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# Ceramic Waveguide Filters with Wide Spurious-Free Stopband Response

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**Abstract**—This work proposes new filter design techniques to improve the out of band spurious performance of integrated ceramic waveguide filters and ceramic loaded filters. Various resonators of different types like non-uniform width, TEM and half ridge were used. The proposed filter designs offer a considerable miniaturization and significantly improved spurious performance up to 85% without compromising the figure of merits of the filters like Q-factor, return loss, etc. Two sixth order filters with best in-band and out-band performance have been fabricated. Measured results of the fabricated filters are in good agreement with the computer simulations, which confirm the validity and accuracy of designs.

## 1. INTRODUCTION

TEM filters are widely used by cellular base stations due to their high Q, low cost, and extremely broad spurious-free stopband [1]. There are increased demands for low loss filters that are compact and have excellent in-band and out of band characteristics. Dielectric resonator filters are also ideal candidates for cellular base stations due to their high quality factor and miniaturized volume [2].

The first dielectric resonator filter was introduced by Cohn in 1968 [3] having a relative permittivity of 100 and loss tangent of 0.0001. Ceramic materials are evaluated by their Q factor, permittivity, and temperature [4]. The major drawbacks of these filters are their crowded spurious modes near the passband. This proximity of higher order modes creates a significant challenge for the design of a filter which meets commercial base stations' out of band rejection specifications [5]. In [6, 7], a high permittivity dielectric waveguide filter achieved 50% size reduction in comparison with an air filled TEM filter, but the designed filter suffered from crowded higher order modes resonating near the passband. Different design techniques have been proposed to improve stopband performance of ceramic waveguide filters. In 1964, Riblet proposed an idea to suppress the parasitic passband by varying the width of rectangular waveguide resonators [8]. In [9], different width resonators were used to suppress the stopband's spurious modes. The fundamental frequency is kept the same by changing the length of the resonators. Introducing capacitive post in the rectangular cavity at a center of a dielectric resonator can also improve the separation between the fundamental mode and higher order modes [10]. There have been other practical approaches to improve the stopband performance of waveguide filters by using stepped impedance resonators (SIR), different shape resonators or by a mixed combline approach [11–14].

In this paper, new design techniques to improve the spurious performances of integrated ceramic waveguide filters and dielectric loaded filters are presented. In the integrated configuration of the filters, a single metal coated ceramic block is used. Inter resonator couplings are achieved by introducing the through holes in the broad wall of filter. Rectangular ceramic waveguide resonator geometry is modified

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to make it resonate at an evanescent mode frequency (Ceramic TEM) by introducing silver coated blind holes at the center of the broad wall. The ceramic TEM resonator allows significant size reductions with improved spurious performance, whereas resonators with different widths offer spurious suppression without degradation in the Q-factor. However, dielectric loaded configuration uses rectangular ceramic blocks with different widths and ridged configuration, placed inside a metal cavity with the top and bottom surfaces touching the cavity walls. Spurious mode frequency separation increases by introducing ridges and different widths in the ceramic blocks. Experimental results for both integrated and dielectric loaded ceramic filter designs are presented along with electromagnetic (EM) simulations. The measured results are in good agreement with the computer simulations.

## 2. DESIGN METHODOLOGY

Different design techniques for monolithic integrated ceramic and ceramic loaded waveguide filters are presented. All of the designs are sixth order Chebyshev filters with the following specifications:

Center Frequency: 1842 MHz

Bandwidth: 75 MHz

Dielectric Permittivity: 43

These specifications are provided by the Radio Design, United kingdom, who is a partner in this research project.

