FOCUSED ISSUE FEATURE

High-Q Tunable Filters

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High-Q tunable filters are in demand in both wireless and satellite applications. The need for tunability and configurability in wireless systems arises when deploying different systems that coexist geographically. Such deployments take place regularly when an operator has already installed a network and needs to add a new-generation network, for example, to add a long-term evolution (LTE) network to an existing third-generation (3G) network. The availability of tunable/reconfigurable hardware will also provide the network operator the means for efficiently managing hardware resources, while accommodating multistandards requirements and achieving network traffic/capacity optimization. Wireless systems can also benefit from tunable filter technologies in other areas; for example, installing wireless infrastructure equipment, such as a remote radio unit (RRU) on top of a 15-story high communication tower, is a very costly task. By using tunable filters, one installation can serve many years since if there is a need to change the frequency or bandwidth, it can be done

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through remote electronic tuning, rather than installing a new filter. Additionally, in urban areas, there is a very limited space for wireless service providers to install their base stations due to expensive real estate and/or maximum weight loading constrains on certain installation locations such as light poles or power lines. Therefore, once an installation site is acquired, it is natural for wireless service providers to use tunable filters to pack many functions, such as multistandards and multibands, into one site.

In satellite systems, the use of flexible reconfigurable payloads has the potential to provide significant advances over current state-of-the-art satellite designs by providing revolutionary concepts that lead to potential new paradigms for space applications. Reconfigurability allows for multimode, multifunctional operation, permitting time sharing of hardware and making it possible to reduce the mass and size of the payload. Mass reductions, in particular, have a dramatic impact on the economics of a satellite program as launch costs are related directly to satellite weight. Alternatively, mass reduction can be exploited to increase the capacity (by adding payload electronics) or extending operational life (by increasing station-keeping fuel). As a result, market factors have constantly been pushing hardware suppliers to reduce mass and size of their products. The ability to add reconfigurability to the payload also enhances system flexibility and adds to the reliability of the space system.

The fixed filters that are currently used in wireless base station and satellite applications have very stringent requirements, and, if tunable filters are used to replace such filters, they must meet the same stringent requirements. In particular, they must exhibit high-Q and maintain the desired bandwidth and a reasonable return loss over the tuning range. The current baseline design being used in today's wireless base station and satellite systems employ three dimensional (3-D) coaxial, dielectric resonator or waveguide filters mainly to achieve a high-Q value. Thus, if tunable filters are ever employed in wireless base station or satellite applications, they need to be implemented using 3-D filters.

Integration of tuning elements such as mechanical motors, piezoelectric actuators, and microelectromechanical systems (MEMS) switches with high-Q tunable filters can potentially lead to the realization of high-Q tunable filters with superior linear performance. However, there are several challenges associated with maintaining good Q, constant bandwidth and reasonable return loss over a wide tuning range. As of today, the goal of using tunable filters to replace fixed filters in wireless and satellite systems still remains formidable. Perhaps the only successful efforts to achieve this goal rely on using motor-based tuning. Nevertheless, motors are bulky and costly, and they have slow tuning speeds.

Over the past two decades, several publications have been reported on tunable filters [1]–[43]. A more recent comprehensive review on tunable filters can be found in this current issue of *IEEE Microwave Magazine* and in an issue published in 2009 with four articles on tunable filters [1]–[4]. A recent workshop [5] presented in the 2013 IEEE International Microwave Symposium (IMS) also contains a comprehensive review of advances on radio-frequency (RF)/microwave multifunction filtering including tunable filters. In view of the existing material in the open literature, one can observe the following:

- The majority of papers published on tunable filters are on microstrip tunable filters. To start with, microstrip filters have very low Q values (100–200), moreover the achievable Q degrades further once the filter is integrated with tuning elements. Such a type of microstrip tunable filters cannot be used in most practical applications, let alone stringent applications such as wireless base station or satellite applications. More recently, some work has been reported on silicon micro-machined filters [16]–[18] and substrate integrated waveguide (SIW) tunable filters [19]–[23], yet the achievable Q of such filters is still low to be used in advanced reconfigurable system applications. It is also observed that most of the publications on tunable filters deal with low-order filters (2–3 poles). In addition, the majority of such publications do not address real system requirements that cannot accept return loss degradation and changes in absolute bandwidth over the tuning range.
- Only a few papers have been published on high-Q 3-D coaxial, waveguide and dielectric resonator tunable filters [4], [6]–[15]. While there is a significant effort going on in wireless industry on the development of motor-based tunable filters, most of this work is not reported in the open literature.

The objective of this article is to bring the attention of microwave researchers to the potential of high-Q coaxial and dielectric resonator tunable filters and to outline the challenges in realizing such filters.

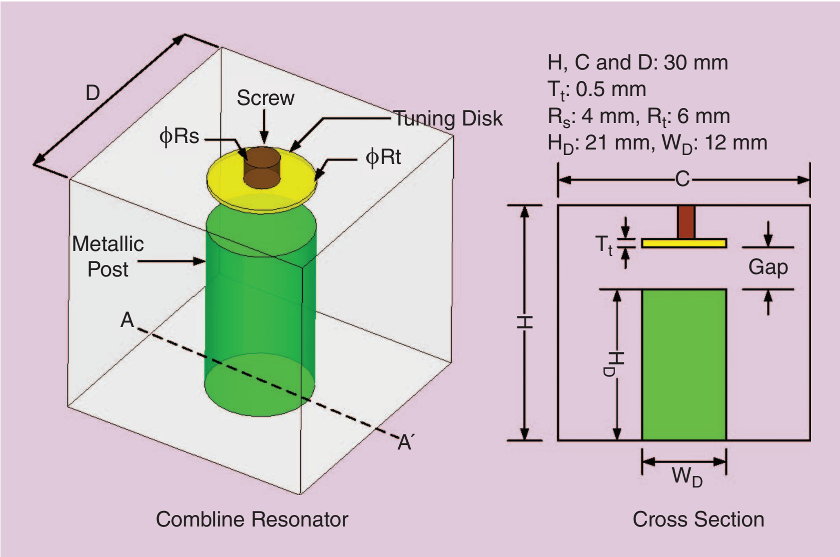

Figure 1. *A conventional cavity combline resonator.*

Maintaining Constant High-Q Value over a Wide Tuning Range

Most 3-D tunable filters start with a relatively high-Q value and exhibit a significant Q degradation over the tuning range. This problem can be easily explained by considering the case where we have a screw or a disk attached to a moving mechanism and is penetrating inside a 3-D cavity resonator to tune its resonance frequency. As the resonator is tuned over a wide tuning range, the screw/disk needs to have more penetration inside the cavity, which in turn reduces Q significantly. A similar effect takes place when using MEMS/varactors to tune resonators, such high loading capacitance can significantly reduce the resonator Q value.

Major Challenges in Realizing High-Q 3-D Tunable Filters

Maintaining Constant Bandwidth and a Reasonable Return Loss over a Wide Tuning Range

To minimize the number of tuning elements and to improve the loss performance of the tunable filter, it is preferable to use tuning elements only to tune the resonator center frequencies. However, the variation of interresonator coupling with frequency is different from that of the input/output coupling. This in turn results in deterioration of the filter return loss and changes in the filter absolute bandwidth over the tuning range. Of course the simplest solution is to add tuning elements to control the inter resonator coupling and the input/output coupling as well. In many cases, this solution may not be even feasible because of size limitation, design complexity, and the inherent difficulty to tune sequential and cross-interresonator coupling. Therefore, one needs to use only tuning elements for the resonators to tune their frequency and rely on other means to maintain constant interresonator and input/output coupling or to compensate for their variations somehow over the tuning range. One approach is to use nonsynchronous tuning of the resonators, where the resonator frequencies are not varied by the same shift during the tuning process, which may help to compensate for changes in interresonator coupling. However, this approach can help to certain extend, and fails to yield acceptable results in wide tuning ranges (over 5%). In the case of microstrip tunable filters, several approaches were reported to maintain constant bandwidth [33]–[40]. However, very limited work has been reported on maintaining constant bandwidth in high-Q 3-D tunable filters.

