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Multi-Tunable Quasi-Circulator with Co-Designed Bandpass Filter and Switching-Off Functionality

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***Abstract* — This paper reports on the RF design and practical validation of a multi-tunable quasi-circulator with co-designed bandpass filtering and switching-off functionality (QCFS). The QCFS concept is based on two tunable unilateral frequency-selective stages (UFSs), which are integrated with a Wilkinson divider and microstrip resonators. The UFSs in combination with Wilkinson divider facilitates fully-directional signal transmission in each of the Tx/Rx paths of the QCFS. Microstrip resonators and resonant stages are added to facilitate highly-selective bandpass filtering (BPF) and create transmission zeros (TZs). By tuning their resonances, center frequency and bandwidth tunability can be achieved. An intrinsic-off function is also facilitated by moving the TZs at the center frequency of the passband. For experimental validation purposes, a QCFS was designed, manufactured, and measured at L band. In its direction of propagation, it exhibits a three-pole/two-TZ frequency-selective response with center frequency tuning between 1.4 to 1.8 GHz and insertion loss (IL) ranging from 1.6 to 4.3 dB, fractional bandwidth tuning from 7.5% to 11.3% with IL ranging from 2.5 to 4.3 dB, and RF switching with more than 30 dB isolation. In the reverse direction, it facilitates an isolation between 25-39 dB within the entire center frequency tuning range.**

***Keywords* — Quasi-circulator, directional filter, non-reciprocal filter, unilateral filter, RF co-design.**

I. Introduction

Driven by the need for improved spectrum utilization, emerging applications such as joined communication and sensing (JCAS) and in-band full-duplex (IBFD) communications aim to use the same or closely spaced frequency bands requiring high levels of isolation [1]. Moreover, they will need to support multiple frequency bands, while dealing with high levels of interference. Consequently, it is essential to incorporate RF components that are tunable, and provide the required selectivity and isolation between the different RF front-end functions.

Unilateral or non-reciprocal RF components, such as circulators, isolators and gyrators facilitate isolation. However, traditional integration concepts using ferrites are expensive and bulky due to their dependence on ferrite materials requiring external magnetic biasing [2]. To address these size constraints and enable integration with chip-scale devices, non-magnetic circulators are under investigation [3]. However, they consume power and don't provide any filtering selectivity or adaptivity.

To further enable miniaturization in the RF front-end, co-design techniques and the development of multifunctional RF components are viable strategies. In the realm of RF filters, co-design techniques are increasingly being explored for integration with various components such as isolators [4] and circulators [5]-[7]. Notably, the integration of filters and circulators primarily involves transistor-based configurations and spatio-temporally modulated (STM) resonator arrays. Transistor-based configurations utilize the unilateral properties of transistors to achieve directionality, exhibiting insertion loss (IL) of 4.3 dB with high power consumption of 284.6 mW and static operating frequency [5]. On the other hand, STM approaches employ modulated passive resonators for the realization of directional transfer functions. While these concepts can be made tunable, their operating frequency is limited up to 1 GHz, with isolation levels of 24-35 dB, IL of 1.75-2 dB, and static operating frequency [6]-[7].

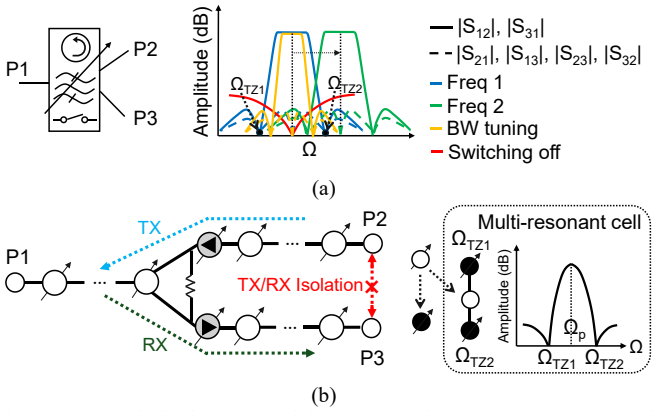


Fig. 1. (a) Symbol of QCFS and its conceptual power transmission and isolation responses demonstrating center frequency, BW tunability, and switch-off capability, and (b) block diagram of tunable RF co-designed QCFS based on a Wilkinson power divider, transistor-based unilateral frequency-selective stages (grey circle with triangle) and passive resonators (white circle), which can be simple resonators or multi-resonant cells.

