Optimization Approaches for Digital Controlled Tunable Filters for Receivers

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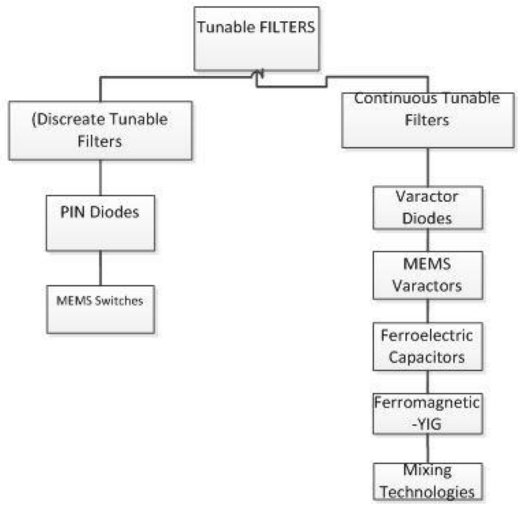
***Abstract*— Last decade, increasing of data and voice communications and transferring of them propose us wide band systems and technologies. Reconfigurable/tunable microwave filters have lots of contributions to RF receivers in wireless, 5G, radar and satellite communications. They are used in pre-selection and IF Bandpass filter parts to eliminated unwanted signals in receivers. According to application areas, prefering of different solutions which are RF MEMS, semiconductor diodes, ferroelectric materials, YIG filters etc have been discussed and revealed which techonology is applicable with related system. In this paper, significance and comprassion of these different tunable filter techonologies explained as well as their three different control level, tuning element, resonator and filter level discussed. Also finally, tuning methods,open loop, closed loop filter approachment and optimization techniques have disscused as well as control algorithm has designed to drive the circuits.**

Keywords—Tunable filter, Receivers, BST, filter frequency control, closed loop control,DAC

i. INTRODUCTİON

In recent days, the operating frequency bands for the cellular systems have been increased to over 40 bands due to the increasing demanding on the channel capacity of the mobile communication networks. To raise communication speed, LTE (Long term evolution) and 5G have been developed. The solution to the multiband and multimode communication for achieving smaller size and lower cost is to adapt reconfigurable RF systems in transceivers. The reconfigurable RF filter is the most common member of these systems and they are being used in receivers, software defined radios and cognitive radios as indispensable components. Tunable filter can satisfy compactness, wide tuning range greater functionality, better channel selectivity, reduced size, and lower weight. In addition, while they eliminate unwanted signals, LNA linearity is better and power consumption of ADC is reduced in receivers. Their bandwidth and center frequency vary according to tunable capacitor values.

Microwave tunable filters can be divided in two groups, filters with discrete tuning, and filters with continuous tuning. Filter topologies presenting a discrete tuning generally use PIN diodes or MEMS switches. On the other hand, filter topologies using varactor diodes, MEMS capacitors, ferroelectric materials or ferromagnetic materials are frequently used to obtain a continuous tuning device. And also combining of them is possible.



PIN diodes are frequently used to produce reconfigurable discrete states on a filter response. This technique has been used to implement a few switchable bandstop or bandpass filters, these filters have been implemented to provide the same fractional bandwidth at defined center frequencies [1-2]. In addition,MEMS switches produce discrete tuning of reconfigurable parameters. The switches can be capacitive type switches used for low frequency applications or direct contact switches used for low frequency applications [3].

Varactors are typically used for continuous tuned filters.varactor diodes use the change in the depletion layer capacitance of a p-n junction as a function of applied bias voltage. Varactor tuned devices have been used for high tuning speeds. Although, varactors tunable filters have a small power consumption and a relatively fast tuning speed, they suffer from a low Q value. Another drawback of varactors is power handling. Since varactor diodes are originally non-linear devices, the large input signal generates unwanted nonlinear distortions. RF MEMS varactors reconfigurable devices offer small size and good integration capabilities with microwave electronics [4].

