

High Q -Factor Narrow-Band Bandpass Filter Using Cylindrical Dielectric Resonators for X -Band Applications

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Abstract—This paper presents a narrow-band bandpass filter (NBBPF) using three cylindrical dielectric resonators (CDRs) placed on three rectangular metallic cavities (RMCs). Two U-shaped planar resonators located between RMCs are used to realize narrow-band response effectively. The 3 dB fractional bandwidth (FBW) of the proposed filter is 0.275%. The filter is designed for X -band (9.85 GHz), with 20 MHz bandwidth for radar, satellite, and medical accelerators applications. High Q -factor (Q -factor = 400) and low fabrication cost are other advantages of the proposed design. The proposed NBBPF was fabricated, and its performance was measured to verify the design. Good agreement between the measured and simulated data is obtained.

1. INTRODUCTION

Filters are an essential component in microwave communication systems. Due to recent requirements in microwave circuits design, compact dimensions, low implementation cost, high quality factor (Q -factor), and low losses including the needs of researchers and designers. Dielectric resonators (DRs) are an appropriate idea to be used for the above requirements, because of their huge benefits [1]. DRs are designed with different types and various shapes. The most common and popular DRs employed in today's designs are rectangular and cylindrical dielectric resonators (CDRs), operating in the dominant modes $TE_{11\delta}$ and $TE_{01\delta}$, respectively [2].

During recent years, various high-performance microwave devices and circuits based on the DRs, such as antennas, oscillators, and power dividers, have been explored which validate the potential of DRs in different topology applications [3–5]. However, the design of filters is more based on the use of microstrip and coplanar waveguide (CPW) technologies [6–8]. DRs filters usually consist of a high permittivity DR, placed in a metallic cavity that limits studies available on DRs filters in microwave integrated circuit environment. Over the past few years, single-mode DRs filters have been investigated and widely used in the wireless industry [9–11]. However, the sizes of DR filters are still considered large. Therefore, multiple degenerate modes in a DR have been explored [12–14]. The use of dual or higher order operation modes leads to size reduction, which is important for wireless communication systems. Substrate integrated waveguides (SIWs) have received considerable attention in the design of microwave filters because of the low loss, low cost, and easy integration of such waveguides [10]. In [10] a bandpass filter (BPF) by using a cavity-loaded dielectric rod in an SIW is demonstrated. This BPF is compact, has low insertion loss, and is easy to integrate with other microwave circuits. Although combine coaxial and DRs filters have good Q -factors, insertion losses, and compact sizes, this filter still faces integration difficulties with other components and systems. On the other hand, the BPF with less than 5% 3 dB fractional bandwidth (3 dB FBW) is among the ideals ahead of the designers. To further reduce the 3 dB FBW, the insertion loss of the passband would inevitably become worse, generally [11].

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Thus, the design of narrow-band BPF with good bandpass response is a challenging issue based on the above-mentioned technologies.

In this paper, a narrowband bandpass filter (NBBPF) with three CDRs and three rectangular metallic cavities (RMCs) is presented. The 3 dB FBW of the proposed filter, corresponding to the $TE_{1\delta}$ mode of the CDRs, is 0.275%. The basic configuration and the Q -factor of CDRs are all reported in Section 2. This design can be a tunable filter that is demonstrated in Section 3. Also, performances of the filter can be improved by the introduction of U-shaped planar resonators which are located between cavities. By adding the proposed U-shaped planar resonators, the unwanted harmonics go away from the desired frequency resonance of the filter. By exploiting U-shaped planar resonators and coupling between CDRs, an NBBPF resonating at 9.85 GHz with 20 MHz bandwidth is designed for radar, satellite, and medical accelerators applications. A compact design of the proposed filter is fabricated. The measured results demonstrate improvement of the filter frequency response.

2. ANALYSIS AND DESIGNS

In this section, in addition to a comprehensive review of how to design the proposed structures, the CDRs and their performances will also be examined. Figure 1 shows the proposed single CDR placed on the RMC in different views.

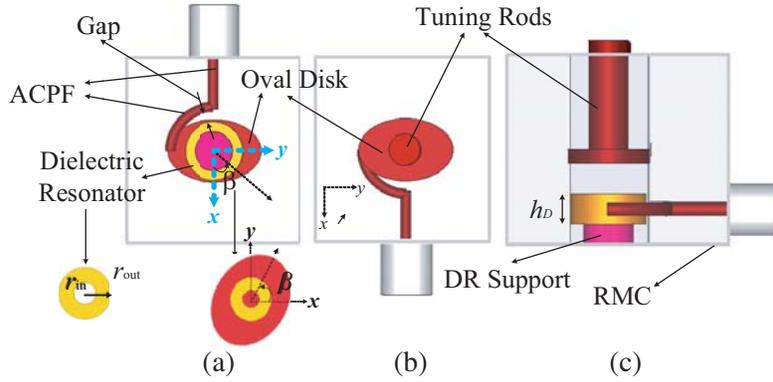


Figure 1. Configuration of the single CDR. (a) Top view. (b) Bottom view. (c) Side view.