Integration of Tuning Elements with 3-D Filters

The integration of MEMS or semiconductor tuning elements with 3-D high-Q resonators is a major challenge. MEMS have a small size, while 3-D cavity resonators (waveguide, coaxial, dielectric resonators) have much larger dimensions. The MEMS tuning elements need to be integrated in a way to interact with the electromagnetic (EM) field inside the resonator and, accordingly, tune the resonator over a wide tuning range without major Q-degradation. Another major challenge in the case of MEMS tuning is to achieve a large number of tuning states, this requires the development of a large switched capacitor bank of order 5 or 6 (i.e., to achieve 32 or 64 states). While there are RF MEMS switches commercially available [44], [45], these switches need to be integrated with a bank of capacitors to realize the switched capacitor bank. However, such hybrid integration leads often to high losses and to a very low self-resonance frequency of the loading switched capacitor bank.

Motor-Based High-Q Tunable Filters

Figure 1 shows a conventional cavity combline resonator. The resonator can be tuned by adjusting the gap between the metallic post and tuning disk. This can be achieved by using a driving mechanism such as motors. The use of conventional mechanical stepper motors can result in fine tuning steps; however, these motors are usually very expensive and bulky, increasing the overall size of the tunable filter. Alternatively, piezomotors [46], [47] can be used to replace traditional motors. Piezomotors have high resolution and are available with various sizes and can be easily integrated with the tunable filter. A motor-based cavity combline tunable filter has been demonstrated

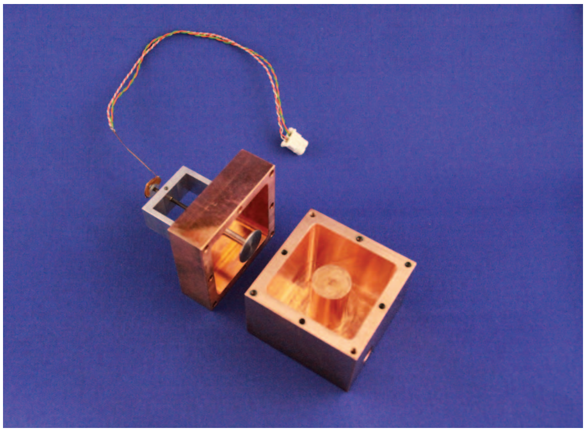

Figure 2. *A cavity combline resonator integrated with a piezomotor [9].*

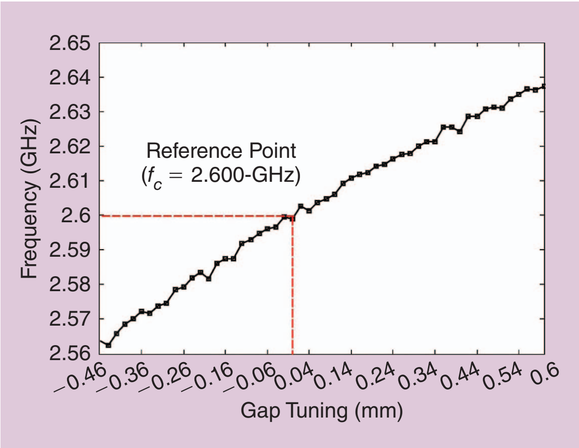

Figure 3. *The measured tuning performance of the cavity shown in Figure 2 [9].*

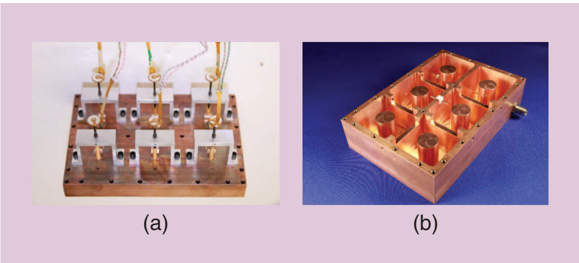

Figure 4. *A photo of a six-pole WIMAX tunable filter [9]: (a) top cover with piezomotors and (b) bottom housing.*

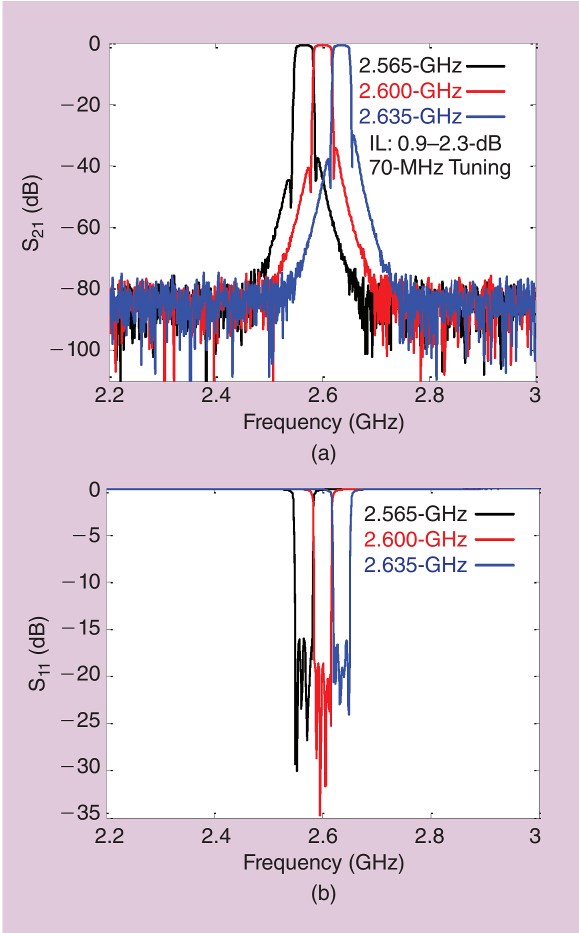

Figure 5. *The measured results of the WiMAX tunable filter shown in Figure 4 [9].*

in [9] for WiMAX applications. The filter is designed to operate continuously over the frequency range of 2,550–2,650-MHz, with a bandwidth of 30-MHz. The basic building block of the filter is the cavity shown in Figure 2. It has a size of 30 mm × 30 mm × 30 mm. The post has a height of 21 mm and a diameter of 12 mm. The cavity is integrated with a piezomotor [46] that is mounted to the lid while its shaft is attached to a tuning disk, as a result the disk can move up and down over the metallic post. The measured tuning performance of the cavity is shown in Figure 3. By changing the gap in 20-μm steps, the cavity was tuned from 2.565 to 2.645-GHz demonstrating a measured Q from 2,252–2,914. The cavity in this case is made of copper with a tuning disk made of a gold plated aluminum. It is noted that almost a 25% degradation in Q value was observed over a 4% tuning range. Certainly, the degradation can be potentially reduced by optimizing the dimensions of the cavity and tuning disk, yet this example illustrates that Q can degrade considerably over the tuning range.

A six-pole filter was selected to meet the WiMAX requirements [9]. Figure 4 shows the filter configuration assembled with pieozomotors. It is a 6–2 pole filter designed to have two transmission zeroes, realized using a probe inserted between resonators 2 and 5 to provide a negative coupling. The piezomotors were used only to tune the resonance frequency of the resonators. The measured performance of the WiMAX tunable filter is shown in Figure 5 for three frequencies. The filter is capable of meeting all WIMAX requirements demonstrating a constant absolute bandwidth over the desired tuning range. The variation of interresonator and input/output coupling over the tuning range could be circumvented in this case by the use of nonsynchronous tuning since the tuning range is only 4%.

