Recent Advances in Reconfigurable Microwave Filter Design

—Invited Paper—

Dimitra Psychogiou[1], Roberto Gómez-García[2], and Dimitrios Peroulis[1]

[1]Dept. Electrical & Computer Engineering, Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907, USA
[2]Dept. Signal Theory & Communications, University of Alcalá, Alcalá de Henares, Madrid, 28871 Spain
E-mails: pdimitra@purdue.edu; roberto.gomez.garcia@ieee.org; dperouli@purdue.edu

***Abstract*— Next-generation multi-mode RF transceivers will require fully-adaptive, high-frequency filtering components with increased levels of spectral agility. Highly-selective single/multi-band filtering actions for various signal-band selection processes and flexible bandstop filtering functions for dynamic interference mitigation will be highly desirable in these systems. Taking into consideration the aforementioned needs, recent advances in the field of adaptive-transfer-function filters are reported in this paper. Specifically, multi-band bandpass filters (BPFs) with tunable passbands, circuits with selectable BPF and bandstop-filter (BSF) operational modes, and broad-band BPFs with incorporated in-band controllable notches are presented.**

***Index Terms*— Bandpass filters (BPFs), bandstop filters (BSFs), dual-band filters, multi-band filters, notch filters, planar filters, reconfigurable filters, tunable filters, wide-band filters.**

I. INTRODUCTION

Modern trends towards universal RF wireless systems call for highly-versatile high-frequency transceivers with multi-functional operability to enable flexible radio access. In their RF front-ends, tunable microwave filtering devices with fully-reconfigurable transfer functions are highly desirable to facilitate the adaptive pre-selection of the signal(s) of interest and/or the mitigation of the unwanted electromagnetic (EM) interference and out-of-band noise [1], [2]. Whereas flexible RF filters can pave the way to RF transceivers with reduced complexity and enable the integration of new applications, more stringent requirements need to be met that in turn create challenges in terms of design, tuning principles, and RF performance.

Over the last decades, a vast number of practical implementations of spectrally-agile high-frequency filtering components have been reported to address the needs of a diverse number of applications. Currently, research activities in the field of reconfigurable microwave filters can be grouped into two main categories, as follows:

- At the design level, the invention of innovative circuit topologies that enable the synthesis of more-sophisticated tunable filtering transfer functions. Among them, some exponents of tunable filtering devices based on novel circuit architectures to be highlighted are quasi-elliptic-type bandpass filters (BPFs) with tunable center frequency and bandwidth (BW) and low in-band group-delay variation [4], reconfigurable dual-mode BPFs with transmission-zero (TZ) control [5], intrinsically-switchable filter banks [6], and BPFs with ultra-large BW-tuning ratio [7].
- At the physical material/device side, the conception of new tuning mechanisms that enable enhanced operational performance to be attained. Some recent examples in this context are microfluidically-reconfigurable BPFs with improved power-handing capability [8] and switchable BPFs that make use of a new set of RF switches using phase change materials [9].

This review paper focuses on recent research findings in the area of advanced adaptive-transfer-function filters for a variety of applications. Specifically, multi-band BPFs with fully-controllable transmission bands, double-functionality filtering devices that simultaneously exhibit BPF and BSF operational modes at the same filter volume, and wide-band BPFs with embedded reconfigurable notches for dynamic in-band interference suppression are addressed.

II. ADVANCED RECONFIGURABLE MICROWAVE FILTERS

A. Multi-Band Bandpass Filters

Multi-band BPFs are expected to become essential high-frequency components of modern multi-standard wireless communications and multi-frequency radar architectures as signal-preselection devices with the ability to simultaneously select various sets of RF channels that are closely/widely spaced in the frequency radio spectrum [10]. Spectral tunability is a highly-desirable feature for these circuits to make the referred multi-band signal-acquisition process completely dynamic towards the development of fully-adaptive RF transceivers with increased levels of flexibility. Nevertheless, although several solutions of tunable multi-band BPF configurations have been reported in the last few years as in [11]–[15], none of them exhibits all the required operational capabilities. They are summarized as follows:

- Realization of multi-band bandpass transfer functions with an arbitrary number of passbands.
- Independent reconfiguration of each transmission band in terms of center frequency and BW.
- Generation of multiple out-of-band TZs that can be synchronously tuned so that their passbands preserve highly-selective transfer functions (i.e., quasi-elliptic-type sharp-rejection transfer function) in all reconfigured states.