A $50\ \Omega$ arc coaxial probe feeding (ACPF) is used to excite $TE_{01\delta}$ mode of the CDR [12]. Relative permittivity of the CDR is chosen as 35.5, and its dimensions are: $r_{in} = 1.15$ mm, $r_{out} = 2.8$ mm, although CDR height (h_D) is 2.24 mm. The CDR resonates with lots of modes at different frequencies. The resonance frequencies are obtained by [13]:

$$(f_r)_{mnp}^{TE^z} = \frac{1}{2\pi\sqrt{\mu_d\epsilon_d}} \sqrt{\left(\frac{\chi_{mn}}{r_{out}}\right)^2 + \left(\frac{p\pi}{h_D}\right)^2} \quad (1)$$

$$(f_r)_{mnp}^{TM^z} = \frac{1}{2\pi\sqrt{\mu_d\epsilon_d}} \sqrt{\left(\frac{\chi'_{mn}}{r_{out}}\right)^2 + \left(\frac{p\pi}{h_D}\right)^2} \quad \begin{array}{l} m, p = 0, 1, 2, \dots \\ n = 1, 2, 3, \dots \end{array} \quad (2)$$

where χ_{mn} and χ'_{mn} represent zeroes of the Bessel function of order m and zeroes of the derivative of the Bessel function of order m , respectively. μ_d is the permeability, and ϵ_d is the relative permittivity of the CDR.

According to Figures 1(a) and 1(b), the distance between the ACPF and CDR (gap parameter), and the angle between CDR and oval disk (β parameter) play a very important role in determining the Q -factor and resonant frequency of the proposed structure. Figure 2 shows Q -factor and resonant frequency changes for several values of the gap (dashed blue line) and β (continuous black line) parameters. The simulated Q -factor is varied from 250 to 400 for several values of the gap. So, the gap parameter equal to 0.5 mm is selected. The simulated Q -factor of the filter is varied from 45 to 400, for several values β

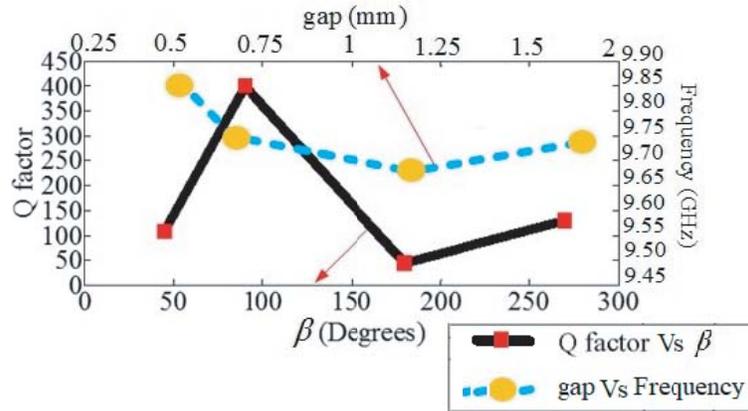


Figure 2. *Q*-factor and resonance frequency changes for several values of the gap and β parameters.

angle. Thus, by choosing β equal to 90° , *Q*-factor = 400 will be achieved. It should be noted that the frequency resonance variations are from 9.5 to 9.85 GHz, for several values of the gap and β angles. So according to the design presented in this section, an NBBPF will be designed in Section 3.

3. NBBPF DESIGN PROCEDURES

This section presents design of the proposed NBBPF based on what is presented in Section 2. BPFs are generally designed using the insertion loss method [14]. In this method low pass filter (LPF) prototype values can be obtained by the specification given, such as insertion loss at some frequency in the passband of the filter and attenuation in the stopband. LPF prototypes values can be transformed into BPF values by using frequency transformation defined as [14]. Three CDRs have been used in this design. Obviously, with increasing number of CDRs, the order of the filter increases, and achieving narrower bandwidth will be easier. On the other hand, in order to avoid increasing the structure dimensions, three CDRs have been selected. In this design, each CDR is placed on a low-permittivity dielectric support as shown in Figure 1(c). The design parameters of the BPF such as external *Q*-factor (Q_{ex}) and coupling coefficient ($K_{i,i+1}$) can be determined by Eqs. (3) and (4) [14]. It is necessary to mention that FBW is the fractional bandwidth, and g_i ($i = 1, 2$) are lumped-element values of a lowpass prototype filter.

