

Compact Ultra-Wideband Bandpass Filter Using Additively Manufactured TM-Mode Dielectric Resonators

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Abstract — This paper reports a compact ultra-wideband C-band dielectric filter using electrically-coupled TM_{016} resonators in longitudinal coupling topology. Uniquely, this configuration enables large inter-resonator couplings to be obtained, introducing broadband responses. All dielectric resonators are realized as a single highly integrated, additively-manufactured dielectric piece. The presented wideband dielectric filter is successfully designed, manufactured, assembled, and measured with excellent agreement between simulations and measurements. The implemented prototype operates at 6.1 GHz with a wide bandwidth of 2.70 GHz and a high unloaded quality factor of 1000. Also, the filter features a small mass of only 102 grams and a compact volume of $90 \times 41 \times 32$ mm³.

Keywords — Additive manufacturing, ceramic, dielectric filter, wideband.

I. INTRODUCTION

Thanks to their excellent characteristics and distinctive volume-saving capabilities compared to other 3-D technologies, TM-mode dielectric resonator (DR) filters are attracting increasing attention in high-performance narrowband applications including cellular base stations and satellite payloads [1]-[3]. For example, [1] introduced a compact base station filter using TM_{010} mode DRs with fractional bandwidth of 1% at UMTS 1.95 GHz frequency band. Also, narrowband 2.7% L-band TM-mode dielectric filters and diplexers were presented for high-power space applications in [3].

Similar to their narrowband counterparts, wideband bandpass filters represent a key element of many RF front-end units. Accordingly, the proposal of compact and high-Q wideband filters using dielectric resonators is highly desirable. However, this is always challenging since high input-output and inter-resonator (IR) coupling strengths are required to obtain wide passband responses whereas most of the fields are confined inside the dielectric resonators. Additionally, wide spurious-free bands with a frequency ratio larger than 1.5 to the next spurious mode are needed. Unfortunately, this cannot be satisfied using the conventional TE and hybrid TEH mode resonators due to their close spurious resonances. Considering these two constraints, very limited DR filters were reported in