Considering the aforementioned limitations, this paper introduces a new concept to realize a multi-tunable quasi-circulator with co-designed bandpass filter and switching-off (QCFS) functionality as shown in Fig. 1. It is based on the combination of the unilateral frequency-selective stage (UFS), exhibiting frequency-selective power transmission in the forward direction and signal cancellation in the reverse direction [8]. By cascading a Wilkinson power divider, two or more UFSs, tunable simple resonators and multi-resonant cells which create transmission zeros (TZs), a highly selective QCFS can be realized with center frequency and bandwidth (BW)

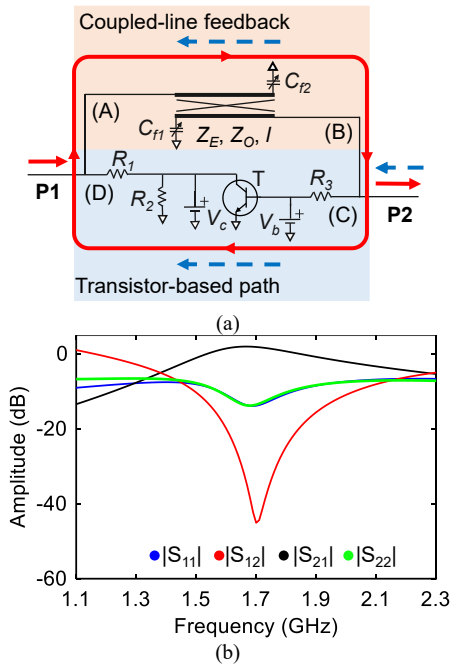


Fig. 2. (a) Circuit schematic of the tunable UFS based on coupled-line feedback. T: BFU760F, V_b = 0.78 V, V_c = 0.8 V, C_{f1} =1.14pF, C_{f2} = 1.1 pF, R_1 = 63.5 Ω, R_2 = 18 Ω, R_3 = 58 Ω, Z_E = 163 Ω, Z_O = 64 Ω, l = 36° at 1.7 GHz. (b) Circuit-simulated S-parameters of the UFS at 1.7 GHz.

tunability and intrinsic-off functionality. The structure of the paper is as follows: Section II outlines the operating principles of the tunable QCFS concept. The experimental validation of the concept is discussed in Section III. Finally, Section IV summarizes the main contributions of this work.

II. Theoretical Foundations

A. Tunable unilateral frequency-selective stage (UFS)

The circuit schematic and S-parameters of an example UFS designed at 1.7 GHz are depicted in Fig. 2(a) and (b) respectively. It consists of two parallel branches, namely a: i) a transistor-based branch, comprising a transistor and a resistive attenuating and matching network, and ii) a coupled line section introducing a phase delay [8]. The unilateral properties of the transistor lead to distinct power transmission characteristics in each direction of the UFS: forward (from P1 to P2) and reverse (from P2 to P1). In the reverse direction, signal attenuation occurs when the RF signals from the transistor-based path and the feedback reach P1 with a phase difference close to 180°, cancelling each other out (red trace in Fig. 2(b)). Conversely, in the forward direction, the RF signal from P1 reaches P2 after traversing a loop formed by the feedback in series with the transistor-based path. When this loop has a zero phase, RF signals at P2 add up in phase (shown by the black line in Fig. 2(b)). Additionally, deviation from the center frequency weakens the balance of the RF signals that pass through the two paths, resulting in a frequency-dependent power transmission response within the UFS. Center frequency tunability of the UFS can be achieved by adjusting the capacitances loaded on the coupled line section and by modifying the bias voltage of the transistor.

