FOCUSED ISSUE FEATURE

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Controlled Agility

High-performance filters with electronically controlled transfer functions are needed for future microwave systems. In commercial applications, frequency agility is necessary to address ever-evolving standards and an increasingly congested spectrum, while military requirements include cosite interference mitigation for broadband systems and adjacent-channel simultaneous transmit and receive. These filters will enable new system architectures, which will, in turn, allow for improved performance and new capabilities. For example, as analog-to-digital converter (ADC) technology continues to advance, it is expected that, eventually, intermediate-frequency (IF) stages will not be needed; instead, direct detect schemes could be used, with the entire radio-frequency (RF) chain consisting basically of an ADC preceded by a filter. This places very high performance requirements on the filter, not only in terms of loss and selectivity but also frequency agility.

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Optimally, these filters would be tunable in the sense that center frequency and/or bandwidth can be changed, as well as reconfigurable in the sense that transfer function order and/or number and location of transmission zeroes can be changed. A filter that is both electronically tunable and reconfigurable allows the filter to be optimized for a given application or spectral situation [1].

To function, frequency-agile filters require control elements, such as tunable capacitors (varactors) and RF switches. The performance of the control elements has a substantial impact on the overall performance of the filter. To date there is no control element available with the performance necessary to meet the demands of current and future systems. Semiconductor varactor diodes are fast and offer wide tuning ranges but are lossy and possess limited linearity, and microelectromechanical systems (MEMS) switches and varactors [2] are low loss and linear but slow. Switches based on phase-change materials [3] show great promise but are still years away from being practical.

This article showcases recent work aimed at minimizing the undesirable effects of control elements on filter performance (e.g., increased insertion loss) while maximizing positive attributes (e.g., tuning range). Advanced circuit design techniques are discussed that are capable of providing significant improvements in performance over conventional approaches, allowing for the best possible performance to be achieved given the limitations of available control elements.

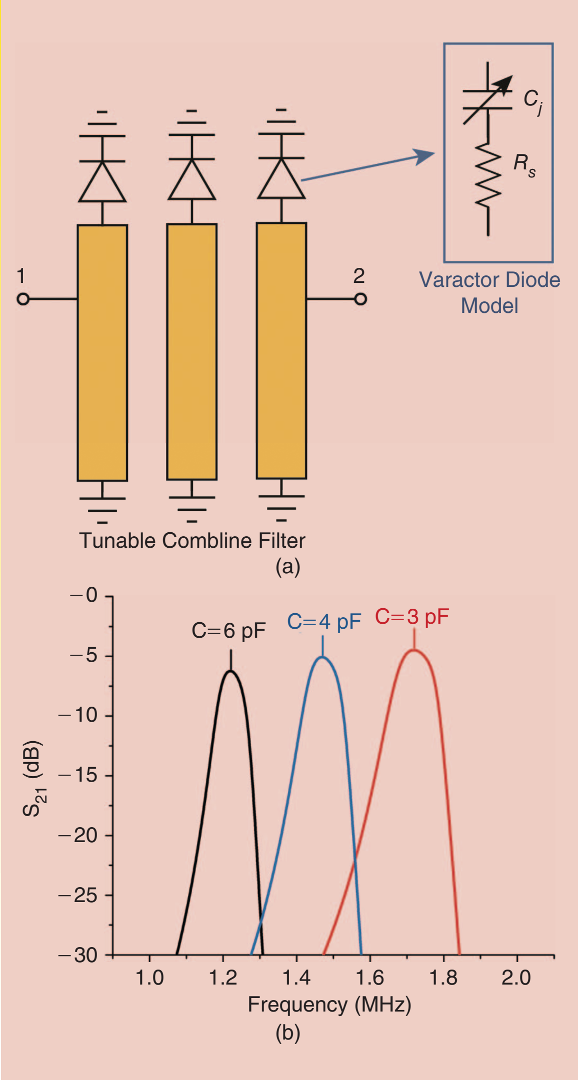

Figure 1. *(a) A simplified schematic of a conventional varactor-tuned combline filter and (b) a simulation showing typical center frequency tuning response.*

