, -33 dBm or -23 dBm for $|f - f_o| < 1.6\,MHz$, $1.6\,MHz \le |f - f_o| < 3\,MHz$, $|f - f_o| \ge 3\,MHz$ respectively.

The FDD WCDMA standard (3GPP, 2005) specifies that the out-of-band blocking characteristics of the receiver should be such that the BER remains smaller than 10^{-3} when different signals are simultaneously input to the receiver:

- a useful signal modulated at frequency f_o with a power at -114 dBm (3 dB above the reference sensitivity) and
- a blocking signal with a power equal to -44 dBm, -30 dBm, -15 dBm, at a frequency f in the range [2050 MHz - 2095 MHz], [2025 MHz - 2050 MHz], [1000 - 2 025 MHz] respectively.

1.2.2 Image frequency

In super-heterodyne receivers, the RF filter is used to suppress the image frequency. Indeed, for a given useful RF frequency f_{RF} and a given intermediate frequency f_{IF}, it is possible to down-convert the RF frequency to the IF frequency, by mixing the RF signal with a local oscillator at a frequency f_{LO} such that:

$$f_{IF} = |f_{RF} - f_{LO}| \tag{4}$$

As the mixing generates both the difference and the sum frequencies of the input signals plus possibly some other spurious frequencies, the resulting signal is filtered after the mixing by a selective IF filter to select the down-converted signal corresponding to the desired channel. Unfortunately, not only the desired RF frequency will be down-converted to the IF frequency but also the frequency called the "image frequency" f_{im}. The image frequency satisfies the same equality and is symmetrical to f_{RF} with respect to f_{LO} and:

$$f_{IF} = |f_{im} - f_{LO}|,\ f_{LO} = \frac{f_{RF} + f_{im}}{2} \text{ and } f_{im} = 2f_{LO} - f_{RF}\,. \tag{5}$$

Therefore this possible image frequency has to be filtered before the mixer by an RF band-pass filter. Otherwise, if there is some undesirable signal power at the image frequency, at the receiver input, it will add as a noise to the down-converted useful signal.

1.3 Characteristics of some cellular communication and connectivity standards

Many standards exist for wireless communications, including standards for 2G, 3G and beyond 3G cellular systems (e.g. GSM, UMTS, LTE), Wireless Metropolitan Area Networks WMAN (e.g. WiMAX IEEE 802.16), Wireless Local Area Networks WLAN (e.g. Wi-Fi IEEE 802.11a/b/g/n) and Wireless Personal Area Networks WPAN (e.g. Bluetooth IEEE 802.15.1). Most of these are in the frequency range below 6 GHz but some new standards have appeared in the millimeter wave range (60 GHz radio in particular). In the first case, the data rates are in the range of several tens to several hundreds of Mbps and in the second case they can be in the range of several Gbps.

In Table 1 we consider some of the most widely used standards for wireless communications and we give some of their characteristics (for the case of a Mobile Station, uplink) that influence the design of the RF band-pass filters.

Standard	Frequency Range (MHz)	Transmission Bandwidth (MHz)	Channel Bandwidth	Duplex scheme / Frequency offset in FDD
GSM 900	890 – 915	25	200 kHz	FDD / 45 MHz
DCS 1800	1710 – 1785	75	200 kHz	FDD / 95 MHz
UMTS WCDMA (Band 1)	1920 – 1980	60	5 MHz	FDD / 190 MHz
UMTS-TDD TDCDMA	1900 – 1920 and 2010 – 2025	20 and 15	5 MHz at 3.84 Mcps	TDD
WLAN (802.11 b/g)	2400 – 2483.5	83.5	11 MHz	Half-duplex
WLAN (802.11a)	5150 – 5350	200	20 MHz	Half-duplex
WMAN Mobile WiMAX (802.16e)	2300 – 2400	100	Variable (3.5, 5, 7, 8.75, 10 MHz)	Mainly TDD
	2496 – 2690	194		
	3300 – 3400	100		
	3400 – 3600	200		
	3600 – 3800	200		

Table 1. Some parameters of mobile communications standards related to the transmitter

The relative bandwidth, i.e. the ratio between the transmission bandwidth and the central frequency of the RF band-pass filter, for these standards varies between 1 % for UMTS-TDD and 7 % for WiMAX 2496 – 2690 MHz frequency range. The value of the relative bandwidth may influence the choice of the filter technology.

It is clear from Table 1, that a single reconfigurable RF filter could not be used in a multi-radio transceiver and that the necessary RF front end filter bank is quite complex.

However tunable RF filters are necessary for reconfigurable multi-radio front-ends that can support several standards and applications. Since not all of the applications are used at the same time, it is interesting to share some RF resources between the different radios in order to reduce the hardware size of the transceiver. Reconfigurable tunable filters are one of the elements that make this possible.

A challenge is to achieve tunable filters that can be integrated on-die. For an RF band-pass filter, the characteristics that should be tunable or reconfigurable include center frequency, bandwidths, selectivity, pass-band ripple and group delay.

1.4 Case of UWB standard with an MB-OOK transceiver

As seen before, in the case of very wide or ultra wide band communications, it can be useful to split the available frequency bandwidth into several smaller bandwidths by a filter bank. An example of such an approach is the UWB architecture proposed in (Paquelet et al., 2004). UWB wireless systems based on impulse radio have the potential to provide very high data rates over short distances. Fig. 2 represents the spectral mask for UWB systems in Europe.

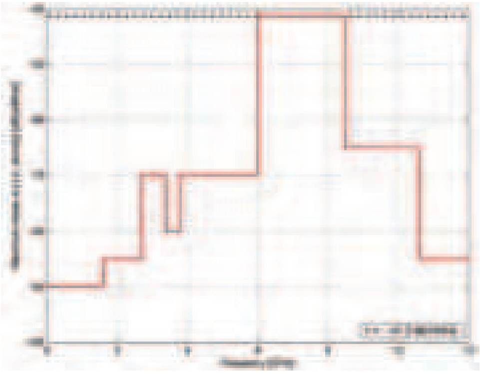


Fig. 2. Spectral mask for UWB systems in Europe

One of the possible solutions for UWB communication systems is the Multi Band On-Off Keying (MB-OOK) proposed in (Paquelet et al., 2004) which consists of an OOK modulation generalized over multiple frequency sub-bands and associated with a demodulation based on a non-trivial energy threshold comparison. Fig. 3(a) represents the architecture of the UWB MB-OOK transmitter and Fig. 3(b) shows the non-coherent processing in one sub-band of the receiver.