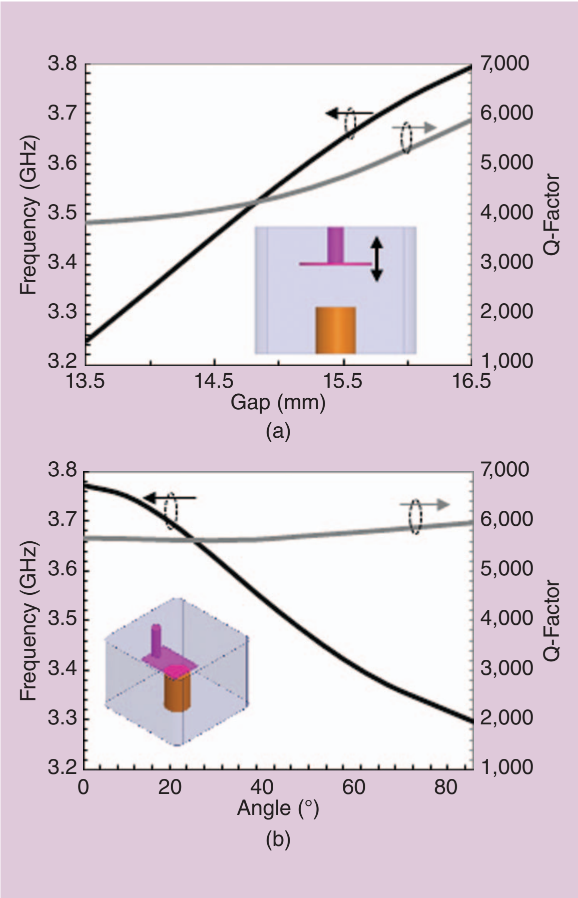

Figure 6. *A comparison between a resonator tuned using (a) vertical tuning and (b) angular tuning [48].*

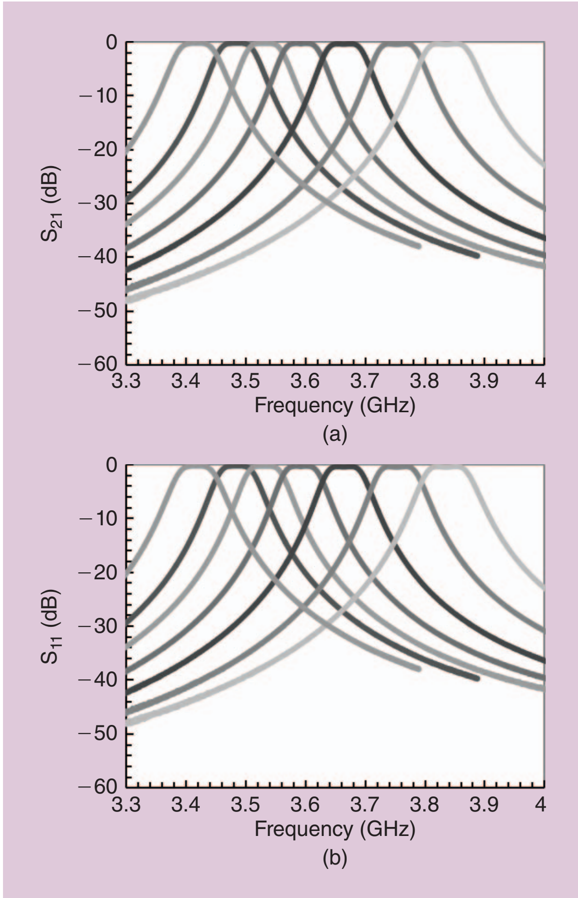

Figure 8. *The measured results of the two-pole tunable filter shown in Figure 7 [48].*

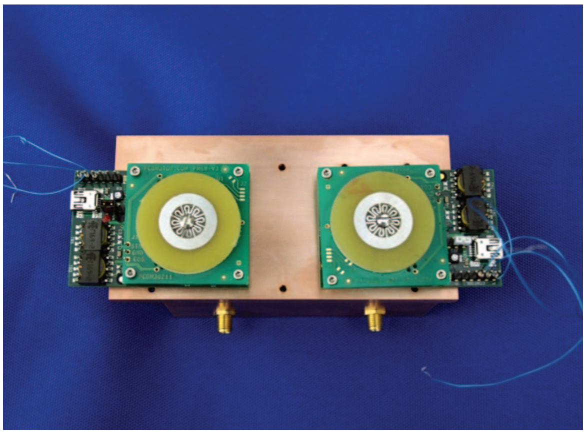

Figure 7. *A two-pole combline filter tuned using the concept of angular tuning employing planar piezomotors [48].*

While the obvious approach to mechanically tune a combline resonator is to use a screw or disk that is moving up and down over the metallic post, such a technique yields a noticeable Q degradation over the tuning range. An alternative approach is to use a disk that moves radially over the metallic post. This will help to maintain almost a constant Q over a relatively wide tuning range. More importantly, it makes it possible to use simple motor designs where the motor shaft rotates radially eliminating the need to use any complicated mounting jigs that are often required to get vertical displacement of the motor shaft. To illustrate the difference between vertical tuning versus angular tuning, we consider a cavity combline resonator tuned by both techniques [48]. Figure 6(a) shows the resonance frequency and Q versus gap of a resonator employing vertical tuning whereas Figure 6(b) shows the Q and resonance frequency of a similar combline resonator employing angular tuning. The starting point for the resonance frequency and Q was kept the same in both cavities. The tuning range is also kept the same. It can be seen that the use of angular tuning approach yields almost a constant Q over a 15% tuning range. The vertical tuning approach yields close to 30% Q degradation over the same tuning range. A two-pole filter is demonstrated in [48] employing the angular tuning concept. The filter configuration is shown in Figure 7. It uses planar piezomotors [47] that are easily mounted on the top cover of the filter housing since the motor shaft only needs to rotate around its axis. Figure 8 shows the measured results of the two-pole filter. The filter exhibits only less than 0.11-dB insertion loss variation over the 15% tuning range.

For tunable filters where the tuning elements are used to tune only the resonance frequency of the resonators,

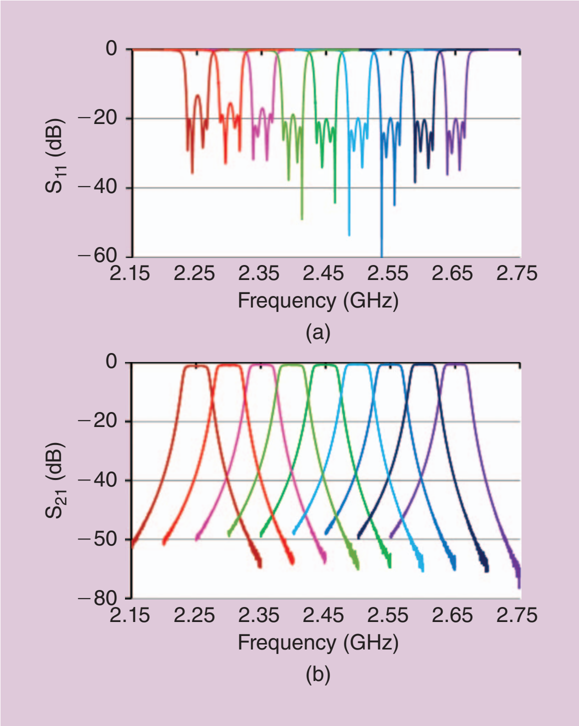

Figure 9. *The measured results of a four-pole cavity combline tunable filter tuned; the filter housing is made of copper [49].*

the degradation in filter return loss and variation in bandwidth over the tuning range is a much more serious problem in comparison with Q degradation, particularly in dealing with larger-order filters and in applications that require a tuning range over 10%. A technique has been developed in [49] to achieve an absolute constant bandwidth over a relatively wide tuning range. The technique was used to realize a four-pole tunable filter at 2-GHz with a tuning range of 400-MHz, a five-pole tunable filter at 5-GHz (for Wi-Fi applications) with a tuning range of 1-GHz and a seven-pole 7.5-GHz tunable filter with a tuning range close to 1-GHz. The measured results for these three tunable filters are shown respectively in Figures 9–11. It can be seen that almost an absolute constant bandwidth with an acceptable return loss performance was achieved for the three filters [49]. These filters were tuned by piezomotors. The 2-GHz filter was built using a copper housing, whereas the 5-GHz and the 7.5-GHz filters were built aluminium housing. A much better insertion loss can be realized with the use of filter housings made of copper or silver-plated aluminum.