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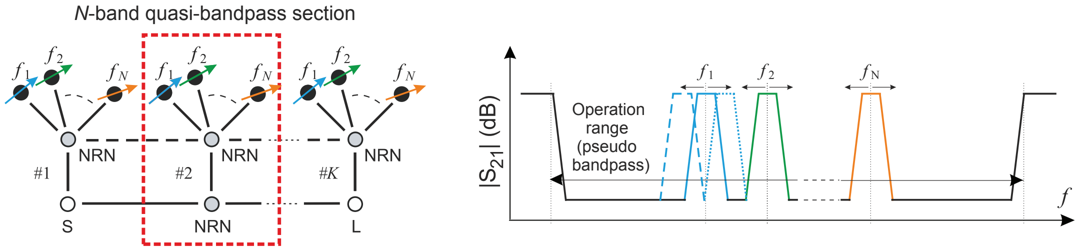


Fig. 1. Conceptual coupling-matrix diagram and operational principle of the fully-tunable quasi-elliptic-type multi-band BPF concept in [17].

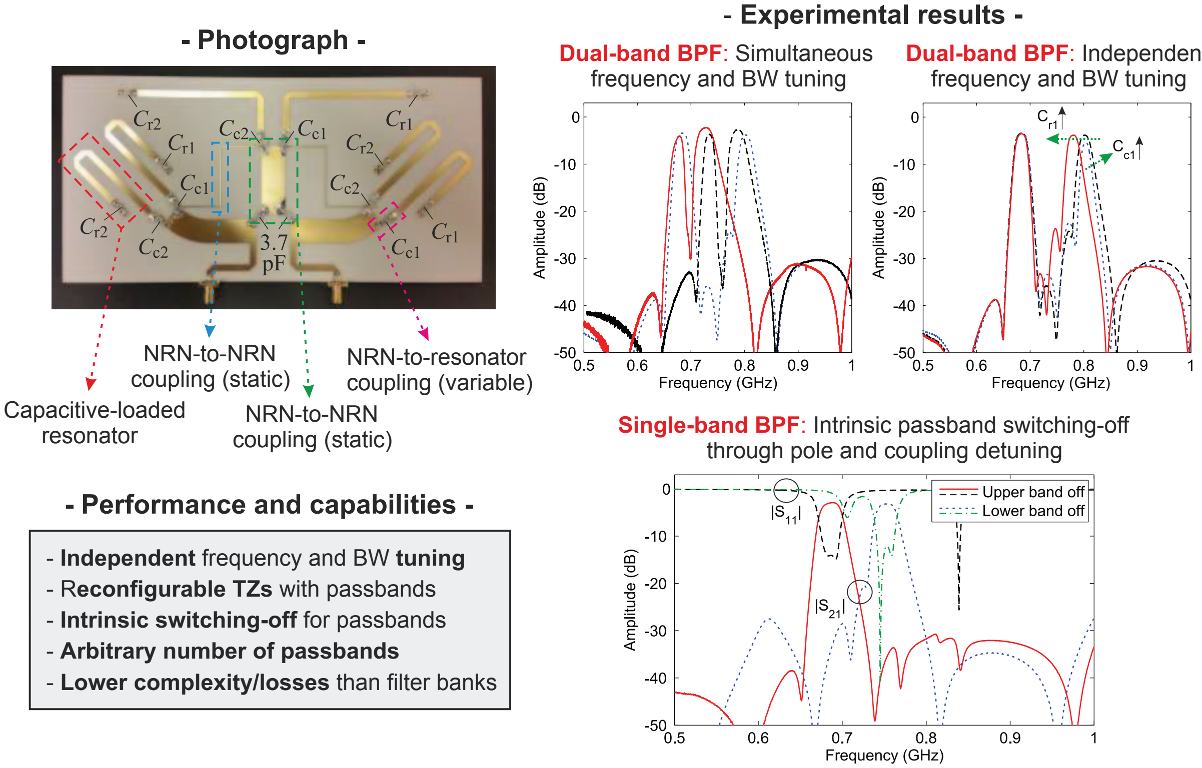


Fig. 2. Photograph, measured power transmission ($|S_{21}|$) and reflection ($|S_{11}|$) responses for several example dual- and single-band BPF states, and performance/capabilities of the developed fully-tunable quasi-elliptic-type dual-band BPF prototype in [17]. Integration concept: microstrip lines (resonators and static impedance inverters) and lumped capacitors (variable/static impedance inverters and tuning elements of resonators).

- Intrinsic switching-off of each of the transmission bands (i.e., without RF switches) to control the number of active channels in the frequency radio spectrum.
- Passband-merging capability to shape broader, and for certain realizations, higher-order transmission bands.

Recently, a new philosophy for the implementation of fully-adaptive multi-band BPFs that simultaneously offers all the aforementioned features was reported. It enables the highest reconfiguration capability to date for this class of devices. Such a solution was initially proposed in [16] and subsequently improved in [17] for higher-selectivity multi-band BPF realizations. Its conceptual filter architecture and operational principle are illustrated in Fig. 1. As can be seen, it consists of the series cascade through impedance inverters of replicas of a so-called "N-band quasi-bandpass section" as basic building block of this multi-band BPF configuration for an N-band transfer function design. Its constituent N-band quasi-bandpass section is made up of two non-resonating nodes (NRNs) and N resonating nodes that interact by means of impedance inverters. These resonators—each of them shaping a different transmission band—are coupled to the direct source-load path of the multi-band BPF without direct interaction between them and result in the following characteristics for the overall circuit:

- The multi-band BPF action is spectrally embedded in a bandstop range of the entire transmission profile associated to the part shaped by the NRNs of the circuit.
- By making the resonating nodes and the resonator-to-NRN impedance inverters tunable, respectively, spectral reconfiguration in terms of center frequency and BW is

incorporated into the whole filter. Furthermore, since the resonators that form different passbands in each quasi-bandpass section do not directly interact between them, the tuning process of each transmission band does not significantly affect the remaining ones.

- The intrinsic switching-off of the passbands is feasible by detuning the resonators and the resonator-to-NRN impedance inverters—i.e., couplings—of those transmission bands to be commuted-off.
- By generating cross couplings between the NRNs of adjacent quasi-bandpass sections, multiple out-of-band TZs are produced for all tuned transfer-function states.
- Less impedance inverters can be used when a large number of bands are desired—leading to compactness and insertion-loss advantages—with regard to conventional multi-band realizations that use parallelized filter banks [3], [6].

A photograph and various example measured responses of a UHF-band third-order two-band proof-of-concept microstrip prototype are shown in Fig. 2 [17]. Mechanically-adjustable trimmer capacitors are utilized as variable-reactance elements that are either inserted into the resonating nodes—frequency tuning—or into the adjustable impedance inverters between the resonators and their adjacent NRNs—BW tuning—. Fixed capacitors and inductive/capacitive-type transmission-line segments are employed for the realization of the static couplings between NRNs. As can be seen in Fig. 2, the simultaneous and independent center-frequency and BW reconfiguration of the transmission bands in quasi-elliptic-type dual-band bandpass filtering mode is proven. Furthermore, the intrinsic switching-off of one transmission band to attain single-band BPF states is also verified.

