

TUNING OPTIMIZATION APPROACHES FOR DIGITALLY CONTROLLED TUNABLE FILTERS

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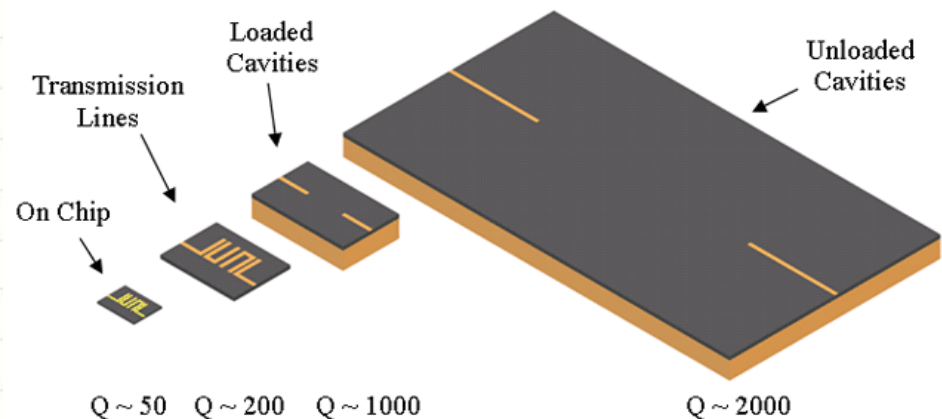
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Tunable Filter

Tunable filters' passband can be control by varing of resonators values. Different tunable capacitances or inductances technologies are used.

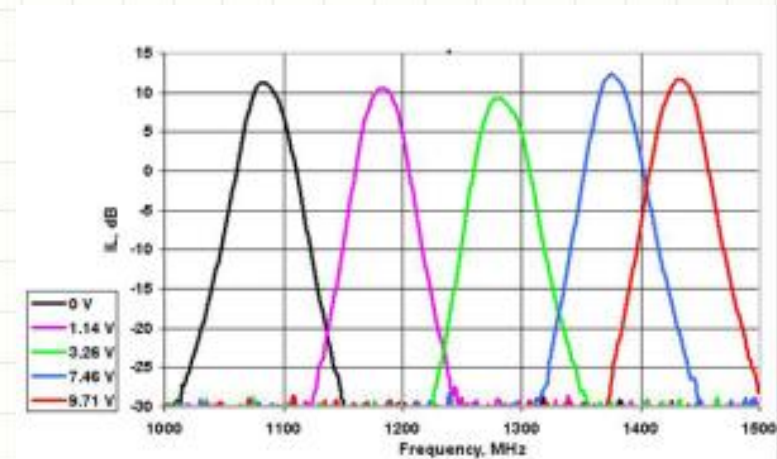
Due to the occurrence of multi-frequency bands in different regions and diverse applications, requirement of tunable filters exists.



Tunable Filter Parameters

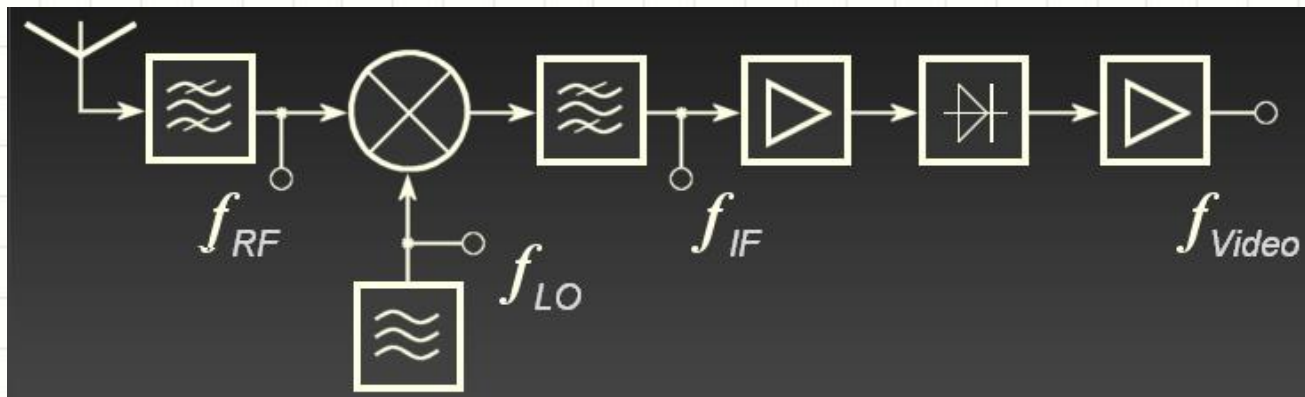
Tunable filters used in Radio Receiver Front End should have below specifications.

