Simple Coupled-Line Tunable Bandpass Filter With Wide Tuning Range

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ABSTRACT In this paper, a tunable bandpass filter using coupled line with a wide tuning range is proposed. The proposed filter has a simple structure which is composed of a coupled-line section and two pairs of varactors. Meanwhile, simultaneously tuning on bandwidth and center frequency are introduced by varactors. The tunability is mainly realized by varactors connected to one end of the coupled line and varactors between ports and coupled line provide an impedance matching. A theoretical analysis is presented to illustrate the tunability by using even- and odd-mode theory. Additionally, the detailed effect of the two types of varactors is researched, respectively. To verify the concept, a prototype is designed, fabricated, and measured. The transmission zero exhibited in measurement is introduced by bias circuits. The measured results show that the tunable bandpass filter achieves a tunable center frequency of 0.494-1.257 GHz (87.15%) and a 3-dB bandwidth of 0.282-0.943 GHz (334%).

INDEX TERMS Bandpass filter, coupled line, tunable filter, wide tuning range.

I. INTRODUCTION
Reconfigurable or high-performance microwave devices, such as power dividers [1]–[3], phase shifters [4]–[7], couplers [8]–[10], and filters [11]–[33], are extensively studied in past several years. Due to the reconfigurability, these key components used in modern wireless communication systems are capable to realize the agile frequency to support different standards, as well as reduce the size and complexity of systems. Thus, the flexibility and applicability of systems will eventually be realized.

As indispensable components, tunable filters are widely used in modern wireless communication systems because of their selectivity. From general perspective, tunable filters involve the following categories, including tunable bandstop filters [31], low-pass filters [32], high-pass filters [33], and bandpass filters (BPFs) [11]–[19], [21]–[29]. Moreover, the tunable BPFs with widespread applications can be classified as filters with tuning frequency with constant absolute bandwidth [15], [19], controllable operating bandwidth with fixed center frequency [29], and both bandwidth and frequency reconfigurable [16], [17]. Various methods can be employed to achieve the tunability of bandpass filters, such as varactors [21], PIN diodes [27], microelectromechanical systems (MEMS) devices [28], and so on. As far as varactors are concerned, many structures have been adopted to implement tunability, including the modified parallel-coupled line [11], the comb line [12], and the coupled line resonator [13], etc. However, these agile frequency filters cannot provide a relatively wide tuning range, which simultaneously need high bias voltages, multiple varactors, or complicated structures. A tunable BPF using short parallel-coupled lines is presented in [22], which includes six varactors and three DC voltages. However, a better performance on tuning range can be obtained with a simpler structure, thus decreasing design complexity of bias circuits. Such a design can reduce the cost and increase the reliability, which is more applicable in modern multi-band communications.

In [4], the author presents a tunable reflection phase shifter based on short section of coupled lines. Then, a phase reconfigurable microwave power divider is proposed in [34]. Through loaded with reflection-type loads, coupled line can be tunable as an effective variable length transmission line (TL) approximately. Based on these fundamental
Theories, a coupled line-based coupler with simultaneously tunable phase and frequency is displayed in [9]. The proposed varactor loaded coupled-line structure is introduced between two quarter-wavelength coupled-line sections to implement the simultaneously phase and frequency tunable coupler. Enhancement in both bandwidth and phase tunable range has been come true. In addition, only using coupled lines loaded with impedances can design the high-power amplifier [35] and dual-band DC-block transformer [36]. Furthermore, novel rat-race couplers based on coupled lines demonstrate tunable frequency with unequal power division [37]. Besides, the reconfigurable idea can also be applied in antenna [38] to achieve polarization diversity, by adopting a reconfigurable feeding network using a quasi-lumped coupler and PIN diodes. Therefore, a simple coupled-line BPF with wider tuning range is possible to be a part of microwave devices to achieve superior performance. Different from the previous bandpass filters [40], [41], this article focuses on the wider tuning range on bandwidth and frequency with simple coupled-line structure.