B. Bandpass/Bandstop Filters

Microwave filtering devices with the ability to simultaneously exhibit BPF and BSF transfer functions at the same filter volume will be highly desirable in next-generation RF wireless systems to either enable the transmission of a desired signal or to suppress an in-band EM interference that could saturate the receiver. When employed in tunable multi-port filtering networks as channelizing filters, they can result in more-advanced levels of reconfiguration through the implementation of frequency-selective signal-routing paths that can be flexibly switched-on/off. However, despite their potential interest, the development of such high-frequency components that simultaneously exhibit BPF and BSF transfer functions in the same device can be a challenging task taking into account the very different circuit topologies that are associated to a BPF and BSF response (see, e.g., [18] and [19] for combline BPF and BSF schemes, respectively). The complexity of such a design could be even higher if frequency agility in terms of center frequency and BW is also desired for both BPF and BSF states.

A limited number of filtering circuits providing the referred BPF-to-BSF switching functionality have been recently proposed in [20]–[24]. Nevertheless, they do not exhibit independent control of poles and zeros for their BPF and/or BSF states. In addition, most of them can hardly be scaled to higher-order realizations. These limitations have been resolved in a new type of fully-versatile BPF/BSF device published in [25], in which frequency reconfiguration is achieved through TZ reallocation. Indeed, by controlling the positions of multiple generated TZs, adaptive bandpass-type transfer functions in terms of center frequency, BW, and TZs are created. Furthermore, for specific spectral distribution of the TZs, virtually-zero-BW states that result in the intrinsic switching-off of the filter passband are attained, leading to a reconfigurable bandstop-type filtering behavior.

The conceptual filter scheme and operational principles for BPF and BSF modes of the frequency-agile BPF/BSF in [25] are illustrated in Fig. 3. As observed, it is based on the series cascade of double-TZ-creation cells that are shaped by two resonating nodes that separately interact with the same NRN through different static impedance inverters. In this manner, two TZs are generated in the whole filter at the resonant frequencies of the resonators. By making controllable the natural frequencies of these resonators through variable-reactance elements, the spectral positions of these TZs can be modified so that the following capabilities are incorporated into the overall circuit:

- By placing the two TZs of each double-TZ-creation cell at different locations and the maximum power transmission of all the cells at the same inter-TZ spectral position, a bandpass-type response is synthesized. For these BPF states, BW is defined by the closest-to-passband TZs whereas out-of-band isolation (IS) performance—i.e., out-of-band BW and power rejection levels—is determined by the distribution of the remaining TZs.
- By generating the two TZs of at least one double-TZ-creation cell at the same spectral position—that is equal to the center frequency of those cells in BPF mode—, an overall bandstop-type filtering action is attained.

From the above description, it is clear that the tuning of the TZs gives rise to a full control of the spectral characteristics of this BPF/BSF device. Advantages associated to this tuning mechanism when compared to reconfigurable filter solutions with inter-resonator variable couplings are as follows:

- It is suitable for very-high-frequency designs, in which adjustable inter-resonator couplings for BW tuning can be more difficult to realize and control.
- Lower in-band insertion-loss levels—this is especially remarkable for narrow-BW states—are achieved [26].
- Independent control of each passband/stopband side by only adjusting the TZs associated to it is feasible.
- When compared to a classic channelized filter bank, BPF-to-BSF commutation is carried out without RF switches.

The schematic, photograph—modular two-stage assembly and its constituent BPF/BSF cell—, and several example measured transfer functions of an experimental proof-of-concept prototype that can be reconfigured in the range 2.9–3.6 GHz are shown in Fig. 2. Substrate-integrated-waveguide (SIW)

