IWPC Mobile RF Filter Group

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We Are…

- **IWPC**: technology neutral organization of more than 140 WIRELESS and RF PRODUCT OEM's and their SUPPLIERS.
- **Marcus Spectrum Solutions LLC**: consulting practice of Dr. Michael Marcus – 25 years in the FCC
- **RF Filter Suppliers**:
  - **Avago Technologies**
  - **MuRata**
  - **TDK-EPC**
  - **TriQuint Semiconductor**

✓Collectively represent majority market share of RF filtering solutions for mobile devices

Meeting Objectives

1. To inform the FCC as to the practical limits of RF filtering technology for mobile devices

2. To understand the FCC's direction for spectrum allocation in the future

3. To encourage the FCC to consider the present limits of RF filtering technology when establishing spectrum rules & regulations

4. To establish contacts which can be cultivated in the future between each member company and the FCC whether can communicate technology improvements.

IWPC and its members recognize the interrelationship between practical filter performance and spectrum allocations. We intend to update the FCC and the NTIA on a regular basis on the state of the art of commercial filter components and we welcome inquiries on what is practical.

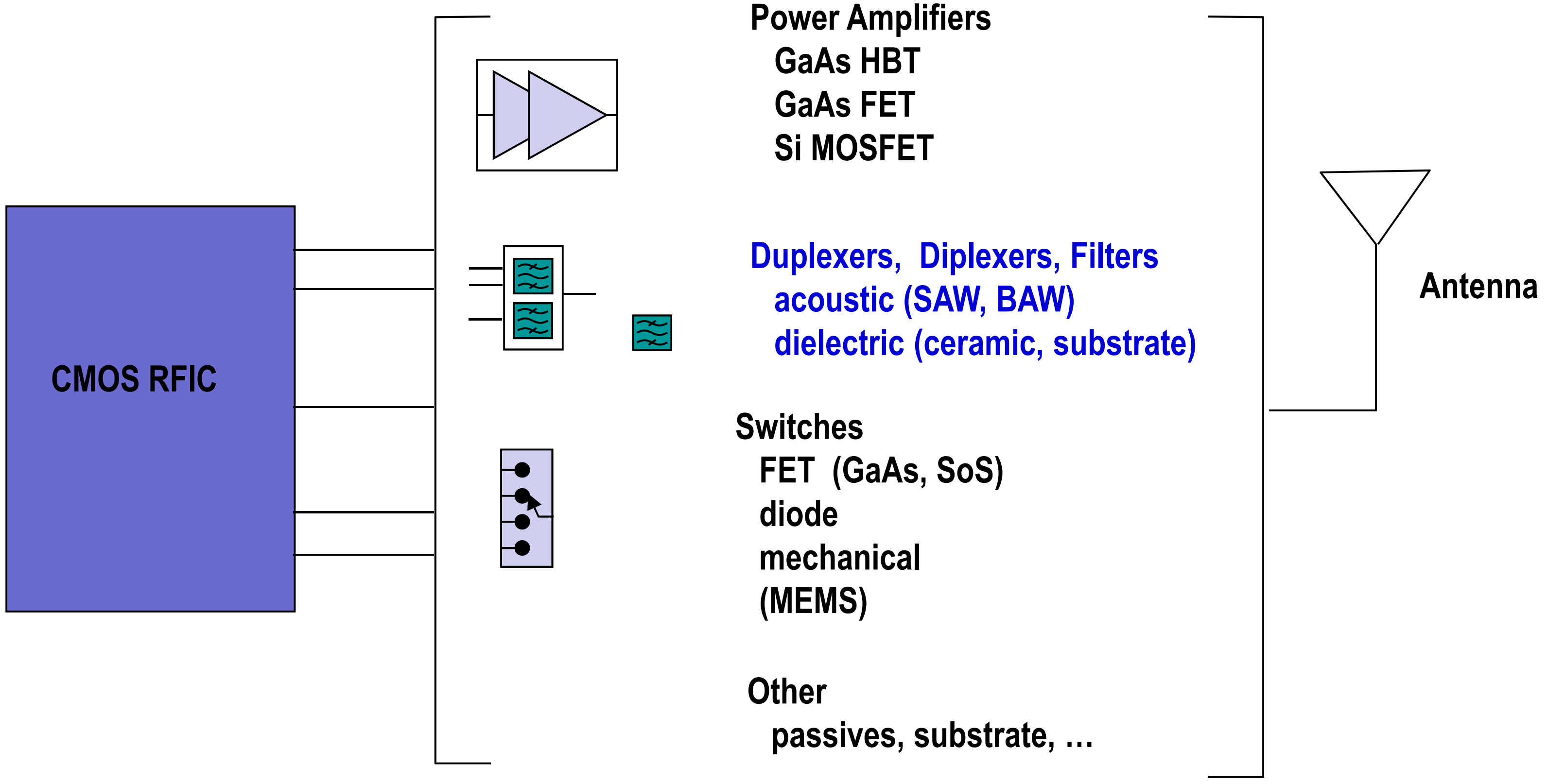
IWPC SM
INTERNATIONAL WIRELESS INDUSTRY CONSORTIUM SM

Topics

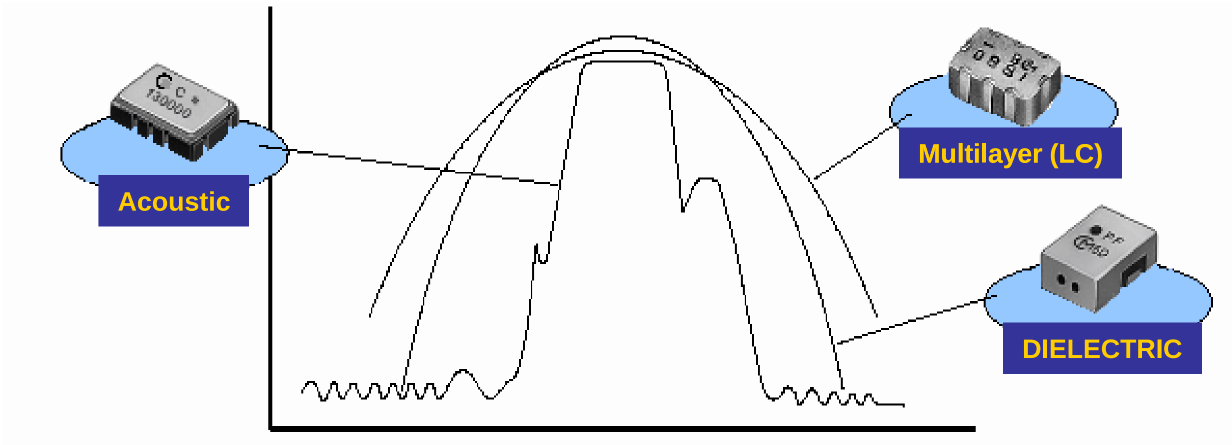
- ✓Introduction
- ✓Background
- ✓Real vs. Ideal Filters
- ✓Slope, Variation, Temperature, and Bandwidth
- ✓Considerations by Band
- ✓Closing Thoughts