In this paper, a tunable BPF using a coupled line with a wide tuning range is proposed and analyzed based on the work [34]. Because of the introduced tunable capacitors, a relatively wide tuning range and preferable impedance matching are achieved. By the even- and odd-mode analysis approach, the equivalent circuits of the design are analyzed thoroughly. As ideal results demonstrate, the design realizes a shift of the center frequency (0.663-1.581 GHz, 81.82%) and bandwidth (345-838 MHz, 243%). For verification, a prototype is modeled, simulated, manufactured, and measured. The experimental results indicate the proposed BPF achieves the tunability under three different states, yielding a tuning range of 87.15%. Beside the introduction, theoretical analysis and parameters study are presented in section II. In section III, the simulated and measured results are displayed and discussed. At the end, conclusions of the design are exhibited in section IV.

II. THEORETICAL ANALYSIS

A. EVEN- AND ODD-MODE ANALYSIS

Fig. 1 shows the schematic diagram of the proposed tunable BPF, which consists of a section of coupled line loaded with two types of tunable capacitors. Through connecting tunable capacitors to the end of the coupled line, the frequency tunability is introduced.

To analyze the performance of the structure, the even- and odd-mode analysis method is utilized. The equivalent circuits of the tunable BPF displayed in Fig. 2(a) simplifies the analysis of asymmetrical structure, through adding two loads $Z_{L1}$ which are the impedance of loaded varactors $C_1$ [22], [34]. To eliminate the effect of the added $Z_{L1}$, $-Z_{L1}$ are also implemented. $Z_{L2}$ represents the impedance of loaded varactors $-C_1$ and $C_2$. The even- and odd-mode equivalent sub-circuits of Part I are presented in Fig. 2(b) and Fig. 2(c).

For Part I, the impedance matrix can be extracted as a function of even- and odd-mode input impedances and $A$ element of $ABCD$ matrix

$$Z_{11} = \frac{Z_{\text{even}} + Z_{\text{ino}}}{2},$$

$$Z_{21} = \frac{Z_{\text{even}}/A_e - Z_{\text{ino}}/A_o}{2}.\tag{1b}$$

where $Z_{\text{even}}$ and $Z_{\text{ino}}$ are the even- and odd-mode input impedance of Part I, $Z_{ij}$ ($i, j = 1, 2$) is the two-port matrix impedance of the coupled line, and $A_e$ and $A_o$ are $A$ elements of even- and odd-mode $ABCD$ matrix.

$Z_{\text{even}}$ and $Z_{\text{ino}}$ can be calculated as:

$$Z_{\text{even}} = \frac{Z_{L1}(Z_{L1} + jZ_c \tan \theta)}{2Z_cZ_{L1} + j(Z_c^2 + Z_{L1}^2) \tan \theta}.$$

$$Z_{\text{ino}} = \frac{Z_{0}Z_{L1}(Z_{L1} + jZ_c \tan \theta)}{2Z_cZ_{L1} + j(Z_c^2 + Z_{L1}^2) \tan \theta}.$$

$$Z_{L1} = \frac{1}{j\omega C_1}.\tag{4}$$

$A_e$ and $A_o$ can be written as:

$$A_e = \cos \theta + \frac{jZ_c \sin \theta}{Z_{L1}},\tag{5}$$

$$A_o = \cos \theta + \frac{jZ_c \sin \theta}{Z_{L1}}.\tag{6}$$

FIGURE 1. Schematic diagram of the tunable BPF.

FIGURE 2. (a) Equivalent circuit of the tunable BPF. (b) The even-mode equivalent circuit of Part I. (c) The odd-mode equivalent circuit of Part I.
By using the transfer formulas between ABCD matrix and Z matrix, the ABCD matrix of Part I can be expressed as:

\[ A_1 = \frac{A_0A_e(Z_{ine} + Z_{ino})}{A_0Z_{ine} - A_eZ_{ino}}, \quad (7a) \]
\[ B_1 = \frac{(Z_{ine} + Z_{ino})^2 - (Z_{ine}/A_e - Z_{ino}/A_0)^2}{2(Z_{ine}/A_e - Z_{ino}/A_0)}, \quad (7b) \]
\[ C_1 = \frac{2A_0A_e}{A_0Z_{ine} - A_eZ_{ino}}, \quad (7c) \]
\[ D_1 = A_1. \quad (7d) \]