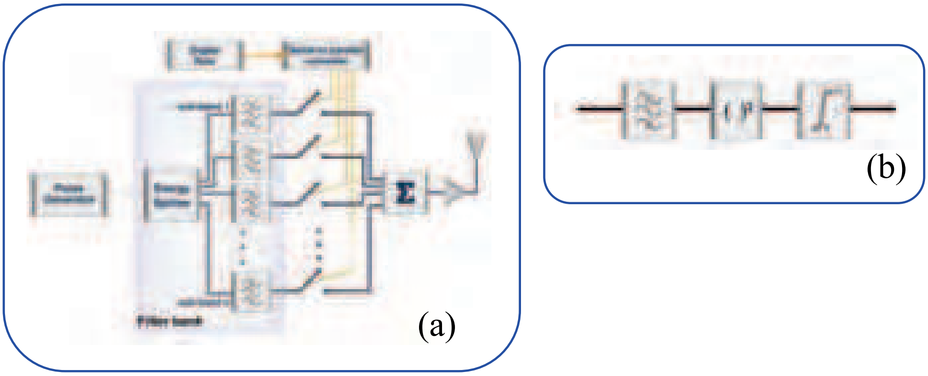


Fig. 3. (a) UWB MB-OOK transmitter architecture. (b) Non-coherent receiver: energy integration for one sub-band of the receiver

In the transmitter architecture, a pulse covering the allowed frequency band is generated with a repetition period T_r. The pulse generator is followed by a multiplexer that splits the input signal into N sub-bands. Pulses in each band are filtered and modulated by digital data at a rate $1/T_r$. Then, the modulated signals are combined and amplified before being sent through the UWB antenna.

The receiver architecture is symmetrical to that of the transmitter. It includes a low noise power amplifier (LNA), a splitter, a band-pass filter bank and then in each band, a squarer and an integrator.

Integration time in reception (T_i) and repetition time in transmission (T_r) are chosen considering the channel delay spread (T_d). To avoid inter-symbols interference, the symbol repetition period is chosen so that:

$$T_r > (T_d + T_s + T_f) \tag{6}$$

where T_s is the duration allocated to the symbol waveform and T_f is the duration of the impulse response of one filter of the filter bank. Maximal throughput of the communication system can be estimated by multiplying its number of sub-bands and the pulse repetition rate $1/T_r$ (as long as the repetition time is long enough in comparison).

The splitter and the filter bank are common elements in the transmitter and receiver. The filter bank may be uniform or non uniform (Suarez et al., 2007a) depending on the constraints of the technology. Section 4 will present an example of a filter-bank for this architecture using BAW technology.

2. Applications and specifications of RF band-pass filters for Multi-Band reconfigurable transceiver architectures

This section considers the different characteristics of RF band-pass filters required in mobile transceivers. It's important to emphasize that the precise role and specifications of the RF band-pass filters depend on the regulation, on the standard requirements, on the architecture of the transceiver and also on the duplex scheme as detailed in the first section.

Among the important parameters that can influence RF band-pass filter's specifications and the choice of the filtering technology are: frequency bands (filter's central operation frequency), allocated bandwidth (filter's bandwidth), transmit power (filter's power handling for the transmitter case), output RF spectrum mask, limit on spurious emission and adjacent channel interference (filter's out-of-band rejection). Furthermore, low insertion loss, temperature stability and integrability are expected in mobile multi-radio filters.

The central operation frequency depends on the considered standard. As presented in the first section, wireless communication standards such as cellular and connectivity standards or Ultra Wide Band systems have specific frequency allocation. Regulation entities determine the frequency allocation chart and also the maximum output power in each frequency band. This may vary depending on the geographical region or the country. Most of the wireless communication standards are in the frequency range below 6 GHz. Allocated frequency bands determine the filter's central frequency. This is a key parameter to choose the filtering technology which should stand a high maximal operation frequency (up to 6 GHz for multi-radio applications).

The RF filter's bandwidth is not defined by the channel bandwidth but by the allocated frequency bandwidth. Table 1 presents the different bandwidths of the RF transmission filters in a multi-radio.

In the transmitter case, since the filtering is usually carried out after the power amplification, the RF transmission filters must offer high power handling capability. Input signals may have high power dynamics (e.g. mobile WiMAX or LTE signals) and the maximum power levels may vary up to 33 dBm in the GSM case, for example.

The out-of-band rejection of the filter is generally expressed in dBc (relative power in dB to the carrier). Maximal rejection is specified at a certain frequency offset from the carrier, known as the stop bandwidth and the frequency bandwidth to reach the required attenuation is also specified as the transition bandwidth. For communications standards, the out-of-band rejection is set from the output RF spectrum mask, the limits on spurious emission and the maximal adjacent channel interference expressed by the ACLR or the ACPR (usually considering the most stringent requirements).

An example of the power spectrum mask for mobile WiMAX standard is presented in Fig. 4. This power spectrum mask has not been proposed by the WiMAX IEEE standard but by the European Telecommunications Standards Institute (ETSI, 2003).

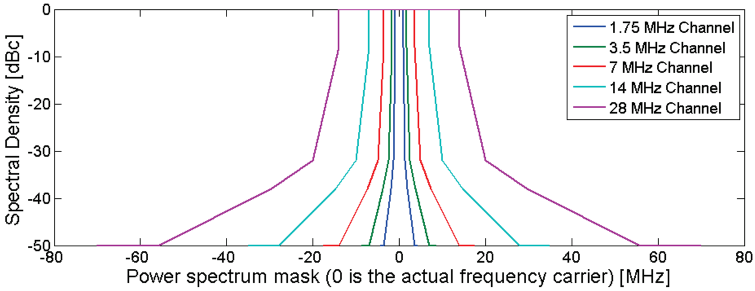


Fig. 4. WiMAX Power Spectrum mask for a high complexity modulation format.

The Power Spectrum mask is defined around the carrier and depends on the channel bandwidth. Recent standards like mobile WiMAX and LTE are very flexible and propose different channel bandwidths, number of carriers and coding and modulation formats for each carrier in order to adapt the transmission to the environment conditions (channel, network, user needs, etc). Power masks illustrate this flexibility, for example the mask of Fig. 4 is proposed just for the case of high complexity modulation format (e.g. 64 states or equivalent), which leads to the most stringent filtering constraints because of the small transition bandwidth.

In order to define the out-of-band rejection of the RF filter, a common practice is to extrapolate the power spectrum mask for a given channel bandwidth to the first and last channels in the allocated frequency band and to establish a new mask covering all the allocated frequency bandwidths.

Another important characteristic of RF band-pass filters is the Insertion Loss (IL) which should be as low as possible to increase the whole architecture power efficiency.

The group delay is another parameter to consider. For a filter's transfer function $H(s)$, at real frequencies, with $s = j\omega$:

$$H(j\omega) = \left|H(j\omega)\right| \cdot e^{j\theta(\omega)} = G(\omega) \cdot e^{j\theta(\omega)} \tag{7}$$

Where $G(\omega)$ and $\theta(\omega)$ are the gain-magnitude, or simply the gain, and the phase components respectively. Group Delay $\tau(\omega)$ is defined as:

$$\tau(\omega) = -{}^{\partial\theta(\omega)}\!\big/_{\partial w} \tag{8}$$

The group delay is expected to be constant in the whole filter's bandwidth.

