Abstract: In this paper, a novel intrinsically switched tunable bandpass filter based on a dual-mode T-shaped varactor-loaded resonator is presented. The varactors loaded in the T-shaped resonator are capable of efficiently tuning the resonant frequencies of the even and odd modes, as well as the transmission-zero frequency. Without any additional RF switches, the passband of the filter can be intrinsically switched off by adjusting the transmission zero to the resonant frequencies. In the switch-on state, the constant absolute bandwidth (CABW) or constant fractional bandwidth (CFBW) passband can be achieved by controlling the frequency space between the two resonances. For a demonstration, a 0.8–1.1 GHz intrinsically switched tunable bandpass filter with 74 MHz CABW or 8.5% CFBW was fabricated and tested. In the whole operating band with $|S_{11}| < 10$ dB, the insertion losses for CABW and CFBW are better than 3.3 dB and 3 dB, respectively, and the isolations are better than 20 dB in the switch-off state. The measured results have a good agreement with simulated results, which verifies the design theory.

Keywords: tunable filter; intrinsic switch; CABW; CFBW

1. Introduction

Reconfigurable filters have been extensively applied in the frequency-agile and software-defined radio systems due to their adjustable operating performance [1,2]. To meet the requirement of having constant passband characteristics in the whole tuning range, center-frequency-tunable bandpass filters with CABW or CFBW have been reported. Two methods are always used to achieve CABW or CFBW. The first way is to control the coupling strength by using varactors or selecting a proper coupling region [3–7]. The other method is to control the distance between the in-band transmission poles [8,9].

To adapt to complex operating environment, reconfigurable filters with switching capability have aroused a wide attention recently. By using the pin diodes as switches, the proposed filters in [10–14] can be operated in four states. Through utilizing combinations of pin diodes and varactors, the center-frequency-tunable filters can be switched in on/off state or in high/low passband [15,16]. However, it is worth noting that switching the pin diodes requires extra control voltages.

In order to reduce the number of external control variables and simplify the control complexity, intrinsically switched tunable bandpass filters are proposed [17]. In these structures, the off states can be obtained by the tuning elements which are also used to tune the center frequencies, bandwidths or coupling coefficients. Normally, two typical methods are utilized to realize intrinsically switched function. One way to switch off the passband is by changing the varactors embedded between the resonators that can control the coupling coefficients of the filters [17–19]. However, the magnetic coupling between the resonators has to be generated in these works in order to cancel the negative electric coupling from the coupling varactors. The other efficient way is to use the transmission zeros to switch off the passbands constructed by the spacing between transmission zeros [20–22]. However, these bandpass filters require more cascaded bandstop filters to realize wide out-band suppression.
In this paper, a novel intrinsically switched tunable bandpass filter with CABW/CFBW properties based on dual-mode varactor-loaded T-shaped resonator is presented. The varactors, in which the resonant frequencies are able to be tuned, adjust the transmission zero and switch off the passband, simultaneously. In addition, a feature of tunable passband with CABW/CFBW can be achieved by controlling the resonant frequencies and the spacing between them. As a demonstration, a prototype of a 0.8–1.1 GHz tunable 74 MHz CABW or 8.5% CFBW filter with intrinsically switchable function is developed and characterized. The proposed design possesses multiple functions only realized by two control voltages, which can simplify the control complexity extensively.

2. Filter Design and Analysis

2.1. Transmission Line Model Analysis

The schematic diagram of the proposed filter is provided in Figure 1a, which consists of a dual-mode T-shaped resonant loaded with two types of varactors (C_1 and C_2) and a pair of feed lines. The capacitor C_b and resistor R_b are applied as dc block and dc bias, respectively.

Due to the symmetrical structure, the odd–even mode method is utilized to analyze the proposed filter [23,24]. In order to simplify the analysis process of the dual-mode T-shaped resonator, the basic transmission line model of the proposed resonator is presented in Figure 1b, ignoring the influences of C_b and R_b, where Y_1, Y_2 and Y_3 are the characteristic admittances and θ_1, θ_2 and θ_3 are the electrical lengths.