### 2.1. Nonuniform Width Resonator Filter

Ceramic waveguide resonators with different widths are used to improve the overall spurious performance of a ceramic waveguide filter. A waveguide resonator's resonances are a function of its physical dimensions, i.e., length, width, and height. Therefore, by altering the geometry, the distance between fundamental and higher order modes would also be changed. The change in width spreads out the higher order resonances, so that they will not contribute as strongly as they did in a conventional waveguide. Riblet firstly patented this idea in air-filled waveguide filters [8]. The Q-factor and resonant frequencies of all these resonators are determined by [15]. As the two resonators have different physical dimensions, their lengths and widths can be computed using the following equations [9]:

$$W_n = \frac{1}{\sqrt{\varepsilon_r}}\left(\frac{c}{2}\sqrt{\frac{3}{4(f_o)^2-(f_1)^2}}\right) \tag{1}$$

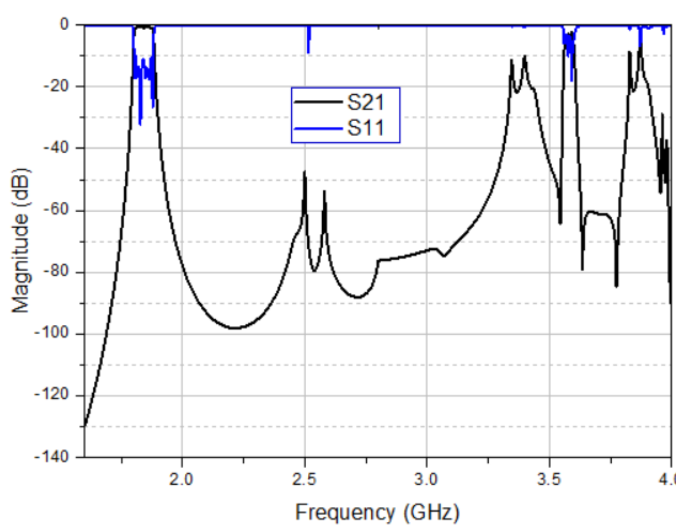


**Figure 1.** Broadband response of non-uniform width ceramic waveguide filter [16].

$$L_n = \frac{1}{\sqrt{\varepsilon_r}} \left( \frac{W_n}{\sqrt{\left(\frac{f_o}{f_1}\right)^2 - 1}} \right) \quad (2)$$

where $W_n$ and $L_n$ are the widths and lengths of resonators, and $f_c$, $f_1$, and $f_o$ are the cutoff, first spurious and fundamental frequencies, respectively. The design of the ceramic nonuniform width filter is proposed by the author in [16], and the broadband response is shown in Figure 1.

### 2.2. Ceramic Waveguide Filter with All Metal Posts

An evanescent mode ceramic TEM resonator filter is conceived as an alternative approach to improve the spurious performance of the integrated ceramic filters. The proposed ceramic resonator consists of a metal coated rectangular high permittivity ceramic bar, with a metal coated blind hole at the centre of the broad wall of the resonator. The resonant frequency and Q-factor of the proposed ceramic TEM resonator can be readily computed by [15]. Due to ceramic loading, the physical size and unloaded Q-factor of the resonator decrease by a factor of $\frac{1}{\sqrt{\varepsilon_r}}$ [17]. The metal coated blind hole introduced at the center of the resonator perturbs the fundamental resonant frequency and shifts it down without affecting the second resonance. This leads to benefits of increased spurious separation and miniaturization of the resonator. All the resonators have same size metal coated blind hole (TEM post in air filled waveguide) placed at the center of the broad wall to reduce the physical size of the resonators, besides improving the spurious behaviour. Various through holes were also introduced to provide the inter-resonator inductive couplings between the adjacent resonators [18]. Their inverter susceptance can be adjusted by varying the distance between the holes placed symmetrically across the large dimension of the waveguide for suppressing higher order modes [4]. Input/output coupling is achieved by coaxial probes placed at the center of the broad wall of the external resonators. The probe position, diameter and depth inside the filter determine the amount of coupling, bandwidth, and center frequency. A six pole integrated ceramic TEM chebyshev filter design is shown in Figure 2. The simulated broadband response of the proposed filter is shown in Figure 3. The unloaded Q factors of all the resonators are around 1845, and passband insertion loss is 0.76 dB showing the overall filter Q factor of 1000. It is evident that the proposed filter provides spurious free performance up to $1.83 * F_o$. The authors have also proposed the idea of a ceramic TEM filter with variable post heights in [19], where difference in post heights further spread the higher order resonances which contribute to better overall stopband attenuation.