Fundamental Concerns

It is instructive to begin with a discussion of the well-known varactor-tuned combline filter [4], [5]. Figure 1(a) shows a simplified schematic of a third-order combline filter loaded with varactors at the ungrounded ends of the resonators. Also shown is the equivalent circuit of a varactor diode—a tunable capacitance C_j in series with a resistance R_s. The unloaded quality factor (Q_u) of a varactor is given by

$$\frac{1}{\omega C_j R_s}. \tag{1}$$

Due to the variance of C_j and, to a lesser degree, R_s, in general, varactor Q_u changes with tuning. Varactor Q_u is typically lower than the intrinsic Q_u of the unloaded combline resonators. This results in decreased resonator Q_u as the tuned frequency is decreased (varactor capacitance C_j is increased). Also, the bandwidth of the filter response changes with frequency due to the frequency-dependent characteristics of the coupling between the combline resonators. Figure 1(b) shows a simulation of a typical tunable combline filter response. For a given varactor, tuning range can be increased to some extent by changing the electrical lengths of the combline resonators and/or impedances, but at the expense of increased insertion loss and a degraded filter response.

In an effort to circumvent the relationship between insertion loss and tuning range, multiple tunable filters with overlapping tuning ranges can be combined using RF switches at the input and output in a switched-bank configuration [Figure 2(a)]. While at first glance this approach appears to be a good solution, in practice, the insertion loss of the RF switches significantly limits the amount of performance improvement that can be achieved. This loss tends to increase as the number of filters in the bank increases, which significantly diminishes and eventually eliminates the insertion loss improvement provided by reducing the tuning range of each of the individual constituent filters. In addition, the switches increase the size, weight, power consumption, and control complexity, and they can degrade the linearity of the filter bank. The insertion loss of the switches is especially problematic when

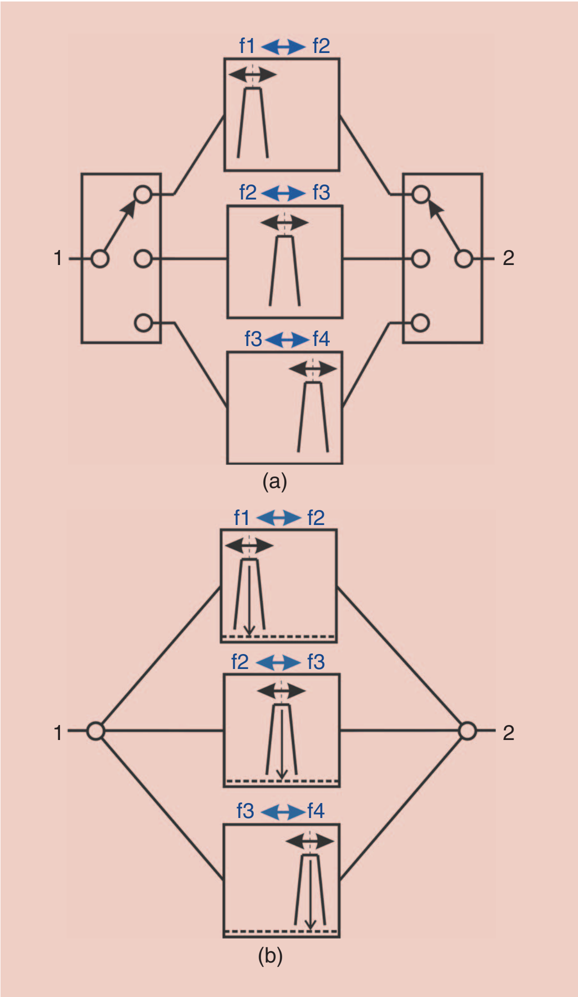

Figure 2. *(a) A conventional switched tunable bandpass filter bank. RF switches are used at the input and output to select the desired filter. (b) A switchless tunable bandpass filter bank utilizing intrinsically switched tunable bandpass filters. As the filters are self-switching, RF switches are not required.*

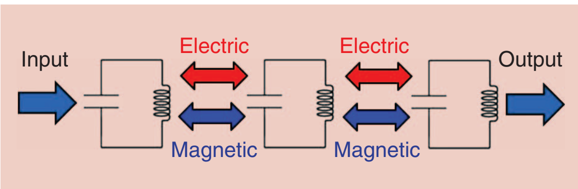

Figure 3. *Intrinsic switching in a bandpass filter: cancellation of interresonator coupling using out-of-phase and equal-magnitude electric and magnetic couplings.*

the goal is very low insertion loss, a requirement, for example, in the front end of a receiver.

