

Miniaturized All-Reconfigurable Dual-Mode Dielectric Filter Using Piezomotors for Future Satellite Communications

Abdulrahman Widaa¹, Chad Bartlett², Michael Höft³

Chair of Microwave Engineering, Kiel University, Germany

{¹aw, ²chb, ³mh}@tf.uni-kiel.de

Abstract — A compact fully-reconfigurable C-band pseudo-elliptic bandpass filter for the applications of next-generation flexible satellite systems is introduced. The filter is realized using a dual-mode TM-mode dielectric resonator attributing ultra-high miniaturization and volume saving $> 70\%$. A wide 790 MHz tuning window is obtained from 4.72 – 5.51 GHz with a constant bandwidth of 50 MHz. Additionally, two independently reconfigurable transmissions zeros are introduced through the use of a doublet configuration and non-resonating modes. A piezomotor-based fixture is utilized for accurate fine-tuning. The measured results show good agreement with simulations. The prototype filter has demonstrated high-Q measurements across the whole tuning band (> 500) while maintaining a low insertion loss of less than 1 dB and return loss higher than 18 dB.

Keywords — bandpass filter, dielectric resonator, reconfigurable, satellite.

I. INTRODUCTION

Next-generation flexible satellites are regarded as a revolutionary game-changer in the space communication market due to their great advantages in comparison with conventional fixed satellite technologies [1]. Traditionally, satellite payloads are configured on the ground with specific fixed bandwidth and frequencies which cannot be changed after launch, even if the market and/or application demands evolved. In contrast, flexible payloads are a software-defined and digitally-controlled platforms which enable remote users to re-define and adopt new technologies/operation channels while the satellite is in orbit. This provides key desirable merits and features including flexibility in bandwidth and frequency, reduced cost, lighter weight, and less time-to-fly lead times.

Filter units represent a fundamental part of every RF front-end subsystem including satellite payloads which require compact filters with high unloaded Q-factors (> 500) and high-power handling capabilities. Similarly, high-performance reconfigurable filters are major components in next-generation flexible satellite systems. Various high-Q reconfigurable waveguide filters were presented in the open literature with low-loss and high-power capabilities in [2] – [6]. For example, [2] introduced a second-order frequency and bandwidth reconfigurable filter using a dual-mode TE_{311} waveguide cavity for High Throughput Satellite systems (HTS). The frequency is tuned from 11.125 GHz to 11.275 GHz with a constant 52 MHz bandwidth using a stepper motor mechanism.

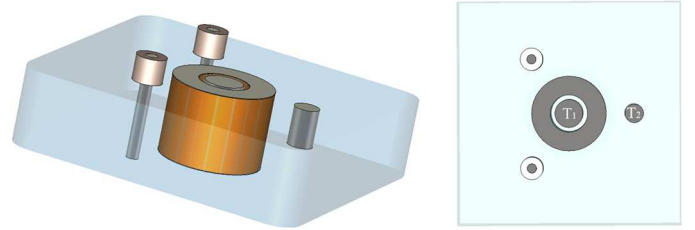


Fig.1. 3D (left) and top view (right) of the proposed miniaturized reconfigurable dual-mode TM-mode DR filter.

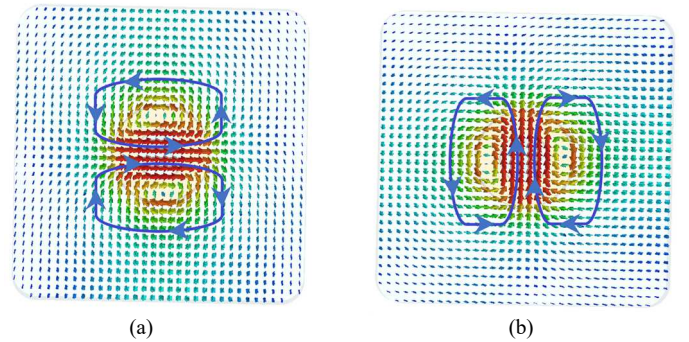


Fig. 2. Top view of the proposed dual-mode filter showing H-field distribution at the two degenerate modes: (a) TM_{120} and (b) TM_{210} .