MEMS-Based Tunable Combline Filters

Cavity combline filters can be also tuned using MEMS or semiconductor varactors. The idea is to use an isolated disk located over the metallic post. The disk and

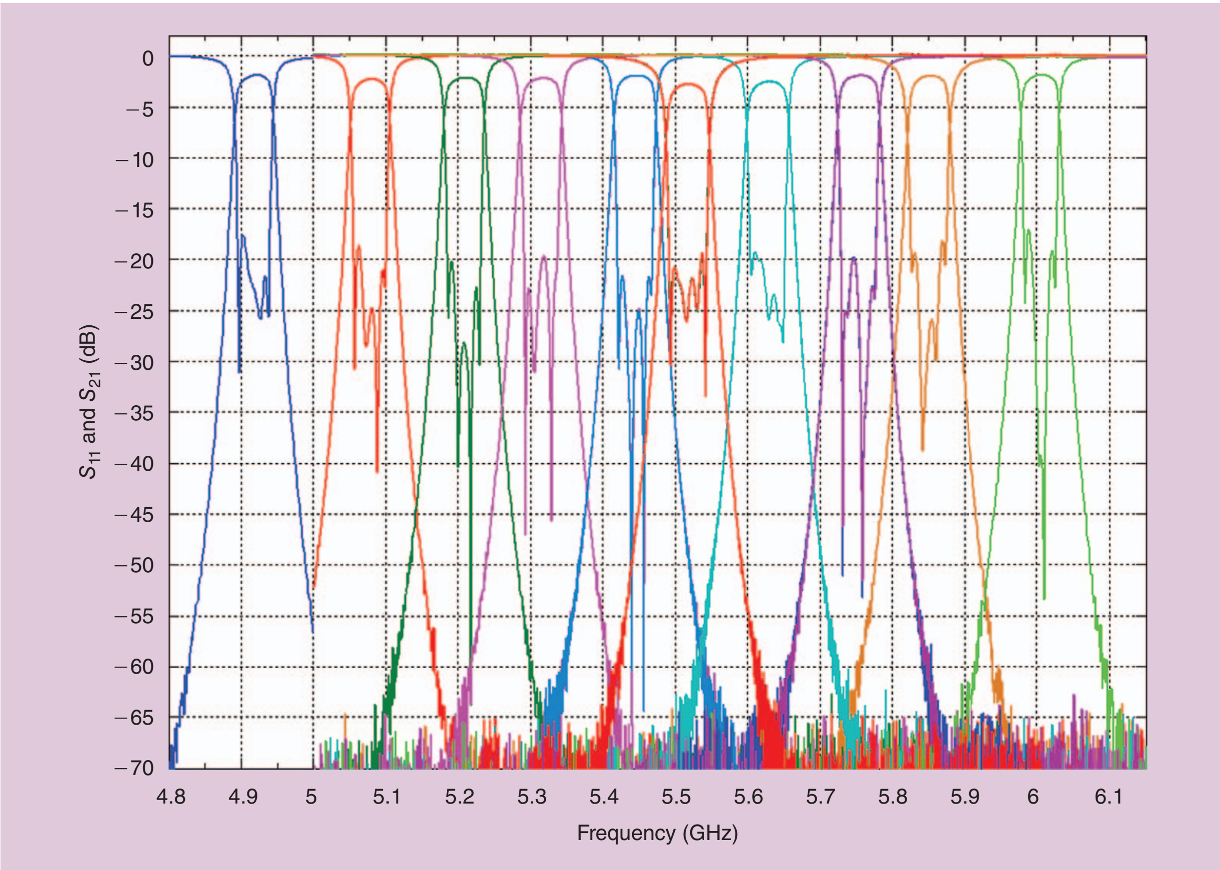

Figure 10. *The measured results of a five-pole 5-GHz Wi-Fi cavity combline tunable filter; the filter housing is made of aluminum [49].*

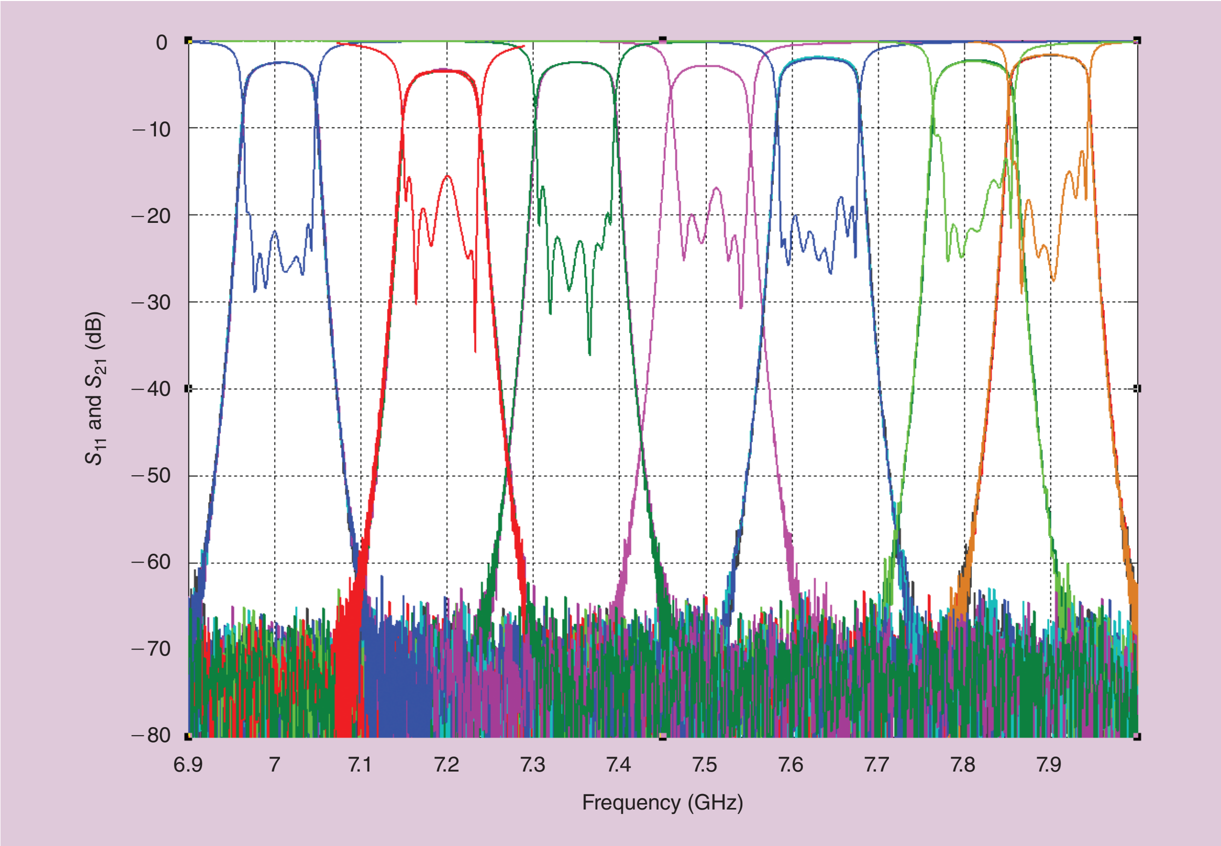

Figure 11. *The measured results of an X-band seven-pole cavity combline tunable filter; the filter housing is made of aluminum [49].*

the metallic post will form a floating capacitance that is not connected to ground. This capacitance can be connected to a MEMS-based capacitance or semiconductor varactor that is shorted to ground at the other end. Thus, the total capacitance that is loading the metallic post consists of the capacitance that is formed by the gap between the disk and the metallic post and the capacitance of the tuning element. Figure 12 shows a tunable combline resonator tuned by the RF-MEMS switched capacitor bank [9]. The switched capacitor bank is assembled on a printed circuit board (PCB) and is mounted on the top wall of the cavity. One end of the switched capacitor bank is attached to the tuning disk which is isolated from the cavity wall with a Teflon spacer, the other end is attached to the ground with the use of via hole. The variable loading effect of the capacitor bank on the tuning disk is used to tune the resonator. The switched capacitor bank consists of high-Q capacitors in series with RF-MEMS contact type switches. A simplified schematic view and the equivalent circuit diagram of the RF-MEMS tuning circuit is presented in Figure 13. By turning the MEMS switches on and off, using a dc actuation voltage, it is possible to change the value of loading capacitor and adjust the resonant frequency of the cavity.

