A VHF Tunable Lumped-Element Filter with Mixed Electric-Magnetic Couplings

Kaiyuan Zeng, Dimitra Psychogiou and Dimitrios Peroulis
School of Electrical and Computer Engineering, Birck Nanotechnology Center
Purdue University, West Lafayette, Indiana, USA

***Abstract*— A lumped-element varactor-tuned bandpass filter (BPF) with variable center frequency and constant absolute bandwidth (BW) is presented in this paper. Mixed electric/magnetic inter-resonator coupling schemes─implemented with parallel LC resonators─facilitate the actualization of an almost constant BW passband over a wide frequency tuning range (1.6:1). The linearity performance of the varactor-tuned BPF is studied and an investigation to reduce the RF swing on the filters' tuning elements is presented. A third-order lumped-element BPF was designed, built and measured. It exhibited a tunable center frequency between 230-370 MHz with constant 3-dB bandwidth of 56.3±0.2 MHz across the entire frequency band. Within this band, the insertion loss was measured between 0.9-1.4 dB and the third-order intermodulation intercept point (IIP3) was measured between 28.1-41.4 dBm.**

Keywords- Bandpass filter; constant bandwidth; lumped-element filter; tunable filter; tunable frequency; varactor.

I. INTRODUCTION

Tunable bandpass filters (BPFs) have attracted considerable attention due to their applicability in multiband communication systems. They are used to enable adaptive preselection of the desired frequency band and rejection of the unwanted interference. Furthermore, they occupy a significantly reduced volume when compared to conventional filter-banks [1]-[3]. One fundamental application of these filters is the selection of constant bandwidth channels that are widely separated in the frequency radio spectrum. In this scenario, BPFs with tunable center frequency, constant bandwidth, low loss and small physical size are highly desirable and in particular for frequencies at the lower part of the microwave spectrum (UHF-VHF band) due to the large number of existing RF applications.

Alternative filter tuning concepts have been reported in the open technical literature to-date including PIN-diode switches, RF-MEMS and varactors diodes [1]-[8]. Among them, center frequency tuning by means of tunable varactors in the resonant elements is the most widely tuning scheme due to its advantages of low-power consumption, tuning speed and broad tuning [4]-[8]. However, the employment of varactors results in intermodulation distortion which is attributed to their non-linear behavior. This is mostly expressed in terms of the third-order intermodulation intercept point (IIP3) which is typically between 6-26 dBm for single-end varactor-tuned filters [5]-[7]. Linearity improvement techniques such as the one reported in [8]─static capacitor in series to the tunable varactor reduces the RF voltage swing─results in an IIP3 of the order of 40 dBm. However, it comes to the expense of reduced tuning range. Another drawback to be mentioned is the passband bandwidth (BW) degradation when tuning the filter away from its designed frequency. This is attributed to the frequency dependence of the inter-resonator coupling elements. Filter tuning schemes in which the filter BW remains constant by means of mixed electric/magnetic coupling schemes have been addressed in [5], however their frequency can only be tuned by <50%. In yet another way, a constant BW scheme that is implemented with two variable transmission zeroes that are arranged below and above the desired passband so as to compensate for BW variations is presented in [2].

In this paper, a varactor-tuned third-order BPF with tunable frequency, constant BW and reduced intermodulation distortion is reported. The constant BW attribute is realized by means of a mixed electric/magnetic inter-resonator coupling scheme that is actualized with a parallel LC resonator. The linearity performance of the varactor-tuned BPF is studied and an investigation to reduce the RF swing on the filters' tuning elements is presented. A filter prototype with variable center frequency 230-370 MHz, constant BW of 56.3±0.2 MHz,