Another output filter for satellite payloads based on an air-filled waveguide structure was also presented in [3]. The fabricated filter has 200 MHz tunability at a center frequency of 19.8 GHz and 54 – 72 MHz of bandwidth tuning. Also in [5], a frequency reconfigurable combline filter was presented using piezomotors with a 2.7% tuning window. Another tunable dielectric combline filter was also introduced in [6] where a piezoelectric transducer is used to control the movement of a flexible sidewall to change the resonant frequency of the cavity. A fourth-order TEM mode reconfigurable filter is implemented with a frequency range of 4.97 – 5.22 GHz and extracted Q factor of 550. However, the integration of those filters in future satellites is still burdened by their bulky structures, limited tuning functionalities, and poor spurious-mode responses. Therefore, the introduction of more efficient tunable structures is thoroughly required.

In recent years, TM-mode dielectric resonators have attracted an increasing amount of attention in satellite filter applications due to their miniaturized size and better spurious-

free ranges, while also being able to exhibit decent unloaded Q-factor values [7] – [10]. For instance, a miniaturized L-band TM₀₁₀ mode DR input filter was introduced in [7] for mobile satellite services (MSS) providing a 50% volume reduction with enhanced rejection levels. Also in [8], two degenerate dual-mode TM-mode DRs were employed in transversal configuration to implement a highly compact C-band filter. Additionally, another desirable feature of TM-mode DR filters, especially for the implementation of tunable filters, is that tuning is more feasible than in the other waveguide structures [10]. Therefore, all of the aforementioned advantages strongly promote the employment of TM-mode DR filters for the next-generation of flexible satellite systems.

In this paper, a highly miniaturized reconfigurable dual-mode TM-mode dielectric bandpass filter is introduced for the next generation of flexible satellite payloads. All filter parameters including frequency, bandwidth, and TZs can be effectively and flexibly reconfigured due to the compact planar configuration. Advantageously, due to this high degree of freedom, frequency tuning can be obtained over a wide frequency range with constant absolute bandwidth responses (CABW). Also, two transmission zeros are positioned below and above the passband offering very good out-of-band rejection characteristics. To meet the remote control requirement of future flexible payloads, a piezomotor tuning mechanism is utilized providing an accurate fine-tuning.

II. FILTER DESIGN

A. Dual-Mode TM-Mode Dielectric Bandpass Filter

The proposed pseudo-elliptic C-band dual-mode TM-mode dielectric resonator filter is depicted in Fig. 1. The 2nd order filter is designed using two orthogonal degenerate modes, namely TM₁₂₀ and TM₂₁₀, in a single resonator structure as shown in Fig. 2. The resonator dimensions are carefully chosen in order to assure adequate separation between the operating modes and the other unwanted lower and upper spurious modes. The selected TM-mode resonator has a dielectric constant (ϵ_r) of 45 with an 8 mm outer diameter (D), 4 mm inner diameter (d), and a height of 6 mm. It is also worth mentioning that as the TM operating modes are independent of Z-axis; the resonator height is chosen based on the desired unloaded-Q, structure compactness, and the spurious modes separation.

The coupling topology and the corresponding S-parameter responses of the proposed miniaturized two-pole dual-mode TM-mode filter are shown in Fig. 3 and Fig. 4, respectively. The two degenerate modes (TM₁₂₀, TM₂₁₀) constitute a doublet operating at 4.74 GHz with a bandwidth of 50 MHz. The filter is designed to obtain a high-selectivity pseudo-elliptic response by introducing two independent transmission zeros in the lower and upper stopband regions. The doublet configuration introduces one TZ on the left side of the passband while the fundamental TM₁₁₀ non-resonating mode (NRM) creates a source-load bypass path (-M_{SL}) to introduce another TZ on the right side. The first transmission zero is located closely at 4.57 GHz while the second TZ is positioned at a frequency of 5.76 GHz. Sub-miniature connectors (SMA)

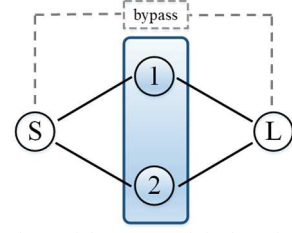


Fig. 3. Coupling topology of the proposed dual-mode filter.

