RF-Design of Narrowband Absorptive Bandstop Filters for UHF Applications

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***Abstract* — This paper addresses the RF-design of absorptive bandstop filters (ABSFs) that feature narrow fractional bandwidth (FBW) and quality factors (*Q*s) of the order of a thousand. The aforementioned functionality is realized by means of a mixed implementation scheme in which one-port acoustic wave (AW) resonators and lumped-element impedance inverters are effectively combined in a compact geometry. The non-ideal effects—fabrication tolerances—of the utilized lumped-element components on the ABSF performance—theoretically infinite isolation and input reflection—are analyzed. A method to maintain the large stopband attenuation by adjusting the effective *Q* of each resonator with the aid of a tunable resistor is also reported. A filter prototype that makes use of commercially available surface acoustic wave (SAW) resonators and surface-mounted devices (SMDs) has been built and tested at 418 MHz for verification purposes. It exhibits a 0.02% 3-dB FBW and a maximum stopband isolation of 62 dB.**

Keywords—Absorptive bandstop filter (ABSF), bandstop filter, high quality-factor (Q) filter, narrow bandwidth, narrowband filter.

I. INTRODUCTION

Bandstop filters have been extensively utilized in various microwave and millimeter wave systems to protect the RF receiver from strong interference and blocking signals [1]. As the frequency radio spectrum becomes more congested, the demand for notch filters with increased selectivity, large stopband attenuation and small physical size is growing rapidly and in particular for systems in the UHF band (300-3,000 MHz) due to the large number of co-existing RF applications. Whereas the realization of these filters using traditional reflective-type schemes fails to meet the above requirements, absorptive bandstop filters (ABSFs)—i.e., filters that create stopbands by absorbing the RF signals rather than reflecting them—actualize infinite attenuation and input reflection despite the finite quality factor (Q) of the resonators [2]. ABSF architectures that have been reported in the open technical literature up to date are primarily based on lumped-element and microstrip-line resonators. They feature fractional bandwidths (FBWs) between 2-20% that are inversely proportional to the resonators' Q [2]-[6]. It is apparent that for the realization of ABSFs with narrow FBWs, waveguide resonators—e.g. evanescent-mode or helical resonators [7], [8]—need to be utilized, which in turn result in increased volume filters as in [7], [8].

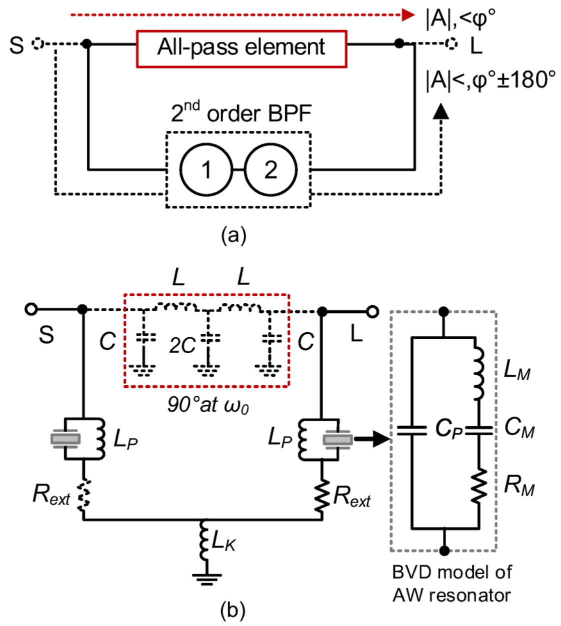

Fig. 1. (a) Generic block diagram of a two-path ABSF [2]. (b) Schematic circuit of a narrowband ABSF that makes use of high-Q one-port SAW resonators—represented by the Butterworth Van-Dyke circuit model in [11]—and lumped-element impedance inverters.