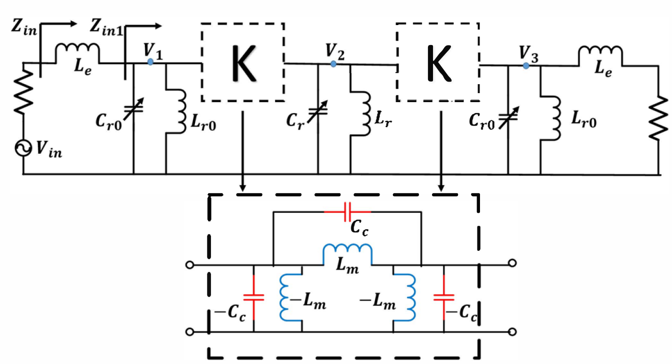

Figure 1. Circuit schematic of a third-order bandpass filter. The inter-resonator couplings K are realized with a mixed electric/ magnetic scheme that is actualized with a parallel LC (represented by Cc and Lm) resonator. The external coupling is realized by means of inductive elements (represented by Le).

insertion loss between 0.9-1.4 dB and IIP3 between 28.1-41.4 dBm was designed, built and measured as a proof-of-concept demonstration.

II. Filter Design Aspects

A. Bandwidth considerations

Fig. 1 illustrates the generic schematic circuit of a third-order BPF. It consists of three parallel LC resonators—represented by L_r, C_r—, two inter-resonator coupling elements K—commonly implemented with impedance inverters—and two external coupling elements that are realized with the series inductors L_e. As briefly described in the previous section, center frequency tuning by adjusting the capacitance of the resonator results in variable BW passbands whose magnitude is proportional to: a) the center frequency f_0 and b) the inter-resonator coupling coefficient k as described in (1). An illustrative example of this dependence is illustrated in Fig. 2. In this figure the BW variation of an octave tunable BPF (0.21-0.42 GHz) is plotted for alternative inter-resonator coupling elements: inductive impedance inverters (magnetic coupling), capacitive impedance inverters (electric coupling), mixed inverters (mixed electric/magnetic coupling, inset of Fig. 1) and tunable mixed inverters. As can be seen, the BW variation is different for each coupling scheme—33-66 MHz for an inductive inverter, 14-112 MHz for a capacitive inverter and 55-60 MHz for a mixed inverter—due to the different frequency dependence of each coupling structure as also described in equations (2)-(3). The mixed electric/magnetic coupling—defined by coupling coefficient k_{mix} in (4)—shows the smallest BW variation due to the coupling cancellation that occurs at a frequency f_r as specified by (5). It results in a bandwidth bending trend within the frequency band of interest as shown in Fig. 2. Such a mixed coupling structure can be readily realized with a parallel LC resonator—represented by L_m, C_c in Fig. 1— and will be used for the proposed filter. It is apparent that by introducing a tunable varactor in C_c, the location of the transmission zero—location of bandwidth cancellation—can be readily controlled which in turn results in a passband with constant BW throughout the entire band.

$$BW = kf_0 \qquad (1)$$

$$k_m = L_r/L_m \qquad (2)$$

$$k_e = C_c 4\pi^2 {f_0}^2 L_r \qquad (3)$$

$$k_{mix} = \big||k_m| - |k_e|\big| \qquad (4)$$

$$f_r = 1/(2\pi\sqrt{L_m C_c}) \qquad (5)$$

B. Linearity considerations

As discussed in the previous section, the RF performance of a tunable filter might be severely degraded by the presence of intermodulation distortion when varactors are used as tuning elements. The filter linearity commonly measured by the IIP3 is highly dependent on the type of the varactors

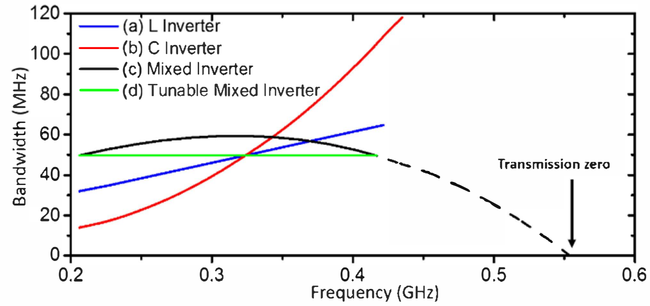

Figure 2. Filter bandwidth as a function of frequency for alternative inter-resonator coupling schemes.