Ferroelectric materials can change permittivity values proportionally to an applied DC electric field where some ferroelectrics are suitable for thin film deposition. We focus on tunable microwave filters using the most common ferroelectric, the Barium-Strontium-Titanate oxide (BST) [5] . BST material has a high Q and so, it is a good candidate for tunable components, and their harmonic performances and suppressions in stopband are better than those of GaAsvaractors, this comparison is provided in my last work [6]

Tunable filters using ferromagnetic materials like Yttrium-Iron-Garnet (YIG) results in high quality factor resonators with high power handling capabilities and high power consumption. The filters require very precise fabrication involving high costs, and also other drawbacks are a low tuning speed and a complex tuning mechanism [7].

TABLE 1 COMPRASION OF DIFFERENT TUNABLE TEHNOLOGIES

Tuning Method	Mechanical	YIG	GaAs Varactor	RF MEMS	BST Thin Film
Tuning range	5:1	Multi oct.	3:1	< 2:1	2 - 3:1
Q	> 1000	> 500	10 – 40	High	20 - 100
Insertion Loss (dB)	0.5 - 2.5	3 - 8	2 – 10	2 - 8	3 - 8
Tuning Speed	Millisec.	Millisec.	Nanosec.	Microsec.	Micro sec.
Power Capability	High	2 W	~ mW	1 - 2 W	~ mW

In a communication systems customer needs is much less than the entire bandwidth of the system. For UHF, tactical and cognative radios, voice conversation needs no more than 25 kHz, to approach good performance namely the ideal condition is to assign 25 kHz. But in pratical RF world it is almost impossible to design filter which bandwith is order of around 25 kHz. Fitting the near 10 MHz will be the best condition, improving selectivity of the receiver, reducing noise, and preventing a variety of spurious interference. When deciding which technology (detailed upper part) is adequate for a given application, the designer must consider the following issues: cost, power consumption, size, performance and operating frequency. For example, when the tunable speed is the priority design criteria, designer must choice GaAs Varactor Diode or BST capacitors, when narrow bandwith and wide tuning range are privileged specifications, YIG filters must be used.

ii. CONTROL LEVELS OF TUNABLE FILTERS

We will discuss three levels of control for a tunable filter. These are the tuning element level, resonator level and the filter level.

a. ***Device-level control*** is directed at controlling the tuning element itself and satisfying that its value is precisely set.

b. ***Resonator Based control*** involves tuning each resonator to a precise resonant frequency. For example, Lumped VUHF narrowband tunable filter designed [6]. The advantage of this technique is that the state measurement is performed at a frequency outside the operating band of filter.

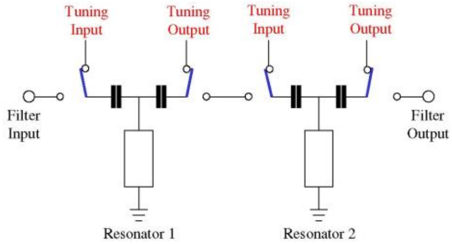


Fig.2 Resonator Based Tuning[8]

c. ***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 is adjusted while adjusting couplings affects the filter's bandwidth. RoboCAT or robotic computer aided tuning can be given as a example.

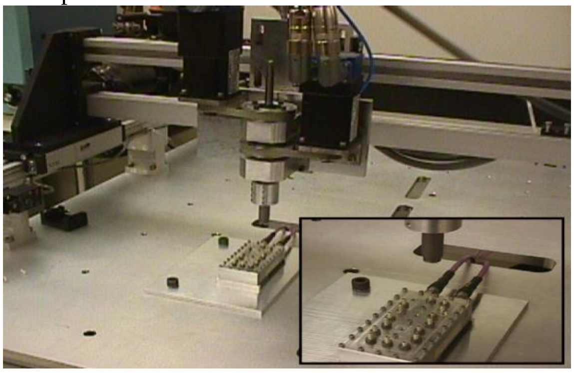


Fig.3 RoboCAT Based Tuning[9]

iii. MEASUREMENT METHODS OF TUNABLE FILTERS

a. **Single-frequency reference signal ,** A single reference tone is used to tuneeach resonator for maximum response at the center frequency.

b. **Multi-frequency reference signal** | A multi-tone signal is used to reduce the number of necessary measurements.

c. **Swept-frequency signal** | A series of measurements are performed similar to a network analyzer to determine the response of the filter over a frequency range.