INTERNATIONAL WIRELESS INDUSTRY CONSORTIUM

The "Front End": Where Acoustic Filters Fit



Mobile Device Filtering Technologies



Acoustic:

Surface Acoustic Wave

Miniature, Q of 700-800, 10 MHz through 3.5 GHz

Optionally provides balun functionality

Bulk Acoustic Wave

Miniature, Q in 1000's, 500 MHz to 10 GHz

Electric:

Ceramic / Dielectric

Large, Q and frequency supported varies with design and dimensions

Lumped / Passives

Large, Q in 10's, frequency supported varies with parasitics

Real vs. Ideal Filters

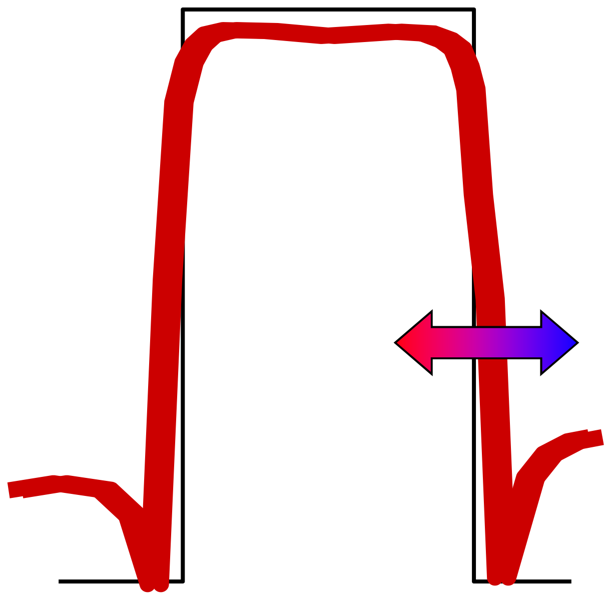
Ideal

No loss

"Brick Wall" rolloff

Identical

Unmoving with temperature



Real

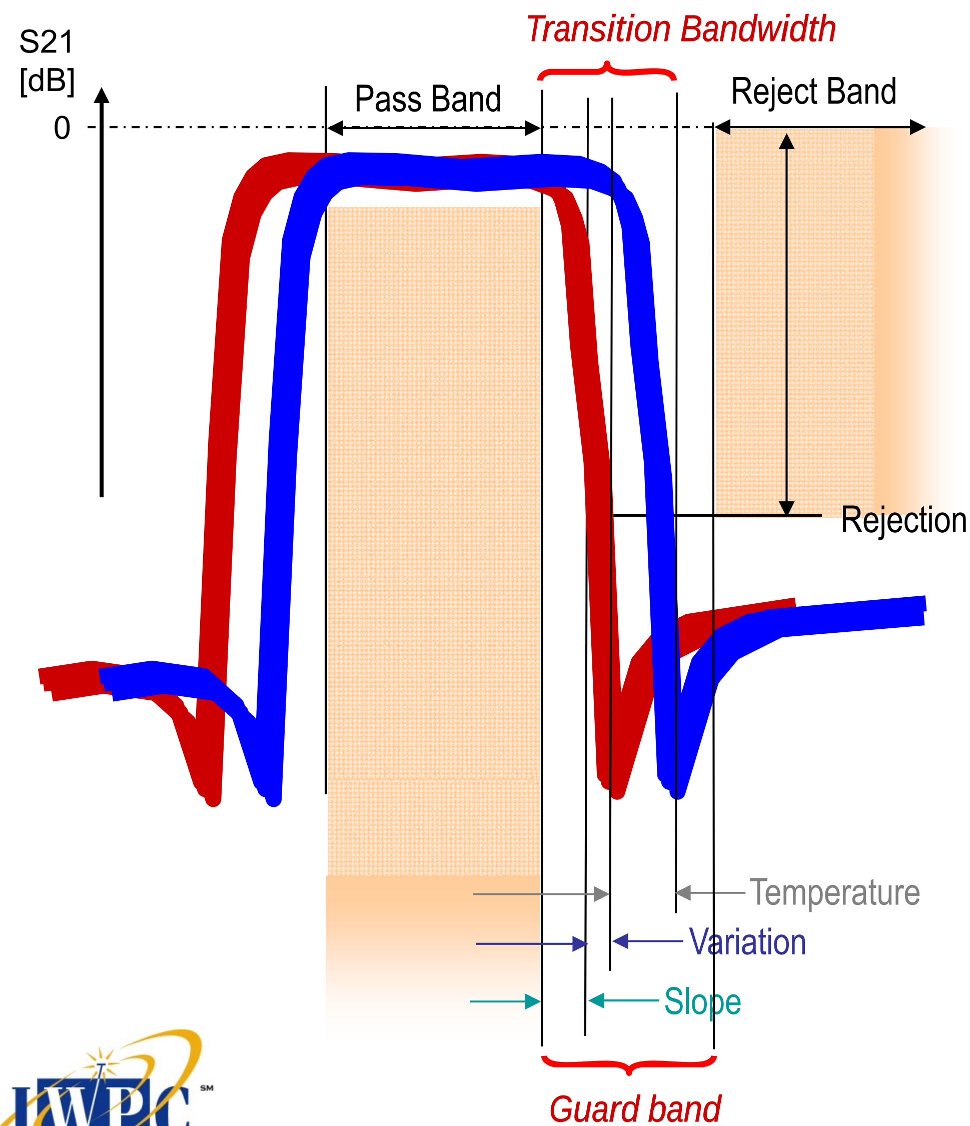
insertion loss

Filter slope

Filter-to-Filter variation

Motion with temperature

Transition Bandwidth vs. Guard Band



The **Transition Bandwidth** is the amount of frequency separation needed between the pass band and the reject band to ensure the required level of rejection and insertion loss is achieved across all filters and over the operating temperature range.