(abrupt or hyper abrupt), their DC biasing point, the RF voltage swing and the number of the non-linear elements. Linearity can be improved by using the varactor at high DC biasing states due to the decrease in the C-V slope versus voltage which results in capacitances that are less sensitive to the voltage variation. However, it comes to the expense of reduced tuning range. Such an example is given in Fig. 3. In an alternative manner, linearity can be improved by reducing the RF voltage swing V_{RF} on the varactor geometry due to the capacitance dependence on V_{RF}^2 as described in (6) for a pair of varactors in a back-to-back configuration [9].

$$C = \frac{K_0}{2} + \frac{K_2}{8}\left[1 - \frac{1.5{K_1}^2}{K_0 K_2}\right]{V_{RF}}^2 + \cdots \qquad (6)$$

When building a tunable RF filter the aforementioned parameters need to be considered in order to obtain the highest IIP3 across the entire tuning range. This is achieved by optimizing the filter geometry so that the RF voltage swing across its tuning elements is as low as possible. Fig. 4 illustrates the RF voltage swing at nodes V1—same as V3—and V2 for the third-order BPF of Fig. 1 for alternative resonator inductances L_r, a center frequency tuning between 210 and 385 MHz and constant bandwidth of 55 MHz. As can be seen, the RF voltage swing reduces with the decrease of L_r and center frequency. On the other hand, reducing L_r results in a smaller L_e selection to match the circuits across the whole tuning range. However, this becomes not possible when L_r is too small (50 Ohm cannot be achieved with a single value of L_e), as illustrated in Fig. 5, and the filter will have large input reflection. Based on the aforementioned trade-offs, for a high

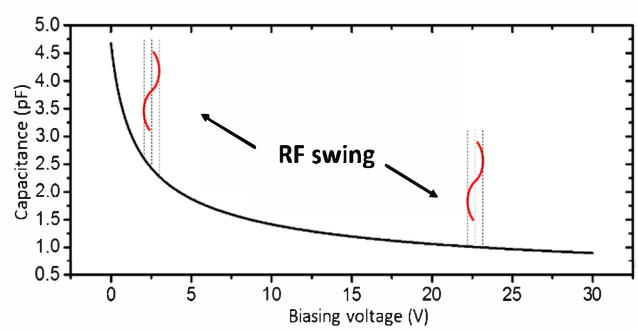

Figure 3. C-V curve of a PIN-varactor with n=0.5

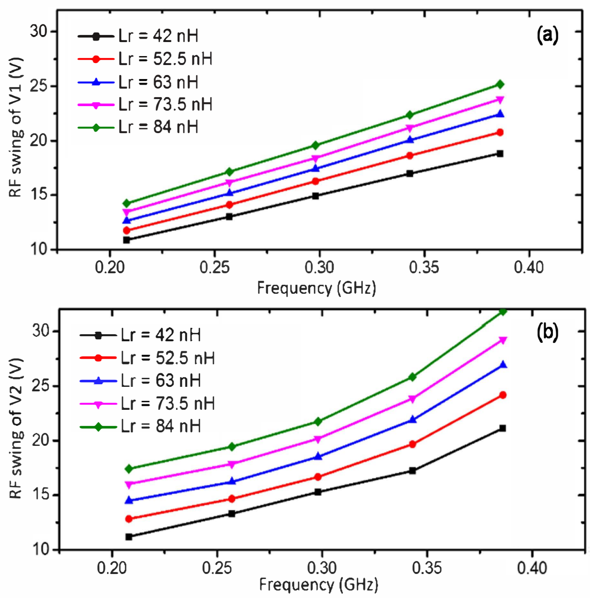

Figure 4. RF swing on different resontor nodes of the filter architecture in Figure 1 for a 10 V AC input voltage. Note that the voltage at node V3 is the same as the voltage at node V1 for various levels of L_r. Furthermore, the indicated RF swing corresponds to tunable BPF responses that cover the same tuning range and feature constant BW of 55 MHz.

IIP3 filter, resonators with small inductance L_r need to be considered. However, the smallest L_r that can be utilized─smallest RF swing─is limited by the desired levels of input reflection as shown in Fig. 5.