The ABCD matrix of whole circuit can be described by

\[
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix} = \begin{pmatrix}
1 & 0 \\
1/Z_{L2} & 1
\end{pmatrix} \begin{pmatrix}
A & B \\
C & D
\end{pmatrix} \begin{pmatrix}
1 & 0 \\
1/Z_{L2} & 1
\end{pmatrix}, \quad (8)
\]

\[ Z_{L2} = \frac{1}{j\omega(C_2 - C_1)}. \quad (9) \]

The input admittance \( Y_{in} \) can be derived from the equation

\[ Y_{in} = \frac{CZ_{L2} + D}{AZ_{L2} + B}, \quad (10) \]

where \( Z_{L} \) denotes the load impedance. In addition, the value of \( Z_{L} \) is 50 Ω.

The resonant frequency can be determined by

\[ \text{Im} \{ Y_{in} \} = 0. \quad (11) \]

Herein, the relationship between center frequency \( f_c \) and tunable capacitors can be calculated which are listed in TABLE 1. It is worth noting that considering the impedance matching, the tuning range of \( C_2 \) are limited from 3-6.5 pF. The details about impedance matching are shown in the Section-B of parameters analysis.

**TABLE 1. Relationships between \( C_1 \) (C_2) and tuning range (\( Z_e = 100 \Omega, Z_o = 48.6 \Omega, \text{and} \theta = 55^\circ \text{at} f_0 = 1 \text{GHz} \)).**

| \( f_c \) (GHz) | 0.78 | 0.89 | 1.09 | 1.18 | 1.3 |
|-----------------|------|------|------|------|-----|
| \( C_1 \) (pF), \( C_2 = 4 \) pF | 10.80 | 6.02 | 3.15 | 2.50 | 1.40 |
| \( f_c \) (GHz) | 0.90 | 0.95 | 1.01 | 1.02 | 1.02 |
| \( C_2 \) (pF), \( C_1 = 4 \) pF | 6.5 | 6 | 5 | 4 | 3 |

**FIGURE 3.** The theoretical S-parameter curves of the proposed tunable BPF. (a) Varied \( C_1 \) with fixed \( C_2 \). (b) Varied \( C_2 \) with fixed \( C_1 \).

**B. PARAMETERS ANALYSIS**

In this section, the specific influence of \( C_1 \) and \( C_2 \) on tunability of the tunable BPF are discussed, separately. For demonstration, we choose \( Z_e = 100 \Omega, Z_o = 48.6 \Omega, \) and \( \theta = 55^\circ \text{at} f_0 = 1 \text{GHz}. \) Fig. 3 depicts \(|S_{11}| \) and \(|S_{21}| \) tuned by \( C_1 \) (\( C_2 \)) with fixed \( C_2 (C_1) \). The simulations are accomplished using Advanced Design System (ADS) software.

It can be observed that when \( C_2 \) is fixed, \( C_1 \) primarily affects the operating frequency of the design in Fig. 3(a), and \( C_2 \) has the main impact on the impedance matching while \( C_1 \) is fixed, as demonstrated in Fig. 3(b). Moreover, similar with the performance of \(|S_{11}| \) for \( C_1 \) and \( C_2 \), the curves of \(|S_{21}| \) also verify what roles \( C_1 \) and \( C_2 \) play in the performance of the tunable BPF. It is seen that when the tunable varactor \( C_1 \) changes from 1 pF to 10 pF with \( C_2 = 4 \) pF, the operating frequency varies obviously from a high frequency to a low frequency. Otherwise, the upper band of \(|S_{21}| \) extends to be steep in the upward tuning process of \( C_2 \) when \( C_1 \) is fixed to 4.0 pF.