- **Wide Tuning Range**
- **Minumum Insertion Loss**
- **Fast tunable speed**
- **Maximum Return loss**
- **Narrow bandwith**

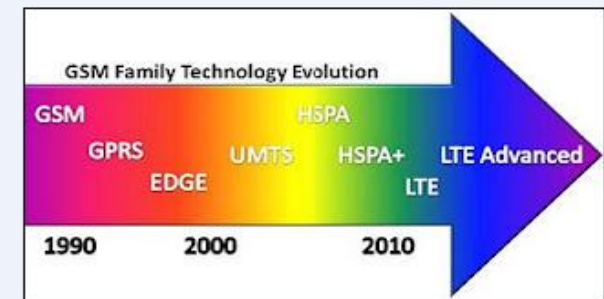


Where Are They Used

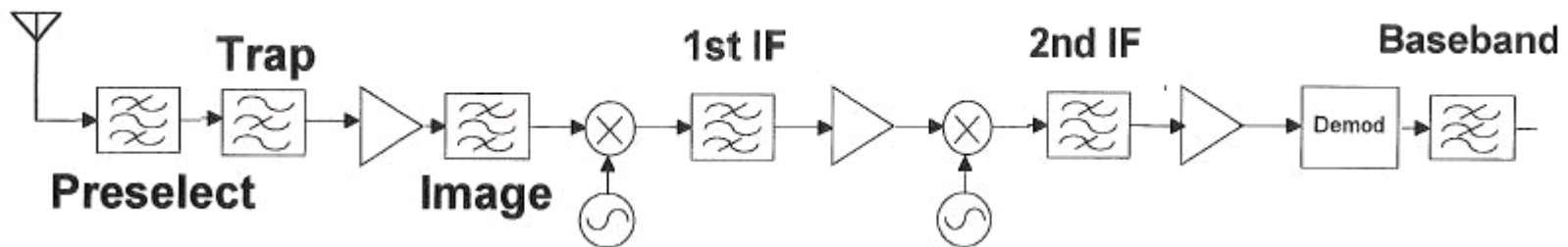
- Narrowband and wideband receivers
- Signal generators in communications (GSM, GPS, WI-FI, BLUETOOTH, LTE, ADVANCE LTE)



- Tunable Oscillators
- Tunable Power Amplifiers

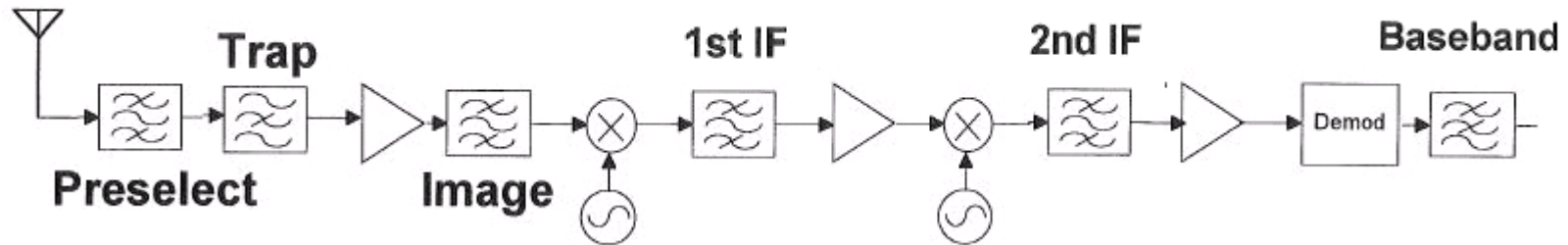


Filters In Receivers



- **Preselect (roofing) filter:** Passes desired service band and attenuates out of band interferences.
- **Trap:** Optional bandstop filter used if strong interference at certain frequencies is expected.
- **Image:** Attenuates noise at image frequency to improve receiver noise figure.