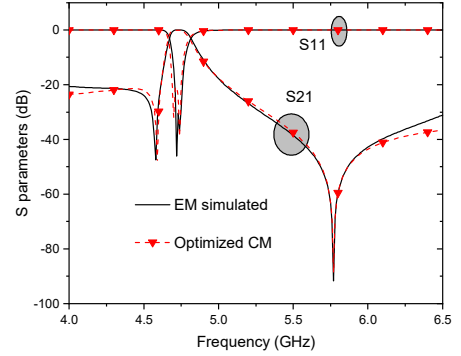


Fig. 4. EM simulated S-parameter responses and optimized coupling matrix (CM).

are used for input/output feeding through grounded inductively-coupled pins as shown in Fig. 1. The I/O feedings are aligned angularly in mirror configuration in order to excite both orthogonal modes simultaneously. Next, following the above design specifications, the corresponding coupling matrix $[M]$ can be synthesized by extracting the different coupling components following the procedure stated in [11] for the doublet configuration and [12] for the non-resonating mode representation. The final optimized coupling matrix is:

$$[M] = \begin{bmatrix} & S & R_1 & R_2 & L \\ S & 0 & 0.78 & -1.1 & -0.018 \\ R_1 & 0.78 & 2.21 & 0 & 0.78 \\ R_2 & -1.1 & 0 & -1.69 & 1.1 \\ L & -0.018 & 0.78 & 1.1 & 0 \end{bmatrix}$$

It should be noted that, unlike the transversal configuration presented in [9], the proposed dual-mode TM-mode filter here is designed in a planar configuration for the purpose of easier and more flexible tuning from the top side as it's highly favorable for the implementation of reconfigurable filters.

B. Reconfigurable Dual-Mode TM-Mode Dielectric BPF

In this section, a fully and flexibly reconfigurable filter is designed using the presented dual-mode TM-mode DR filter. All filter parameters including the frequency, bandwidth, and transmission zeros can be effectively reconfigured using just two metallic tuning pins (T_1 , T_2). The resonant frequencies of both modes are reconfigured simultaneously using the T_1 through the inner hole of the TM-mode resonator. In the TM₁₂₀ and TM₂₁₀ modes, unlike the fundamental TM₁₁₀ mode where the max E-field is focused in the centre of the resonator and H-field is rotating in the surroundings, the max H-field is

primarily located in the centre of the resonator (see Fig. 2 (a), (b)). Thus, the frequency shifts upwards as the T_1 tuning pin is introduced into the resonator body. Since there is no intracavity coupling between the two orthogonal modes ($M_{12} = M_{21} = 0$), the filter bandwidth can be controlled by tuning each mode separately. The bandwidth, however, is reconfigured by tuning the TM_{120} mode using the tuning pin T_2 . This advantage of flexibility in BW tuning remarkably contributes to the implementation of reconfigurable filters with constant passband responses throughout the tuning band. Fig. 5. shows the simulated results of the presented reconfigurable dual-mode TM-mode DR filter with constant absolute bandwidth responses of 50 MHz. The filter is tuned from 4.74 GHz to 5.51 GHz providing 15% of frequency tuning. Also, bandwidth reconfiguration capability is demonstrated in Fig. 6. with more than one-octave of BW tuning.

In addition to the frequency and bandwidth reconfiguration functions of the proposed pseudo-elliptic filter, the positions of the two transmission zeros are also independently controllable. One of the unique features of the generalized doublet configuration is the introduction of a TZ on one side of the passband without the need for any axillary cross-coupling/extracted-pole configurations. Furthermore, the TZ can be easily configured to either side of the passband by just changing the self-coupling sign of the operating degenerate modes [11]. This can be seen in Fig. 7. wherein which the TZ that is produced through the bypass coupling remains fixed while the doublet TZ is shifted to the right side of the passband by changing the self-coupling sign of the first mode TM_{120} using T_2 pin. On the other hand, the position of the TZ produced through the bypass coupling can also reconfigured independently by the I/O feeding arrangement and the control of the coupling ratio between the resonant orthogonal TM-modes and the TM_{110} NRM as explained in [12] and shown in Fig. 8.

III. EXPERIMENTAL RESULTS

For the purpose of validation and demonstration of the proposed all-reconfigurable dual-mode DR filter, a prototype filter was built and measured. The hollow TM-mode dielectric resonator that has been used is a compact E6045 ($\epsilon_r = 45$, Q-factor = 8000 @ 5 GHz) from EXXELIA [13]. The resonator is then metalized inside a $24 \times 24 \times 6$ mm³ metallic brass box. In reference to the accurate and digitally-controlled tuning requirement of future flexible satellite payloads, a dual piezomotor fixture is attached to the tuning pins T_1 and T_2 . The filter setup and the measured results are shown in Fig. 9. and Fig. 10., respectively. Measurements show very good agreement with simulations. The frequency is tuned from 4.72 GHz to 5.51 GHz with a constant absolute bandwidth of 50 ± 5 MHz. The fabricated filter has demonstrated a high unloaded Q-factor ranging from 1100 to 540 with low mid-band insertion loss ranging from 0.2 – 0.9 dB and return loss higher than 18 dB. The Q-factor can even be enhanced further by ensuring perfect metallization and also by silver-plating the filter cavity and the associated tuning pins.