EVM is typically measured at the receiver and constitutes a common indicator of signal information integrity. The maximum accepted EVM is usually given by the communications standards and in the case of WiMAX and LTE, a table with EVM values for different modulations and coding rates is established, e.g. in mobile WiMAX EVM limit is -30 dB (3.16%) for a 64-QAM (3/4) modulation (IEEE, 2005). The EVM is calculated observing all the imperfections of the transmission chain blocks. Therefore, the maximum acceptable group delay and in-band ripple of the filter depend on this EVM value and on the imperfections generated by all the other blocks of the architecture.

Finally, as size and cost are critical parameters for manufacturers, it is very often required to use a filtering technology that enables integration.

3. Available filtering technologies: advantages and trade-offs

3.1 Available technologies

The most notable RF filtering technologies include LC filters, ceramic filters, surface acoustic wave (SAW) filters, bulk acoustic wave (BAW) filters and low temperature co-fired ceramic (LTCC) filters.

LC filters can support high frequencies and can be integrated as a SoC. However, their main drawback is that they require too much area and can offer only a limited quality factor (Q).

Ceramic filters offer low IL (about 1.5 - 2.5 dB), high out-of-band rejection (> 35 dB) and low cost. On the other hand the large size of ceramic filters significantly penalizes the integration.

SAW filters are smaller than LC and ceramic filters, but have limitations in the frequency domain (up to 3 GHz). Depending on the application, their maximum output power rating could also be insufficient (up to 1 W). Typical IL varies between 2.5 and 3 dB and out-of-band rejection can reach up to 30 dB. The main drawback is that SAW filters are not compatible with silicon integration.

LTCC is a multi-layer technology that offers integration of high Q passive components along with low IL, high maximal operation frequency and acceptable out-of-band rejection. LTCC filters are smaller than LC and ceramic filters and can be integrated as SIP.

BAW filters use Film Bulk Acoustic Resonators (FBAR) that are characterized by a high quality factor Q. Moreover, they have low IL (1.5 – 2.5 dB), significant out-of-band rejection (≈ 40 dB) and high maximal operation frequency (up to 15 GHz). BAW filters can also deal with high output power (3 W). They are CMOS compatible and can be integrated “above IC”.

CMOS-SOI technology evolution allows today to consider LC filters implementation. Indeed, the achievements in terms of quality factor are significantly improved compared to Si technologies.

3.2 SAW Technology

SAW technology is based on the use of surface acoustic waves in a piezoelectric material. Acoustic waves propagate at a speed lower than electromagnetic waves ($v_{SAW} \approx 3\,km/s$ and $v_{EM} < 3\cdot 10^5\,km/s$ depending on the substrate used). This reduces the filter's size ($\lambda = v/f$). The Fig. 5 shows the basic structure of a SAW filter. Piezoelectric material choice, usually quartz, is important because it determines the propagation speed of the acoustic wave.

Fig. 5. Basic structure of a SAW filter.

The major drawbacks of the SAW technology are the operating frequency (<3 GHz), the significant insertion losses and the power handling (<1W). It is possible to perform filtering functions involving more complex cells, using, for example, ladder topologies:

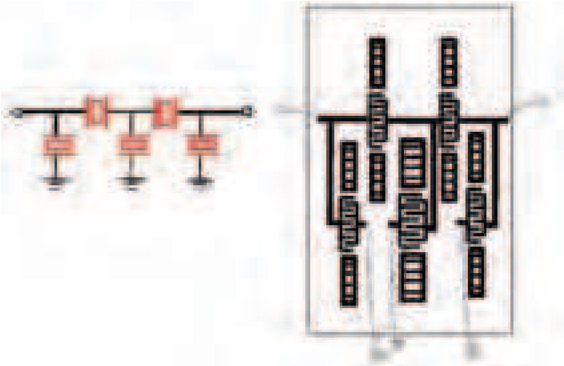


Fig. 6. (a) Ladder topology. (b) Example of a SAW filter in ladder topology

3.3 BAW Technology

3.3.1 Principle

The basic element of the BAW device is the thin film resonator which is very similar to a basic quartz crystal scaled down in size. A piezoelectric film is sandwiched between two metal films as shown in Fig. 7.

Fig. 7. BAW technology principle

The key properties of the BAW resonator are chosen to store the maximum acoustic energy within the structure, achieving a high electrical *Q*. The boundary conditions outside of the metal films must maintain a very high level of acoustic reflection with a vacuum being the ideal interface. The materials chosen must optimize both electrical and mechanical properties. Although there are many piezoelectric materials, Aluminium Nitride (AlN) has been established as the best balance of performance, manufacturability, and reliability.

The metal films range from Al, which offers the best performance with limited power handling, to Mo or W which offer high power handling with the cost of additional resistivity losses. The resonant frequency (f_r) is inversely proportional to the film thicknesses with both, the metal and piezoelectric dielectric, contributing to the resonant point.

$$f_r = {}^{v}\!/_{2d} \tag{9}$$

where v is the acoustic material velocity and d is the thickness of the piezoelectric material. BAW technology using AlN piezoelectric material allows frequency operation up to 15 GHz.

3.3.2 Resonator modeling

The Butterworth Van Dyke (BVD) model is an electric circuit model that characterizes FBAR resonators. The BVD equivalent circuit of the resonator is shown in Fig. 8.

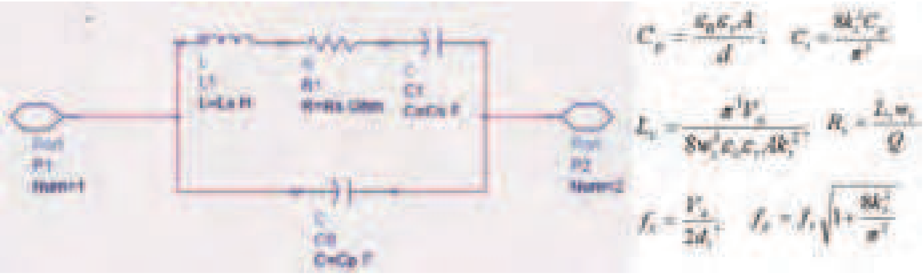


Fig. 8. FBAR resonator – BVD model.

The resonator is in the form of a simple capacitor, having a piezoelectric material as the dielectric layer and suitable top and bottom metal electrodes. The simplified equivalent circuit of the piezoelectric resonator has two arms. C_p is the geometric capacitance of the structure. The R_s, L_s, C_s branch of the circuit is called the "motional arm," which arises from mechanical vibrations of the crystal. The series elements R_s, L_s, C_s are controlled by the

acoustic properties of the device and they cause the motional loss, the inertia and the elasticity respectively. These parameters can be calculated from equations presented in Fig. 8. ε_r is the material's relative permittivity (10.59 for the AlN), k_t^2 is the electromechanical coupling constant (6% for the AlN), V_a is the acoustic material velocity (10937 for the AlN), A is the surface area of the electrodes, d is the thickness of the piezoelectric material, and Q is the quality factor. w_s and w_p correspond to a 2π multiple of the resonance (f_s) and anti-resonance (f_p) frequencies of the resonator. Thickness of series and shunt resonators may be different; d_1 and d_2 refer to the thickness of the series and the shunt resonator respectively.
The frequency response of the FBAR resonator depends on the thickness of the thin piezoelectric film. The Fig. 9 shows an example of resonator frequency response.

