# RF Co-Designed Bandpass Filter/Circulator With Tunable Center Frequency, Bandwidth, and Out-of-Band Isolation

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Abstract—This letter reports on a new type of miniaturized RF co-designed bandpass filter/circulator (BPFC). Miniaturization is achieved by: 1) capacitively loading a multi-mode ferritebased disk resonator; 2) combining the function of an RF circulator and a bandpass filter (BPF) within the volume of a single microwave component; and 3) by tuning its transfer function. The proposed BPFC exhibits a quasi-elliptic power transmission response in the forward direction—passband inbetween four transmission zeros (TZs)—and an all-stop response in the reverse one. Reconfigurability is achieved by tuning the capacitive loads of the ferrite disk and the mixed electromagnetic coupling elements in the RF input/output. For proof-of-concept validation purposes, an S-band tunable prototype was designed, built, and measured. It demonstrated multiple levels of tuning. These include the frequency tuning of 1.27:1, the bandwidth tuning of 1.73:1, the out-of-band isolation tuning, and intrinsic switching-off.

Index Terms—Bandpass filter (BPF), circulator, miniaturization, reconfigurability, tunable circulator, tunable filter.

# I. Introduction

RECENT advances in wireless communication and radar systems call for RF front ends with simultaneous transmit and receive (STAR) capabilities and the ability to cover a wide range of communication bands. In order to facilitate their deployment, non-reciprocal components must be incorporated in the RF front end to enable high isolation between the transmit and receive chains. Furthermore, tunable bandpass filters (BPFs) are needed in these systems to dynamically access the different bands of operation while suppressing interference and noise. However, the practical development of STAR systems remains a great challenge due to the lack of compact non-reciprocal passive components [1].

To miniaturize the RF front end, reconfigurability of passive components has been thoroughly examined within the past two decades. Current research efforts are focusing on the realization of BPFs with multiple levels of RF tuning [2]–[4]. Tunability of non-reciprocal components, such as frequency-selective isolators [5] and quasi-circulators [8], has also

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been presented using spatio-temporally modulated resonators (STM) [5]–[7] and transistor-based stages [8].

In yet another approach, RF front-end miniaturization is targeted through the RF co-design and reconfigurability of passive components and antenna elements [9]-[18]. Example demonstrations include the co-design of BPFs with power dividers [9], [10], impedance transformers [2], and antennas (i.e., filtennas) [18]. An example case of an RF co-design BPF/circulator (BPFC) was also shown in [11]. However, it exhibits static operational characteristics. Building upon this concept, the focus of this letter is on the design and practical development of a highly reconfigurable and miniaturized BPFC with multiple levels of transfer function tunability that is reported in this work for the first time. These include tunability in terms of center frequency, out-of-band isolation, bandwidth (BW), and intrinsic switching-off, as shown in Fig. 1. The major function of the proposed BPFC component is to replace the circulator and its neighboring filters in the RF front end with a single multi-functional RF component. Frequency selectivity and non-reciprocity are obtained by: 1) utilizing a capacitively loaded multi-mode ferrite disk resonator and 2) introducing parallel LC resonators in the input and output ports of the device. In this manner, a quasielliptic power transmission response shaped by two poles and four transmission zeros (TZs)—TZ<sub>1</sub>-TZ<sub>4</sub>—is obtained in the forward direction and an all-stop response in the reverse one.

# II. THEORETICAL FOUNDATIONS

# A. Miniaturized Non-Reciprocal Resonant Cavity

The block diagram and 3-D EM model of the miniaturized non-reciprocal resonator is shown in Fig. 2(a). It comprises a ferrite-based disk resonator that is capacitively loaded at its periphery through three inserts (length  $N_L$  and width  $N_w$ ) and three lumped capacitors  $C_R$ 's. The design starts by selecting the dimensions of the unloaded resonator (i.e., without the capacitive loads) using the design methods in [19] and (1) and (2), where D is the ferrite diameter,  $\varepsilon_r$  and  $\mu_{r,\text{eff}}$  are the material properties of the ferrite,  $f_m$  is the magnetization saturation frequency, and  $f_g$  is the gyromagnetic frequency. As such, for a center frequency of 3 GHz, the resonator diameter D needs to be initially selected equal to 13.6 mm. Afterward, by adding the insert and loading it with capacitor  $C_{R_1}$  the resonator diameter can be made smaller due to the capacitive load that results in a lower operating frequency. For example, for  $C_R = 1$  pF, D needs to be altered to 7.4 mm, resulting in a 70.4% smaller area compared with the unloaded case, for a

