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EXECUTIVE SUMMARY

“TESLA” is an EU-funded project under Horizon 2020 research and innovation programme. The goal of TESLA project is to conduct a research on advanced technologies for future European satellite applications.

The first work package of TESLA: “Technologies for satellite flexible payloads” aims to propose compact, high-performance, and efficient tuning solutions for next-generation flexible satellite systems. As part of WP1, this document presents an extensive review on the different tuning techniques and means of microwave filters.

- This deliverable provides a general overview of tunable filters and their importance in enhancing the capabilities of communication and satellite systems.
- The document also discusses the mechanism of tuning for filters and its different types: capacitance tuning, inductance tuning, and capacitance-inductance tuning.
- A discussion of the major tuning techniques (mechanically, electrically, and magnetically-based techniques) is presented in terms of operation concepts, advantages, and limitations. Also, the different means utilized in the realization of the available state-of-the-art tunable filters are discussed in detail.
- Some of the new and promising tuning components and methods are also considered in the report content including ferroelectric components and resonators, liquid crystal-based tuning, and microfluidically reconfigurable filters.
- TESLA ESR 7 project: “Synthesis, design, and fabrication of novel tunable components for satellite communication” will use the outcome of this deliverable to propose novel tunable filters and efficient tuning configurations for future satellite communications.

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1. INTRODUCTION

The contribution that space and its related services incorporate to the growth and future development of humankind is certainly of prime importance in all aspects, starting from space exploration, monitoring and navigation, to internet and telecommunication applications. A huge increase in the frequency spectrum is essential to provide more channels and higher data rates for this wide range of expanding space services. Accordingly, new design techniques and manufacturing technologies are required to cover the emerging satellite services and technological challenges. On the grounds of that, TESLA project is a multidisciplinary collaborative cluster of industry and academia, uniquely equipped to develop the Advanced Technologies for future European Satellite Applications.

Tunable RF front-end components are playing an essential role in the future flexible satellite systems because of their significant advantages in comparison with the conventional fixed configurations. In the same context, the employment of high-Q, compact, and low-loss tunable filters in satellite payloads becomes more and more important. Tunable filters are key components in realizing these compact high-performance flexible satellite payloads. In recent years, tunable filters have attracted much more and rapidly increasing attention in research and industry due to their main role in improving the capabilities of current and future communication systems [1]. Common applications for tunable bandpass filters include multi-band transceivers, cognitive radio (CR) systems, next-generation cellphones, wideband RADAR and satellite payloads, and flexible radio systems like software-defined radios (SDR).

Generally speaking, in view of performance and specification requirements, these classes of applications require better frequency spectrum utilization, more functionality, smaller circuit size, more efficient power consumption, and lower implementation cost. Moreover, in addition to all of these requirements, it's now a key trend in RF-front-end systems to integrate multi-band/multi-standard operations and technologies in a single-board structure.

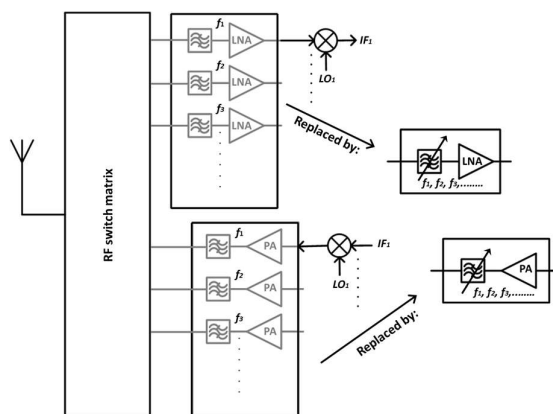


Figure 1: RF front-end of multi-band transceiver with conventional filter banks and tunable filters.

“Technologies for satellite flexible payloads” (WP1) is one of the key pillars of TESLA project. The different flexible payload systems in future satellite communications have ever-stringent requirements of high Q, low-loss, and miniaturized frequency reconfigurable front-end units. Unfortunately, these requirements are usually contradicting each other and cannot all be maintained simultaneously without experiencing some performance deterioration. Therefore, the need to employ compact high Q resonators and more efficient tuning mechanisms is essential to meet those challenging characteristics more effectively. In WP1, efficient designs and technologies will be presented for flexible satellite payloads applications.

As part of WP1, the first deliverable (D1.1) is devoted to reporting the different tuning means of tunable filters. The key objective of D1.1 is to provide a comprehensive overview and comparison between the various tuning methods and designs available in the open literature, aiming to understand the operations concepts and identify the advantages and drawbacks of each technique. A detailed review of related state-of-art research is presented addressing the key features and parameters in addition to the major challenges and trends.

2. FILTERS TUNING MECHANISM

Microwave filter is constructed by a composition of resonators mutually coupled to each other to obtain predefined passband characteristics. Generally, each resonator has three main components: resistance (R), capacitance (C), and inductance (L). The resonator loss is represented by the resistance value, while the resonant frequency (f_r) is determined by the capacitance and inductance values. Figure 2 demonstrates a circuit model of a second-order lossless bandpass filter. The resonant frequency can be calculated by the formula: $f_r = 1/2\pi\sqrt{LC}$. So, the centre frequency tuning can be done by changing the values of the resonators' inductances and/or capacitances.