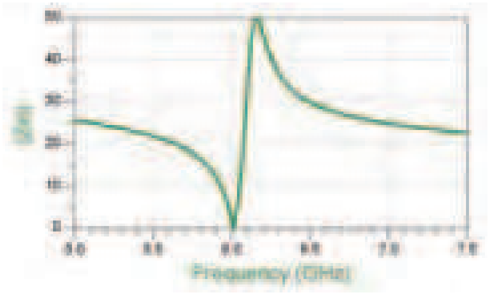


Fig. 9. FBAR resonator frequency response.

3.3.3 Filter's design principle

The filter's design is done by association of resonators. This is performed using two topologies: ladder and lattice topologies (Fig. 10). The filter's responses will be different both in terms of rejection and ripple in the band.

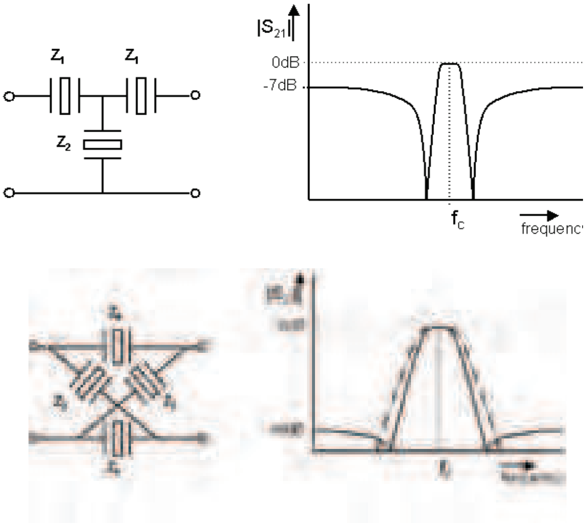


Fig. 10. Ladder and lattice topologies and filter's response.

An important parameter defining the filter bandwidth is the value of the difference between resonance frequency and anti resonance frequency. This value depends on the physical material properties.

In the case of the ladder topology design, the basic principle is to combine two resonators of different thicknesses, one serial and one parallel. The maximum bandwidth is determined by the material. The electrode's surfaces adjust impedances (Fig. 11).

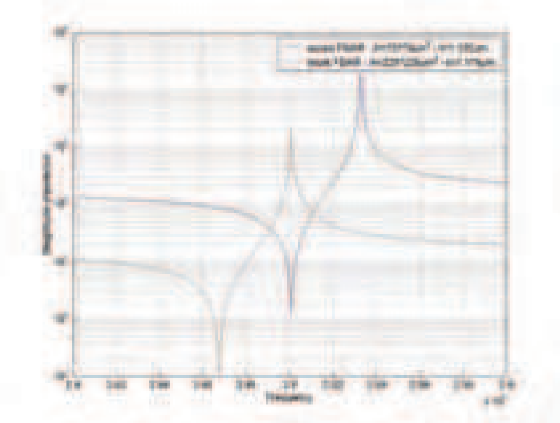


Fig. 11. Magnitude impedance of a series and a shunt FBAR resonator.

The series and the shunt resonators form a stage. In order to achieve the required frequency response and out-of-band rejection, particular stages are put together to build cascades. Each additional stage (a couple of series-shunt resonators) increases the filter order by one. Therefore, a six resonators ladder filter is a third order filter. Fig. 12 shows the evolution of the filter's frequency response according to the number of stages.

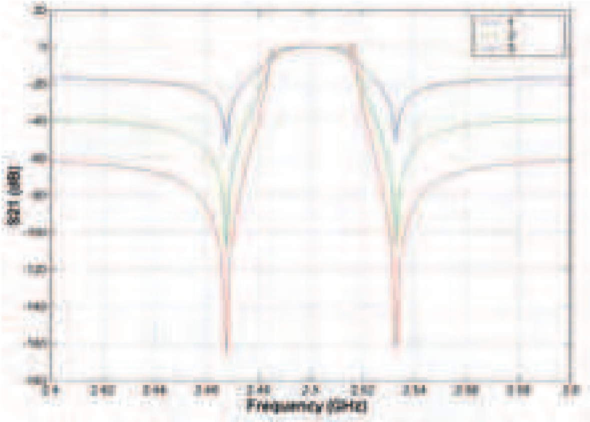
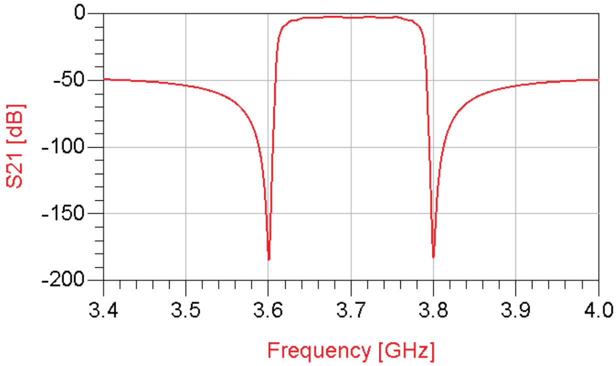


Fig. 12. Influence of the number of stages in the filter's frequency response.

Ladder filters are single ended, while lattice filters are double ended. If the filter output is at the antenna input, the ladder topology may be preferred to the lattice topology due to unbalanced signal effects.

Only two parameters need to be optimized in order to design a band-pass filter. These parameters are the area *A* (expressed as *l x l*) and the resonator thickness (d_1 and d_2).

An example of a WiMAX filter in the 3.6 – 3.8 GHz frequency band was proposed in (Suarez et al., 2008). The emission filter in this case has a bandwidth of 200 MHz (Fig. 13). The out-of-band rejection is 50 dB at twice the channel bandwidth (20 MHz from the edge for a 10 MHz channel) and has been fixed from the power spectrum mask presented in Fig. 4.



Stage	L_{serie} [µm]	L_{shunt} [µm]
1	122	87
2	102	98
3	113	107
4	124	117
5	136	128
6	150	142
7	168	132

Insertion Loses	3.06 dB
Rejection	49.03 dB

Fig. 13. [S_{21}] parameter of a WiMAX RF filter using BAW technology (7th order ladder).

3.3.4 Manufacturing technologies

There are essentially two main families of technologies for achieving the BAW filters:

- FBAR technology
- SMR technology (Solidly Mounted Resonator)

For FBAR technology, Fig. 14 shows two processes:

Fig. 14. FBAR processes: (a) Substrate etching (b) Substrate micro-machining.

The FBAR technology advantages are:

- a power confined to the piezoelectric material, therefore, lower losses
- low number of layers to achieve
- integration in SOC technology

The drawbacks are:

- membrane's fragility
- process complexity
- thermal dissipation

SMR technology uses a Bragg reflector as presented in Fig. 15.