In our works, we have used swept frequency signal technique in network analyzer to take more accurate results .

iv. TUNING ALGORITHM FOR TUNABLE FILTERS

a. **Look-up table** | In frequency domain, the filter is pre-characterized and the tuning states are pre configured into the memory of the controller or derived for operator to drive the circuit defined frequency in.

b. **Optimization** | A goal function is established and an iterative algorithm employed to find optimal tuning voltages to minimize the value of the objective function.

c. **Parameter extraction and space mapping** | It is similar to optimization but the optimization is used to extract the model parameters and the correction is applied based on the extracted model. In this method, coupling matrix derived from s parameters, be calculated to determine which elements of the coupling matrix need to be adjusted

d. **Fuzzy logic** | fuzzy control algorithm is applied using a combination of tuning techniques defined using fuzzy methods. Since there are many interrelated variables in a filter tuning problem, deterministic models are difficult to define. However tuning element will affect the resonator frequency, coupling and cross couplings. It creates a tuning algorithm from expressions.

e. **Sequential techniques** | Sequential techniques include time domain tuning and group delay method

v. OPEN LOOP AND CLOSED LOOP APPROCHMENT

In traditional tunable filter, after the filter has tuned the desired position, it is difficult to observe and measurement results. They are controlled same control signals after production, and initial values are accepted always right. It shows open loop modality. However, tuning errors including hysteresis especially for YIG filters, non-linearity, frequency drift over temperature, and aging of the components can not be compensated. In order to correct these errors, closed loop systems are used. This loop utilizes the transmitter carrier as a reference signal and uses its reflection phase change from the notch filter to tune the notch filter frequency. Since the notch filter S_{21} presents a 180 phase jump at its notch, we need to use the phase information of the S_{11} reflected reference signal from the filter. Because of S_{11} reflection phase behavior versus frequency is continuous and magnitude is very high. Designed closed loop archtitecture and implemantations will be mentioned another papers.

Our motivation is in this paper, in order to optimize open loop designed tunable filters which are not working same operating frequecy band and different topologies, look up table is developed and optimization software methods are used.

vi. IMPLEMENTATION OF DEVELOPING LOOK-UP TABLE METHOD

VHF narrowband tunable filter was designed by ASELSAN [6], for receviers to eleminate unwanted signals, with varactor diodes. Due to aging of component (internal resistance and leakage inductance) and using different temperatures, filter response can be changed or shifted. To compansate these affects, regularly calibration table must be developed and must be used by top level controller or operator. And thus, we can reach more accurate results to control of filter response.

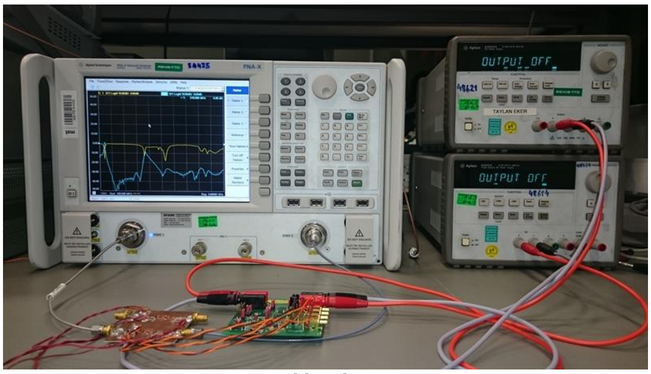


Fig.4 Tunable Filter Measurement Setup

Direct RF Tunable filter measurement setup with swept frequency signal method has showed in figure 4.

YIG devices is excellent for military applications because of their low loss, wideband tuning, and excellent linearity. However to compansate hystersis affect, our work was done with open loop methodology. DAC should be used for stable voltage variation to drive filters. Both external DAC can be used as well as integral drivers (YIG filters) also used. In addition, degradation of driver circuit causes response of filter dramatically. YIG doped with Gallium material is tuning sensitivity is nearly 20 MHz/mA. It means, if the driver circuit current changes 1 mA at related bias, filter response will shift 20 MHz. Thus, Calibration table will compansate these errors.