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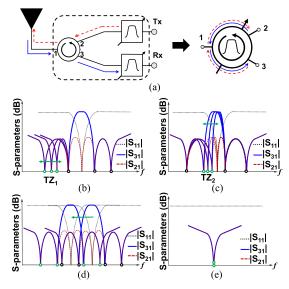


Fig. 1. (a) Conventional STAR RF front-end module in which the transmit and receive chains are separated by a circulator and two reconfigurable filters, and the proposed multi-functional BPFC that exhibits: 1) a tune-all quasi-elliptic transfer function [see (b)–(e)] in its forward direction (e.g.,  $|S_{31}|$ ,  $|S_{23}|$ , and  $|S_{12}|$ ) that is shaped by two poles and four TZs and 2) an all-stop response with five TZs in the reverse directions (e.g.,  $|S_{21}|$ ,  $|S_{32}|$ , and  $|S_{13}|$ ). (b)–(e) Tune-all capabilities of the BPFC. (b) Out-of-band isolation tuning by altering the location of TZ<sub>1</sub>. (c) BW and out-of-band isolation tuning by altering the location of TZ<sub>2</sub>. (d) Center frequency by altering the location of the poles and TZs. (e) Intrinsic switching-off by canceling the poles through TZs.

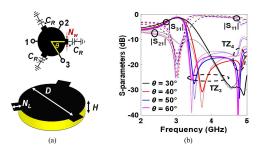


Fig. 2. (a) Top view and bird-eye view of the circuit schematic and the 3-D EM model of the miniaturized non-reciprocal disk resonator made up of a capacitively loaded ferrite disk. The disk is symmetrically loaded by three inserts and  $C_R$  loads ( $N_L=1$  mm,  $N_w=1$  mm, and  $C_R=1$  pF).  $C_R$  is angularly separated from the RF ports by  $\theta$ . (b) S-parameters of the non-reciprocal capacitively loaded ferrite-based cavity resonator as a function of  $\theta$ .

TransTech TT1-105 ferrite disk biased under 0.178 T

$$D = 1.84 /_{\pi} f_0 \sqrt{\varepsilon_r \mu_{r,\text{eff}}}; \quad f_{\pm} = f_0 \left( 1 \pm 0.418 \frac{\kappa}{\mu} \right)$$
 (1)

$$\kappa = \mu_0 \frac{f_0 * f_m}{f_g^2 - f_0^2}; \quad \mu = \mu_0 \left( 1 + \frac{f_g * f_m}{f_g^2 - f_0^2} \right). \tag{2}$$

To illustrate the functionality of the capacitively loaded ferrite-based disk resonator, an example case is shown in Fig. 2(b) where the RF input/output feeds of the device have been materialized as  $50-\Omega$  microstrip transmission lines on a Rogers 4350B substrate. As shown, the capacitively loaded ferrite resonator exhibits a frequency-selective response with an out-of-band region shaped by two TZs (TZ<sub>3</sub> and TZ<sub>4</sub>). Their locations can be reconfigured by altering the angular distance  $\theta$  of the insert from the input/output ports. Note that

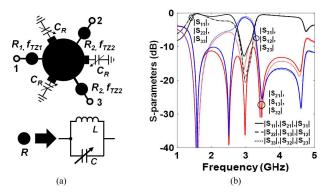


Fig. 3. (a) Block diagram and (b) S-parameter response of the capacitively loaded ferrite disk resonator with mixed EM couplings (S-parameters of the 3-D EM model). The mixed couplings are realized with parallel *LC* resonators in the input/output ports.

the smallest value of  $\theta$  is limited (30° in this case) by the insert dimensions and the width of the RF input/output port.