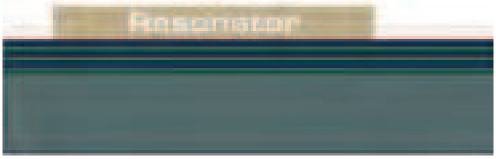


Fig. 15. SMR technology - Bragg reflector.

The SMR technology advantages are:
- the possibility to process "stand alone" BAW
- good thermal dissipation in the reflector's layers

The drawbacks are:
- more important losses
- a larger number of layers

3.3.5 BAW filter's tuning

The main drawback of BAW filters (such as SAW filters) is the complexity of achieving frequency tuning. It's still possible to move the series or parallel resonance frequency using varactors. This allows a tuning of 1% of the relative bandwidth. It is also possible to use inductors (active inductors or MEMS). In this case, tunability can reach 5% of the relative bandwidth. These techniques are mostly used to achieve a post-process tuning.

4. RF band-pass filters for transmitters: implementation examples.

4.1 RF filter bank for an UWB Multi-Band On-Off Keying transceiver

This example is related to the RF band-pass filter bank in an UWB OOK architecture as described in section 1.4. In such an architecture the filter bank is a common element in transmitter and receiver. A filter bank is uniform if all the band-pass filters have the same bandwidth. In the MB-OOK architecture, the filter bank may be uniform or non uniform (Suarez et al., 2007a) depending on the constraints of the technology.

A good value of relative bandwidth (i.e. the ratio between the transmission bandwidth and the central frequency of the RF band-pass filter) for AlN BAW technology is 3%. A filter bank where all the band-pass filters keep the same relative bandwidth leads to the conception of a non uniform filter bank. The example presented in this section validates by simulations the viability of using a non-uniform filter bank (AlN BAW tehcnology) in MB-OOK UWB applications.

The filters distribution in the frequency band between 6 GHz and 8.5 GHz (Fig. 2) is calculated for a relative bandwidth of 3%. It leads to a filter bank of 10 filters. A higher number of sub-bands would allow the system to reach higher throughput. Nevertheless, the required electronic components (filters, switches, combiners, isolators) also result in increased active surface, power losses and higher power consumption. Therefore, there is a trade-off between throughput and system complexity. A ten filter configuration offers a throughput of 125 Mbps over Non Line Of Sight (NLOS) conditions, a reasonable number of sub-bands and a suitable relative bandwidth for AlN BAW filters design (Suarez et al., 2007a).

Measurements and simulations in (Diet et al., 2005) established that the Cauer or elliptic filter behavior is a good approximation to the BAW filter response. Therefore, Cauer filters were used in simulations. The band pass ripple and the out-of-band attenuation of each band-pass filter is chosen for maximal attenuation between sub-bands with the purpose of reducing the intersymbol interference in reception. Simulated filters in this filter bank are order 5 filters. Each filter has 40 dB of out-of-band rejection and less than 2.5 dB of in band ripple; as the MB-OOK architecture is based on energy detection, the values of ripple less than 3dB have been considered acceptable.

Fig. 16 presents the frequency response of the first filter of the filter bank simulated with a BVB model and without the Cauer approximation (Suarez et al., 2007b).

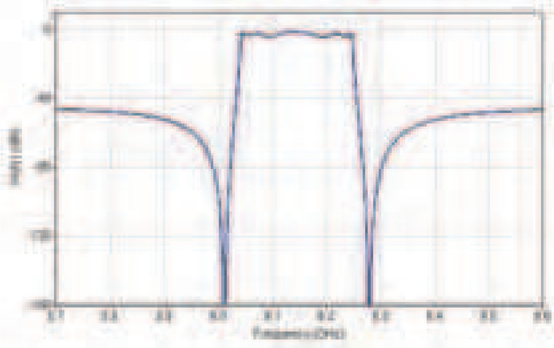


Fig. 16. Frequency response of the first filter of the filter bank.

Fig. 17 presents simulation results in time and frequency of the transmitter architecture presented in Fig. 3a including the non-uniform filter bank.

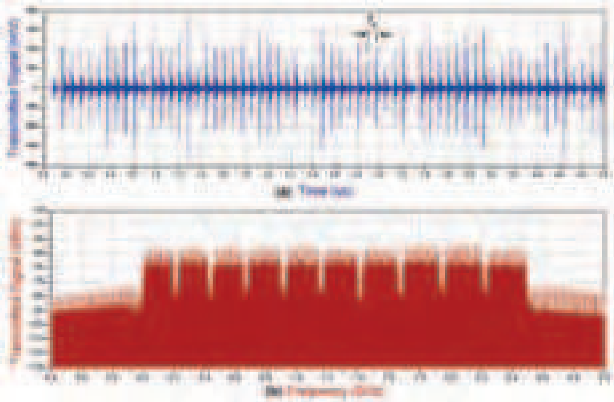


Fig. 17. UWB MB-OOK transmitter simulation results (a) Time (b) Frequency.

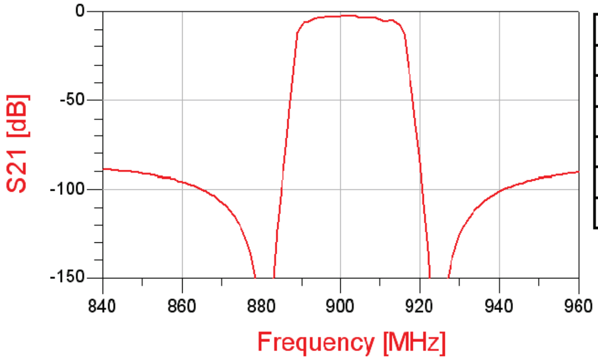
The duration of the filter impulse response can be longer than the channel delay spread. Thereby, the throughput depends on the channel conditions and also on the filter's response. This conclusion has been previously stated in Eq. 6. Performances of the simulated architecture validate the viability of using a non-uniform filter bank of AlN BAW tehcnology in a MB-OOK UWB transmitter: for a maximal mean error probability of 10^{-5}, the covered distance is 3.3m on the LOS case and 1.9 m on the NLOS case (Suarez et al., 2007a).

4.2 RF filter bank for a multi-radio transmitter

This example deals with a BAW RF filter bank of a multi-radio transmitter in the 800 MHz - 6 GHz frequency band. Considered communications systems include cellular phone and Wireless LANs and MANs in Europe. BAW band-pass filters are designed with AlN FBARs. Filter bank design is based on the parameters defined by the regulations (allocated frequency bands, power spectrum mask, etc.). Results presented correspond to simulations on Agilent Advanced Design System (ADS).

4.2.1 GSM

Global System for Mobile communications operates in the frequency band between 890 – 915 MHz in Uplink and 935 – 960 MHz in downlink (ETSI, 1999b). The emission filter then has a bandwidth of 25 MHz and a central frequency of 902.5 MHz. Out of band rejection must be 90dB. The transmission response of the GSM designed filter is presented in Fig. 18. The thickness of the series resonators is 6.059 µm and the thickness of the shunt resonators is 6.205µm. Fig.18 summarises the resonator's surface areas. The reached rejection is 89 dB and insertion losses are less than 2.3dB.