The odd- and even-mode equivalent circuits are illustrated in Figure 1c,d, respectively, the input admittances of the odd- and even-mode can be derived by the following equations:

\[
Y_{\text{odd}1} = -jY_1\cot\theta_1 \times 2\pi fC_1/(−Y_1\cot\theta_1 + 2\pi fC_1) \quad (1)
\]

\[
Y_{\text{odd}} = -jY_3\cot\theta_3 + Y_{\text{odd}1} \quad (2)
\]

\[
Y_{\text{even}1} = Y_3(Y_{\text{odd}1} + jY_3\tan\theta_3)/(Y_3 + jY_{\text{odd}1}\tan\theta_3) \quad (3)
\]

\[
Y_{\text{even}2} = (Y_1/2)(2\pi fC_2 + jY_2\tan\theta_2)/(Y_2 - 2\pi fC_2\tan\theta_2) \quad (4)
\]

\[
Y_{\text{even}} = Y_{\text{even}1} + Y_{\text{even}2} \quad (5)
\]
Under the resonance condition ($\text{Im} (Y_{\text{odd}}) = 0$ and $\text{Im} (Y_{\text{even}}) = 0$), the resonant frequencies can be extracted by Equations (1)–(5). It can be observed that odd-mode resonant frequency $f_{\text{odd}}$ is only controlled by $C_1$, and the even mode resonant frequency $f_{\text{even}}$ is determined by $C_1$ and $C_2$ at the same time. Moreover, the transmission zero produced by the shunt stub taped with $C_2$ can be used not only to improve the selectivity of bandpass filter as the normal way but also to switch off the passband. The input admittance of the shunt stub taped with the varactor $C_2$ can be derived by:

$$Y_{\text{zero}} = Y_2 (j2\pi f_2 + jY_3 \tan \theta_2)/(Y_2 - 2\pi f_2 \tan \theta_2)$$  \hspace{1cm} (6)

From Equation (6), it is observed that the frequency of transmission zero $f_{\text{zero}}$ can be deduced under the condition ($Y_2 - 2\pi f_2 \tan \theta_2 = 0$), which indicates that $f_{\text{zero}}$ can be adjusted by $C_2$.

Table 1 shows the tuning ranges of $f_{\text{even}}$ and $f_{\text{odd}}$ as $C_1$ and $C_2$ vary. $Y_1 = 0.01 \, \text{S}, Y_2 = Y_3 = 0.02 \, \text{S}, \theta_1 = 55^\circ, \theta_2 = 25^\circ$ and $\theta_3 = 5^\circ$ at 1 GHz.

| $C_1$ & $C_2$ (pF) | $f_{\text{odd}}$ (GHz) | $f_{\text{even}}$ (GHz) |
|-----------------|-----------------|-----------------|
| $C_1 = 0.6$     | $C_2 = 2–12$    | 1.188           |
| $C_1 = 1.1$     | $C_2 = 2–12$    | 0.994           |
| $C_1 = 1.6$     | $C_2 = 2–12$    | 0.870           |
| $C_1 = 2.2$     | $C_2 = 2–12$    | 0.754           |

![Figure 2](image_url) **Figure 2.** $f_{\text{even}}, f_{\text{odd}}$ and $f_{\text{zero}}$ Versus $C_1$ and $C_2$. $Y_1 = 0.01 \, \text{S}, Y_2 = Y_3 = 0.02 \, \text{S}, \theta_1 = 55^\circ, \theta_2 = 25^\circ$ and $\theta_3 = 5^\circ$ at 1 GHz.

2.2. Analysis of $f_C$, $BW$ and $Q_e$

According to the filter synthesis method in [25,26], the center frequency $f_C$ and bandwidth $BW$ of the passband are estimated by Equations (7) and (8):

$$f_C = (f_{\text{odd}} + f_{\text{even}})/2$$  \hspace{1cm} (7)

$$BW = f_{\text{even}} - f_{\text{odd}}$$  \hspace{1cm} (8)
In Figure 3, the weak coupling transmission line responses are investigated. As indicated above, through tuning $C_1$ and $C_2$, the separation between $f_{\text{odd}}$ and $f_{\text{even}}$ can be suitable for 74 MHz CABW and 8.5% CFBW, respectively.