In addition to the frequency tuning, other filter parameters can also be controlled like bandwidth and transmission zeros. The bandwidth can be tuned through either adjusting the external quality factor (Q_{ex}) and/or the inter-resonant coupling between the resonators ($K_{i,i+1}$). Also, the transmission zeros can be controlled the same as frequency and bandwidth, but the required tuning mechanism is more challenging and more complex controlling approaches are needed.

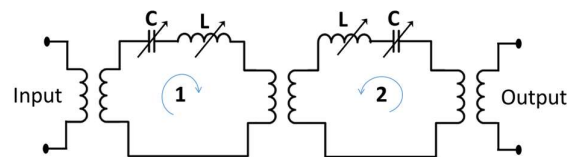


Figure 2: Circuit model of a 2-pole tunable filter.

2.1 Capacitance tuning

The most common and straightforward method of realizing tunable filters is by loading variable-capacitance elements on the resonators' structures. The vast majority of the presented tunable filters in literature are realized using one of the capacitance tuning components. For example, [1] introduced a tunable microstrip combline filter loaded by variable capacitors for frequency tuning. Three variable capacitors were mounted on each of the combline resonators to make the filter structure tunable. The designed third-order bandpass filter demonstrated a wide tuning range of 0.6 GHz across a band of 0.7 - 1.3 GHz with different capacitances from 0.8 pF to 3.5 pF.

2.2 Inductance tuning

Another alternative approach to design tunable filters is by changing the inductance of the resonators to obtain the required control on the centre frequency. However, in comparison with the capacitance tuning method, inductance tuning is limited and more challenging. Therefore, very small

number of research have been conducted on tunable filters based on inductance tuning. One example of the inductance tuning method is the filter introduced in [3]. The filter is composed of four series coupling MIM capacitors and three resonators. The tuning concept is to change the inductance value of each resonator while keeping all of the capacitance values constant. The inductance change is done by using a metal-metal contact switch to change the length of the short-stub. The measurement results show that the center frequency of the tunable filter shifts from 8 to 12.3 GHz, and that the 3 dB bandwidth maintains about 10% of fractional bandwidth over the tuning window. However, the insertion loss varies from 9 dB to 11 dB. the extracted RLC values from the measurements are listed in Table 1. As can be seen, the frequency tuning is obtained mainly due the inductance variation while the capacitance remained unchanged.

Lumped elements	Curve-fitted values					
	8.0	9.2	10.5	11.7	12.8	14.0
f_0 (GHz)	8.0	9.2	10.5	11.7	12.8	14.0
C (fF)	190	190	190	190	190	190
L_1 (nH)	2	1.5	1.23	0.98	0.83	0.66
L_2 (nH)	0	0.5	0.77	1.02	1.17	1.34
L_{sw} (pH)	20	20	20	20	20	20
R (Ω)	1.8	1.6	1.6	1.6	1.4	1.4
R_{sw} (Ω)	0.8	0.8	0.8	0.8	0.8	0.8

Table 1: Curve-fitted values of the lumped elements in the tunable resonator (based on [3])

2.3 Capacitance-inductance tuning

Designing a tunable filter with a wide tuning range and more flexibility while maintaining good performance all over the tuning window is a challenging task for RF/MW designers especially with the limited conventional techniques and means. A promising solution to increase the tunable filter functionality and tunability, and to improve the filter response is by employing both capacitance and inductance tuning at the same time. For instance, a high-performance and a widely tunable millimeter-wave low pass filter was presented in [4]. The filter is tuned from 53 GHz to 20 GHz and maintained good low passband characteristics with an improved out-of-band rejection performance. The wide tuning range of the filter was achieved by using a combination of MEMS-switched capacitors

and reconfigurable coplanar waveguide lines to control the capacitance and the inductance simultaneously as shown in Table 2.

State		C_1 (fF)	C_2 (fF)	L(nH)	$f_{3\text{-dB}}$ (GHz)
Design	Wide band	95	142	0.17	57
	Narrow band	286	426	0.52	19
Measurement	Wide band	110	160	0.18	53
	Narrow band	270	410	0.5	20

Table 2: Lumped Element values for 0.5 dB Ripple Chebyshev 5th order low pass filter (based on [4]).

Generally, there is a wide range of tunable filter designs have been introduced in previous literature based on different topologies and using various tuning methods. However, it can be concluded that most of the available tunable filters fall into one of three major groups: mechanically tunable filters, electrically tunable filters, and magnetically tunable filters. In the following chapter, a review of these common tuning mechanisms and also some of the other promising tuning means is presented. Also, tunable waveguide filters including tunable DR filters will be discussed in more detail due to their more desirable features and specifications to the applications of future satellite payloads.

