Tunable RF and Microwave Filters

(Invited Paper)

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***Abstract*—**

Tunable filters at RF and microwave frequencies can potentially place an important role in the implementation of future reconfigurable wireless systems.This paper provides a general review of several competing technologies in realizing high performance tunable filters with a slight focus on recent progress in the design and implementation of evanescent-mode cavity based filters with both frequency and bandwidth tuning capabilities.

***Index Terms*—microwave filter, tunable filter**

I. Introduction

The last decade has seen tremendous progress in the development of wireless communication technologies. Ubiquitous connectivity and increased functionality are the main driving forces of ever increasing complexity in modern wireless communication systems. For example, with the advent of 4G networks, cell phones are expected to be compatible with several standards (2G to 4G) covering 40+ frequency bands from 700 MHz to $2,700$ MHz [1]. Such complexity coupled with stringent low-cost and low-power requirements impose unique challenges to the RF system designers.

The well-known Software Defined Radio (SDR) [2] and Cognitive Radio (CR) [3] concepts have been proposed to tackle these challenges. While a number of different SDR and CR architectures have been proposed, in general, SDR or CR systems should be able to sense the frequency spectrum and alter their operating parameters depending on the available bands. This typically requires the ability to reconfigure the radio's hardware and particularly the RF front-end, over a wide frequency range.

The implementation of a fully reconfigurable RF front-end relies heavily on the availability of reconfigurable RF components. Whereas active circuits are relatively easier to tune, making high-quality low-power widely tunable passive components in mobile form factors has proven to be particularly challenging. For example, RF filters are common but critical components in the RF front-end. Traditional technologies for making tunable RF filters, such as ferrimagnetic resonators, micromechanical resonators, cavity resonators, varactor loaded planar resonators, offer excellent performance in few important areas, but fail to satisfy all necessary requirements and desires.

This paper provides a general review of recent progress in the design and implementation of tunable RF and microwave filters.

II. Design Considerations

Insertion loss (IL) of the filter is a critical concern in many applications. For example, the band pre-selection filter in the receiver channel must have very low IL to ensure the sensitivity of the system. In the tranmitter channel, the IL of the output filter directly impacts the efficiency of the system.

The IL of a filter is directly related to the Q_u of its resonators. To demonstrate this, the ILs of 2-pole 0.5% and 2% bandwidth Chebyshev filters with 0.1 dB ripple at 4.5 GHz are shown in Fig. 1. It is evident that high Q_u resonators are needed to make filters with low IL. This is particularly true for very narrow bandwidth filters. In order to get $IL < 2$ dB for a 2-pole 0.5% Chebyshev filter at 4.5 GHz, the resonator must have a $Q_u > 800$.

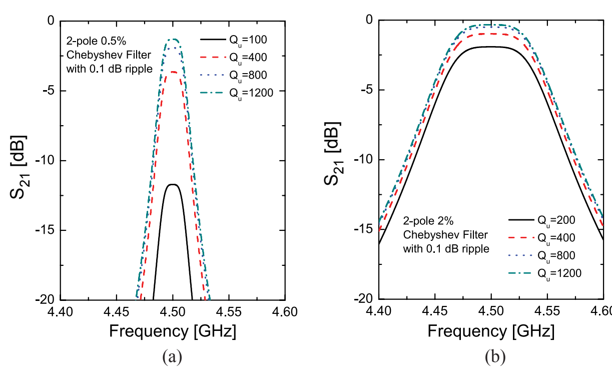

Fig. 1. Simulated S_{21} of two Chebyshev bandpass filters with different Q_u. It is evident that high-Q_u resonators are necessary achieve low IL.

Tuning range is another critical metric for tunable filters. Tuning range is strongly dependent on the specific technology of the tuning element. As it will shown later in this section, it is very challenging to make a widely tunable ($> 2:1$) filter with simultaneous high Q_u.

Apart from Q_u and tuning range, there are other system requirements that a tunable filter may need to meet. These requirements can include,

1) Power handling
2) Power consumption
3) Tuning speed
4) Linearity
5) Size, weight, volume
6) Cost, compatibility with low-cost electronics
7) Analog or digital tuning

8) Immunity to vibration, shock, temperature, noise on tuning voltage

III. A Review of Frequency Tuning Technologies

A. Ferrimagnetic Tunable Filters

Today, the highest performance (in terms of tunability and loss) tunable filters are based on ferrimagnetic resonators, such as a yttrium-iron-garnite (YIG) crystal. YIG tunable filters find wide applications in measurement instruments and base stations for cellular networks. The resonant frequency of a YIG resonator can be tuned higher by increasing the external magnetic field. YIG tunable filters offer multi-octave tuning range ($2-18$ GHz) and very high Q_u ($2000-5000$ at $2-10$ GHz). One disadvantage of the YIG filters is their large power consumption ($0.75-3$ W) used to generate the external magnetic field and to maintain a constant temperature. It is therefore very difficult to integrate YIG filters in portable wireless devices where battery life is a critical concern. In addition, there is a minimum tuned frequency when the external magnetic field is equal to the demagnetizing field strength. This minimum frequency is usually between 1 GHz and 2 GHz [4].

