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# FREQUENCY-TUNABLE BANDPASS FILTERS WITH CONSTANT ABSOLUTE BANDWIDTH AND IMPROVED LINEARITY

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**Abstract**—This paper presents a frequency-tunable bandpass filter with constant absolute bandwidth and improved linearity. The proposed resonator is composed of an open-ended transmission line with back-to-back varactor diodes loaded at one end. The back-to-back varactor diodes are used to enhance the linearity of the filter, which is better than that of the single varactor counterparts. A mixed electric and magnetic coupling scheme is utilized to control the overall coupling coefficients so that the absolute bandwidth can be kept constant when the frequency is tuned. For validation, two frequency-tuning filters with 30-MHz and 44-MHz absolute bandwidth are implemented. The experimental and simulated results are presented to verify the proposed design.

## 1. INTRODUCTION

Tunable filters have been investigated for applications in multifunctional multiband RF and microwave systems. Compared to a bank of fixed filters, a well-designed tunable filter promises greater performance. Therefore, extensive studies have been done and many technologies have been considered in this topic [1–21]. Different tuning components have been employed in the tunable filter designs, i.e., MEMS switches [1–3], semiconductor varactors [4–6]. Ferroelectric [7–9] and ferromagnetic techniques [10, 11] are also utilized to design tunable filters. These MEMS switches possess higher $Q$ and linearity [1–3], but their switching time is slower than the varactor diodes [12].

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Therefore, semiconductor diodes are still widely used in tunable filter designs.

Center frequency and bandwidth are the two parameters to be controlled when designing tunable filters. Bandpass filters with tunable center frequency and switchable bandwidth are presented in [13, 14]. In [13], a new approach is demonstrated to tune bandwidth of filters by changing the size of perturbation patch of dual-mode resonators. In [14], a uniplanar tunable bandpass filters are designed by using the centrally-loaded slot-line resonators. These filters can have adjustable frequency and switchable bandwidth, but their bandwidths are non-constant. In certain applications, the channel bandwidth is identical and the absolute bandwidth should be constant. Thus, it's valuable to design frequency-tunable bandpass filters with constant absolute bandwidth.

In order to maintain constant absolute bandwidth as the passband frequency is tuned, various methods have been utilized. Introducing a fixed or variable attenuation pole near the passband has been shown to be a useful method to maintain a nearly constant bandwidth as the passband frequency is tuned [15, 16]. And the variable capacitor can also be utilized to control the coupling so as to achieve constant absolute bandwidth [17]. In [18], an independent electric and magnetic coupling scheme is used to maintain the constant bandwidth. Besides, a mixed electric and magnetic coupling structure is introduced to obtain constant absolute bandwidth [19, 20]. In [21], a balanced bandpass filter is introduced with constant fractional bandwidth (FBW) and constant absolute bandwidth (ABW).

Besides constant bandwidth, linearity is another important issue in frequency-tunable bandpass filter designs. If the linearity is poor, it will affect the quality of information transmission. In [22], two miniaturized tunable filters were designed by using single and back-to-back varactor diodes. In [23], the authors presented the tunable lumped-element bandstop filters with single diode and back-to-back diodes. By comparing the linearity characteristics, it is found that the back-to-back diodes can enhance the linearity of the filter.

Considering the importance of both constant bandwidth and linearity, a frequency-tunable bandpass filter with constant absolute bandwidth and enhanced linearity is proposed in this paper. The proposed resonator is composed of an open-ended transmission line with back-to-back varactor diodes loaded at one end, which can enhance the linearity of the filter. A mixed electric and magnetic coupling method is utilized to control the coupling coefficients. And the lumped capacitors are put in the input and output ports to control the external quality factor ($Q_e$). So the bandwidth can be maintained constant by selecting proper coupling region and controlling the $Q_e$. Based on the proposed idea, two filters with 30 and 44 MHz constant bandwidth are implemented.

## 2. FILTER DESIGN

Figure 1 shows structure of the proposed filter, which is a second-order filter. The resonator is composed of an open-ended microwave transmission line with back-to-back varactor diodes loaded at one end. The resonators are folded to reduce circuit area. The capacitors $C_1$ and $C_2$ are utilized to control the external quality factor $Q_e$. And the inductors ensure that both ends of the varactor diode are grounded so that the varactors are reversely biased and the capacitance can be changed under different bias voltage $V_t$.

