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Widely Tunable TM-Mode Dielectric Filters With Constant Absolute Bandwidth Using Re-Entrant Caps

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ABSTRACT This paper reports octave tunable dielectric combline bandpass filters with constant absolute bandwidth (CABW) using a novel *re-entrant cap* tuning technique. The resonant frequency is tuned by the hollow re-entrant cap penetrating into the filter cavity as an envelope around the dielectric resonator. This mechanism of tuning provides wider tuning capabilities and better spurious performance than the conventional screw-based tuning. Also, the cap tuners can be employed effectively to tune the input-output and inter-resonator couplings simultaneously with the frequency reconfiguration, enabling a CABW over a wide frequency tuning window. For proof of concept purposes, a single widely tunable resonator is presented with octave tuning ratio of 2.64:1, high quality factor from 1705 to 5480, and spurious-free band up to $3.44 \cdot f_0$. Afterwards, two octave tunable re-entrant cap filters are designed, fabricated, and tested. The first filter is a 78% widely tunable two-pole filter with a CABW of 43.5±12% MHz, low insertion loss equals to 0.28±0.03 dB, and a compact volume of 39 cm^3. The second design is a four-pole octave tunable bandpass filter from 2.96 GHz to 1.36 GHz with a constant 69±13% MHz bandwidth, low insertion loss better than 0.6 dB, return loss higher than 16 dB, and a compact 62 cm^3 structure. According to our own knowledge, thanks to the proposed tuning mechanism, the presented designs are the first CABW octave tunable high Q waveguide-based filters, having the widest tuning ranges over all similar state-of-the-art-designs.

INDEX TERMS Cap, constant bandwidth, dielectric resonator, high-performance, re-entrant, tunable.

I. INTRODUCTION

Tunable RF filters are expected to play a crucial role in many evolving frequency-agile applications including multi-band cellular base stations and flexible satellite payloads [1], [2], [3], [4]. However, to replace the current fixed filter banks, tunable filters must provide similar capabilities fulfilling the stringent requirements of the various frequency-adaptable applications. With regard to this, the achievable tuning range and the ability to maintain a constant absolute bandwidth are two challenging characteristics of frequency tunable filters in addition to the high quality factor. While many widely tunable planar and evanescent-mode cavity filters were reported in the open literature as [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], few of them were able to maintain constant ABW responses [19], [20], [21], [22], [23], [24], [25], [26], [27], [28]. For example, the authors in [20] introduced a two-pole 25 MHz constant ABW tunable evanescent-mode filter with a 56.5% tuning window and a relatively low quality factor varies from 310 to 225. Also, [23] presented a second-order L-band varactor-tuned microstrip filter with a constant 3-dB bandwidth over a wide 54.2% tuning range. The majority of these designs are based on low-order filters (i.e., 2nd-order). This implies that for higher-order filters, the design of constant ABW will more complicated, and the tuning mechanism associated losses will increase. Consequently, the achievable tuning range will be impacted. Furthermore, planar and evanescent-mode structures are not suitable for high-performance applications of tunable filters due to their low quality factor and limited high-power handling capabilities. On the other hand, CABW reconfigurable filters based on hollow waveguides suffer from bulky structures and very narrow tuning windows (i.e., < 5%) despite their superior Q factor and ability to handle high levels of power [4]. For instance, a 4-pole 180 MHz K-band reconfigurable TE_{311} waveguide filter was presented in [29] with 1.74% of frequency tuning and a Q factor from 3100 to 2600 using dielectric plates. To this end, coaxial and dielectric-loaded waveguides have gained more interest in many tunable filter applications due to their advantages of miniaturized structures, high Q, and good power handling capabilities [3], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49]. For example, a CABW tunable coaxial filter was reported in [3] for future agile 5G Base Transceiver Stations (BTSs). The filter operates from 942.5 MHz to 737.5 MHz (24.4%) with a CABW of 23 MHz±8% and a quality factor ranges from 2900 to 2300. Also in [41] and [42], our group recently presented 40% tunable CABW coaxial filters with the least variation of Q factor over the tuning window using inset resonators. To provide more compactness and a higher Q factor than the coaxial filters, a couple of tunable dielectric resonator (DR) filters were proposed [43], [44], [45], [46], [47], [48], [49]. A four-pole 65 MHz C-band tunable dielectric combline filter was reported in [47] with a tuning window of 4.9% and a Q factor of 548 to 536. Also, [49] introduced a compact tunable dual-mode C-band filter based on TM-mode dielectric resonators. The filter has a tuning range of 15.4% with a CABW of 50 MHz±10% and a Q factor varies from 1100 to 500. Despite that this group of loaded-waveguide constant ABW tunable filters features good tuning capabilities of up to 40%, the introduction of new designs that cover wider octave tunable ranges and maintain a CABW is still highly desirable.

In [50], we introduced a novel tuning technique for TM-mode dielectric resonators using *re-entrant caps*. In this expanded article, widely octave-tunable TM-mode DR filters with constant absolute bandwidth are presented based on re-entrant caps. The proposed tuning mechanism has the key advantages of simple configuration, high Q, improved spurious performance, and the ability to achieve wide tuning ranges while maintaining constant ABW responses. First, the design requirements of octave tunable CABW filters are discussed. Then, the unique employment of re-entrant caps in widely tunable CABW filters design is detailed and compared with the conventional tuning mechanism using screws. Finally, two BPF examples are designed, implemented, and compared with similar state-of-the-art filters.