It consists of three components:

1. The slope of the filter
2. The variation in frequency centering filter to filter
3. The motion the filter has over the specified operating temperature range

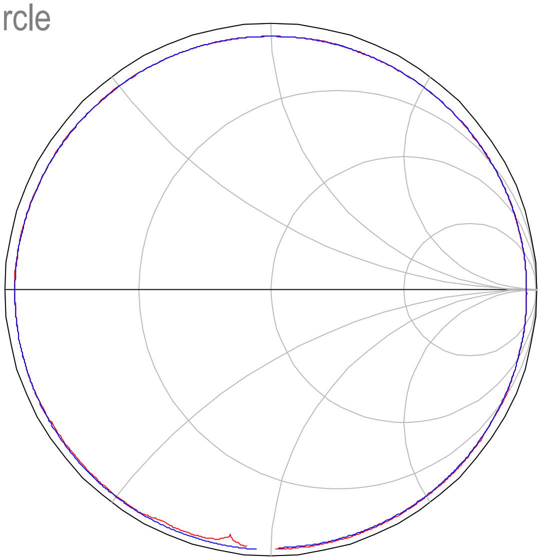
The **Guard Band** is the frequency separation between adjacent bands for which interference concerns are relevant.

Slope

The **Slope** of the filter is the amount of frequency required to go from pass band edge to minimum rejection. Slope depends on a number of factors, among them:

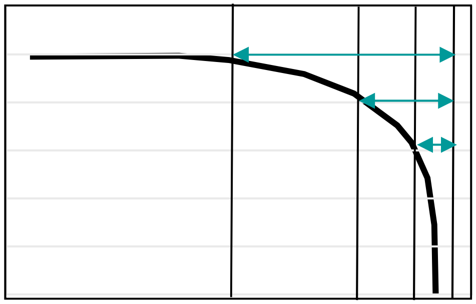
1. Resonator Q: In general, the higher the Q the steeper the slope.
2. Acoustic Coupling (k_T^2): In general, the lower the coupling, the steeper the slope. However adequate acoustic coupling to support filter band width is required. As a rule of thumb, bandwidth will be no more than k_T^2 / 2.
3. Filter design. Filter slope can be enhanced by circuit elements at the cost of out-of-band rejection and / or insertion loss. It is also affected by filter topology.
4. Corner sharpness. For a high Q filter the roll off of the filter is quite fast, and most of the frequency for slope is actually needed to start the roll off. The definition of the point to start measuring from (how much IL) can have a significant effect on the resulting value for slope.
5. Slope is proportional to frequency.

Q Circle



freq (1.700GHz to 2.300GHz)

Slope vs. Corner Sharpness



Slope vs. Insertion Loss

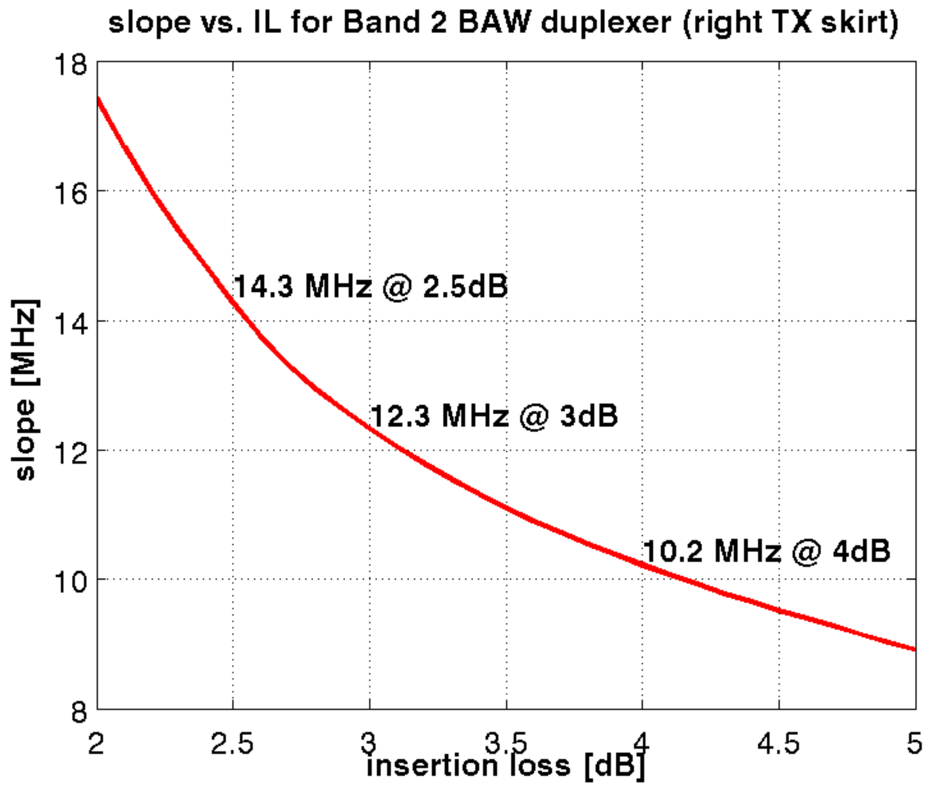
For a fixed Rx rejection level (system requirement approx. 45dB) the filter slope varies with the maximum insertion loss guaranteed for the highest Tx frequency.

Demand for low insertion loss (efficient use of battery / long talk time) increases the necessary slope and hence transition band width.