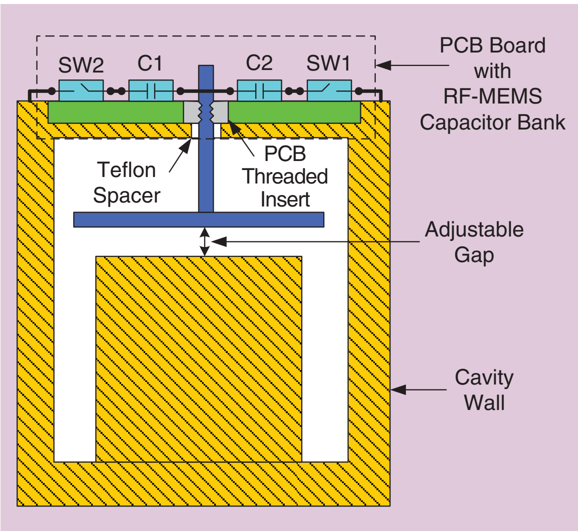

Figure 12. *A tunable combline resonator tuned by the RF-MEMS switched capacitor bank [9].*

The capacitor bank is assembled using Radant single-pole, single-throw (SPST) switches [44] connected to ceramic capacitors. Each MEMS switch is actuated separately. The resonator is tuned from 2.503 to 2.393-GHz (110-MHz), while the measured Q is ranging from 1,300 to 374 over the same tuning range. It should be noted that the values listed in [9] for Q and tuning range were obtained for a specific cavity structure. A better Q value and a larger tuning range can be potentially achieved by optimizing the resonator structure and the PCB design.

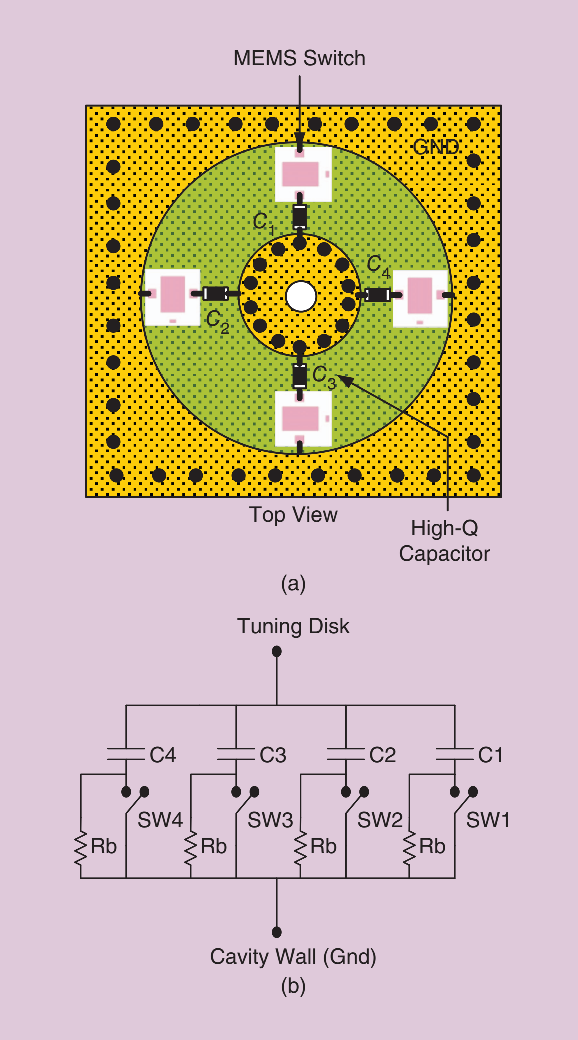

Figure 13. *Details of the tuning circuit and its equivalent circuit [9].*

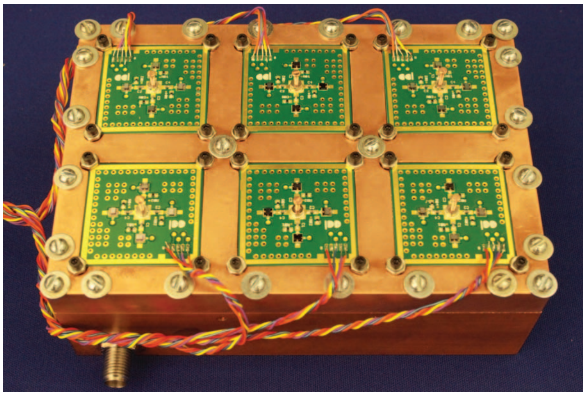

Figure 14. *A photo of the MEMS-based tunable combline filter [9].*

A six-pole WiMAX tunable combline filter employing this concept is demonstrated in [9]. Figure 14 shows the filter configuration. It has six PCBs with the RF MEMS tuning elements are assembled on the top cover of the filter. It is very important to establish a good ground contact between the MEMS capacitor banks and the cavity

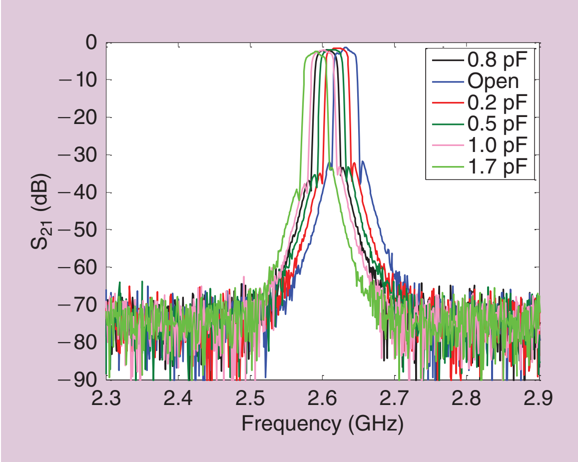

Figure 15. *Measured results of the combline filter shown in Figure 14 [9].*

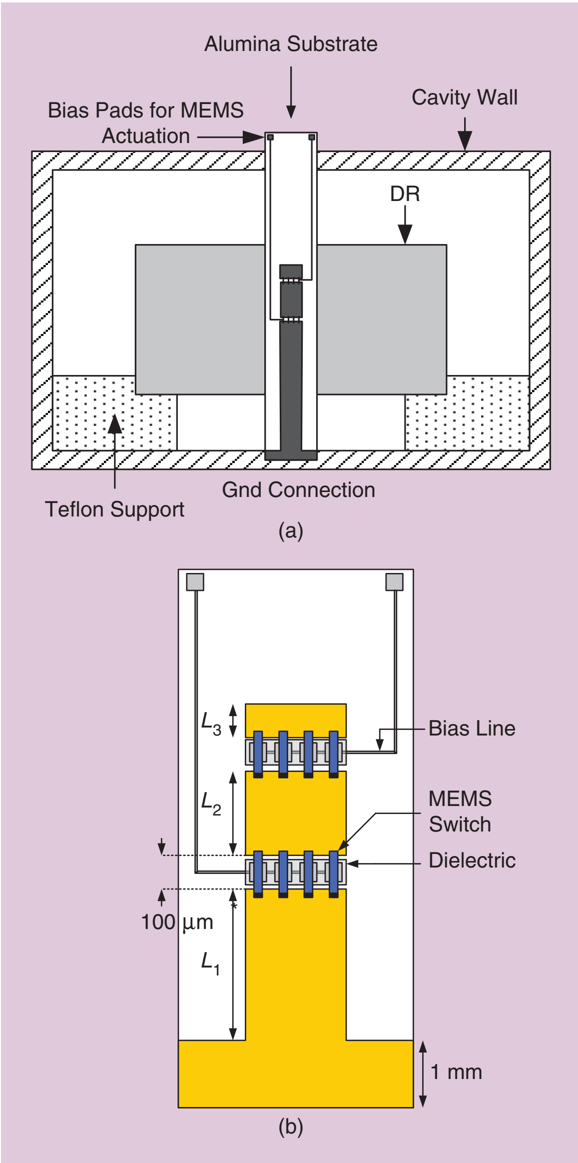

Figure 16. *(a) A dielectric resonator integrated with a tuning strip loaded with MEMS switches and (b) details of the tuning circuit [7].*