II. TUNING CONCEPT AND DESIGN PRINCIPLES

A. TUNABLE TM-MODE DIELECTRIC RESONATOR

Fig. 1 illustrates a perspective view of TM-mode dielectric resonator with a re-entrant cap for frequency tuning. The chosen configuration is the dielectric combline resonator, which has high quality factor and good spurious performance, combining the merits of the dielectric-loaded resonators and metallic coaxial resonators [51]. The operation mode is the fundamental TM-mode $TM_{01\delta}$ where the E-field is focused in the middle of the resonator and the H-field resonates mainly in the DR surroundings [50]. The movable re-entrant cap tunes the resonant frequency by two means, simultaneously: 1) the part which intrudes the cavity around the DR, and 2) the part outside the cavity which functions as a movable sidewall. As result, wider tuning ranges (i.e., > 90%) can be obtained in comparison with the traditional screw-based tuning [50]. Besides, the proposed technique has the advantage of improved spurious performance over tuning [50], unlike in the other screw/disk-based designs where unwanted spurious resonances could appear at lower states due to the tuning elements. To verify the aforementioned features, a single resonator prototype is implemented and measured as depicted

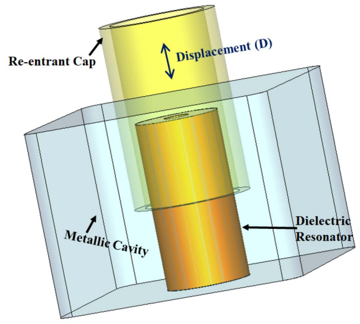

FIGURE 1. Tunable dielectric combline resonator with a re-entrant cap.

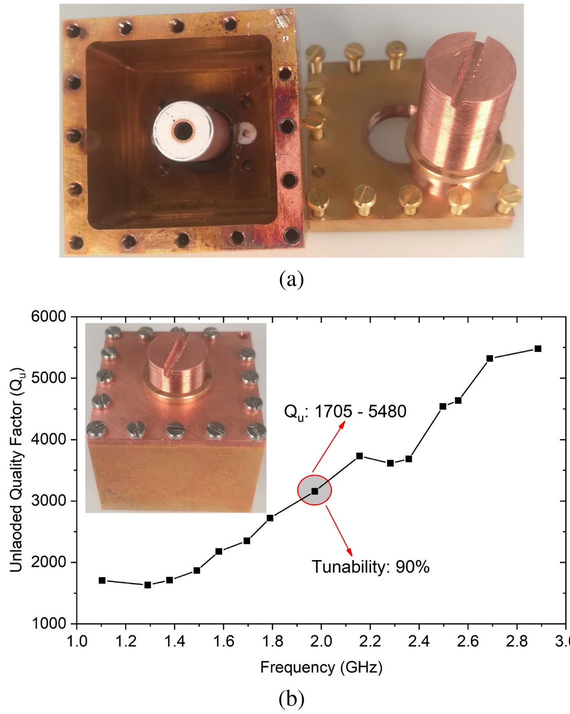

FIGURE 2. Tunable resonator prototype. (a) Disassembled parts. (b) Measured tunability and unloaded quality factor.

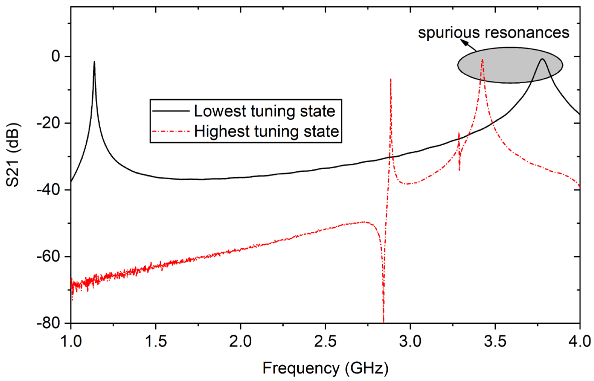

FIGURE 3. Spurious measurements at the lowest and highest tuning frequencies.

in Figs. 2 and 3, respectively. The TM-mode dielectric resonator (length = 20 mm, inner diameter = 3 mm, outer diameter = 10 mm) has a dielectric constant of 44, and a loss tangent of 4×10^{-5} @ 3.5 GHz. The metallic housing ($30 \times 30 \times 22$ mm^3) and re-entrant cap (length = 21 mm, inner diameter = 11 mm, outer diameter = 14 mm) were milled from copper metal. The DR is soldered in the metallic cavity, and the resonator prototype is then assembled and tested. As can be seen in Fig. 2(b), the resonator has a wide 90% octave-tuning window from 2.9 GHz to 1.1 GHz with a high unloaded quality factor ranging from 5480 to 1705. Also, the resonator has a good spurious-free band of 520 MHz at the highest tuning frequency, and improves gradually up to $3.44{\cdot}f_0$ at the lowest tuning state, as shown in Fig. 3. It is worth mentioning that excellent electrical contact is always needed between the re-entrant cap and the cavity (e.g., using nuts), similar to the screw/disk-based designs. Besides, it is advised to have a relatively thin contact area to reduce the related losses (e.g., the chosen lid thickness here is 2 mm). Alternatively, the designer can use dielectric caps where no electrical contact is required, however, at the cost of narrower tuning ranges.