By optimizations of these two types varactors, the optimized theoretical curves of proposed tunable BPF are displayed in Fig. 4. In the simulation of theoretical analysis, the return losses are better than 20 dB, and complete with a center frequency shift of 81.82% and bandwidth of 243%, as shown in Fig. 4(a). From what are plotted in Fig. 4(b), it can be seen that the upper band of \(|S_{21}| \) extends towards high frequency, which is consistent with above analyses.

The designed tunable bandpass filters can be extended to higher-order filter via loading additional varactors. As shown in Fig. 5(a), a third-order filter is displayed as an example. The third-order BPF are composed of three lines and three types of varactors. The varactor \( C_3 \) are utilized for the controllable and additional third pole in the passband.
Fig. 5(b) indicates the performances of the third-order filter. As the third-order tunable BPF, $C_1$ is mainly aimed to affect the center frequencies of any states, in the meantime, $C_2$ and $C_3$ determine the impedance matching and operating bandwidths.

### III. SIMULATED AND MEASURED RESULTS

#### A. DESIGN AND SIMULATED RESULTS

In order to validate the design theory, an experimental structure is modeled by the full wave electromagnetic simulator ANSYS HFSS and the 3D structure of the proposed tunable BPF is shown in Fig. 6. The layout of the fabricated tunable BPF is shown in Fig. 7. The optimized physical dimensions of the design are demonstrated in TABLE 2.

Aimed at realizing the tunability through DC voltages, suitable bias circuits have to be designed and applicable lumped elements are required to be chosen. In simulation, the values of $C_1$ and $C_2$ are set at the range from 0.7 pF to 13.3 pF. Chip inductors and capacitors are used as radio frequency chokes (RFC) and DC blocks, respectively. Chip resistances are utilized for limiting current to avoid damaging the tunable capacitors. The length $S_1$ reserved for the placement of chip components and varactors are 1.2 mm. The radius of via holes are 0.575 mm which is half the width of the microstrip line. DC voltages are equivalent to be shorted for radio frequency
The simulated scattering parameters of the proposed tunable BPF at three states including $|S_{11}|$ and $|S_{21}|$ are shown in Fig. 8. It can be observed from Fig. 8(a) that when the tunable capacitors are $C_1 = 13.3 \, \text{pF}$ and $C_2 = 13.3 \, \text{pF}$, the initial center frequency and 3-dB bandwidth of the design are 536 MHz and 240 MHz, respectively. By regulating the values of the tunable capacitors, the tuning range accomplishes of tuning center frequency $f_c$ from 536 MHz to 1.397 GHz and bandwidth from 240 MHz to 837 MHz. It should be noted that the simulated results of $|S_{21}|$ indicate that there occurs transmission zeros (TZs) at the edge of the upper band (Fig. 8(b)). Due to the addition of the DC-block capacitors placed between microstrip lines as well as the coupled line, and the necessary microstrip line at the end of coupled line for the placement of inductors and varactors, a TZ is generated under the range of the frequency researched in our study, compared with the ideal results in Fig. 4(b). In fact, a TZ exists at 3.3 GHz in the ideal simulation, while the available frequency responses are not shown, because such frequencies are outside the scope of the study. The arrangement of metal lines in printed circuit board (PCB) for actual test, principally the indispensable microstrip lines for radio frequency signals, results in the movement of the TZ.

### TABLE 3. Simulated and measured center frequency ($f_c$) and 3-dB bandwidth under three states.

| State    | Center frequency (GHz) | 3-dB ABW (MHz) /RBW |
|----------|------------------------|---------------------|
|          | simulated | measured |      | simulated | measured      |
| State 1  | 0.536      | 0.494     | 240  | (44.78%)  | 282 (57.09%)  |
| State 2  | 0.829      | 0.762     | 452  | (54.52%)  | 549 (72.05%)  |
| State 3  | 1.397      | 1.257     | 837  | (59.91%)  | 943 (75.02%)  |
| Tuning range |          |           | 89.08% | 87.15%       | 349% (75.02%) |

ABW: absolute bandwidth; RBW: relative bandwidth.