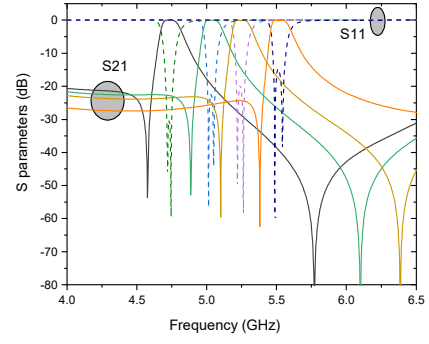


Fig. 5. Simulated S-parameter responses of the proposed all-reconfigurable dual-mode TM-mode DR filter with CABW.

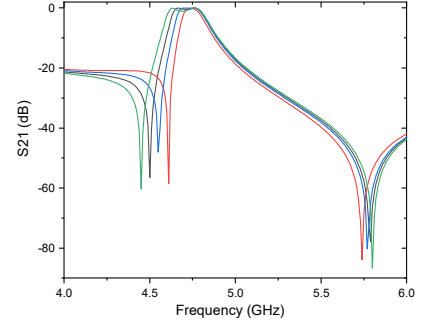


Fig. 6. Bandwidth reconfiguration of the proposed all-reconfigurable dual-mode TM-mode DR filter.

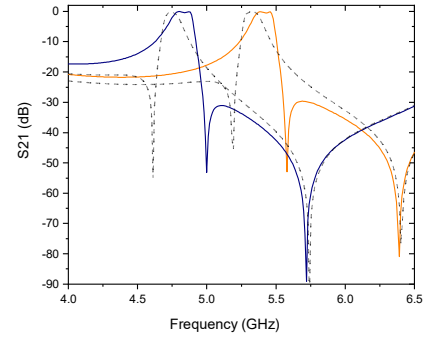


Fig. 7. An example of the doublet's TZ reconfiguration at the lowest and highest tuning states: TZ at the left side where $f_{120} < f_{210}$ (dashed line), and TZ shifted to the right side after M_{11} sign changes where $f_{120} > f_{210}$ (solid line).

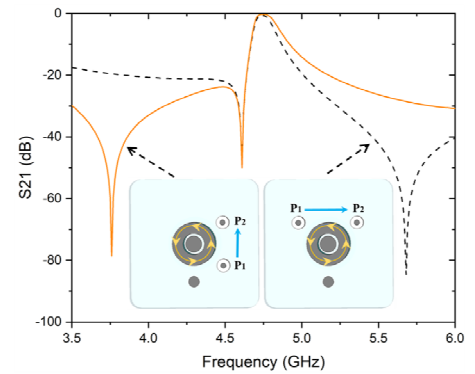


Fig. 8. An example of the TM_{110} non-resonating mode TZ reconfiguration at the lowest tuning state: TZ positioned at the left side where source (P_1) – load (P_2) is in the same direction of TM_{110} H-field (M_{StL}) (solid line), and TZ shifted to the right side where S-L is in opposite direction to TM_{110} propagation ($-M_{StL}$) (dashed line).



Fig. 9. Photograph of proposed filter setup.

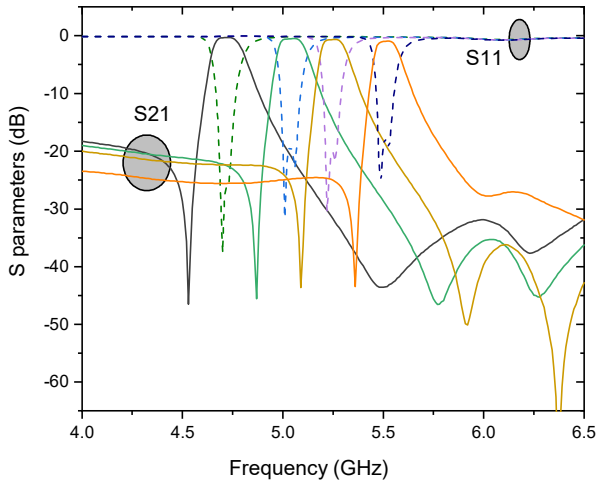


Fig. 10. Measured S-parameter responses of the proposed reconfigurable dual-mode TM-mode DR filter.

