

## **DEVELOPING ONE-DIMENSIONAL ELECTRONICALLY TUNABLE MICROWAVE AND MILLIMETER-WAVE COMPONENTS AND DEVICES TOWARDS TWO-DIMENSIONAL ELECTROMAGNETICALLY RECONFIGURABLE PLATFORM**

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**Abstract**—An overview of state-of-the-art frequency tunable technologies in the realization of tunable radio frequency (RF) and microwave tunable circuits is presented with focus on filter designs. Those enabling techniques and materials include semiconductors, micro-electro-mechanical systems (MEMS), ferroelectric and ferromagnetic materials. Various performance indicators of one-dimensional tunable filters are addressed in terms of tunability, losses, signal integrity and other aspects. Fundamental limitations of the classical one-dimensional tuning method are discussed, which makes use of only one type of tunable elements such as either electric or magnetic tuning/controlling of circuit parameters. Requirements of simultaneous electric and magnetic two-dimensional tuning techniques are highlighted for achieving an unprecedented and advantageous wider modal tuning. It is believed that this emerging scheme will lead its way in the realization of future highly efficient and tunable RF and microwave components and devices.

### **1. INTRODUCTION**

Since the past decades, there has been a significant development of electronically reconfigurable or tunable devices and circuits in the field of radio frequency (RF) and microwave wireless systems, which is even now moving towards the millimeter-wave domain. This has been fuelled by the emerging needs for multi-band and multi-function specifications within the same compact-structured design platform.

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*Received 30 December 2013, Accepted 7 February 2014, Scheduled 10 February 2014*

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Invited paper dedicated to the memory of Robert E. Collin.

Indeed, current communication devices are able to offer multiple functionalities that are generally operating in different frequency bands. In addition to the popular 3G and 4G communication systems, for example, a portable handheld device also supports WLAN and Bluetooth applications. Therefore, it is obvious that wireless systems are becoming more complex and smart due to the inclusion or convergence of multiple standards and applications into a single device. In order to meet the stringent design requirements of those wireless systems, the related RF front ends must be adaptive and flexible in nature, which could become standard design requirements in future generation wireless systems. The quality of RF front-end is directly responsible for the performances of an entire system as it is directly related to critical electrical specifications of the system such as noise, dynamic range and channelization. This becomes much more involved in multi-band and multi-function systems as the performances should be consistent and uniform for all system states. An adaptive RF front-end has been recognized as a viable and effective solution in incorporating multi-band and/or multi-channel circuits with multi-functions to satisfy several wireless system standards. One desirable way of realizing such multi-band or multi-channel systems is through deploying fast and tunable RF and microwave components and circuits, which should be enabled electronically. For example, a frequency agile filter with embedded tuning elements can carry out a switching function between several individual filters in order to have more than one frequency response. Compared with a bulky bank of filters, a single tunable filter offers higher flexibility, better functionality, lighter weight and denser integration. The same hardware circuitry can be used to cope with the requirement of multiple purposes, which also reduces the total cost and size of related components and systems. In addition, such a circuit tuning allows an easier controlling of systems through baseband signal processing, which can add attractive “features” of smartness and multi-format.

There are basically two different methods of electronically tuning components and circuits. In the first method, tuning elements like PIN diodes and MEMS switches are used to obtain discrete tuning states. The use of switches does not support a continuous tuning of device with fine details. Therefore, it would not cover the entire frequency tuning range when switches are used in a tunable filter. In the second method, a continuous tuning of device is achieved by using tunable elements such as varactor diodes, MEMS capacitors, ferroelectric and ferromagnetic materials. In this case, fine frequency details can be described through electronic tuning. Of course, the switchable tuning and continuous tuning may be combined to offer a broadband tuning

capability. Those classical tuning techniques should be said to be only one-dimensional, which means that only either electric or magnetic parameters are tuned. In the design of a coupled cavity filter, for example, such one-dimensional tuning is made through the changing of electric or magnetic fields in cavities and/or in connection with inter-cavity coupling sections. In fact, this creates a perturbation scenario on resonant modes rather than a true modal tuning.

In order to realize the RF and microwave tunable devices, a special tuning element has to be integrated into the device circuitry. The most widely and commercially used tuning elements include but not limited to: semiconductors (varactor diodes, PIN diodes, and transistor), micro-electro-mechanical systems (MEMS), ferroelectrics materials, and ferromagnetic materials. Each of these tuning elements has their own advantages and disadvantages. Their use largely depends upon the required type of tunability (discrete or continuous), operating power, design frequency, and also manufacturing complexity and total cost. The RF and microwave systems are made up of number of components and devices including: oscillator, antenna, phase-shifter, amplifier etc.. Each of these devices can be made tunable by incorporating any one of the above mentioned tuning elements. To cover all of the microwave tunable devices is beyond the scope of this paper. Therefore, a general overview of each tuning element in the realization of a tunable microwave filter is only presented.

In this paper, a brief overview of state-of-art tunable filters is discussed with highlights on the one-dimensional techniques. In Section 2, selected tunable devices using semiconductor based tuning elements such as PIN diode, varactor diode and transistor are described. In Section 3, the use of MEMS techniques as tuning elements is discussed. Section 4 provides an overview of tunable devices based on ferroelectric materials. In Section 5, tunable components and circuits based on ferromagnetic materials are summarized. Finally in Section 6, an emerging tuning concept now known as two-dimensional tuning of microwave components and circuits is presented where both electric and magnetic tuning schemes are simultaneously used in a device to achieve the highest possible tuning range in connection with the best possible tuning performance. In Section 7, a conclusion is presented where an overall discussion on all the tuning techniques is made.

## **2. SEMICONDUCTOR TUNING ELEMENTS**

In this section, a detailed discussion on RF and microwave tunable techniques that make use of semiconductor devices as building tuning

elements is presented. Semiconductor is known to be the most popular and widely used technology in the realization of fast tunable integrated RF and microwave components and circuits. They are always associated with low cost, light weight and small footprint, and most importantly they are known to offer a very wide tuning range with adaptive options, depending on diodes and transistor design platforms. However, they can only offer a low  $Q$  factor at microwave frequencies [1]. For example, the  $Q$  factor of a varactor diode is proportional to frequency and junction capacitance at low frequencies (1 MHz) whereas it is inversely proportional at higher frequency ( $> 100$  MHz) values [2]. Moreover, parasitic series resistance of the diode caused by packaging also increases at higher frequency. Thus, the use of varactor techniques is generally limited to frequencies below 10 GHz as they suffer from higher insertion loss. However, an attempt has been made to compensate the loss and increase the  $Q$  factor by incorporating FETs as a negative resistance device [3]. Of course, any active compensation can be made possible at the expense of additional power consumption and potential nonlinear effects. There are basically three reported types of semiconductor devices that are integrated inside a microwave circuit as tuning elements, which include varactor diode, PIN diode, and field effect transistor (FET). Naturally, any active diodes and transistors can be used as tuning elements, depending on their technical merits. The tuning elements are used in the realization of tunable devices that are made either in discrete mode or in continuous mode.