B. IMPLEMENTATION AND MEASURED RESULTS

To verify the proposed design, a prototype operating at the center frequency $f_0$ of 1 GHz is fabricated and measured, as demonstrated in Fig. 9. The substrate RO4350B with a relative permittivity of 3.48, a size of $L_p \times W_p \times h$, and a loss tangent of 0.0037 is used for the tunable BPF.


TABLE 4. Comparisons of the proposed filter with other referenced prototypes.

| Refs. | Center frequency tuning range (GHz) | BW tuning range (GHz) | Insertion loss (dB) | Bias voltages (V) | No. of varactors | Simple structure |
|-------|-----------------------------------|-----------------------|--------------------|------------------|------------------|----------------|
| [14]  | 0.97-1.72 (55.7%)                 | Constant ABW          | 3-4.5              | ≤14.6            | 4                | No             |
| [22]  | 0.56-1.15 (69%)                   | 0.065-0.18 (277%)     | 1.4-4.5            | ≤20              | 6                | No             |
| [11]  | 0.95-1.45 (41.7%)                 | 0.08-0.1 (125%)       | <3                 | ≤20              | 3                | No             |
| [12]  | 1.5-2.2 (37.84%)                  | 0.05-0.17 (340%)      | <9.5               | ≤19              | 9                | No             |
| [13]  | 0.58-1.22 (71.1%)                 | 0.065-0.18 (277%)     | 1.8-4.6            | ≤26              | 12               | No             |
| This work | 0.494-1.257 (87.15%) | 0.282-0.943 (334%) | 2.38-5.52          | ≤16              | 4                | Yes            |

ABW: absolute bandwidth; a 1dB bandwidth; b 3 dB bandwidth.

The chosen values of lumped elements including DC-block capacitors $C_b$, RF-block inductors $L_c$, current-limiting resistances $R_b$, and varactors $C_1$ and $C_2$ (SMV1281-011LF SKYWORKS SOD323) [39] are listed as follows: $C_b = 4.7 \, \text{nF}$, $L_c = 3.3 \, \text{uH}$, $R_b = 10 \, \text{kΩ}$, and $C_1(C_2) = 0.69-13.30 \, \text{pF}$. As demonstrated in [1], four DC-block capacitors $C_b$ are adopted to isolate two tunable voltages, which are located between coupled line and microstrip line. In addition, two capacitors $C_b$ are placed to eliminate the influence of DC voltages on ports. All $S$-parameter measurements are carried out by using R&S vector network analyzer ZVA-8.

Fig. 10 illustrates the measured return losses and transmission coefficients of the fabricated tunable BPF at three different states. Fig. 10 reveals that the 3-dB operating bandwidth extends from 282 MHz to 943 MHz, and center frequency $f_c$ shifts from 494 MHz to 1.257 GHz. Specific tuning range of center frequency ($f_c$) and 3-dB bandwidth under three states in simulations and measurements are listed in TABLE 3. The operating bandwidths are increasing, as the center frequencies go up, as shown in TABLE 3. Due to the addition of DC-block capacitors $C_b$ and gap capacitances, the equivalent capacitance loaded at the end of the coupled line are increased, which leads to the TZs shifting compared to simulation results.

Moreover, the measured return losses are better than 10 dB and the insertion losses are less than 5.52 dB, which are attributed to the loss of lumped elements and SMAs. Besides, the comparisons of the proposed filter with other referenced prototypes are summarized in TABLE 4. It can be seen that the proposed filter based on coupled line achieves a wider center frequency and bandwidth tuning range with only two relatively low bias voltages and 4 varactors.

IV. CONCLUSION

A tunable bandpass filter using coupled line with wide tuning range is demonstrated. By introducing four tunable capacitors into the coupled line, the operating center frequency and bandwidth can be easily controlled by bias voltages. A prototype of the design has been manufactured and experimented. The experimental results have presented that the proposed tunable BPF realizes wider tuning range, compared with other designs. Hence, it can be expected that the proposed design is potential to apply in wideband tunable devices.

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