B. Planar Tunable Filters

RF/Microwave filters based on planar resonators, such as microstrip, stripline and coplanar waveguide (CPW) resonators, are widely used in wireless communication systems because of their compact size and high manufacturing cost. Tunable filters can be made by loading the planar resonators with tuning elements to change their effective electrical lengths. Fig. 2 shows several planar tunable filter architectures. The "diode" symbol represents a general tuning element, which can be implemented with a variety of technologies, such as semiconductor varactors, ferroelectric varactors, RF MEMS switches/varactors, and etc.

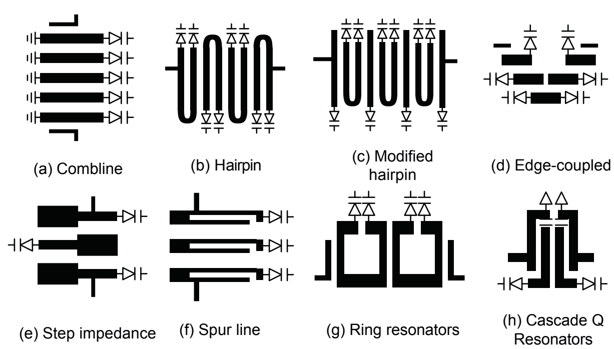

Fig. 2. Planar tunable filter architectures (adapted from [5]): (a) Combline; (b) Hairpin; (c) Modified Hairpin; (d) Edge-coupled; (e) Step impedance; (f) Spur line; (g) Ring resonators; (h) Cascade Q resonators. The "diode" symbol represents a general tuning element, which can be implemented with a variety of techniques.

Semiconductor varactors, such as PIN diodes and GaAs Schottky diodes, are popular tuning elements because of their availability, low price and high tuning range. The very low response time(nanosecond range) of semiconductor varactors is another big advantage where high tuning speed is required. Many planar tunable filters have been demonstrated with semiconductor varactors [6, 7]. The major disadvantages of semiconductor varactors are low Q_u (< 150), low linearity and low power handling. Due high loss at higher frequencies, semiconductor varactors are seldom used above 10 GHz.

RF MEMS is another promising candidate for making tuning elements. Due to their high Q and simple biasing requirement, RF MEMS varactors make it possible to design more complex tunable filters with lower loss. Many RF MEMS enabled tunable filters have been demonstrated in the past decade [8–10]. Excellent tuning performances have been achieved over wide frequency ranges. However, the Q_u of planar RF MEMS tunable filters are generally less than 200. The major limitation is the low Q_u of the planar resonators.

Ferroelectric materials, such as Barium Strontium Titanate (BST), can also be used to make varactor at RF/microwave frequencies [11–14]. The permmitvity of the ferroelectric materials can be tuned with an external applied electric field. Therefore, voltage tunable capacitors can be readily made by sandwiching a thin film of ferroelectric material between two metalic electrodes. Material loss is a particular problem for ferroelectric varactors. Although a lot of effort has been spent on perfecting the deposition and fabrication processes, this type of varactor still suffers from a relatively low Q ($50-100$ at $1-10$ GHz). Temperature sensitivity and non-linearities are also known issues for ferroelectric varactors.

In general, planar tunable filters are well suited for compact RF/microwave systems that require broad frequency coverage with Q_u of generally less than 250. The IL of these tunable filters are primarily limited by either the low Q_u of the varactors or the low Q_u of the resonators themselves. In order to make even lower loss tunable filters, intrinsically high-Q resonators need to be used for making tunable filters.

C. 3-D Tunable Filters

In order to further increase Q_u, 3-D cavity based tunable filter have been investigated in the last few years. Dong et al. presented a tunable on-chip cavity filter and a tunable dielectric resonator filter using electro-thermal tuners [15, 16]. These filters have limited tuning range ($< 5\%$) and rather large power consumption (300 mW) due to the use of electrothermal actuators.

