Research Article

A Compact High-Pass Filter Using Hybrid Microstrip/Nonuniform CPW with Dual-Mode Resonant Response

Hui Chen,¹ Di Jiang,² Ke-Song Chen,¹ and Hong-Fei Zhao¹

¹School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

²School of Communication and Information Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

Correspondence should be addressed to Hui Chen; huichen@uestc.edu.cn

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A novel and miniature high-pass filter (HPF) based on a hybrid-coupled microstrip/nonuniform coplanar waveguide (CPW) resonator is proposed in this article, in which the designed CPW has exhibited a wideband dual-mode characteristic within the desired high-pass frequency range. The implemented filter consists of the top microstrip coupled patches and the bottom modified nonuniformly short-circuited CPW resonator. Simulated results from the electromagnetic (EM) analysis software and measured results from a vector network analyzer (VNA) show a good agreement. A designed and fabricated prototype filter having a 3 dB cutoff frequency (f_c) of 5.78 GHz has shown an ultrawide high-pass behavior, which exhibits the highest passband frequency exceeding $4.0f_c$ under the minimum insertion loss (IL) 0.75 dB. The printed circuit board (PCB) area of the filter is approximately $0.062\lambda_g \times 0.093\lambda_g$, where λ_g is the guided wavelength at f_c .

1. Introduction

In RF/microwave wireless applications, the high-pass filters (HPFs) are important circuit elements, while the conventional procedures of implementing the HPFs often utilize the distributed units or quasi-lumped elements, which require grounded via-holes. As a result, these methods might lead to fabrication problems and also require large PCB sizes [1]. Recently, some new HPFs using various physical structures and design methods have been reported successively [2–7]. Among the newly published HPFs, the filters based on the various metamaterial concepts have been demonstrated in [2–5]. A new approach to designing a maximum flat Butterworth HPF, which transforms an open circuit series stub to short circuit shunt stub, has been extensively investigated in [6]. An elliptic-function response HPF based on SIR in coplanar waveguide (CPW) technology has also been researched in [7]. The above-overviewed high-pass frequency ranges of HPFs are basically up to $(2\sim 3)f_c$.

Generally, the dual-mode (or multimode) resonant characteristics have been extensively applied to design UWB BPF and dual-band (or multiband) filters [8–13]. However, they are rarely used to implement the HPF. In this paper, a nonuniformly modified short-circuited CPW has been used to design the ultracompact HPF without any via-hole, as the via-hole often leads to some fabrication problems. Different from CPW resonators discussed in [14, 15], the proposed CPW is based on the multisection stepped impedance structure, while a conventional and uniform CPW and a composite CPW using two $\lambda/4$ CPW resonators and a short-circuited stub have been introduced in [14] and [15], respectively. The improved CPW resonator is obtained by etching slots in the ground plane of the two coupled microstrip rectangular patches. In this design, the nonuniform resonator has shown an ultrawide dual-mode frequency characteristic within the desired high-pass range. With the help of the two top microstrip parallel-coupled patches, the lower frequency attenuation for the band-stop

FIGURE 1: (a) Conventional short-circuited CPW resonator and its transmission-line equivalent circuit and (b) proposed nonuniform short-circuited CPW resonator with dual-mode property and its transmission-line equivalent circuit.

and the upper passband transmission have been achieved. This excellent filtering circuit, having the high-pass frequency response exceeding $4.0f_c$ and the minimum IL 0.75 dB within the passband, is designed on 0.254 mm PCB substrate with relative dielectric constant 2.2. As a result, the effective dimensions of the fabricated HPF are approximately $2.8 \text{ mm} \times 4.2 \text{ mm}$ ($\approx 0.062\lambda_g \times 0.093\lambda_g$), where λ_g is the guided wavelength at the 3 dB cutoff frequency f_c in the substrate.

2. Proposed Nonuniform CPW with Dual-Mode Resonator and HPF

In Figure 1(a), a traditional short-circuited CPW resonator and its transmission-line equivalent circuit are shown. In general, the conventional uniform CPW with short-circuited structure only exhibits a single-mode resonant property, as shown in Table 1.