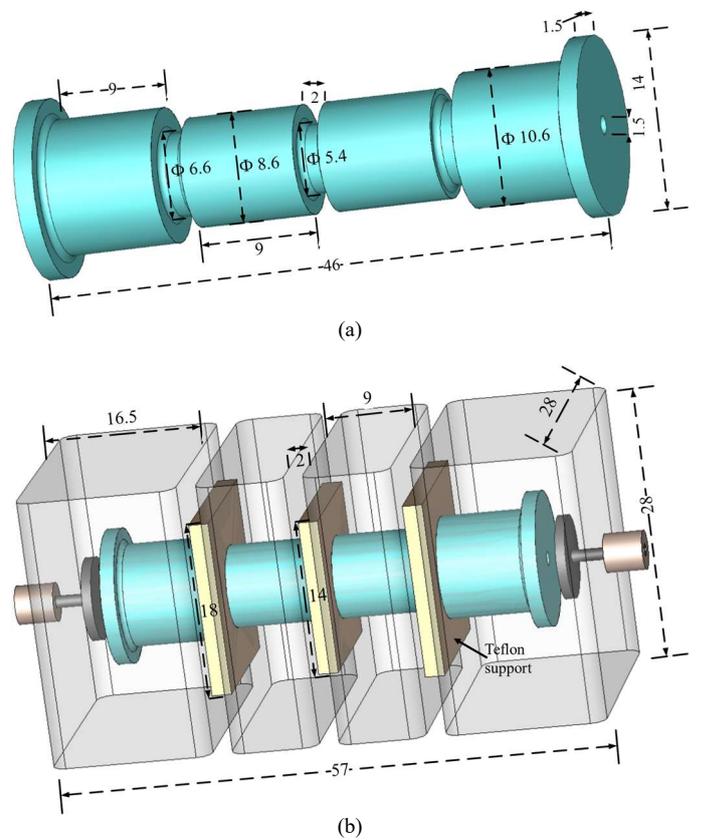


Fig. 1. Perspective view of the proposed broadband DR filter. (a) Dielectric Alumina core ($DK = 9.5$, $\delta = 8 \times 10^{-5}$ @ 7.5 GHz). (b) Filter structure. All dimensions are in mm unit. The first and fourth resonators are identical, as well as the second and third resonators. Teflon supports are inserted in the square-shaped iris sections. The first and third irises are identical. The IO feeding is realized using metallic disks with diameter $D = 8.6$ mm, and 1.5 mm gap G from the dielectric core).

the open literature aiming to obtain relatively wider bandwidths ($>10\%$ of FBW) [4]-[7]. In [4], a 2nd-order dual-mode conductor-loaded DR filter was introduced with a 10.5% fractional bandwidth. However, the capability of either realizing higher-order structures or increasing the bandwidth

response was not demonstrated. The authors in [5] presented compact dielectric substrate-loaded filters with FBWs of 9% – 13%. Unfortunately, the integration and assembly requirements deteriorate the unloaded quality factor and limit their industrial employment and high-performance applications. Kobayashi *et al.*, introduced electrically-coupled TM_{010} filter using a dielectric rod in longitudinal configuration offering up to 15% of fractional bandwidth [6]. This structure has the interesting characteristic of easily realizing multistage filters using a single dielectric resonator rod. Similarly, the authors in [7] and [8] investigated the design of wideband $TM_{01\delta}$ DR filters using stereolithography and conventional machining. This structure is quite similar to the one we propose, however, has many drawbacks including the relatively small bandwidth (5%), increasing losses, too many tuning elements, and low accuracy of the ceramic manufacturing process. The main difference between this structure and our structure is related to the coupling mechanism. Indeed, in [7] and [8] the dielectric resonators' part is directly anchored to the metallic irises. In our opinion this can be very problematic as it is difficult to guarantee a perfect contact and this could explain why simulated and measured results are so different (the measured band is a half of the simulated band). In order to overcome this problem, according to Fig. 1(b), in our structure a low permittivity dielectric material (Teflon) is exploited for holding the dielectric resonator.

Considering the aforementioned limitations of all presented wideband dielectric filters, there is still a fundamental need for wider bandwidth (>20% FBW), easily assembled dielectric filters, eliminating the need for any tuning components. In this paper, we preliminary investigate the introduction of wideband dielectric filters covering those stringent goals and exploiting the capabilities of ceramics' additive manufacturing state-of-the-art technologies. The design process and experimental results of a compact broadband C-band DR filter are introduced in the following sections.

II. WIDEBAND DIELECTRIC RESONATOR FILTER

A. Filter Specification and Structure

The filter is designed to operate at 6.2 GHz with a wide 20-dB BW of 2.6 GHz to explore the feasibility of the proposed configuration in obtaining ultra-wide passbands. Accordingly, the corresponding coupling matrix of the designed wideband BPF is extracted as follows:

$$\mathbf{M} = \begin{bmatrix} S & 1 & 2 & 3 & 4 & L \\ S & 0 & 1.03 & 0 & 0 & 0 & 0 \\ 1 & 1.03 & 0 & 0.91 & 0 & 0 & 0 \\ 2 & 0 & 0.91 & 0 & 0.70 & 0 & 0 \\ 3 & 0 & 0 & 0.70 & 0 & 0.91 & 0 \\ 4 & 0 & 0 & 0 & 0.91 & 0 & 1.03 \\ L & 0 & 0 & 0 & 0 & 1.03 & 0 \end{bmatrix}$$