3. TUNING MEANS

3.1 Mechanical-based tuning

The mechanical-based tuning technique is known as the earliest and most straightforward method for the implementation of tunable 3-D filters. In this mechanism, the resonant frequency is tuned by changing the field distribution in the filters' cavities using physically adjustable elements (e.g. screws, discs, side-walls). The mechanical adjustment of the elements can be done either manually or using any electro-mechanical transducing mechanism (e.g. stepper/piezo motors, piezo/MEMS actuators). Mechanically-tuned waveguide filters have many advantages in comparison with the other tuning approaches including the low insertion loss, high unloaded quality factors (Q), and also the capability of high-power handling. However, they are burdened by the bulky size, high complexity, relatively high cost, and low speed of tuning. All above is in addition to the very small and limited tuning ranges. Despite that the requirements of the specifications of the various current and future communication systems include the compact size and fast tuning speed, mechanically tunable filters still attract attention due to their unbeatable power handling capabilities and high-quality factors. The following section reviews and compares the mechanically tunable filter designs presented in previous literature with different tuning approaches.

3.1.1 Mechanically tunable filters

Mechanical tuning techniques have been realized in different 3-D filter structures including evanescent-cavity and waveguide configurations [5]-[32]. Various tunable hybrid evanescent cavity filters were reported based on capacitively-loaded structures by changing the gap between the inner post and a flexible top cavity as in [5] and [6]. A second-order tunable filter is realized in [5] using a piezoelectric actuator mounted on a flexible substrate to change the parasitic capacitance and tune the resonant frequency. Similarly, in [6], thin MEMS actuated diaphragms are used for frequency tuning. Despite the good tuning capabilities, such structures require very sensitive and accurate micro-tuning and have limited Q factor and power performance. Therefore, the application of evanescent-mode cavity configurations in high-performance and high-power flexible systems is not favorable.

On the other hand, tunable filters based on waveguide structure have received an increasing attention due to their desirable features for next-generation agile filters. High-power and high-performance mechanically reconfigurable waveguide filters were presented previously in different

empty-cavity, coaxial, and dielectric-loaded structures. In its simplest configuration, tunable waveguide filters are realized using metallic plungers [7]. Unfortunately, more efficient tuning means are needed as such screw-based designs suffer from significant performance deterioration. Therefore, a couple of high-Q mechanically reconfigurable waveguide filters were introduced with special tuning mechanisms to minimize the Q-factor degradation while tuning in [11]-[19]. A high-Q manually reconfigurable K-band dual-mode waveguide filter was introduced in [11]. The proposed filter is a fifth-order Chebyshev with 3.5% tunability at 26 GHz center frequency and an extreme narrowband of just 0.1% fractional bandwidth (FBW). Adjustable sidewall cavities are utilized for frequency reconfiguration with enhanced Q-factor measures in comparison to the conventional inline tuning screws method. The extracted effective Q-factor of the proposed reconfigurable filter is 11200. A bellow-mounted technique was presented in [12] on waveguide cavities bringing the advantages of low-loss and stable tuning responses. A thin flexible copper bellows are mounted on the cavity to control the frequency using a manual micrometer driver. The filter has a tuning window of 527 MHz at 11.95 GHz with low loss < 2 dB and stable 3.5% bandwidth variation. Similarly, in [13], a movable metallic end-cap was employed for frequency tuning to offer less degradation across the whole tuning band and also a wide spurious-free range. The presented filter operates at 20 GHz K-band frequency with a stable 500 MHz tuning band, and high unloaded Q-factor (15500 – 16000). An additional feature of 40 – 160 MHz bandwidth tuning was also introduced through two cascaded pseudo-high and pseudo-low tunable filters.

In [14], a screw-based manually frequency and bandwidth reconfigurable waveguide filter was proposed using a tunable coupling resonator configuration. The fabricated filter has 200 MHz tunability at center frequency 19.8 GHz and 54 – 72 MHz of bandwidth tuning. Another tuning mechanism based on the use of rotating dielectric perturbations to change the resonant frequency inside the cavity was introduced in [15] and [16]. The key advantage of this configuration is that there is no requirement of electrical grounding as in the other tuning techniques, therefore, a reduced complexity. In [15], the measured frequency tuning range is 9.92 – 10.12 GHz with a Q-factor 1400 – 2150, while the filter in [16] operates at 19.36 – 19.7 GHz with a Q-factor 2600 – 3100. Also, to offer more design flexibility, reconfigurable filters using contactless tuning elements were presented in [17]-[19]. In [17], a motorized special corrugated tuning plunger is designed to maintain high-Q levels. The filter has a tuning window of 19 – 19.48 GHz with a constant absolute bandwidth of 54.5 ± 2.5 MHz and a high extracted unloaded Q factor of 9080. Another tuning approach was introduced in [18] using a single tunable sidewall to reduce the tuning complexity. A Ku band reconfigurable filter is implemented with a constant 2% narrow bandwidth and 15% tunability. Recently, Basavarajappa et al. presented a fourth-order reconfigurable dual-mode filter at 11.5 GHz with a constant narrow

bandwidth of 50 MHz and 3.3% tunability using a single linearly-displaced metallic tuning element [19].