Regarding the filter, the coupling coefficient $k$ of the filter is determined by

$$k = \frac{ABW}{f_0\sqrt{g_2 g_1}} \tag{1}$$

where $ABW$ represents the absolute bandwidth; $g_1$ and $g_2$ are the lumped element values of the prototype filter; $f_0$ is the center frequency. From the equation, it is found that the coupling coefficient should become lower as the center frequency increases so as to obtain the constant absolute bandwidth. In this paper, we utilize a mixed electric and magnetic coupling scheme to control the coupling coefficient. The coupling coefficient can be expressed by the electric coupling coefficient ($k_e$) and magnetic coupling coefficient ($k_m$). When

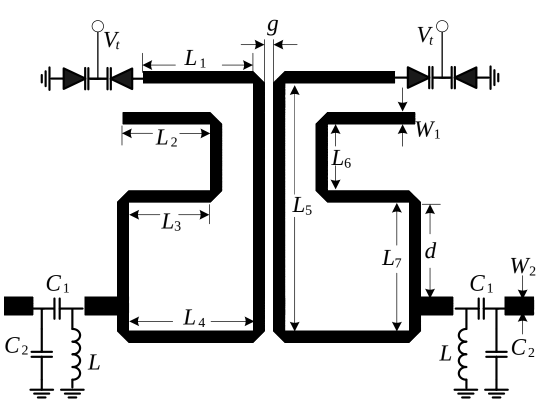


**Figure 1.** Layout of the proposed microstrip filter.

$|k_m|$ is larger than $|k_e|$, the magnitude of coupling coefficient is given by

$$|k| = |k_m| - |k_e| \tag{2}$$

If $|k_m|$ varies inversely with frequency while $|k_e|$ varies directly with frequency, the coupling coefficient $k$ will vary inversely with the center frequency.

In this design, the characteristic of constant bandwidth is obtained by using mixed electric and magnetic coupling. As detailed in [20], the coupling strength can be manipulated to satisfy the constant bandwidth requirement without extra circuits. In the coupling region, the magnetic coupling coefficient will vary inversely with frequency while the electric coupling coefficient will vary directly with frequency, namely,

$$|k_{m,L}| > |k_{m,H}| \tag{3}$$

$$|k_{e,L}| < |k_{e,H}| \tag{4}$$

where $L$ and $H$ represent the lower and upper frequencies, respectively. If the magnetic coupling is dominant, Equation (2) is satisfied. From Equations (2)–(4), we can find that the formula $|k_L| > |k_H|$ can be realized. And it is fitted with the requirement that the coupling coefficient varies inversely with the center frequency.

As for the $Q_e$, it is determined by the shunt capacitor $C_1$, series capacitor $C_2$ and the tap position. So we can tune these parameters to control it. In order to obtain the constant bandwidth, the $Q_e$ should increase as the frequency increases. Since the capacitors $C_1$ and $C_2$ are fixed, the admittance will vary with frequency. This property can be used to obtain various $Q_e$ at different frequencies. Thus, desired $Q_e$ will be obtained if we select proper parameter values.

In addition, the back-to-back varactor diodes are used to improve the linearity of the filter. The capacitance of single diode and matched diode pair can be expressed by

$$C_1(v) = C_0 + C_1 v + C_2 v^2 + \ldots \tag{5}$$

$$C_2(v) = \frac{K_0}{2} + \frac{K_2}{8}\left(1 - \frac{1.5K_1^2}{K_0 K_2}\right) v^2 + \ldots \tag{6}$$

where $C_1(v)$ is the capacitance of single diode, $C_2(v)$ the capacitance of two matched diodes, $v$ the total incremental voltage [24], and $C_n$ $(n = 0, 1, 2\ldots)$ and $K_n$ $(n = 0, 1, 2\ldots)$ are the constant. After comparing these two formulas, it is found that the constant term is halved and the linear term disappears in Equation (6). Thus second-order distortion is ideally zero. The term in $v^2$ (which causes third-order distortion) shows two significant factors. First, the factor $\frac{1}{8}$ arises from the fact that each diode has approximately half the ac voltage and thus third-order distortion is reduced by $\left(\frac{1}{2}\right)^3$. Secondly, the term in parentheses shows a second-order interaction term and it is possible to reduce this coefficient to zero. This will occur if $\frac{1.5K_1^2}{K_0K_2} = 1$, and it can be obtained by choosing two diodes with proper exponents [24]. In practice, it is relatively easy to produce variable capacitance diodes with exponents close to this value and hence to achieve very low levels of second- and third-order distortion using the back-to-back varactor diodes. As expected from the analysis, the back-to-back diodes design can increase linearity performance over the single-diode design with the proper design of the varactor biasing network.

