Filters

Select the frequencies you want to receive.
Avoid transmitting out of band energy
Major Ideal Filter Types

LPF

HPF

BPF

BSF
Major Filter Implementations

- Active
- Inductor & Capacitor (Lumped Element)
- Stripline and microstrip (Distributed Element)
- Ceramic LTCC
- Cavity
- Piezoelectric
  - Quartz crystal
  - Ceramic
  - SAW
  - BAW
  - FBAR
- YIG
Active Filters

• Generally incorporate op-amps
• Limited to relatively low frequencies due to gain-bandwidth limitations
• Examples:
  – Sallen-Key
  – State Variable
  – Biquad
• Refer to the Analog Devices Linear Circuit Design Handbook Chapt 8 for excellent discussion.

Conversions

• It is common for filters to be initially thought of as low pass filters.
• The low pass filter model can then be converted through various techniques to other filter forms.
LC Filters

- Well suited to mid-range frequencies
- Excellent design flexibility
- Limitations:
  - Component parasitics and dimensions
    - Component dimensions < $\lambda/10$
    - Inductors operating well below their SRF
  - Temperature coefficients, particularly capacitors
  - Losses at high frequencies
  - Space requirements may be larger than other options
- Concepts may apply to other filter implementations
A general LC filter topology

\[ Z_{S1} \rightarrow Z_{S2} \rightarrow Z_{S(n-1)} \rightarrow Z_{Sn} \]

Optional

[Diagram showing the general LC filter topology with blocks labeled \( Z_{S1}, Z_{S2}, Z_{S(n-1)}, Z_{Sn} \) and \( Z_{P1}, Z_{P2}, Z_{Pn} \).]
Inductor $Z$ and $Y$

$$Z = j\omega L$$

$$Y = \frac{1}{j\omega L} = -\frac{j}{\omega L}$$

$L1$ chosen such that $Z = 100\,\Omega$ @ 10 MHz

L1 chosen such that $Z = 100\,\Omega$ @ 10 MHz
Capacitor Z and Y

\[ Z = \frac{1}{j\omega C} = -\frac{j}{\omega C} \]

\[ Y = j\omega C \]

C1 chosen such that \( Z = 100\Omega \) @ 10 MHz
Series LC Z and Y

\[ Z = 0 \text{ when } \omega_0 L = \frac{1}{\omega_0 C} \]

\[ \omega_0^2 = \frac{1}{LC} \quad \omega_0 = \frac{1}{\sqrt{LC}} \]

\[ Z = j\omega L - \frac{j}{\omega C} \]

\[ Y = \frac{j \omega C}{1 - \omega^2 LC} \quad \text{If } \omega = \omega_0 \text{ then } Y \rightarrow \infty \]
Parallel LC Z and Y

\[ Z = \frac{j\omega L}{1 - \omega^2 LC} \]

If \( \omega = \omega_0 \) then \( Z \to \infty \)

\[ Y = 0 \text{ when } \omega_0 L = \frac{1}{\omega_0 C} \]

\[ \omega_0^2 = \frac{1}{LC} \quad \omega_0 = \frac{1}{\sqrt{LC}} \]

\[ Y = j\omega C - \frac{j}{\omega L} \]
Fundamental Definition of Q

\[ Q = 2\pi \frac{\text{Energy stored in a resonator}}{\text{Energy dissipated per cycle}} \]

\[ Q = 2\pi f_0 \frac{\text{Energy stored in the resonator at } f_0}{\text{Average power lost in the resonator}} \]
Definitions of Q
First order circuit

Series L-R

\[ Q = \frac{X_L}{R} = \frac{\omega L}{R} \]

Parallel C-G

\[ Q = \frac{B_C}{G} = \frac{\omega C}{G} \]
Definitions of Q for Second Order Circuit

(a) Parallel

\[ Q = R \sqrt{\frac{C}{L}} \]

\[ Z = \frac{R}{1 + jQ \left( \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)} \]

(b) Series

\[ Q = \frac{1}{R} \sqrt{\frac{L}{C}} \]

\[ Y = \frac{1/R}{1 + jQ \left( \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)} \]
Magnitude and Phase vs. Q & $\zeta$

$$Q = \frac{1}{2\zeta}$$

$$Q = \frac{\omega_0}{2} \left| \frac{d\phi}{d\omega} \right|$$

FIGURE 13.3-11 Bode diagram of $H(j\omega) = \frac{1}{1 + (2\zeta/\omega_0)j\omega + (j\omega/\omega_0)^2}$ for two decades of frequency.
Definitions of Q

\[ Q = \frac{f_0}{BW} \]
Typical LC Filter Topologies
General Filter Model

\[
\Gamma_1 = \frac{Z_1 - R_S}{Z_1 + R_S}
\]