Mechanically tunable coaxial filters were reported in [20]-[23]. A refined manually tunable coaxial filter was presented in [20]. The capacitive loading is changed through a simplified tuning mechanism composed of rotating cams controlled by a single common driving shaft covering a tuning range of 0.95 – 2.05 GHz and return loss less than 11 dB. A tunable high-Q narrowband combline filter was proposed in [21] with a 70 MHz tuning range from 2.565 GHz to 2.635 GHz with a high Q factor of 2252 - 2914. Vertically-positioned tuning posts are utilized for frequency control in upward and downward movement using piezomotor actuators. In [22], an angular technique using a rectangular tuning shaft was introduced to maintain high Q measures in comparison with the conventional vertical tuning mechanism. The frequency is tuned by changing the angle of the rectangular shaft using a miniature piezomotor mechanism. A tuning range of 11.9% is achieved at 3.6 GHz with low insertion loss better than 0.32 dB and nearly constant high-Q. A tunable high Q coaxial filter was introduced using a single reduced-complexity tuning mechanism in [23]. The tuning concept is based on the rotational displacement of the coaxial resonators using a common single motorized tuning post. The measured results show a 20% tunable low-loss filter at 2.5 GHz with a small bandwidth variation of ± 10 MHz.

Dielectric resonators are broadly used in communication systems and components due to their superior performance over other resonators. They offer a high unloaded Q and have excellent temperature stability. The frequency tuning concept of dielectric filters was presented few-decades ago by Gil and Martínez in [24]. Also, Chen et al. presented a temperature compensated manually reconfigurable four-pole hybrid-mode HEH_{11} dielectric filter in [25]. A detailed temperature sensitivity optimization is made to the filter structure to obtain the proper dimensions for best tuning with the least temperature variation. Double-resonator tuning configuration is employed to eliminate the problem of severe Q-factor degradation caused by the conductor-dielectric interface in the conventional tuning mechanisms. The measured tuning range is 4.6 – 4.8 GHz with low insertion loss and high unloaded Q-factors of 5200 and 4700, respectively. A three-pole filter is implemented with a tuning window of 15.6 – 16 GHz with insertion loss 1.5 – 4.5 dB and a high Q-factor up to 1500. A tunable dielectric-loaded filter was presented in [27] with a dielectric plug as a tuning element. A wide tuning range is achieved while other features of the resonator are maintained over the whole range. The filter can be tuned from 1930 to 1990 MHz and has an unloaded Q factor of 22000 - 23000.

The DR tunable bandpass filter presented in [27] has displayed good tuning properties in terms of the filter size and tuning range, but, the filter's tuning speed is very low due to the large travel distance of the tuning element and screw-like configuration.

Piezoelectric-based tuning technique was reported in [28] – [30] with various dielectric resonator configurations. The operation concept is based on the movement of a resonator/plate attached to an electrically-induced piezoelectric element. Firstly, the concept was presented in [28] where a piezoelectric frequency adjusting unit is attached in different configurations to double dielectric resonators. The frequency is tuned due to the change in the space between the resonator and the part attached to the piezoelectric unit. Similarly, in [29], a piezoelectric-based tunable dielectric dual-mode HEM_{11} mode filter was introduced with a piezoelectric bimorph connected to the metallic tuning discs to control its movement for frequency tuning. The filter is designed with a tuning range of 2.24 – 2.45 GHz with 0.5% FBW and insertion loss less than 1 dB. Another filter was also presented in [30] where a piezoelectric transducer is used to control the movement of a flexible sidewall to change the resonant frequency of the cavity. Fourth-order TME mode filter is implemented with a frequency range of 4.97 – 5.22 GHz with an extracted Q factor of 550.

Due to its desirable features, Micro Electro Mechanical Systems (MEMS) have gained an increasing attention in a wide range of RF applications including filters. Yan et al. in [31], introduced a mechanically tunable TE_{01} mode dielectric filter using MEMS-based actuators. Similar to the piezoelectric-based tuning technique, the proposed concept of tuning used MEMS thermal actuators to control the displacement of the tuning discs.

In summary, despite the advantages of obtaining high Q-factors and high-power handling capabilities, mechanically tunable filters still suffer from one or more key limitations as the large bulky size, low speed of tuning, high complexity, and the high cost of implementation. Accordingly, the need for fast and more efficient tuning techniques is fundamental.

3.2 Electrical-based tuning

Electrical-based tuning is widely known as the most common technique all over the available state-of-the-art tunable filters because of its highly desirable and competitive features in comparison with the other tuning approaches. These advantages include the high tuning speed, low power consumption, low cost, and compact size. In addition to all, it can be easily integrated and mounted on the different printed-circuit boards (PCBs). Therefore, it has been widely employed in the realization of tunable planar and nonplanar structures [33]-[72].

The operation concept of electrical tuning means is based on loading the resonator structure with lumped switching/tuning circuits to change the electrical field distribution, and thereby, tune the resonant frequency. Generally, electrically tunable filters can be categorized into two main groups: discretely-switched filters where in which the frequency is reconfigured between separated predefined individual tuning states, and continuously tunable varactor-loaded filters where the filter

can be tuned freely at any frequency across a specified span. The following parts of this section discuss various tunable filter designs realized based on various means of both groups in different planar, hybrid, and waveguide structures.

