Tunable Ferroelectric Filters for Software Defined Tactical Radios

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ABSTRACT: Tunable filters are critical size, weight, power, and cost (SWAP-C) enabling components for military radios: Joint Tactical Radios (JTRS), Weapons Data Link (WDL), Tactical Target Networking Technology (TTNT), and cognitive radios. The ability to tune (center frequency, bandwidth) and reconfigure (bandpass, notch) filters dynamically in the system allows agile communications. In this paper we will present experimental results on tunable radio frequency (RF) filters using low loss thin film high dielectric constant Barium Strontium Titanate (BST) ceramics. The circuit design, simulation, and experimental results on 2-pole and 3-pole lumped circuit filters will be presented from VHF to L-band frequency ranges. Results will be shown on three tunable filters: 137-225 MHz, 450-750 MHz, and 1500-2000 MHz. These filters met all the critical performance specifications such as insertion loss < 3 dB, return loss < -15 dB, frequency tunability of 1.7:1, and input intercept point of +35 dBm for an operating bias voltage of 0-10V DC. These filters also exhibited the following features compared to PIN diode switched capacitor filters: Parts count reduction: 3X, Area Reduction: 4X, Power Reduction: > 10X, and Assembly/Tuning Labor Reduction: >>10X.

Key words: Ferroelectric, Tunable Filters, Software Defined Radio

1. INTRODUCTION

Wideband Software Defined Radios (SDRs) need a lower Size, Weight, and Power tunable filter technology and frequency channelizers to meet needs of mobile communication and sensors. This is essential for the SDR operating in a battery powered environment such as JTRS Cluster 5. Software controlled tunable filters promise to replace the number of fixed ones by a factor of 4. Miniaturized tunable filters capable of multifunction operations, leveraging across multiple programs such as different JTRS clusters enable substantial manufacturing and test economies. Integrated filter set solutions will enable *cost* (<1/5) and *size* (<1/10) reductions over conventional designs in programs such as Satcom-On-The –Move (SOTM), Weapons Data Link Architecture (WDLA), and JTRS. Tunable filters will enable new generation of systems that are adaptable and effective against dynamic signatures and rapidly changing threats.

In an earlier paper [1], we reported a highly tunable radio frequency filter using bulk ferroelectric materials. These filters exhibited 2:1 tunability of center frequency by using bulk BST ferroelectric ceramics obtained from Rockwell Scientific Company (RSC).

2. FERROELECTRIC MATERIALS

High breakdown voltage of ferroelectric BST material allows high intercept point (IP3) tunable filters with *increased* system dynamic range. Insulating properties of BST also reduce system power drain. Even though the useful operation of this material takes place in the paraelectric domain, the more prevalent ferroelectric term will be used in the rest of this paper. Our earlier work [1] used thinned bulk BST substrates from RSC which exhibited an impressive capacitance tunability of 5:1 @ <200 Volts DC, and 3:1tunability and @ < 50 Volts DC. These capacitors had a capacitance density of 800 pF/mm^2, but their temperature performance was poor. Since JTRS radios demanded more stringent temperature performance, and the desired operating voltage for these radios was < 30 Volts DC, we decided to use BST thin film tunable capacitors from Agile Materials and Technologies, Inc. These capacitors showed a 3:1 tunability @ 0-10 Volts DC, and a respectable Q > 100 @ 100 MHz, and Q > 60 @ 1.5 GHz as shown in Figure 1, which is an Agilent E4991A RF Impedance Analyzer plot of capacitance C, quality factor Q, and R_S (series resistance of the capacitor) vs. frequency. These capacitors exhibit high capacitance density (10-20 nF/mm^2), and the stacked 11X11 capacitor array spreads voltage and current evenly over multiple devices so that each capacitor sees less power, a desirable characteristics for low intermodulation.