B. DESIGN GUIDELINES OF OCTAVE TUNABLE FILTERS WITH CONSTANT ABSOLUTE BANDWIDTH

It is known from [42] that the physical inter-resonator (IR) and input-output (IO) couplings should also change with the frequency tuning to maintain a constant ABW and a stable return loss level. In practice, keeping this harmony is a very challenging task, especially for broad tuning ranges. This is mainly because the design process and IR/IO tuning elements' capabilities (e.g., varactor diode capacitance, tuning screw penetration) cannot cover such wide ranges of required coupling variations. For this reason, we can see that the majority of CABW tunable filters cannot provide octave tunable ranges (tuning ratio $\geq$ 2:1), while the few reported octave tunable filters are not able to maintain a CABW allover the operation frequencies. To overcome these limitations and enable octave frequency tuning with CABW, the solution is by employing the frequency tuning elements to also tune the IR and IO

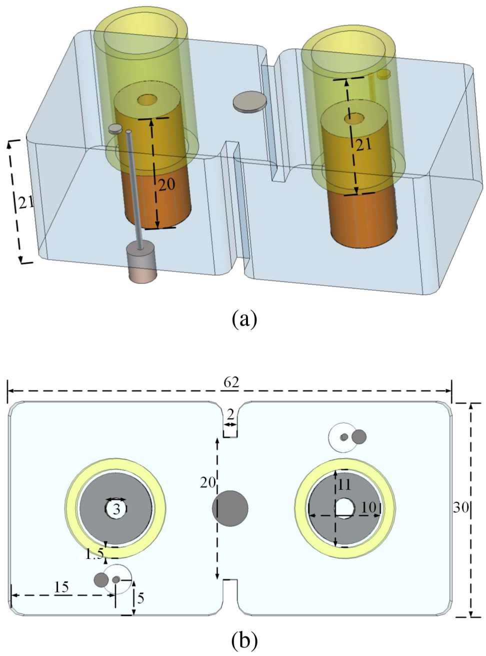

FIGURE 4. Second-order tunable dielectric combline filter using re-entrant caps. (a). Perspective view. (b) Top view. All dimensions in mm unit.

couplings in a way that the required IR and IO couplings to maintain a CABW can be obtained with (or without) the IR and IO tuning elements. In most of the available tuning techniques, when the frequency is tuned downwards, the IR and IO couplings will either decrease or remain fixed. Therefore, the IR and IO tuners cannot provide the required coupling over a wide range, and the ABW becomes narrower with the frequency tuning as can be noticed in [8] and [15], for example. Contrary, in the proposed re-entrant cap tuning technique, when the caps intrude the filter housing, they mainly cut the E-field in the area around the resonators (close to the irises and IO feeding structure), resulting in an increase in the (magnetic) IO and IR couplings. This advantageously reduces the required coupling adjustment for a CABW, allowing the desired IR and IO couplings to be obtained effectively over a wide tuning window. In the following section, a second-order CABW octave-tunable BPF is designed using the proposed tuning mechanism, and compared with another design using the conventional tuning screws.

III. TUNABLE CABW TWO-POLE BANDPASS FILTER: RE-ENTRANT CAPS VS. TUNING SCREWS

To validate to proposed tuning concept, a two-pole bandpass filter is designed and tuned over a wide frequency span using re-entrant caps and tuning screws for comparison, as presented in Figs. 4 and 5, respectively. First, both filters are designed at 2.67 GHz with 20-dB bandwidth of 42.3 MHz. The required physical inter-resonator coupling (K_{12}) for both filters is realized using a simple inductive iris, while the IO feeding is obtained using an inductive loop wire. Initially, we investigated the variation in the IR and IO couplings due

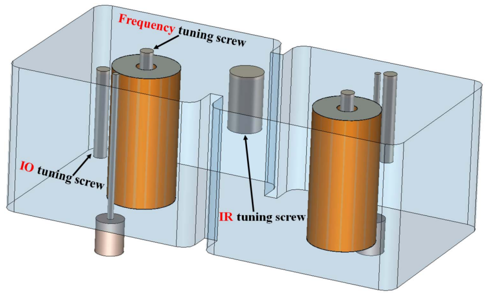

FIGURE 5. Second-order tunable dielectric combline filter using tuning screws. All dimensions are similar to the first filter except the cavity height = 22.1 mm, and iris width = 19.7 mm.

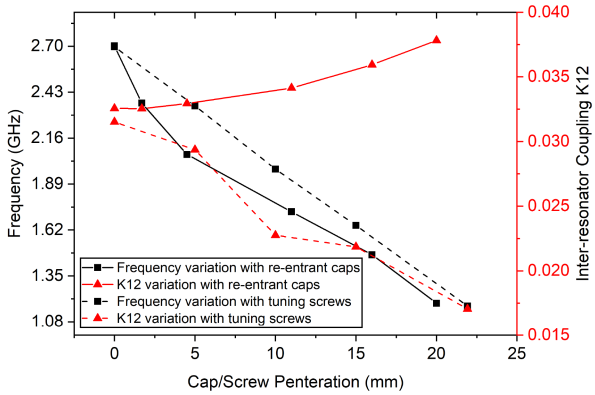

FIGURE 6. Resonant frequency and physical inter-resonator coupling variation of the presented two-pole filters with respect to the frequency tuning elements displacement.