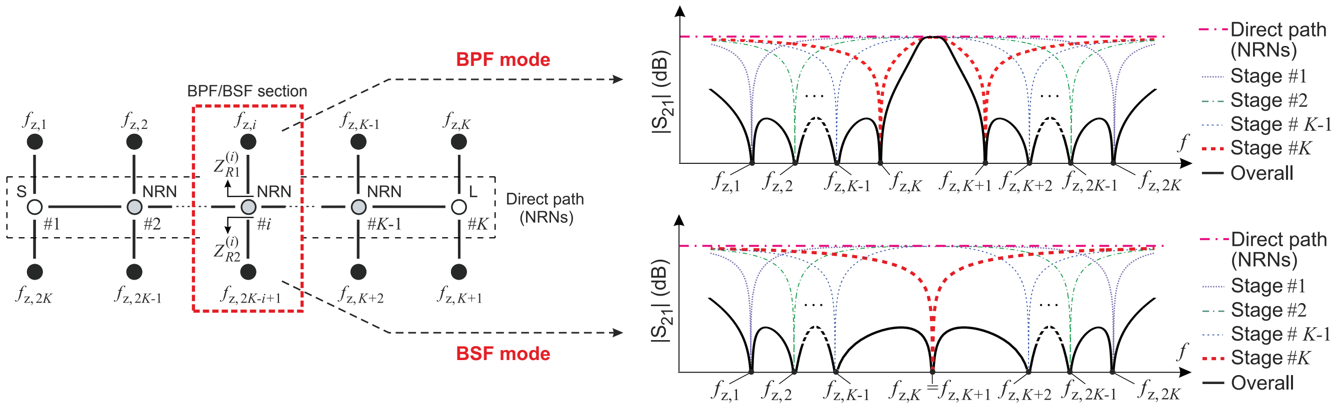
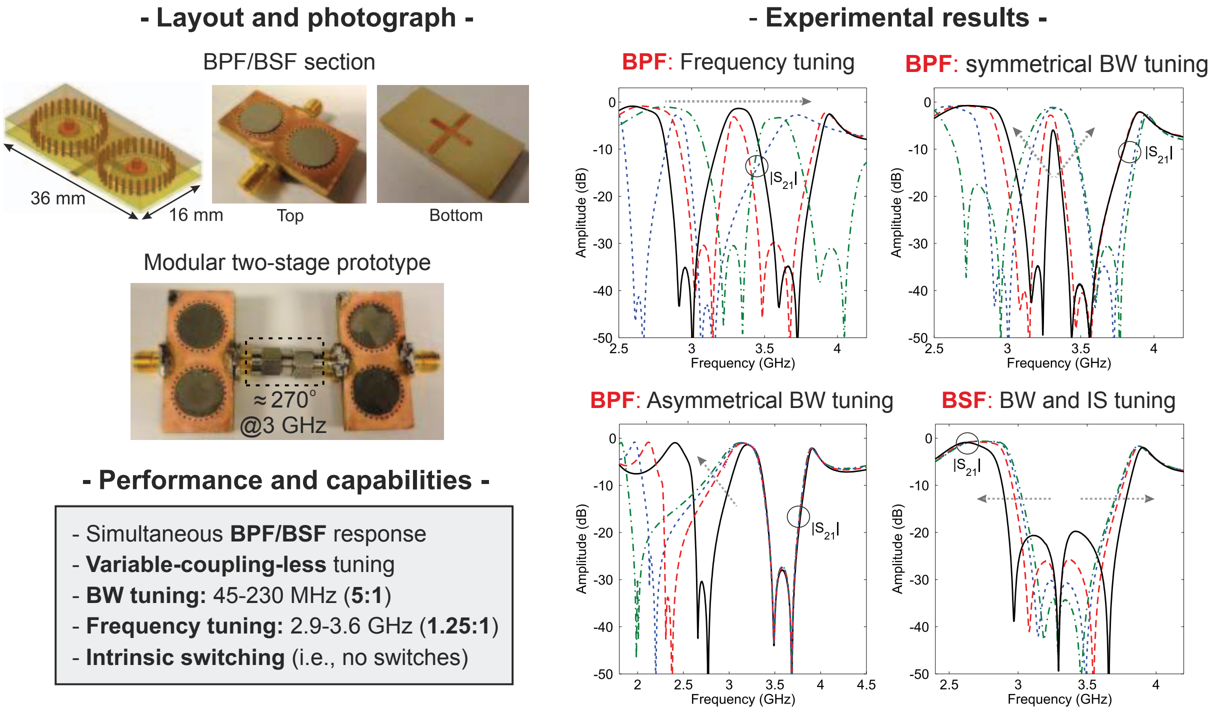


Fig. 3. Conceptual coupling-matrix diagram and operational principles for the BPF and BSF modes of the fully-reconfigurable BPF/BSF concept in [25].



