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Bandwidth-Reconfigurable Coaxial Bandpass Filter With Multi-Octave Tuning Using a Single Element

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Abstract—A bandwidth tunable coaxial-loaded waveguide filter is presented in this letter based on a novel concept using a single tuning element. The operation principle relies on the rotation of coaxial resonators with respect to fixed irises in order to change the inter-resonator coupling strengths that control the bandwidth. This mechanism features multi-octave tuning while maintaining a fixed operating frequency and a stable unloaded quality factor with only one rotary post. Furthermore, the filter can be switched off by using the same tuning mechanism. A prototype is manufactured and measured to verify the proposed filter. The measured results demonstrate multi-octave bandwidth tunability from 12 MHz to 83 MHz (tuning ratio $> 6.9:1$), promoting the technique for multi-standard communication systems and applications.

Index Terms—Bandwidth tuning, coaxial filter, tunable filter.

I. INTRODUCTION

TUNABLE filters have gained increasing attention in recent years because of their highly favorable features compared with traditional fixed structures. In future flexible satellites for instance, it is essential that both operating frequency and bandwidth be remotely adjustable and can be re-defined whenever it is required. Generally, the majority of the available tunable filters in both the literature and the market focus on frequency reconfiguration. Whereas on the other hand, despite their key importance in a wide range of applications, bandwidth (BW) tunable filters are not so common due to the challenging design and realization [1].

In particular, BW reconfigurable cavity-based filters are more desirable than planar structures like [1]–[3] because of their lower loss and ability to handle higher power levels. Accordingly, several BW tunable empty-waveguide and coaxial-loaded filters were presented [4]–[9]. A cascaded lowpass filter and highpass filter configuration was used in

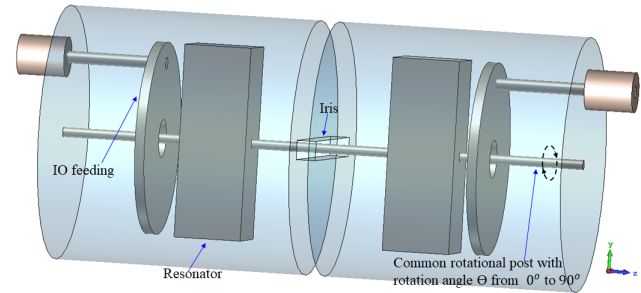


Fig. 1. Perspective view of the proposed bandwidth tunable filter. A single rotational element is used for tuning with respect to angle θ . The inter-resonator coupling is largest when $\theta = 0^\circ$ (the shown position), and decreases with the rotation of the resonators until the switch-off state at $\theta = 90^\circ$.

[4] to realize a 160 MHz to 40 MHz Ka-band BW tunable bandpass response based on TE_{011} cavities using movable metal rings. Another BW reconfiguration concept, also for TE_{011} hollow-waveguide filters, was presented in [5] based on the use of coupling resonators instead of conventional iris structures. A third BW tuning approach was introduced in [6] using a movable plunger on a dual-mode TE_{113} cavity. A later concept was presented in [7] at Ku-band with 35% BW tuning based on two common tuning elements. However, all these empty-cavity-based concepts suffer from various limitations including bulky size, limited BW tuning capabilities, multiple tuning elements (2 to $N+1$), and increased losses due to the employed tuning mechanism. In the case of compact structures with an extended tuning range, a combine S-band BW tunable filter was reported in [8], based on the introduction of additional bandstop resonators. Also, [9] presented a fully reconfigurable miniaturized dual-mode C-band filter using TM-mode dielectric resonators. Nevertheless, despite that these two loaded-waveguide designs are compact, they still share the aforementioned limitations of empty-cavity structures, and therefore, there is still an essential need for more efficient BW tuning solutions.

This paper introduces a novel bandwidth tuning concept for coaxial-loaded waveguide filters using a single tuning element. This concept advantageously enables a very flexible bandwidth reconfiguration, from up to 10 times wider BW to a *switched-off* passband state using a single common rod, regardless of the filter order. Unlike other concepts, no extra tuning components are needed, and goes on to demonstrate a stable high quality factor with a fast and simple tuning process.