### 2.1. Varactor Diodes

Varactor diode is also known as a variable reactor, which means a device whose reactance can be made variable by the application of a DC bias voltage. The reactance in the case of a varactor diode is a simple depletion layer capacitance, which is formed at the junction of  $p$ -type and  $n$ -type semiconductor materials. Depending upon the polarity and the strength of the applied bias voltage, the depletion layer width is changed, which in turn also changes the junction capacitance value. Since the capacitance value of the varactor diode can be changed even by a slight variation of applied bias voltage, it finds application as a continuously tunable device. Varactor diodes are very useful in realizing a variety of devices including tunable filter, tunable phase shifter, voltage-controlled oscillator (VCO), parametric amplifier, and mixer. In this paper, a brief overview of tunable filters based on varactor diodes is discussed and presented.

There is a growing interest in the design and realization of RF and microwave systems that have multi-channel and multi-band

functionalities. Since filter is one of the most critical parts of the system design, it is highly beneficial to realize such a filter that is fully adaptive to any changes in connection with the system behaviour. Tunable filter can reduce the complexity of a system design by avoiding the need of filter banks, which consist of multiple filters with distinct filter responses for each frequency band. The use of a tunable filter allows the coverage of the whole frequency bandwidth. Early work of tunable filter designs involved the tuning of center frequency using various kinds of tuning devices and materials. Presently, the focus of tunable filter design has not only been on changing the center frequency but also on making it fully reconfigurable in terms of bandwidth and selectivity. Varactor diode has been one of the most promising technologies that have been widely used in the realization of a wide variety of electronically tunable filters. In the early work of varactor tuned filter developments, the center frequency was tuned by loading the varactor diodes at the ends of resonating stubs [4]. It was noticed that, the bandstop characteristic of the filter was largely dependent upon the coupling gap between the feeding transmission line and the parallel stubs. Since the coupling gaps of the parallel stubs are highly frequency dependent, it was suggested in [4], to tune the capacitance of the gaps in accordance with the tuning capacitances in order to preserve the bandstop characteristics. In [5], a varactor tuned ring resonator filter using microstrip technology was presented. The center frequency of the filter was configured by changing both filter's coupling and tuning capacitances. In [6] and [7], a continuously frequency and bandwidth tunable bandpass filter using compact hairpin resonators and a combline structure was described. In [8], a fully adaptable bandstop filter, which is able to reconfigure its center frequency, bandwidth, and selectivity, was demonstrated. The bandwidth tuning is achieved by varactor diodes that are used in coupling resonators to transmission line while the center frequency is controlled by varactor diodes connected at the end of transmission line resonators.

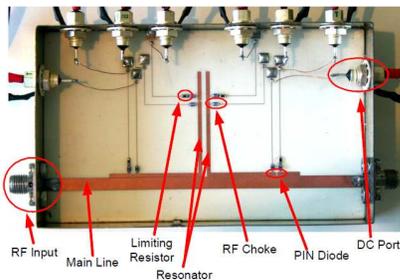
Since the varactor diodes are made up of semiconductor materials, they suffer from non-linearity when injected with high power signals. Despite non-linear behaviours of semiconductor materials, it has been demonstrated that the varactor diodes can also be used for realizing high power filters [9] at UHF band. Recently, a varactor tuned bandpass filter with improved linearity has been presented in [10]. The filter topology consists of an open-ended transmission line with back-to-back varactor diodes loaded at one end. The back-to-back varactor diodes enhance the linearity of filter while the mixed electric and magnetic coupling scheme keeps the absolute bandwidth at a constant value when the frequency of the filter is tuned. Thus, varactor diode

presents itself a very promising low cost, highly tunable, and adaptive semiconductor tuning element that can be used in realizing efficient tunable filters at relatively low tuning voltage.

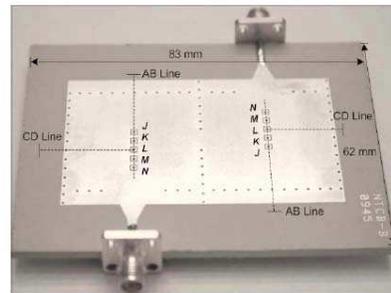
## 2.2. PIN Diodes

PIN diodes are semiconductor-based tuning devices, which are popularly used to produce discrete states reconfigurable filters. In this section, a brief review of tunable filters based on PIN diodes is presented. In [11], a PIN diode based reconfigurable filter for wireless applications is demonstrated. The designed filter falls into a category of admittance inverter coupled resonator filter, with two discrete bandwidths at 5.6 GHz. In [12], a bandpass filter which is switchable between two central frequency states is presented. The designed filter uses PIN diodes for switching, such that in each frequency states a constant bandwidth is maintained. In Figure 1, the fabricated prototype of the switchable bandpass filter is illustrated. By changing the polarity of the bias voltage, the filter is switched between 1.5 GHz and 2 GHz center frequencies, respectively [12].

In [13] a miniaturized reconfigurable and switchable band pass filter is presented. By shorting the open stubs of the filter using PIN diodes, the UWB filter is reconfigured from bandpass to bandstop response. Moreover, with the addition of half-wavelength stub to the existing reconfigurable filter, it is switched from UWB to 2.4 GHz narrowband filter response. A new type switchable bandpass filter based on SIW technology and using PIN diodes is presented in [14]. The two-pole bandpass filter is switched between six states ranging from 1.55 GHz to 2.0 GHz. The SIW cavity resonators are equipped



**Figure 1.** Photograph of the fabricated switchable bandpass filter [12].



**Figure 2.** Fabricated SIW filter with via posts islands for the connection of PIN diodes [14].

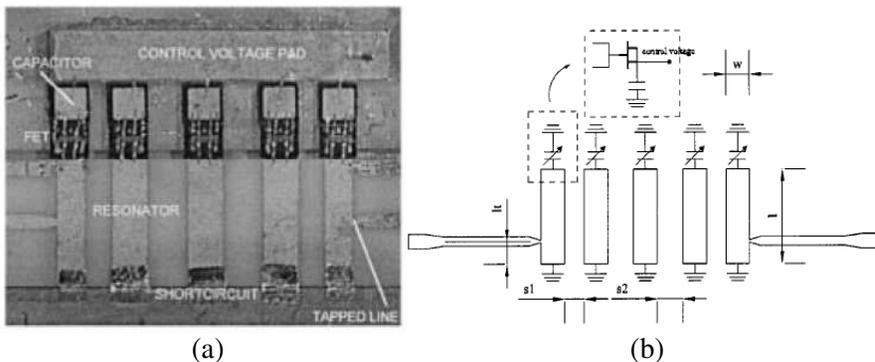
with multiple via posts, which are either connected or disconnected from the top metal layers using PIN diodes, thus producing different switching states. In Figure 2, the fabricated prototype of the SIW based filter is illustrated.