![Figure 3](image-url)

**Figure 3.** Typical response using week couple (solid line: 74 MHz CABW case; dash line: 8.5% CFBW case).

The external quality factor $Q_e$ of the proposed filter can be extracted by using [26]

$$Q_{ee/ee} = f_{ee/co} / \Delta f_{e/o \pm 90^\circ}$$

(9)

$$Q_e = (Q_{ee} + Q_{ee}) / 2$$

(10)

where $Q_{ee/ee}$ and $\Delta f_{e/o \pm 90^\circ}$ are the even/odd mode external quality factors, resonant frequencies and bandwidths, respectively. In Figure 4, $Q_{e,CABW,\text{min/max}}$ and $Q_{e,\text{CFBW, min/max}}$ mean the minimum/maximum curves of $Q_e$ to realize 74 MHz CABW and 8.5% CFBW with <12 dB return loss, respectively [26].

![Figure 4](image-url)

**Figure 4.** Desired $Q_e$ for 74 MHz CABW and 8.5% CFBW.

2.3. **Current Density Distribution Analysis**

Current density distribution is employed to investigate the effect of being intrinsically switched off [27]. By utilizing the parameters of point A depicted in Figure 2, the filter is switched at 0.994 GHz, and the current density distribution is plotted in Figure 5. As seen, the T-shaped resonator does not allow flowing strong current, representing that the filter’ passband is switched off.
2.4. Designing Produce

The designing produces are as follows:

Step (1) Based on the analysis of even–odd mode and transmission zero, choose the appropriated admittances \((Y_1, Y_2 \text{ and } Y_3)\), electrical lengths \((\theta_1, \theta_2 \text{ and } \theta_3)\), and varactors \((C_1 \text{ and } C_2)\) and calculate the \(f_C\) and \(BW\) to make sure that the tuning range of \(f_{\text{even}}, f_{\text{even}}\) and \(f_{\text{zero}}\) can meet the design requirements of the filter.

Step (2) Calculate the \(Q_e\) in the tuning range needed for specified return loss and bandwidth.

Step (3) Simulate and extract the \(Q_e\) in the whole tuning under different space \(s\) between the resonant and the feedline.

Step (4) Choose the proper \(s\).

3. Experimental Verification

An intrinsically switched tunable filter is designed based on a 0.508 mm thick Rogers RO4350B substrate with a relative dielectric constant of 3.48 and a loss tangent of 0.0037, where the \(f_C\) is tuned in the range of 0.8–1.1 GHz and the bandwidth satisfies 74 MHz CABW or 8.5% CFBW. The design parameters of the T-shaped resonant are chosen as \(Y_1 = 0.01\ S, Y_2 = 0.02\ S, Y_3 = 0.02\ S, \theta_1 = 60^\circ, \theta_2 = 22^\circ\) and \(\theta_3 = 5^\circ\) at 1 GHz. By Equations (9) and (10), the filter’s \(Q_e\) versus \(f_C\) with different \(s\) are extracted in Figure 6, where \(s\) is the spacing between resonant and feed line in Figure 1a. It is noteworthy that, with \(s\) in range of 0.2–0.25 mm, the values of \(Q_e\) basically meet the requirements for 74 MHz CABW and 8.5% CFBW shown in Figure 4 at the same time.

The simulations are conducted by using SONNET software. After optimization, the physical parameters of the filter are determined as in Table 2. The varactors MA46H201 (the capacitance tuning range is about 0.4–2.2 pF) and MA46H204 (the capacitance tuning...
range is about 1.8–20 pF) from M/A COM are employed as $C_1$ and $C_2$, which are controlled by voltages $V_1$ and $V_2$, respectively. $C_b = 30$ pF and $R_b = 10$ kΩ are used as dc block and dc bias, respectively. The photograph of the proposed intrinsically switched tunable filter is displayed in Figure 7. The prototype circuit size of the proposed filter is about $0.31 \lambda g \times 0.11 \lambda g$, where $\lambda g$ is the guided wavelength at the lowest operating frequency (i.e., 0.8 GHz). The measurements are carried out by the ROHDE&SCHWARZ ZVA24 network analyzer.

Table 2. Physical parameters of the proposed filter.

| Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|
| $l_1$     | 18.4       | $w_1$     | 0.5        |
| $l_2$     | 29.8       | $w_2$     | 0.3        |
| $l_3$     | 2.5        | $w_3$     | 1.1        |
| $l_4$     | 7.6        | $w_4$     | 1.1        |
| $s$       | 0.22       |           |            |

Figure 7. The photograph of the proposed filter.