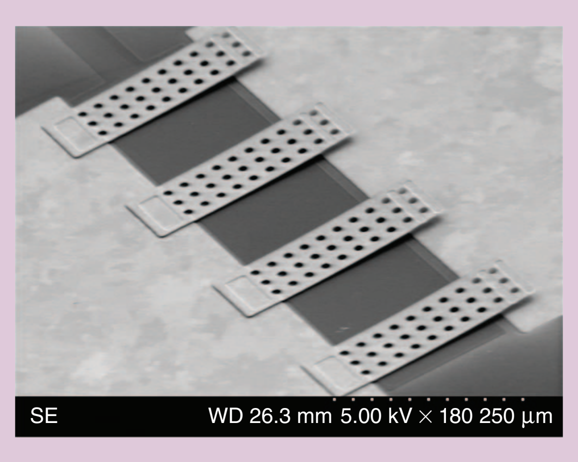

Figure 17. *A SEM photo of the MEMS switches used in Figure 16 [7].*

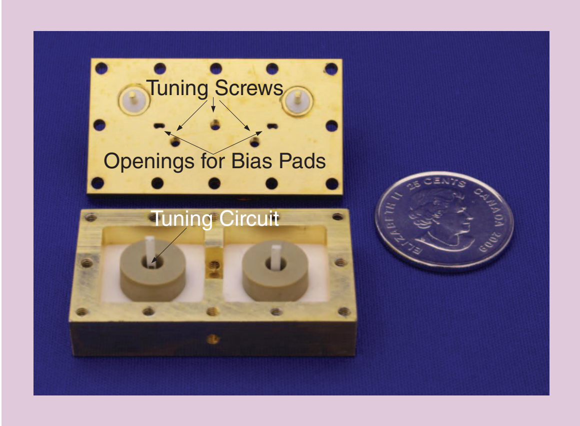

Figure 18. *A photo of a two-pole MEMS-based tunable filter [7].*

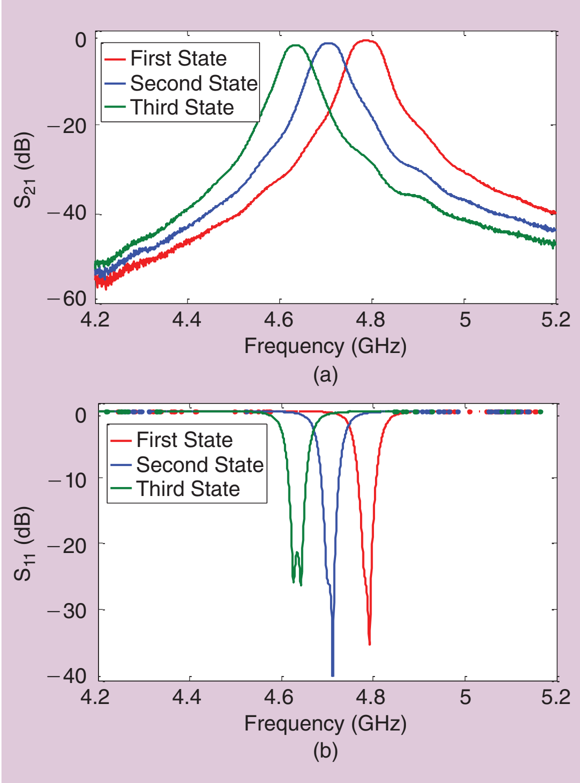

Figure 19. *The measured results of the MEMS-based tunable dielectric resonator filter shown in Figure 18 [7].*

wall. For this reason, grounding gaskets on the lid and also sufficient number of via holes between the bottom ground plane of the PCB and the top ground plane of the MEMS capacitor bank are required, as shown in Figure 14. The measured performance of the MEMS-based tunable filter is shown in Figure 15. A small tuning range is achieved due to the fact that this particular filter was tuned using synchronous tuning. The use of nonsynchronous tuning should yield a wider tuning range. This, however, will require the use of a continuously variable capacitor or the use of switched capacitor bank with a large number of states to allow selection of the appropriate capacitance value. An alternative solution is to apply the technique [49] to achieve an absolute constant bandwidth over a wide tuning range.

It should be mentioned that not only the capacitance loading degrades the Q of the tunable resonator but also the resistive loading associated with this capacitance. The resistance is the sum of the resistance of the MEMS switch, the resistance associated with the chip ceramic capacitor, and the resistance associated with the PCB and the via holes needed to connect the tuning elements to the filter housing (ground).

Tunable Dielectric Resonator Filters

Dielectric resonator filters are emerging as the current baseline designs for the majority of RF filters used in wireless and satellite applications. They offer high Q-value with a relatively high Q/volume ratio in comparison with any other known filter technology. High Q dielectric materials with dielectric constant ranging from 20 to 90, are commercially available from various manufacturers. Dielectric resonators with $\varepsilon_r = 30$ are commercially available with Q$\times$frequency factor (f) values of 100,000, i.e., an unloaded Q value of more than 50,000 can be achieved at 2.0-GHz. Dielectric resonators can operate at various modes giving the designers of tunable filters the flexibility to select the tuning element that can easily interact with field distribution of that particular mode. The resonators can be easily machined to have various shapes using low-cost water jet machining allowing ease of realization of highly novel resonator configurations [50]. A comprehensive review on tunable dielectric resonator filters reported in literature up to 2009 is given in [4]. In this section, we summarize the work reported over the past five years in the literature on tunable dielectric filters.

Similar to cavity combline filters, dielectric resonator filters can be tuned by motors through the use of a disk that can moves vertically or radially over the resonator to perturb the EM field. The piezomotors can be replaced by piezoelectric actuators as demonstrated in [4] or by MEMS actuators as demonstrated in [4] and [6]. The concept of using a MEMS actuator is applicable only to high-frequency applications where the size of the MEMS actuator is compatible to that of the dielectric resonator to cause a significant field perturbation and achieve a reasonable tuning range. In [6], a dielectric resonator tunable filter operating at 16-GHz was successfully demonstrated using MEMS actuators. A MEMS actuator having a disk shape of size 2 mm × 2 mm and with a vertical displacement of 500 µm was placed on top of a dielectric resonator of diameter 5 mm demonstrating a tuning range of 800-MHz. The use of the same concept for large diameter dielectric resonators operating at lower frequencies yields a very small tuning range.

The realization of tunable dielectric resonators that are tuned by MEMS switches and semiconductor tuning elements requires integrating the tuning element with the dielectric resonators (DRs) in a way to interact and perturb the EM field. The two common single modes that DR resonators that are widely used in filter applications are: TME and TEH modes [50]. While TME modes offer lower Q values in comparison with THE modes, the field distribution of TME makes it easy to integrate MEMS or the semiconductor tuning element with the DR resonator. In [7] a conductive strip loaded with MEMS switches is placed inside a dielectric resonator operating