Another SIW-based digitally tunable bandpass filter is demonstrated in [15], where discrete frequency tuning with nearly 8 equal spaced frequency responses from 4–4.4 GHz is obtained. In [16], switchable bandpass filter using stepped impedance resonator is presented. The designed operates between two states, in the first stated the filter produces a band-stop response. By switching the PIN diodes to ON state, the filter response then changes from band-stop to all-pass filter characteristics.

### 2.3. Transistors

In [17], using the concept of three-terminal MESFET varactor tunable active bandpass filter is demonstrated. In the two pole filter configuration, one transistor is used to provide center frequency tuning, while the other is used to provide the negative resistance to the circuit. The negative resistance of the transistor improves the overall  $Q$  factor and improved filter response. In [18], wideband tunable combline filter using gallium arsenide field effect transistor as a tuning element is presented. The filter resonators are loaded with field effect transistors to produce the desired tunability. A systematic approach in designing tunable combline filters and the non-ideal effects in the overall performance of the filter are also discussed.

In [19] a high  $Q$  tunable with a single transistor active inductor



**Figure 3.** Wideband tunable combline filter. (a) Fabricated filter prototype, (b) schematic diagram of filter [18].

(AI) is presented. The first order bandpass filter has a central frequency of 2400 GHz, the total frequency tuning range is 100 MHz.

### 3. MEMS TECHNIQUES

Although it has been studied since early 60s, MEMS has become a re-emerging technology that is very useful in realizing variable capacitors, switches, and reconfigurable RF and microwave devices. Compared with semiconductors, ferrites and ferromagnetic materials based tunable devices; MEMS techniques offer much higher  $Q$  factor with very low power consumption. Moreover, as opposed to the solid state devices, they offer a linear signal transmission with low signal distortion. Hence, MEMS schemes have attracted much attention, which present a very promising scheme in realizing a wide range of RF and microwave tunable components and devices. In the literature, many types of tunable devices based on MEMS technology can be found, including phase shifters [20, 21], antennas [22] and filters [23–39]. In this paper, a short overview regarding the current status of MEMS based tunable filters is presented. Tunable filters, realized by using MEMS technology generally make use of MEMS switch or MEMS varactors as tuning elements. This section show several filter topologies to produce discrete and continuous tuning of the filter parameters.

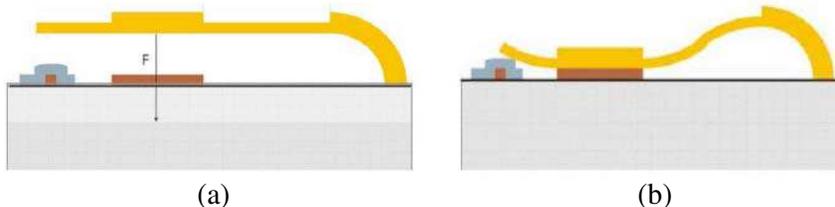
#### 3.1. Tunable Filters Using MEMS Switch

MEMS switches are generally used for re-routing RF signals and also they are widely used in realizing tunable filters. Since MEMS-based switches operate in only two states: on and off, the tunability of filters designed using MEMS switches are discrete in nature. From the structure point of view, such switches are either cantilever types or bridge types. An example of cantilever type MEMS switch is illustrated in Figure 4.

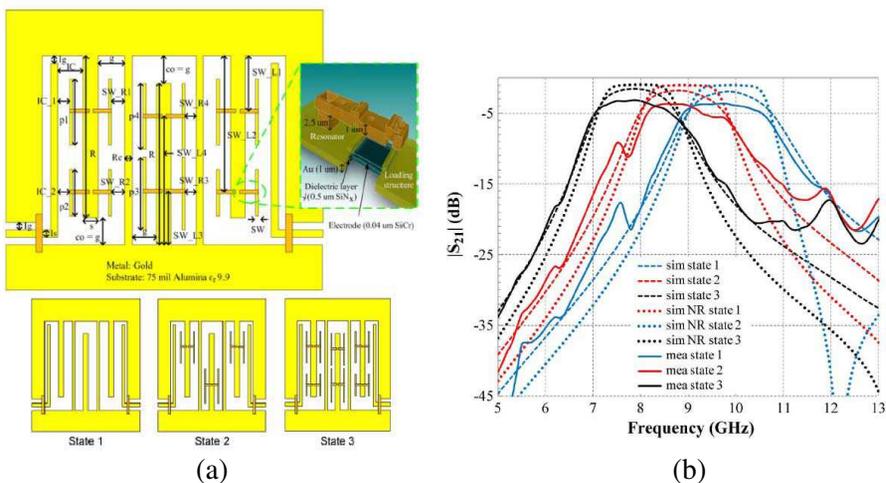
The electrical performance of a cantilever type switch largely depends upon the quality of contact in the ON state as illustrated in Figure 4(b). There are basically two types of electrical contacts used in MEMS switches: direct contact and contact through a capacitive membrane also known as Metal-Insulator-Metal (MIM) contact. Compared to the MIM contact, the direct contact switches have lower insertion loss and better isolation. However, due to direct contacts between metals, the direct contact switch suffers from metal corrosion and has a shorter life time compared to MIM switches [24]. Two well-known problematic issues in the development of MEMS devices are related to high actuation voltage and relatively low speed

because of a mechanical process. In addition, MEMS techniques may not be well suitable for high-power applications even though significant research efforts have been invested to remedy this situation.

