A high stability fully tunable filter with frequency, bandwidth and transmission zero tuning

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Abstract: Based on the double folded 1/4 mode substrate integrated waveguide (DFQMSIW) resonator, a two-pole DFQMSIW tunable filter with frequency, bandwidth and transmission zeros tuning is proposed in this paper. In order to increase the stability of the filter, the constant bandwidth can be maintained by changing the coupling coefficient by two varactor diodes when tuning frequency and transmission zeros. The center frequency can be tuned in the range of 1.1 GHz to 1.5 GHz, transmission zeros can be tuned from 1.41 GHz to 1.5 GHz with bandwidth unchanged, and bandwidth can be tuned from 120 MHz to 200 MHz. The insertion loss is about −1.3 dB to −3 dB.

Keywords: fully tunable, high stability, bandwidth-control

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Fully tunable filter is a new type of microwave device with adjustable center frequency, bandwidth and transmission zero [1, 2, 3, 4]. It represents the development trend and ideal state of tunable filter. In order to better filter and select frequency in the environment where frequency resources are scarce, scholars have done a lot of research on fully adjustable filter [5, 6, 7, 8, 9, 10]. The realization of tunable function can be realized by mechanical method, loading electric element, magnetic material [11] and so on. However, the current fully tunable filter has less function, and it is difficult to adjust multiple parameters at the same time.

Substrate integrated waveguide is a new material for filter design in recent years. It has the advantages of high Q value and low loss of traditional waveguide and small size of microstrip structure [12, 13, 14]. In the field of miniaturization, half mode, 1/4 modes, 1/8 modes, and multi-layer folding techniques have been introduced [15, 16, 17, 18], which greatly reduce the size of the filter. Some achievements have also been made in the tunable aspect of SIW filter: In [19], the frequency and bandwidth can be adjusted by using electric element and magnetic ferrite on the basis of half-mode substrate integrated waveguide. In [20], the frequency is tuned by using RF MEMS switch at the quarter mode substrate integrate waveguide resonator. However, the fully tunable filter that can implement a variety of parameters may not be well integrated with the SIW technique.

In order to combine miniaturized SIW filter with fully tunable function, this paper proposed a two-pole filter which designed using a double folded 1/4 mode substrate integrated waveguide as the resonator. Its area is only 12.5% of the full-mode SIW filter, and it is fully tuned by PIN diodes and varactor diodes. Compared with other fully tunable filters, this one can achieve frequency, bandwidth, and transmission zero tunable, besides, it has a smaller size.

2. Design of the fully tunable filter

2.1 Structure of the DFQMSIW filter

As shown in Fig. 1 and Fig. 2, The structure of the fully tunable filter is composed of three layers of metal and three layers of dielectric layer, each metal layer is deposited on the lower surface of the dielectric layer, and then the three layers of dielectric layer are pressed together to make the through holes of the substrate integrated waveguide run through from top to bottom. the top layer mainly used as gasket for electrical elements. The other two dielectric layers are formed by folding of the full-mode substrate integrated waveguide. Five pairs of PIN diodes ABCDE (A’B’C’D’E’) and three varactor diodes are mounted on the surface of the first layer of the medium and connected to the metal layer below through the tuner column, which achieve the tunable function. Varactor C1 is installed at the top of the coupling window to adjust the cross coupling to realize the transmission zero tuning, and the varactors C2, C3 are installed between the coupling windows to adjust the coupling to realize the bandwidth tuning. There is an inverted U-slot above C1 on the second metal layer to assist the coupling, whose length is N.

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The two parallel cascaded resonators in Fig. 1 are coupled through the coupling window of the intermediate metal layer and the inverted U-slot above the coupling window, where the width of the coupling window and the length of the slot will determine the coupling between the two poles, as shown in Fig. 3. It can be seen that the coupling between poles increases with the increase of slot length $N$ and the width of coupling window $W$.

As is shown in Fig. 4, the main coupling of the two resonators $K_{12}$ is magnetic coupling, the phase shift is 90°, the cross coupling $K_{L1}$ and $K_{S2}$ are electrically coupling, and the phase shift is $-90°$. When the phase difference between main and cross coupling is 180°, a transmission zero will be generated on the high side of the passband [21, 22, 23].

Its resonant frequency is $f_0 = 1/2\pi\sqrt{LC}$. When the switch is closed, the tuning column is connected, which means a inductor $L_p$ is paralleled in the cavity. Now the resonant frequency of the cavity is $f_0 = 1/2\pi\sqrt{C_{eq}}$ ($L_{eq}$ is the parallel value of $L$ and $L_p$). Smaller equivalent inductor $L_p$ and parallel inductors $L_{eq}$ cause greater frequency offset. Similarly, the larger number of tuned columns makes the equivalent inductance smaller, leading to a larger frequency shift. According to the density of the electric field, the distribution of the five groups of tuned columns is shown in Fig. 1. Through the on-off combination of the tunable columns at different positions, there can be a shift of 32 frequencies in theory, which can basically realize the continuous tunable effect in this passband.