# B. Multi-Level Tunable Quasi-Elliptic Bandpass Filter

Considering that the capacitively loaded ferrite disk resonator creates a transfer function in the forward direction that is shaped by two poles and two TZs above the passband, additional TZs can be added at lower frequencies by introducing mixed EM coupling elements at the RF input/output ports. As shown in Fig. 3(a), they are materialized by parallel LC resonators,  $R_1$  and  $R_2$ , which are, respectively, set to resonate at the location of the desired TZs  $(TZ_1 \text{ and } TZ_2)$ while maintaining good match and out-of-band performance. Example response of the quasi-elliptic BPFC concept with two poles and four TZs in its forward direction and five TZs in its reversed directions is illustrated in Fig. 3(b). It has been designed by considering the design tradeoffs in Fig. 4(a) and (b). As shown in Fig. 4(a),  $N_W$  controls the inter-mode coupling, which subsequently controls the passband BW. The minimum achievable BW state is determined by the widest achievable  $N_W$ , which is restricted by the angular spacing of the RF posts. Furthermore, the matching levels in the passband and the out-of-band isolation levels are controlled by  $R_1$  and  $R_2$ . For example, by increasing the capacitance of  $R_1$  and  $R_2$ , but keeping the location of the TZs constant (i.e., L of the resonator is selected to resonate at  $f_{TZ}$ ), the outof-band isolation decreases, whereas the matching levels in the passband increase, as shown in Fig. 4(b), for the example case of  $C_2$ . Furthermore, by changing the locations of  $TZ_1$  and  $TZ_2$ , the out-of-band isolation and the passband BWs can be altered [see Fig. 1(b) and (c)].

Tunability in the forward direction of the BPFC can be obtained by altering  $C_R$ ,  $R_1$ , and  $R_2$ . The tuning capabilities are conceptually shown in Fig. 1. In particular, Fig. 1(b) illustrates how the out-of-band isolation can be altered by tuning  $TZ_1$ , which is controlled by the capacitance  $C_1$  of  $R_1$  in Fig. 3. BW tuning in Fig. 1(c) can be obtained by tuning  $TZ_2$  by altering the capacitance  $C_2$  of  $R_2$  in Fig. 3. Furthermore, the center frequency in Fig. 1(d) can be obtained by tuning  $C_1$ ,  $C_2$ , and  $C_R$  in Fig. 3. Moreover, the transfer function can be intrinsically switched-off [see Fig. 1(e)] by setting  $TZ_1$  and  $TZ_2$  right above the passband by altering  $C_1$  and  $C_2$  in Fig. 3.

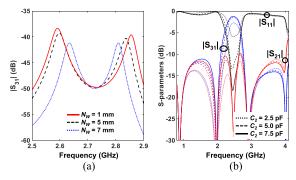


Fig. 4. (a) Inter-mode coupling control with  $N_W$ . (b) In-band matching and out-of-band isolation control with varying  $C_2$ .

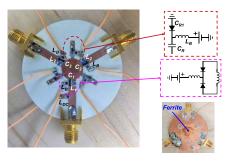


Fig. 5. Photograph of the manufactured prototype of the BPFC along with the circuit schematics of its tuning elements. The following components were used:  $L_{\rm DC}=120$  nH,  $L_B=120$  nH,  $C_1={\rm SMV}1281$ ,  $C_2={\rm SMV}1281$ ,  $C_{R1}={\rm SMV}1232$ ,  $C_R=2.4$  pF,  $L_1=10$  nH, and  $L_2=2.5$  nH. The ferrite is implemented by a TransTech TT1-105 circular puck with a radius of 4.97 mm.