- Simultaneous **BPF/BSF** response
- **Variable-coupling-less** tuning
- **BW tuning:** 45-230 MHz (**5:1**)
- **Frequency tuning:** 2.9-3.6 GHz (**1.25:1**)
- **Intrinsic switching** (i.e., no switches)

Fig. 4. Layout, photograph, measured power transmission ($|S_{21}|$) responses for several example BPF and BSF states, and performance/capabilities of the developed modular two-stage fully-reconfigurable BPF/BSF prototype in [25]. Integration concept: SIW evanescent-mode cavity resonators integrated in a TMM 3 substrate and tuned by piezoelectric actuators.

evanescent-mode cavity resonators that are controlled through piezoelectric actuators are used as resonating nodes, whereas slot openings in the ground-plane layer of short-circuited microstrip lines are utilized to realize the couplings between the resonators and the NRNs. As can be seen in Fig. 4, capabilities related to center-frequency and symmetrical/assymetrical BW tuning for BPF states, as well as BW and IS control for BSF operational modes, are experimentally demonstrated.

C. Wide-Band Bandpass Filters with Embedded Notches

After the U.S. Federal Communication Commission authorized the use of frequency spectrum between 3.1–10.6 GHz for ultra-wideband (UWB) applications, the development of RF/microwave circuits with broad-band operational capabilities has attracted a considerable attention [27]. Wide-band pre-selection BPFs are strongly required by these systems, for which a rich variety of solutions based on different principles—e.g., BPFs made up of series cascades of lowpass and highpass filtering sections [28], BPFs based on multi-mode resonators [29], and transversal signal-interference BPFs [30]—have been proposed during the last decade. However these broad-band systems must coexist with a large plurality of wireless applications in a congested radio spectrum that may seriously affect their operation. To avoid it, the incorporation of controllable sharp-rejection notches in the low-loss

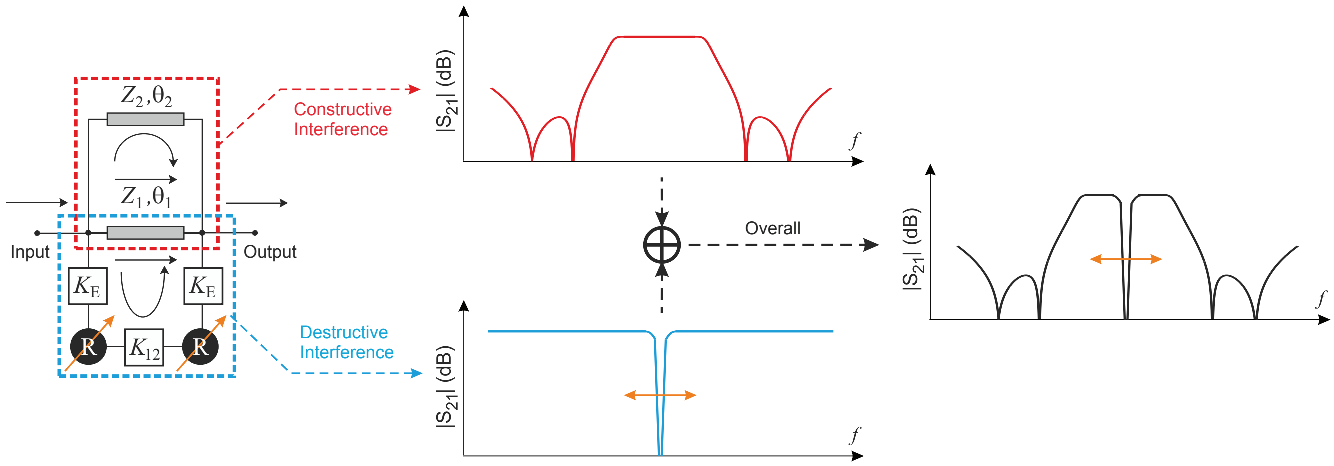
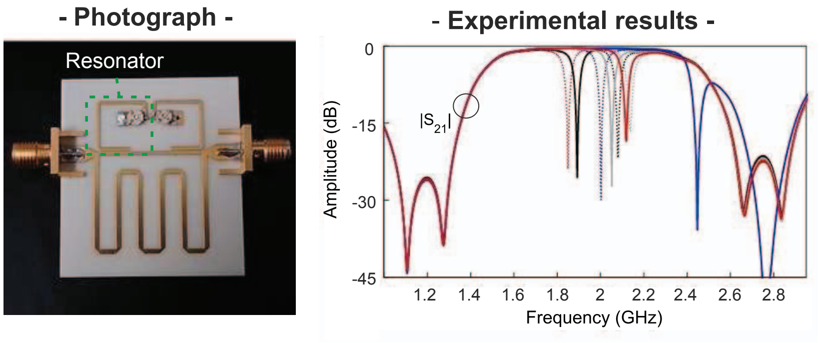