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II. BANDWIDTH TUNING CONCEPT

The structure of the proposed bandwidth reconfigurable filter is depicted in Fig. 1. The filter arrangement was inspired from the frequency tunable filter, with a constant absolute bandwidth, presented in [10]. However, both the purpose and the operational concept are different. Besides, the authors believe that this arrangement is more suitable for BW tuning than for operating frequency reconfiguration, as the inter-resonator couplings can be tuned broadly and easily while maintaining a high Q-factor. Furthermore, besides the more complicated design procedure, the frequency tuning concept of [10] has limited tuning capabilities and suffers from noticeable Q-factor degradation [11]. The proposed BW tuning concept in this work is based on the rotation of coaxial resonators with reference to a fixed iris structure, in order to change the inter-resonator (IR) coupling strength and tune the bandwidth. The resonators are rotated simultaneously using a single common rotational post with an angle θ ranging from 0° to 90° . The iris structure is designed carefully based on the distribution of the fields of the operating mode. Here, our resonating mode is the fundamental TM-mode which propagates similar to conventional $\lambda/2$ resonators (as in [10], [12]), where the H-field rotates primarily in the center of the structure, and the E-field is perpendicularly concentrated at the ends, in the area between the coaxial resonators and the cavity. Accordingly, the IR coupling is realized using a rectangular iris positioned at the center of the structure. When $\theta = 0^\circ$ (Fig. 1), the coupling (i.e., magnetic) is the strongest and the BW is the largest. Then, with the rotation of the post, the IR coupling strength decreases and the BW becomes narrower. Similarly, the filter can be detuned and switched off through the proposed mechanism (i.e., $\theta = 90^\circ$: $f_m \approx f_e \rightarrow K \approx 0$). Basically, the filter cavities are chosen in circular shapes to keep the resonant frequency fixed with the rotation of the inner resonators. Alternatively, elliptical cavities can be used to also tune the resonant frequency (as in [10]) and balance any frequency shifts that might occur due to the BW tuning process.

III. FILTER DESIGN

A. Filter Specifications

The filter is a second-order bandpass filter that operates at 4.19 GHz with a 20-dB reconfigurable bandwidth from

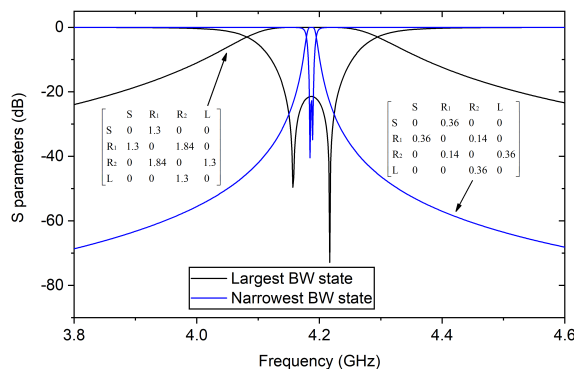


Fig. 2. Optimized coupling matrix responses of the proposed bandwidth tunable filter at the largest (82 MHz) and narrowest (8 MHz) bandwidths.

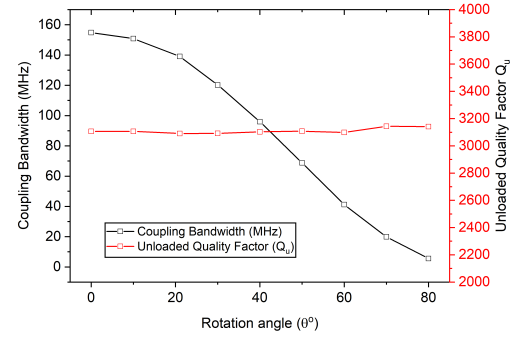


Fig. 3. Relationship between the coupling bandwidth and unloaded quality factor with the rotation angle θ .

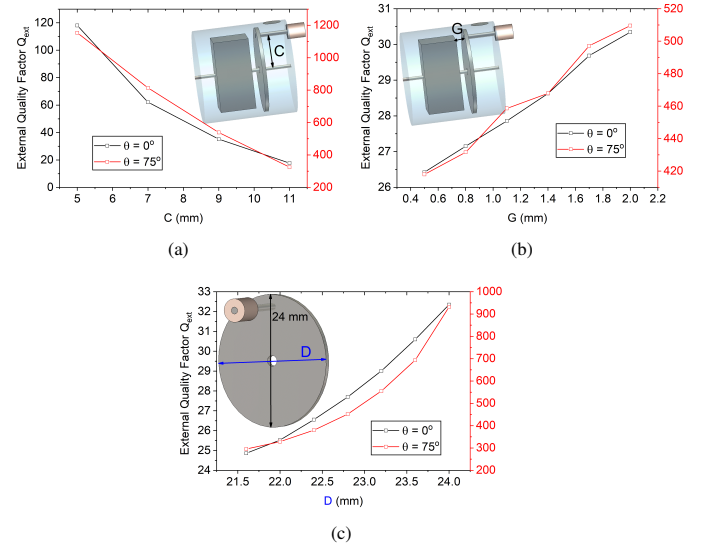


Fig. 4. Relationship between external quality factor (Q_{ext}) and the (a) probe position C , (b) disk spacing from the resonator G , and (c) minor axis of the disk D .