In this section, tunable filters using direct and MIM contact-based MEMS switches are presented. The cantilever type MEMS switch illustrated in Figure 4 is used to realize a tunable hairpin line filter in [23]. The filter tunability is achieved by loading identical MEMS switches at the end of hairpin resonators. When the switches are changed between the on and off states, the equivalent electrical length of resonators are also changed, thereby making the filter tunable. In [25], another reconfigurable hairpin bandpass filter using

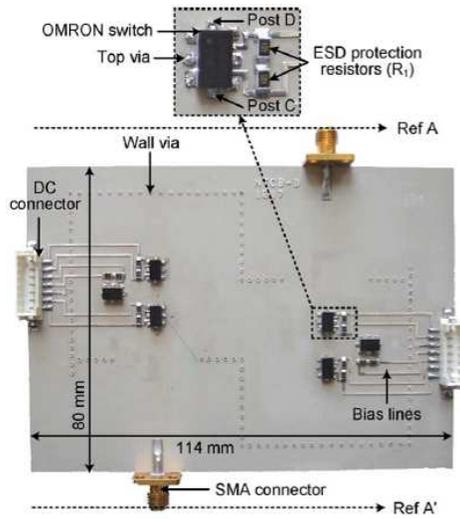


**Figure 4.** Schematic of electro-statically actuated cantilever type RF MEMS switch. (a) OFF state, (b) ON State [23].

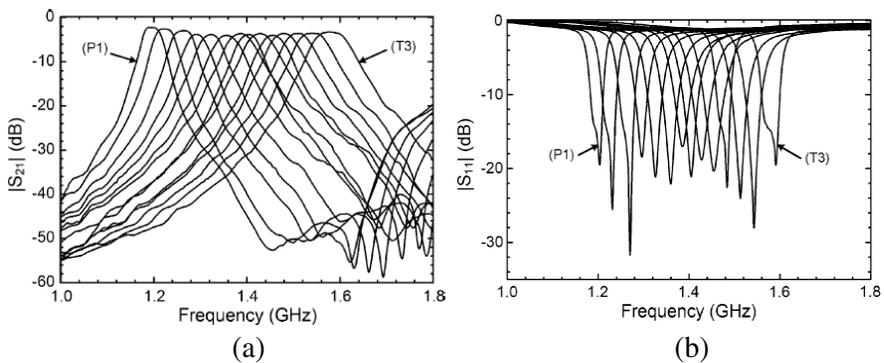


**Figure 5.** Schematic of electro-statically actuated cantilever type RF MEMS switch. (a) Layout of the filter, (b) simulation and measurement results illustrating three states of tuning [26].

MEMS switches was presented. The MEMS switches in this filter are used to change inter-resonator coupling, which in turn changes the bandwidth of filter. Therefore, the filter presented in [25] is a bandwidth tunable filter. Another example of tunable filter using MEMS switch was described in [26], where the filter is switched between three states. It is a good example in which MEMS switches are used in controlling resonant frequency, input/output couplings, and couplings between resonators to achieve a fully-reconfigurable



**Figure 6.** Fabricated tunable SIW-based low-frequency band-pass filter using direct contact MEMS switches [27].



**Figure 7.** Measurement results of tunable band-pass filter [27].

bandpass filter at microwave frequency. The measured filter response shows three different states of filters at 8, 9 and 10 GHz, respectively. In Figure 5(a), the filter layout with tuning elements is presented, and its simulation and measurement results are presented in Figure 5(b). A new type of tunable filter based on substrate integrated waveguide (SIW) technology was presented in [27]. As illustrated in Figure 6, the filter topology consists of two SIW cavities that are coupled to each other via an iris window. Commercially available packaged RF MEMS switches are surface-mounted in each cavity to tune them separately. From the measurement result presented in Figure 7, the two-pole filter implemented using two-layer SIW circuit has a total tuning range of 28% with reflection loss better than 15 dB.

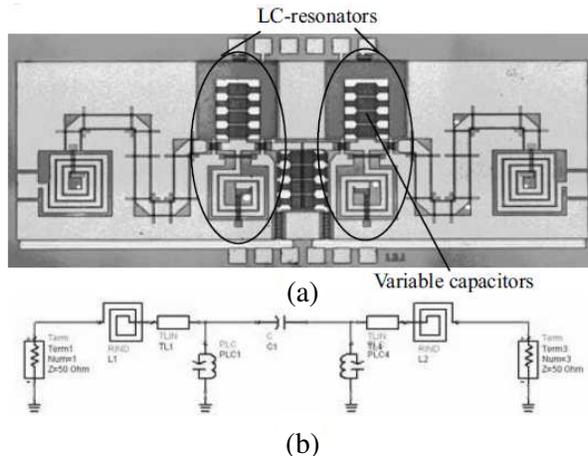
MEMS switches are also used in realizing tunable filters that are of lumped element and periodic structure types. In [28], a commercially available MEMS switch was used to realize tunable high-pass and low-pass filters. The designed filters cover the frequency tuning range over 6–15 GHz. During the synthesis of the filter, a lumped element model was first derived that was later converted into a microstrip line model. Another example of a lumped-element filter presented in [29] also uses commercially available MEMS switches as tuning elements. The designed filter covers a frequency tuning range from 25 to 75 MHz [30]. A coplanar waveguide (CPW)-based fully reconfigurable filter was studied in [31]. The filter topology consists of cascaded CPW-based periodic structures which are loaded with MEMS switches for tunability. By a suitable combination of MEMS switches, 3-unit CPW lines are combined to form a single-cell low pass filter. In this way, the length of the filter is increased by three-times the original length, and subsequently reducing the low-pass cut-off frequency also by three-times. In a similar way, a reconfigurable bandpass filter was also realized in [31], where three bandpass units are cascaded together using MEMS switches to realize a single larger bandpass filter having a filter response at low frequency region.