With the aim of obtaining increased levels of selectivity and narrow FBWs in a compact volume, acoustic wave (AW) resonators can be effectively combined with lumped-element impedance inverters [4]. Based on this concept, the design of ABSFs that feature FBWs of the order of 0.02% and are formed by commercially available one-port surface acoustic wave (SAW) resonators and lumped-element components is reported in this paper. The RF performance—theoretically infinite isolation and input reflection—of the engineered ABSF is furthermore analyzed in terms of the presence of fabrication tolerances in the utilized components. A method to maintain infinite stopband attenuation despite the presence of manufacturing variations is also presented. This approach is verified with an experimental ABSF filter prototype at 418 MHz that features 0.02% 3-dB FBW and maximum stopband isolation of 62 dB.

II. FILTER DESIGN

A generalized block diagram of a two-path ABSF that exhibits a second-order notch response is shown in Fig. 1(a). It consists of an all-pass network and a second-order bandpass filter (BPF) that result in output RF signals with equal magnitude and 180° phase difference at a desired center frequency ω_0. As such, perfect signal cancellation occurs at ω_0 in the output node with $|S_{21}|$ and $|S_{11}|$ being equal to zero even for resonators with finite Q [2], [3]. Fig. 1(b) illustrates a schematic circuit architecture of a narrowband ABSF that is based on a mixed implementation scheme in which high-Q one-port AW resonators are effectively combined with lumped-element impedance inverters as described in [4]. For the successful realization of an absorptive notch response at ω_0 with 3-dB fractional bandwidth FBW_{3dB}—that corresponds to an effective Q equal to $(2/FBW_{3dB})$—the filter components need to be selected as derived from equations (1)-(4). The circuit parameters L_M, C_M, R_M are respectively the motional inductance, motional capacitance, and motional resistance of the one-port AW resonator that features a Q equal to Q_{AW}. R_{ext} is an external resistance that is in series cascaded with the AW resonator for design cases where R_M—typically in the range of 15-22 Ohm for most of the commercially available one-port SAW resonators (e.g., AW resonators from Abracon Corp. [9] and EPCOS AG [10]—is smaller than 25 Ohm. The parameters L_K, L, C in (3) are the constituent components of the filters' impedance inverters. It should be further noted that AW resonators with $Q_{AW} \geq 2/FBW_{3dB}$ and series resonant frequency equal to ω_0 need to be selected and cascaded in parallel with an inductance L_P as specified by (4). In such a way, the parallel capacitance of the SAW resonator C_P is effectively cancelled at ω_0. An example of an ABSF ideal frequency response that is obtained from a filter topology with components values that are specified using (1)-(4), so as to realize a 3-dB FBW of 0.02% at 418 MHz, is illustrated in Fig. 2.

$$L_M \approx \frac{Z_0}{\omega_0 FBW_{3dB}}, \quad C_M = FBW_{3dB} / Z_0\omega_0 \tag{1}$$

$$R_M = (\omega_0 L_M) / Q_{AW}$$

$$R_{ext} = 25 - R_M \tag{2}$$

$$L_K = Z_0 / 2\omega_0$$

$$L = \frac{Z_0\sqrt{2}}{\omega_0 2}, \quad C = \frac{2-\sqrt{2}}{Z_0\omega_0\sqrt{2}} \tag{3}$$

$$L_P = 1/(\omega_0^2 C_P) \tag{4}$$

In a realistic implementation scenario where commercially available lumped-elements and AW resonators are incorporated into the filter architecture, non-idealities—fabrication tolerances—in the components' nominal values need to be considered for the RF design. Fig. 2(a)-(d) depict the resulting filter performance in terms of transmitted and reflected power for up to ±20% variation in R_{ext}, L_P, L_K and L, C parameters, respectively, and compare this performance with the ideal filter response—green trace—. As can be seen, variations in R_{ext} result in reduced stopband isolation—around 33 dB for ±20% variance—whereas the filters' input reflection remains almost