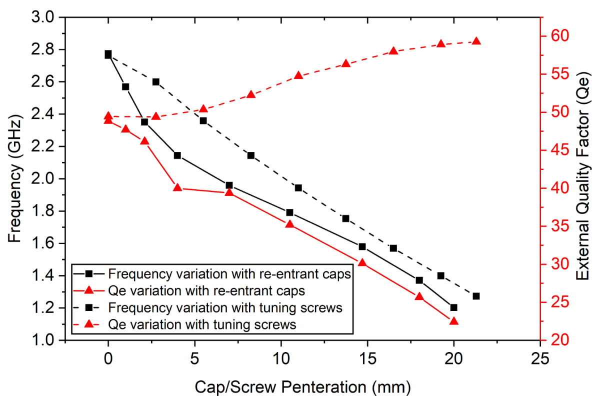

FIGURE 7. Resonant frequency and external quality factor change of the presented two-pole filters with respect to the frequency tuning elements displacement.

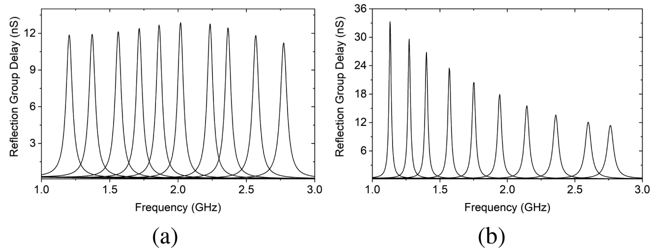

FIGURE 8. Peak reflection group delay over the frequency tuning window of the designed two-pole tunable filters: (a) with re-entrant cap tuners, (b) with tuning screws.

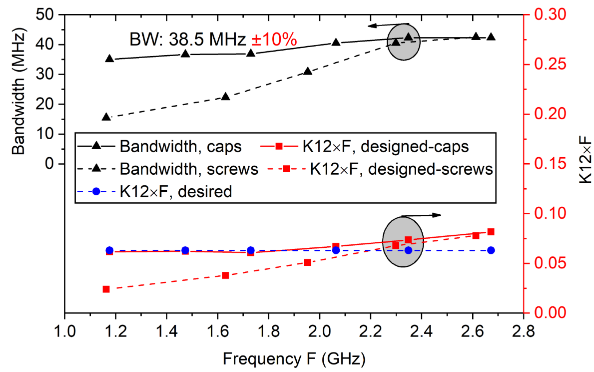

FIGURE 9. Inter-resonator couplings and bandwidth variation in relation to the frequency tuning for the two-pole tunable filter with re-entrant caps (Fig. 4) and tuning screws (Fig. 5).

to the frequency tuning elements of both designs (caps and screws) as depicted in Figs. 6 and 7, respectively. As can be seen in Fig. 6, the IR coupling (K_{12}) increases with the frequency decrease when using re-entrant cap tuners, whereas it decreases with frequency when using screws to tune the operation frequency. Similarly, in Fig. 7, we can see that the IO coupling strength (represented in form of external quality factor) increases with the frequency tuning in the re-entrant cap example, while it decreases with the frequency decrease in the tuning screws design. These observations of the IR and IO couplings confirm the proposed tuning mechanism and allow the design of re-entrant cap frequency tunable filters while maintaining a CABW over a wider tuning range than the conventional tuning screws. It is also worth to remark that tuning disks generally behave similarly to the tuning screws. Also, they are not a favorable option as more vicinity is needed inside the cavity to obtain more tuning which results in large, bulky structures. Then, in this part, we explore the tuning capabilities of the two presented filters. The desired design is an octave tunable filter from 2.67 GHz to 1.17 GHz (tuning ratio 2.28:1) with a constant 20-dB bandwidth of 38 MHz. Following the design procedure of CABW tunable filters detailed in [42], the required $K_{12} \times f$ product and reflection group delay are calculated as 0.063 and 11.2 nS, respectively. Then, one M5 tuning screw and two M2 tuning screws were introduced at both filters to obtain the desired IR and IO couplings, respectively. As can be seen in Fig. 8, the reflection group delay is stable over the tuning window (the IO coupling is increasing with frequency tuning) in the re-entrant filter, while it increases noticeably in the screw-based design (the IO coupling is decreasing with frequency tuning). This tells that the M2 screws can effectively adjust the IO coupling in the re-entrant cap filter, and will not be able to obtain the desired IO coupling in the screws-tuned filter. Also, Fig. 9 shows that the re-entrant cap design, with the aid of the M5 tuning screw, fulfills the required IR coupling requirement, while the screw-tuned filter cannot provide the required IR coupling, even with

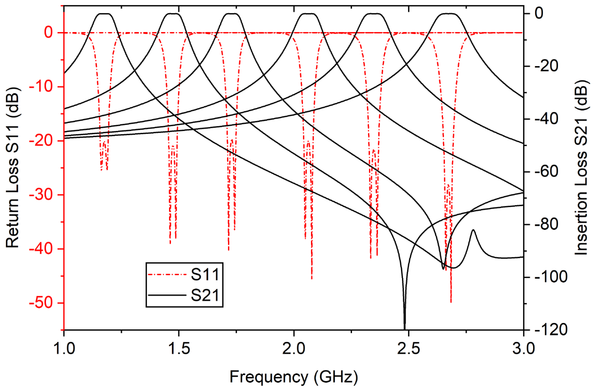

FIGURE 10. Simulated S-parameters of the two-pole re-entrant cap widely tunable BPF. Tuning ratio: 2.28:1, 20-dB CABW: 38.5 MHz±10%.