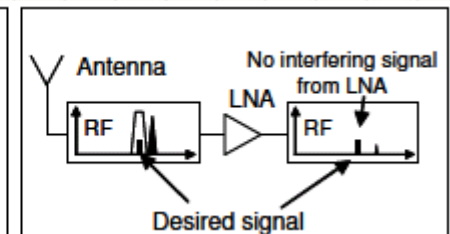
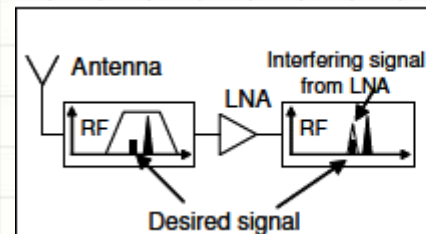
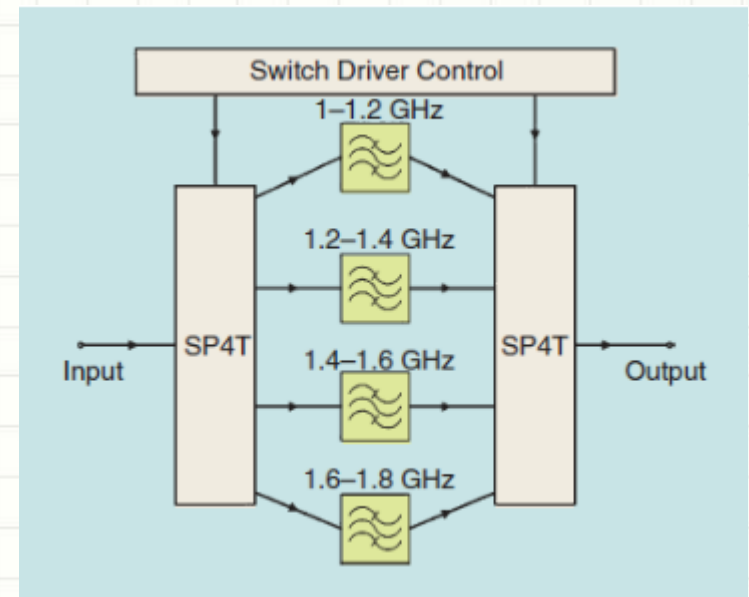
Filters In Receivers



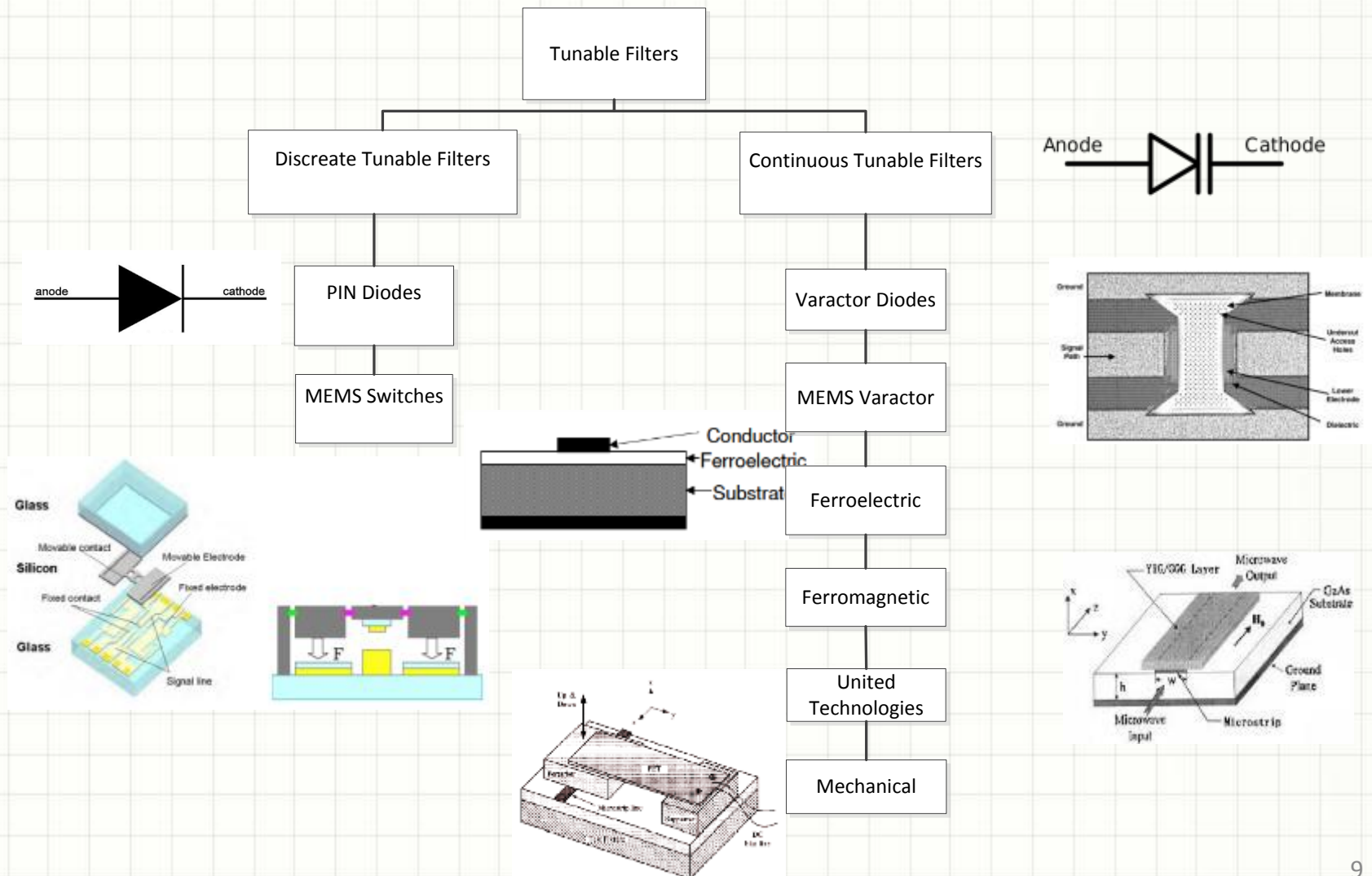
- **1st IF:** Narrow bandwidth to one or a few channels. Also prevents 'image' responses in second downconversion.
- **2nd IF:** Narrow bandwidth to one channel. Together with 1st IF filter, it determines receiver selectivity and noise bandwidth.
- **Baseband:** Assist in or implement final IF channel selection.