Power delivered to load:
\[
P_L = \frac{V_2^2}{R_L}
\]

Power delivered by source into a matched load:
\[
P_S = \frac{V_S^2}{4R_S} = \frac{V_1^2}{R_S}
\]
From the previous page:

\[ \Gamma_1 = \frac{Z_1 - R_S}{Z_1 + R_S} \]

\[ P_L = \frac{V_2^2}{R_L} \]

\[ P_S = \frac{V_S^2}{4R_S} = \frac{V_1^2}{R_S} \]

The Transfer Function

\[ T = \sqrt{\frac{P_L}{P_S}} = 2 \sqrt{\frac{R_S V_2}{R_L V_S}} = \sqrt{\frac{R_S V_2}{R_L V_1}} \]

Note that: \( \Gamma_1 = S_{11} \) and if \( R_L = R_S \) then \( T = \frac{V_2}{V_1} = S_{21} \)

If the filter is lossless, comprised of purely ideal reactive elements, then all power supplied at it input is either passed to the load or reflected back to the source. That means that:

\[ \Gamma_1^2 + T^2 = 1 \]
An example LPF

With different termination impedances

Response of the filter with non 50 ohms terminal impedances.

Primary Classical Filter Types

• Butterworth – Maximally Flat Amplitude
• Bessel – Maximally Flat Group Delay
• Chebyshev filter – Provides steeper slope with ripple in the response
  – Type I fast rolloff, ripple in the passband
  – Type II slower rolloff, ripple in the stopband
• Elliptic – Fastest rolloff, ripple in both bands
A Comparison of Types

Bessel Filter

Based on work done by German mathematician Friedrich Bessel (1784 – 1846) W.E. Thomas applied the Besssel functions to filter design in 1949 Maximally flat group delay but slow rolloff. Commonly used in audio crossover circuits

The low-pass filter transfer function is:

\[ H(s) = \frac{\Theta_n(0)}{\Theta_n(s/\omega_0)} \]

where: \( \Theta_n(s) \) is a reverse Bessel polynomial

\[ \Theta_n(0) = \lim_{x \to 0} \Theta_n(x) \]

\[ \Theta_n(s) = \sum_{k=0}^{n} a_k s^k \]

where:

\[ a_k = \frac{(2n - k)!}{2^{n-k} k! (n-k)!} \quad k = 0, 1, ..., n \]

\[ n = \text{number of poles} \]

https://en.wikipedia.org/wiki/Bessel_filter
Butterworth Filter

Described in 1930 by British engineer and physicist Stephen Butterworth.

\[ G(\omega) = \frac{1}{\sqrt{1 + \left(\frac{\omega}{\omega_c}\right)^{2n}}} \]

Characteristic gain & delay plot for the Butterworth filter

Comparison of the Butterworth and Bessel filters

Butterworth

Bessel


Chebyshev Type I Filter

\[ \text{Gain} = \frac{1}{\sqrt{1 + \varepsilon^2}} \]

\( \varepsilon \) is the ripple factor

Response of the Type I Chebyshev Filter

\[ \varepsilon = \sqrt{10^{\delta/10}} - 1 \]

\( \delta \) is the passband ripple in dB

\[ G_n(\omega) = |H_n(j\omega)| = \frac{1}{\sqrt{1 + \varepsilon^2 T_n^2 \left( \frac{\omega}{\omega_0} \right)}} \]

\( T_n \) is a Chebyshev polynomial of the \( n^{th} \) order

[Chebyshev Filter Wikipedia](https://en.wikipedia.org/wiki/Chebyshev_filter)
Chebyshev Type II Filter

Named after Pafnuty Chebyshev, derived from the Chebyshev polynomials. Type II filters are usually called “inverse Chebyshev filters.”

\[ \text{Gain} = \frac{\epsilon}{\sqrt{1 + \epsilon^2}} \]

Response of the Type II Chebyshev Filter

\[ \varepsilon = \sqrt{10^{\delta/10}} \]

\[ G_n(\omega) = |H_n(j\omega)| = \frac{1}{\sqrt{1 + \frac{1}{\varepsilon^2 T_n^2 \left(\frac{\omega_0}{\omega}\right)}}} \]

\( T_n \) is a Chebyshev polynomial of the \( n^{th} \) order

https://en.wikipedia.org/wiki/Chebyshev_filter
Elliptic (Cauer) Filter

\[ G = \frac{1}{\sqrt{1 + \varepsilon^2}} \]

\[ G = \frac{1}{\sqrt{1 + \varepsilon^2 L_n^2}} \]

Cauer Topologies

Example of an exotic LC Filter

Transition between types

The elliptic filter is characterized by the ripple in both pass-band and stop-band as well as the fastest transition between pass-band and ultimate roll-off of any RF filter type. The levels of ripple in the pass-band and stop-band are independently adjustable during the design. As the ripple in the stop-band approaches zero, the filter becomes a Chebyshev type I filter, and as the ripple in the pass-band approaches zero, it becomes a Chebyshev type II filter. If the ripple in both stop-band and pass-band become zero, then the filter transforms into a Butterworth filter.