IV. CONCLUSION

A highly compact fully-reconfigurable C-band pseudo-elliptic BPF is presented for future flexible satellite payload applications. Thanks to the miniaturized dual-mode TM-mode dielectric resonator, the proposed filter offers a significant volume reduction of up to 75% in comparison with the conventional waveguide technologies. Both frequency and bandwidth are effectively tuned offering 15% of frequency tuning with constant absolute bandwidth and high unloaded Q throughout the tuning window ($Q > 500$). Additionally, two independently reconfigurable transmission zeros are introduced attributing a high-selectivity and excellent out-of-band rejections. Furthermore, a piezoelectric motor-based tuning mechanism is employed for accurate and fine remote control. All of these attractive features strongly promote the proposed reconfigurable filter for the next-generation flexible satellite systems.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 811232.

REFERENCES

- [1] (2021) AIRBUS website. [Online]. Available: <https://www.airbus.com/space/telecommunications-satellites/flexible-payloads.html>.
- [2] U. Rosenberg et al., "Reconfigurable doublet dual-mode cavity filter designs providing remote controlled center frequency and bandwidth re-allocation," *2016 46th European Microwave Conference (EuMC)*, London, UK, 2016, pp. 532-535, doi: 10.1109/EuMC.2016.7824397.
- [3] C. Arnold, J. Parlebas and T. Zwick, "Reconfigurable Waveguide Filter with Variable Bandwidth and Center Frequency," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 8, pp. 1663-1670, Aug. 2014, doi: 10.1109/TMTT.2014.2332298.
- [4] E. Laplanche et al., "Tunable Filtering Devices in Satellite Payloads: A Review of Recent Advanced Fabrication Technologies and Designs of Tunable Cavity Filters and Multiplexers Using Mechanical Actuation," in *IEEE Microwave Magazine*, vol. 21, no. 3, pp. 69-83, March 2020, doi: 10.1109/MMM.2019.2958706.
- [5] S. Fouladi, F. Huang, W. D. Yan and R. R. Mansour, "High-Q Narrowband Tunable Combline Bandpass Filters Using MEMS Capacitor Banks and Piezomotors," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 1, pp. 393-402, Jan. 2013, doi: 10.1109/TMTT.2012.2226601.
- [6] F. Huang and R. R. Mansour, "Tunable compact dielectric resonator filters," *2009 European Microwave Conference (EuMC)*, Rome, Italy, 2009, pp. 559-562, doi: 10.23919/EUMC.2009.5295901.
- [7] L. Pelliccia et al., "On-board miniaturized L-band input filter based On TM-mode dielectric resonator for MSS applications," *2017 47th European Microwave Conference (EuMC)*, Nuremberg, Germany, 2017, pp. 981-984, doi: 10.23919/EuMC.2017.8231010.
- [8] L. Pelliccia, F. Cacciamani, P. Vallerotonda, C. Tomassoni and R. Sorrentino, "Miniaturizing high-performance bandpass filters for satellite applications," *2017 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)*, Pavia, Italy, 2017, pp. 1-3, doi: 10.1109/IMWS-AMP.2017.8247345.
- [9] L. Pelliccia, F. Cacciamani, C. Tomassoni and R. Sorrentino, "Ultra-compact high-performance filters based on TM dual-mode dielectric-loaded cavities," *Int. J. Microw. Wireless Techn.*, pp. 151-159, Apr. 2014, doi:10.1017/S1759078713001001.
- [10] A. Widaa and M. Höft, "Microfluidic-Based Ultra-Wide Tuning Technique for TM_{010} Mode Dielectric Resonators and Filters," *2021 IEEE MTT-S International Microwave Filter Workshop (IMFW)*, Perugia, Italy, 2021, in press.
- [11] U. Rosenberg and S. Amari, "Novel design possibilities for dual-mode filters without intracavity couplings," in *IEEE Microwave and Wireless Components Letters*, vol. 12, no. 8, pp. 296-298, Aug. 2002, doi: 10.1109/LMWC.2002.802028.
- [12] S. Bastioli, C. Tomassoni and R. Sorrentino, "A New Class of Waveguide Dual-Mode Filters Using TM and Nonresonating Modes," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 12, pp. 3909-3917, Dec. 2010, doi: 10.1109/TMTT.2010.2086068.
- [13] (2021) EXXELIA website. [Online]. Available: <https://exxelia.com/uploads/PDF/e7000-v1.pdf>.