Switched-bandwidth SAW-based bandpass filters with flat group delay

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Tunable surface-acoustic-wave-(SAW)-based bandpass filters (BPFs) with flat in-band group delay (τ_g) and variable passband bandwidth (BW) are reported. They are based on N hybrid acoustic-wave-lumped-element-resonator (AWLR) modules shaped by one lumped-element resonator and K RF-switched SAW resonators that are arranged in a Gaussian-type source-to-load impedance-inverter network. Fractional bandwidth (FBW) tuning is achieved by reconfiguring the number of SAW resonators within the AWLR modules. Major advantages of the proposed filter concept when compared to conventional SAW BPFs are as follows: (i) they do not depend on the electromechanical coupling coefficient (k_t^2) of the SAW resonators – FBW>k_t^2 can be realised –, (ii) they do not require lossy elements or SAW resonators with different frequencies, and (iii) they can be tuned. For experimental-validation purposes, a 433.9 MHz two-pole/four-transmission-zero prototype was built and measured. It exhibited flat-in-band-τ_g passbands with discretely-tunable BW between 0.18 and 0.45 MHz (i.e. 2.5:1 tuning ratio).

Introduction: Modern wireless-communication systems and, in particular, the ones addressing 5G applications are increasingly calling for miniaturised RF transceivers with multi-standard operability. In order to facilitate their deployment, RF bandpass filters (BPFs) with advanced RF processing capabilities need to be developed. These include flat in-band group delay (τ_g) and tunable transfer function to carry out adaptive RF-signal selection processes without significant phase distortion. However, these requirements remain a great challenge for the currently-employed surface-acoustic-wave (SAW) or bulk-acoustic-wave (BAW) RF filtering architectures, since their performance characteristics depend on the electromechanical coupling coefficient (k_t^2) of their substrates. Important shortcomings of existing SAW/BAW filters include: (i) fractional bandwidth (FBW) less than k_t^2 (~0.6 k_t^2) [1], (ii) limited variety of realisable transfer functions (i.e. only bandpass-type), (iii) large τ_g variation, (i.e. 60% within the passband of commercially-available SAW filters [2]), and (iv) static RF response [3]. Despite significant research efforts to enhance the FBW using new types of substrates that sacrifice RF performance by lowering the quality factor (Q) of their constituent resonators, there exist a very few tunable SAW BPF topologies. In addition, to the best of the authors' knowledge, none of them exhibits flat in-band τ_g. In [4, 5], static SAW-based BPFs with almost constant-in-band-τ_g characteristics were designed using modified transducers (slanted type in [4] and resonant type in [5]) or by introducing lossy elements [6] but at the expense of increased levels of insertion loss (IL) in the range 5–25 dB. In an alternative configuration, acoustic-wave-lumped-element resonators (AWLRs) were employed for the realisation of low-IL transmission bands. However, none of these architectures allows for transfer-function tunability.

Considering the aforementioned drawbacks, this Letter presents a SAW-based BPF concept which, unlike conventional ladder/lattice-SAW-based BPF approaches, exhibits the following RF performance merits: (i) quasi-elliptic-type transfer function whose FBW can be designed to be higher than k_t^2, (ii) flat in-band τ_g, (iii) discretely-tunable bandwidth (BW), and (iv) RF operational characteristics that neither depend on k_t^2 nor require the integration of lossy elements. The content of this Letter is summarised as follows. First, the theoretical foundations and basic RF design guidelines of the flat τ_g SAW-based BPF principle are described. Afterwards, its experimental viability is verified. Finally, a summary of the most relevant contributions of this work is provided.

Theoretical foundations: The generalised circuit details and theoretically-synthesised transfer function of the proposed SAW-based BPF with flat in-band τ_g and tunable BW characteristics are shown in Figs. 1 and 2, respectively. It is based on N multi-resonant AWLRs (for an Nth-order transfer function) that are in-parallel connected through N impedance inverters (Z_T) to the source-to-load path – composed of $N+1$ $Z_{0,1}$-to-$Z_{N,N+1}$ impedance inverters – as shown in Fig. 1*a*. Each multi-resonant AWLR is shaped by K identical (for K selectable BW states) one-port-type acoustic-wave resonators (AWRs) – motional capacitance C_M, motional inductance L_M, motional resistance R_M, parallel capacitance C_P, series resonant frequency ω_S, and anti-resonant frequency ω_a – and one lumped-element (LE) resonator – shaped by C_R and L_R. By appropriately selecting C_R so that together with $K{\cdot}C_P$ and L_R it resonates at ω_S, each multi-resonant AWLR contributes to the overall transfer function with one high-Q pole (at ω_S: centre frequency of the passband) and two transmission zeros (TZs at ω_{z1}, ω_{z2}) that can be further exploited for the realisation of high-Q quasi-elliptic-type filtering profiles. This is shown in Fig. 1*b*. Moreover, in order to synthesise flat τ_g, the impedance-inverter values of the source-to-load network need to be selected as detailed in (1) and (2), where Z_0 is the reference impedance and g_0-to-g_N are the element values of the normalised Gaussian-type prototype

$$Z_{0,1}=\left(\frac{Z_0 g_0 g_1 Z_T^2}{\mathrm{FBW}\,\omega_S L_M}\right)^{0.5},\quad Z_{i,i+1}=\frac{(g_i g_{i+1})^{0.5} Z_T^2}{\mathrm{FBW}\,\omega_S L_M} \qquad (1)$$

$$Z_{N,N+1}=\left(\frac{Z_0 g_N g_{N+1} Z_T^2}{\mathrm{FBW}\,\omega_S L_M}\right)^{0.5} \qquad (2)$$