3.2.1 Electrically tunable filters

3.2.1.1 Switched reconfigurable filters

With the increasing development in various multi-standard and multi-band communication systems, the conventional fixed filters became an un-efficient solution. Therefore, switch-based reconfiguration techniques were introduced to provide more efficient and flexible front-end units. The centre frequency is controlled through a switched loading element/network (e.g. transmission line, capacitor). Various Electrical switches were used to implement switched filters with different reconfiguration responses [33]-[51]. The most common switching-elements used in reconfigurable filter design are solid-state RF PIN diodes due to their advantages of wide market-availability, low cost, and easy fabrication and integration. The use of PIN switches in reconfigurable filters applications was firstly presented in [33] and expanded widely in various designs introducing many desirable switching functions as can be seen in [34]-[36]. In [34] for instance, a switchable WiFi/UMTS microstrip bandpass filter was presented. Six microstrip sections are switched by PIN diodes to reconfigure the two frequency bands.

In spite of the various advantages of the PIN switches, their application in frequency-agile filters is still faced with major challenges especially at higher frequencies > 2 GHz including the increasing losses, relatively high power consumption, and increasing nonlinearities. Therefore, the introduction of more efficient RF switching solutions is highly required.

In recent years, MEMS got an increasing attention against PINs especially at higher bands because of the advantages of high Q factor, low loss, and very low power consumption [37]-[47]. In [38], a tunable coplanar-waveguide (CPW) filter was proposed using high-Q capacitors connected in series with MEMS switches. Similar planar and hybrid RF MEMS switched filters were also introduced on microstrip, SIW, High-Temperature Superconductors (HTS), and evanescent-mode cavities [39]-[42].

RF MEMS switches were also integrated with the different waveguide structures to introduce high-Q tunable filters [43] – [46]. Chan et al., introduced an ON/OFF switchable iris waveguide BPF using an RF MEMS switchable planar resonator placed inside the waveguide cavity. When the MEMS switch is turned on, the planar resonator resonates a suppressing notch frequency to the waveguide passband [43]. On the other hand, the embedded tuning circuit will have a small impact on the waveguide resonance frequency when the MEMS switch is turned off. Also, [47] recently presented a

Ku-band two-channel reconfigurable waveguide filter using the same MEMS-based detuning concept. Four operation states (dual-band, the lower band only, the upper band only, and all-rejects) were successfully obtained through the MEMS switching mechanism. The fabricated channel aggregation filter operates at 14.25 and 16.5 GHz channels with an insertion loss of less than 2 dB and a Q factor > 800.

Another MEMS tunable waveguide filters were introduced by Pelliccia et al. with three different configurations [45]. In the first approach, the MEMS switches are employed as current perturbation elements to control the distribution of the electromagnetic field. A two-pole K-band filter is designed with 160 MHz bandwidth and Q factor 1000/500 for on and off states, respectively. In the second configuration, the cavity sidewall is made virtually movable to change the resonant frequency. MEMS switched conductive lines were utilized to create virtual change in the cavity. The fabricated fourth-order filter showed 3.2% tunability with a Q factor of 500 at the ON states and 650 at the OFF-states. Switchable strips are loaded in an E-plane waveguide cavity for frequency tuning in the third implementation. The simulation results demonstrated a 4th order filter with 1.6% frequency tuning and an expected Q of the order of 1000.

Another high-Q MEMS reconfigurable BPF was successfully proposed using coaxial combline resonators in [46], where the tuning disk is loaded by MEMS capacitor banks for frequency tuning. A second-order tunable filter is fabricated with a 2.503 – 2.393 GHz frequency range with 1.32 dB insertion loss. Also, a sixth-order filter is implemented with a tuning frequency of 2.59 – 2.63 GHz and an insertion loss of 2.5 – 4.25 dB.

RF-MEMS were also employed in two different configurations with dielectric resonators to design high-Q tunable filters [47]. In the first mechanism, MEMS-switched conductive strips are placed in the inner hole of the DR resonator to control the resonant frequency. When the MEMS is turned on, the effective length of conductive strips will increase, and then the frequency will shift due to the change of current distribution. The implemented second-order filter is designed at 4.72 GHz with a 160 MHz tuning window and Q factor from 510 to 1200. In the second configuration, the MEMS-switched conductive strips were replaced by MEMS capacitor banks. This approach has a wider tuning range from 5.02 to 5.20 GHz with a Q factor of 550 – 800.

In recent years, RF switches based on Phase Change Materials (PCM) were also introduced in a couple of tunable planar and hybrid filters based on Vanadium Dioxide (VO₂) and germanium telluride (GeTe) switches [48]-[51]. Nevertheless, the performance of such switching solutions must be enhanced to qualify the requirements of low-loss and high-performance switchable filters.

Overall, switchable filters offer many advantages and functions in comparison with the conventional fixed configurations as the reduced circuit size, lower cost, and more flexible passbands.

However, some limiting drawbacks also clearly appear in contrast, including the low tuning speed, increased complexity, limited Q and power handling capabilities.