3. TUNABLE FILTER DESIGN

The filter design is based on the direct coupled min-loss topology. The circuit consists of resonators coupled by an inductive inverter: 2 parallel LC resonators coupled by

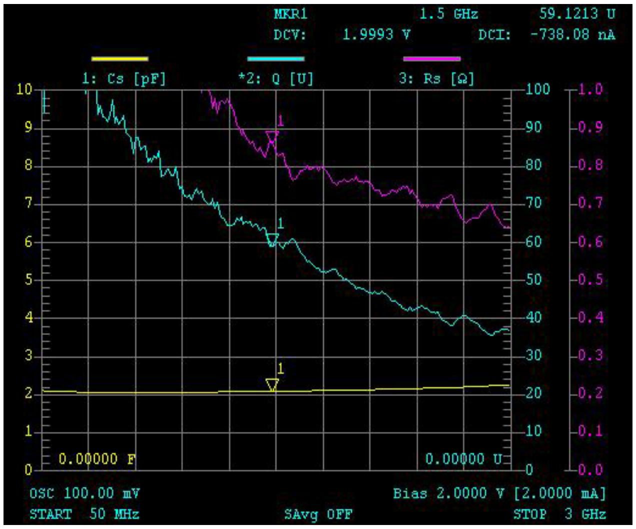

Figure 1. – Measured results of C, Q, and R_s of ferroelectric BST thin film capacitors using an Agilent E4991A RF Impedance Analyzer

inductor for a 2-pole design, and 3 parallel LC resonators coupled by 2 inductors for a 3-pole design. Prototype component values were replaced with the actual measured S-parameter data for ferroelectric capacitors and S-parameter data for Coilcraft inductors and used in Agilent ADS (Advanced Design Systems) circuit simulation. Due to specific requirements for the filters for each of the frequency ranges, different coupling coefficients were chosen as well as input/output matching circuits. The final design is an optimum compromise between insertion loss, 3dB bandwidth and stopband attenuation.

4. EXPERIMENTAL RESULTS

The filters were fabricated on Rogers RO4003 printed circuit boards, Figure 2. The DC bias on the tunable ferroelectric capacitors was varied from 0 to 12 V. An Agilent HP8753D Vector Network Analyzer (VNA) was used to measure the filter response. The insertion and return loss measurements on two extreme points are shown in figures 3 and 4 for the frequency range 120-205 MHz, and 490-790 MHz respectively. The CITIFILES obtained from the VNA measured data were imported to ADS and plotted as a composite response for different bias voltages. Figures 5 and 6 show the results for the lowest (30-50 MHz) and the highest frequency bands (1500-2000 MHz). Table I gives a summary of the measured insertion loss and return loss as well as intermodulation measurements. The filters have shown an IIP3 (Input Third Order Intercept Point) as high as + 47 dBm, measurement limited by the test setup IP3. We tested some of the filters over a temperature range of- 40°C to +125°C. The observed frequency shift and change in loss were < 10%.