82 MHz to 8 MHz. The first design step is to synthesize and extract the corresponding coupling matrices of the largest and narrowest BW states, as shown in the inset of Fig. 2. Here, the coupling matrix of the largest bandwidth state is firstly extracted, and then normalized and optimized again for the second coupling matrix of the narrowest tuning state. The design procedure only needs these two coupling matrices, while all the other intermediate tuning states can be then obtained without the need for any further design steps.

B. Inter-Resonator Coupling

Based on the aforementioned design specifications, the required physical inter-resonator couplings (K_{12}) for the largest and narrowest BWs can be calculated, and then realized under weak input-output (IO) excitation condition using:

$$K_{12} = \frac{CBW}{f_0} = \frac{f_2 - f_1}{f_0} \quad (1)$$

where CBW is the coupling bandwidth, f_0 is the centre frequency, f_1 and f_2 are the lower and upper frequencies, respectively. Then, the rectangular coupling iris is designed to provide the required inter-resonator couplings at the largest

state ($\theta = 0^\circ$) and narrowest state ($\theta = 75^\circ$), simultaneously. As earlier mentioned, all other BW tuning states in-between will be realized accordingly as demonstrated in Fig. 3.

C. Input-Output Coupling

Similarly, the input-output feeding structure should be able to provide the required couplings at the largest and narrowest BW states. This implies that the input coupling topology should be the maximum at the largest BW case, and decreases gradually with the tuning process until the narrowest bandwidth. Based on this, the input feeding is realized through capacitively-coupled disks fed by SMA connectors as shown in Fig. 1. At the largest bandwidth case ($\theta = 0^\circ$) where the coaxial resonator is in-face to the disk, the (electrical) input coupling is the highest. Then, with the rotation of the resonators, the input coupling strength will decrease as fewer E-field lines are being coupled. As shown in Fig. 4, the coupling strength is controlled through the gap between the disk and the resonator (G), the position of the feeding pin (C), and the shape of the feeding disk. For simplicity, the disk can be circular, and then tuning screws can be slightly introduced at the narrow BW states. Nevertheless, here we use an elliptical disk to provide the required couplings for all states without the need for any tuning screw. As can be seen in Fig. 4(c), the narrowest BW state at $\theta = 75^\circ$ is very sensitive to the change in the minor diameter of the disk, whereas the input coupling strength at the widest tuning state ($\theta = 0^\circ$) is not impacted much.

D. Loaded-Resonant Frequency

When designing a BW tunable filter, it is important to keep the centre frequency fixed while the BW is changing. Here, if circular cavities are used, there will be a slight shift in the frequency when the BW is tuned. This is because only f_m will move with the tuning process while f_e remains fixed. This small change in the centre frequency can be adjusted easily by using tuning screws. However, alternatively, by using elliptical cavities instead of circular ones, the frequency can be also tuned at the same time with the BW tuning to balance any shift due to the BW tuning process, and keep the operating frequency unchanged as can be seen in Fig. 5.

Following the aforementioned design steps, a BW tunable filter is then realized, and its simulated S-parameters are depicted in Fig. 6 with various tuning states. As shown, the BW is effectively tuned from 82 MHz to 8 MHz (tuning ratio = 10.2:1) with a fixed centre frequency at 4.19 GHz and a return loss level better than 17 dB. Also, the filter can be intrinsically switched-off at $\theta = 90^\circ$ without the need for any auxiliary switching elements. The key feature of this filter, besides the wide BW tuning capabilities, is that the whole tuning process is done through a single element without any need for tuning screws. This advantageously results in a stable and high unloaded quality factor of 3100 (with copper) throughout the tuning range without any degradation, as can be seen in Fig. 3, unlike the other tuning concepts.