$$Q_{ex} = \frac{g_0 g_1}{FBW} \tag{3}$$

$$K_{i,i+1} = \frac{FBW}{\sqrt{g_i \times g_{i+1}}}, \quad i = 1, 2. \tag{4}$$

The Chebyshev NBBPF with a center frequency 9.85 GHz, attenuation of 23.5 dB, and a 0.15 dB-ripple FBW of 0.275% is designed as shown in Figure 3(a). According to the specifications, the lumped-element values of a LPF prototype filter are found to be: $g = 1$, $g_1 = 1.0992$, $g_2 = 1.1532$, and $g_3 = 1.0992$. The design parameters of the proposed filter such as coupling coefficient and external *Q*-factor, which can be determined by formulas (3) and (4) are $Q_{ex} = 399$ and $K_{1,2} = K_{2,3} = 0.0024$, respectively.

According to Figure 3(a), the proposed NBBPF consists of three identical RMCs. Based on what is reported in [13], the RMCs cause narrowing performance. They also provide the ability to design a tunable filter. As shown in Figure 3(a), this condition is established. Coupling between the CDRs removes radiation fields, improves the narrow-band performance, and as a result, the *Q*-factor will be increased by using RMCs.

Now in order to realize the filter's tunability, oblique metallic rods are used for the CDRs in order to tune their resonance frequencies. Two oval disks are connected to the first and third metallic rods to change central frequency. According to Section 2, by changing the position of two oval disks connected to the tuning rods, the resonance frequency will change. The filter exhibits the first center frequency

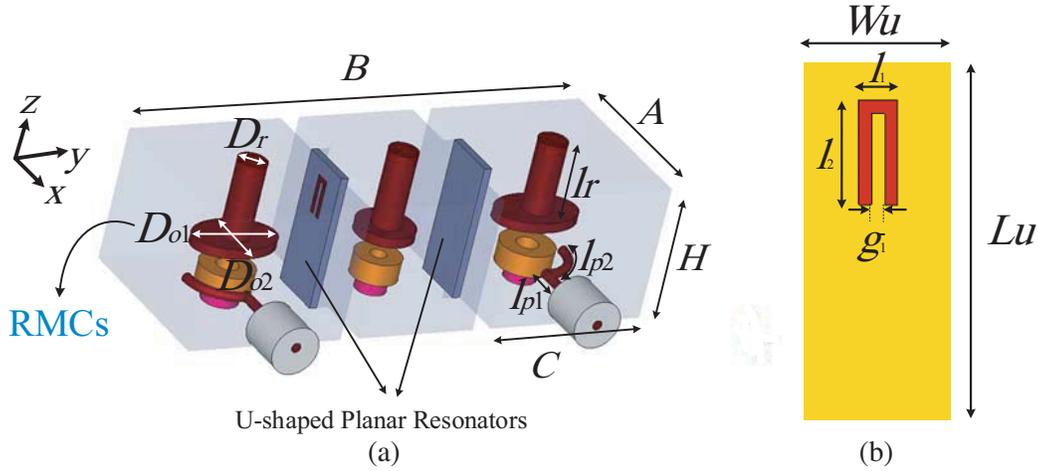


Figure 3. Configuration of the NBBPF. (a) overview of the filter. (b) U-shaped planar resonator.

f_{c1} when those oval disks are positioned at β_1 and show the second center frequency f_{c2} when those oval disks are at β_2 . As an example based on Figure 3, with the choices $\beta_1 = 90^\circ$ and $\beta_2 = 180^\circ$, f_{c1} and f_{c2} are equal to 985 GHz and 9.5 GHz, respectively. It can be seen that about 35% tuning range can be obtained by varying the oval disks angles.

Two U-shaped planar resonators are used to realize a narrow-band frequency response in the upper stopband to further improve the upper cutoff region. This resonator is shown in Figure 3(b). These structures are designed on an RT/Duroid 5880 substrate with relative permittivity of 2.2, thickness of 0.78 mm, and $\tan \delta = 0.0009$. Some other properties of this dielectric are: thermal coefficient is -125 (ppm/C); volume resistivity and surface resistivity are 2×10^7 (Mohm cm) and 3×10^7 (Mohm), respectively; specific heat is 0.96 (J/g/K).