Intrinsically Switched Filters

As opposed to switching between filters using external RF switches, it is possible to turn off the coupling internal to the filter. This technique utilizes the resonator coupling internal to a filter to block energy flow as opposed to external switches that have inherent parasitics and allows for graceful hand-offs between multiple filters to cover additional frequency range. This coupling-cancellation technique is referred to here as "intrinsic switching" [6]. Intrinsic switching allows for the full control of the coupling coefficient along with the ability to create a zero coupling state, which enables the creation of a wide range of filter functions and allows a filter to simultaneously function as a low-loss, high-isolation switch. The resulting dual-function device, termed an "intrinsically switched filter," improves performance by essentially eliminating extra losses associated with using external RF switches and allows for the realization of new types of reconfigurable devices that are difficult to realize using conventional RF switches. Both intrinsically switched bandpass and bandstop filters have been developed. In its off state, an ideal intrinsically switched bandpass filter rejects signals of all frequencies, and an ideal intrinsically switched bandstop filter passes signals of all frequencies.

An intrinsically switched tunable bandpass filter bank configuration is shown in Figure 2(b). Switched filter banks are a class of component for which intrinsic-switching has direct application with significant performance benefits resulting from the elimination of RF switches. The intrinsically switched bank approach removes the switch-loss-imposed upper limit to the number of filters that can be used, so realizing low-loss tunable filter banks comprising large numbers of low-loss narrow-tuning-range filters becomes a problem of manifold design rather than the much more difficult problem of realizing low-loss high-throw or cascaded switches.

Bandpass Design

Intrinsic switching of bandpass filters involves the controlled cancellation of coupling between resonators. Partial coupling cancellation has previously been explored to implement bandwidth tuning [7]. In contrast, intrinsic switching allows for complete cancellation. One way that this can be achieved is by using electromagnetic resonators that are coupled with both electric and magnetic couplings that can be made out-of-phase, as illustrated in Figure 3. When these couplings are out-of-phase and of equal magnitude, zero net interresonator coupling results and the filter turns off. The key is to do this in such a way that the loading effects of the control elements used are minimized. One way to accomplish this is to strongly couple the resonators with large amounts of both electric and magnetic coupling. Under this condition, it only takes a relatively small perturbation to move from the off state, where electric coupling equals magnetic coupling, to an on state with significant net coupling (and therefore significant bandwidth).