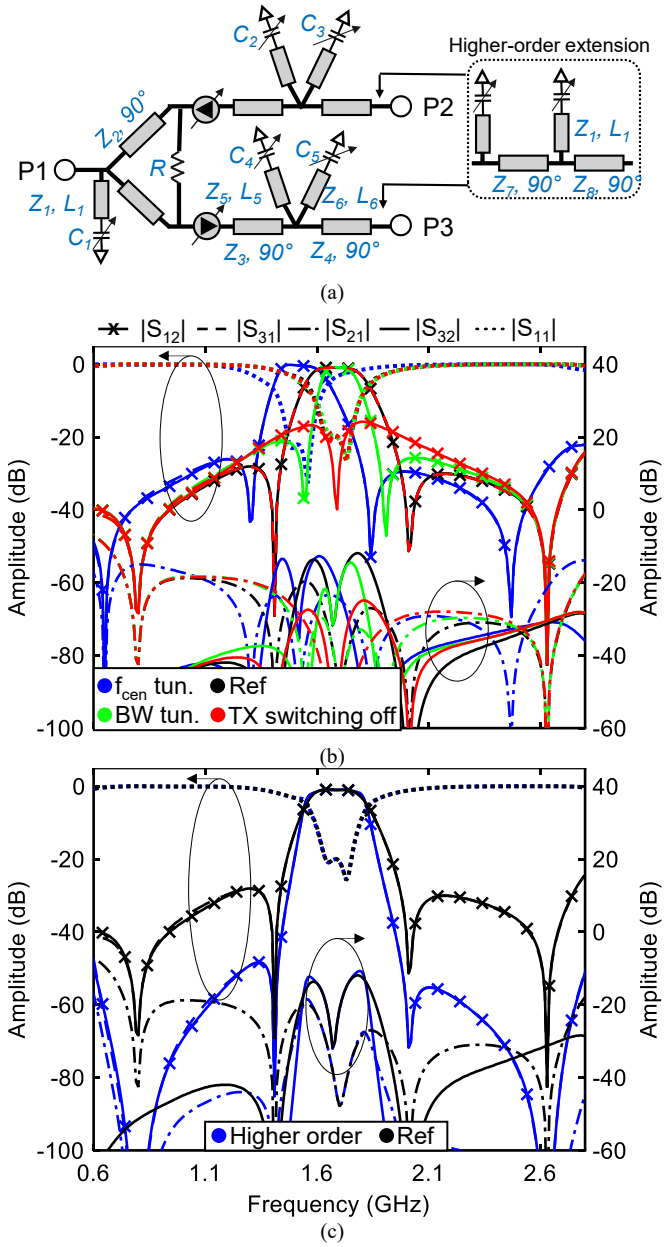


Fig. 3. (a) Block diagram of reference QCFS that comprises two UFS, one half-wavelength and two multi-resonant microstrip resonators, with option of high-order extension. (b) Circuit-simulated center-frequency, BW tuning, TX switching off responses of (a). (c) Comparison with higher-order design. Z_1 = 13.5 Ω, L_1 = 137 °, Z_2 = 61 Ω, Z_3 = 28 Ω, Z_4 = 25 Ω, Z_5 = 55 Ω, L_5 = 27 °, Z_6 = 48 Ω, L_6 = 55 °, Z_7 = 58 Ω, Z_8 = 52 Ω, R = 123 Ω. For Ref case: C_1 = 7.2 pF, C_2 = C_3 = C_4 = C_5 = 2.3 pF; for f_{cen} tuning case: V_b = 0.785 V, V_c = 0.56 V, C_{f1} =1.49 pF, C_{f2} = 1.44 pF, C_1 = 14 pF, C_2 = C_3 = C_4 = C_5 = 2.8 pF; for BW tuning case: C_2 = C_4 = 2.6 pF, C_3 = C_5 = 1.8 pF; for TX switching off case: C_2 = 3.4 pF, C_3 = 1.4 pF.