Why We Need Tunable Filters

- Reducing switching loss.
- The amount of noise entering the system is reduced. So Power consumption of ADC has decreased.
- Component count is reduced
- Minimum cost
- To be Reconfigurable



Tuning Methods



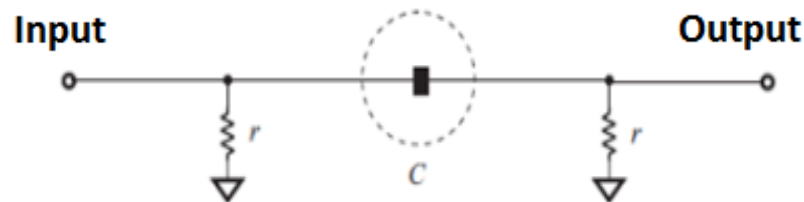
Tunable Capacitors

| Tuning Method | Mechanical | YIG | GaAs Varactor | RF MEMS | BST thin film |
|------------------------------|-------------|------------------|------------------|-----------------|---------------|
| Tunability | 10-20% | Multi- octave | 3:1 | < 2:1 | 2 - 3:1 |
| Unloaded Q | > 1000 | > 500 | 10 - 40 | High | 20 - 100 |
| Insertion Loss (dB) | 0.5 - 2.5 | 3 - 8 | 2 - 10 | 2 - 8 | 3 - 8 |
| Tuning Voltage (V) | NA <10 | < 15 | 100 | 20 - | 5 - 20 |
| Tuning Speed | Millisecond | Millisecond | Nano second | Micro second | Micro second |
| Power Handling | Ver High | 2 W | ~ mW | 1 - 2 W | ~ mW |
| Power Cons. | High | High | middle | low | low |
| Linearity (IP3 : dBm) | > 60 | < 30 | 15 - 25 | > 65 | 30 - 55 |
| Volume | Big | Big | Small | Small | Small |
| Integration | Diffucult | Diffucult | Easy | Easy | Easy |

The Varying of Tunable Filter Bandwidth

- When we analyze frequency response of filter below side;

C (Capacitive) Coupling Tunable Filter



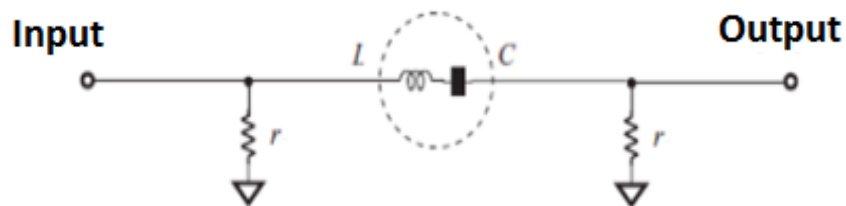
$$Q = \frac{I^2 \cdot 1 / j\omega C}{2 \cdot I^2 \cdot r}$$

$$\frac{f_c}{BW} = \frac{1}{4\pi r \cdot C \cdot f_c}$$

$$BW = 4\pi r \cdot C \cdot f_c^2 \quad \frac{dBW}{df_c} = 8\pi r C \cdot f_c$$

The Varying of Tunable Filter Bandwidth

Series L-C (Capacitive-Inductive) Coupling Tunable Filters



$$Q = \frac{I^2 \cdot (j\omega L + 1/j\omega C)}{2 \cdot I^2 \cdot r}$$

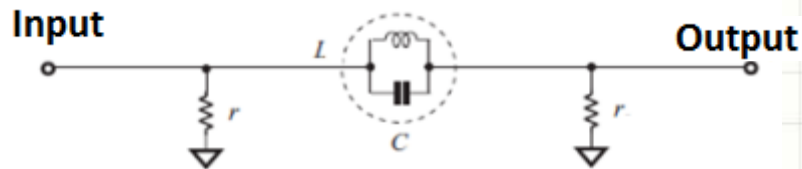
$$\frac{f_c}{BW} = \frac{4\pi f_o^2 LC - 1}{4\pi r \cdot C \cdot f_o}$$

