Filter using cylindrical quadruple mode SIW resonator

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Abstract:

This letter proposes a filter using a cylindrical quadruple mode SIW resonator. In the proposed resonator, the resonant frequency of each mode can be handled by the number of the ground via in a crisscross arrangement. Also, the external Q-factor of each mode is handled by the length and position of the I/O port line, and thus the filter structure was derived. As a result, it was confirmed that a quadruple-mode filter could be designed.

Keywords: quadruple mode, SIW, BPF

Classification: Microwave and millimeter wave devices, circuits, and systems

References

[1] X. P. Chen and K. Wu: “Substrate Integrated Waveguide Filters: Practical Aspects and Design Considerations,” IEEE Microw. Mag., 15 (2014) 75. DOI: 10.1109/MMM.2014.2355751
[2] Y.L. Zhang, et al.: “Novel substrate integrated waveguide cavity filter with defected ground structure,” IEEE Trans. Microw. Theory Tech., 53(2005) 1280. DOI: 10.1109/TMTT.2005.845750
[3] D. D. Zhang, et al.: “A triple-mode ring dielectric resonator band-pass filter using substrate integrated waveguide (SIW),” Proc. EuMC, (2013) 163. DOI: 10.23919/EuMC.2013.6686616
[4] W. Shen, et al.: “Compact substrate integrated waveguide (SIW) transversal filter with triple-mode microstrip resonator,” Proc. IEEE APMC, (2010) 1875.
[5] S. Tomida, et al.: “Design approach for bandpass filter using triple-mode stripline resonator,” IEICE Electron. Express , 13 (2016) 380. DOI: 10.1587/elex.13.20160380
[6] R. J. Cameron: “Advanced coupling matrix synthesis techniques for microwave filters,” IEEE Trans. Microw. Theory Tech., 51 (2003) 1. DOI: 10.1109/TMTT.2002.806937
[7] R. J. Cameron, et al.: Microwave Filters for Communication Systems: Fundamental Design, and Applications, (John Wiley & Sons, NJ, 2007).
[8] D.M. Pozar: Microwave Engineering, (John Wiley & Sons, NJ, 2011)4th ed.
[9] J.-S. Hong and M. J. Lancaster: Microstrip Filters for RF/Microwave Applications (John Wiley & Sons, NJ, 2011) 2nd ed.
1 Introduction

With the realization of the next generation of wireless systems, compact bandpass filters in millimeter wave bands are required. The filter using a metal cavity is characterized by a high unloaded $Q$-factor, but is heavy in weight and difficult to miniaturize. The microstrip line filter is characterized by excellent properties of miniaturization and workability. However, its unloaded $Q$-factor is low. In particular it decreases at high frequency due to the increase in radiation loss. Research on a Substrate Integrated Waveguide (SIW) filter capable of filling these performance gaps has been advanced. In the SIW structure, a waveguide structure is formed in the substrate by arranging a via hole in the dielectric substrate. Therefore, the SIW filter has a unloaded $Q$-factor higher than that of the microstrip line, and miniaturization can be realized by the wavelength shortening effect. Generally, a filter is designed by combining a plurality of resonators. However, this design method has a problem in that the filter size cannot be reduced. In this paper, we design a quadruple-mode filter by a novel method to handle the resonant frequency of the four resonant modes in one cylindrical multimode SIW resonator such as [3] and [4].

2 Design of quadruple mode SIW resonator

With the cylindrical SIW resonator depicted in Fig. 1, it is possible to control the resonant frequencies of the resonant modes by crisscross arranging vias at even intervals from the center of the resonator [5].