Distributed Element Filters

• Stripline or Microstrip
• Typically used for frequencies > 1 GHz ($\lambda < 30$ cm)
• PCB geometry limitations and losses can be problematic in the multi-GHz range (> 10 GHz)

Stripline Filters

\( \lambda/2 \) end-coupled filter

\( \lambda/2 \) side-coupled filter

https://www.mwrf.com/rf-classics/design-strip-line-band-pass-filters
Microstrip Examples

Figure 1. A circuit featuring many of the filter structures described in this article. The operating frequency of the filters is around 11 gigahertz (GHz). This circuit is described in the box below.

The PCB inside a 20GHz Agilent N9344C spectrum analyser showing various microstrip distributed element filter technology elements

K and J are impedance and admittance transformers respectively.

Low Pass Filter Example

LPF and equivalent lumped circuit

Capacitive gap BPF
Limited BW (Q>5) for practical implementation


Coupled Line filters from a spectrum analyzer PCB

Example of Combline Filter
LTCC Ceramic Filters

• Ceramic substrates provide high $\varepsilon'$ and low $\varepsilon''$
• This allows for smaller geometries and lower losses
• $\varepsilon'$ can range from 4.5 to around 100.
• Tradeoffs include temperature coefficients and dielectric losses ($\varepsilon''$).
• As frequencies increase, lower $\varepsilon'$ becomes more appropriate.
• Designs are proprietary

Mini-Circuits
BFCN-1445+
LTCC Band Pass Filter, 1420-1470 MHz

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<thead>
<tr>
<th>Quantity</th>
<th>Unit Price</th>
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<tbody>
<tr>
<td>20</td>
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<tr>
<td>50</td>
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</tr>
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<tr>
<td>200</td>
<td>$3.35</td>
</tr>
<tr>
<td>500</td>
<td>$3.25</td>
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Mini-Circuits
BFCN-8650+
LTCC Band Pass Filter,
8550-8750 MHz

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<th>Quantity</th>
<th>Unit Price</th>
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<td>20</td>
<td>$3.95</td>
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<tr>
<td>50</td>
<td>$3.75</td>
</tr>
<tr>
<td>100</td>
<td>$3.55</td>
</tr>
<tr>
<td>200</td>
<td>$3.35</td>
</tr>
<tr>
<td>500</td>
<td>$3.25</td>
</tr>
</tbody>
</table>


Cavity Filter
Figure 4.16: Structure of the optimized stepped impedance Chebychev filter (N=6, RL=15 dB, R1=50 ohms, R2=71.6 ohms)
Combline Filter Design

Figure 6.3: Physical dimensions involved in the design of a combline microwave filter, and main views of the structure
ZVBP-11G3-S+
Connectorized Band Pass Filter,
11200-11400 MHz
Connector Type: SMA

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<th>Quantity</th>
<th>Unit Price</th>
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<tbody>
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<td>1 - 4</td>
<td>$340.00</td>
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<tr>
<td>5 or more</td>
<td>$340.00</td>
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</table>


Quartz Crystal Filter

Very high Q, 10,000 to 100,000
Frequencies up to ~ 75 MHz
Murata examples of crystal filters