### 3.2. Tunable Filters Using MEMS Switch Capacitors

In this section, an overview of tunable filters based on MEMS switch capacitors is presented. Similar to the direct contact counterparts, the switch capacitors can also be cantilever or bridge type as illustrated in Figure 4. However, in the MEMS switch capacitors, an electrical connection is established not through an ohmic contact but through a capacitive membrane. Therefore, the switch operates between two different capacitance values: one for the ON state and the other for the OFF state. A central frequency and bandwidth controlled filter using MEMS cantilever type capacitive switches was presented in [32]. The

switches are loaded at the end of coplanar resonators to achieve two center frequency states. A high  $Q$  tunable filter based on microstrip technology for a wireless local area network (WLAN) system was discussed in [33]. The filter is composed of microstrip based high  $Q$  resonators, which are loaded with RF MEMS switch capacitors for tunability. A total tuning range of 5% over 5.15–5.70 GHz was demonstrated. A tunable dielectric resonator bandpass filter with embedded MEMS tuning elements was also shown in [34]. The MEMS tuning element is used herewith to perturb the field surrounding the dielectric resonator. Compared to the MEMS tunable planar filters, the designed dielectric resonator filter offers a very high  $Q$  of 1300. Moreover, the filter requires a relatively low tuning voltage for tuning and the tuning speed is relatively high. By changing the height or the distance of the tuning disc from the dielectric resonator, the field surrounding the dielectric is varied thereby making it frequency tunable. This operation is similar to the MEMS switch capacitors where the position of the cantilever or air bridge determines the value of gap capacitance. The MEMS switch capacitors are also used in realizing the lumped element type tunable filters.

A lumped element type tunable filter using MEMS capacitive switch was demonstrated in [35] for WLAN applications. The filter is designed to select frequency bands at 2.4 and 5.1 GHz. In Figure 8, the fabricated prototype of the lumped element filter and its equivalent circuit are illustrated. In [36], a lumped-element filter with frequency coverage from 600 MHz–1 GHz was demonstrated. To obtain



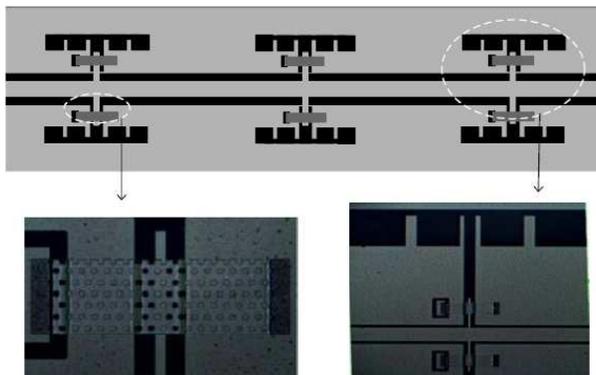
**Figure 8.** Lumped element filter using MEMS switch capacitors for tuning. (a) Fabricated prototype, (b) equivalent circuit [35].

a continuous tuning, 12 electro-statically actuated MEMS capacitors were used in the structure.

### 3.3. Tunable Filters Using MEMS Varactors

MEMS varactors present an advanced form of MEMS capacitive switches. Similar to the MEMS capacitive switches, they are also composed of capacitive membrane between the two metal contacts. Unlike the capacitive switches that operate only between ON or OFF states, MEMS varactor capacitance membrane can be tuned continuously with an applied analog voltage. From the operation point of view, they are very similar to semiconductor biased varactor diodes and are useful in realizing continuously tunable RF/microwave filters. They are more attractive than semiconductor varactor diodes in terms of  $Q$  factor, power consumption and linearity. However, they have lower tuning speed and are more sensitive to environmental conditions for example temperature, moisture and vibration. A lumped element type tunable K-band filter using MEMS bridge varactor was presented and discussed in [37]. The filter consists of J-inverters and shunt-type resonator sections. The variable capacitors are loaded in the shunt type resonators to vary the center frequency of the filter.

In [38], a distributed type bandpass filter was designed using bridge type MEMS varactors. The coplanar transmission line is loaded with MEMS varactors to reconfigure the center frequency of the filter. A coplanar waveguide tunable band-stop filter using RF MEMS variable capacitor was also presented in [39]. The filter is designed to operate from 8.5 to 12.3 GHz with 35% of tunability. This filter is another example of MEMS varactors-loaded distributed type of filter. In Figure 9, the fabricated prototype of the filter is presented.

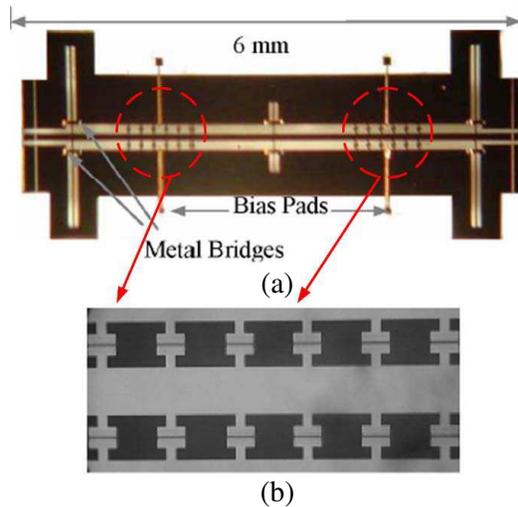


**Figure 9.** Fabricated tunable bandpass filter [39].

#### 4. TUNABLE FILTERS USING FERROELECTRIC MATERIALS

Ferroelectrics are one of the most promising materials in realizing electronically tunable RF and microwave components and circuits for wireless front-end applications. A number of tunable devices including phase shifters, oscillators, and filters have been demonstrated by using ferroelectric materials as key tuning elements. The dielectric constant of ferroelectric materials varies with the applied DC voltage, ranging from a few hundreds to a few thousands. Therefore, a device incorporating ferroelectric material or loaded with ferroelectric material locally generally in the form of thin-films becomes tunable with respect to the effective permittivity change. Compared to MEMS, ferroelectric materials offer a very fast tuning time like semiconductor techniques, but they have lower  $Q$ -factor. Their figure of merit is always limited by the conflict of a better tuning range associated with a poorer line loss. In addition, the quality and properties of ferroelectric thin-films can be strongly dependent on processing techniques. The most commonly used ferroelectric material in microwave regime is Barium-Strontium-Titanate oxide (BST). In this section, a brief review of tunable microwave filters based on BST is presented.