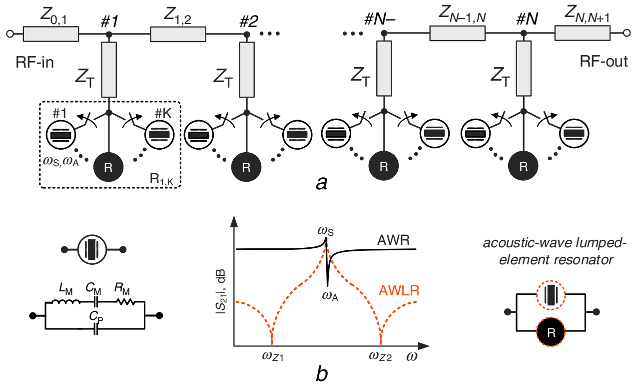

Fig. 1 *SAW-based BPF with flat in-band τ_g and RF-switched BW*

a Block diagram for a transfer function shaped by N poles and $2N$ TZs. BW tuning is realised by varying the number of AWRs in each multi-resonant module through RF switches

b Circuit equivalent and transfer function of the AWR and an AWLR that comprises one AWR and one LE resonator

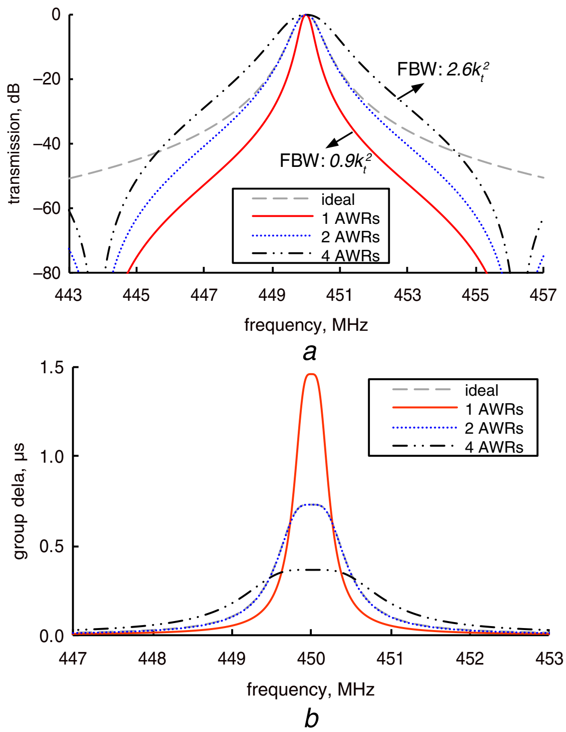

Fig. 2 *Ideally-synthesised responses for a two-pole Gaussian-type BPF (ideal) and a two-pole/four-TZ SAW-based BPF that consists of multi-resonant branches with 1, 2, and 4 AWRs with $f_S = 450$ MHz and $k_t^2 = 0.08\%$. The normalised impedance-inverter values are identical for all demonstrated states: $Z_{0,1} = 1$, $Z_{1,2} = 0.36$, $Z_{2,3} = 0.43$, and $Z_T = 1$*

a Power transmission response

b τ_g

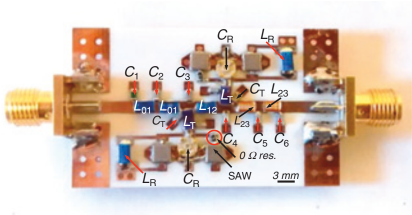

Fig. 3 *Manufactured prototype.* C_1 = *ML03V11R7BAT2A,* C_2 = *251R14S3R3BV4T,* C_3 = *251R14S3R9BV4T,* C_4 = *251R14S5R1CV4T,* C_5 = *251R14S5R6CV4T,* C_6 = *251R14S3R0BV4T,* L_{01} = *1206CS330,* L_{12} = *1206CS470,* L_{23} = *0806SQ19,* L_R = *1206CS100,* L_T = *1206CS390*

In order to better illustrate the aforementioned principles, various transfer functions examples are shown in Fig. 3 along with an ideally-synthesised response of a conventional Gaussian-type BPF. In particular, Figs. 2*a* and *b*, respectively, represent the power transmission response and τ_g of a second-order SAW-based BPF whose multi-resonant AWLR branches consist of one, two, and four AWRs. It can be seen that by only altering the number of AWRs in each AWLR module and keeping its impedance-inverter values constant, the filter's FBW can be altered while maintaining the flat τ_g for all reconfigured states. This characteristic can be further exploited in a practical implementation by readily switching on/off the number of resonators in each multi-resonant AWLR module and adjusting the LE capacitance C_R. As can be also seen in Fig. 2*a*, the passbands can exhibit FBWs>k_t^2 as opposed to conventional SAW-based BPF designs whose FBW is 0.4 k_t^2–0.8k_t^2 [1]. Furthermore, although FBWs up to 2.6k_t^2 are demonstrated, wider FBWs can be obtained by appropriately selecting $Z_{0,1}$-to-$Z_{N,N+1}$.