3.2.1.2 Varactor based tunable filters

For many of the current and future frequency-agile systems, it is required to have a compact, low-cost and reduced-complexity tuning circuitry with high tuning speeds > 1 GHz/microseconds. To meet these fundamental requirements, varactor tuning configurations are quite popular in various microwave applications. Varactor diode is defined as a special kind of PN – junction diode in which its capacitance is varied with the applied reverse voltage. As the applied reverse-biasing voltage increases, the PN junction gets narrower and the junction capacitance then decreases, and vice-versa. A more detailed explanation of the varactor diodes operation can be found in [53].

Semiconductor varactor diodes are widely commercially available in a broad range of specifications and packages. It is available in two main types: abrupt and hyperabrupt junction varactors which are constructed based on either a silicon or Gallium Arsenide (GaAs) materials. Generally, silicon varactor diodes have a relatively larger capacitance range but suffer from lower Q factors. Due to that, they are only used at low microwave frequencies up to a few GHz at max. While the GaAs varactors have less capacitances, they have higher Q and can be applied at higher frequency bands.

Extensive research has been made on the design of varactor-tuned microwave filters including the designs presented in [52]-[72], where various degrees of tuning have been achieved with different structures. Notably, most of those varactor-tuned implementations are of low Q planar and hybrid bandpass filters [52]-[66], while the conducted research on high Q waveguide structures is very limited [67]-[72].

In general, research in tunable bandpass filters has been mainly focusing on the realization of frequency tunable filters with some effort towards bandwidth control and other tuning functions (e.g. IO coupling, transmission zeros). Among the different structures, planar microstrip filters are the most broadly presented in the literature as in [52]-[62] due to their desirable advantages of low-cost, simple fabrication, and easy integration of lumped tuning components. For example, compact tunable varactor-loaded microstrip filters with the feature of constant absolute bandwidth (CABW) were presented using dual-mode resonators [54], miniaturized corrugated transmission lines [55], and shorted folded resonators and also with improved linearity [56]. Some papers had also proposed additional features of bandwidth and external Q-factor tuning [57], and transmission zeros reconfiguration [58]. Also, more advanced tunable dual-band filters with independently tunable passbands were proposed [59].

Most varactor-tunable filters employ commercially available semiconductor varactors, however, these varactors suffer from limited linearity performance and not suitable for high power applications. Therefore, other promising alternatives as ferroelectric and MEMS varactors were successfully presented in many tunable filter designs as in [62] and [63].

Due to the limited Q factor of the microstrip structures, higher Q filters were introduced using Substrate Integrate Waveguides (SIW) [64]-[65], and hybrid evanescent cavities [66]. [48] introduced a compact tunable varactor-loaded SIW filter with the advantage of wide stopbands. A hybrid 3-D printed varactor-based tunable evanescent-cavity BPF was presented in [66] with flexibly tunable center frequency and bandwidth.

In regards to varactor-tuned waveguide filters, only a few publications based on coaxial and dielectric resonators were reported [67]-[72]. Xu et al. reported a high Q tunable coaxial bandpass filter with constant absolute bandwidth and wide tuning range [67]. Three high Q GaAs varactors are mounted in parallel to offer larger loading capacitance and also to minimize the overall parasitic resistance. The measured frequency tuning range is 30.7% at 700 – 960 MHz with 1.58 – 3.97 dB insertion loss and a Q factor of 173 – 418.

Couple configurations of tunable varactor-loaded dielectric resonators/filters were introduced in the previous literature [68]-[72]. The first implementation was proposed in [68] where two tuning varactors connected using semi-circuited patches and positioned on top of the DR with low-loss quartz spacer in between. The measurements showed a 0.75% tuning range with a maintained Q above 1000. Following in [69], a similar varactor PCB was placed in a different position beneath a TE_{01} mode resonator device. This configuration achieved 1.7% tunability and a high Q factor up to 8000. Although the high Q factors are obtained, those configurations have a major drawback of a very narrow tuning range. This because the tuning circuits just control the available field around the DR, while most of the field is focused inside the resonator body. Accordingly, [70] proposed an invasive tuning technique in which the varactor is directly embedded on a customized slot in a TE_{01} mode resonator structure. The measured tuning window was 7.1% at 4.7 GHz center frequency with a comparable Q factor due to the direct integration of the tuning varactor on the dielectric resonator. Varactor-tuned TME mode dielectric filters were also introduced in [71] and [72]. In [71], a tuning structure composed of a varactor-loaded conductive strip is placed in the inner hole of the disk resonator to change the field distribution and tune the resonant frequency. The measurements demonstrated a tuning range of 4.87 – 4.97 GHz with 170 – 660 Q factor. While in [72], a TME mode resonator was connected in series with a top-positioned tuning varactor circuit. The filter is implemented with a 4.98 – 5.28 GHz frequency range and Q factor from 303 to 576.

3.3 Magnetically-based tuning

In spite of the large complex structures, magnetic-based tuning is still favorable in some military and commercial applications due to its advantages of low insertion loss and high-power handling capabilities. The magnetic tuning operation principle is based on changing the magnetic field distribution in the filter structure using ferrite materials to tune the resonant frequency. Yttrium iron garnets (YIG) are the most common ferrites used in the tunable microwave and high-frequency devices because of their low magnetic and dielectric losses, and moderate saturation magnetization values.