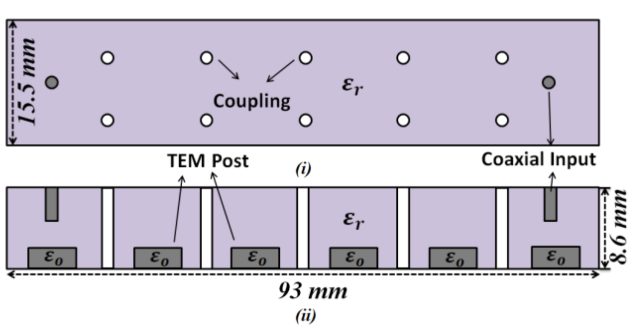


Figure 2. Ceramic filter. (i) Top view. (ii) Side view.

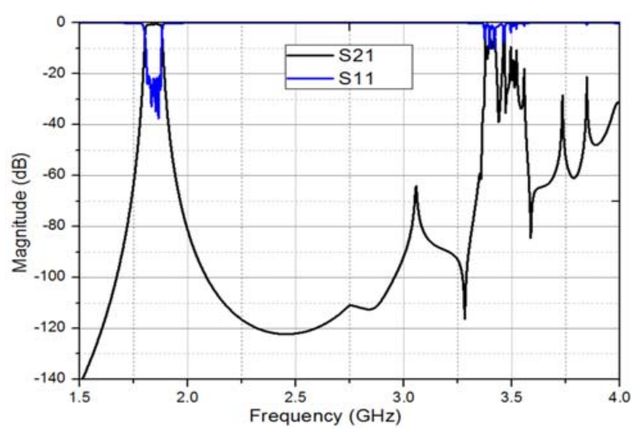


Figure 3. Simulated broadband response.

### 2.3. Ceramic Waveguide Filter with Two Metal Posts and Non-uniform Width Resonators

A mixed resonator approach combines the resonators with posts and non-uniform width, to integrate the advantages of both individual resonators types. The authors have already validated the idea of a mixed resonator approach using HFSS simulations of a ceramic filter with given specifications in [20]. The simulated filter design and its S-parameter response are shown in Figure 4. In order to validate the EM simulations of the design, the simulated design is fabricated in an air filled waveguide.

#### *2.3.1. Fabrication Details*

The proposed filter design is fabricated in air filled configuration. Therefore, for the same size, the fundamental frequency is shifted up by a factor of $\sqrt{\varepsilon_r}$. The scaled fundamental frequency is now 12.07 GHz, and spurious free region extends up to 24 GHz ($1.99 * f_o$) which is very similar to simulated ceramic filter. The tuning screws are introduced in the fabricated design to mitigate the effects of physical dimension tolerances and material discrepancies. 1 mm diameter screws are placed at the center of each resonator to perturb the E-field of the fundamental mode which is maximum at the center, except for the first and last resonators. A photograph of fabricated air filled waveguide filter with two metal posts and non-uniform width resonators is shown in Figure 5. A comparison of simulated and measured results of filter passband and broadband response are shown in Figures 6 and 7, and group delay of a filter is shown in Figure 8. Q factors of all the resonators used in a filter are provided in