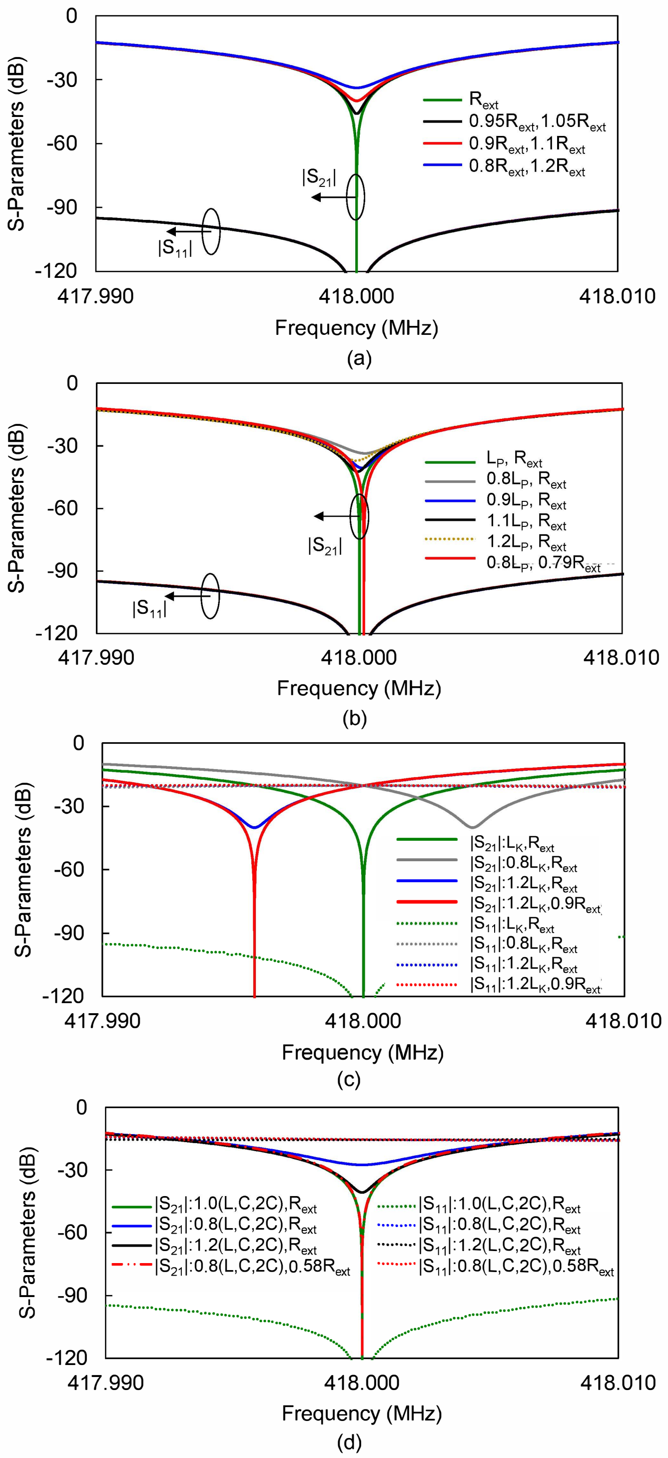

Fig. 2. S-parameters of a narrowband ABSF. The parameters in the inset of each figure L, C, $2C$, L_P, L_K, R_M, L_M, C_M, R_{ext} represent the ideal values of the filter components that are calculated using (1)-(4) for one-port AW resonators with Q_{AW} of 12,500 and an ideally designed FBW_{3dB} of 0.02%. The rest of the indicated parameters indicate variations from the parameters' original values—e.g, $0.8R_{ext}$ denotes that the demonstrated response is obtained from a filter geometry with all components values calculated from (1)-(4) except R_{ext} that is 80% of its original value in (1)—. (a) Variation of R_{ext}. (b) Variation of L_P. (c) Variation of L_K. (d) Variation of L, C, $2C$.

