High-Q Tunable Filters for Wireless Base Station Applications

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ABSTRACT – This review paper presents recent developments in high-Q three-dimensional tunable filters tuned by piezomotors, MEMS and semiconductor elements for wireless base station applications. It also addresses main challenges in designing tunable filters with an absolute constant bandwidth and a constant Q over the tuning range. Experimental results are presented for a wide range of tunable bandpass filters.

Index Terms - Tunable Filters, Reconfigurable Filters, MEMS

I. INTRODUCTION

High performance RF tunable filters are needed in reconfigurable systems to facilitate efficient utilization of the available frequency spectrum. They are in demand in front-end receivers for suppression of interfering signals and for relaxation of oscillator phase noise and dynamic range requirements. Tunable filters are also used to replace large filter banks in advanced systems concepts that self-adapt to environmental requirements. Tunable filters have been proposed as well for high power applications. The advantages in this case are suppression of harmonics generated from the power amplifiers.

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 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 estates 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 in order to pack many functions such as multi-standards and multi-bands, into one site. The availability of tunable/reconfigurable hardware will also provide the network operator the means for efficiently managing hardware resources, while accommodating multi-standards requirements and achieving network traffic/capacity optimization.

A relatively recent survey on progress in tunable filters can be found in [1]-[9]. The fixed filters that are currently used for wireless base station applications have very stringent requirements, 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 baseline design being used in today's wireless base station systems employ three dimensional (3D) coaxial, dielectric resonator or waveguides filters mainly to achieve a high Q value. Thus, if tunable filters are ever employed in wireless base station systems, they need most likely to be implemented using three dimensional (3D) filters.

Integration of tuning elements such as mechanical motors, piezoelectric actuators and Micro-electro-mechanical system (MEMS) switches with high-Q tunable filters can potentially lead to the realization of high-Q tunable filter 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 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. The MEMS technology can be potentially employed to circumvent such limitations.

This review paper provides an outline of recent development [1]-[2], [10]-[16] in tunable filters for wireless base stations addressing several design considerations including the realization of tunable filters with an absolute constant bandwidth over a wide tuning range.

II. MAJOR CHALLENGES IN REALIZING HIGH-Q 3D TUNABLE FILTERS

A. *Maintaining constant bandwidth and a reasonable return loss over a wide tuning range.*

In order to minimize the number of tuning elements and to improve the loss performance of the tunable filters, it is preferable to use tuning elements only to tune the resonator center frequencies. However, the variation of inter-resonator coupling with frequency is different from that of the input/output coupling. This in turn results is deterioration in 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

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cross inter-resonator coupling. Therefore, one needs to use only tuning elements for the resonators to tune their frequency and rely on other means to maintain constant inter-resonator coupling and input/output coupling or to compensate for their variations somehow over the tuning range. One approach is to use non-synchronous 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 inter-resonator 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. However, very limited work has been published maintaining constant bandwidth in high 3D tunable filters [1].

B. Maintaining constant high Q value over a wide tuning range

Most 3D 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 3D 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 even if the varactor is assumed lossless [1].

C. Integration of tuning elements with 3D filters

The integration of MEMS or semiconductor tuning elements with 3D high-Q resonators is a major challenge. MEMS have a small size while 3D cavity resonators (waveguide, coaxial, dielectric resonators) have a much large dimensions. The MEMS tuning elements need to be integrated in a way to interact with the electromagnetic 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 these switches need to be integrated with a bank of capacitors to realize the switched capacitor bank. However, such hybrid integration leads to high losses and to a very low self-resonance frequency of the switched capacitor bank [1].

III. HIGH Q 3D TUNABLE FILTERS

Fig. 1 shows a conventional 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 [13], [14] 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 combline tunable filter has been demonstrated in [13] for WiMAX applications. The filter is designed to operate continuously over the frequency range of 2550-2650 MHz, with a bandwidth of 30 MHz. Fig. 2 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 motors were used only to tune the resonance frequency of the resonators. The measured performance of the WiMAX tunable filter is shown in Fig. 3 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 inter-resonator and input/output coupling over the tuning range could be circumvented in this case by the use of nonsynchronous tuning since tuning range is only 4% [1].

While the obvious approach to mechanically tune a combline resonator is to use a screw or disk that is moved up and down over the metallic post, such technique yields a Q degradation over the tuning range. An alternative approach is to use a disk that is moves radially over the metallic post. This will help to maintain almost a constant Q over a relatively wide tuning range. It also 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. A comparison between vertical tuning and angular tuning is given in [14], where it is shown that angular tuning can help in maintaining Q over tuning range [1].

For tunable filters where the tuning elements are used to tune only resonance frequency of the resonators, 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 [15] to achieve an absolute constant bandwidth over a relatively wide tuning range. The technique was used to realize a 4-pole tunable filter at 2 GHz with a tuning range of 400 MHz, a 5-pole tunable filter at 5 GHz (for WiFi applications) with a tuning range of 1 GHz and a 7-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 Figs. 9, 10 and 11. It can be seen almost an absolute constant bandwidth with an acceptable return loss performance was achieved for the three filters [15]. These filters were tuned by piezomotors and are built using aluminum housings, a much better insertion loss can be realized with the use of filter housings made of copper or silver plated aluminum [1].