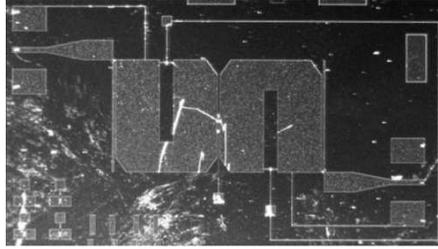
Before beginning with the design of tunable RF and microwave devices using ferroelectric material, it is very important to first characterize in terms of tunability and losses. In [40], a computer-aided-design model is developed, to characterize the BST thin films in the frequency range from 1 to 16 GHz. Coplanar waveguides (CPWs) and inter-digital capacitors (IDCs) are fabricated on BST thin films, to determine the complex dielectric constants, voltage tunability and  $K$ -factor. Once the material is correctly characterized, very accurate designs of the tunable devices can be realized at a given frequency. A theoretical analysis in connection with the use of ferroelectric materials in the realization of a constant bandwidth tunable filter was presented in [41]. The influence of loss factor of a ferroelectric capacitor on the overall performance of the filter was discussed. A tunable combline bandpass filter loaded with BST varactor diodes for tunability was presented in [42]. The BST varactor diodes are loaded at the end of resonators to tune center frequency of the filter from 2.44 GHz to 2.8 GHz. In [43], a slow-wave miniaturized tunable 2-pole filter operating from 11.5 GHz to 14 GHz was demonstrated. The filter consists of a section of coplanar transmission line that is loaded with several ferroelectric BST high  $Q$  capacitors. The total insertion loss of the realized device varies from 5.4 to 3.3 dB in the tuning range of the filter. A DC variation between 0–30 V is applied to achieve



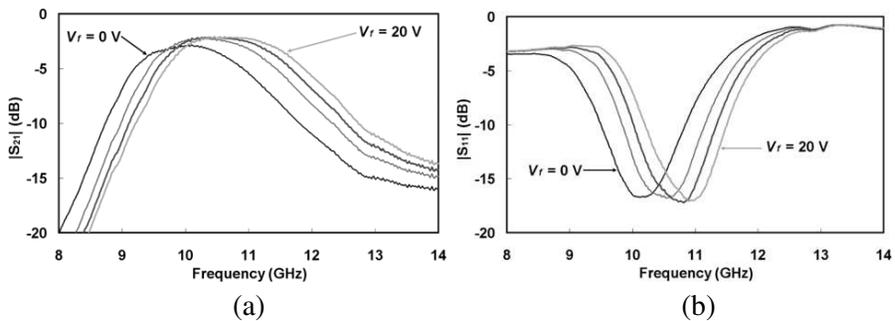
**Figure 10.** Tunable combline bandpass filter. (a) Fabricated prototype, (b) periodic area along CPW line loaded with BST [43].

the tunability of the filter. In Figure 10, the fabricated prototype of a slow wave tunable filter loaded with BST as a tuning element is presented [43]. In order to achieve high tunability using ferroelectric material, in [44] a study is performed to establish a correlation between the lattice parameter of BST films with the dielectric tunability. It was concluded that, a broad tunability can be achieved on low cost microwave devices based on BST films provided the internal elastic stress of the film is low. In [45], a ferroelectric based lumped element tunable filter/switch was presented. The ferroelectric filter was grown on silicon substrate. With the application of an external DC voltage bias, the dielectric constant of  $\text{Ba}_{0.25}\text{Sr}_{0.75}\text{TiO}_3$  is varied, thus making the filter cut-off frequency tunable. When used as a switch, a total isolation of 18 dB at 25 GHz was obtained. A comparative study between tunable microwave filters based on discrete ferroelectric and semiconductors were presented in [46]. The two tunable filters are compared to each other in terms of tuning range, losses and matching. A microstrip-based tunable filter with improved selectivity was studied in [47]. The frequency tuning of the filter is achieved by loading BST-based varactor diodes on microstrip resonators. From the frequency response, it was demonstrated that the designed filter had a better frequency response compared to the conventional combline filter in terms of frequency selectivity.

In [48], a two-pole X-band tunable filter with constant fractional



**Figure 11.** Fabricated prototype of a tunable filter with constant fractional bandwidth and return loss [48].



**Figure 12.** Measured frequency responses indicating (a) constant fractional bandwidths and (b) return loss [48].

bandwidth and return loss was described. To achieve the frequency tunability, a ferroelectric BST material is used. A total tuning range of 7.4% is achieved with a minimum applied voltage of 30 V. In Figure 11, the fabricated prototype of the filter is presented while in Figure 12, measurement results indicating the constant bandwidth and return loss are presented.

In [49], an asymmetric inductively-coupled tunable bandpass filter using ferroelectric BST as tuning elements was presented. Similar to the work in [48], the filter is able to tune the center frequency but at the same time maintain a constant fractional bandwidth and return loss.

## 5. TUNABLE FILTERS USING FERROMAGNETIC MATERIALS

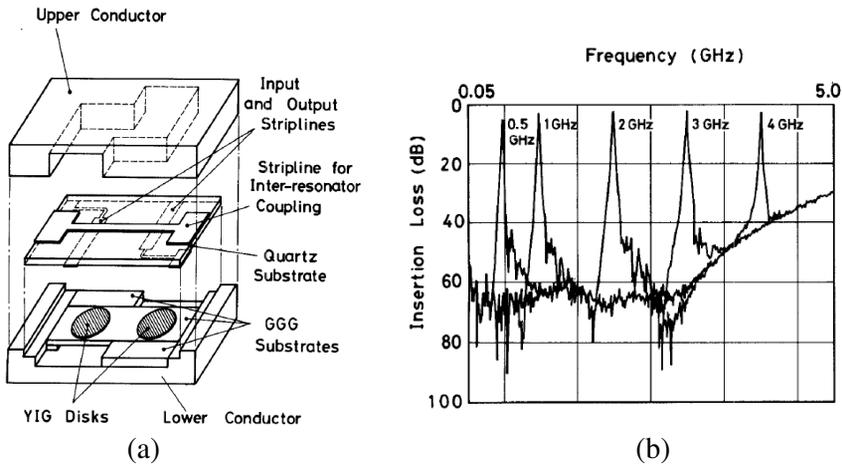
Ferrites or ferromagnetics are materials with an electric anisotropy and they are very useful in realizing non-reciprocal devices including

circulators, isolators and gyrators. Such non-reciprocal devices are generally fixed frequency types, which are designed for particular applications. The frequency of operation for a ferrite material largely depends upon the external DC magnetic bias that is applied on it. Therefore, the non-reciprocal devices operating at a constant frequency constitute a fixed permanent magnet that delivers a constant value of magnetic bias to the ferrite material. When the applied magnetic bias value is changed, however, effective permeability value presented by the ferrite material also changes. Note that permeability and permittivity present the same contributions to the change of transmission phase or propagation constant. Since the frequency of an electromagnetic wave is directly proportional to the square root of permeability, any changes in permeability also changes the frequency. Therefore, ferrite materials are not only useful in realizing fixed frequency non-reciprocal devices but they present also similar features as ferroelectrics in realizing tunable RF, microwave and millimeter wave components and circuits. The evolution of tunable filters based on ferromagnetic materials and their present status are discussed in the following.