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Center Frequency (MHz)</th>
<th>Overtone Order</th>
<th>Number of Poles</th>
<th>3dB Bandwidth (kHz min.)</th>
<th>Stop Band Width (kHz max.)</th>
<th>Guaranteed Attenuation (dB min.) [fo-910kHz]</th>
<th>Spurious (dB min.) within fo±1MHz</th>
<th>Insertion Loss (dB max.)</th>
<th>Ripple (dB max.)</th>
<th>Operating Temperature Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XDCAF21M400RAA00P0</td>
<td>21.4000</td>
<td>Fundamental</td>
<td>2</td>
<td>±7.5</td>
<td>±25 @18dB</td>
<td>70</td>
<td>10</td>
<td>2.0</td>
<td>1.0</td>
<td>-20 to +70</td>
</tr>
<tr>
<td>XDCAF21M700MAA00P0</td>
<td>21.7000</td>
<td>Fundamental</td>
<td>2</td>
<td>±3.75</td>
<td>±20 @18dB</td>
<td>70</td>
<td>18</td>
<td>2.0</td>
<td>1.0</td>
<td>-20 to +70</td>
</tr>
<tr>
<td>XDAG38M850PGA00P0</td>
<td>38.8500</td>
<td>Fundamental</td>
<td>4</td>
<td>±5.0</td>
<td>±25 @45dB</td>
<td>70</td>
<td>40</td>
<td>5.0</td>
<td>1.0</td>
<td>-20 to +70</td>
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<tr>
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<td>44.8500</td>
<td>Fundamental</td>
<td>4</td>
<td>±6.5</td>
<td>±12.5 @20dB</td>
<td>70</td>
<td>40</td>
<td>3.0</td>
<td>1.0</td>
<td>-20 to +70</td>
</tr>
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<td>45.0000</td>
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<td>4</td>
<td>±7.5</td>
<td>±25 @25dB</td>
<td>70</td>
<td>40</td>
<td>3.0</td>
<td>1.0</td>
<td>-20 to +70</td>
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<td>±20 @35dB</td>
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<td>40</td>
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<td>1.0</td>
<td>-20 to +70</td>
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<td>±20 @40dB</td>
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<td>±12.5 @20dB</td>
<td>70</td>
<td>40</td>
<td>5.0</td>
<td>1.0</td>
<td>-20 to +70</td>
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<tr>
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<td>58.0500</td>
<td>Fundamental</td>
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<td>±20 @38dB</td>
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<td>-20 to +70</td>
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<td>±5.0</td>
<td>±25 @45dB</td>
<td>80</td>
<td>60</td>
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<td>-20 to +70</td>
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<td>80</td>
<td>60</td>
<td>4.0</td>
<td>1.0</td>
<td>-20 to +70</td>
</tr>
</tbody>
</table>

Examples of Murata Crystal Filter Performance

XDCAF21M400RAA00P0
1: LOG 1 dB/
2: DLY 5 µsec/ REF 23.6 µsec

XDCAH73M350QHA03P0
1: LOG 1 dB/
2: DLY 15 µsec/ REF 51.529 µsec

1: CNF 21.4 MHz SPF 40 kHz
2: CNF 21.4 MHz SPF 40 kHz

1: CNF 73.35 MHz SPF 30 kHz
2: CNF 73.35 MHz SPF 30 kHz
Ceramic Resonator Filters
1.85 mm Subminiature Ceramic Filter

Applications
- Electronic warfare
- Portable transceivers for both military and homeland security radio communications

Features
- Relatively low insertion loss
- SMT designs
- Frequency range from 350 MHz to 6 GHz
- Power handling, with up to 3 W CW
- Wide operating temperature range
- Light weight
- Smaller profile compared to a typical ceramic design
- Easy drop-in solution
- Quick turnaround on new designs
- RoHS-compliant
- Available in various frequencies

Skyworks Green™ products are compliant with all applicable legislation and are halogen-free. For additional information, refer to Skyworks Definition of Green™, document number SQ04-0074.

Description
Skyworks, through its wholly owned subsidiary, Trans-Tech, offers a family of ultra-small profile filters available in surface-mount technology (SMT) designs. We can design and manufacture filters from 350 MHz up to 6 GHz, with higher power handling ability up to 3 W, continuous wave (CW). We also offer rapid response times on all filter design requirements.

The small-profile ceramic filter designs offer customers the option to go with a lighter weight, and reduced X Y Z dimensions as solutions to their requirements.

These ceramic filter solutions allow design flexibility beyond traditional ceramic styles. Table 1 provides the electrical specifications.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Test Condition</th>
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1 Performance is guaranteed only under the conditions listed in this table.
CSBP-D1228+
Ceramic Resonator Band Pass Filter, 1203-1253 MHz

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<td>$23.95</td>
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</table>

Typical Ceramic Resonator filter Performance

N = Number of Sections

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<th>Frequency (MHz)</th>
<th>3 dB%</th>
<th># of Sections</th>
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<tr>
<td>400 - 6000</td>
<td>0.5% - 25%</td>
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<table>
<thead>
<tr>
<th>Typical VSWR</th>
<th>Max Power (Watts)</th>
<th>Operating Temperature</th>
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<tr>
<td>1.5 : 1</td>
<td>10</td>
<td>-50° C ~ +100° C</td>
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</tbody>
</table>

BAW-SAW Filter Options

https://cdn.embedded.com/ContentEETimes/Images/EDN1Wireless/13MayJune/C1000Figure%20Alternative_Apr%202013.jpg
SAW Resonator