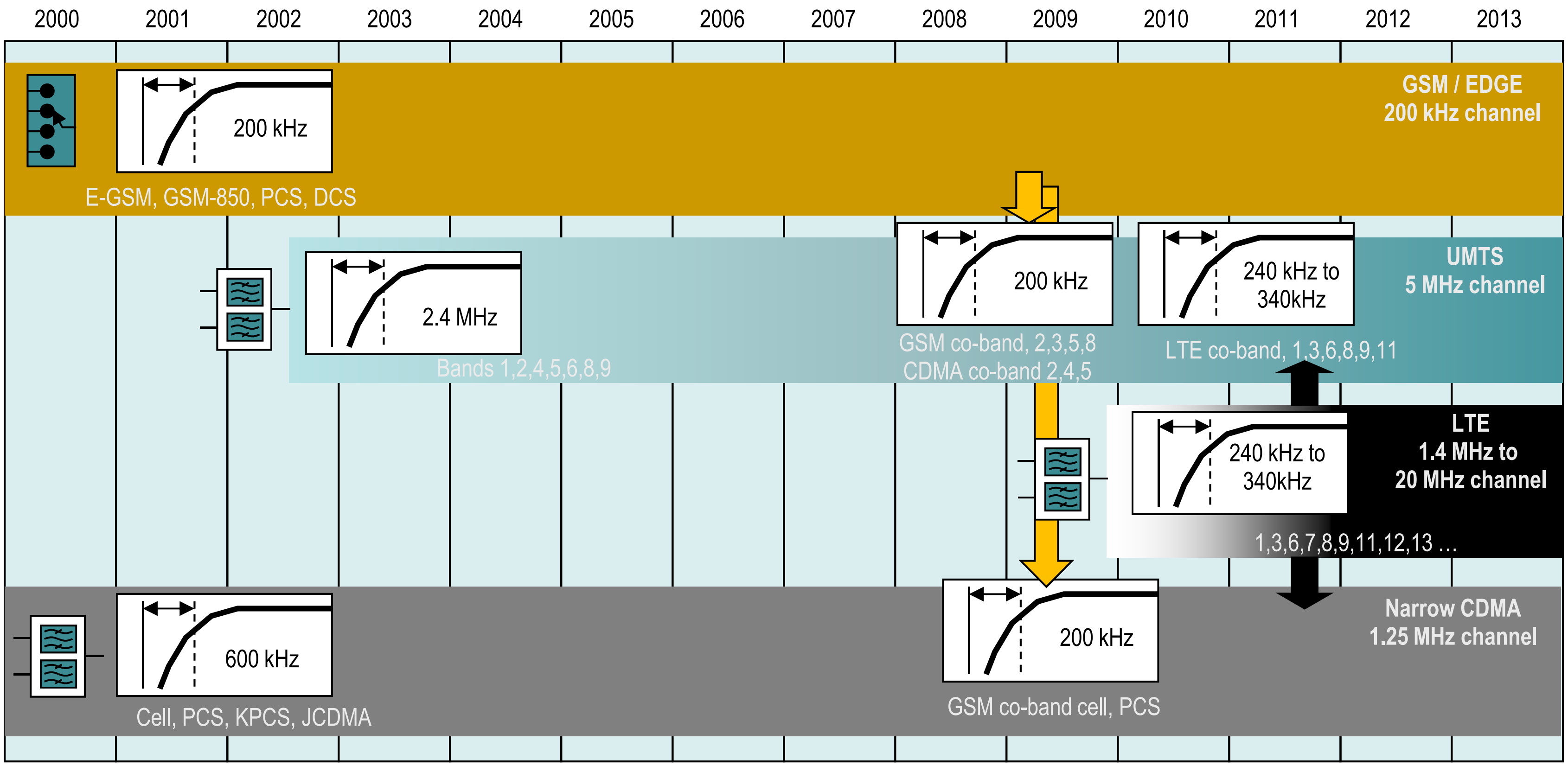
There is a trade-off between transition band and talk time / user experience.

Similarly, for the Rx filter, there is a trade-off between sensitivity (which influences data rate and network efficiency) and transition bandwidth.

At Right is an example for a PCS BAW duplexer, the right Tx skirt is shown.



Insertion Loss vs. Modulation



Different modulation types change the portion of the pass band the modulated signal occupies, and hence change how far from the nominal edge of the band the filter insertion loss is actually specified. This "offset" in insertion loss specification point effectively adds to the available guard band.

Corner offsets have generally been decreasing with time due to new modulation types and architectural changes like co-banding (using the same filter for multiple modulations, e.g. GSM and UMTS)

Manufacturing Variation

Small variations in the manufacturing process lead to variations in frequency centering from filter to filter.

1. Tuning techniques such as ion milling can be used to "tune" the filters to a relatively narrow range.
2. Since the distribution is "created" rather than natural, it tends to be square rather than Gaussian
3. The variation that can be held is proportional to frequency, and can be though of as a percentage.
4. For low volume applications, variation can be arbitrarily small if one is willing to incur the yield loss. That's another way of saying you can narrow the variation range somewhat by paying more for the filter if you only need a few of them.
5. For high volume applications it may not be practical to artificially narrow the frequency variation as sufficient supply might not be guaranteed.

For Acoustic Filter at 2 GHz,

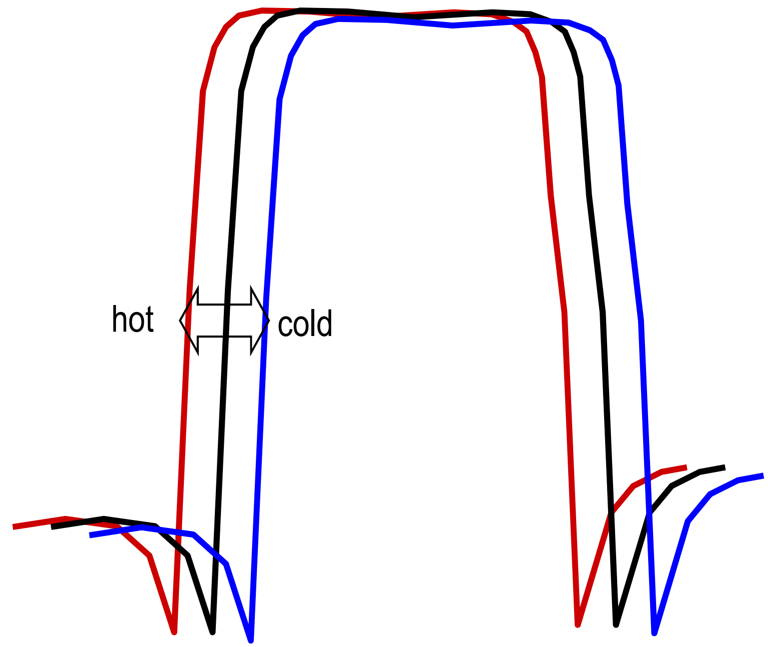
0.15 percent variation * $2x10^9$ Hz

= 3.0 MHz

Temperature Motion

The temperature motion of a filter is defined by its temperature coefficient (**Tempco**), expressed in parts per million per degree C.