TABLE I
COMPARISON WITH SOA BPFCS AND NON-RECIPROCAL BPFS

Ref.	Appr.	f <sub>cen</sub> (GHz)	IS Range (dB)	S <sub>21</sub>   Range (dB)	FC	No. of TZs/TZ tuning range	$f_{cen}$ /BW tuning ranges	Int. Sw.
[5]	STM	0.14	~20 to 25	-3.7 to -4.1	Yes	0/No	1.2:1/No	No
[7]	STM	1	20 to 23.2	-3.9 to -4.6	Yes	2/No	1.16:1/No	No
[11]	Fer.	2.5	30	-1.4	Yes	4/No	No/No	No
This work	Fer.	3	11.5 to 33.1	-2.7 to -4.5	Yes	4/1.3:1& 1.35:1	1.3:1/ 1.73:1	Yes

Fer.: Ferrite, FC: Filtering capabilities, Int. Sw.: Intrinsic switching

# III. EXPERIMENTAL VALIDATION

To evaluate the validity of the RF co-designed BPFC concept, a tunable *S*-band prototype was designed, manufactured, and measured. It was designed on a Rogers 4350B substrate using ANSYS HFSS. The ferrite puck that was used in the prototype was a TransTech TT1-105. Skyworks varactors SMV1232 and SMV1281 were used as tuning elements. A photograph of the manufactured prototype along with the bias networks is shown in Fig. 5.

The RF measured transfer functions of the BPFC with multiple levels of tuning are shown in Fig. 6. In particular, Fig. 6(a) shows the out-of-band isolation tunability by altering  $f_{\rm TZ1}$ . The measured RF performance and EM-simulated S-parameters for one state (State 1) are also shown in the same figure and are in good agreement, successfully validating the operating principles of the co-designed BPFC concept. BW tunability is demonstrated in Fig. 6(b) by altering  $f_{\rm TZ2}$ . In

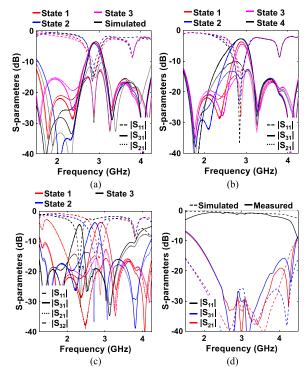


Fig. 6. RF measured S-parameters of various reconfigurable states. (a) Out-of-band isolation tuning by altering  $TZ_1$  and a comparison with EM-response of a symmetric state. (b) BW tuning by altering  $TZ_2$ . (c)  $f_{cen}$  tuning by reconfiguring  $C_R$  and the capacitance of  $R_1$  and  $R_2$ . (d) Intrinsic switching-off.

particular, the fractional BW (FBW) was tuned from 9.7% to 17.7% (1.73:1). Furthermore, center frequency tuning in Fig. 6(c) is achieved by changing  $R_1$ ,  $R_2$ , and  $C_R$ , exhibiting a tuning range of 1.27:1. Finally, intrinsic switching-off is demonstrated in Fig. 6(d). While a finite number of states are provided in Fig. 6, the BPFC exhibits continuously tunable transfer function characteristics. A comparison of the BPFC and other state-of-the-art RF co-designed BPFCs and tunable non-reciprocal BPFs is provided in Table I. As shown, the BPFC is the only co-designed non-reciprocal RF component with tune-all filtering capabilities and wide levels of RF tuning. As shown, it can be tuned in terms of center frequency and BW, and it can be intrinsically switched-off. Furthermore, it has increased out-of-band isolation through the presence of TZs, which is reported in this work for the first time. Compared to tunable BPFs using varactors [12]-[17], it exhibits comparable IL (2.38-5.52 dB in [14]), has more TZs in the out-of-band (four TZs versus a maximum of two TZs in [17]), and has the added functionality of an RF isolator, leading to significantly smaller STAR RF front ends.

# IV. CONCLUSION

This letter discussed the RF design and operational characteristics of a new class of an RF co-designed component that exhibits the function of a circulator and a tunable BPF. The proposed concept allows the realization of a quasi-elliptic power transmission response in the forward directions and an all-stop response in the reverse ones. We showed that multiple levels of RF tuning can be obtained by reconfiguring the capacitive loading of the ferrite-based cavity and its coupling to the RF input/output ports.

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