## 3. EXPERIMENT

For demonstration purpose, two filters with 30-MHz and 44-MHz bandwidth are implemented. The experimental filters are fabricated on the substrate with a relative dielectric of 3.38 and thickness of 0.81 mm. The dimensions of the 30-MHz one are determined as follows: $L_1 = 11.35$ mm, $L_2 = 9.1$ mm, $L_3 = 8.5$ mm, $L_4 = 12.85$ mm, $L_5 = 26$ mm, $L_6 = 7$ mm, $L_7 = 13.5$ mm, $d = 9.93$ mm, $g = 1.1$ mm, $W_1 = 1.2$ mm, $W_2 = 1.87$ mm, $C_1 = 2.7$ pF, $C_2 = 1.5$ pF, $L = 100$ nH. The fabricated circuit is shown in Fig. 2. Using these parameters, the coupling strength is extracted as tabulated in Table 1. As can be observed, the coupling strength varies inversely with the center frequency, which can meet the requirement of constant bandwidth.

The simulation results are accomplished by Zealand IE3D and ADS, and the test results are obtained by the network analyzer. Fig. 3 depicts the simulated and measured responses of the filter with 30-

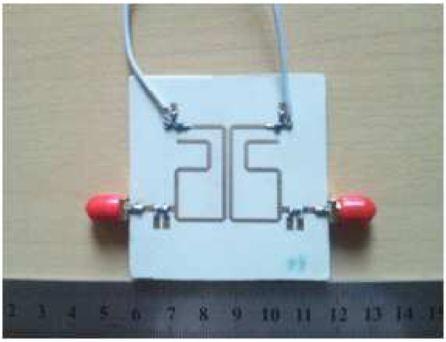

**Figure 2.** Photograph of the filter with 30-MHz bandwidth.

**Table 1.** Coupling strength at various frequencies.

| $V_t$ (V) | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Center Frequency (MHz) | 697 | 767 | 820 | 855 | 878 |
| $k$ | 0.048 | 0.044 | 0.041 | 0.035 | 0.032 |

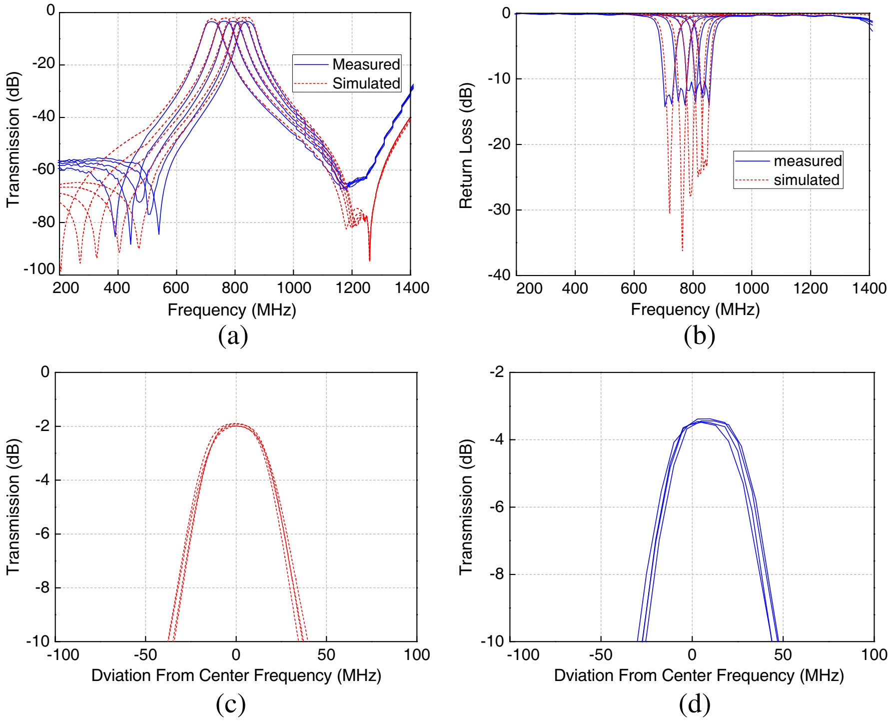


**Figure 3.** Simulated and measured results of the filter with 30-MHz bandwidth. (a) $S_{21}$. (b) $S_{11}$. (c) Superposition of the simulated passband responses. (d) Superposition of the measured passband responses.

MHz bandwidth and the superposition of the passband responses at various frequencies. The passband frequency can be tuned from 700 to 900 MHz. The simulated in-band return loss is greater than 20 dB for all the tuning states. The 1-dB absolute bandwidth is $30 \pm 2$ MHz, which is nearly invariant. And the measured responses agree reasonably well with the simulated responses. As can be observed, the insertion loss, passband shape and absolute bandwidth are kept nearly constant over the frequency tuning range. The unloaded $Q$ is range from 41 to 53. The simulated IIP3 with 1-MHz frequency spacing of the back-to-back diodes and the single-diode filters are demonstrated in Table 2.