Fig. 5. Circuit architecture and operational principle of the wide-band BPF concept with embedded in-band tunable notch in [33].



- Performance and capabilities -

- **Wide-BPF/ absorptive-notch** response
- **Low-loss (0.49-dB)** wide passband range
- Tunable notch:
  - **1.8-2.5-GHz** (1.39:1) frequency **tuning**
  - **17-to-36-dB** notch **depth**

Fig. 6. Photograph, measured power transmission ($|S_{21}|$) responses for several example states, and performance/capabilities of the developed wide-band BPF prototype with an embedded in-band tunable notch in [33]. Integration concept: microstrip lines (transmission-line paths and resonators) + lumped capacitors (tuning elements of resonators).

passband range of the wide-band filter can be advantageous to efficiently suppress blocking signals that could dynamically appear in the receiver BW.

Examples of broad-band BPFs with embedded controllable notches developed in planar schemes can be found in [31] and [32]. However, they show some performance limitations, such as the very-narrow frequency tuning range (1.1:1 frequency-tuning ratio) of notches in [31] or the poor rejection capabilities (≈10 dB) of the reconfigurable in-band stopband in [32].

Recently, in [33], an interesting design concept that allows the realization of highly-selective wide-band BPFs with controllable deep-rejection stopbands inserted into its transmission band was reported. Its conceptual circuit scheme and operating principle is shown in Fig. 5. As observed, it is based on a three-path transversal signal-interference circuit in which one of these electrical paths is reused for both the wide-band filtering and the tunable-notch-creation functionalities. In particular, the broad-band filtering action is produced from the feedforward signal-interference effect taking place between the two transmission-line-type paths of the circuit as in [30], whereas an absorptive notch is integrated into the passband by using one of these paths along with a third resonator-based one [34], [35]. This filter features half of the size of a classic solution in which the wide-band transversal filtering and absorptive filtering units are cascaded in series to synthesize the same transfer function. Moreover, several replicas of this dual-function wide-band/tunable-notch filtering cell can be connected in series to increase selectivity and add more controllable notches to the transmission range.

The photograph and some measured power transmission responses for different locations of the in-band notch of a proof-of-concept prototype of the filter concept in Fig. 5 are provided in Fig. 6 [33]. A microstrip implementation with mechanically-adjustable trimmer capacitors loading the resonators of the absorptive-notch filter path is used for it. As shown, this circuit features an absorptive notch that can be tuned in the range 1.8-2.5 GHz having notch depths as high as 36 dB within a low-loss passband centered at 2 GHz.

III. CONCLUSION

This paper has presented an overview of recent research advances in the field of frequency-agile RF/microwave filters. Different examples of adaptive filtering devices in alternative technologies with beyond the state-of-the-art reconfiguration capabilities have been reported. Among them, i) quasi-elliptic-type multi-band BPFs with independently-tunable transmission bands for multi-standard RF systems, ii) filtering circuits that simultaneously feature BPF/BSF operational modes with fully-controllable spectral characteristics, and iii) signal-interference broad-band BPFs with embedded tunable notches for in-band interference mitigation in UWB receivers. For these filtering architectures, main operational principles and experimental results of manufactured proof-of-concept demonstrators have been described.

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