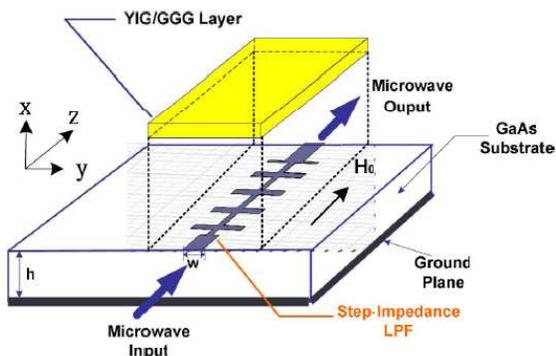
From mid-1950's, ferrite materials have drawn considerable interest in the realization of tunable devices including tunable cavities, filters and frequency modulated signals [50,51]. It can be observed that in both works presented in [50] and [51], rectangular waveguide technology is used to realize the desired tunable devices. The higher power handling capabilities, lower loss, and more convenient of biasing ferrites could have been few of the reasons why rectangular waveguide technology would have been used. Moreover, within the rectangular waveguide, the positions of electric and magnetic fields for a given mode of operation ( $TE_{10}$ , for example) are clearly defined. Since ferrite materials strongly interact with magnetic fields, they can be placed at positions of the highest magnetic field strength without perturbing electric fields. In this section, tunable filters based on rectangular waveguide technology and their subsequent evolutions into planar forms are briefly discussed.

In [51], a magnetically tunable cavity resonator based on rectangular waveguide technology was described. The tunability is achieved by placing a slab of YIG along one sidewall of the rectangular waveguide where the magnetic field component of  $TE_{101}$  mode is dominant. By the application of an external DC magnetic bias, the resonant frequency of the cavity is tuned towards higher frequency. The magnetically tunable cavity resonator presented in [51] makes use of a block YIG slab to achieve the desired tunability. Since the ferrite blocks are usually made of a polycrystalline material therefore they suffer from losses when used in microwave and millimeter wave

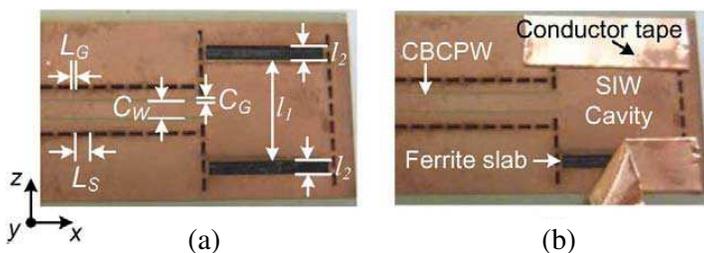
regions. In order to improve the total tuning range and also to reduce the losses, a magnetically-tunable filter consisting of single-crystal YIG was proposed and demonstrated in [52]. It is shown that single-crystal YIG techniques are very useful in realizing low loss and highly tunable microwave filters. In [52], a filter with adjustable 3 dB bandwidth and center frequency tunability was demonstrated. However, the filter has a low tuning speed, and possesses certain fabrication difficulties in precisely placing and biasing the single-crystal YIG sphere. Following the earlier work of filter design using rectangular waveguide technology, interest has slowly been shifted towards incorporating the ferrite materials in planar form, thereby realizing magnetically tunable planar filter circuits. In [53], tunable bandpass filter using YIG film that is grown by Liquid Phase Epitaxy (LPE) was investigated. A total wide tuning range from 0.5 GHz to 4 GHz has been achieved with a low insertion loss. The filter structure and the measurements presented in [53] are also illustrated in Figure 13. A tunable resonator based on ferromagnetic resonance was discussed in [54]. The designed cavity resonator is tunable due to magnetoelectric interactions between the layers of ferrite and ferroelectric, which make up the resonator. In [55] a tunable resonator fabricated on a polycrystalline ferrite substrate was presented. It is demonstrated, the applied stress can influence the magnetization of the ferrite material. Frequency tunability is achieved by an application of stress on the ferrite substrate. Maximum tunability of 300 MHz was experimentally achieved. In [56], tunable bandpass and bandstop filters



**Figure 13.** Structure of a planar tunable filter using ferromagnetic disks. (a) Filter structure, (b) frequency response [51].



**Figure 14.** Schematic of a tunable microwave band-stop filter based on FMR [56].

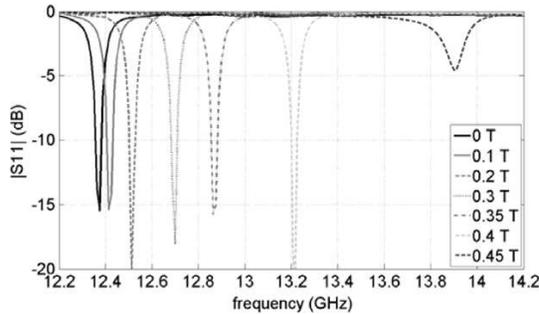


**Figure 15.** Fabricated prototypes of SIW magnetically tunable resonators. (a) Single ferrite slab loaded cavity, (b) two ferrite slabs loaded cavity [57].

based on ferromagnetic resonance (FMR) absorption were reported. The schematic of the studied tunable bandstop filter topology is presented in Figure 14.

As illustrated in Figure 14, the bandstop filter consists of a YIG/GGG layer placed upon the microstrip line which is fabricated on a GaAs substrate. A bandstop characteristic of the filter occurs when the incoming microwave signal is absorbed by the YIG/GGG substrate layer. This takes place when the FMR frequency of the YIG/GGG substrate coincides with the frequency of the incoming signal. A magnetically tunable cavity resonator based on SIW technology was reported in [57]. Planar YIG slabs are loaded along the sidewalls of SIW where the strength of the magnetic field is highest. A total frequency tuning range of 10% with unloaded  $Q$  factor better than 150 is measured at X-band.

In Figure 15, fabricated prototypes of the resonator are presented. The measured  $S$ -parameters of a single ferrite loaded cavity resonator



**Figure 16.** Measured  $S$ -parameters of SIW cavity resonator loaded with a single ferrite slab [57].

are presented in Figure 16. It can be noticed in Figure 16, with the application of external DC magnetic bias, the resonant frequency of the ferrite loaded cavity resonator shift towards the higher frequency value. At 0.45 T of external magnetic bias, the YIG slab is operating near the ferromagnetic resonance region (FMR) therefore the resonator suffers from higher losses.