By introducing a U-shaped planar resonator in the dielectric slab between two segments of the rectangular cavity, as shown in Figure 3, a notch is introduced in the filter response. The band-stop response of the U-shaped structure serves to suppress the out-of-band spuri in the proposed NBBPF. As the length l_2 varies from 3.5 to 4.5 mm, the transmission zero is increased from 10.4 GHz to 10.65 GHz. By placing this resonator in the filter structure and applying optimization, the value of $l_2 = 4$ mm is selected. According to this method, by placing U-shaped planar resonators between CDRs, unwanted harmonics can be removed from the desired resonance. So, the bandwidth and Q -factor can be eventually equal to 20 MHz and 400, respectively.

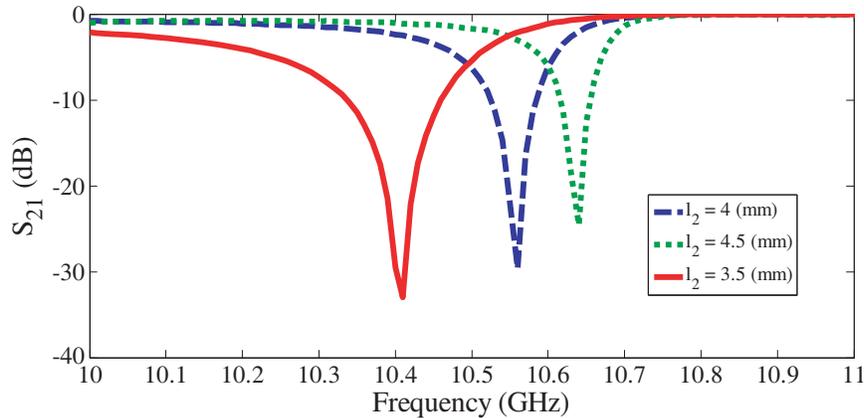


Figure 4. S_{21} parameter of U-shaped planar resonators with varying l_2 .

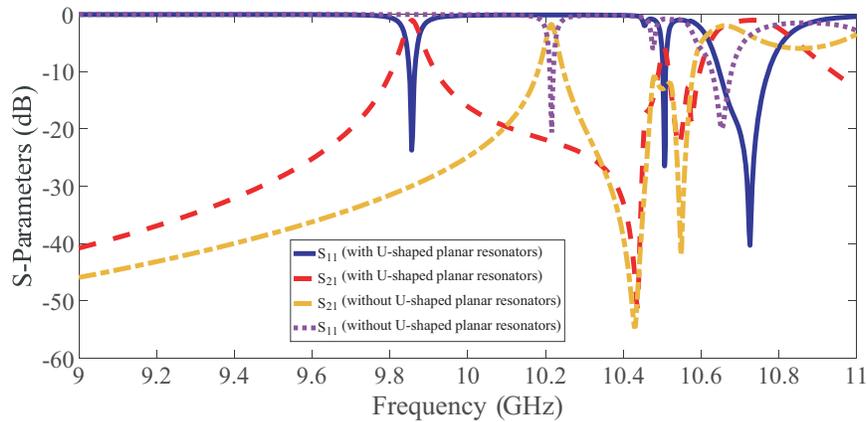


Figure 5. *S*-parameters of the proposed NBBPF with and without U-shaped planar resonators.

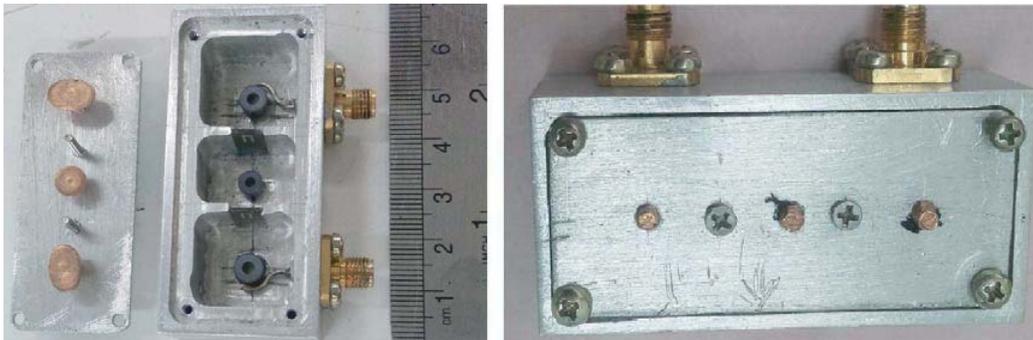


Figure 6. A photograph of the proposed NBBPF.