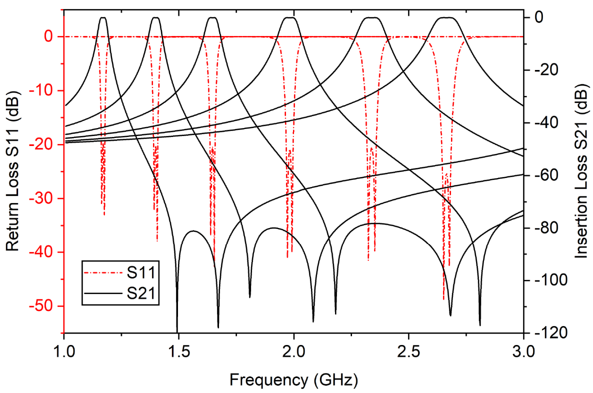

FIGURE 11. Simulated results of the two-pole screws-based tunable filter. Tuning ratio: 2.28:1, 20-dB BW: varies from 42.3 MHz to 15.5 MHz.

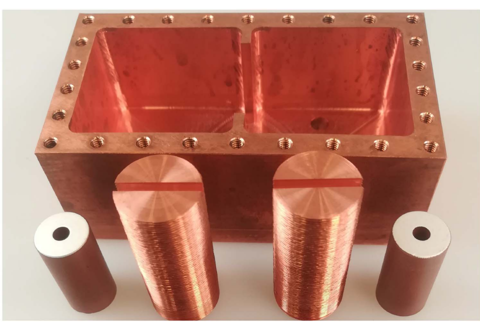

FIGURE 12. Disassembled components of the fabricated second-order tunable dielectric filter with re-entrant caps.

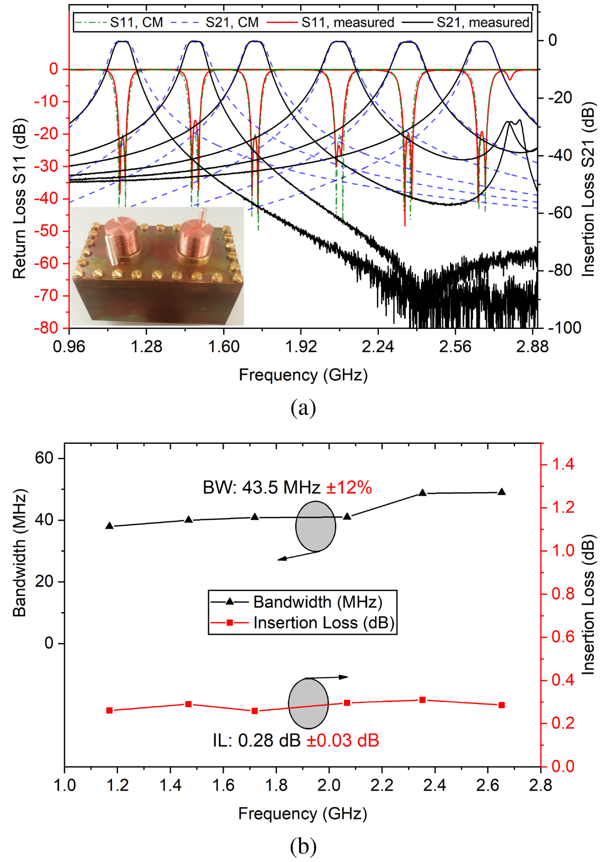

FIGURE 13. Measured results of the implemented two-pole CABW octave tunable filter. (a) S-parameter responses compared to their associated coupling matrices (20-dB BW = 38 MHz, Q_u = 4000): frequency tuning range: 2.67 GHz to 1.17 GHz, tunability: 78.13%. (b) Bandwidth and insertion loss variation over the tuning window.

the M5 tuning screw. The simulated S-parameter responses of the two tunable filters are exhibited in Figs. 10 and 11, respectively. It can be seen clearly that the re-entrant cap filter maintains a CABW response of 38.5 MHz±10%, while the bandwidth decreases significantly in the screw-based design from 42.3 MHz at 2.67 GHz to only 15.5 MHz at 1.17 GHz and cannot be recovered. Then, a prototype is manufactured and measured to validate the designed octave-tunable CABW re-entrant cap filter. The disassembled parts and the final prototype, made of copper metal, are depicted in Fig. 12. The measurements in Fig. 13 show that the filter can be tuned over a wide range of 78.13% from 2.67 GHz to 1.17 GHz with a constant ABW of 43.5 MHz±12% (at S11 = -15 dB), low insertion loss of 0.28 dB ±0.03 dB, and return loss higher than 15.6 dB. The estimated unloaded quality factor varies from 1350 to 850.