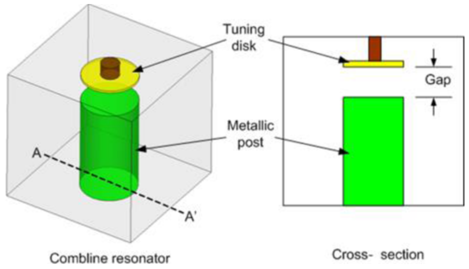

Fig. 1 A conventional combline resonator

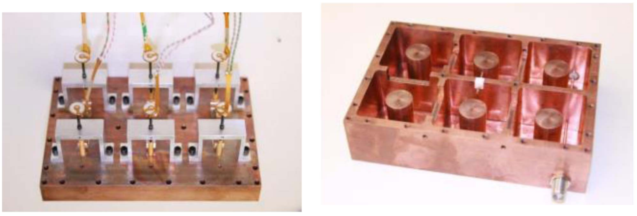

Fig.2 A picture of the a 6-pole WIMAX tunable filter [13]

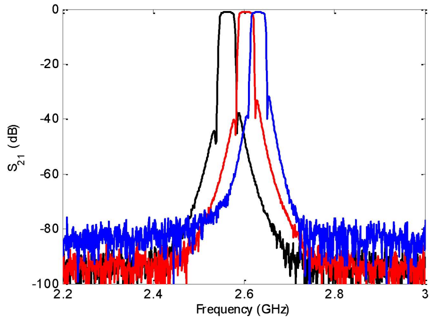

Fig. 3 Measured results of the WiMAX tunable filter shown in Fig. 2 [13]

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 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. Fig. 12 shows a tunable combline resonator tuned by RF-MEMS switched capacitor bank [9]. The switched capacitor bank is assembled on a PCB board 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 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 Fig. 13. By turning the MEMS switches on and off, using a dc actuation voltage, it is possible to change the value of capacitor loading and adjust the resonant frequency of the cavity [1].

The capacitor bank is assembled using Radant SPST switches [17] 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 1301 to 374 over the same tuning range. It should be noted that the values listed in [13] 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 board design [1].

A 6-pole WiMAX tunable combline filter employing this concept is demonstrated in [13]. Fig. 14 shows the filter configuration. It has six PCB boards with the RF MEMS tuning elements are assembled on the top cover of the filter.. The measured performance of the MEMS-based tunable filter is shown in Fig. 15. A small tuning range is achieved due to the fact that this particular filter was tuned using synchronous tuning. The use of non-synchronous 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 in [15], to achieve an absolute constant bandwidth over a wide tuning range [1].

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 board and the via holes needed to connect the tuning elements to the filter housing (ground) [1].

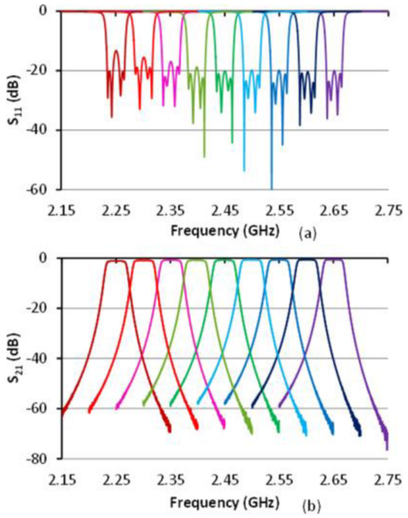

Fig. 4 The measured results of a 4-pole cavity combline tunable filter tuned, the filter housing is made of copper [15].

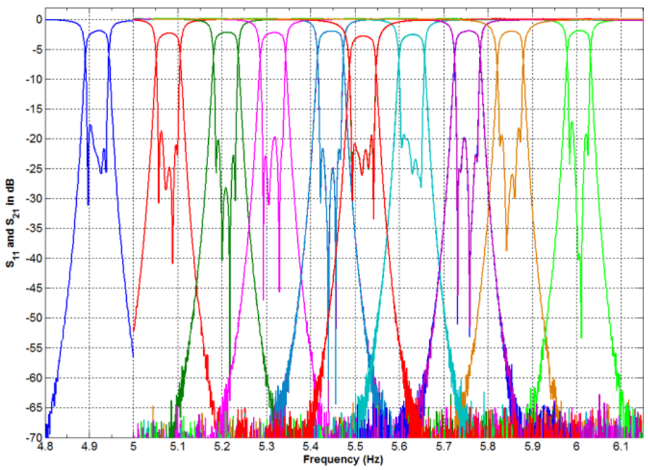

Fig. 5 The measured results of 5-pole 5GHz WiFi cavity combline tunable filter, the filter housing is made of aluminum [15].