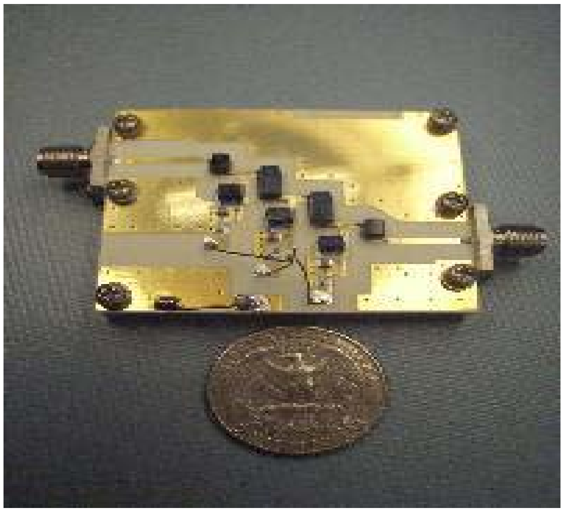

Figure 2. – Picture of a 3-pole tunable filter on test board

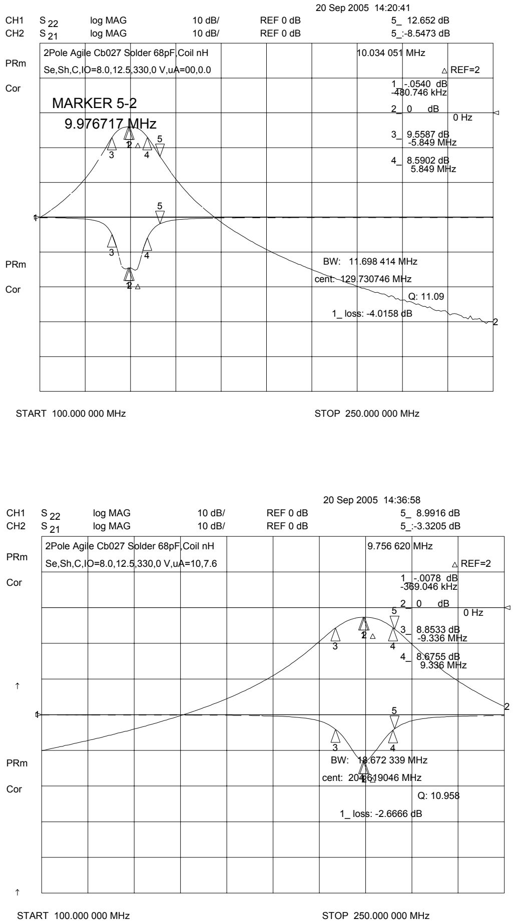

Figure 3. – Vector Network Analyzer (VNA) measured response of a tunable filter operating from 120-205 MHz

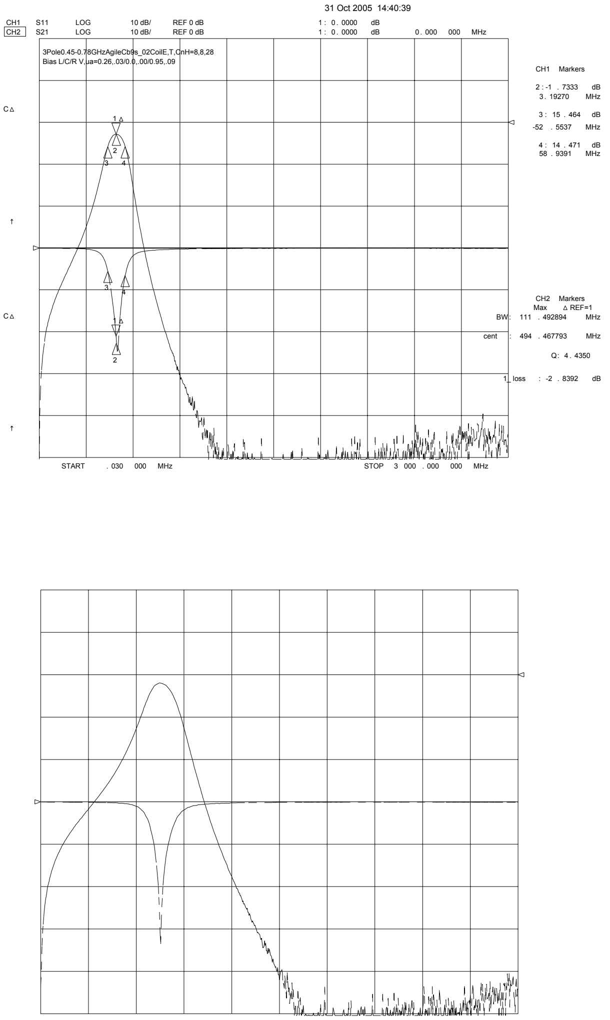

Figure 4– VNA measured response of a tunable filter operating from 490-790 MHz

5. CONCLUSION

Our first prototype tunable ferroelectric filters showed around 3.5 dB of insertion loss against the simulated 2.5 dB of loss with commercially available components including Agile Materials 3: 1 tunable capacitors. The extra losses have been traced to the bond wires for tunable capacitors and lower unloaded Q at low DC voltages. With a new layout incorporating solder bumps instead of bond wires, the loss is projected to be < 3 dB across the bands. We have also implemented an open loop temperature controller to correct for change in filter characteristics over temperature. Table II provides a comparative study of published results over last few years, and we conclude that the results of our work show the best tunability, the lowest loss, and the highest input intercept point to date.