IV. TUNABLE CABW FOUR-POLE BANDPASS FILTER

Fig. 14 depicts a 3-D structure of a fourth-order octave tunable BPF with constant ABW. The filter is designed to operate from 2.86 GHz to 1.34 GHz with a constant 20-dB bandwidth of 71 MHz. Similar to the previous example, the design procedure begins from the desired reflection group delay (8.3 nS) and IR couplings ($K_{(12,34)} \times f = 0.066$, $K_{23} \times f = 0.05$) calculation based on [42]. Next, the required reflection group delay is realized through the IO feeding structure with the aid of two M3 tuning screws as shown in Fig. 15. As can be seen, the IO tuning screws are used at the lower tuning states to decrease the IO coupling strength and maintain the reflection group delay at the desired peak. For the design of the inter-resonator irises, one can use simple inductive irises with tuning screws similar to the earlier two-pole design. However, another way is used here by optimizing the position

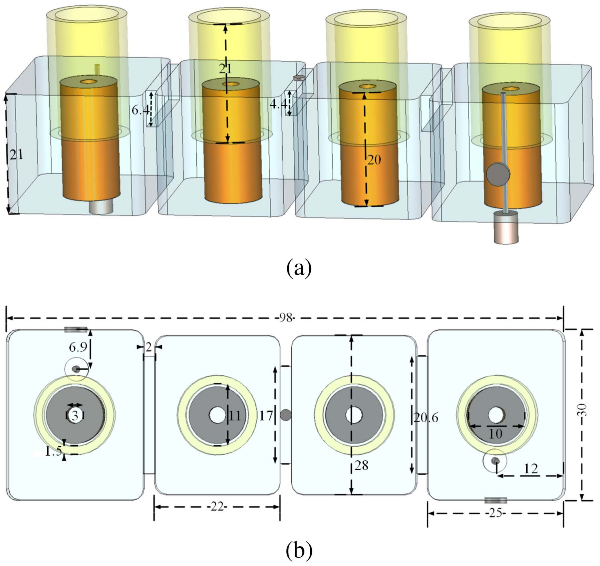

FIGURE 14. Fourth-order CABW tunable dielectric combline filter using re-entrant caps. (a) Perspective view. (b) Top view. All dimensions in mm unit.

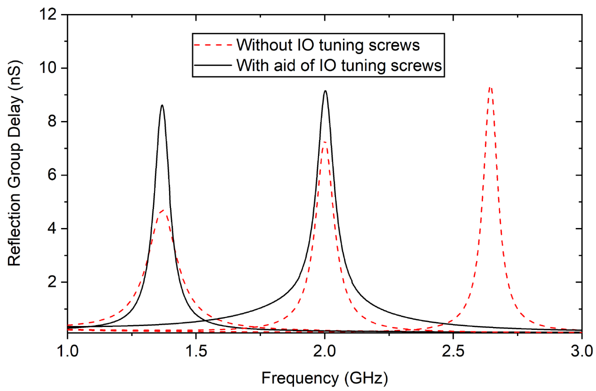

FIGURE 15. Peak reflection group delay over the frequency tuning window of the designed four-pole octave tunable filter.

and dimensions of the iris to provide the required coupling variation for a CABW over the tuning range, eliminating the need for the IR tuning screws, as explained in [35] and [42]. Therefore, we can see that the used IR coupling layout here is distinct from the conventional inductive iris in Fig. 4 filter. However, due to the wide tuning window, one M3 tuning screw is still needed to tune K_{23} at a couple of states. As shown in Fig. 16, the designed irises successfully provide the required IR couplings of the different states within the tuning range. The simulated S-parameter responses are demonstrated in Fig. 17 with a CABW of 72 MHz±10% over a wide tuning range of 1.52 GHz (tuning ratio 2.13:1). The simulated unloaded quality factor ranges from 5900 to 1670 using copper metal. A prototype is then fabricated and tested as depicted in Figs. 18 and 19, respectively. The filter has a wide 74% tuning window from 2.96 GHz to 1.36 GHz with a CABW of 69 MHz±13%, low insertion loss of 0.5 dB ± 0.08 dB, and return loss better than 16 dB. The extracted unloaded quality

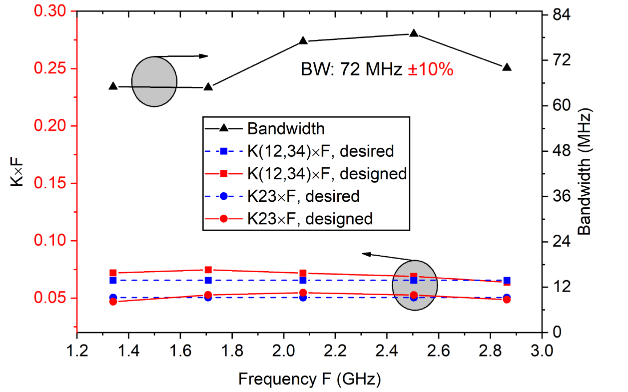

FIGURE 16. Inter-resonator couplings and bandwidth variation in relation to the frequency tuning in the proposed four-pole octave tunable filter.

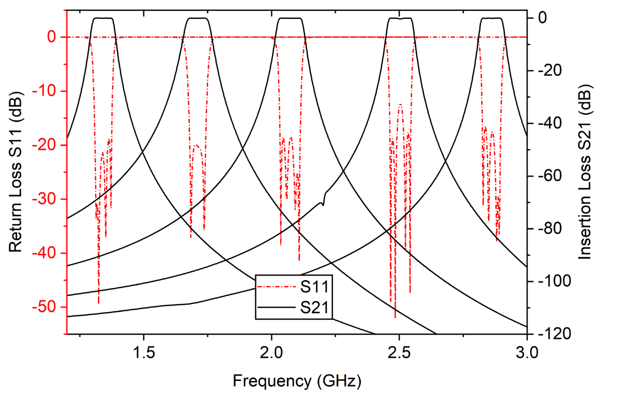

FIGURE 17. Simulated S-parameters of the designed four-pole re-entrant cap octave tunable BPF. Tuning ratio: 2.13:1, 20-dB CABW: 72 MHz±10%.

