A Ferroelectric Tunable Combline Filter With Improved Stopband Transitions

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***Abstract*— In this work the design of a microstrip line based frequency agile bandpass filter with improved selectivity is presented. The original combline bandpass performance is improved, by a transmission zero which is inserted in the lower stopband, resulting in steeper stopband transitions. The frequency agile behavior is obtained by using ferroelectric thin-film varactors as tuning elements at the resonator ends. The implemented prototype filter can be tuned continuously in the frequency region from 1.8 GHz to 2.1 GHz exhibiting a worst case insertion loss of less than 3 dB and passband return loss better than 20 dB at all operating bias states. Excellent agreement between simulation and measurement results is obtained for the proposed topology at all tuning states. An output referred 3^{rd} order intercept point of 36.5 dBm was measured by a two tone setup.**

***Index Terms*— Ferroelectric capacitors, bandpass filters, tunable filters.**

I. INTRODUCTION

Today's mobile communication is clearly moving towards an increased number of standards and additional services, which are spread over an expanding wide frequency range. This trend causes an increased complexity for modern mobile radio front-ends and thus calls for reconfigurable and new architectures with a reduced number of subsystems. One attractive possibility is the introduction of frequency agile and tunable subsystems, such as filters, in order to serve as multi band solutions. Ferroelectric materials have been used extensively for tuning purposes. Among the possible ferroelectric materials for such applications, Barium-Strontium-Titanate (BST) is probably the most suitable candidate due to its high permittivity and well known RF performance. Tunable passive components based on BST, like ferroelectric varactors, have introduced a whole new group of tunable subsystems, e.g., filters [1], and matching networks [2]. In this paper, a frequency agile bandpass filter design is presented with improved stopband transitions. The tuning operation is achieved by using BST varactors as loading elements for the filter resonators. The electrical behavior of those varactors is discussed in section II. The proposed combline bandpass filter topology and its modifications are presented in section III. Finally, the implemented prototype filter and the experimental results are discussed in section IV.

II. FERROELECTRIC THIN-FILM VARACTORS

Ferroelectric BST varactors are typically processed either as a metal-insulator-metal (MIM) parallel plate structure or as planar interdigital capacitors (IDC) [3]. For the parallel plate capacitor, the ferroelectric film is located between two metal electrodes forming a layered structure. An electrical field is created within the dielectric film by applying a bias voltage on the capacitor electrodes. This field is straight forward related to the bias voltage and alters the permittivity ε_r of the BST-film. The overall varactor performance can be described accurately by equivalent models [4]. Since the bias voltage and the RF signal are applied on the same pads, a superposition of both voltages takes place.

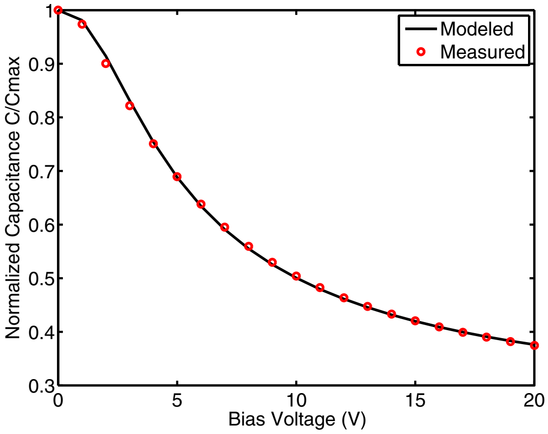

Fig. 1. A comparison between measured and modeled capacitance of BST varactor for different bias voltages.

The voltage dependence of a BST varactor with a zero bias capacitance of 5 pF is depicted in Fig. 1. The measurements were taken with an Agilent E4991A RF-impedance analyzer after the appropriate SOL (Short Open Load) calibration. Due to the high permittivity of the ferroelectric material it is possible to implement reasonable high capacitance values at small dimensions. The capacitance C as well as the varactor quality factor Q have been extracted from the measured input admittance Y according to (1) and

(2), respectively. In the frequency region of interest quality factor values $Q\approx 40$ have been measured.

$$C = \frac{Im\{Y\}}{2\pi f} \qquad (1)$$

$$Q = \frac{Im\{Y\}}{Re\{Y\}} \qquad (2)$$

The tunability, which is defined as $(\varepsilon_{rmax} - \varepsilon_{rmin})/\varepsilon_{rmax}$ exceeds 60 % at a bias voltage range up to 20 V.