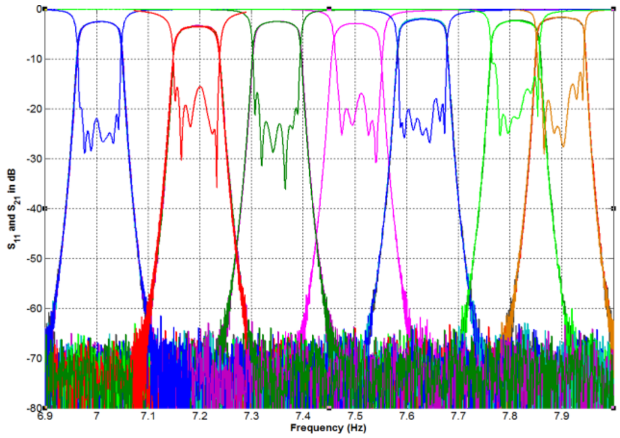

Fig. 6 The measured results of a X-band 7-pole cavity combline tunable filter, the filter housing is made of aluminum [15].

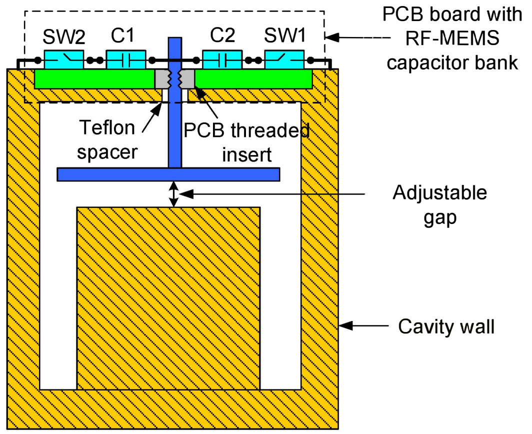

Fig. 7 A tunable combline resonator tuned by RF-MEMS switched capacitor bank [13]

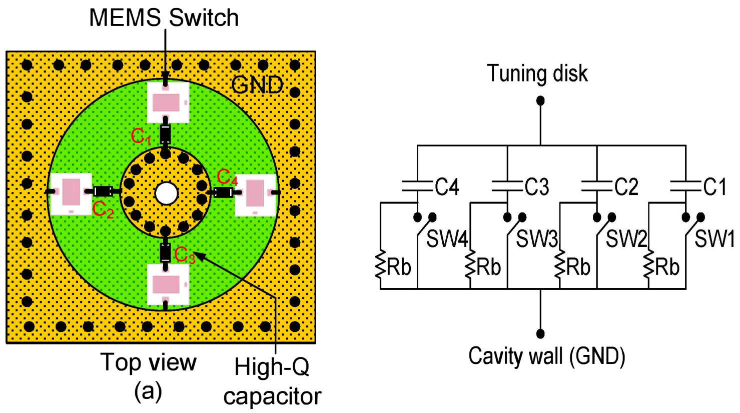

Fig. 8 Details of the tuning circuit and its equivalent circuit [13]

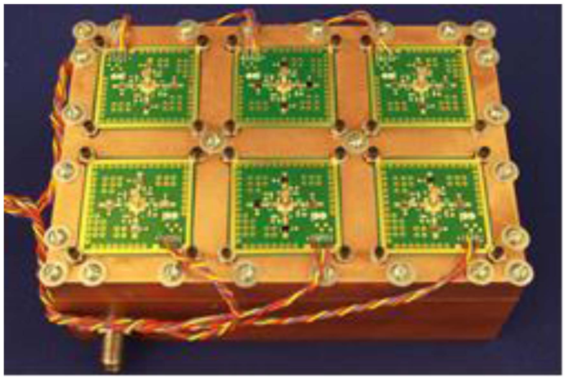

Fig. 9 A picture of the MEMS-based tunable combline filter [13].

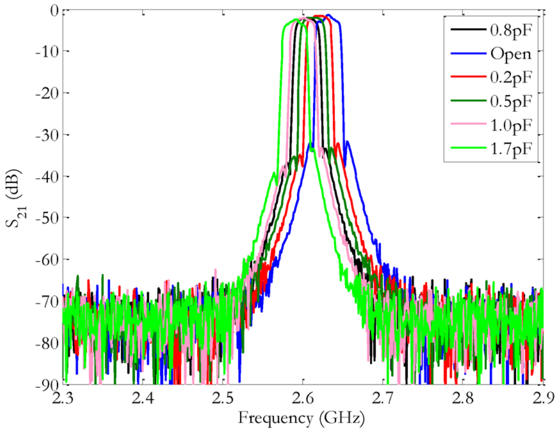

Fig. 10 Measured results of the combline filter shown in Fig. 14 [13].

VII. Conclusion

Tunable coaxial, waveguide and dielectric resonator filters can potentially address wireless base station applications that require very high-Q values (3000 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 high-Q filters while being able to create enough perturbation to the EM field inside the 3D resonators in order to achieve tunability over a wide tuning range. Certainly, more research efforts are needed to explore the potential for realizing three-dimensional high-Q tunable filters that can truly replace the existing filters in wireless base station and satellite applications [1].

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