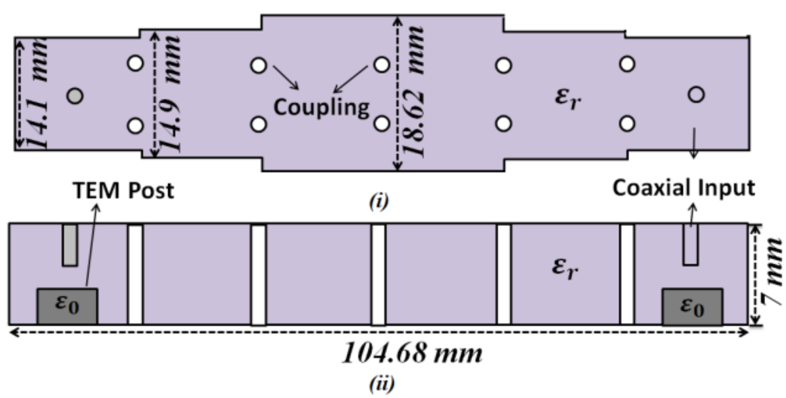


**Figure 4.** Simulated design of ceramic waveguide filter having two metal posts and non-uniform width resonators. (i) Top view. (ii) Side view.

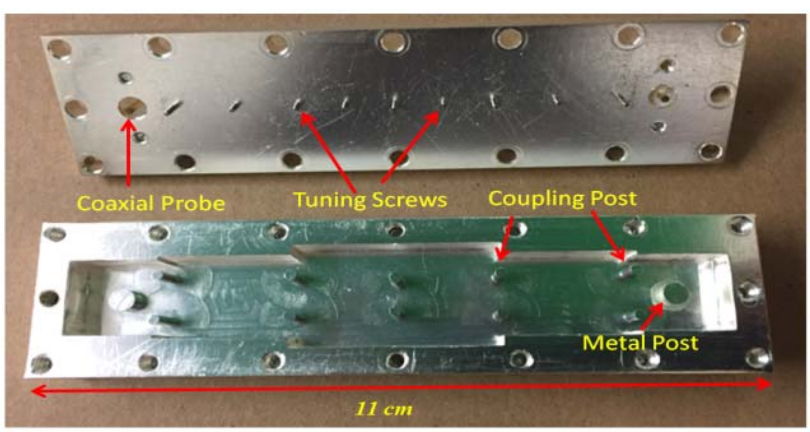


**Figure 5.** Fabricated six order air filled TEM and non-uniform width waveguide filter with tuning screws.

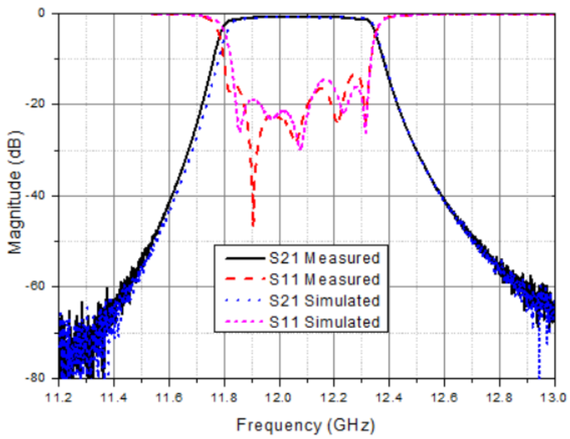


**Figure 6.** Simulated and measured broadband responses.

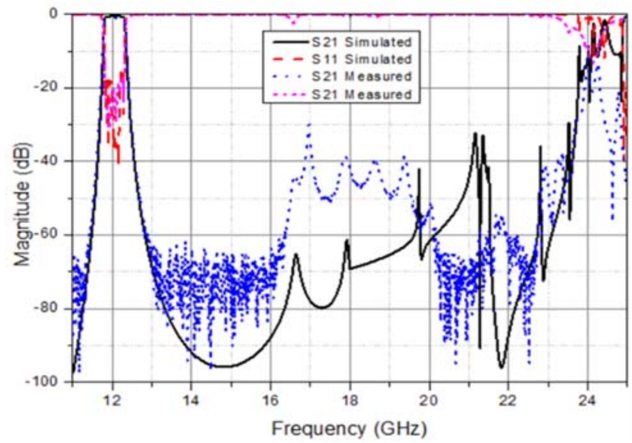


**Figure 7.** Simulated and measured broadband responses.

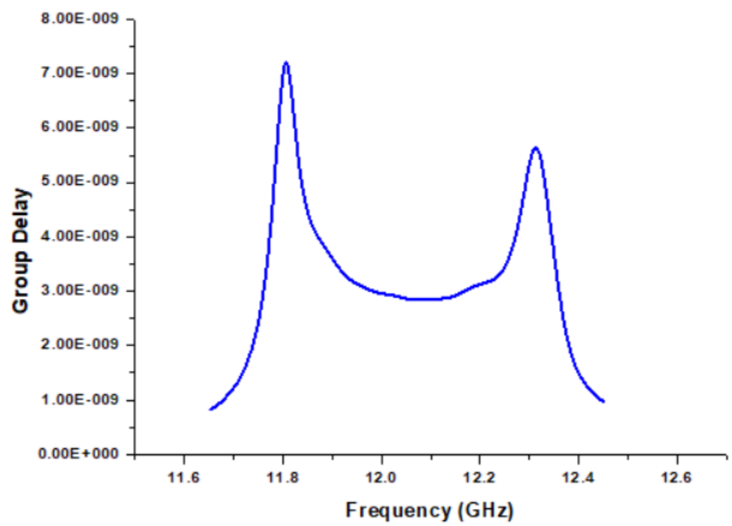


**Figure 8.** Simulated group delay of ceramic waveguide filter with metal posts and non-uniform width resonators.

Table 1 exhibiting the passband insertion loss of 0.75 dB, whereas the passband Q factor of a filter is calculated around 21 at 3 dB point. The simulated and measured results show an excellent agreement of stopband attenuation up to $1.99 * f_o$.

### 2.4. Ceramic Loaded Waveguide Filter with Ridge and Nonuniform Width Ceramic Blocks

Ceramic loaded resonator filters offer high Q with miniaturized volume, but they suffer from bad spurious performance. The idea of cross-coupled dielectric loaded high-Q resonator filter was implemented in [2], but the out of band resonances are in the proximity of the fundamental frequency. The resonator consisted of a rectangular ceramic block with permittivity of 43, placed inside a metal cavity where the top and bottom surfaces of the resonator touched the cavity. The spurious performance of the dielectric loaded filter can be improved by adding nonuniform width ceramic blocks and a ridged ceramic block. The ratio of widths of the ceramic blocks could be calculated as described by Morelli et al. [9]. These ceramic blocks are placed at the center of each metallic resonator with the top and bottom metal coated faces. Inductive couplings are introduced between resonators through irises, and input/output coupling is achieved through the coaxial cable by perturbing the magnetic field around the ceramic blocks of external resonators as [2]. The authors validated the idea and presented the simulated results in [21]. Simulated design and dimensions of ridge ceramic block are shown in Figure 9, which is used to design a sixth-degree dielectric loaded Chebyshev filter with nonuniform width ceramic blocks and ridged ceramic blocks, as shown in Figure 10 [6, 7]. This filter exhibits a good spurious-free window of more than $2.45 * f_o$ shown in Figure 11.