3.3.1 Magnetically tunable filters

Many tunable planar filters were reported using YIG ferrites in different configurations [73]-[81]. An example of a magnetically tunable bandpass filter designed with yttrium iron garnet (YIG) films was presented in [73]. The design is based on a T shaped microwave transducer with a compact coupling structure to reduce the insertion loss. Then a YIG film is buried on another substrate of gadolinium gallium garnet (GGG). The whole structure acts as a BPF filter whose ferromagnetic resonance is tuned via a biased magnetic field. Another tunable low temperature co-fired ceramics (LTCC) BPF using partially magnetized ferrite was introduced in [74]. The proposed filter brought the benefits of size miniaturization and low biasing requirements due to the use of partially magnetized YIG ferrites.

Ferromagnetic tuning techniques were also limitedly presented in the waveguide, coaxial, and dielectric-loaded filter structures [82]-[84]. A ferrite-loaded low-loss tunable X band waveguide bandpass filter was introduced in [82]. A magnetized ferrite slab is placed inside TE_{102} mode waveguide cavity using truncated pyramid-shaped metallic inserts to tune the resonant frequency by changing the magnetic field distribution. The implemented second-order filter operates at 8.74–9.63 GHz with 9.7% tunability and unloaded Q factor 380 – 396. Acar et al. introduced a low-loss ferrite-loaded continuously tunable coaxial filter with high power capabilities [83]. Magnetically-biased ferrite insert was loaded on the combline resonators to change the magnetic field distribution and tune the frequency. The fabricated two-pole filter exhibited a tuning range of 41% from 744 MHz to 1024 MHz with a low insertion loss of less than 3 dB and a high Q factor of 1223 – 2425. Additionally, the proposed filter has the merit of high power handling capability rated up to 800 Watts.

In [84], two second-order magnetically tunable dielectric filters were introduced using magnetized ferrites in axial and circumferential configurations. The implemented filter with the axially magnetized ferrites demonstrated a 20 MHz bandwidth tuning at 2.22 GHz center frequency with insertion loss

less than 1.5 dB and a high Q factor over 2500. While in the axially magnetized ferrites configuration, the filter operated at 2.35 GHz with 28 MHz tunability and a Q factor higher than 3500.

3.4 Other tuning means of filters

In addition to the above three common tuning techniques, there are few other means reported for the design and realization of tunable filters [85]-[106]. In the following, three increasingly interesting tuning approaches are briefly introduced: ferroelectric-based tuning, microfluidic-based tuning, and liquid crystal-based tuning.

3.4.1. Ferroelectric tunable filters

The application of ferroelectric materials in various emerging reconfigurable radios applications is catching an increasing attention because of their highly desirable and promising properties [85]. These features include the high power handling capabilities, good Q factor, and the realization of a wide variety of compact variable components. Ferroelectrics are employed either as tuning elements (varactors, variable capacitors) as discussed earlier or as intrinsically-tunable bulk resonators and filters [85]-[90]. The operation concept of self-tuned ferroelectric resonators is based on the direct tuning of the resonator by applying a DC electric field to change the ferroelectric material properties including the relative permittivity which accordingly shifts the resonant frequency.

Two tunable ferroelectric filters were reported in the previous literature using disc-shaped ferroelectric resonators [89], [90]. In [89], a tunable narrow-band BPF was introduced using TM_{110} dual-mode ferroelectric strontium titanate (STO) resonators. The experimental results showed 8% tunability at 0.5 GHz center frequency with 2% fractional bandwidth (FBW). The filter suffered from the increasing losses and drastically decreasing Q factor with the increase in the DC biasing field, which is a common drawback in ferroelectric materials. The second tunable ferroelectric filter was presented in [90] using a Potassium titanate (KTO) resonator coated with a high superconductive layer to increase the Q factor. The fabricated filter operates at 0.5 GHz center frequency with 1.5% fractional bandwidth and a 5% tuning span.

As can be seen, those filters suffer from the high losses which are mainly related to the ferroelectric material properties and also to the additionally induced losses under the DC biasing. Therefore, such applications of ferroelectrics cannot be expanded further without reducing the material losses. Another additional drawback is that a very high DC field is required for tuning (up to 1 kV) with is impractical for tuning applications. A more promising application of ferroelectrics is in thin-film and

thick-film components as the loss effect is minimized and the required biasing is enormously reduced [85].

3.4.2. Liquid crystal tunable filters

Liquid crystal polymers (LCP) are other functional materials that have recently received increasing attention in tunable filter applications to overcome the high loss limitation in the conventional ferroelectrics especially at high frequencies above 10 GHz [91]-[96]. The tuning principle is based on applying external biasing fields to change the orientation and the relative permittivity of the liquid crystal molecules which will cause a change in the resonant frequency. Various liquid crystal-based tunable planar microstrip and SIW BPFs were presented where an intermediate LC layer is inserted to change the effective relative permittivity and tune the resonant frequency as shown in [91]-[94]. Also, tunable waveguide liquid crystal filters were successfully introduced in [95] and [96]. Liquid crystal containers were placed into the cavity to change the orientation of the fields inside the filter and tune the frequency. A 20 GHz tunable liquid crystal filter was introduced in [95] using a conventional waveguide structure with 2.3% tunability and insertion loss of 6 dB. In [96], a 60 GHz filter was realized using an open nonradiative dielectric waveguide structure to provide more space for the integration of the biasing electrodes. The fabricated three-pole Chebyshev filter has a 2.5% tuning range with 96 Q factor and an insertion loss of 4.9 - 6.2 dB.