![Fig. 1. Proposed SIW resonator.](image)

2.1 Characteristics of the proposed resonator

The resonant modes in the cylindrical SIW resonator will be explained using the three-dimensional electromagnetic field software CST Microwave Studio’s Eigen solver. The cylindrical SIW resonator has four resonant modes consisting of $\text{TM}_{01}$ mode, $\text{TM}_{11\text{odd}}$ mode, $\text{TM}_{11\text{even}}$ mode, and $\text{TM}_{21}$ mode. $\text{TM}_{11}$ mode has two modes in which the electromagnetic field distribution is rotated by 90 degrees at the same frequency. The odd mode is called the $\text{TM}_{11\text{odd}}$ mode and the even mode is called the $\text{TM}_{11\text{even}}$ mode with the y

[10] K. Sato, et al.: “Basic Study of Multi-Mode Resonances Using Cylindrical Substrate Integrated Waveguide (in Japanese),” IEICE Tech. Rep. 116(2016) 123.
axis direction at the center of the resonator as the plane of symmetry. The resonant frequency of each resonant mode is defined in Eq. (1), where the light velocity is $c$, the dielectric constant is $\epsilon_r$, the resonator radius is $a$, and the wave number is $k$. It is derived by finding $p_{n\chi}'$ which is micro decomposition [8]. The substrate of the dielectric constant $\epsilon_r$: 3.4, tan $\delta$: 0.0015 of Panasonic Megtron 6 R-5775 (N), is employed and the resonator radius $a$ is 18 mm.

$$f_{n\chi} = \frac{c}{\lambda \sqrt{\epsilon_r}} = \frac{ck}{2\pi a \sqrt{\epsilon_r}} = \frac{cp_{n\chi}'}{2\pi a \sqrt{\epsilon_r}}$$

(1)

Fig. 2. Electric field distribution of the resonant modes generated in the resonator: (a) TM$_{01}$, (b) TM$_{11\text{odd}}$, (c) TM$_{11\text{even}}$, (d) TM$_{21}$.

To control the resonant frequency of the resonant modes in the proposed resonator, we focus on the electric field distributions of TM$_{01}$ mode, TM$_{11\text{odd}}$ mode, TM$_{11\text{even}}$ mode and TM$_{21}$ mode. In the electric field distribution of the TM$_{21}$ mode, since the field does not exist in a crisscross arrangement from the center of the resonator, if the ground via is crisscross arranged, the electric field distribution does not change. On the other hand, the electric field distributions of TM$_{01}$ mode, TM$_{11\text{odd}}$ mode and TM$_{11\text{even}}$ mode change are close to that of the electric field distribution of TM$_{21}$ mode by the ground via in a crisscross arrangement. By changing this electric field distribution, the resonant frequency of each resonant mode changes. To demonstrate this, we calculate the change in resonant frequency using CST Microwave Studio Eigen solver for the case where the ground via are crisscross arranged at even intervals from the center of the resonator.

Fig. 3 shows the change of the resonant frequency and unloaded $Q$-factor in each resonant mode with respect to the number of ground via.
The ground via interval $L_v$ was set to 3.8 mm. As shown in Fig. 3, the resonant frequency of the TM$_{21}$ mode does not change when the ground via in a crisscross arrangement. In contrast, the resonant frequencies of the TM$_{01}$ mode, the TM$_{11\text{odd}}$ mode, and the TM$_{11\text{even}}$ mode become close to the resonant frequency of the TM$_{21}$ mode. It was confirmed that the unloaded $Q$-factors of TM$_{01}$, TM$_{11\text{odd}}$, and TM$_{11\text{even}}$ modes improved. Since the electromagnetic distributions in three modes approach one of TM$_{21}$ mode by increasing the number of via, these unloaded $Q$-factors also approaches the unloaded $Q$-factor of TM$_{21}$ mode.

2.2 Analysis of external $Q$-factor

![Fig. 4. Simulation model for calculating external $Q$-factor.](image)

The external $Q$-factor of each resonant mode is computed by changing the structural parameters of the cylindrical SIW resonator shown in Fig. 4. The external $Q$-factor is calculated from 1-port method [9]. The power half width $\Delta f_{3\text{dB}}$ is calculated by the peak frequency $f_0$, and we obtain the external $Q$-factor $Q_{\text{ex}}$ from Eq. (2).

$$Q_{\text{ex}} = \frac{f_0}{\Delta f_{3\text{dB}}} \quad (2)$$

![Fig. 5. External $Q$-factor for structural parameter change.](image)