IV. EXPERIMENTAL RESULTS

A prototype is manufactured, assembled, and tested to validate the proposed concept and design procedure. All parts

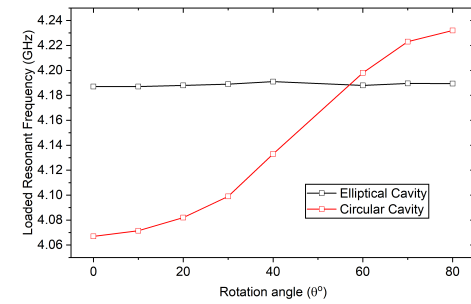


Fig. 5. The variation of the loaded resonant frequency with elliptical (major diameter = 26.44 mm, minor diameter = 26 mm) and circular cavities (diameter = 26 mm).

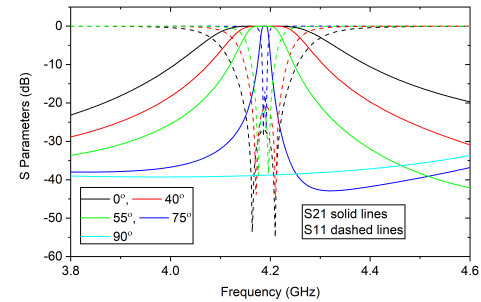


Fig. 6. Simulated S-parameter responses at different bandwidth tuning states.

of the implemented filter were manufactured out of brass metal as depicted in Fig. 7(a), where the cavities are elliptical (major diameter = 26.44 mm, minor diameter = 26 mm). The bandwidth is tuned effectively from 12 MHz up to 83 MHz (at $S_{11} = -15$ dB), providing a very wide multi-octave tuning ratio of 6.92:1 and additional switch-off feature. At the largest BW state, the passband is centred at 4.19 GHz with a midband insertion loss of 0.37 dB, while at the narrowest tuning state, it operates at 4.25 GHz with a midband insertion loss of 1 dB. The increase in loss is mainly due to the assembly and the imperfect input-output feeding through the disks, in addition to the related metal losses including M1 stainless-steel screws which are used to fix the resonators in their respective positions on the post. The use of other metals with higher electrical conductivity and silver-plating could be considered to enhance the unloaded quality factor. Another observation from the measured results is that there are slight shifts in the operating frequency due to the BW tuning process, and the frequency was not tuned as required. The main reason for this is that the feeding disks were not fixed at their exact positions (re-simulations estimate them at 0.7 mm closer), hence, causing this shift in the loaded resonant frequency. In comparison with the other BW reconfigurable designs and concepts from [4]–[9], it can be clearly seen that the proposed technique provides the widest tuning capability (6.92:1) with only a single tuning element, while in other reported works, the minimum number of tuning elements is 2 in [7], but with only 35% of BW tuning. Also, a wide 3:1 multi-octave tuning is presented in [8], however, it requires many tuning elements, i.e. $2N+2$, where N is the filter order. While introducing transmission zeros is challenging in the proposed inline configuration, a possible solution, for example, could be by using orthogonal

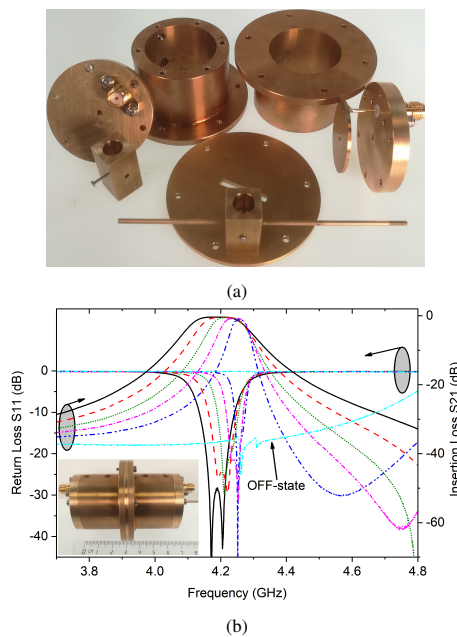


Fig. 7. The fabricated 2nd-order multi-octave BW tunable coaxial filter. (a) Disassembled and (b) measured results. The BW tuning ratio is 6.92:1.