III. Experimental Validation

In order to evaluate the aforementioned study, a third-order BPF with tunable center frequency, constant BW and IIP3 above 28 dBm was designed, constructed and measured. The filter synthesis was performed using the coupled resonator design methodology in [10] and following the investigations for constant BW and reduced voltage RF swing in Section II. Fig. 6 shows the manufactured filter assembly that was built on an RT Duroid 5880 dielectric substrate (ε_r=2.2, h=1.57 mm, and Cu-cladding of 35 μm) for the experimental validation of the proposed tuning concept. Commercially available surface mounded devices (SMD) from Coilcraft Inc. (static inductors: L_r= Coilcraft 1111SQ-43N, L_{r0}= Coilcraft 1515SQ-68N, L_e= Coilcraft 1515SQ-68N, L_m= Coilcraft 2222SQ-161), Johanson Tech. (static capacitor: Johanson 251R14S0R6AV4T) and Skyworks (varactor SMV1413-079LF: n=0.5, biasing voltage 0-30V, capacitance range: 1.77-9.24 pF) were utilized. In this circuit, tunable varactors were inserted in each resonator─four parallel cascaded back-to-back varactor pairs─as well as in the inter-resonator coupling elements─two back-to-back varactor pairs in series cascaded with a static capacitor─as shown in Fig. 6. It is important to note that the aforementioned varactor arrangement schemes were intentionally used with the purpose of reducing the RF voltage swing on each varactor.

The RF performance of the filter assembly was experimentally validated in terms of S-parameters with the Agilent N5230C power network analyzer while applying a DC bias control voltage between 0.5 V and 29.5 V on the varactors. The RF measured frequency response of the filter is plotted in Fig. 7 and can be summarized as follows: center frequency tuning: 230-370 MHz, tuning ratio: 1.6:1, absolute bandwidth: 56.3±0.2 MHz, insertion loss 0.9-1.4 dB and input reflection <15 dB─not shown here─. The simulated response of this filter is also plotted in Fig. 7─evaluated with post-layout electromagnetic simulations in the Advanced Design Systems (ADS) software of Keysight Technologies─and as can be seen it is in a fairly close agreement with the one obtained by RF measurements.

The non-linear behavior of the third-order BPF was also evaluated in terms of IIP3 with the aid of harmonic balance simulations and two-tone RF measurements─RF signals separated by 100 KHz─that were performed across the entire tuning band. The measured IIP3 was found between 28.1-41.4

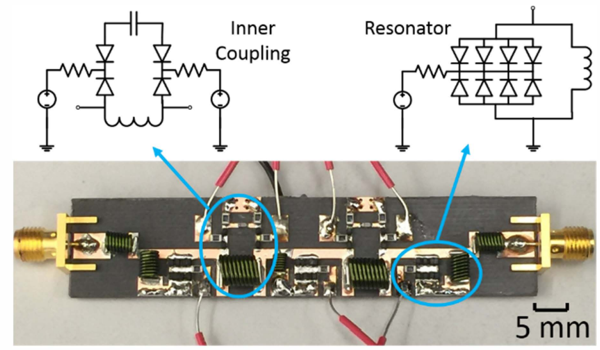

Figure 6. Manufactured prototype of the third-order lumped-element filter with variable center frequency and constant absolute bandwidth.

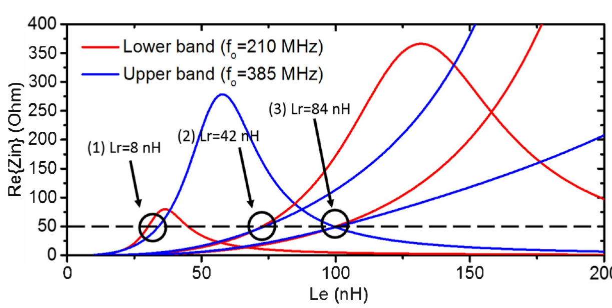

Figure 5. Input impedance of the filter architecture in Figure 1for various levels of L_r, L_e for the two extreme tuning state in which the BPF is located at 210 MHz and at 385 MHz.