While small inter-resonator (IR) couplings of narrowband TM-mode DR filters are commonly realized through transversal magnetic coupling configurations as in [1]-[3], unfortunately, they cannot provide the required large IR couplings for wideband filter applications similar to all other DR filter categories. In contrast and uniquely, the longitudinal

electrically-coupled topology of TM DRs [6]-[8] can be effectively employed to design DR filters with wide passbands where high IR coupling strengths can be realized between the adjacent resonators. Therefore, this configuration is chosen here to design our wideband C-band DR filter as shown in Fig. 1. All DRs are designed as a single piece of Alumina material ($DK= 9.5$, $\delta = 8 \times 10^{-5}$ @ 7.5 GHz) as depicted in Fig. 1(a). Advantageously, this monolithic structure makes the assembly and realization of multi-stage filters simpler and more efficient. Furthermore, it can be manufactured easily using the available high-precision additive manufacturing technologies.

B. Input-Output Coupling

The required large IO coupling is realized using capacitive coupling disks fixed on sub-miniature (SMA) probes as illustrated in Fig. 1. Through this configuration, the electrical field is coupled effectively attributing large IO coupling values as desired. The coupling strength of this fixture can be adjusted mainly through the diameter of the metallic disk (D) and the gap between the disk and the dielectric core (G) as shown in Fig. 2.

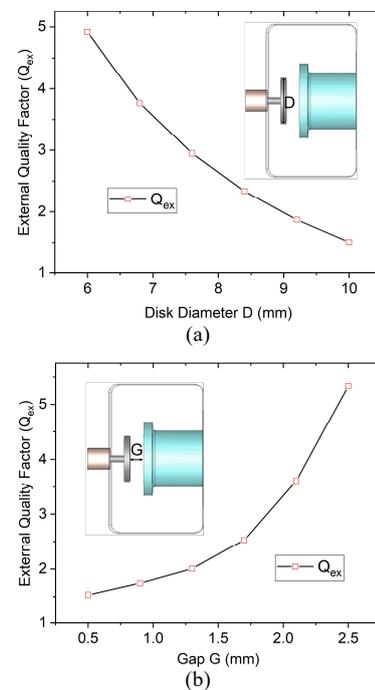


Fig. 2. Relationship between the external quality factor (Q_{ex}) and (a) disk diameter D, and (b) disk spacing from the dielectric core G.

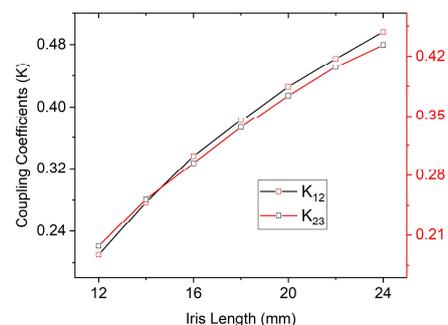


Fig. 3. Dependence of the inter-resonator coupling on the length of the square iris section.

C. Inter-Resonator Coupling

The key advantage of the proposed longitudinal $TM_{01\delta}$ DR configuration is the ability to obtain large IR couplings carried out at the end of resonators by means of the electrical field [6]. The coupling strength is mainly controlled by the iris section through its width, length, thickness, and also the dielectric part inside it. Here, the irises' dielectrics are made smaller than the resonators' diameters to properly fix the dielectric core in the cavity using Teflon supports, and also to eliminate any additional loss or unwanted spurious that could occur in closer dielectric-metal setups (as noticed in [6]-[8]). The dependence of inter-resonator couplings on the iris parameters is presented in Fig. 3. It can be seen that the proposed configuration is capable of obtaining large IR couplings and ultra-wide bandwidths.

Based on the above specifications and design guidelines, the proposed broadband filter is realized in Fig. 1. The simulated S parameter responses are depicted in Fig. 4. The filter operates at 6.2 GHz and has a wide bandwidth of 2.6 GHz with a spurious-free band better than 3 GHz.