Evanescent-mode (EVA) waveguide filters have recently attracted a lot of interest for realizing low-loss, highly-selective tunable filters for reconfigurable RF front-ends [17, 18]. Fig 3 shows the operation concept of an EVA tunable waveguide filter and its equivalent circuit. It is well known that waveguides below cut off can be used to create microwave filters by introducing obstacles inside the waveguide [19, 20]. The simplest and most practical type of waveguide obstacle is a conductive re-entrant post, which represents an effective shunt capacitance. By changing this capacitance, i.e. the gap between the post and waveguide wall (Fig. 3), the center frequency of the filter can be changed. Compared to half-wave cavity resonators, evanescent mode resonators offer several advantages [17, 18, 21], including high Q_u, wide tuning range, substantially reduced volume and weight, large spurious free region, and possibility of monolithic integration.

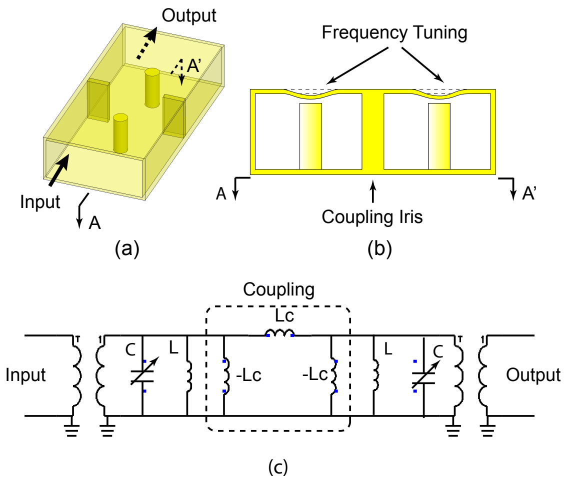

Fig. 3. Tunable evanescent-mode cavity filter. (a) Capacitive post loaded evanescent-mode waveguide filter; (b) Frequency tuning; (c) Equivalent circuit.

This type of MEMS tunable resonators have demonstrated excellent RF performance. Liu et al. [22] reported a continuous tuning range of $1.9-5.0$ GHz $(2.6:1)$ with Q_u of $300-650$. The required actuation voltage is less than 140 V. In [23], such resonators have been used to make a very narrowband 2-pole tunable filter. Fig. 4 shows the measured filter responses across the tuning range. Insertion loss of $3.55-2.38$ dB (without connector loss) has been achieved for a 0.7% fractional bandwidth over $3.04-4.71$ GHz. The extracted Q_u is $470-645$.

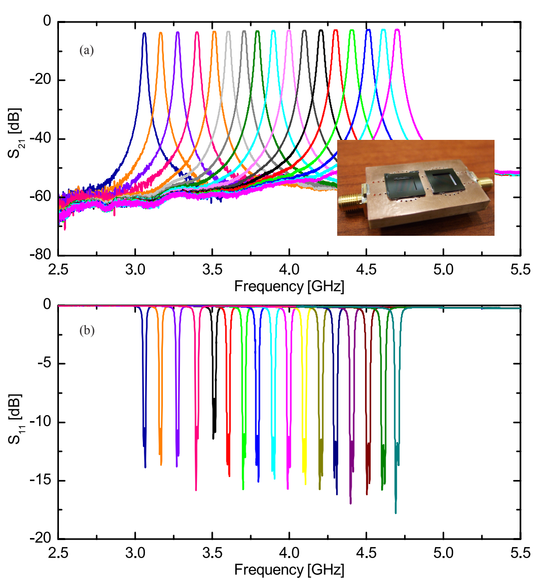

Fig. 4. Measured S-parameters of the 2-pole evanescent-mode tunable filter (a) S_{21} and (b) S_{11} [23]. The inset shows a picture of the measured device.

A distinctive advantage of the MEMS actuators is their stable and hysteresis-free mechanical characteristics. Although piezo-electric actuated tunable filter can achieve a higher tuning range and Q_u [24], the inherent hysteresis and drift of the piezo-electric actuators become a difficult engineering problem when precise automatic control of the filter response is required. Electrostatic MEMS actuators, on the other hand, are known to be hysteresis free. Fig. 5 provides an experimental validation of the hysteresis-free nature of the MEMS actuators.

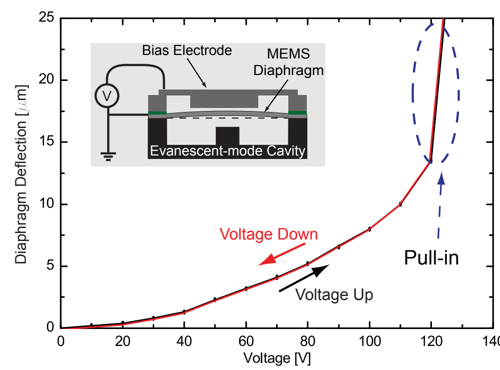

Fig. 5. Measured deflection of the MEMS actuator with bias voltage tuning up and down [23]. No hysteresis is observed.