$$BW = \frac{4\pi f_c^2 \cdot r \cdot C}{4\pi f_c^2 LC - 1}$$

$$\frac{dBW}{df_o} = -\frac{8\pi r C f_o}{(4\pi^2 LC f_c^2 - 1)^2}$$

The Varying of Tunable Filter Bandwidth

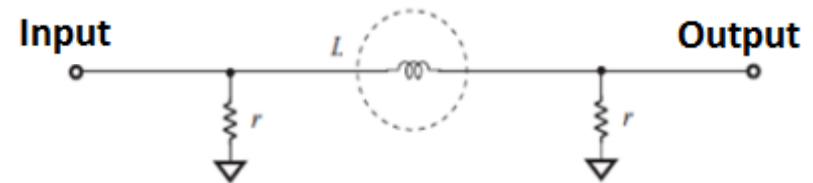
Paralell L-C (Capacitive-Inductive) Coupling Tunable Filters



$$Q = \frac{I^2 \cdot \left(\frac{L \cdot W}{1 - W^2 \cdot LC} \right)}{2 \cdot I^2 \cdot r} \quad \frac{f_c}{BW} = \frac{\pi \cdot L \cdot f_c}{r(1 - 4\pi^2 LC f_c^2)}$$

$$BW = \frac{(1 - 4\pi^2 LC f_c^2)r}{\pi \cdot L}$$

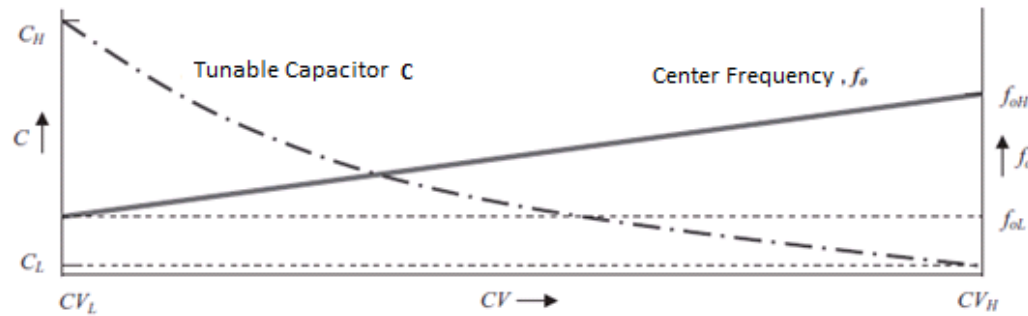
$$\frac{dBW}{dfc} = -8\pi r C \cdot f_c$$



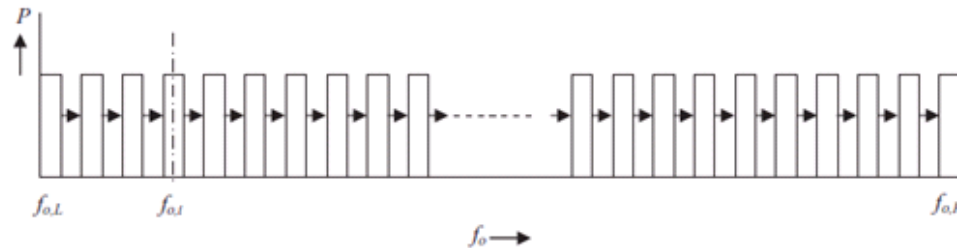
$$Q = W r \cdot \frac{1/2 L \cdot I^2}{2 \cdot I^2 \cdot r} \quad \frac{f_c}{BW} = \frac{W r \cdot L}{4 \cdot r} \quad BW = \frac{4 \cdot r}{2 \cdot \pi \cdot L}$$