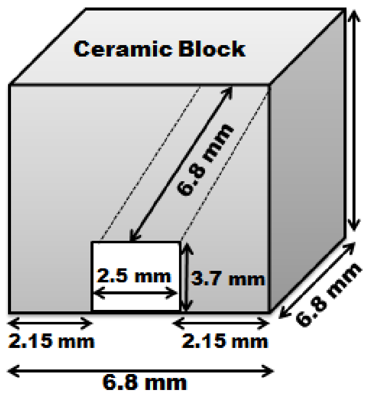


**Figure 9.** Ridged ceramic block.

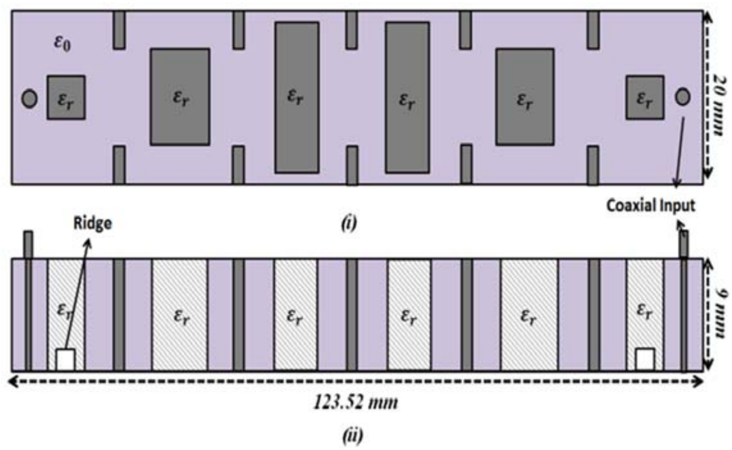


**Figure 10.** Ceramic loaded filter. (i) Top view. (ii) Side view.

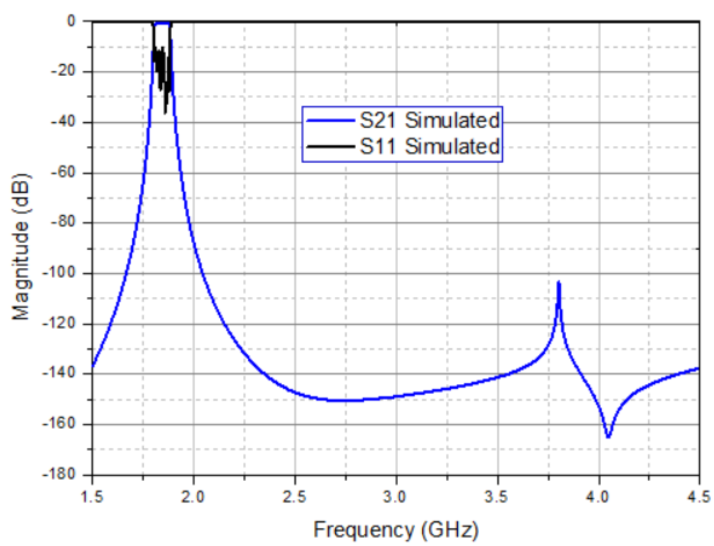


**Figure 11.** Simulated response of six order ceramic loaded filter.

### *2.4.1. Fabrication Details*

The ceramic loaded waveguide filter is fabricated with ceramic blocks with ridge and nonuniform widths placed at the center of the cavity. Tuning screws were used to alleviate the effect of manufacturing tolerances and material discrepancies. It is difficult to remove the air gap between the dielectric slab and external cavity correctly. Therefore, to bring the top and bottom surfaces in contact with the cavity walls, the dielectric blocks are silver plated and then soldered to the cavity lid, as explained in [2]. The top and bottom lids are manufactured with aluminium and then silver plated to make sure the proper

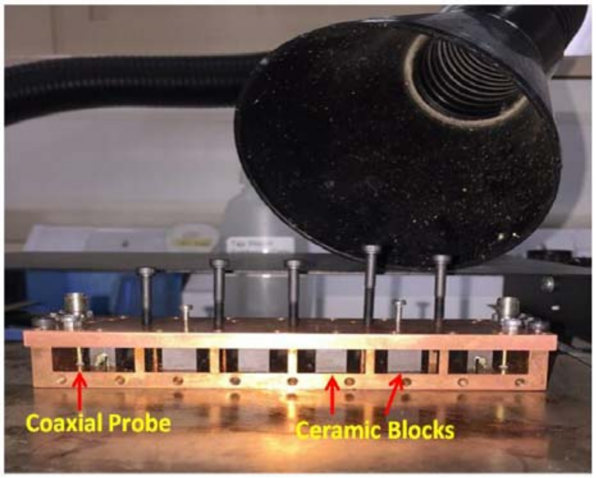


Figure 12. Internal view of ceramic loaded filter.