The simulated and measured frequency responses of the proposed prototype with three reconfigurable states are shown in Figure 8. Figure 8a,b depicts the tuning of the center frequency from 0.8–1.1 GHz with 74 MHz CABW and 8.5% CFBW, respectively. It also can be seen that a transmission zero on the upper band edge increases as the center frequency increases in both Figure 8a,b. The measured 3 dB bandwidth of the CABW filter and 3 dB fractional bandwidth of the CFBW filter are 74 ± 1 MHz and 8.5 ± 0.1%, respectively. The measured insertion losses of the CABW filter and the CFBW filter are better than 3.3 dB and 3 dB, respectively, with measured return losses better than 10 dB. Figure 8c presents the responses of passband in intrinsic switch-off state. As shown, the passband can be switched off at 0.8–1.1 GHz by tuning $C_1$ and $C_2$, and the measured isolations are all better than 20 dB. Comparisons with the previously reported switched tunable filter are listed in Table 3. As can be seen, the proposed filter has all the functions of tuning the center frequency, controlling the bandwidth (CABW and CFBW) and switching off the passband, simultaneously. Moreover, it is worth noting that the number of control voltages used in this work is equal to the order of the filter, which can reduce the control complexity of the design.

Table 3. Comparisons with previously reported switched tunable filter.

| Ref No. | Filter Order | Number of Control Voltages | Intrinsic Switching | Center-Frequency Control | Bandwidth Control | IL in Passband (dB) | Isolation in Off-State (dB) | Size ($\lambda_g^2$) |
|---------|--------------|----------------------------|---------------------|--------------------------|------------------|---------------------|----------------------------|----------------------|
| [15]    | 2            | 3                          | No                  | CABW                     | 2.5–4.08         | >43                 | N.A.                       | 0.090                |
| [17]    | 3            | 3                          | Yes                 | CABW                     | <5               | >50                 |                           |                      |
| [19]    | 4            | 5                          | Yes                 | Tunable                  | 3.5–8.5          | >33                 | 0.082                      |                      |
| [22]    | -            | 4                          | Yes                 | Tunable                  | 0.96             | >20                 |                           | N.A.                 |
| This work | 2            | 2                          | Yes                 | CABW/CFBW                | <3.3             | >20                 | 0.035                      |                     |
The measured insertion losses of the CABW filter and the CFBW filter are better than 3.3 dB and 3 dB, respectively, with measured return losses better than 10 dB. Figure 8c presents the responses of passband in intrinsic switch-off state. As shown, the passband can be switched off at 0.8–1.1 GHz by tuning $C_1$ and $C_2$, and the measured isolations are all better than 20 dB. Comparisons with the previously reported switched tunable filter are listed in Table 3. As can be seen, the proposed filter has all the functions of tuning the center frequency, controlling the bandwidth (CABW and CFBW) and switching off the passband, simultaneously. Moreover, it is worth noting that the number of control voltages used in this work is equal to the order of the filter, which can reduce the control complexity of the design.

**Figure 8.** Simulated and measured $S$ parameters for the proposed filter (solid line: measurement; dash line: simulation). (a) Center-frequency tuning with 74 MHz CABW; (b) center-frequency tuning with 8.5% CFBW; and (c) intrinsic switch-off state.

### 4. Conclusions

A novel intrinsically switched tunable filter based on dual-mode T-shaped resonator embedded with varactors is proposed in this paper. The theoretical basis and characterization of proof-of-concept microstrip prototype have been shown. The proposed filter controlled by only two voltages has the reconfigurable ability of center-frequency tuning, bandwidth controlling and passband intrinsically switching. The proposed filter has the potentiality to be applied in multiband communication systems and reduce its control complexity.

**Author Contributions:** Conceptualization, T.D. and B.G.; Experiment, T.D. and Y.G.; writing—original draft preparation, T.D.; writing—review and editing, D.W.; supervision, P.Z.; funding acquisition, P.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the National Natural Science Foundation of China, grant number 61501153 and 61801153, State Key Laboratory of Millimeter Waves under grant number K202012 and Natural Science Foundation of ZheJiang Province under grant number LQY20F010001.

**Conflicts of Interest:** The authors declare no conflict of interest.

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