III. BANDPASS FILTER DESIGN

Among the possible topologies for relatively narrow band distributed bandpass filters the combline type filter [5] is probably the most popular one. The operating principle relies on loading coupled transmission line resonators with capacitive elements and thus reducing the electrical length of the line. The actual combline filter exhibits attenuation poles at ω_1=0 and ω_2=$\omega_0\lambda_0/(4l)$, where ω_0 is the passband center frequency, λ_0 the wavelength at this point, and l the total resonator length. The asymmetric pole allocation leads to a slow pass- to stopband transition in the lower stopband and a broad upper stopband. Since the topology implies inherently capacitive elements it became attractive to use tunable varactors for altering the resonance behavior. Changing the capacitance value of the resonator load results in shifting the effective electrical length and thus the resonance frequency.

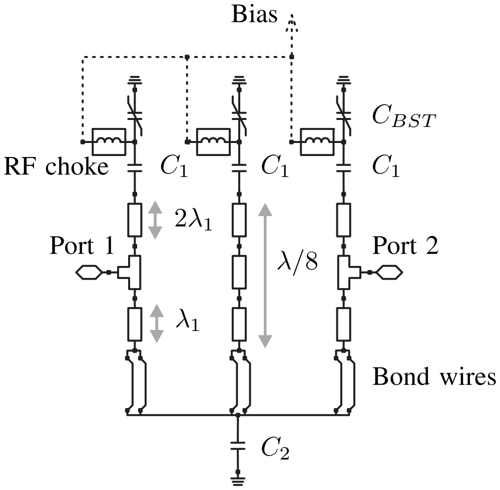

Fig. 2. Tunable bandpass filter.

The proposed tunable combline bandpass filter is presented in Fig. 2. It consists of three coupled microstrip resonator branches with tapped input and output ports and can be designed analytically according to [6]. By using the BST varactors at the resonator ends a continuous tuning of the passband center frequency is achieved. Additional lumped components such as RF choke inductors are used to establish the proper biasing conditions. The cascaded combination of C_1 and C_{BST} represent the tunable capacitive load for the resonator branches.

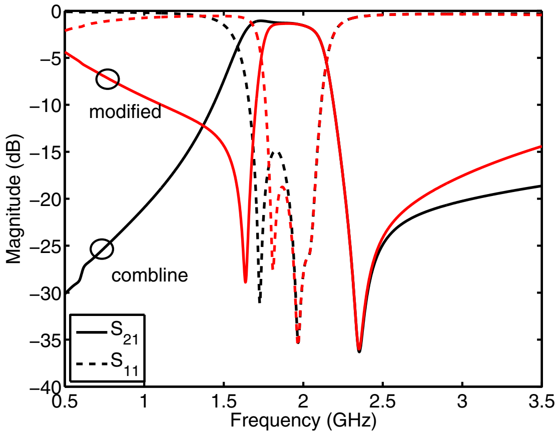

Fig. 3. Comparison between original combline topology and the proposed modified filter.

In order to establish symmetric transitions to both stopband regions an attenuation pole is inserted, through the capacitor C_2, in the lower stopband. This principle is reported in [7]. The transition from the lower resonator end to the common capacitor pad is realized via gold bond wires. As opposed to a layout with metal traces connecting to C_2, this topology retains the coupling between the resonator branches. The skirt steepness in the lower stopband is improved thus higher selectivity is established in this frequency region, as depicted in Fig. 3. Sharper stopband transitions are preferred since several communication bands are located in the targeted operating frequency region.

IV. PROTOTYPE IMPLEMENTATION AND MEASUREMENT RESULTS

A prototype of the proposed combline filter was fabricated on a Rogers RO4003C substrate with height h=0.2 mm and dielectric constant ε_r=3.38. The circuit trace is depicted in Fig. 4.

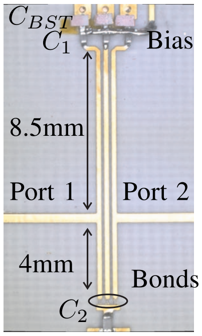

Fig. 4. Fabricated prototype board of the proposed tunable combline filter.