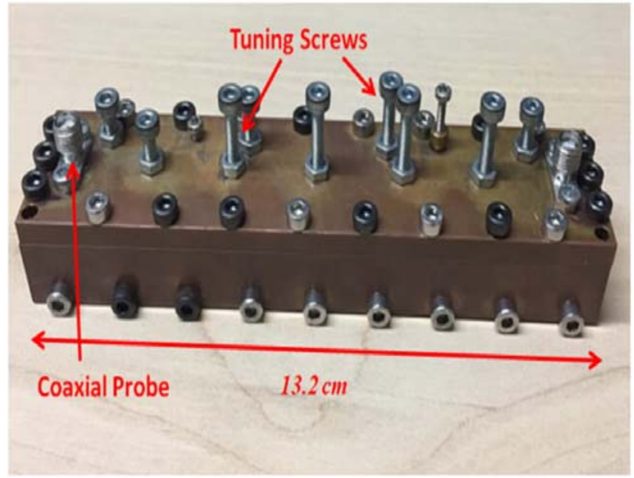


Figure 13. Fabricated filter with tuning screws.

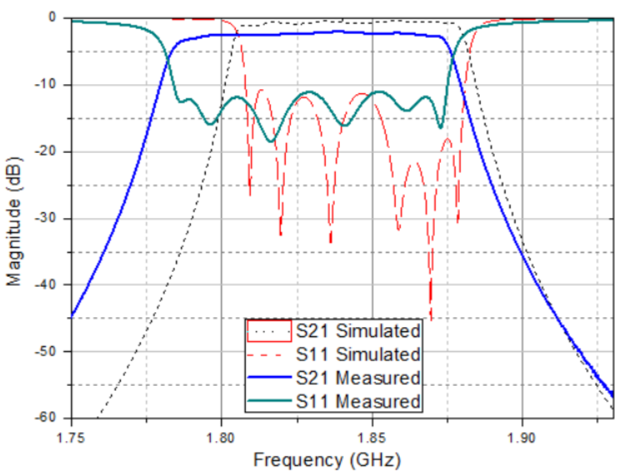


Figure 14. Simulated and measured pass band.

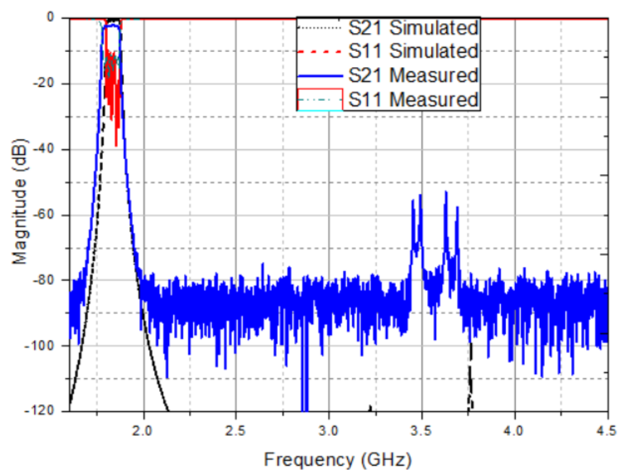


Figure 15. Simulated and measured broadband response.