1. Most materials used for filters have a negative temperature coefficient, that is, the pass band of the filter shifts down in frequency when the filter gets hot, and shifts up in frequency when the filter gets cold.
2. What matters is the excursion of temperature, not the value of the temperature.
3. Tempco is a function of material properties.
   FBAR and BAW has a Tempco of -15 to -30 ppm/C
   LiTaO3 SAWs have a Tempco of -35 to -42 ppm/C
4. Tempco can be altered by adding appropriate materials to the resonator composition, usually at the consequence of reducing Q and bandwidth. Any value can theoretically be obtained, including positive temperature coefficients. Temperature compensated 'TC'-SAWs achieve Tempco of -15 to -30 ppm/C
5. Temperature motion is proportional to frequency.
6. Motion is slightly higher on the high frequency edge of the filter, due to self heating. Note that for forward duplex (i.e. low freq. Tx) this is a consideration for the Tx filter.



Example for a 2 GHz filter with -30 ppm/C:

-30 ppm/C * [85- (-30) C] * 2x10^9 Hz

= 6.9 MHz

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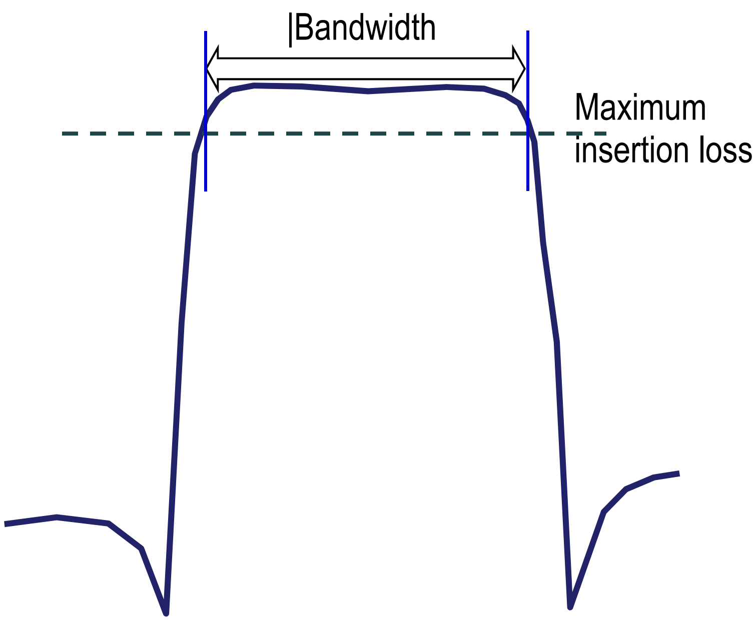
Bandwidth

The **Bandwidth** of a filter is defined by the frequency range over which the insertion loss of the filter is less than the minimum guaranteed insertion loss.

1. For an acoustic filter, the bandwidth is to a first order proportional to the acoustic coupling coefficient k_T^2 of the resonators used to make the filter.
2. As a rule of thumb, maximum available bandwidth < $k_T^2/2$.
3. k_T^2 is a function of material properties.
   LiTaO3 SAWs and AlN BAWs (the most common kinds of acoustic filters) have a maximum k_T^2 of 7% to 8.4%, limiting bandwidths to below 3.5% to 4.2%
4. LiNbO3 SAWs have higher k_T^2 – about 12%, so can support wider bandwidths. However available Qs are lower, and temperature motion is much higher.
5. Bandwidths can also be stretched by adding external components – basically building an L-C / acoustic resonator hybrid filter. With this technique resonators with k_T^2 in the 8% range have been used to make filters with 7.5% bandwidth . However these filters have higher insertion loss and more out-of-band artifacts than conventional filters.
6. The before-mentioned slope vs. insertion loss and insertion loss vs. modulation effects also influence the bandwidth.



Example for a 700 MHz filter with $k_T^2 = 8\%$:

BW $\approx 8\%/2 * 0.7\text{x}10^9$ Hz

≈ 28 MHz

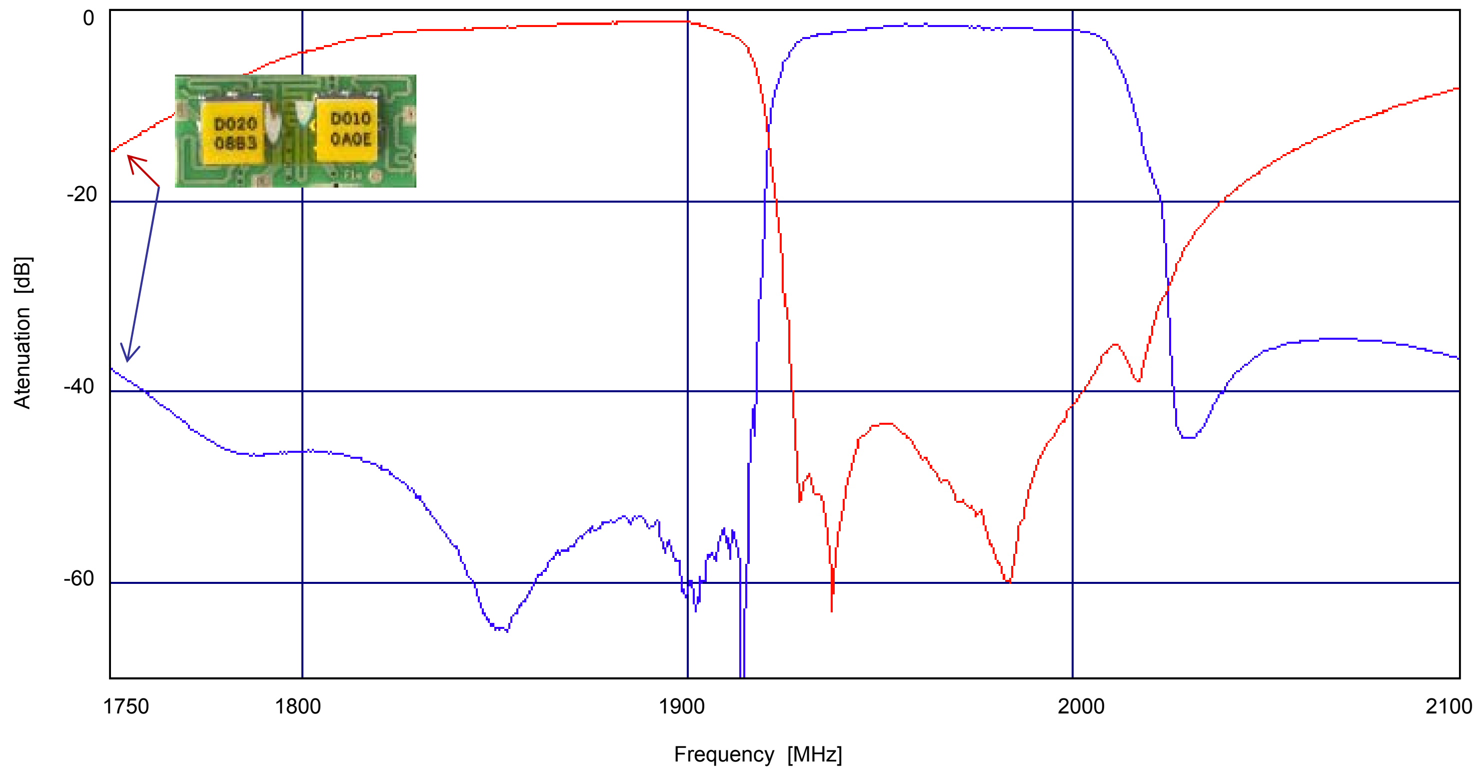
Performance vs. Cost Tradeoffs

POLES	Fo	I.L.	Atten.	BW	Size	ASP
↑	↔	↑	↑	↔	↑	↑

As a general rule, when you increase the number of elements associated with a filter design you are doing so to increase the attenuation of the filter. Therefore, the following are true;

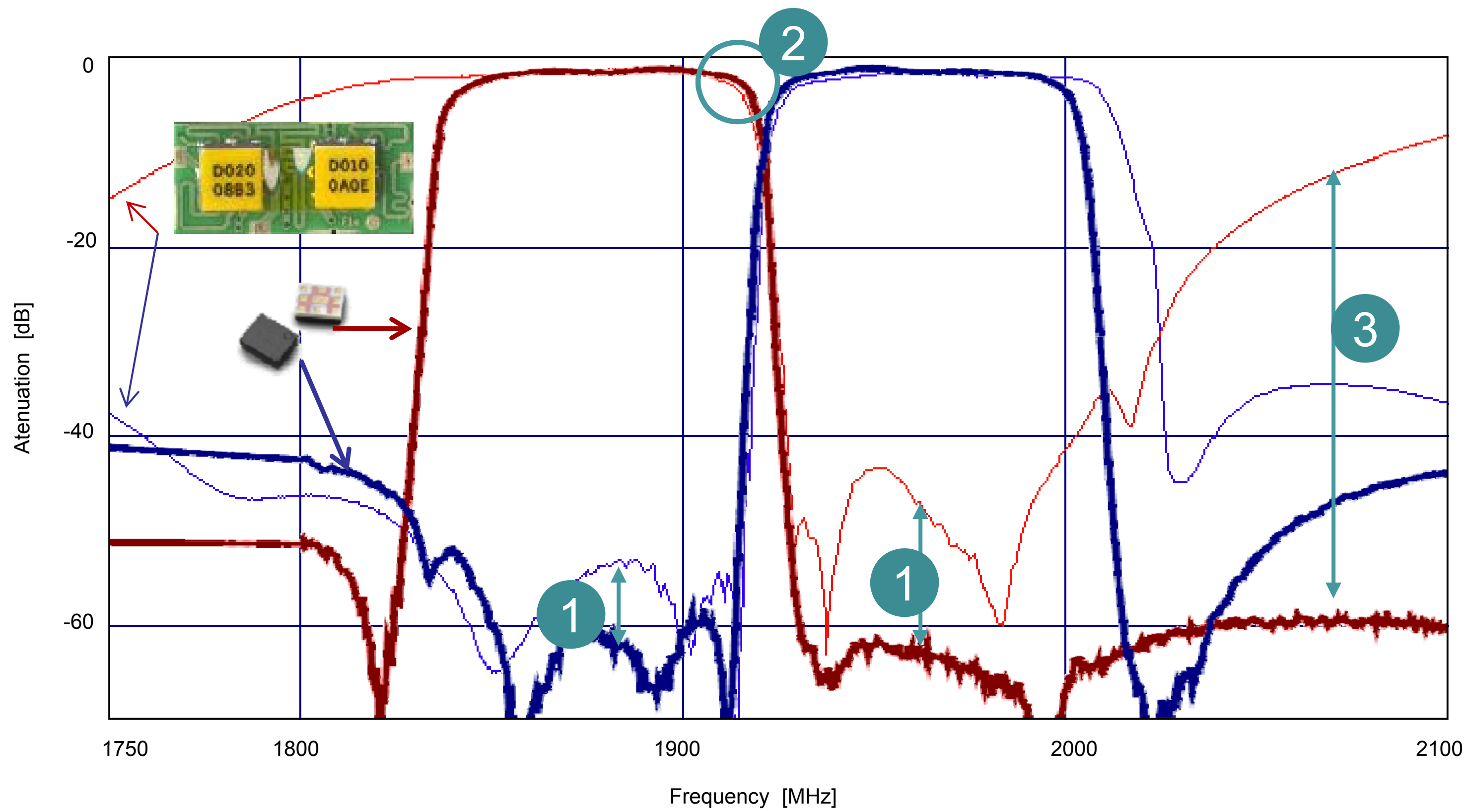
Fo = No direct impact
I.L. = Increases
Attenuation = Increases
Band Width = No direct impact
Size = Increases (same technology based)
Price = Increases due to complexity of filter design, material, and typically tighter specification requirements / testing.

Performance Improvements over Time



PCS duplexer from 2001

Performance Improvements over Time

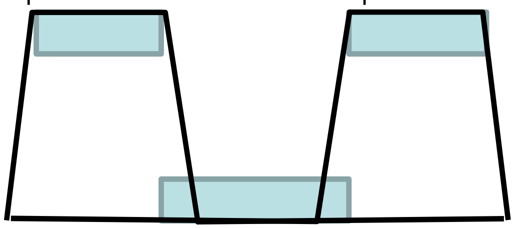


<u>PCS duplexer from 2001 vs. product sold today</u>

1. Higher rejection (both Tx and Rx)
2. Lower Insertion loss (including steeper filter skirt and squarer corner)
3. Better out-of-band rejection levels
4. Smaller size (6x12x2 mm > 2x2.5x0.9 mm)

Bands Aren’t All the Same: Easy Bands

EASY Bands:
reasonable duplex gap (≥2%)
Moderate pass band (≤3%)
No nearby victims or potential jammers