The input impedance of the equivalent transmission-line circuit shown in Figure 1(a) is calculated by the following equation:

$$Z_{in} = jZ_{con0} \tan(\theta_{con0}), \quad (1)$$

where Z_{con0} is the characteristic impedance of the conventional short-circuited CPW resonator and θ_{con0} is the electrical length of the resonator.

In order to obtain a wideband high-pass response within our concerning frequency range, a modified short-circuited CPW resonator with nonuniform stepped impedance structure at the bottom of the dielectric substrate is presented in our study and shown in Figure 1(b), which is used to create an ultrawide dual-mode resonant response. The transmission-line equivalent circuit of the proposed CPW is also given in Figure 1(b), which is composed of five-section stepped impedance units, corresponding to the different

TABLE 1: Comparison of transmission zeros (TZs) and resonant peaks for the conventional and proposed CPW resonator.

Type of resonators	TZs (GHz)	f_{r1} (GHz)	f_{r2} (GHz)
Conventional CPW	5.26	11.51	N/A
Proposed CPW	3.95	8.07	20.25

characteristic impedances. Similarly, the input impedance of the equivalent transmission-line circuit shown in Figure 1(b) is calculated by the following series equations:

$$Z_{in,1} = jZ_{0,1} \tan(\theta_{0,1}) \quad (2a)$$

$$Z_{in,k} = Z_{0,k} \frac{Z_{in,k-1} + jZ_{0,k} \tan(\theta_{0,k})}{Z_{0,k} + jZ_{in,k-1} \tan(\theta_{0,k})}, \quad k = 2, 3, 4, 5, \quad (2b)$$

where $Z_{0,k}$ ($k = 1, 2, 3, 4, 5$) is the characteristic impedance of the proposed CPW SIR and $\theta_{0,k}$ ($k = 1, 2, 3, 4, 5$) is the corresponding electrical length of the proposed resonator.

Based on the following physical dimensions, that is, $w_{c1} = w_{c2} = 2.6 \text{ mm}$, $l_{c1} = 1.6 \text{ mm}$, $l_{c2} = 0.4 \text{ mm}$, $w_{s1} = 0.8 \text{ mm}$, $w_{s2} = 1.2 \text{ mm}$, $l_{s1} = 0.5 \text{ mm}$, $l_{s2} = 0.8 \text{ mm}$, $l_{s3} = 0.4 \text{ mm}$, and $s = 0.1 \text{ mm}$, the dual-mode resonant characteristic of proposed improved CPW has been examined in this paper. The inspected results, including the conventional short-circuited CPW with identical width ($w_c = w_{c1} = w_{c2}$) and total length ($l_c = l_{c1} + l_{c2} + w_{s1} + w_{s2}$) for a comparison with the proposed CPW, are also shown in Table 1. Obviously, the wide dual-mode resonant property of proposed CPW has been clearly observed. The four critical geometrical variables l_{s1} , l_{s2} , w_{s1} , and w_{s2} have been further investigated, and the dual-mode resonant responses from the weakly coupled excitation have been also examined in this design. The frequency ratios, from the dual-mode characteristics of the proposed resonator, have been exhibited in Figure 2, as the above-mentioned four

FIGURE 2: Dual-mode resonant frequency ratio of nonuniform CPW within the high-pass range for different parameters and dimensions (unit: mm). (a) f_{r2}/f_{r1} varies against variable l_{s1} , (b) f_{r2}/f_{r1} varies against variable l_{s2} , (c) f_{r2}/f_{r1} varies against variable w_{s1} , and (d) f_{r2}/f_{r1} varies against variable w_{s2} .