Calibration table was built for 2-18 Teledyne YIG filter, and its software was developed in Visual Studio .NET platform. In control interface showed in figure 5, power sources and PNA connection can be made both manuel and automatically also integral filter driver can be controlled with viperboard.

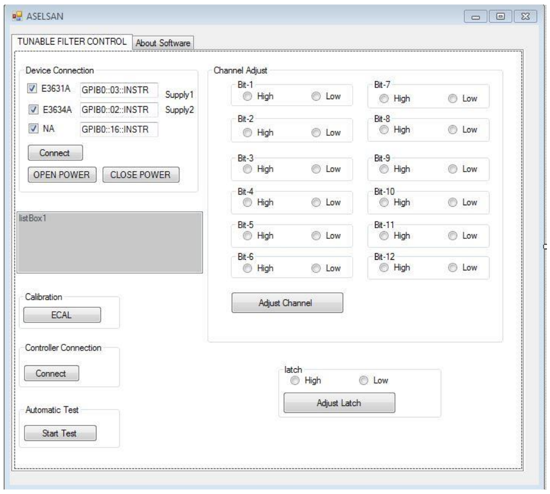


Fig.5 YIG Fılter Control Interface

Measaurement was taken for 12 bit TTL input compatible with latch, it means 4096 steps. For every step, with 3.9 MHz resolution, filter response which S21,S11, 3 dB Bandwith and center frequency have recorded with respect to digital bias. In addition, rejection level from 3 dB Bandwith and Off Resonance Spurious (ORS) can be measured at all steps. If the spurious signals upper than 4 dB, and 3 dB Bandwith bigger than 50 MHz , technican will be warned.

YIG FILTER CALIBRATION TABLE (NOW)								
Digital (Decimal)	Center Frequency (MHz)	S21 Amp (dB)	3 dB Bandwith(MHz)	3 dB AMP(dB)	S11 Amp (dB)	LHS ORS(OFF RESONANCE SPURIOUS)	RHS RESONANCE SPURIOUS)	Rejection Level
0	9987.07	-6.10	106.44	-6.30	-6.28941536	-0.487474501	-0.439345598	-5.81
1	14027.09	-10.27	56.73864	-8.736311	-8.75380802	-0.427474588	-0.655431271	-8.31
2	16050.25	-33.33	14.61136	-7.9924655	-7.80351114	-0.430952281	-0.76388365	-7.56
3	13049.99	-67.83	6.822012	-1.1332394	-0.97882533	-0.431123734	-0.53674984	-0.70
4	13573.68	-12.20	44.06175	-3.8774383	-3.89646101	-0.435154408	-0.65518111	-3.44
5	13276.13	-14.08	36.64803	-10.986748	-11.0295887	-0.434578389	-0.571862221	-10.55
6	11400.00	-67.50	6.830757	-2.2830682	-2.2250998	-0.425068349	-0.428984523	-1.86
7	11369.55	-5.44	156.6281	-5.2301602	-5.64799166	-0.424660742	-0.428372622	-4.81

YIG FILTER CALIBRATION TABLE (BEFORE)									
Center Frequency (MHz)	S21 Amp (dB)	3 dB Bandwith(MHz)	3 dB AMP(dB)	S11 Amp (dB)	LHS ORS(OFF RESONANCE SPURIOUS)	RHS RESONANCE SPURIOUS)	Rejection Level	HYSTERESIS	LINEARITY CALCULATIC
9987.07	-6.10	106.44	-6.30	-6.28941536	-0.487474501	-0.439345598	-5.81	0.00	PASS
14027.09	-10.27	56.73864	-8.736310959	-8.753808022	-0.427474588	-0.655431271	-8.31	-4038.09	PASS
16050.25	-33.33	14.61136	-7.992465496	-7.803511143	-0.430952281	-0.76388365	-7.56	-6061.25	FAIL
13049.99	-67.83	6.822012	-1.133239388	-0.978825331	-0.431123734	-0.53674984	-0.70	0.00	FAIL
13573.68	-12.20	44.06175	-3.877438307	-3.89646101	-0.435154408	-0.65518111	-3.44	0.00	PASS
13276.13	-14.08	36.64803	-10.98674774	-11.0295887	-0.434578389	-0.571862221	-10.55	0.00	PASS
11400.00	-67.50	6.830757	-2.28306818	-2.225099802	-0.425068349	-0.428984523	-1.86	0.00	PASS
11369.55	-5.44	156.6281	-5.230160236	-5.647991657	-0.424660742	-0.428372622	-4.81	0.00	PASS