The microstrip resonators have a width of w=0.25 mm and the spacing between them is s=0.15 mm. All BST varactors have a zero bias capacitance of $C_{BST_{0V}}$=5 pF and were assembled in a flip-chip procedure in order to minimize the interconnection parasitics. Together with the fixed capacitors C_1=1 pF they form the variable capacitive load for the resonators. As previously discussed, an additional attenuation pole is introduced in the lower stopband through the capacitor C_2. In this case, a fixed SMD type capacitor with C_2=12 pF is used.

A. Linear Characterization

All designs and simulations have been carried out with Agilent's ADS 2008 and Momentum tools. The prototype was characterized through scattering parameter measurements which where taken with a Rohde & Schwarz ZVB8 vector network analyzer.

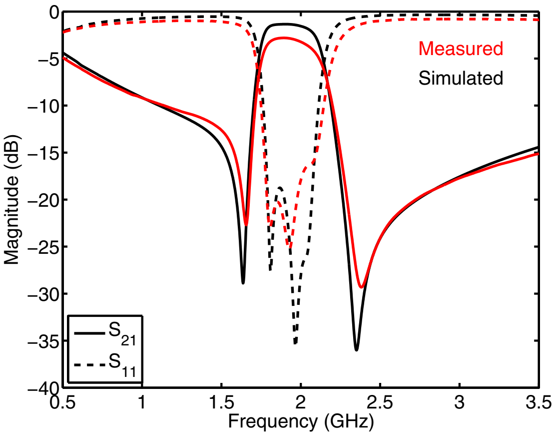

Fig. 5. Measured and simulated performance for the implemented prototype filter at zero bias.

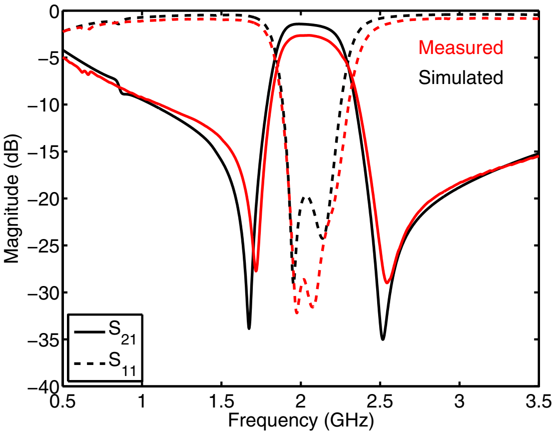

Fig. 6. Measured and simulated performance for the implemented prototype filter at bias voltage U_{bias}=15 V.

As presented in Figs. 5 and 6, excellent agreement is obtained between the simulated and measured performance for different bias states. The simulated data refer to the results of the Momentum EM co-simulation with the models from [4]. Minor deviations are due to varactor value imbalances and mismatches. The passband region of the filter can be tuned continuously from 1.8 GHz to 2.1 GHz with a worst case insertion loss of less than 3 dB while exhibiting return loss of more than 20 dB at all bias conditions. The slightly different performance in terms of transmission and return losses are due to the varying quality factors Q of the varactors. Each bias voltage results in a center passband frequency f_0, insertion- (IL), and return loss (RL), respectively. The filter performance at different bias states is summarized in Table I.

TABLE I
FILTER PERFORMANCE

Bias (V)	f_0 (GHz)	IL (dB)	RL (dB)
0	1.85	2.8	20
5	1.90	2.7	22
10	1.97	2.6	26
15	2.02	2.6	28

Furthermore, it should be noted that the attenuation pole in the upper stopband is clearly shifted when the bias is changed. The allocation of the inserted attenuation pole in the lower stopband remains almost constant, since it is determined by the fixed value capacitor C_2. As a consequence, the bandwidth of the passband region is slightly altered. Compensation of this effect could be implemented by using a variable capacitance at this point. A second tuning element would be inserted at the expense of higher circuit complexity. Nevertheless, a tunable filter bandwidth would result which is an attractive feature for reconfigurable front-end systems.

B. Nonlinear Performance

As discussed in Section II, the ferroelectric varactors are inherently nonlinear thus the nonlinear performance of the implemented circuit has to be investigated. A typical two tone setup used for such measurements is depicted in Fig. 7. A comparison between output power and corresponding intermodulation product power levels can be used for estimating the nonlinear effects of the circuit.