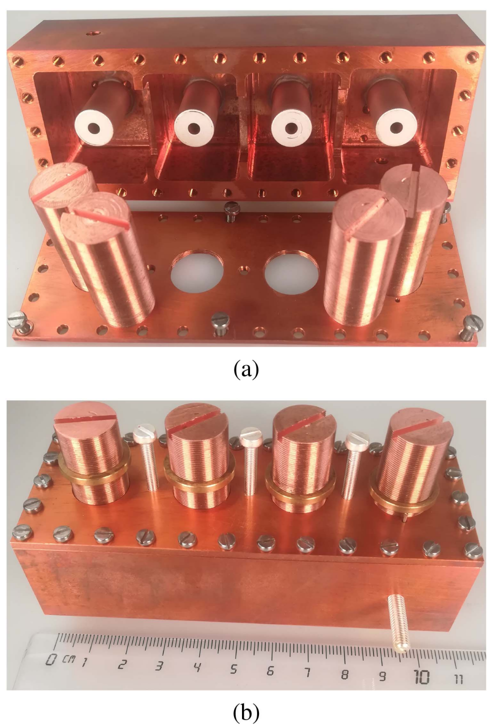

FIGURE 18. The fabricated four-pole octave tunable dielectric combline filter. (a) Disassembled and (b) assembled.

TABLE 1. Comparison of the Proposed Octave CABW Tunable Filters With Similar State-of-the-Art Designs

Ref.	Structure (tuning mechanism)	f (GHz)	Order	Tunability (%)	ABW (MHz)	IL (dB)	RL (dB)	Q-factor	Volume (cm^3)	#
[20]	Evanescent-mode (E)	0.8-1.43	2	56.5%	25±0.27%	1.6-3.1	> 10	225-310	NA	6
[23]	Microstrip (E)	0.78-1.36	2	54.2%	103±5.8%	1.68-2.9	> 13	NA	2.032	2
[29]	Hollow waveguide (M)	19.36-19.7	4	1.74%	181±1.66%	< 1.8	> 11	2600-3100	NA	4
[30]	Combline (M)	1.81-2.17	5	18.1%	25	< 1.8	> 14	2000-2500	NA	1
[32]	Combline (M)	2.565-2.634	6	2.7%	NA	0.9-2.3	> 16.2	2252-2914†	NA	6
[35]	Half-wavelength (M)	2.275-2.775	4	19.8%	106.5±9%	< 0.4	> 7.5	> 4850‡	275.65	1
[36]	Combline (E)	0.707-0.963	3	30.7%	27.5±2.5%	1.58-3.97	> 14	173-418	94.067	3
[37]	Combline (M)	0.68-0.76	4	11.1%	11.2±8.9%	0.8-0.9	> 12	> 5800‡	2291.625	1
[40]	Combline-dual-post (M)	9.15-10.87	4	17.2%	230±3.9%	< 0.6	> 12	1500	NA	8
[42]	Inset (M)	2.66-3.96	4	39.3%	116±6%	0.39-0.44	> 13.5	1820±6%	49.28	4
[45]	Dielectric-TE (M)	15.6-16	3	2.5%	150	1.5-4.5	> 8	421-1630†	NA	3
[47]	Dielectric-combline (M)	4.97-5.22	4	4.9%	66±1.5%	3.9-4.4	> 10	536-548†	NA	4
[49]	Dual-mode dielectric-TM (M)	4.72-5.51	2	15.4%	50±10%	0.2-0.9	> 18	540-1100	3.456	2
This work-1	Dielectric-combline (M)	1.1-2.9	-	90%	-	-	-	1705-5480	19.8	-
This work-2	Dielectric-combline (M)	1.17-2.67	2	78.13%	43.5±12%	0.28±0.03	> 15.6	850-1350	39.06	5
This work-3	Dielectric-combline (M)	1.36-2.96	4	74%	69±13%	0.5±0.08	> 16	750-2000	62.034	5

‡Based on simulated Q-factor. †Based on the measurements of a single-cavity resonator. #: Number of tuning elements. E: Electrical tuning. M: Mechanical tuning.