In Fig. 4, the I/O port line width $W_0$ is 1.4 mm, and the I/O port line slot width $W_{0s}$ is 0.1 mm. Fig. 5 shows the change of the external $Q$-factor with respect to the change of each of the structural parameters which are the I/O port position displacement $P_f$ from the resonator center and the I/O port line length $L_f$. When the value of the I/O port line length $L_f$ is increased, the external $Q$-factor of the TM$_{01}$ mode decreases from 187.89 to 98.47, and the external $Q$-factor of the TM$_{11\text{even}}$ mode decreases from 269.25
to 67.39. The external $Q$-factor of the other resonant modes is about 10, which is smaller than the variation of the I/O port line length $L_f$. Also, by increasing the value of the I/O port line position $P_f$, it can be confirmed that external $Q$-factor of TM$_{11even}$ mode increases from 42.44 to 229.62. The external $Q$-factor of the other resonant modes are as small as about 10 to 40 with respect to the change of the I/O port line length $P_f$. Based on the results in Fig. 5, we confirmed that the external $Q$-factor of the resonator can be handled.

### 3 Design of quadruple-mode SIW filter

#### 3.1 Calculation of design value by coupling matrix

![Coupling matrix](image)

**Fig. 6.** (a) Coupling topology, (b) Coupling matrix.

The design value of quadruple topology SIW filter is performed using a coupling matrix [6][7]. The coupled topology of our filter is a parallel topology as shown in Fig. 6(a). The frequency characteristics are calculated from the coupling matrix shown in Fig. 7.

![Calculated S-parameters by coupling matrix](image)

**Fig. 7.** Calculated S-parameters by coupling matrix.

#### 3.2 Design and discussion

The designed filter and filter response are shown in Fig. 8 and Fig. 9, respectively. Table 1 shows a comparison between the design value of external $Q$-factor from the coupling matrix and the external $Q$-factor by analysis.

| Mode          | Calculated $Q_{ex}$ | Analyzed $Q_{ex}$ |
|---------------|---------------------|-------------------|
| TM$_{01}$     | 60.91               | 137.35            |
| TM$_{11odd}$  | 118.36              | 58.16             |
| TM$_{11even}$ | 118.36              | 118.11            |
| TM$_{21}$     | 60.91               | 60.93             |

From Table 1, the calculated external $Q$-factors of TM$_{11even}$ mode and TM$_{21}$ mode are in very good agreement with the simulated ones. On the
other hand, the calculated external $Q$-factor of TM$_{11odd}$ mode is close to the simulated TM$_{01}$ mode. The calculated external $Q$-factor of TM$_{01}$ mode is also close to the simulated TM$_{11odd}$ mode. Therefore, for the simulated results, although the passband $\Delta f$ is 6.49–6.71 GHz, the reflection characteristic RL is 19.12 dB, the insertion loss IL is 2.17 dB, and the fractional bandwidth FBW is 3.20%. A notch of about 0.2 dB in the passband appears.

Fig. 8. (a) Structural parameters of simulated filter, (b) Fabricated filter.

Fig. 9. Simulated and measured S-parameters of the proposed BPF; (a) wideband response, (b) narrowband response.

For the measured results, the passband is 6.49–6.81 GHz, the reflection characteristic RL is 15.26 dB, the insertion loss IL is 3.18 dB, and the fractional bandwidth FBW is 4.72%. A notch of about 0.9 dB appears in the passband.

4 Summary

In this paper, we proposed a quadruple-mode filter by a novel method to control the resonant frequency of four resonant modes in one cylindrical SIW resonator. It was confirmed that the resonant frequency of each mode can be handled by the number of the ground via in a crisscross arrangement. Moreover, the external $Q$-factor of each resonant mode can be adjusted by changing the position of the I/O port line and the length of the I/O port line. The quadruple-mode filter was fabricated and measured. As a result, it was confirmed that the quadruple-mode filter could be designed, although a notch in the passband appeared. Our future work is to remove the notch.