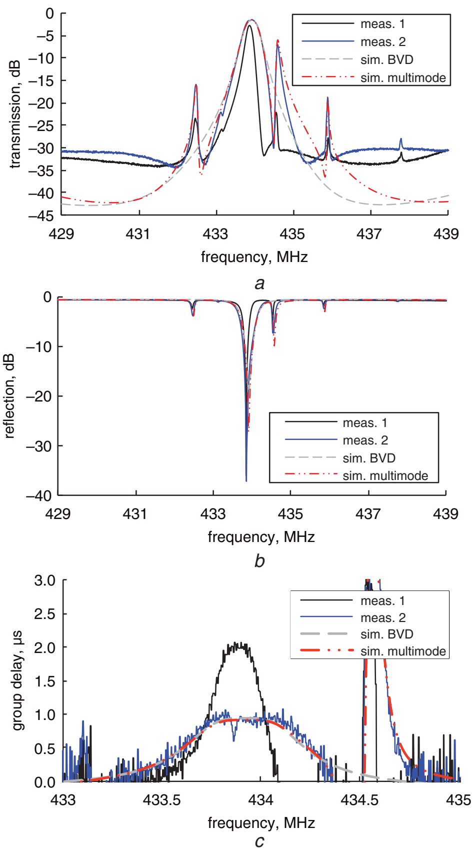

Fig. 4 *RF-measured and EM-simulated response*

a Power transmission response
b Power reflection response
c τ_g

Experimental validation: To verify the practical viability of the proposed flat-in-band-τ_g and tunable-BW SAW-based BPF concept, a 433.9 MHz two-pole/four-TZ prototype was developed. It was designed to feature two tunable BW states – i.e. the AWLRs comprise two RF-switched AWRs and one LE resonator – by using the aforementioned design methodology. Commercially-available SAW resonators from EPCOS (R900) with the following characteristics were employed: C_M = 1.62 fF, L_M = 82.984 μH, R_M = 19 Ω, and C_P = 1.97 pF. A Rogers 4003C substrate with dielectric permittivity ε_r = 3.55, dielectric thickness H = 1.52 mm, dielectric loss tangent tan(δ_D) = 0.0027, and 35 μm-thick Cu-cladding was utilised. All impedance inverters were implemented with their first-order low-pass π-type prototype. Mechanically-tunable capacitors from Johanson Tech. were used as variable C_Rs and RF-switching was performed through ideal 0 Ω resistors. The manufactured prototype is shown in Fig. 3. Fig. 4 depicts its RF-measured response for the two tunable BW states that were obtained by switching the number of AWRs in each AWLR module. It can be seen that a BW tuning ratio of 2.5:1 is obtained while keeping the in-band τ_g constant along the passband for all tuning states. The RF performance characteristics of the BW-switched states are as follows. Narrow-BW state: IL = 2.73 dB (Q_{eff}>10,000), 3 dB BW = 0.18 MHz (i.e. 3 dB FBW = 0.5k_t^2), and τ_g = 1.98 μs. Broad-BW state: IL = 1.45 dB (Q_{eff}>10,000), 3 dB BW = 0.18 MHz (i.e. 3 dB FBW = 1.3k_t^2), and τ_g = 0.98 μs. A comparison between the measured response and the EM-simulated ones by using both the single-mode and multi-mode Butterworth Van-Dyke AWR model is also shown at the same figure. Their close agreement successfully validates the proposed flat-in-band τ_g and switched-BW SAW-based BPF concept.

Conclusion: SAW-based BPFs with flat in-band τ_g and reconfigurable-BW passbands are reported. They are based on RF-switched multi-resonant AWLRs that are appropriately combined with a Gaussian-type source-to-load impedance inverter network. Unlike conventional ladder-/lattice-/self-cascaded SAW-BPF architectures, they exhibit the following merits: (i) realisation of passbands with discretely-selectable BW and flat in-band τ_g, (ii) FBWs>k_t^2, and (iii) avoidance of lossy elements or AWRs with different resonant characteristics as for example in [6]. The engineered flat-in-band-τ_g and BW-switchable SAW-based BPF concept has been experimentally validated through a 433.9 MHz two-pole/four-TZ prototype that makes use of commercially-available SAW resonators.

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One or more of the Figures in this Letter are available in colour online.

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