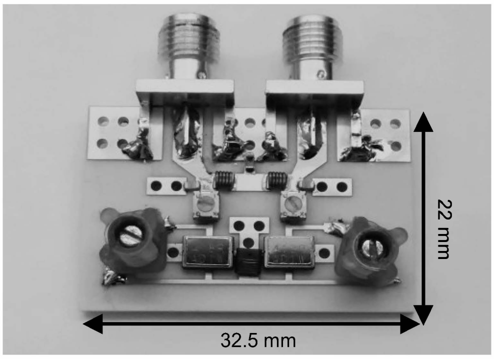

Fig. 3. Manufactured prototype. The utilized components for 0.02% 3-dB FBW are: *C*: Johanson Tech. 250R05L2R7CV4T, *2C*: Johanson Tech. 251R14S5R6CV4T, R_{ext}: Bourns 3314J-1-200E, L_K: Coilcraft 0805HT-6N8, *L*: 0806SQ-12N, SAW resonator: Abracon ASR418S2─L_M=119.67 µm, C_M=1.211 fF, R_M=22.2 Ohm, C_P=1.59 pF are its BVD equivalent parameters that have been extracted from the measured response of a single SAW resonator prototype).

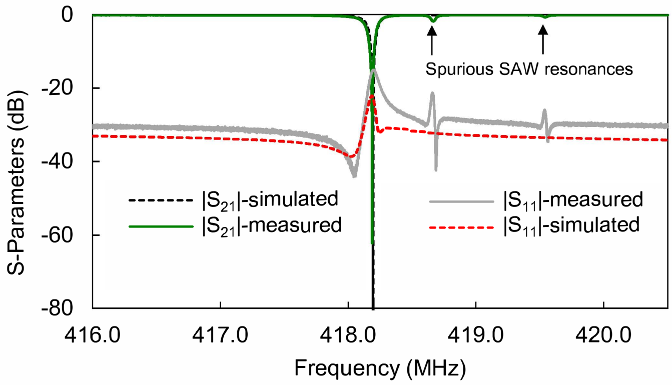

Fig. 4. Simulated and measured responses of the manufactured prototype in Fig. 3.

fixed, Fig. 2(a). A similar behavior is observed for changes in L_P, Fig. 2(b). On the other hand, modifications in the nominal value of the inverter's components L_K and *L*, *C* affect both the stopband isolation and the input reflection, Fig. 2(c) and (d). Note that variations in the resonant frequency of the AW resonator have not been considered in this analysis due the negligible tolerances in commercially available AW resonators─e.g., resonators from Abracon Corp. and EPCOS AG show frequency deviations less than ±0.02% [9], [10]─. It can be observed in Fig. 2 that despite the parameters variations, the isolation of the filter can be always restored by modifying R_{ext}, which needs to be reduced in most of the cases. For example, in a scenario where L_P is 80% of its nominal value, infinite isolation can be obtained by reducing R_{ext} to 79% of its original value, Fig. 2(b). Similarly, for the case of L_K being 120% of its nominal value, 90% of R_{ext} calculated using (2) needs to be utilized. However, in this case, infinite isolation is obtained but at a slightly shifted resonant frequency, Fig. 2(c). In yet another situation where all *L*, *C*, *2C* components of the all-pass elements are 80% of their nominal values, an R_{ext} that is 58% of its original value needs to be used in order to restore the infinite isolation at ω_0. As such, it can be concluded that by implementing R_{ext} with a trimmer resistor, isolation variations due to assembly and fabrication tolerances can be alleviated. Such a feature can be further exploited for the realization of ABSF filter topologies with tunable isolation.