$$\frac{dBW}{dfc} = 0$$

Constant Bandwidth Tunable Filters



Control Voltage vs Center Frequency

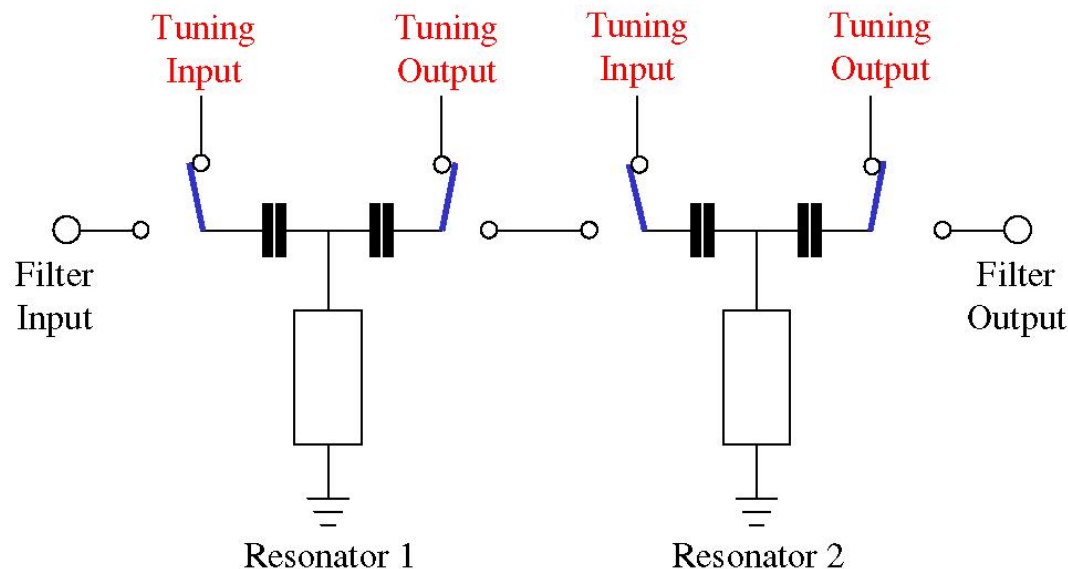


Frequency vs Constant Bandwidth

CONTROL LEVELS OF TUNABLE FILTERS

Three levels of control for tunable filters consist of

- Device level
- Resonator level
- Filter level tuning operations



CONTROL LEVELS OF TUNABLE FILTERS

Device-level control is basically to control the tuning element itself and meet the certain bandwidth and center frequency requirement.

Resonator-based control involves tuning each resonator to a precise resonant frequency. The advantage of this technique is that the state measurement is performed at a frequency outside the operating band of filter.

Filter-level control is tuning both resonators and coupling parameters together. By tuning the resonance frequency of the resonators, the center frequency of the filter the filter is adjusted

TUNING APPROACHES FOR RF FILTERS

For Traditional Filters:

- Sequential techniques which are time domain tuning and group delay methods
- Fuzzy logic fuzzy logic based on artificial intelligence. It techniques attempt to create a tuning algorithm from expressions such as mostly and somewhat. This makes fuzzy logic an excellent framework for formulating the tuning algorithm.
- Parameter extraction is space mapping tuning model through coupling matrix from s-parameters to find error matrix

TUNING APPROACHES FOR RF FILTERS

For Tunable Filters:

Open Loop Method: After designing, production and tuning process of tunable filters, it is difficult to observe and measure results in time. They are controlled through the same control signals and initial values are assumed to be right.

Closed Loop Method: In order to correct the tuning errors during operation, this method is used to track RF signal magnitude and phase which is output of filter. For notch filters S_{11} reflection phase and mag. Behaviors should be used.

TUNING APPROACHES FOR RF FILTERS

For Tunable Filters:

Look-up Table Method: These filters have different responses for applied voltage levels which are in the component specification limits. In the frequency domain, the filter is pre-characterized and the tuning states are pre-configured into the memory of the controller with respect to electrical bias before using in a upper level module

Optimization Method : In the optimization method, a goal function is established and an iterative algorithm is employed to find the optimal tuning voltages in order to minimize the value of the objective function

LOOK-UP TABLE METHOD FOR OPEN-LOOP TUNING

By means of open loop model, a look up table and optimization software were developed for 2-18 GHz YIG tunable filters.

YIG-based filters are excellent for military applications because of their low loss, wideband tuning, and excellent linearity

However, hysteresis effect due to the magnetic properties of YIG material should be compensated.

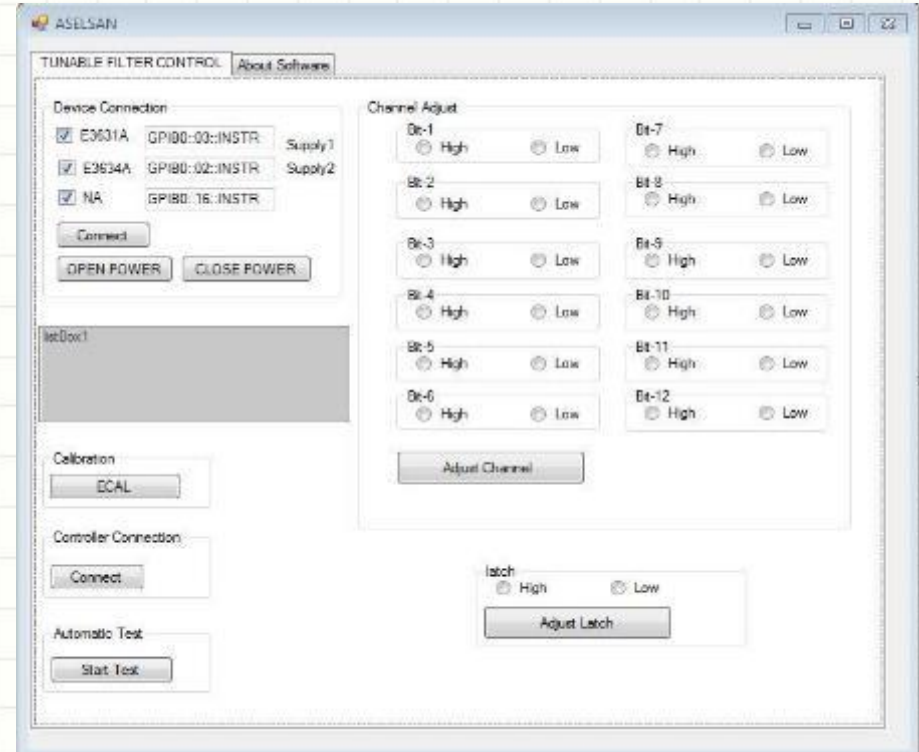
In our work, we developed a software-based compensation method using the open-loop technique in order to compensate hysteresis and aging errors