To demonstrate the wide applicability of this method, a filter with 44-MHz bandwidth is also implemented. The dimensions are as follows: $L_1 = 12.55\,\text{mm}$, $L_2 = 9\,\text{mm}$, $L_3 = 8.5\,\text{mm}$, $L_4 = 13.5\,\text{mm}$, $L_5 = 26\,\text{mm}$, $L_6 = 7\,\text{mm}$, $L_7 = 13.5\,\text{mm}$, $d = 9.93\,\text{mm}$, $g = 0.7\,\text{mm}$, $W_1 = 1.2\,\text{mm}$, $W_2 = 1.87\,\text{mm}$, $C_1 = 3.9\,\text{Pf}$, $C_2 = 1.8\,\text{pF}$, $L = 100\,\text{nH}$.

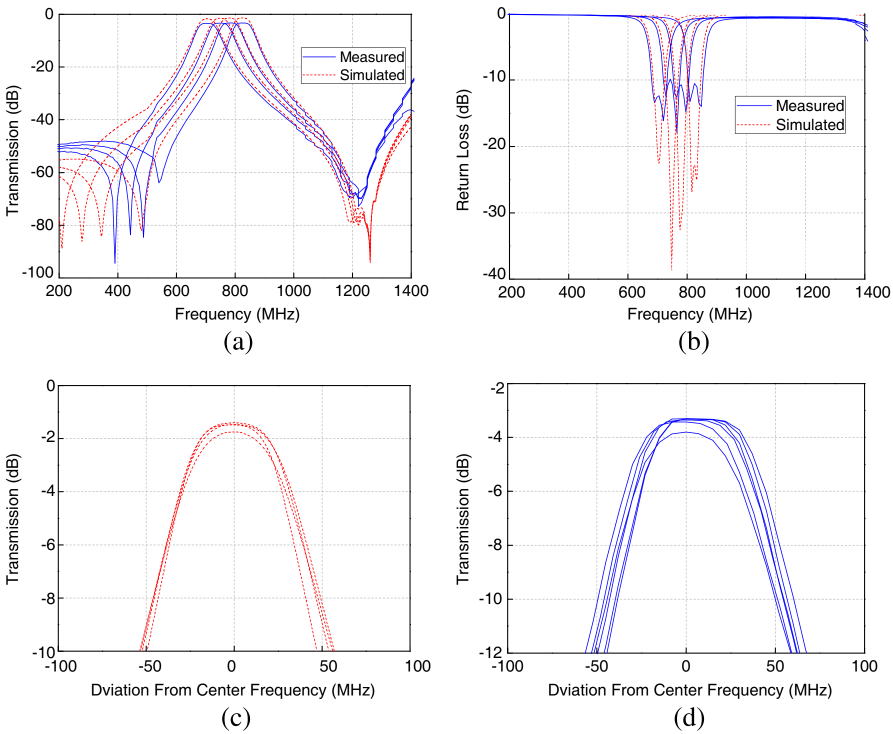


**Figure 4.** Simulated and measured results of the filter with 44-MHz bandwidth. (a) $S_{21}$. (b) $S_{11}$. (c) Superposition of the simulated passband responses. (d) Superposition of the measured passband responses.

**Table 2.** Comparson of IIP3.

| $V_t$ (V) | 4 | 4.5 | 5 | 5.5 |
|---|---|---|---|---|
| IIP3 of back-to-back varactor (dBm) | 19.5 | 22.4 | 26.0 | 34.5 |
| IIP3 of single varactor (dBm) | 12 | 15.4 | 16 | 16.9 |

Figure 4 shows the simulated and measured results of the filter with 44-MHz bandwidth. The passband frequency can be tuned from 700 to 880 MHz. The simulated in-band return loss is around 20 dB for all the tuning states and the insertion loss ranges from 1.5 to 1.8 dB. The 1-dB absolute bandwidth is $44 \pm 2$ MHz. The passband shape and insertion loss are maintained nearly constant over the tuning range. The measured responses agree reasonably well with the simulated responses. And the absolute bandwidth is kept nearly constant.

From the two design examples, it is observed that the absolute bandwidth and passband shape can be maintained constant over the tuning range. Moreover, the bandwidth can be controlled by changing the design parameters, indicating this topology can be used to achieve various bandwidth specifications.

## 4. CONCLUSION

This paper has presented frequency-tunable bandpass filters with enhanced linearity and constant absolute bandwidth. Both theory and experiments have been provided, showing that $Q_e$ and coupling coefficient variation can be controlled to obtain constant absolute bandwidth. Furthermore, the back-to-back varactor diodes can enhance the linearity of the filter. By altering the design parameters, the absolute bandwidth can be controlled, indicating the wide applicability of this method. With the advantage of the high linearity and constant bandwidth, the proposed resonators will be useful for reconfigurable systems.

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