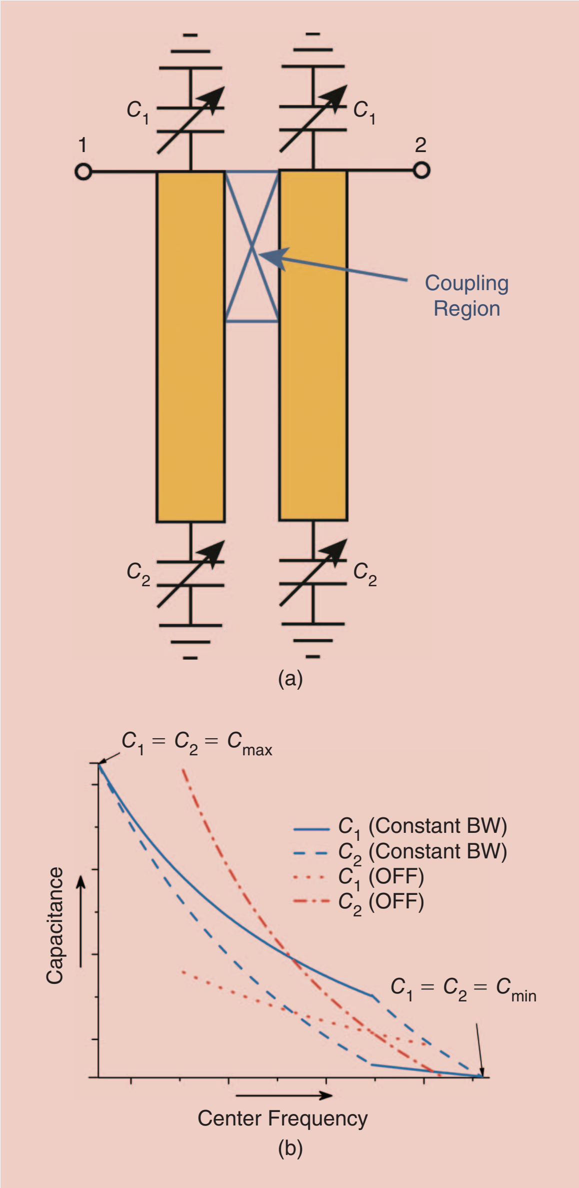

Figure 4. *Symmetric intrinsically switchable resonator topology. (a) Topology consisting of two transmission-line resonators that are coupled over a limited region, with two sets of varactors C_1 and C_2 attached to opposite ends. (b) Calculated normalized varactor tuning curves for constant absolute bandwidth and intrinsic off states. The values of C_1 and C_2 for the intrinsic off state fall within the on-state values for the full tuning range.*

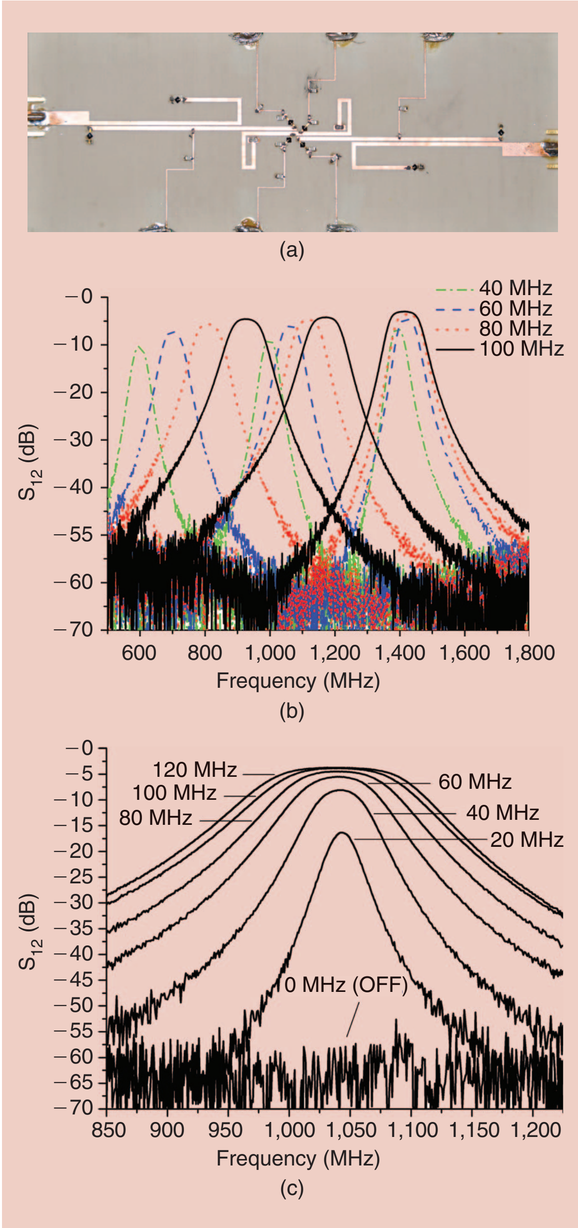

Figure 5. *Third-order intrinsically switched microstrip prototype: (a) Fabricated circuit (5 cm × 13.5 cm). The substrate is 60-mil Roger Duroid 4003. The central resonator is a pseudocombline with grounded ends with two varactors in the center at the ends of the input and output transmission lines. (b) A plot of measurements showing center-frequency tuning range for various bandwidths. (c) A plot of measurements showing bandwidth tuning and the intrinsic-off state (0-MHz bandwidth).*

