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.
free ranges, while also being able to exhibit decent unloaded Q-factor values [7]–[10]. For instance, a miniaturized L-band TM$_{120}$ 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 TM$_{120}$ and TM$_{210}$, 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 ($\varepsilon_r$) 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 (TM$_{120}$, TM$_{210}$) 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 TM$_{110}$ 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) 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 TM$_{120}$ and TM$_{210}$ modes, unlike the fundamental TM$_{110}$ 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 be 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 ($\varepsilon_r = 45$, $Q$-factor = 8000 @ 5 GHz) from EXXELIA [13]. The resonator is then metalized inside a 24×24×6 mm$^3$ 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.
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.

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