parameters vary. From the four subplots, when the other geometrical dimensions are kept unchanged, the frequency ratio f_{r2}/f_{r1} will almost increase with the lengthening of the four variables. That is, the spacing between the dual-mode resonant frequencies (i.e., f_{r1} and f_{r2}) will enlarge as these parameters increase. As a result, the passband width of the filter will be widened. In addition, the second resonant peak has not been nearly affected by the variable l_{s2} ; however, the first resonant peak will move from 8.6 GHz down to the lower frequency 6.8 GHz as the variable l_{s2} increases, when the variable $l_{s1} = 0.5$ mm. Particularly, the first resonant peak will disappear when l_{s2} is greater than 1.2 mm ($l_{s1} = 0.5$ mm, $w_{s1} = 0.8$ mm, $w_{s2} = 1.2$ mm, and other physical dimensions are unchanged). Furthermore, there are two transmission zeros observed in the study, which are distributed at the lower and upper sides of two resonant peaks. This result also explains

the reasons why the second transmission zero within the stopband of proposed HPF is located near 3.5 GHz, and there is a parasitic passband attenuation exceeding 23.0 GHz.

In order to obtain the high-pass frequency response, two identical top microstrip rectangular patches, shown in Figure 3(a), are separated with dimension g_1 , which mainly contributes to the stopband attenuation at the lower frequency band. At the same time, the top microstrip spacing g , which is equivalent to lump capacitance with blocking direct current (DC) property, generates the transmission zero (TZ) near the DC operating point. Additionally, the coupled microstrip patches are in central alignment with the symmetric line of the CPW in the ground of the single substrate. Therefore, the proposed HPF does not use any via-hole to the grounding plane, while the via-hole usually brings about fabricating difficulty. Finally, making use of the hybrid

FIGURE 3: (a) Configuration of the proposed HPF, (b) its lumped-element equivalent circuit, and (c) circuit simulated results of the three-pole high-pass filter prototype for various values of the cross-coupled capacitance C_2 ($C_1 = 0.649$ pF; $L_1 = 1.051$ nH).

broadside coupling between top microstrip patch and bottom dual-mode CPW resonator, an excellent high-pass response will be achieved.

To explain further the operational schematic of the designed HPF, a lumped-element equivalent circuit is given in Figure 3(b), which shows a three-pole high-pass response. The lumped filter will be adopted to generate a very wideband passband. Here, the series capacitances C_1 and the shunt inductance L_1 are selected to decide the cutoff frequency of the high-pass filter, and the cross-coupled capacitance C_2 is introduced to create a transmission zero at the passband edge so that the filter selectivity at the stopband may be improved. Figure 3(c) shows the circuit simulated frequency response of this three-pole high-pass prototype for which the value of cross-coupled capacitance C_2 is adjusted to

control the location of the created transmission zero. In Figure 3(b), the series capacitors C_1 represent the microstrip-to-CPW transition and the shunt inductor L_1 simulates the stepped impedance CPW short-circuited resonator, shown in Figure 1(b). At the same time, the cross-coupled capacitor C_2 is equivalent to the coupling between the two adjacent microstrip patch resonators. In our design, the lumped parameters C_1 and C_2 can be extracted by the full-wave electromagnetic (EM) simulator, while the element L_1 is calculated by the input impedance of the SI CPW resonator, shown in (2a) and (2b).

In Figure 4, a comparison of the magnitude responses on the transmission and reflection loss between the conventional and proposed CPW resonators, based on the identical microstrip patch structure as depicted in Figure 3(a), is

FIGURE 4: Comparison of frequency responses between the HPF using conventional CPW and the one using proposed CPW.

FIGURE 5: Implemented HPF layout and its dimensions. (a) Top coupled microstrip and (b) bottom nonuniform CPW.

shown. It is clearly seen that S_{21} and S_{11} of proposed HPF using nonuniform CPW resonator are better than the ones of conventional HPF using uniform resonator. In addition, the transmission zero of the proposed HPF is lower than that of the conventional one; therefore, its geometrical size is more compact than that of the latter.