B. Tunable RF co-designed QCFS

Having designed the UFS, the QCFS can be created by connecting two reversely oriented UFSs at the two output ports of a Wilkinson divider and tunable resonating elements. The tunable resonating elements can be either simple resonators (creating one pole each) or multi-resonant cells (creating one pole and two TZs) as shown in Fig. 1(a). Among them, a

resonator is added at P1 to increase the selectivity of both transmission paths through pole sharing. Their selectivity can be further increased by adding resonators or multi-resonant stages in-series with the UFS resonators.

Fig. 3(a) illustrates an example case of a QCFS (reference design) whose transmission paths functionalize a filtering response having three poles and two TZs. It comprises a Wilkinson divider, one $\lambda_g/2$ microstrip resonator (placed at the junction of the Wilkinson divider), two UFSs, and two microstrip multi-resonant cells. In the reference QCFS, the UFS enhances signal transmission from P2 to P1 and from P1 to P3 while it cancels the signals from P1 to P2 and from P3 to P1. Isolation between P2 and P3 is enhanced due to the presence of the Wilkinson divider. Whereas the $\lambda_g/2$ resonator adds a pole in each path, the multi-resonant cell realized by two $\lambda_g/4$ resonators adds one pole and two TZs [9]. Therefore, a three-pole transfer function is realized in the transmission from P2 to P1 and from P1 to P3.

The tuning capabilities of the reference QCFS design are provided in Fig.3(b) with its tuning parameters being listed in the caption. f_{cen} tuning is obtained by synchronously tuning all poles towards higher/lower frequencies by decreasing/increasing all C_1-C_5 and tuning f_{cen} of UFS. BW tunability at f_{cen} is realized by asynchronously tuning the TZs through C_2-C_5. The TZs created by the multi-resonant cell can facilitate switching-off of the TX or the RX path. Taking TX ($|S_{12}|$) switching-off as an example, by moving TZs to the center frequency of 1.7 GHz through C_2 and C_3, the TX signal transmission ($|S_{12}|$) is suppressed, as shown in Fig. 3(b). It should be noted that although RX is switched off, the TX path can maintain almost the same transfer function. Similarly, the RX can be switched off by tuning C_4 and C_5. Moreover, both the TX and RX can be switched off by tuning C_2-C_5. These are shown in the measurements.

The QCFS concept can also be extended to a higher-order transfer functions by cascading two more resonators. This is shown in the dashed block in Fig. 3(a) and the resulting circuit creates a five-pole/two-TZ transfer function in each of each transmission paths. A comparison between the reference QCFS and higher-order QCFS are shown in Fig. 3(c), in which the higher-order QCFS gives higher selectivity and out-of-band rejection.