Fig.6 YIG Fılter Calibration Table

On the other hand, previously measured values and current measured values can be stored in a same data file. Also software can calculate hysteresis value at center freqeuncy of filter with using measure data taken before. Thus, altering notch filter center frequency can be determined with 3.90 MHz resolution and sending digital datas should be updated with respect to calibration table. In order to observe linearization of notch filter response, center frequencies for each digital bias has analized with one after step, and the this limit determined 3.95.

$$Linearity = \frac{F2 - F1}{3.95}$$

Figure 7 YIG 2-18 Notch Filter

-YIG filter measurement setup has developed in figure 7 and tuning speed of YIG is accepted nearly 10 milliseconds with respect to measurement.

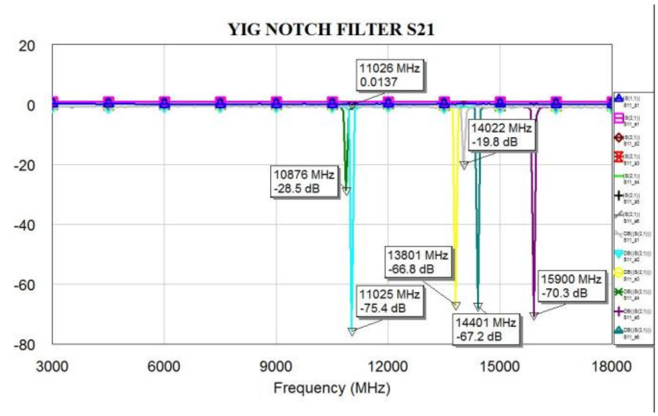


Figure 8 YIG 2-18 Notch Filter S21

RF performance of YIG filter has derived with different digital biases. Every characteristic specifications were measured and recorded in table.

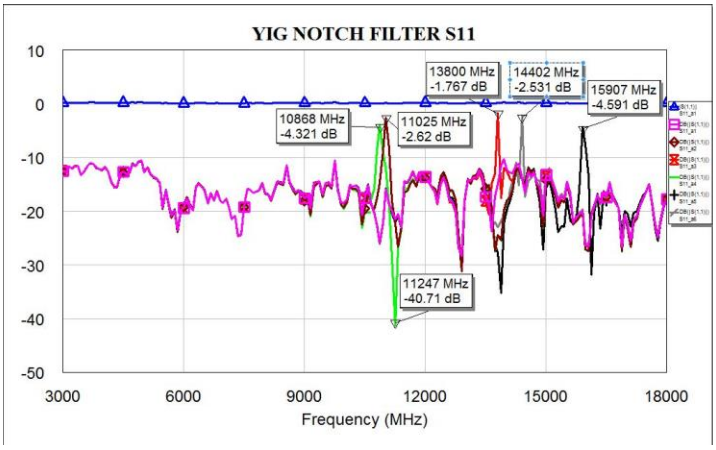


Figure 9 YIG 2-18 Notch Filter S21

vii. RESULT AND CONCLUSION

Significance of digital tunable RF filters for receivers have been mentioned and their designed techonologies have been compared detailed. Also narrowband tunable filters emphasised to derive signal without noise.

Open Loop and Closed Loop control methods have contrasted each other and mentioned that tuning errors can be tolerated via software algorithms. Application has done with YIG tunable notch filter and RF specifications of filter response have recorded on calibration table for every digital biases. Via developing calibration sofware, previous and current measurements can be analyzed and derived hysteresis and linearity of tunable filter.

As a result; when closed loop technologies are not used or prefered, open loop tunable filter performance can be optimized via calibration software .

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