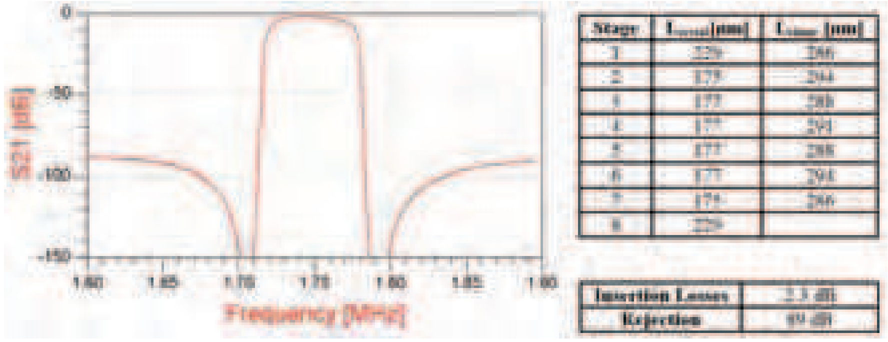
Stage	L_{serial}[µm]	L_{shunt} [µm]
1	514	548
2	280	574
3	247	573
4	243	534
5	218	544
6	281	533

Insertion Losses	2.3 dB
Rejection	89 dB

Fig. 18. Response of a 6th order ladder filter (GSM).

4.2.2 DCS 1800 MHz

Digital Cellular Systems operate in the frequency band between 1710 - 1785 MHz in Uplink and 1805 - 1880 MHz in downlink. The filter should have a bandwidth of 75 MHz and a central frequency of 1747.5 MHz. The reached rejection is 89 dB and insertion losses are less than 2.1 dB. Fig. 19 summarises the resonator's surface areas and the transmission response of the filter.



Stage	L_{series} [µm]	L_{shunt} [µm]
1	229	286
2	179	294
3	177	286
4	177	293
5	177	288
6	177	294
7	179	286
8	229	

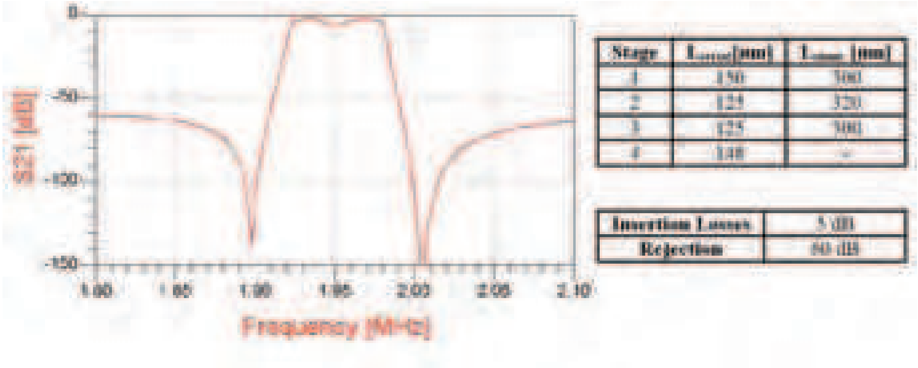
Insertion Losses	2.3 dB
Rejection	49 dB

Fig. 19. Response of a 7th order T ladder filter (DCS).

4.2.3 UMTS and LTE

Universal Mobile Telecommunication Systems operate in the frequency band between 1920 and 1980 MHz (3GPP, 2006). This is also one of the frequency bands allocated to the Long Term Evolution (LTE) standard. The emission filter should have a bandwidth of 60 MHz and a central frequency of 1950 MHz. Out of band rejection must be -50dB. The transmission response of the UMTS designed filter is presented in Fig. 20.

The thickness of the series and shunt resonators are 2.793 µm and 2.881µm respectively. The resonator's surface areas are summarised in Fig. 20. The reached rejection is 60 dB and insertion losses are less than 5 dB across the whole frequency band.



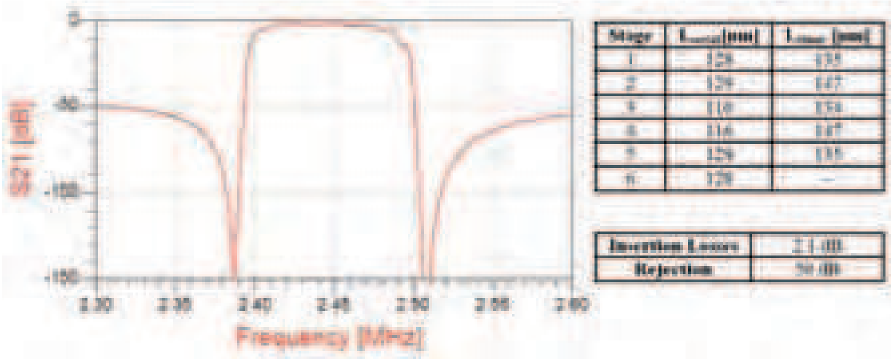
Stage	L_{series} [µm]	L_{shunt} [µm]
1	150	300
2	125	320
3	125	300
4	140	-

Insertion Losses	5 dB
Rejection	60 dB

Fig. 20. Response of a 3rd order T ladder filter (UMTS).

4.2.4 WLAN (802.11b/g)

IEEE 802.11b and 802.11g standards establish specifications for wireless connectivity within a local area network in the 2.4 - 2.483 GHz frequency band (IEEE, 1999a and 1999b). The emission filter has the same specifications for the two standards: a bandwidth of 83.5 MHz and a central frequency of 2441.5 MHz. Out of band rejection must be -50 dB. The transmission response of the WLAN designed filter is presented in Fig. 21. The thickness of the series and shunt resonators are 2.233µm and 2.291µm respectively. Fig. 21 summarises the resonator's surface areas.



Stage	L_{series} [µm]	L_{shunt} [µm]
1	129	135
2	139	147
3	118	154
4	116	147
5	129	135
6	129	–

Insertion Losses	2.1 dB
Rejection	50 dB

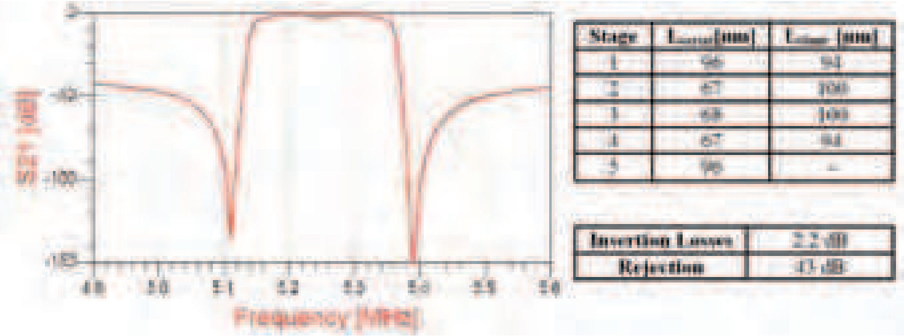
Fig. 21. Response of a 5th order T filter (2.4 GHz WLAN).