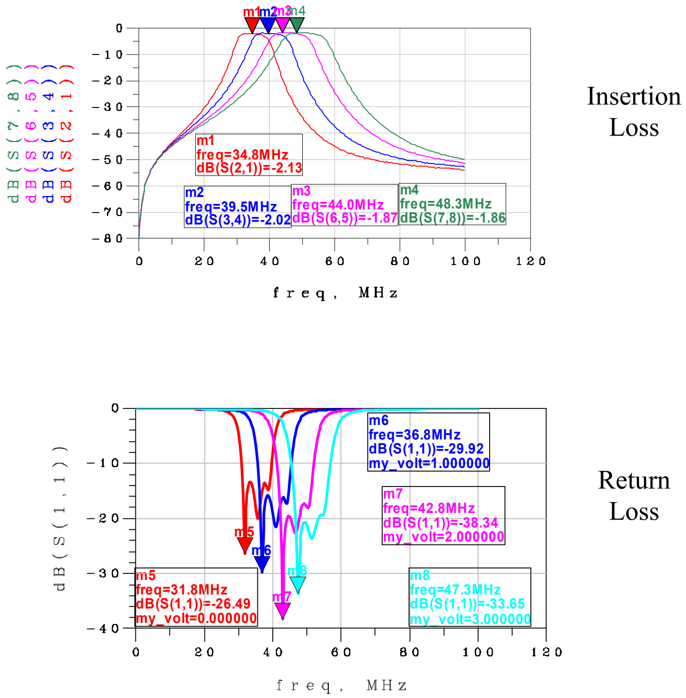

Figure 5 – Composite measured response of a tunable filter operating from 30-50 MHz

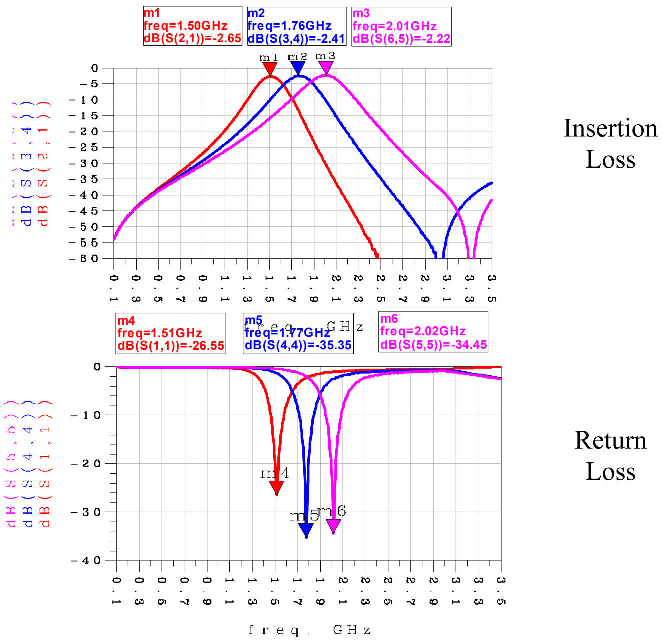

Figure 6 – Composite measured response of a tunable filter operating from 1500-2000 MHz

Vector Network Analyzer Measurements			
Bias Voltage/Current Vdc/µA	Center Frequency MHz	Insertion Loss dB	Return Loss dB
10.00/1.58	**191**	3.16	24
0.69/.001	**117.3**	3.53	22
10.6/1.68	**793.9**	1.7	26
0.95/0.001	**494**	2.9	22
12.3/.63	**2000**	2.2	25
1.90/.001	**1394**	2.87	37

Intermodulation (IMD) Measurements		
	IIP3	IIP3
IMD3	UUT	System
-dBc	dBm	dBm
72.6	46.3	57
41	30.5	57
91	39.5	>40
84	36	>40
85	36.5	>40
83	35.5	>40

Table I. Summary of measured results

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Table II. Comparison of published results

Company Institution	**Frequency MHz**	**Tunability %**	**Voltage Volts**	**Insertion Loss, dB**	**IIP3 dBm**	**Material**
Chalmers Institute of Technology (2002)[2]	550	8	0-500	4-6	N/A	Bulk BST
University of Michigan and North Carolina State University (2005)[3]	176-276	57	0-6	3-5	19	Thin Film BST
North Carolina State University (2005)[4]	1600-2000	25	0-200	4.3	N/A	Alumina Substrate
University of Leeds University of Cambridge (2005)[5]	1500	0.24	100	4.5	37	Bulk BST
Paratek Microwave (2003)[6]	1710-1980	17	N/A	4.5	N/A	Thin Film BST in LTCC
Paratek Microwave (2005)[7]	225-960 1350-2500	54	0-100	5.5	34	Thin Film BST
Rockwell Collins (This work)	490-790	**68**	0-10	**1.7**-2.9	**47**	Thin Film BST (Agile Materials)