The magnetically tunable filters presented so far, either use pure YIG as a pure single crystal or in a polycrystalline form. But there are also other ferrite materials that are composed of iron oxides together with various other elements including aluminium, cobalt, manganese and nickel. In [58], a magnetically tunable dielectric bandpass filter based on nickel ferrite was presented. The filter is tunable from 18–36 GHz and has an insertion loss between 2–5 dBm. A magnetically tunable bandpass filter with partially magnetized ferrite was shown in [59]. A total frequency tuning range of 7% is achieved from 5.77 to 6.2 GHz. Due to a partially magnetized ferrite; the requirement of high magnetic bias for the tunability of the filter is reduced. A total of 100 Oe of magnetic bias is adequate to achieve the desired tuning range. One well-pronounced advantage of the magnetically tuned filters is that such structures are known to support high-power operations, which depend on material properties and geometrical shapes.

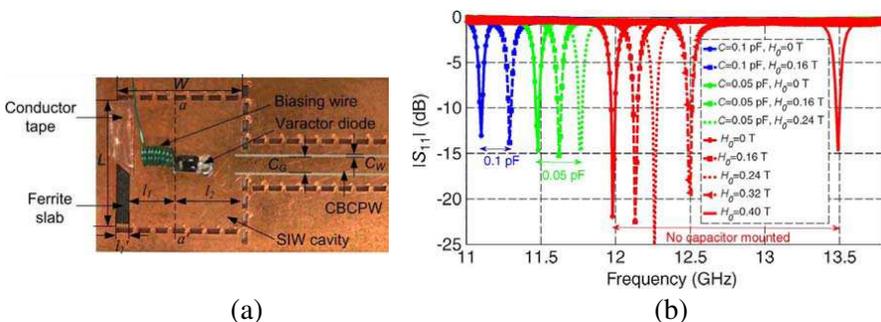
## 6. SIMULTANEOUS ELECTRIC AND MAGNETIC TWO-DIMENSIONAL TUNING

Since the inception of tunable techniques, all tuning mechanisms are based on the above-described one-dimensional parametric tuning such as electric parameters such as permittivity or magnetic parameters such as permeability. Such one-dimensional tuning techniques have

been very successfully but they suffer from a number of problems including limited tuning ranges and augmented tuning complexity.

In [60], an emerging two-dimensional tuning technique was proposed and demonstrated successfully with SIW structures. In this case, tunable SIW cavity resonator and bandpass filter consisting of ferromagnetic material and varactor diodes as combined electric and magnetic tuning elements were presented and studied. Similar to the SIW cavity resonator presented in [57], rectangular ferrite slabs are loaded along the sidewalls of the cavity to produce the magnetic tuning. In order to produce the proposed simultaneous electric and magnetic two-dimensional tuning, a capacitor and a varactor diode are loaded in the central region of the cavity where the electric field strength is highest.

With the simultaneous tuning of electric and magnetic fields at the same time, the total frequency tuning range of the SIW cavity resonator can be increased. In Figures 17(a) and 17(b), the fabricated prototype of the cavity resonator and the measured frequency curves are presented. It can be observed from Figures 16 and 17(b), with such a two dimensional tuning, the total frequency tuning range has increased almost two-folds from 8% to 16%, which was not optimized. It is also demonstrated that, by the use of a simultaneous electric and magnetic tuning, a frequency tunable bandpass filter with a tunable constant bandwidth can be realized without additional elements for controlling the coupling between cavities. In fact, this attractive phenomenon can be explained by the fact that the proposed two-dimensional tuning is indeed the tuning of cavity modes or modal tuning in connection with electric and magnetic fields. This is as opposed to the one-dimensional scheme in which either electric or



**Figure 17.** Simultaneous electric and magnetic two dimensionally tuned SIW cavity resonator. (a) Fabricated prototype, (b) measurement results [60].

magnetic field would be modified, perturbed or changed. Therefore, one field remain unchanged during the process. This would have distorted the profile of resonant or propagating modes in the structure, which leads to a poor or limited tuning range. In addition, natural modal tuning would change the coupling between adjacent cavities as well as the resonant frequency in this cascaded cavity filter topology. Therefore, the frequency bandwidth response profile can be preserved while the center frequency can be tuned.

**Table 1.** Comparison between different tuning technologies.

<b>Tunable element</b>	<b>Q-factor</b>	<b>Tunability</b>	<b>Power consumption</b>	<b>Response time</b>
<b>Semiconductor</b>	Moderate	High	Poor	Fast
<b>MEMS</b>	Very high	Low	Excellent	Slow
<b>Ferroelectric</b>	Moderate	Low to Medium	Excellent	Very fast
<b>Ferromagnetic</b>	High	Very High	Moderate	Moderate

## 7. CONCLUSION

Based on the brief overviews of different tuning elements and techniques that have been widely used in the realization of tunable microwave cavities and filters, it can be concluded that each scheme has its own advantages and limitations in performance. In Table 1, the key parameters of each tuning scheme are compared and summarized in terms of losses, tunability, power consumption and response time, when they are used in the realization of tunable filters.

Semiconductor diodes present lower cost, light weight, easy biasing, low voltage, and small footprint. However, they would inherently produce non-linear effects and suffer from inter-modulation noises and transmission losses. MEMS techniques, on the other hand, are highly linear in comparison to semiconductor schemes. However, the response or the switching time of MEMs is much slower compared to semiconductor counterparts. They are also vulnerable to high-power and environmental conditions, for example, temperature, vibration in which they operate. Thus, they may require a stringent packaging condition. Ferroelectric materials are highly suitable for integrated microwave devices because they can be made in thin-film or thick film forms, and they also offer a relatively high tunability. Nevertheless, the dielectric loss tangent of ferroelectric materials is generally very high

and the inherent permittivity of ferroelectric materials may present highly dispersive behavior, which may not be good for a wide-ranged frequency tuning. Thus, they offer a very low  $Q$ -factor with limited bandwidth applications. Tunable devices based on ferromagnetic materials can handle more power compared to semiconductors and MEMS technologies, and they are highly tunable and higher  $Q$ . However, biasing the ferrite materials requires the use of solenoids wound with current carrying coils or large permanent magnets. Therefore, the tunable circuit using ferrite materials can sometimes be bulky.

It has been found that the one-dimensional electric or magnetic tuning may not be effective in terms of tuning range and design complexity. The proposed two-dimensional tuning technique may present an attractive and emerging alternative for simultaneous electric and magnetic tuning, which may fundamentally change the design landscape of tuning structures and circuits. This will be critical for future generation RF and wireless circuits and systems.

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