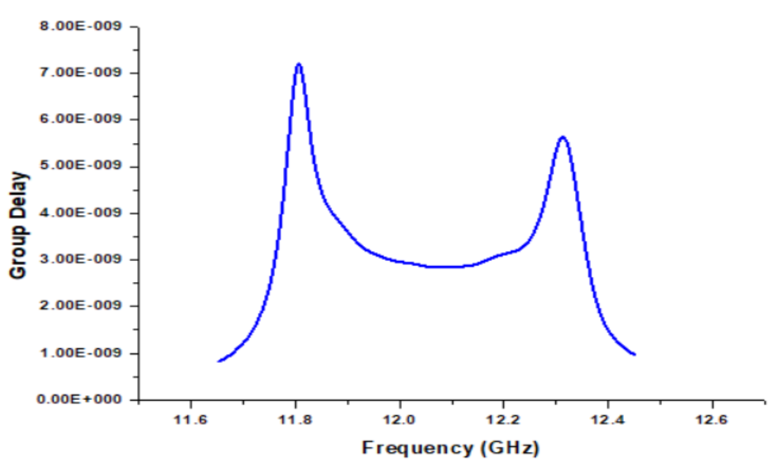


Figure 16. Simulated group delay of dielectric loaded filter.

soldering with ceramic top and bottom surfaces. But still some unavoidable air gaps between the ceramic blocks and top lid increase the insertion loss up to 1.4 dB from 0.8 dB and also shift the passband of a measured response. The Q factors of three different resonators are shown in Table 1, whereas the overall Q factor of a filter is calculated around 20.02. Internal and external views of the fabricated filter with tuning screws are shown in Figure 12 and Figure 13. The comparison of simulated and measured passband responses is shown in Figure 14. These air gaps can be further reduced by screwing the top lid with the ceramic blocks. The out of band performance still provides excellent 55 dB rejection up to 4.5 GHz shown in Figure 15 whereas the group delay of a filter is shown in Figure 16. All of these designs improve the spurious performance of ceramic waveguide filters, but we fabricated the best two designs (C & D) considering the minimum insertion loss and better stopband performance of filters. The comparisons of both fabricated filters with other filters are given in Table 1.

**Table 1.** Comparison of ceramic waveguide filters.

| **Filter design** | **Resonator Volume ($cm^3$)** | **Unloaded Q factor** | **Filter Spurious Performance** | **Insertion loss** | **Return loss** |
|---|---|---|---|---|---|
| Ceramic waveguide Filter [7] | 2.529 | 2268 | $1.5 * f_o$ | 0.85 dB | 15 dB |
| Dielectric loaded filter [2] | 3.6 | 2530 | $1.85 * f_o$ | 0.25 dB | 25 dB |
| Ceramic Non-Uniform Width waveguide Filter [12] | 2.31 | 2298 | $1.87 * f_o$ | 0.83 dB | 13 dB |
| | 2.48 | 2039 | | | |
| Air-filled waveguide filter with two metal posts and non-uniform width resonators | 1.391 | 1760 | $1.99 * f_o$ (meas) | 0.75 dB | 18 dB |
| | 2.33 | 2012 | | | |
| | 2.17 | 1978 | | | |
| Ceramic loaded waveguide filter with ridge and non-uniform width ceramic blocks | 3.6 | 2248 | $2.45 * f_o$ (meas) | 1.95 dB | 12 dB |
| | 3.6 | 2968 | | | |
| | 3.6 | 3031 | | | |

## 3. CONCLUSION

The new design techniques are used to improve the spurious performance of the integrated ceramic waveguide resonator filter and dielectric loaded filters. Integrated ceramic rectangular waveguide resonator geometry is modified to increase the separation between the first and high order resonances. The combination of the nonuniform width resonators with ceramic TEM resonators results in significantly improved spurious performance without significantly degrading the Q-factor. The proposed dielectric loaded filter offers significant improvement in stopband performance with a high Q factor in comparison to all other designs. An air filled TEM, nonuniform width filter and dielectric loaded filter are fabricated and measured. Results of the fabricated filter are in good agreement with the simulated results.

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