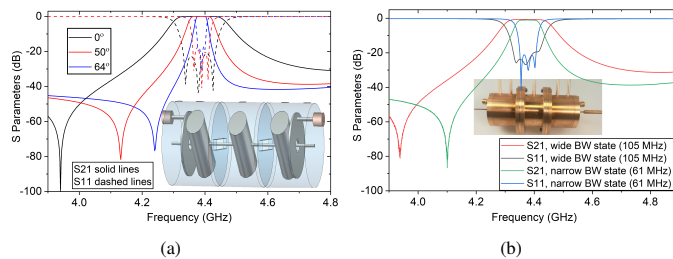


Fig. 8. A 3-pole BW tunable coaxial filter. (a) Simulation results and 3D-model. (b) Measurements at two BW tuning states (BW tuning range is 72%).

resonators topologies to realize cross couplings similar to [13] and [14]. For further investigation, a 3-pole filter is also designed and implemented as depicted in Fig. 8. Here, the filter is designed using circular cavities (diameter = 26 mm) instead of the elliptical ones, and tuning screws were included to tune and keep the operation frequency fixed. Fig. 8(b) shows the measurements of the filter at 4.38 GHz with two different states of 105 MHz and 61 MHz (at $S_{11} = -15$ dB), respectively. The BW reconfiguration is 72% with an insertion loss better than 1 dB, and a return loss higher than 19 dB, at both states. It is worth to note that despite this realization being able to offer more tuning flexibility, the tuning process is more time-consuming and complicated than in the first configuration.

V. CONCLUSION

A wide bandwidth tunable coaxial-loaded waveguide filter was presented in this paper using a single tuning element. Also, the intrinsic switch-off feature was demonstrated with no need for any further switching circuits. The filter cavities and input-output feeding were designed to keep a fixed operating frequency and provide the required input coupling at all tuning states, therefore, eliminating the need for any additional tuning elements.

REFERENCES

- [1] M. Sanchez-Renedo, R. Gomez-Garcia, J. I. Alonso and C. Briso-Rodriguez, "Tunable combline filter with continuous control of center frequency and bandwidth", *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 1, pp. 191-199, Jan. 2005.
- [2] X. Huang, Q. Feng and Q. Xiang, "Bandpass filter with tunable bandwidth using quadruple-mode stub-loaded resonator", *IEEE Microw. Wireless Compon. Lett.*, vol. 22, no. 4, pp. 176-178, Apr. 2012.
- [3] J. Ni, J. Hong, and P. M. Iglesias, "Compact bandwidth tunable IF filters for reconfigurable converters", *Int. J. Microw. Wireless Technol.*, vol. 14, no. 3, pp. 313-324, Apr. 2022.
- [4] B. Yassini, M. Yu and B. Keats, "A Ka-band fully tunable cavity filter", *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 12, pp. 4002-4012, Dec. 2012.
- [5] C. Arnold, J. Parlebas and T. Zwick, "Reconfigurable waveguide filter with variable bandwidth and center frequency," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 8, pp. 1663-1670, Aug. 2014.
- [6] U. Rosenberg et al., "Novel remote controlled dual mode filter providing flexible re-allocation of center frequency and bandwidth", *Proc. 2016 IEEE MTT-S Int. Microw. Symp.*, pp. 1-3, 2016.
- [7] G. Basavarajappa and R. R. Mansour, "A novel bandwidth reconfigurable waveguide filter for aerospace applications", *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 6, pp. 577-580, Jun. 2020.
- [8] A. I. Abunjaileh and I. C. Hunter, "Tunable bandpass and bandstop filters based on dual-band combline structures", *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 12, pp. 3710-3719, Dec. 2010.
- [9] A. Widaa, C. Bartlett and M. Höft, "Miniaturized all-reconfigurable dual-mode dielectric filter using piezomotors for future satellite communications," *Proc. 2021 51st Eur. Microw. Conf.*, pp. 107-110, 2022.
- [10] G. Basavarajappa and R. R. Mansour, "Design methodology of a high-Q tunable coaxial filter and diplexer", *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 12, pp. 5005-5015, Dec. 2019.
- [11] A. Widaa, C. Bartlett and M. Höft, "Tunable coaxial bandpass filters based on inset resonators", *IEEE Trans. Microw. Theory Techn.*, vol. 71, no. 1, pp. 285-295, Jan. 2023.
- [12] M. Yu, D. Smith and M. Ismail, "Half-wave dielectric rod resonator filter", *Proc. IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 619-622, 2004.
- [13] Y. Wang and M. Yu, "True inline cross-coupled coaxial cavity filters", *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 12, pp. 2958-2965, Dec. 2009.
- [14] M. Höft and F. Yousif, "Orthogonal coaxial cavity filters with distributed cross-coupling", *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 10, pp. 519-521, Oct. 2011.