LOOK-UP TABLE METHOD FOR OPEN-LOOP TUNING

Calibration table was built and its software was developed in Visual Studio.NET platform.

Power sources and PNA connections can be made both manual and automatic.

Also integral filter driver can be controlled by viperboard which is managed by the operator.

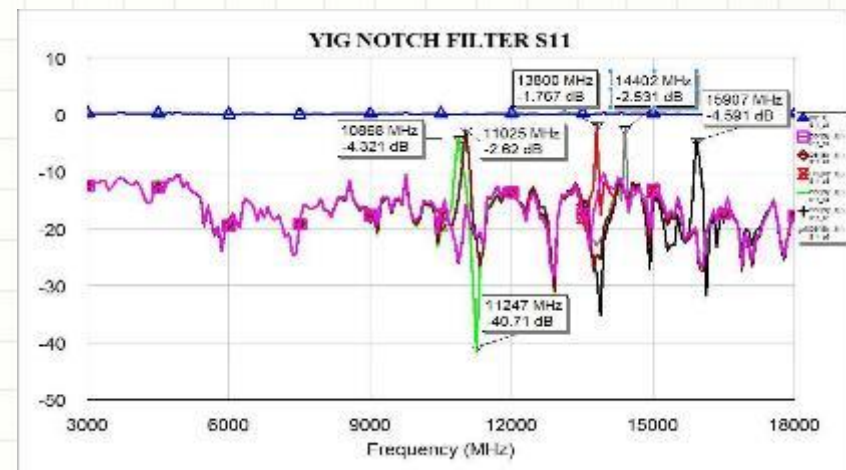
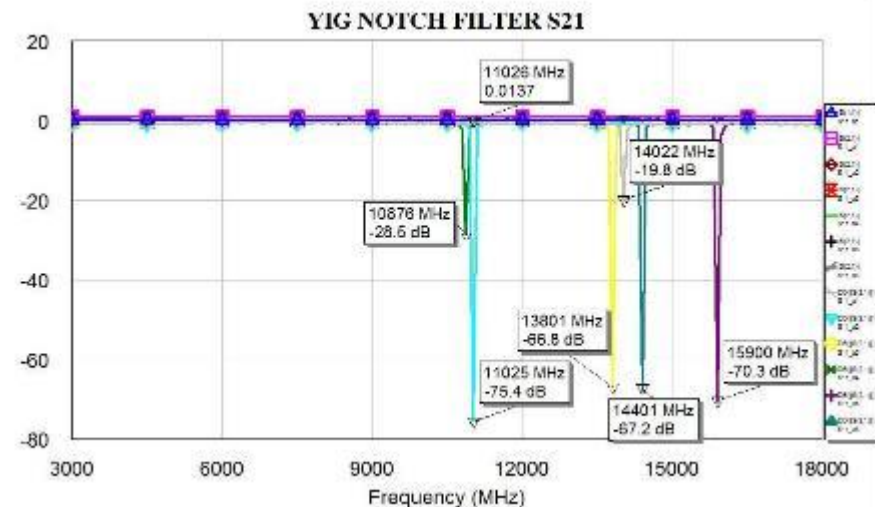


LOOK-UP TABLE METHOD FOR OPEN-LOOP TUNING

Measurement was performed for 12 bit TTL input compatible with latch in 4096 steps. For every step, filter response, i.e., S_{21} , S_{11} , 3 dB bandwidth, and center frequency have been measured with 3.9 MHz resolution

S_{21} notch amplitudes can be varied from -5 dB to -78 dB

Reflection signals can be varied from -1.4 dB to -6.2 dB at the notch frequencies, where suppressions are extremely high



LOOK-UP TABLE METHOD FOR OPEN-LOOP TUNING

Since showing all responses in same graph is not comprehensible, results are presented for 8 different voltage levels.