The reached rejection is 50 dB and insertion losses are less than 2.1 dB across the whole frequency band.

4.2.5 WLAN (802.11a)

The IEEE 802.11a standard establishes specifications for wireless connectivity within a local area network in the 5.150 – 5.350 GHz frequency band in Europe (IEEE, 1999c). The emission filter should have a bandwidth of 200 MHz and a central frequency of 5250 MHz. Out of band rejection must be -40 dB. The transmission response of the WLAN designed filter and the resonator's surface areas are presented in Fig. 22.

The thicknesses of the series and shunt resonators are 1.039µm and 1.070µm respectively. The reached rejection is 43 dB and insertion losses are less than 2.2 dB across the whole frequency band.



Stage	L_{series} [µm]	L_{shunt} [µm]
1	96	94
2	67	100
3	68	100
4	67	94
5	96	–

Insertion Losses	2.2 dB
Rejection	43 dB

Fig. 22. Response of a 4th order T filter (5 GHz WLAN).

4.2.6 WMAN (802.16e)

The IEEE 802.16e standard supports operation of wireless metropolitan area networks in licensed frequency bands below 11 GHz (IEEE, 2005). In Europe, the 3.6 – 3.8 GHz frequency band is one of the bands allocated to mobile WiMAX. The emission filter, in this case, should have a bandwidth of 200 MHz and a central frequency of 3700 MHz. Out of band rejection must be -50 dB (ETSI, 2003). The transmission response of the WiMAX designed filter has already been presented in Fig. 13.

In the example presented in this section each band-pass filter has being considered independently. It is a first approach of multi-radio filter bank. The drawback of assembling 2 or more BAW filters on the board is that it requires space for chip positioning. Unitary manipulation of BAW filters is time and cost consuming. The trend is going towards a duplexer (or multiplexer) module and providing a single BAW chip with 2 or more filters (Reinhardt et al., 2009).

4.3 Other examples of RF band-pass BAW filters

This section presents some examples of band-pass filters obtained with FBAR and SMR BAW resonators for radiofrequency microelectronics applications within some European projects.

The MARTINA European project (ended in 2005) was about the design and implementation of an RF front-end for WCDMA applications using an above-IC BAW band-pass filter (SoC integration). This project validated the monolithic integration of active and passive devices on the same wafers. A filter resulting of the MARTINA European project is a stand-alone filter designed for the RX chain of a WCDMA mobile phone, and fabricated at the wafer level above BiCMOS active integrated circuits (Kerherve et al., 2006). It is a FBAR filter with 8 resonators in double lattice topology. The measured IL is -3.5dB over the 60 MHz measured bandwidth. The TX-band rejection is lower than -50 dB.

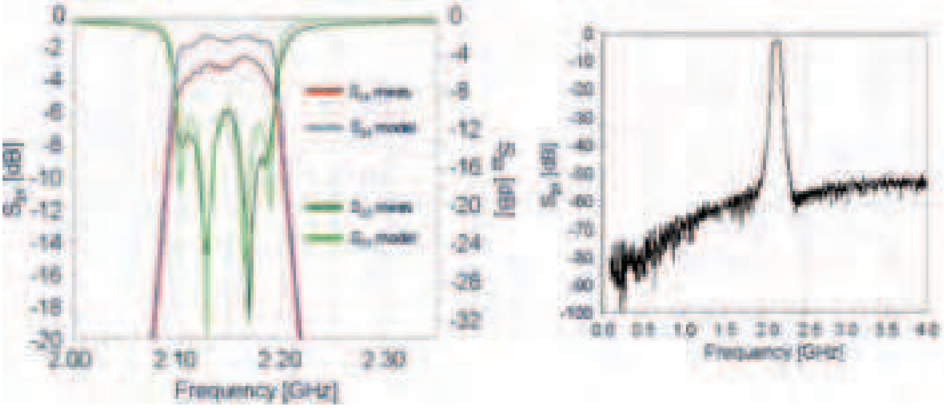


Fig. 23. FBAR Filter (a) Transmission and reflection coefficients. (b). Broadband of S_{21}

The MIMOSA European project dealt with developing a technological platform for embodiment of various RF functions, sensors and microsystems for Ambiant Intelligent applications in a mobile-phone centric approach. It proposed a SiP integration to make an ISM-band wake-up radio receiver using a selective low-noise amplifier (LNA). A modular approach was applied to an ISM-band receiver, where a stand-alone SMR-type BAW double-lattice filter was wire-bonded with CMOS LNA on the same PCB (a major differentiation to Above-IC approach). The differential BAW filter covers the whole ISM band from 2.4 to 2.48 GHz, with 3dB insertion loss and 40 dB out-of-band and image

rejection. It is a double-stage lattice SMR-type BAW filter. The fabricated filter has IL of -4dB, bandwidth of 70 MHz and rejection of -36dB (Kerherve et al., 2006).
Another European project is the MOBILIS European project. The objective of the MOBILIS project is to develop a robust and cost-effective integrated high-power RF filtering technology and demonstrate the feasibility of a mixed SoC (nanometric CMOS/system integration) and SiP (BiCMOS/power-BAW) RF power transmitter. The targeted transmitter is based on a Digital Radio transmitter architecture and addresses both the WCDMA and DCS standards. An UMTS BAW filter designed and implemented in this project is presented in Fig. 24.

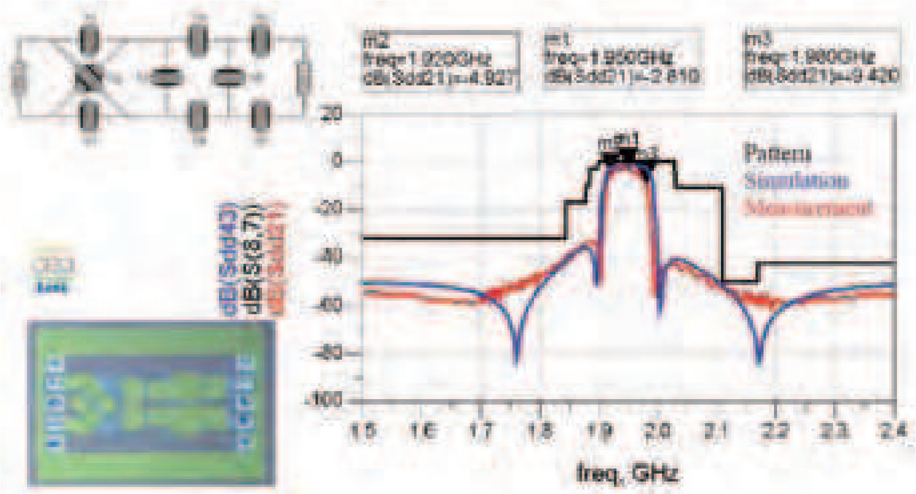


Fig. 23. UMTS band-pass filter proposed in the MOBILIS European project (Kerherve, 2009).