In Fig. 6 and Fig. 7, the even- and odd-mode analysis method is used to analyze the equivalent circuit of symmetric structure, $C_{eq}$ is the equivalent capacitance of $C2$ and $C3$ in parallel, $L_{eq}$ is the equivalent inductance of PIN diodes combination, and $l_1/l_2$ is the equivalent inductance of DFQMSIW filter.

The coupling coefficient is calculated by input admittance [9] as (1):

$$\text{Fig. 2. Filter model in HFSS}$$

$$\text{Fig. 3. Coupling coefficients between resonators}$$

$$\text{Fig. 4. Topological graph of coupled structure}$$

$$\text{Fig. 5. Schematic diagram of PIN diode}$$

$$\text{Fig. 6. Equivalent circuits of the proposed filter}$$
3. Simulated and measured results

We use the dielectric layer (the thickness is h) as the main body of the filter, and deposit the three-layer metal on the corresponding dielectric layer, the top layer use FR4 ($\varepsilon_r = 4.4$), and other two layers use Rogers RT5880 ($\varepsilon_r = 2.2$). All varactor diodes use SMV2020-079LF for C1, C2, C3. The parameters labeled in Fig. 1 are shown in Table I, and the picture of filter is shown in Fig. 9.

### Table I. Specific parameters of the filter (unit: mm)

|    | L1 | L2 | L3 | L4 | Lf |
|----|----|----|----|----|----|
| d  | 42 | 18 | 15.6 | 17.15 | 0.5 |
| b  | 1.2 | 1.4 | 6 | 2.5 | 0.8 |

For frequency tuning, we change the different combinations of five pairs of PIN diodes, where “1” means through, “0” means disconnected, and ABCDE’s digital combination is used to represent its different frequencies. According to the previous analysis, connecting the PIN diodes is to increase the equivalent inductance in the resonator, the position and the number of the diodes will be the main factors affecting the frequency shift. The filter can realize the frequency tuning in the range of 1.1 GHz–1.9 GHz, and variation of its unloaded $Q$ ($Q_u$) value is 235–386. The relationship between PIN diode and frequency can be seen in Table II.

### Table II. The relationship between PIN diode and frequency

| State | ABCDE (A’B’C’D’E’) | Frequency (GHz) |
|-------|---------------------|-----------------|
| 1     | 00000               | 1.1             |
| 2     | 00001               | 1.3             |
| 3     | 10001               | 1.5             |
| 4     | 10101               | 1.7             |
| 5     | 11111               | 1.9             |

The return loss of each state is less than −15 dB, and the absolute bandwidth can be kept around 200 MHz by tuning C2, C3. The simulated results in Ansoft HFSS 15.0 and measured results are shown in Fig. 10.

For different frequencies, C1 can be adjusted to generate and tune transmission zeros, and C2, C3 can maintain the constant bandwidth at 200 MHz. $V1, V2, V3$ are the...
voltages that control the $C_1$, $C_2$, $C_3$. Fig. 11 shows the range of transmission zeros at the center frequency of 1.1 GHz is 1.41 GHz–1.5 GHz. Due to the limitation of machining precision, the measured range of transmission zeros will be smaller than the simulation range.

Adjusting three varactor diodes at different frequencies can achieve bandwidth tunable, as shown in Fig. 12.

In order to compare the performance of the filter studied in this paper with some similar fully tunable filters, some parameters are compared in the following Table III.

| Ref. | CF (GHz) | BW (MHz) | TZs (GHz) | size (mm) |
|------|----------|----------|-----------|-----------|
| [6]  | 1.25–2.1 | 54–162   | Lower to upper of stopband | 39 × 18   |
| [10] | 3.75–4   | 140–180  | NO        | 88 × 20   |
| [30] | 0.56–1.15| 65–180   | Lower to upper of passband | 46 × 15   |
| [31] | 0.8–1.5  | 216–534  | NO        | 35 × 12   |
| This | 1.1–1.9  | 120–200  | 1.41–1.5  | 66 × 45   |

4. Conclusion

Based on the double folded 1/4 mode substrate integrated waveguide resonator, a fully tunable bandpass filter is designed and simulated by HFSS 15.0. The measured results are in good agreement with the simulated results. The flexibility of filter in application is increased and passband selectivity is improved. The absolute bandwidth is maintained by adjusting the varactors. Compared with the previous research results, this filter has higher tunable performance and better stability.

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