According to this table, each bias voltage corresponds to a filter center frequency. After a certain time, it is expected that these frequency and bias pair will not match to each other

So the table must be updated frequently.

All performance values can be seen in the table, and it gives a guidance to the operator about the in-spec or out-of-spec filters. For a proper notch filter, supression values should be lower than -10 dBm

YIG FILTER CALIBRATION TABLE

| Digital (Decimal) | Center Frequency (MHz) | S21 Amp (dB) | 3 dB Bandwidth (MHz) | 3 dB AMP(dB) | S11 Amp (dB) | LHS ORS | RHS ORS | Rejection Level |
|-------------------|------------------------|--------------|----------------------|--------------|--------------|---------|---------|-----------------|
| 2064 | 10676.12 | -6.10 | 106.444 | -6.296 | -6.289 | -0.487 | -0.439 | -5.81 |
| 2154 | 11028.34 | -10.27 | 56.739 | -8.736 | -8.754 | -0.427 | -0.655 | -8.31 |
| 2856 | 13801.42 | -33.33 | 14.611 | -7.992 | -7.804 | -0.431 | -0.764 | -7.56 |
| 2912 | 14022.61 | -67.83 | 6.822 | -1.133 | -0.979 | -0.431 | -0.537 | -0.70 |
| 3008 | 14401.77 | -12.20 | 44.062 | -3.877 | -3.896 | -0.435 | -0.655 | -3.44 |
| 3362 | 15800.32 | -14.08 | 36.648 | -10.987 | -11.030 | -0.435 | -0.572 | -10.55 |
| 3524 | 16439.21 | -67.50 | 6.831 | -2.283 | -2.225 | -0.425 | -0.429 | -1.86 |
| 3669 | 17012.11 | -5.44 | 156.628 | -5.230 | -5.648 | -0.425 | -0.428 | -4.81 |

LOOK-UP TABLE METHOD FOR OPEN-LOOP TUNING

Hysteresis means different tuned frequency of filter at the same coil current and it is caused by an unstable magnetization. Frequency shifts over time can be seen clearly in calibration table

Linearity tells us whether stability of the filter has deteriorated or not over time. In order to find linearity of the notch filter response, center frequencies for each digital bias have been analyzed for each sequentail step and this limit is determined to be 3.95 MHz.

| YIG FILTER CALIBRATION TABLE (NOW) | | | | FILTER CALIBRATION TABLE (BEFORE) | | | HYSTERESIS (MHz) | LINEARITY CALCULATION |
|------------------------------------|------------------------|--------------|--------------|-----------------------------------|--------------|--------------|------------------|-----------------------|
| Digital (Decimal) | Center Frequency (MHz) | S21 Amp (dB) | S11 Amp (dB) | Center Frequency (MHz) | S21 Amp (dB) | S11 Amp (dB) | | |
| 2064 | 10676.12 | -6.10 | -6.289 | 10756.12 | -6.10 | -6.289 | -80.00 | FAIL |
| 2154 | 11028.34 | -10.27 | -8.754 | 11115.34 | -10.27 | -8.754 | -87.00 | FAIL |
| 2856 | 13801.42 | -33.33 | -7.804 | 13911.42 | -33.33 | -7.804 | -110.00 | FAIL |
| 2912 | 14022.61 | -67.83 | -0.979 | 14109.61 | -67.83 | -0.979 | -87.00 | FAIL |
| 3008 | 14401.77 | -12.20 | -3.896 | 14510.77 | -12.20 | -3.896 | -109.00 | FAIL |
| 3362 | 15800.32 | -14.08 | -11.030 | 15902.32 | -14.08 | -11.030 | -102.00 | FAIL |
| 3524 | 16439.21 | -67.50 | -2.225 | 16510.21 | -67.50 | -2.225 | -71.00 | FAIL |
| 3669 | 17012.11 | -5.44 | -5.648 | 17101.11 | -5.44 | -5.648 | -89.00 | PASS |

$$Linearity = \frac{F_2 - F_1}{3.95}$$

CONCLUSION

Open loop method was used to optimize 2-18 GHz YIG tunable notch filter with deriving of calibration table via our design software

It was presented that tuning errors which are hysteresis, non-linearity and aging of components were corrected with calibration software algorithm based compensation method by comparing the previous and current measurements .

As the result it is shown that when closed loop technologies are not used, open loop tunable filter performance can be optimized via calibration software.

Finally, radar warning and electronic intelligence (ELINT) systems or rejecting signals in commercial test equipment measurement set-ups which cover tunable filters, work more stable and efficient.



THANK YOU VERY MUCH