After discussing the dual-mode characteristic of CPW resonator, explaining the operational scheme of the lumped equivalent circuit for the proposed HPF and investigating the important physical dimensions, the initial geometric parameters have been calculated by the above-described frequency response characteristic. Taking advantage of advanced optimum and simulation performances from the full-wave EM simulator HFSS, the final geometric sizes have been obtained. These complete dimensions of designed HPF have been shown in Figure 5. The dimensions of top microstrip patches are marked clearly in Figure 5(a), while the sizes of bottom CPW resonator are indicated explicitly in Figure 5(b).

3. Experimental Results

Based on the above-defined physical dimensions of the designed HPF shown in Figure 5, an advanced and miniaturized HPF has been simulated, fabricated, installed, and measured. The photograph of implemented filter is shown in Figure 6. The simulation and measurement have been accomplished using the commercially available EM simulation software HFSS and a vector network analyzer (VNA), respectively. Figure 7(a) shows the simulated and measured insertion loss and return loss of the proposed filter. It can be seen that a good agreement between the simulated and measured results has been achieved, except that there is a little deviation at the lower stopband response of $|S_{21}|$, which might be mainly fabrication and installation errors for the dual-metal-plane layout. Seen from Figure 7(a), the measured 3 dB cutoff frequency is $f_c = 5.78$ GHz, and the high frequency (HF) passband range of 3 dB IL is up to 22.96 GHz,

FIGURE 6: Photographs of fabricated HPF. (a) Top microstrip and (b) bottom modified CPW.

FIGURE 7: Simulated and measured results of the implemented HPF. (a) Magnitude responses and (b) measured group delay.

which exhibits the highest passband frequency approximately $4.0f_c$. Within the passband, the measured minimum IL is 0.75 dB at 7.51 GHz. At the same time, there are three transmission poles observed within the passband, that is, 7.62, 12.69, and 18.73 GHz, respectively. The measured return loss within the high-pass range is better than 20 dB from 7.16 GHz to 20.51 GHz. In addition, two transmission zeros have been obtained, which are near DC operating point and an attenuation -52.1 dB at 3.42 GHz, respectively. From DC to 3.74 GHz, the measured transmission attenuation at the lower stopband is better than about 30 dB. In Figure 7(b), the group delay (GD) of the fabricated HPF is also measured. Within the main passband range, the variation of GD is lower than 0.15 ns from 5.0 GHz to 23.0 GHz. In addition, a comparison of measured results or other important parameters from our work and some typical references is listed in Table 2.

4. Conclusion

In this paper, a new and ultraminiature HPF based on a dual-mode CPW resonator with an ultrawide resonant response has been designed, manufactured, and measured. The wideband high-pass response has been implemented by

the CPW resonator coupled broadside to the top microstrip patches. The fabricated HPF has exhibited an ultrawide passband filtering response of 3 dB IL up to about $4.0f_c$, a good return loss better than 20 dB within the passband 7.16 GHz to 20.51 GHz, and a good stopband attenuation characteristic with two transmission zeros. In addition, the proposed HPF has a very simple geometrical structure and circuit topology. Therefore, the filter is easily designed and implemented via the conventional PCB technology. The concept and approach to the HPF proposed in this paper could also be used to implement the ultra-wideband (UWB) bandpass filters (BPFs), which are based on the cascade of high- and low-pass filters.

Competing Interests

The authors declare that they have no competing interests.

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TABLE 2: Comparison of various HPFs in different works.

Ref.	f_c /GHz at 3 dB	ILmin/dB in the passband	Sizes ($\lambda_g \times \lambda_g$)	f_{pmax}/f_c	ILmin/dB in the stopband	RL/dB in the passband	GD/ns in the passband
[4]	1.74	0.33	N/A	4.5	>60	≈10	N/A
[5]	1.5	2.2	0.37 (length)	2.0	>40	≈10	N/A
[6]	1.45	2.0	N/A	1.7	>30	≈10	N/A
[7]	1.8	1.3	0.08×0.09	3.0	>40	≈7	N/A
[8]	3.0	N/A	0.092×0.185	2.0	>40	≈15	N/A
This work	5.78	0.75	0.062×0.093	4.0	>30	>20	<0.15

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