Figure 5 shows the designed NBBPFS-parameters ($|S_{11}|$ and $|S_{21}|$) in comparison with U-shaped planar resonators and without them. The HFSS software has been used to simulate the structure. In order to perform the simulation, hexahedron is chosen as the mesh type with these statistics: the smallest cell size is 0.09 mm; the largest cell size is 1.33 mm; the total number of cells is 709520.

The frequency range between the desired resonance and unwanted harmonics is 300 MHz. However, with loading U-shaped planar resonators that frequency range is increased by 850 MHz. Therefore, unwanted harmonics will be eliminated from the frequency range by this method. Dimensions of U-shaped planar resonators, as well as other NBBPF dimensions shown in Figure 3(b), are reported in Table 1. It is necessary to mention that the overall dimensions of the proposed filter are $A \times B \times H = 17.7 \times 49.8 \times 14 \text{ mm}^3$.

To validate the proposed design concept, a compact NBBPF is designed, fabricated, and measured. Photographs of the fabricated NBBPF are shown in Figure 6. The measured frequency responses (*S*-

Table 1. Dimensions of different element of Figure 4.

Item	Dimensions (all in millimeter)
Rods and oval disks	$l_r = 8 \quad D_r = 3 \quad D_{o1} = 9 \quad D_{o2} = 6$
ACPFs	$l_{p1} = 5 \quad l_{p2} = 5.8$
RMCs	$A = 17.7, B = 49.8, H = 14, C = 16.6$
U-shaped planar resonators	$L_u = 14, W_u = 5.7, l_1 = 1.5, l_2 = 4, g_1 = 0.5$

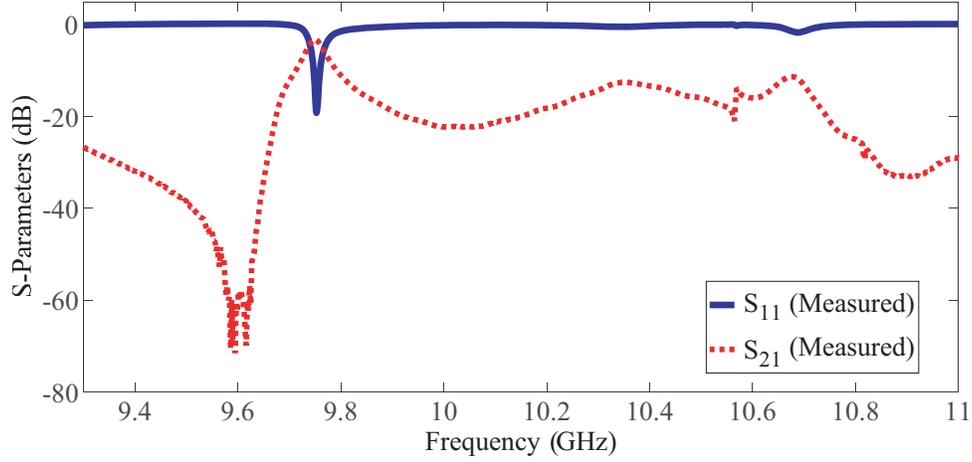


Figure 7. Measured S -parameters of the proposed NBBPF.

parameters) of the proposed filter are presented in Figure 7. It has a transmission zero at 96 GHz. In measurement, center frequency of the filter is centered at 9.75 GHz, and 3 dB bandwidth is about 20 MHz, while the filter has more than 19.0 dB return loss in the stopband and 1.18 dB insertion loss in the passband. Due to manufacturing tolerances passband insertion loss is large in comparison with the chosen specification. The measured results show good agreement with the simulation ones.

The performances of the proposed filter are compared with earlier published work shown in Table 2.

Table 2. Comparison of simulated response of NBBPF.

Ref.	f (GHz)	Technology	3 dB Bandwidth (MHz)	Return Loss (dB) (in Center Freq.)	Insertion Loss (dB)(in Center Freq.)	Q -factor	Harmonic suppression
[2]	1.82	DR	58	31	0.55	302	no
[10]	2.11	SIW-DR	158	18	0.52	> 400	yes
[11]	3.967	PCB-DR	50	12.5	1.3	344	yes
This Work	9.85	DR	20	19	1.18	400	yes

4. CONCLUSION

A novel method to design a compact narrow-band BPF was explained. The basic idea consists of using arc coaxial probe feeding to excite $TE_{01\delta}$ mode of CDR placed on the rectangular metallic cavities with dielectric supports. Two U-shaped resonators are used to realize a narrow-band frequency response in the upper stopband to further improve the upper cutoff region. The proposed design has the ability of bandwidth control due to the use of two oval disks. The proposed NBBPF is suitable for microwave integrated circuit environment and X-band applications.

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