Band Name	Uplink	Downlink	Duplex	Where	Comment
AWS-1 3GPP B4 3GPP2 BC15	1710-1755 (2.6%)	2110-2155 (2.1%)	FDD (18.4%)	US	“interesting” – wide gap = hard to match antenna
Cell 3GPP B5 3GPP2 BC0	824-849 (3.0%)	869-894 (2.8%)	FDD (2.3%)	US / Asia	“easy” plan
IMT 3GPP B1 3GPP2 BC6	1920-1980 (3.1%)	2110-2170 (2.8%)	FDD (6.4%)	World wide except US	“easy” plan
3GPP B6	830-840 (1.2%)	875-885 (1.1%)	FDD (4.1%)	Japan	“easy” plan
3GPP B9	1749.9-1784.9 (2.0%)	1844.9-1879.9 (1.9%)	FDD (3.1%)	Japan	“easy” plan
3GPP B10	1710-1770 (3.4%)	2110-2170 (2.6%)	FDD (17.5%)	S. America	“interesting” – wide gap = hard to match antenna

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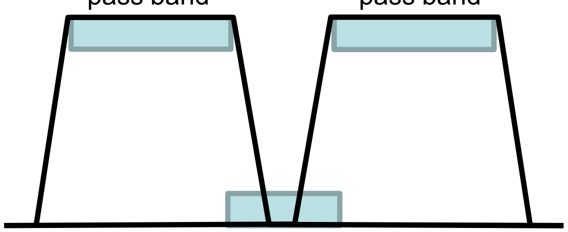
Bands Aren’t All the Same: Hard Bands

HARD Bands:
frequency plan makes the filtering difficult:
Narrow duplex gap (<1.5%)
and / or Wide pass band (>3.5%)



Band Name	Uplink	Downlink	Duplex	Where	Comment
PCS 3GPP B2 3GPP2 BC1	1850-1910 (3.2%)	1930-1990 (3.1%)	FDD **(1.04%)**	US	“hard” – narrow gap
2500 MHz 3GPP B41	2496-2670 (**6.7%**)	2496-2670 (**6.7%**)	TDD n.a.	US	“hard” – very wide BW, near WiFi
DCS 3GPP B3	1710-1785 (**4.3%**)	1805-1880 (**4.1%**)	FDD **(1.11%)**	Worldwide except US	“hard” – narrow gap, wide % BW
EGSM 3GPP B8	880-915 (**3.9%**)	925-960 (**3.7%**)	FDD **(1,09%)**	Worldwide except US	“hard” – narrow gap, wide % BW
3GPP B20	832-862 (**3.7%**)	791-821 (**3.5%**)	FDD **(1.33%)**	Europe	“hard” – narrow gap, wide % BW

Note that using wide sections of present TV spectrum for Wireless Services would create new “hard” bands

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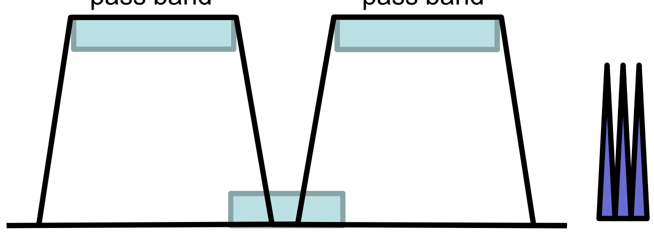
Bands Aren't All the Same: Very Hard Bands

CHALLENGING Bands:
Very narrow duplex gap (<1.0%) or
nearby victims / potential jammers
make the filtering very difficult



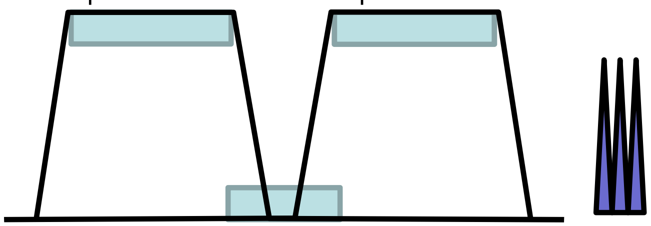
Band Name	Uplink	Downlink	Duplex	Where	Comment
700L A+B+C 3GPP B12	699-716 (2.4%)	729-746 (2.3%)	FDD (1.80%)	US	"almost impossible" – E Block (722-728) is 1 MHz (**0,14%**) below downlink
700L B+C 3GPP B17	704-716 (1.7%)	734-746 (1.6%)	FDD (2.48%)	US	"very hard" – E block (722-728) is 6 MHz (**0,83%**) from up- and downlink
700U C 3GPP B13	777-787 (1.3%)	746-756 (1.3%)	FDD (2.74%)	US	"almost impossible" – 2 MHz (**0,26%**) to Public Safety Radio (763-775), second harmonic @ GPS
700U D 3GPP B14	788-798 (1.3%)	758-768 (1.3%)	FDD (2.57%)	US	**overlaps with Public Safety Radio** (763-775 and 793-805)
PCS+G block 3GPP2 BC14 3GPP "B25"	1850-1915 (**3.5%**)	1930-1995 (**3.3%**)	FDD **(0.78%)**	US	"very hard" – very narrow gap reduced performance at extreme temperatures
S-Band 3GPP "B23"	2000-2020 (1.0%)	2180-2200 (0.9%)	FDD (7.62%)	US	"almost impossible"- G block/PCS (1930-1995) 5MHz (**0.25%**) to uplink
L-Band 3GPP "B24"	1626.5-1660.5 (2.1%)	1525-1559 (1.9%)	FDD (4.49%)	US	"very hard" – 15.42MHz (**1.00%**) below GPS (1574.42-1576.42) and **very low insertion attenuation** for GPS, overlaps Compass (Chinese GNSS)

It is increasingly common that new bands are near other services

INTERNATIONAL WIRELESS INDUSTRY CONSORTIUM

Bands Aren't All the Same: Very Hard Bands

CHALLENGING Bands:
Very narrow duplex gap (<1.0%) or
nearby victims / potential jammers
make the filtering very difficult



Band Name	Uplink	Downlink	Duplex	Where	Comment
Sprint 800 ext. 3GPP BC10	817-824 (0.9%)	862-869 (0.8%)	FDD 4.51%	US	only 1 MHz to re-banded Public Safety Radio
3GPP B7	2500-2570	2620-2690	FDD	Worldwide	"very hard" – 16.5MHz (**0,66%**) above WiFi, no guard band to B38
3GPP B38	2570-2620	2570-2620	TDD	Europe, China	currently "impossible" – **no guard band** to B7 uplink and downlink
3GPP B40	2300-2400	2300-2400	TDD	China, India, E. Europe	currently "impossible" – only 1 MHz guard band from B40 (2300-2400) to WiFi CH1
WiFi	2400-2483.5	2400-2483.5	TDD	US Europe / Asia	"very hard "–16.5MHz (**0.66%**) to B7, Only 1 MHz guard band from B40 (2300-2400) to CH1, 12.5MHz (0.05%) to B41 (2496-2690)