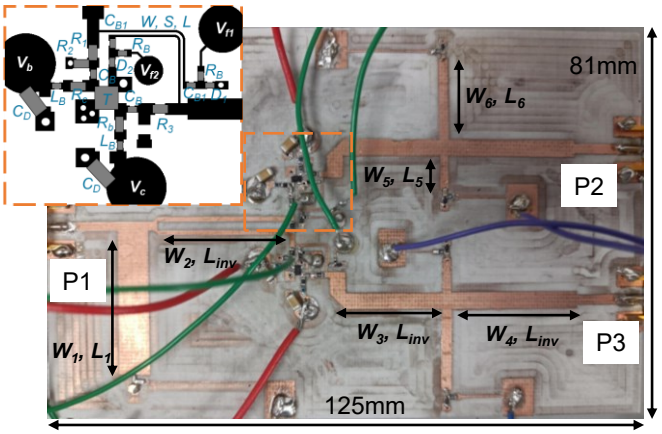


Fig. 4. Photograph of the manufactured QCFS prototype. The UFS components are listed as follows. T: BFU760F, D_1&D_2: SMV1405, R_b = 511 Ω, R_c = 0 Ω, L_B = 30 nH, C_D = 220 μF, C_B = 100 pF, C_{B1} = 3 pF, R_B = 10 MΩ, R_1 = 57.6 Ω, R_2 = 14 Ω, R_3 = 46.4 Ω, coupled line: W = 0.2 mm, S = 0.2 mm, L = 11 mm. Other dimensions are listed as follows. W_1 = 6.5 mm, L_1 = 30 mm, W_2 = 1 mm, L_{inv} = 26.5 mm, W_3 = 3.1 mm, W_4 = 3.3 mm, W_5 = 1.5 mm, L_5 = 7 mm, W_6 = 1.9 mm, L_6 = 17 mm. Varactors in reciprocal resonators: MA46H072 (left side) and four SMV1405s (right side).

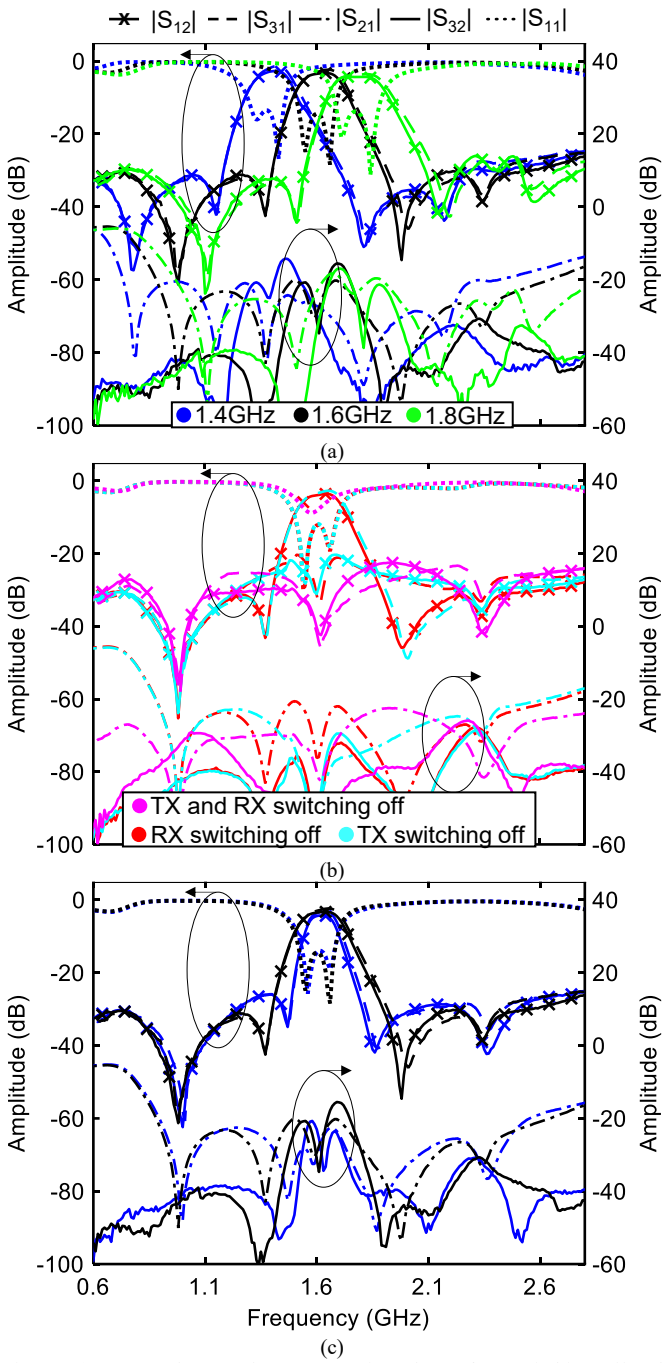


Fig. 5. (a) Measured center frequency tuning, (b) RX/TX switching-off and (c) BW tuning response.

III. Experimental Validation

To validate the concept, the QCFS with three-pole/two TZ transfer function was designed, manufactured, and tested at L

Table 1. Comparison of the proposed QCFS with state-of-the-art circulators.