An intrinsically switchable resonator topology, consisting of a symmetric pair of transmission-line resonators coupled together over a specific region of their length is shown in Figure 4(a). The size and location of the coupling region plays an important part in determining the relative amounts of electric and magnetic coupling. The resonators are loaded with two sets of varactors: C_1 at the top of the figure, and varactors C_2 at the bottom. The ratio of C_1 and C_2 determines the voltage and current distributions within the coupling region at resonance. When both sets of varactors C_1 and C_2 are tuned simultaneously, the resonant frequencies of the resonators shift, while the ratio of electric to magnetic coupling is not significantly affected. However, if the C_1 and C_2 varactors are offset tuned with respect to one another, for example, increasing C_1 while decreasing C_2, the resonant frequency can be made to remain constant while the electric to magnetic coupling

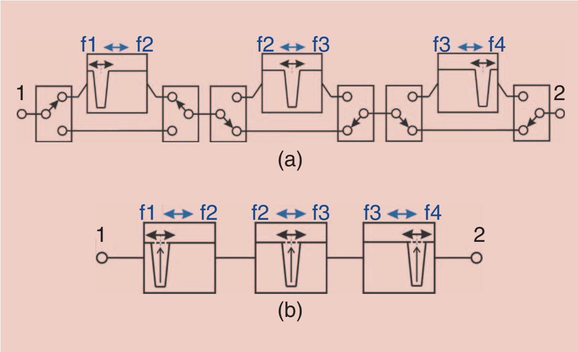

Figure 6. *(a) A conventional switched tunable bandstop filter bank. (b) A switchless tunable bandstop filter bank utilizing intrinsically switched tunable bandstop filters.*

ratio is changed. With the proper choice of coupling region, it is possible to design a tunable filter with this resonator topology that can turn itself off without requiring varactors with tuning ranges greater than that of a comparable conventional tunable filter (e.g., combline). In other words, due to the relationship between tuning range and insertion loss, the switching function is achieved without an increase in overall insertion loss. Plotted in Figure 4(b) are varactor tuning curves for both a constant absolute bandwidth on state and the intrinsic off state; note that the off-state varactor values fall within the constant absolute bandwidth on-state values.

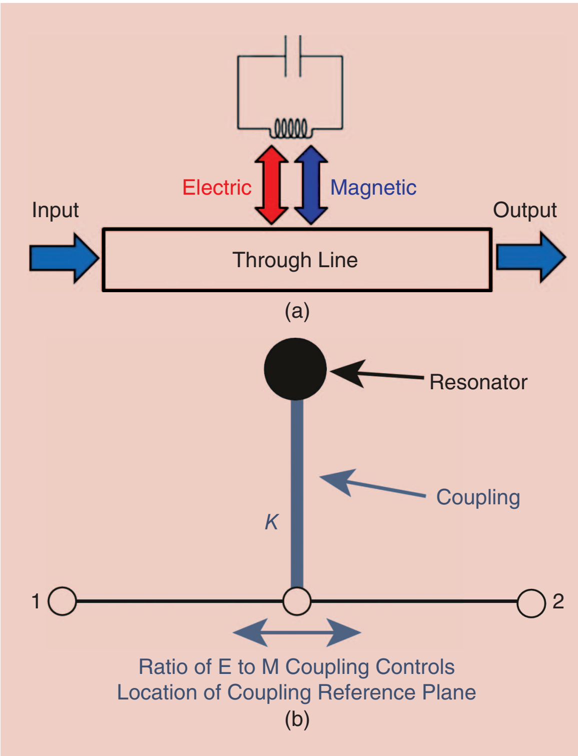

Figure 7. *(a) A conventional first-order bandstop section, consisting of a resonator coupled to a through line. The coupling can be a mix of electric and magnetic, but they do not cancel each other out as in the bandpass case. Instead, the ratio of electric to magnetic couplings determines the location of the effective coupling reference plane. (b) Coupled-resonator representation showing the effect of changing the ratio of electric to magnetic coupling.*

The first intrinsically switched bandpass filter was demonstrated in 2009 [8]. Figure 5(a) shows the fabricated microstrip circuit. It is a third-order filter using varactors as tuning elements, and it utilizes resonators similar to those shown in Figure 4. The center frequency is tunable from 600 to 1,400 MHz [Figure 5(b)], and the bandwidth is tunable from 120 MHz down to zero, the intrinsic off state [Figure 5(c)].