III. Experimental Validation

To verify the ABSF design that was discussed in Section II, a filter prototype has been designed and implemented on a Rogers 4003 dielectric substrate (ε_r=3.55, h=1.52 mm, 35 µm-thick Cu cladding) for a center frequency around 418 MHz and 0.02% 3-dB FBW. The filter design was performed by first calculating the initial components values using equations (1)-(4) which are then finalized with post-layout simulations in the software package Advanced Design System (ADS) from Keysight Technologies in order to take into consideration all layout parasitics. The manufactured prototype of the filter is shown in Fig. 3. It is based on commercially available one-port SAW resonators and SMD components as listed in the caption of Fig. 3. Trimmer resistors and inductors were chosen to implement the R_{ext} and L_P components enabling the realization of a high stopband isolation despite potential fabrication and assembly tolerances.

Fig. 4 depicts the RF-measured response of the filter prototype in Fig. 3 that was evaluated with an Agilent-E8361A network analyzer. The measured 3-dB FBW, effective *Q*, return loss, isolation and out-of-band insertion loss were extracted from the measured S-parameters as 0.08 MHz, 0.02%, 10,000, 62 dB, 0.17 dB (evaluated 2 MHz away from 418 MHz), respectively. Furthermore, the ADS post-layout simulation results are also shown in Fig. 4. They are in a fairly-close agreement with the experimental data, hence successfully validating the conceived ABSF design approach.

IV. Conclusion

This paper has focused on the design of narrowband ABSFs that are realized with a mixed technology of AW resonators and lumped-element components and result in FBWs as low as 0.02%. Non-idealities in the filter components values were analyzed and a method to dynamically restore infinite-attenuation despite fabrication or assembly tolerances have been reported. Its feasibility has been experimentally verified with a filter prototype at 418 MHz that exhibited a 0.02% 3-dB FBW and maximum stopband isolation of 62 dB.

References

[1] I. Hunter, A. Guyette, and R. D. Pollard, "Passive microwave receive filter networks using low-Q resonators," *IEEE Microw. Mag.*, vol. 6, no. 3, pp. 46–53, Sep. 2005.

[2] D. R. Jachowski, "Passive enhancement of resonator *Q* in microwave notch filters," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Fort Worth, TX, USA, Jun. 9-11, 2004, pp. 1315–1318.

[3] A. Guyette, I. Hunter, and R. Pollard, "Design of absorptive microwave filters using allpass networks in a parallel-cascade configuration," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Boston, MA, USA, Jun. 7-12, 2009, pp. 733–736.

[4] D. Psychogiou, R. Gómez-García, and D. Peroulis "Acoustic wave resonator-based absorptive bandstop filters with ultra-narrow bandwidth," *IEEE Microw. Wireless Compon. Lett., under review.*

[5] B. Kim, J. Lee, J. Lee, B. Jung, and W. J. Chappell, "RF CMOS integrated on-chip tunable absorptive bandstop filter using Q-tunable resonators," *IEEE Trans. Electron Device.*, vol. 60, no. 5, pp. 1730-1737, May 2013.

[6] D. Psychogiou, R. Mao, and D. Peroulis, "Series-Cascaded Absorptive Notch-Filters for 4G-LTE Radios," accepted in *2015 IEEE Radio Wireless Symp.*, San Diego, CA, USA, Jan. 2015.

[7] T. Snow, J. Lee, and W. Chappell, “Tunable high quality-factor absorptive bandstop filter design,” in *IEEE MTT-S Int. Microw. Symp. Dig.*, Montréal, QC, Canada, Jun. 17-22, 2012, pp. 1–3.

[8] D. Psychogiou and D. Peroulis, “Tunable VHF miniaturized helical filters,” *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 2, pp. 282–289, Feb. 2014.

[9] Abracon Corp., http://www.abracon.com

[10] EPCOS AG, http://www.epcos.com

[11] J. D. Larson III, R. C. Bradley, S. Wartenberg, and R. C. Ruby, “Modified Butterworth-Van Dyke circuit for FBAR resonators and automated measurement system,” in *IEEE Ultrason. Symp.*, San Juan, Puerto Rico, Oct. 22–25, 2000, pp. 863–868.