While the MEMS-enabled evanescent-mode tunable filter exhibits excellent RF performance, this structure is complex in fabrication compared to planar structures because it requires multiple layers and requires precise assembly to align the actuator with the cavity post. A further development in the technology focuses on improving the assembly of filter structure and investigated the use of lumped tuning elements for both frequency and bandwidth tuning (Fig. 6) [25, 26].

Fig. 7 shows measured S21 and S11 as both BW and center frequency are tuned. Though the filter can continuously tune center frequency and BW, only the maximum and minimum BWs at selected frequencies are shown. Octave frequency tuning (0.55–1.13 GHz) is demonstrated with BW ranging between 20100 MHz (1.77–8.85% FBW) around 1.13 GHz,20100 MHz (2.5–12.5% FBW) around 0.80 GHz, and 34–40 MHz (6.27.3% FBW) around 0.55 GHz. The BW is limited by external coupling at lower frequencies. A return loss better than 10 dB is maintained at all measured BWs. In summary, this filters achieves a constant BW of 20100 MHz from 0.8 GHz to 1.13 GHz and 34–40 MHz over the octave tuning range of 0.55–1.13 GHz.

IV. Conclusion

A general review of several competing technologies in realizing high performance tunable filters is presented in this paper with a slight focus on recent progress in the design and implementation of evanescent-mode cavity based filters with both frequency and bandwidth tuning capabilities. With the rapid development in intelligent and adaptive wireless communication technologies, tunable filters can potentially

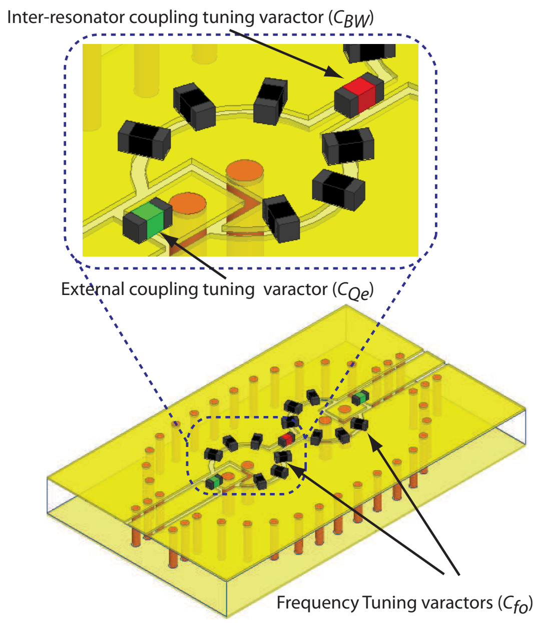

Fig. 6. Proposed substrate-integrated 3-D coaxial cavity two-pole filter and close up of top surface showing the various lumped components [26].

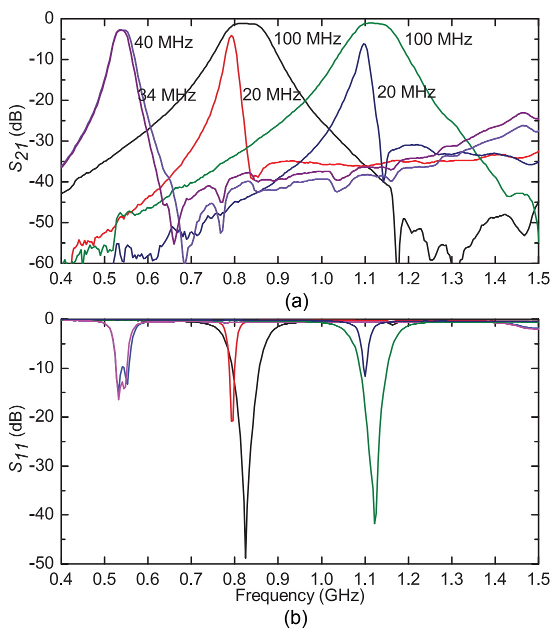

Fig. 7. Measured (a) S21 and (b) S11 showing the maximum and minimum bandwidths at selected frequencies. The filter can continuously tune center frequency and BW [26].

place a more important role, if future technology development can improve the tuning range, insertion loss, reliability and resistance to temperature variation, vibration, and shock.

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