Two RF signal sources are used to produce the sinusoidal tones with individual frequencies f_1 and f_2. Their output is lowpass filtered in order to cut off the spurious harmonic parts and then amplified by highly linear power amplifiers (PA). By connecting two isolators right after the PA modules a reverse intermodulation is avoided. The hybrid coupler is used to combine coherently the two narrow spaced tones and feed them to the DUT's input port. The attenuation between the power amplifier modules and the DUT is corrected thus the absolute power level P_{in}

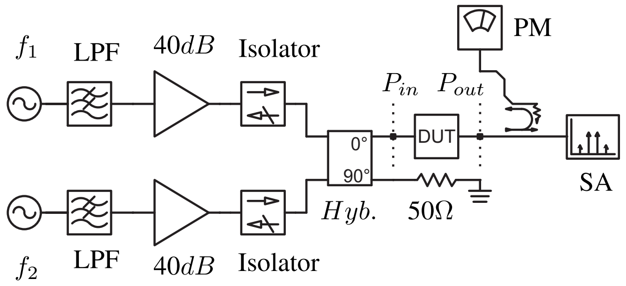

Fig. 7. Schematic of two tone measurement setup.

is presented at the input port of the DUT. The output port is connected through a coupler to a power meter (PM) and a spectrum analyzer (SA) to capture the corrected output power and the intermodulation product levels, respectively.

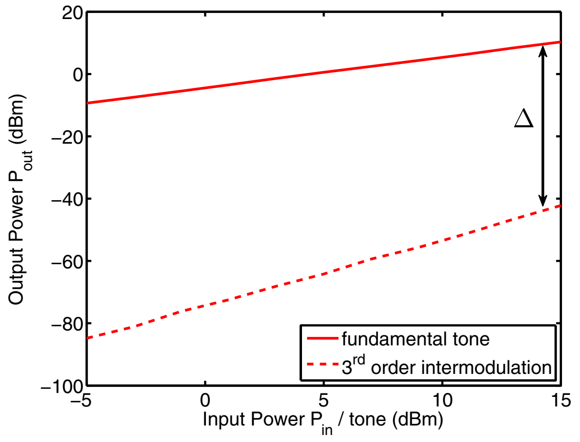

Fig. 8. Measured output power levels of fundamental tone and 3^{rd} order intermodulation products for a two tone setup with f_1=1948 MHz and f_2=1952 MHz.

The output power at one fundamental tone as well as the power of the third order intermodulation products is displayed in Fig. 8. The applied bias voltage was 5 V and no significant nonlinear effects are noticed when the power of each input tone is swept over a range of 20 dB. For the maximum applied input power level of 15 dBm per tone, the output referred third order intercept point (OIP_3) is calculated as

$$OIP_3 = P_{out} + \frac{\Delta}{2} = 36.5\,\text{dBm}. \tag{3}$$

In (3), P_{out} and Δ are the output power and the level difference between fundamental tone and intermodulation product, respectively. Further improvement of the linearity is expected when using cascaded topology for the varactors [8], since the RF voltage swing across each element would be reduced. This reduced voltage swing would cause a smaller capacitance variation and thus reduced intermodulation products at the output. For ferroelectric thin-film varactors this is an attractive solution since their high capacitance density allows for implementation of large capacitance values at compact dimensions. Thus the penalty in terms of overall assembly dimensions is held considerably small.

V. CONCLUSION

A frequency agile combline filter with improved stopband transitions is presented based on ferroelectric thin-film varactors. The operating principle relies on the well known combline topology and is modified by inserting a capacitive termination at the common resonator ground plane. Thus, an attenuation pole is inserted in the lower stopband improving the selectivity of the filter. The proposed design is scalable for different operating frequencies and verified by a prototype. The implemented combline filter can be tuned continuously from 1.8 GHz to 2.1 GHz with a worst case insertion loss less than 3 dB and return loss better than 20 dB within the passband at all bias conditions. The linearity performance of the filter is demonstrated with a two tone measurement setup. Such frequency agile microwave subsystems could serve as multi band solutions in future reconfigurable front-end architectures and thus reduce the number of functional blocks and overall complexity.

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