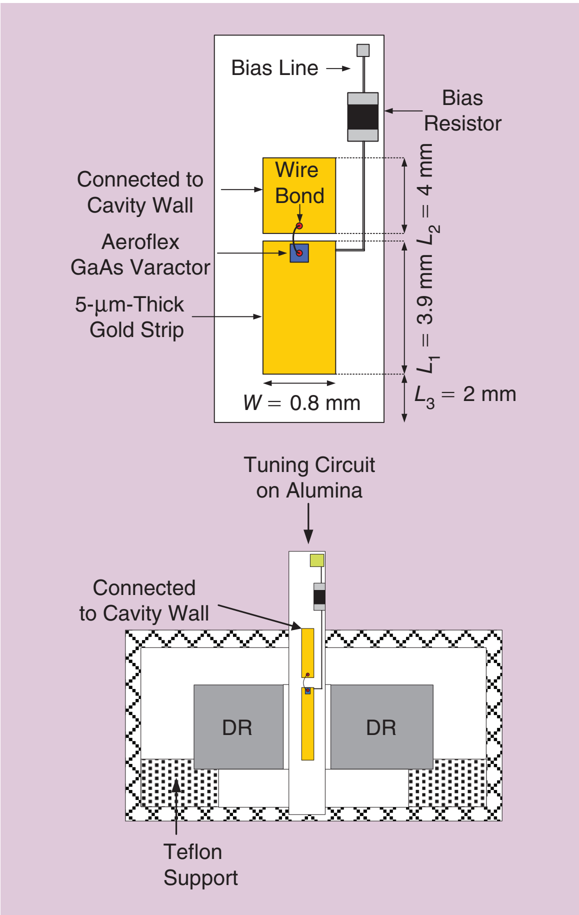

Figure 20. *A dielectric resonator tuned by a varactor [7].*

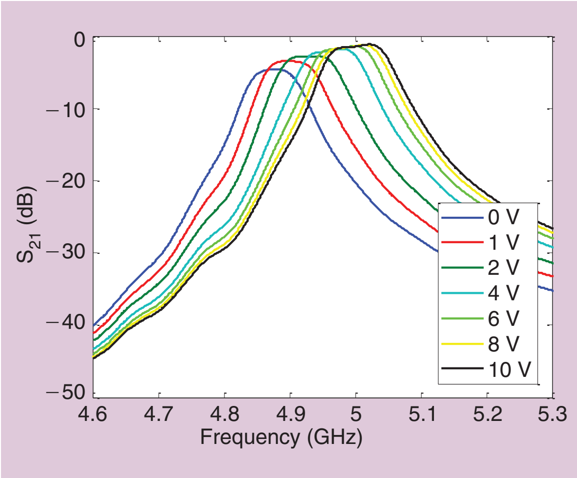

Figure 21. *The measured results a two-pole varactor-based tunable dielectric resonator filter [7].*

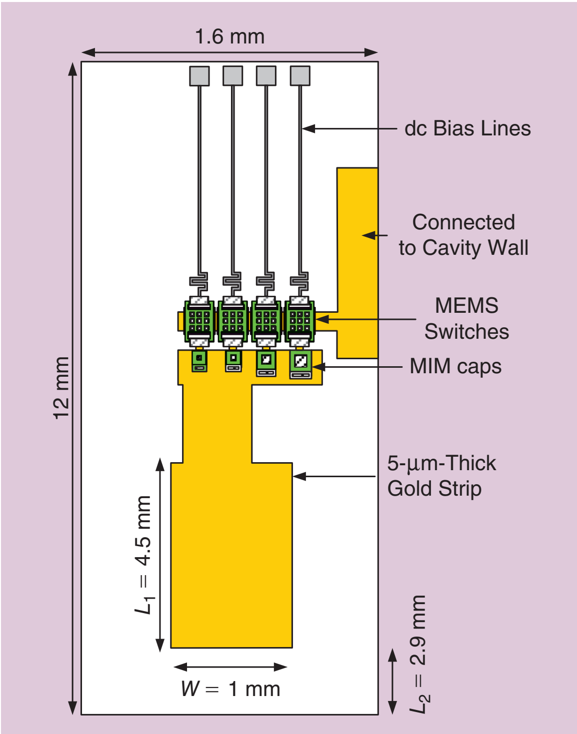

Figure 22. *A circuit employing 4-bit RF-MEMS switched capacitor for tuning a dielectric resonator filter [7].*

in the TME mode as shown in Figure 16(a). The tunable resonator consists of a dielectric resonator with hole in the center mounted on a Teflon support and is inserted inside a metal enclosure. Dielectric resonator with holes in the middle are traditionally used to improve the spurious performance of DR resonators operating in the TEH modes. In this case the hole is used to provide the room to place the tuning circuit inside the resonator. The idea of tuning here is to have a metallic strip whose surface current interacts strongly with the field distribution of the TME mode. The tuning circuit, as shown in Figure 16(b), consists of three conductive strips made of gold

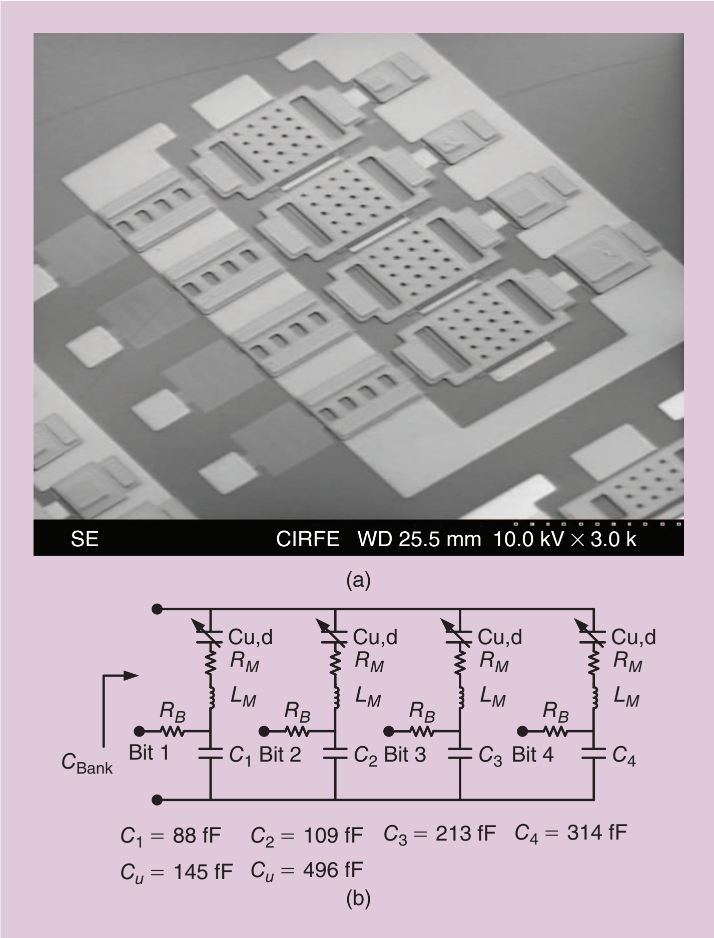

Figure 23. *A SEM photo of the 4-bit RF MEMS switched capacitor bank and its equivalent circuit [7].*

on a 625 µm alumina substrate. The three strips have different lengths (L_1,L_2, and L_3) separated by a 100 µm gap from each other. Two sets of contact type RF-MEMS switches are utilized over the 100 µm gap between these conductive strips. Figure 17 shows a scanning electron microscope (SEM) photo of the MEMS switches used. The switches were fabricated at the University of Waterloo using the UW-MEMS process [51].

Each set of MEMS switches has a separate bias line connected to bias pads outside the cavity and can be actuated independently. When the bias voltage on the MEMS switches is zero, the effective length of the conductive strip is L_1. When the first set of switches are actuated to the down state, the second segment of conductive strip is electrically connected to the first strip and the total length of the strip is increased to $L_1 + L_2$, causing EM field perturbation and hence tuning the resonance frequency of the resonator. A third state can be achieved by simultaneously actuating both sets of the MEMS switches A two-pole filter operating at around 4.8-GHz with a 20-MHz bandwidth was demonstrated in [7] using this concept. Figure 18 shows the fabricated tunable filter unit, whereas Figure 19 shows its measured results in the three states. The return loss is better than 20-dB over a tuning range of 160-MHz from 4.64 to 4.8-GHz. The Q was ranging from 1,220 to 510. It should be noted that a DR resonator used for that structure was from old dielectric resonator stock with a relatively low $Q \times f = 40{,}000$. The use of dielectric resonator materials with $Q \times f = 100{,}000$ should provide higher Q-values than what reported in [7].

To obtain continuous tuning, semiconductor varactors can be used to replace the RF MEMS switches. Figure 20 shows the schematic diagram of the tuning circuit with the varactor elements [7]. It consists of two gold strips of different lengths on an alumina substrate connected by a semiconductor varactor. A commercial GaAs varactor with a capacitance ranging from 1.1 pF to 0.32 pF with a reverse bias voltage varying from 0 to 10 V is used to connect the two conductive segments. The first conductive strip is placed inside the hole within the DR, whereas the other conductive strip makes contact with the cavity lid and establishes a ground connection. The measured results achieved are shown in Figure 21. The filter demonstrated an insertion loss of 1.17-dB and 4.6-dB for a bias voltage of $V_{\text{bias}} = 10$ V and $V_{\text{bias}} = 0$ V, respectively. The high insertion loss is attributed to the lower Q value of the varactor.