It is increasingly common that new bands are near other services

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Approximate Transition Band (Avago, TriQuint)

	Temp. range [2]	Transition Band for BAW [1]
US cell band / 3GPP Band 5 824-849 MHz / 869-894 MHz	-30 to +85 C	6 MHz (0.70%)
US PCS band / 3GPP Band 2 1850-1910 MHz / 1930-1990 MHz	-30 to +85 C	13 MHz (0.69%)
US 700 MHz / 3GPP Bands 12/13/14/17 698-806 MHz	-30 to +85 C	5 MHz – 6 MHz (0.73%)
AWS-1 / 3GPP Bands 4/10 1710-1770 MHz / 2110-2170 MHz	-30 to +85 C	12 MHz (0.62%)
L-Band / 3GPP Band 1626.5-1660.5 MHz / 1525-1555 MHz	-30 to +85C	10MHz (0.63%)
E-GSM / 3GPP Band 8 880-915 MHz / 925-960 MHz	-10 to +80 C	6.5 MHz (0.71%)
DCS / 3GPP Band 3 1710-1785 MHz / 1805-1880 MHz	-10 to +80 C	13 MHz (0.72%)
3GPP Band 1 1920-1980 MHz / 2110-2170 MHz	-10 to +80 C	13 MHz (0.64%)
3GPP Band 7 2500-2570 MHz / 2620-2690 MHz	-10 to +80 C	18 MHz (0.69%)
ISM 2400 / WiFi / Bluetooth 2400-2484 MHz	-30 to +85C (in US handsets)	16 MHz (0.64%)

Guard Band must be greater than Transition Band

Note 1: These numbers are first order approximations, and do not take into account factors such as deep out-of-band rejections that can impact filter design. Such factors can only be considered on a case by case basis. Generally these “transition band” numbers can be thought of as a minimum amount of frequency necessary for filters to do useful RF filtering at various bands.

Note 2: in general The US has more stringent temperature requirements than do other countries. Typically the US temperature range covers -30 to +85 C, whereas GSM family devices worldwide are often specified over a reduced temperature range (-10 to +80 or even -10 to +70 C)

Approximate Transition Band (EPC-TDK)

	Temp. range	Transition Band for SAW / BAW
US cell band / 3GPP Band 5 824-849 MHz / 869-894 MHz	-30 to +85 C	10 MHz (1,16%)
US PCS band / 3GPP Band 2 1850-1910 MHz / 1930-1990 MHz	-30 to +85 C	20 MHz (1.04%)
US 700 MHz / 3GPP Bands 12/13/14/17 698-806 MHz	-30 to +85 C	8 MHz (1.06%)
AWS-1 / 3GPP Bands 4/10 1710-1770 MHz / 2110-2170 MHz	-30 to +85 C	20 MHz (1,03%)
L-Band / 3GPP Band 1626.5-1660.5 MHz / 1525-1555 MHz	-30 to +85C	17 MHz (1.07%)
E-GSM / 3GPP Band 8 880-915 MHz / 925-960 MHz	-10 to +80 C	10 MHz (1.09%)
DCS / 3GPP Band 3 1710-1785 MHz / 1805-1880 MHz	-10 to +80 C	20 MHz (1.11%)
3GPP Band 1 1920-1980 MHz / 2110-2170 MHz	-10 to +80 C	21 MHz (1.03%)
3GPP Band 7 2500-2570 MHz / 2620-2690 MHz	-10 to +80 C	27 MHz (1.04%)
ISM 2400 / WiFi / Bluetooth 2400-2484 MHz	-30 to +85C (in US handsets)	27 MHz (1.08%)

Note 1: Required guard band evaluated for CW specification according to LTE requirements (insertion loss < 4dB, attenuation approx. 50dB).
Note 2: Evaluation based on proofed filter designs providing sufficient out-of-band rejection levels.
Note 3: Temperature range depends on band (US vs. EU/Japan) and customer (for PAiD modules up to +125°C).
Note 4: Further design and process improvements needed to meet customer demands for lower insertion attenuation (longer talk time).

Approximate Transition Band (MuRata)

	Temp. range	Transition Band for SAW
US cell band / 3GPP Band 5 824-849 MHz / 869-894 MHz	-30 to +85 C	13 MHz (1.51%)
US PCS band / 3GPP Band 2 1850-1910 MHz / 1930-1990 MHz	-30 to +85 C	17 MHz (0.89%)
US 700 MHz / 3GPP Bands 12/13/14/17 698-806 MHz	-30 to +85 C	10MHz (1.32%)
AWS-1 / 3GPP Bands 4/10 1710-1770 MHz / 2110-2170 MHz	-30 to +85 C	38MHz (2.12%)
L-Band / 3GPP Band 1626.5-1660.5 MHz / 1525-1555 MHz	-30 to +85C	17 MHz (1.07%)
E-GSM / 3GPP Band 8 880-915 MHz / 925-960 MHz	-10 to +80 C	8.5 MHz (0.93%)
DCS / 3GPP Band 3 1710-1785 MHz / 1805-1880 MHz	-10 to +80 C	20 MHz (1.11%)
3GPP Band 1 1920-1980 MHz / 2110-2170 MHz	-10 to +80 C	60MHz (2.93%)
3GPP Band 7 2500-2570 MHz / 2620-2690 MHz	-10 to +80 C	27 MHz (1.04%)
ISM 2400 / WiFi / Bluetooth 2400-2484 MHz	-30 to +85C (in US handsets)	27 MHz (1.08%)

NOTE: Bands 1 & 2 transition bands are based on Murata standard SAW duplexer specifications. The I.L. characteristics are:

- B1 DPX Tx (1920-1980MHz): 1.6dB max. at 25deg.C
- B2 DPX Tx (1850.48-1909.52MHz): 3.1dB max. at 25deg.C

Other Solutions

Filtering is not the only solution to potential interferers

- ✓ Filtering: Block the interferer

Other possible solutions include:

- ✓ System Timing: Dodge the interferer
- ✓ Receiver Linearity: Withstand the interferer
- ✓ Noise Reduction: Don’t create the interferer
- ✓ Antenna techniques (diversity, MIMO): improve quality & reliability of link

Practical System Solutions may combine these methods.

Thank you!

Questions, please contact:

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