5. Conclusion

This chapter presented the interest of RF band-pass filters in the actual communications context. Specifically, the importance of the RF filter in the mobile transceivers and the band-pass RF filters requirements at the front-end of a mobile transmitter have been described. Some different available filtering technologies have been considered as well and their advantages and trade-offs have. The potential of BAW technology for RF band-pass filters is highlighted. Two RF BAW filters applications proposed by the authors have been described, one for an UWB application and the other one for a multi-radio system. Other examples of RF band-pass filters designed and fabricated within some European Projects have also been presented. All these implementation examples probe the interest of using BAW technology for wireless transceivers for communications. The actual trend is going towards duplexer (or multiplexer) modules and providing a single BAW chip with 2 or more filters. Filter's reconfigurability is also a research subject.

6. References

3GPP. (2005). 3rd Generation Partnership Project (3GPP), "UE Radio Transmission and Reception (FDD)," technical specification 25.101, vol. 6.8.0, 2005.

3GPP (2006). TS 25.101, 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; User Equipment (UE) radio transmission and reception (FDD) (Release 7).

Diet, A.; Villegas, M.; Vasseure, C.; Baudoin, G. (2005). Impact of BAW emission filter's characteristics on 3rd Generation standards modulations. Proceedings of the International Wireless Summit, WPMC - Wireless Personal Multimedia Communications, Septembre 2005, Aalborg, Danemark.

ETSI. (1999a). European Standard, Telecommunications Series, *ETSI EN300910V8.5.1 (2000-11)*, Digital cellular telecommunications system (Phase 2+); Radio transmission and reception (GSM 05.05 version 8.5.1 Release 1999).

ETSI. (1999b). European Standard, Telecommunications Series, *ETSI TS100910V8.20.0 (2005-11)*, Digital cellular telecommunications system (Phase 2+); Radio Transmission and Reception (3GPP TS 05.05 version 8.20.0 Release 1999).

ETSI. (2003). European Standard, Telecommunications Series, *ETSI 301021 V1.6.1 (2003-07)*. Fixed Radio Systems; Point-to-multipoint equipment; Time Division Multiple Access (TDMA); Point-to-multipoint digital radio systems in frequency bands in the range 3GHz to 11GHz.

Heyen, J.; Yatsenko, A.; Nalezinski, M.; Sevskiy, G.; Heide, P. (2008). WiMAX System-in-package solutions based on LTCC Technology, *Proceedings of COMCAS 2008*.

IEEE (1999a). St. 802.11b-1999, Supplement to IEEE Standard for Information technology - Telecommunications and information exchange between systems—Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band. Reaffirmed 12 June 2003.

IEEE (1999b). St. 802.11g-1999, Supplement to IEEE Standard for Information technology - Telecommunications and information exchange between systems—Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band. 27 June 2003.

IEEE (1999c). St. 802.11a-1999, Supplement to IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications High-speed Physical Layer in the 5 GHz Band. Reaffirmed 12 June 2003.

IEEE. (2005). IEEE Standard 802.16e. Air interface for fixed and mobile broadband wireless access systems amendment 2: physical and medium access control layers for combined fixed and mobile operation in licensed bands, 2005.

Kerherve, E.; Ancey, P.; Kaiser, A. (2006). BAW Technologies: Development and Applications within MARTINA, MIMOSA and MOBILIS IST European Projects. 2006 IEEE Ultrasonics Symposium.

Kerherve, E. ; Kaiser, A. (2009). Intégration Mixte SiP/SoC d'un Transmetteur en Technologie CMOS/BiCMOS/BAW/IPD pour des Applications Multimodes WCDMA/DCS. Fetch 2009. Chexbres, Switzerland.

Kim, D.; Dong Ho Kim; Jong In Ryu; Jun Chul Kim; Chong Dae Park; Chul Soo Kim; In Sang Song. (2008). A quad-band front-end module for Wi-Fi and WiMAX applications using FBAR and LTCC Technologies, *Proceedings of APMC 2008.*

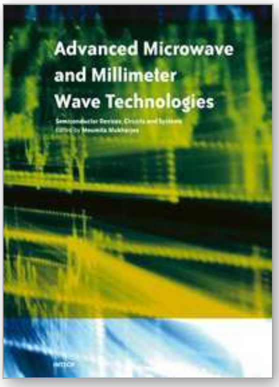
Paquelet, S.; Aubert, L.-M. & Uguen, B. (2004). An impulse radio asynchronous transceiver for high data rates. *Proceedings of IEEE Joint UWBST&IWUWBS Conf.*, ISBN 0780383737, May Kyoto, 2004, IEEE, Piscataway, New Jersey.

Reinhardt, A. (2009). BAW technology for advanced RF architectures. Workshop on BAW Technologies WSE. 2009 International Microwave Symposium. June, 2009. Boston.

Suarez, M.; Villegas, M.; Baudoin, G; Andia Montes, L. (2007a). Considering a non-Uniform filter bank in an UWB Multi Band On-Off Keying transceiver, *Journal of communications (JCM)*, Vol. 2, N° 6, Nov. 2007, pp. 24-29, ISSN 1796-2021.

Suarez, M.; Villegas, M.; Baudoin. BAW filter bank for an UWB Multi Band On-Off Keying transceiver (2007b). *Proceedings of IEEE APMC Conf.*, December Bangkok, Thailand, 2007.

Suarez, M.; Villegas, M.; Baudoin, G. (2008). Front end filtering requirements on a mobile cognitive multi-radio transmitter, *Proceedings of the 11th International Symposium on wireless Personal Multimedia Communications,* 8-11 Sept. 2008, Saariselka, Finlande.



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This book is planned to publish with an objective to provide a state-of-the-art reference book in the areas of advanced microwave, MM-Wave and THz devices, antennas and systemtechnologies for microwave communication engineers, Scientists and post-graduate students of electrical and electronics engineering, applied physicists. This reference book is a collection of 30 Chapters characterized in 3 parts: Advanced Microwave and MM-wave devices, integrated microwave and MM-wave circuits and Antennas and advanced microwave computer techniques, focusing on simulation, theories and applications. This book provides a comprehensive overview of the components and devices used in microwave and MM-Wave circuits, including microwave transmission lines, resonators, filters, ferrite devices, solid state devices, transistor oscillators and amplifiers, directional couplers, microstripeline components, microwave detectors, mixers, converters and harmonic generators, and microwave solid-state switches, phase shifters and attenuators. Several applications area also discusses here, like consumer, industrial, biomedical, and chemical applications of microwave technology. It also covers microwave instrumentation and measurement, thermodynamics, and applications in navigation and radio communication.

Martha Suarez, Martine Villegas and Genevieve Baudoin (2010). RF and Microwave Band-Pass Passive Filters for Mobile Transceivers with a Focus on BAW Technology, Advanced Microwave and Millimeter Wave Technologies Semiconductor Devices Circuits and Systems, Moumita Mukherjee (Ed.), ISBN: 978-953-307-031-5, InTech, Available from: http://www.intechopen.com/books/advanced-microwave-and-millimeter-wave-technologies-semiconductor-devices-circuits-and-systems/rf-and-microwave-band-pass-passive-filters-for-mobile-transceivers-with-a-focus-on-baw-technology

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