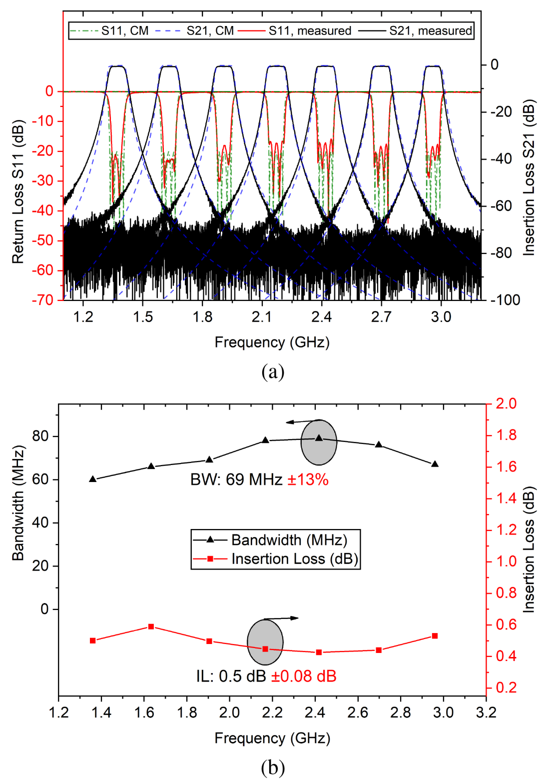

FIGURE 19. Measured results of the implemented four-pole CABW widely tunable filter. (a) S-parameter responses compared to their associated coupling matrices (20-dB BW = 72 MHz, Q_u = 4000): frequency tuning range: 2.96 GHz to 1.36 GHz, tunability: 74%. (b) Bandwidth and insertion loss variation over the tuning window.

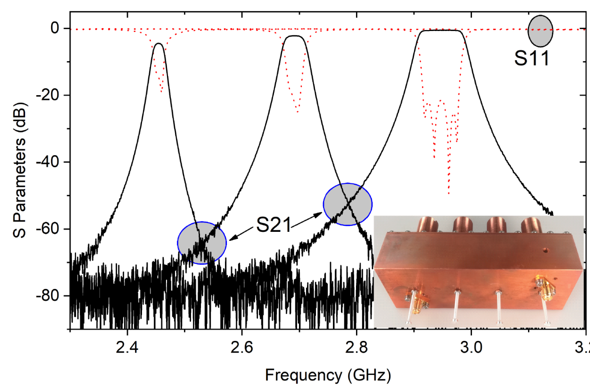

FIGURE 20. Measured results of the proposed filter using screws to tune the operation frequency instead of re-entrant caps (caps are fixed at the lid of filter cavity).

factor varies from 2000 to 750, where degradation can be noticed compared with simulations, which could be due to the metal properties and imperfect contact between the caps and the metallic housing. It is worth noting here that despite the IO tuning screws were considered in the prototype, they were not employed in obtaining the measured results. For curiosity, the filter is tuned with silver-plated M2 tuning screws instead of the re-entrant caps as exhibited in Fig. 20. As expected, there is an obvious variation in the absolute bandwidth, confirming the advantage of the presented tuning technique. The wide-band response of the implemented filter using re-entrant caps and tuning screws is provided in Fig. 21, at the lowest and

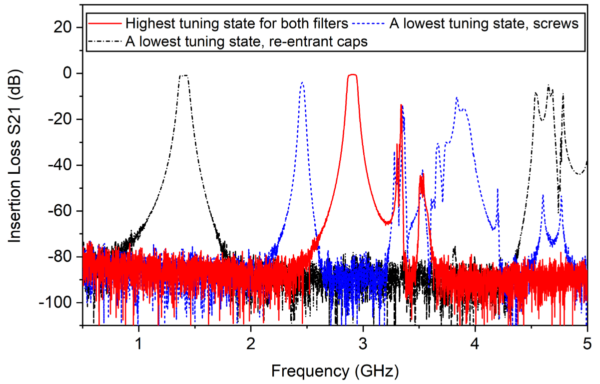

FIGURE 21. Wideband response of the fabricated 4th-order tunable filter with re-entrant caps (Fig. 18 filter) and tuning screws (Fig. 20 filter) at the extreme ends of tuning window.

highest tuning states. As shown, the spurious performance is being improved with frequency tuning in the re-entrant caps filter up to 4.5 GHz at the lowest tuning state, while it remains fixed at around 3.4 GHz when using tuning screws.

V. STATE-OF-THE-ART COMPARISON

Table 1 provides a comparison between the proposed re-entrant cap tunable filters and similar state-of-the-art designs with constant absolute bandwidth. As evident, the re-entrant cap designs have the widest tuning capabilities providing up to 90% of tunability and octave 2.64:1 tuning ratio with a high Q up to 5480. Besides, they feature a stable return loss level better than 15.5 dB and low insertion loss with a maximum ±0.08 dB of variation allover the broad band of tuning. All these advantages are added to the compact structures, simple tuning configuration, and improved spurious performance over tuning. Concerning the number of tuning elements, the proposed technique requires a least N tuning elements (N is the filter order), which must be in excellent electrical and mechanical contact with the cavity. Accordingly, this attributes a slower tuning speed than the designs which use a single tuning mechanism as [30], or contactless tuning like [41]. Hence, further research and unconventional solutions that enable faster tuning processes are still needed.

VI. CONCLUSION

Octave CABW frequency tunable TM-mode dielectric filters were presented in this paper using a novel re-entrant cap tuning technique. First, a single resonator is implemented providing a wide 90% tuning range from 2.9 GHz to 1.1 GHz and a spurious-free band up to $3.44\cdot f_0$. Then, the design guidelines of widely tunable BPFs with CABW are discussed, and octave tunable filters are designed, manufactured, and measured. The fabricated filters have the merits of wide tuning ranges (tuning ratio $>$ 2:1), high Q, compact structure, good spurious performance, and simple tuning mechanism. All these highly desirable features strongly promote the proposed tuning technique and tunable components in a wide range of frequency-agile systems and applications.

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