- Utilizes Surface Acoustic Waves
- “Acoustic” in this context refers to energy transferred through mechanical vibrations.
- The acoustic waves travel on the surface of the piezoelectric material
- Typical materials:
  - Lithium Niobate – LiNbO$_3$
  - Lithium Tantalate – LiTaO$_3$
  - Aluminum Nitrate – AlN
SAW Resonator Operation

- Wavelength of traveling wave is \( \lambda = \frac{v}{f} \)

- Constructive interference happens when the finger spacing \( d_F = \frac{\lambda}{2} \) or \( f = \frac{v}{2d_F} \)
SAW Properties

- Generally bandpass filters
- Typical frequency range is 0.1 to 2.5 GHz
- Typical insertion loss 1 dB to 3 dB
Murata SF2124E
Bulk Acoustic Wave Resonator

• BAW-SMR  Solidly Mounted Resonator
• FBAR – Film Bulk Acoustic Resonator
• Both achieve very high Q values, e.g. 2500 @ 2 GHz
• Acoustic waves travel vertically through substrate
BAW

https://m.eet.com/media/1182779/c1000fig1new.jpg
QPQ1289
LTE Band 4 / 10 / 66 BAW Duplexer

9 Pad 2.00 mm x 2.50 mm x 0.91 mm SMP

Notes:
1. Distance from left side of L2 to right side of U1: 5 mils.
Qorvo BAW Frequency Response

Uplink Frequency Response

Downlink Frequency Response
FBAR

Lower-side electrode

Piezoelectric thin film

Upper-side electrode

Si

Cavity

Si
The quality factor $Q_s$ at the series resonant frequency in the free-standing air-backed FBAR is calculated to be 1,322. It is about six times larger than that in the FBAR with 0.9μm thick Si$_3$N$_4$ as a support diaphragm. The quality factor $Q_p$ at the parallel resonant frequency in the case (e) is calculated to be 513, three times that in the case (a). Figure of Merit (FOM) of an FBAR is defined as the product of $Q$ and $k_t^2$. Insertion loss in an FBAR-based filter is inversely proportional to the FOM of the FBARs. In the free-standing air-backed FBAR, we have increased $k_t^2$ twice and the quality factor six times, and filters made out of this kind of resonator are expected to have larger bandwidth and much lower insertion loss compared to that made by an FBAR built on a support diaphragm.

http://mems.usc.edu/fbar.htm
SAW Devices in Cellular Phones

https://pdfs.semanticscholar.org/358b/55d82445129e3d47a132292cee213cd09c58.pdf
Following are the benefits or **advantages of FBAR Filter:**

➤ It offers lower insertion loss. As a result it consumes less current. This leads to long battery life and fewer dropped calls.

➤ It offers steeper filtering. Hence better coexistence with adjacent bands can be achieved.

➤ It offers better out-of-band rejection. Hence multi-band capability can be achieved.

➤ It offers ultra small size devices. Hence it can be fit easily with other semiconductor chips.

➤ FBAR filters operate reliably in high power and worst temperature conditions.

Following are the drawbacks or **disadvantages of FBAR Filter:**

➤ Thermal path for heat generated in the device is crucial in the design of FBAR and BAW-SMR filters. In BAW-SMR type, heat has conduction path into the substrate from which heat can be spread. However in FBAR type, there is air gap on each side of the resonator. Hence in FBAR designs, thermal conduction path is weaker.

The ACFM-7024 features a single antenna connection, which eliminates the need for antenna switching. All ports are matched to 50 ohms. The ACFM-7024 is designed with Avago Technologies’ film bulk acoustic resonator (FBAR) technology. The ACFM-7024 also utilizes Avago Technologies’ innovative microcap bonded-wafer, chip scale packaging technology. This process allows the filters to be assembled in a module with a footprint of only 3.6 mm × 2 mm with a maximum height of 0.80 mm.
YIG sphere resonator

https://www.microlambdawireless.com/resources/ytfdfinitions2.pdf

https://en.wikipedia.org/wiki/YIG_sphere
Features of YIG resonators

- Resonant frequency linearly related to magnetic field
- Wide tuning range – Generally 1 – 3+ octaves
- Can resonate in the range of 1 – 50 GHz
- High Q, typically 100 to 200
- Commonly used for either a filter or oscillator
- Temperature sensitive, commonly use heater
- Filters may have multiple (e.g. 2 – 8) stages

https://www.microlambdawireless.com/components/wide-tuning-range-oscillators/
https://www.microlambdawireless.com/components.band-pass-filters/