Ref.	Technique	Freq. (GHz)	Insertion of TX/RX (dB)	Tx-Rx max IS (dB)	RX NF (dB)	TX IIP3 (dBm)	P_{DC} (mW)	Size (λ×λ)	Filt.	Tun.
[3]	Active, MMIC	24	-5.7	>20	10.1	NA	7.2	0.1×0.044	No	No
[10]	Active, MMIC	6.3	10.5/-5	>30	20	20	415	0.034×0.02	No	f_{cen}
[5]	Active, MMIC	8.7	-4.3	15.9	NA	25.2	284.6	0.053×0.082	Yes	No
[11]	Active, PCB	3.2	7/4.8	36	5.2	NA	830	0.34×0.38	No	f_{cen}
[7]	STM, PCB	1	-2	24	2.5	31	N/A	0.043×0.037	Yes	f_{cen};
[2]	Ferrite	38	-4	>18	N/A	N/A	N/A	1.5×2	No	No
This work	Active, PCB	1.6	-3.3/-2.7	34	11.7	-2	25.4	0.67×0.43	Yes	f_{cen}; BW; Off

Filt.: filtering capabilities; Tun: tuning capabilities; f_{cen}: center frequency tuning capability; Off: switching off capability.

band. The design was performed with full-wave electromagnetic (EM) post-layout simulations using software packages Advanced Design System (ADS) from Keysight and High-Frequency Structure Simulator (HFSS) from ANSYS. The prototype was fabricated on a Rogers RO4003C substrate with a thickness of 0.813 mm, dielectric permittivity of 3.55, and a dielectric loss tangent of 0.0027. The RF performance of the QCFS was characterized in terms of S-parameters, noise figure (NF), and third-order input intercept point (IIP3) using an N5244A PNA-X Network Analyzer from Keysight.

The manufactured prototype and utilized SMD components are depicted in Fig. 4. The capacitance tuning elements are implemented using varactors in series with a DC block (C_B) and a DC feed (R_B). Center-frequency tunability is shown in Fig. 5(a) with the following performance characteristics: f_{cen} tuning from 1.4-1.8 GHz, IL between 2.8-4.3 dB for the TX and between 1.6-3.6 dB for the RX and maximum isolation (IS) from 25 to 39 dB. At 1.6 GHz, the NF was measured 11.7 dB, and the IIP3 of -2 dBm. As discussed in [8], the UFS can be designed to have alternative levels of gain, however at the expense of NF. In this case, it has been designed for a gain of 1.3 dB and an NF of 6.2 dB based on EM simulation. Fig. 5(b) shows the RX (and TX) switching off, with isolation larger than 30 dB. BW tuning is depicted in Fig. 5(c), in which IL ranges from 2.5 to 4.3 dB by tuning BW from 7.5% to 11.3% IL.

A comparison with state-of-the-art circulators is shown in Table 1. As evidenced, this is the only multi-functional circulator having the RF co-designed functionality of a filter alongside multiple levels of tunability including f_{cen}, BW, and intrinsic switching-off. When compared with ferrite-based circulators [2], the QCFS exhibits smaller size, filtering, and tunability. Although the active approaches in [5] and [10] realize either filtering or frequency tuning capabilities, their power consumption is high. Compared with STM-based approaches in [7], it can operate at a higher frequency and has additional tuning capabilities.

IV. Conclusion

This paper presents a tunable multi-functional RF component, integrating the functionalities of a quasi-circulator, a multi-tunable bandpass filter, and an RF switch. The proposed QCFS concept is based on transistor-based UFS incorporated with a Wilkinson divider and frequency-tunable capacitively loaded microstrip resonators. It facilitates a highly selective filtering transfer function in the TX and RX paths with f_{cen} and BW tuning and intrinsic switching-off while achieving high levels of IS between the TX and RX paths. The concept has been experimentally validated at L band.

Acknowledgment

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