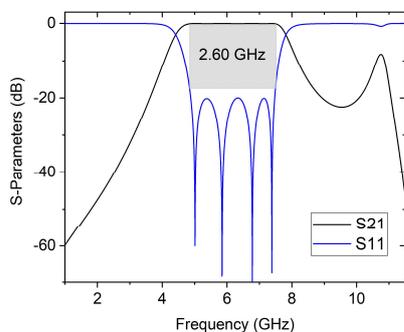


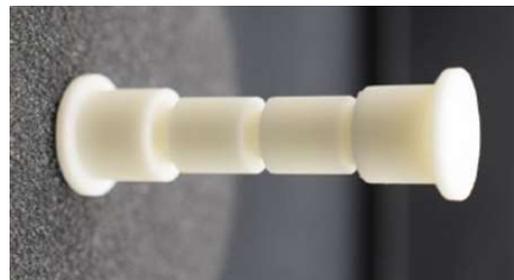
Fig. 4. Simulated S parameters of the proposed wideband dielectric filter.

III. EXPERIMENTAL RESULTS AND COMPARISON

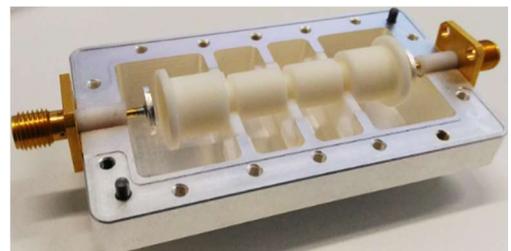
To verify the design procedure of the proposed wideband DR filter, a dielectric core has been manufactured, and a filter prototype is implemented and tested. The dielectric core depicted in Fig. 5(a) is additively manufactured by LITHOZ out of Alumina material ($DK = 9.5$, $\delta = 8 \times 10^{-5}$ @ 7.5 GHz) [9]. A 1.5 mm inner pass-through hole is introduced in the ceramic part to facilitate the sintering process. Also, 0.5 mm radii are needed in the transitions between the different sections of the dielectric core. These two manufacturing constraints were considered accordingly during the design phase of the above section. The ceramic part is then fixed inside a silver-plated metallic Aluminium housing using Teflon supports as shown in Fig. 5(b). The assembled filter features a compact size of $90 \times 41 \times 32$ mm³ and a lightweight of only 102 grams. The measured S parameters of the filter are depicted in Fig. 6 with an excellent agreement to simulated results. The filter exhibits a wide bandwidth of 2.70 GHz corresponding to 44.3% of BW ranging from 4.70 GHz to 7.40 GHz. Also, the filter has a very good in-band insertion loss of 0.06 dB – 0.16 dB and return loss better than 19 dB. It should be remarked that these excellent results were obtained without the need for any tuning elements. The next spurious resonance appears at ≈ 10.5 GHz which is a common issue in DR filters. Nevertheless, it can be improved

by using more TM_{010} alike structures as [6]. Small spikes can be noticed mainly due to asymmetries exciting unwanted spurious modes. They can be eliminated through proper optimization of the filter parameters including the I/O feeding mechanism, dielectric piece geometry, and the iris configuration. The propagation of the EM fields (Fig. 7) suggests a possible solution by including longitudinal cuts in the cavity to interrupt the current of spurious modes and suppress unwanted spikes. The cut version of the presented broadband filter and its measurements are depicted in Fig. 8. As it can be seen, this proposed solution worked properly and all in-band spikes disappeared. The measured in-band insertion loss spans from 0.05 dB to 0.22 dB corresponds to a Q_u of 1000.

Table 1 summarizes a comparison between the implemented wideband filter and similar reported wideband dielectric filters. It is apparent that the proposed wideband dielectric-based solution has a significantly wider bandwidth than the other filters (five to nine times larger FBW). Besides, the presented filter doesn't need any auxiliary tuning components, thus reducing the cost and post-manufacturing tuning effort. Furthermore, thanks to its monolithic ceramic structure, the filter can be assembled easily, and required supports can be inserted effectively.