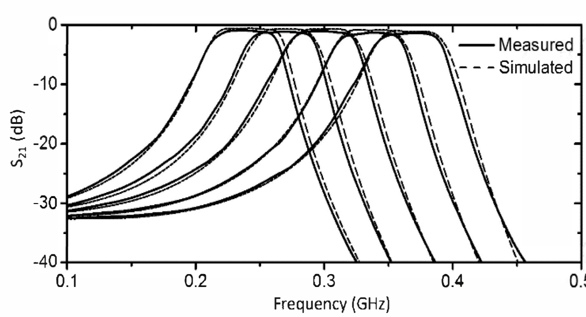

Figure 7. Transmission response of the tunable third-order bandpass filter: RF-measured and ADS simulated.

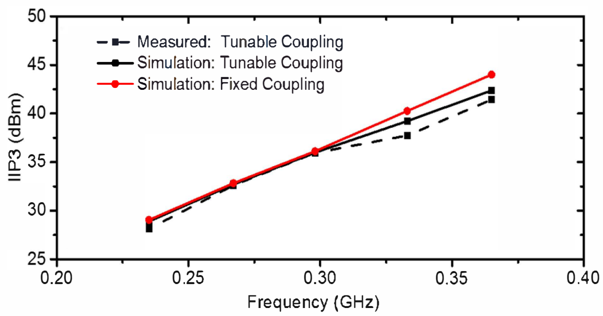

Figure 8. Measured and simulated IIP3 versus filter center frequency.

dBm and as can be seen in Fig. 8 it agrees well with the one predicted by harmonic balance simulations. At the same figure the simulated IIP3 of a third-order BPF with fixed inter-resonator coupling sections (resonant couplings in which C_c is constant) is also plotted─note that this filter architecture exhibits similar tuning range but its bandwidth variation is between 53-62 MHz (not shown here) due to the lack of tuning elements in the inter-resonator couplings─. As can be seen, the IIP3 of this topology is very close to the one obtained by the filter architecture with varactor tunable coupling sections which indicates that the impact of the varactor elements that are located in the inter-resonator coupling sections is minimal on the overall IIP3 of the filter. In TABLE I the RF performance of the third-order filter is compared with state-of-the-art tunable bandpass filter architectures. As can be seen, the filter architecture of this work exhibits the highest frequency tuning range in which constant absolute bandwidth with the smallest variance is achieved. Furthermore, the measured IIP3 is always above 28 dBm.

IV. CONCLUSION

In this paper a third-order bandpass filter with tunable center frequency, constant absolute bandwidth and reduced RF-swing is presented for a given type of varactors and frequency tuning range. The constant bandwidth attribute is achieved by introducing a mixed electric and magnetic coupling element (LC resonator) in the inter-resonator coupling sections to minimize the bandwidth variance with frequency increase. The filter's IIP3 is optimized by means of reducing the RF swing on the utilized varactors which is realized by appropriately selecting the resonator's impedance. A filter prototype was built and measured and exhibited a tunable center frequency between 230-370 MHz, a 3-dB bandwidth of 56.3 ± 0.2 MHz and an IIP3 between 28-41 dBm.

TABLE I. STATE-OF-THE-ART TUNABLE BANDPASS FILTERS WITH VARABILE CENTER FREQUENCY AND CONSTANT BANDWIDTH

Ref.	*Order*	*Tuning range (MHz)*	*Tunin g ratio*	*BW (MHz)*	*I.L. (dB)*	*IIP3 (dBm)*
[5]	2	1.32-1.89	1.43:1	70±4	2.5-2.9	6-26
[6]	2	0.43-0.6	1.40:1	55±3	1.4-1.6	22-26
[7]	2	1.7-2.2	1.29:1	98±7	1.6-2.0	7-13
[8]	2	1.45-1.96	1.35:1	215±5	1.6-2.4	42-45
This work	3	0.23-0.37	1.61:1	56±0.2	0.9-1.4	28-41

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