3.4.3. Fluidic-based tunable filters

Recently, various micro-fluidics have been explored as promising switching and reconfiguration candidates [97]-[106], mainly because of their linear properties, low loss, and high-power handling capabilities. Many fluidic-based planar and nonplanar reconfigurable/tunable filters were introduced using different fluids [98]-[106]. Various tunable microstrip filters were proposed using intermediate or top-placed microfluidic tubes (e.g. distilled water, dielectric liquids, metallic liquids) for frequency and bandwidth control [99]-[103]. For example, [99] introduced a microfluidic frequency and bandwidth tunable microstrip filter using microfluidically movable surface metalized plates (SMPs). Also in [102], water-filled tubes were placed beneath the microstrip resonator to tune the resonant frequency by changing the overall effective dielectric constant (ϵ_r).

Another fluidic tuning approach was introduced with both planar and 3-D cavity structures by filling the inner posts with fluids to reconfigure the resonant frequency [104]-[106]. Sara, et., reported a switchable dual-band C-band SIW filter using liquid metal actuation through reconfiguring the inner posts [104]. The proposed filter works in four different reconfiguration states: all-pass, lower

passband, upper passband, and all-reject. Also, in [106], a rectangular waveguide filter was loaded by water-filled tuning posts to control the resonant frequency. Additionally, tunable tri-band filters were presented with independent passband reconfiguration on $TE_{101}/TE_{011}/TM_{011}$ modes with less than 3% tunability in all three bands and a low Q factor less than 30.

4. CONCLUSIONS

This deliverable provided a comprehensive review of different state-of-the-art tuning means of microwave filters. The major tuning techniques: mechanical tuning, electrical tuning, and magnetic tuning, were investigated and discussed in various aspects including the operation concepts, features and specifications, advantages and limitations. The different implementation methods of tunable filters under each of these tuning groups were also discussed. The deliverable also discussed some of the new and promising tuning components and means as the PCM switches, ferroelectric capacitors and resonators, LC and microfluidic-based tuning. A comparison between the common tuning techniques in tunable filters is summarized in Table 3 [1], [2].

Tuning technique	Mechanical-Piezo transducer	PIN diode	RF MEMS	Si varactor diode	BST	YIG
Unloaded Q	> 1000	$R_s = 1-4\Omega$	50-400	30-50*	30-150*	> 500
Tuning speed	> 10 μ s	ns	μ s	ns	ns	ns
Biasing	> 100 V	0-40 mA	20-100 V	< 30 V	< 30 V	NA
Linearity (IIP3, dBm)	high	> 33	> 60	10-35	10-35	< 30
Power consumption	high	medium	negligible	low	negligible	high
Power handling	excellent	~ mW	1-2 W	~ mW	~ mW	2 W
Temperature sensitivity	low	low	low	low	high	high
Size	large	small	small	small	small	large
Cost	high	low	moderate	low	low	high
Integration	difficult	easy	moderate	easy	easy	difficult

* at 10 GHz.

Table 3: Comparison between the common tuning techniques

The D1.1 deliverable will also contribute to ESR 7 project providing a broad review of the available tunable filter solutions and identifying the key challenges and drawbacks to be improved. The outcome of this deliverable will represent the bedrock to ESR 7 project key objective aiming to introduce novel designs of tunable filters suitable for next-generation satellite and space applications.

LIST OF ABBREVIATIONS

TESLA – Advanced Technologies for future European Satellite Applications

WP – Work Package

D1.1 – Deliverable 1.1

ESR – Early Stage Researcher

Q – Quality factor

RF – Radio Frequency

BPF – Bandpass Filter

FBW – Fractional Bandwidth

MW – Microwave

PIM – Passive Inter-modulation

MEMS – Micro-Electro Mechanical System

CR – Cognitive Radio

RADAR – Radio Detection and Ranging

SDR – Software Defined Radio

G – Generation

ECM – Electronic Countermeasure

ESM – Electronic Support Measures

PA – Power Amplifier

DC – Direct Current

LNA – Low Noise Amplifier

LTE – Long Term Evaluation

LO – Local Oscillator

PIN – Bipolar Junction

PCB – Printed Circuit Board

CPW – Coplanar Waveguide

SIW – Substrate Integrated Waveguide

HTS – High Temperature Superconductor

PCM – Phase Change Material

VO₂ – Vanadium Dioxide

GeTe – Germanium Telluride

GaAs – Gallium Arsenide

YIG – Yttrium Iron Garnets

GGG – Gadolinium Gallium Garnet

LTCC – Low Temperature Co-fired Ceramics

MIM – Metal-Insulator-Metal

BST – Barium Strontium Titanate

STO – Strontium Titanate

KTO – Potassium Titanate

LC – Liquid Crystal

RLC – Resistance, Inductance, Capacitance

3-D – Three Dimensional

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