(a)



(b)

Fig. 5. Manufactured wideband BPF. (a) 3D-printed DR core. (b) Assembled prototype (top-cover is removed).

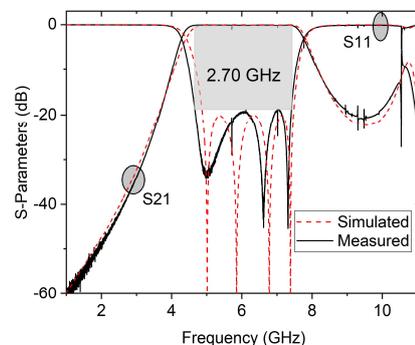


Fig. 6. Measured versus simulated results of the proposed wideband DR filter.

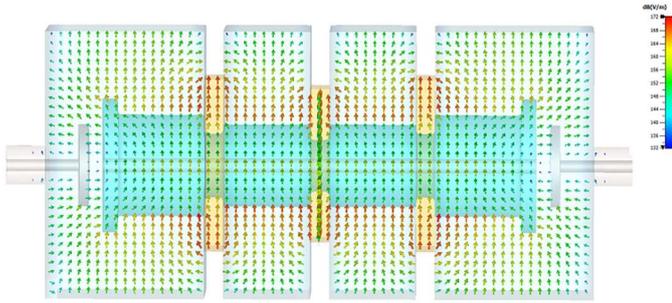
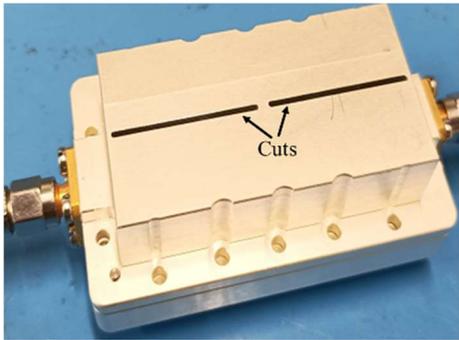
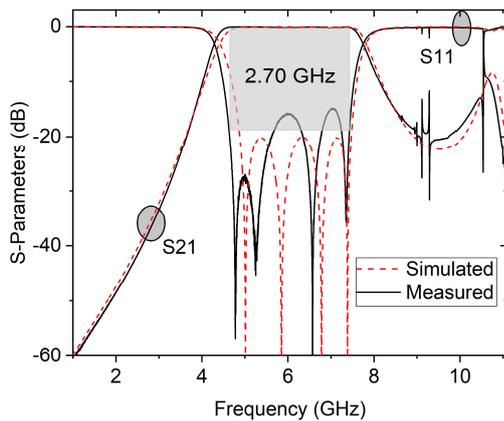


Fig. 7. E-field of a spike at 5.8 GHz in half-cut view.



(a)



(b)

Fig. 8. Proposed wideband dielectric BPF with longitudinal cuts. (a) Assembled filter. (b) Measured S parameter responses.

Table 1 Comparison between the presented filter and similar wideband C-band dielectric filters:

Filter	f_0 (GHz)	Filter order	FBW (%)	Q_u	Need for tuning elements	Assembly complexity
[5]	5.0	4	9.0	310	Yes	Not easy
[7]	4.05	4	4.94	1100	Yes	easy
This work	6.1	4	44.3	1000	No	easy

IV. CONCLUSION

A compact wideband C-band bandpass filter using electrically-coupled TM_{018} DRs in longitudinal configuration providing large inter-resonator coupling values was reported in this paper. All dielectric resonators were manufactured as a single dielectric element exploiting state-of-the-art 3D printing technologies. This advantageously makes the filter assembly process easier and more accurate, eliminating the need for any tuning elements. Additionally, the presented wideband filter has several advantages compared with similar designs including wider passband responses ($> 40\%$ of FBW), compact size, and high- Q_u .

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