To improve the loss performance of the tunable DR filter while achieving a continuous tuning (or more tuning states), a tuning circuit utilizing 4-bit RF MEMS switched-capacitor bank is also employed in [7]. Figure 22 shows a schematic diagram of the tuning circuit. It has two conductive strips, one connected to the cavity wall and the other is placed inside the hole within the DR. A SEM image of the 4-bit RF-MEMS capacitor bank and its equivalent circuit are given in Figure 23. It consists of four metal–insulator–metal (MIM) capacitors C1, C2, C3, and C4 and four capacitive RF MEMS switches with up-state and down-state capacitance values of Cu and Cd respectively. This 4-bit RF MEMS circuit was fabricated at the University of Waterloo using the UW-MEMS process [50]. The capacitance value changes from 347 to 744 fF. The fabricated filter unit is shown in Figure 24, whereas the measured results for the 16 tuning states are given in Figure 25. A tuning range from 5.20 to 5.02-GHz (180-MHz) is achieved, with a return loss close to 15-dB. The maximum insertion loss is better than 2.8-dB. The measured Q value changes from 800, when all of the MEMS switches are up, to 550 when all of the MEMS switches are actuated to the down state position.

More recently, a concept similar to what used in [9] for combline filters is used to realize tunable dielectric resonator filters [8]. Figure 26 shows the 3-D view of the tunable dielectric resonator. It consists of a dielectric resonator

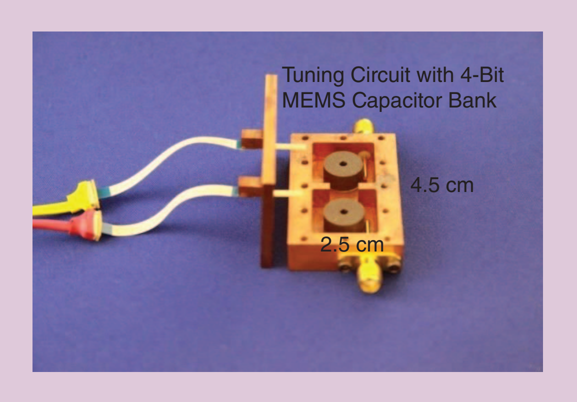

Figure 24. *A photo of a two-pole tunable MEMS-based tunable dielectric resonator filter [7].*

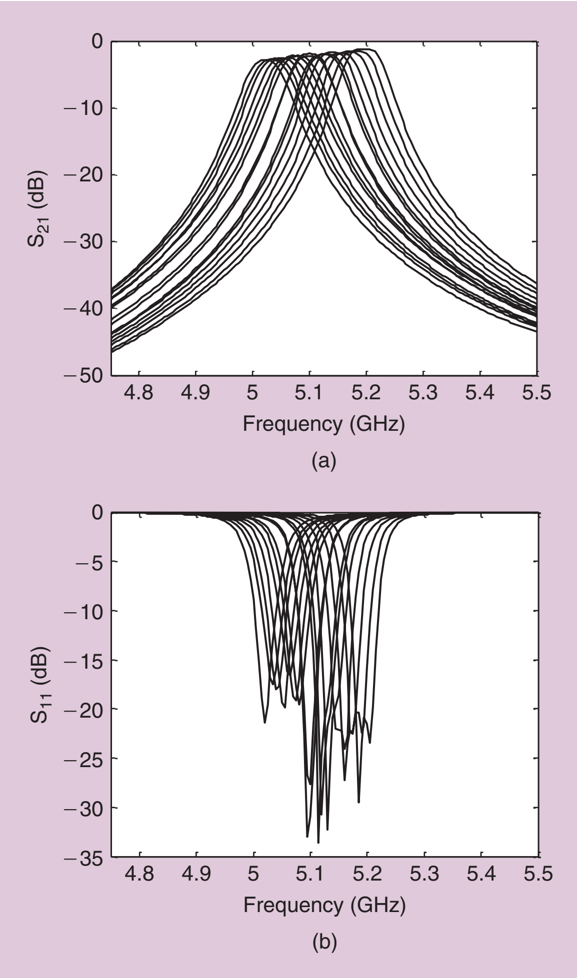

Figure 25. *The (a) isolation and (b) return loss measured results of the 16 tuning states of the MEMS-based tunable dielectric resonator shown in Figure 24 [7].*

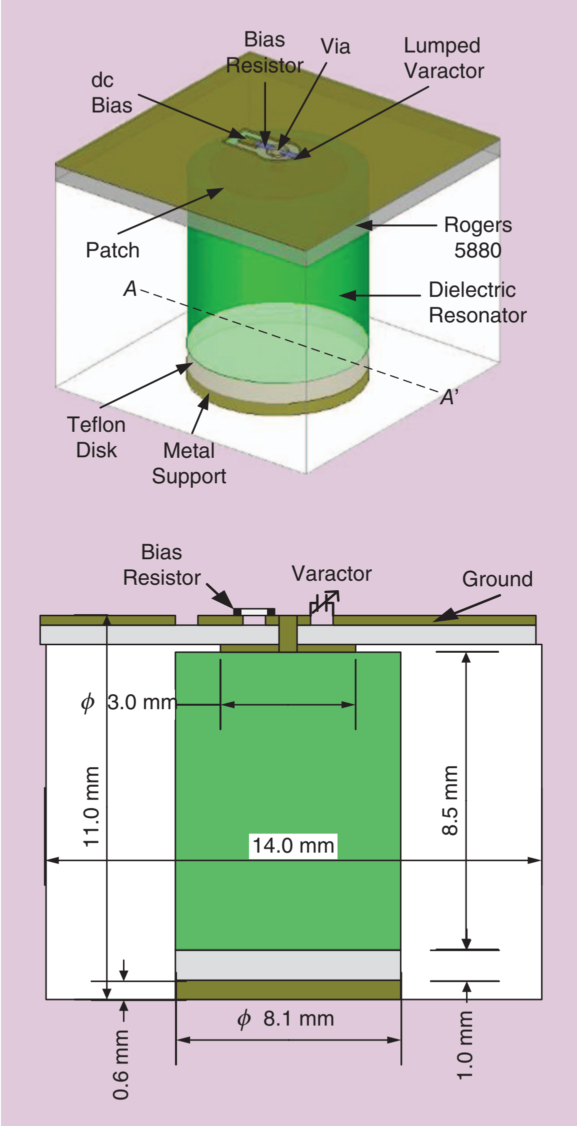

Figure 26. *A dielectric resonator cavity tuned by a varactor [8].*

placed in the center of a metal cavity and is supported by a thin Teflon disk. The metal disk at the bottom of the cavity is used to align the dielectric resonator during the assembly process. The cavity is covered by a patch-printed PCB. A disk patch is printed on the bottom surface of the PCB, and linked to top patch of the PCB through a via hole. A slot is made around the via hole to isolate it from the grounded top patch. A varactor is placed over the slot, and a high-value dc bias resistor is used to avoid RF leakage while applying dc voltage to the varactor. A two-pole 5-GHz tunable filter was demonstrated using this concept, exhibiting a 300-MHz tuning range [8].

Conclusions

Tunable coaxial, waveguide, and dielectric resonator filters can potentially address wireless base station and satellite applications that require very high-Q values (3,000 and up). Yet there are still several challenges in developing such high-Q tunable filters for real system applications. These challenges include: realization of an absolute constant bandwidth, a reasonable return loss, and a high Q value over a relatively wide tuning range. It is also challenging to integrate tuning elements such as MEMS or semiconductor varactors with three-dimensional (3-D) high-Q filters while being able to create enough perturbation to the EM field inside the 3-D resonators to achieve tunability over a wide tuning range. Certainly, more research efforts are needed to explore the potential for realizing 3-D high-Q tunable filters that can truly replace the existing filters in wireless base station and satellite applications.

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