Bandstop Design

Intrinsically switched bandstop filters are also of interest, especially for applications that call for individual bandstop filters to be switched in and out, which if done using a conventional signal-routing approach requires a very large number of RF switches [see Figure 6(a)]. The use of intrinsically switched bandstop filters allows for the switching of multiple filters without the insertion loss penalty of multiple RF switches in cascade [Figure 6(b)]. While intrinsically switched bandstop filters share the same basic operating principle with that of intrinsically switched bandpass filters, coupling cancellation, the details of its application are quite different. In the bandstop case, it is not the coupling between resonators that needs to be canceled but rather the coupling between a resonator and a through line. The basic topology of a first-order bandstop filter section composed of a resonator coupled to a through line is shown in Figure 7(a). Due to the nature of the coupling mechanism between an electromagnetic resonator and a through line, it is not possible to cancel out the coupling in the same way as in bandpass topologies. In the bandstop case, the ratio of electric to magnetic coupling determines the location of the coupling reference plane, the effective point along the

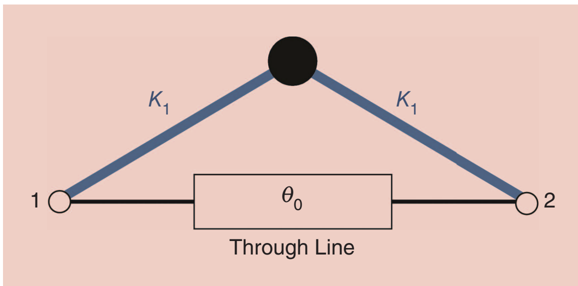

Figure 8. *A two-path bandstop section—bandwidth is dependent on the strength of the couplings K_1 as well as the length of the through line θ_0. By realizing the couplings K_1 using a mix of electric and magnetic coupling, the ratio of which can be controlled, it is possible to tune θ_0 by shifting the coupling reference planes using the property illustrated in Figure 7.*

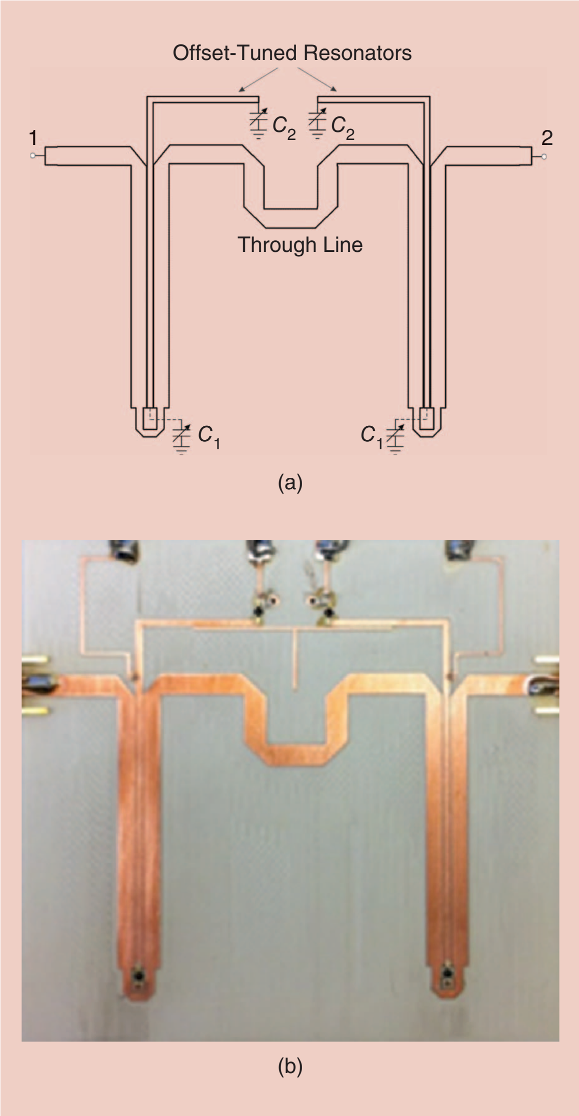

Figure 9. *An intrinsically switched tunable notch prototype: (a) simplified layout, consisting of two first-order intrinsically switchable bandstop sections with 4-mil coupled-line gaps and (b) fabricated circuit of overall dimension 8.6 cm × 8.1 cm. The substrate is 60-mil Roger Duroid 4003.*

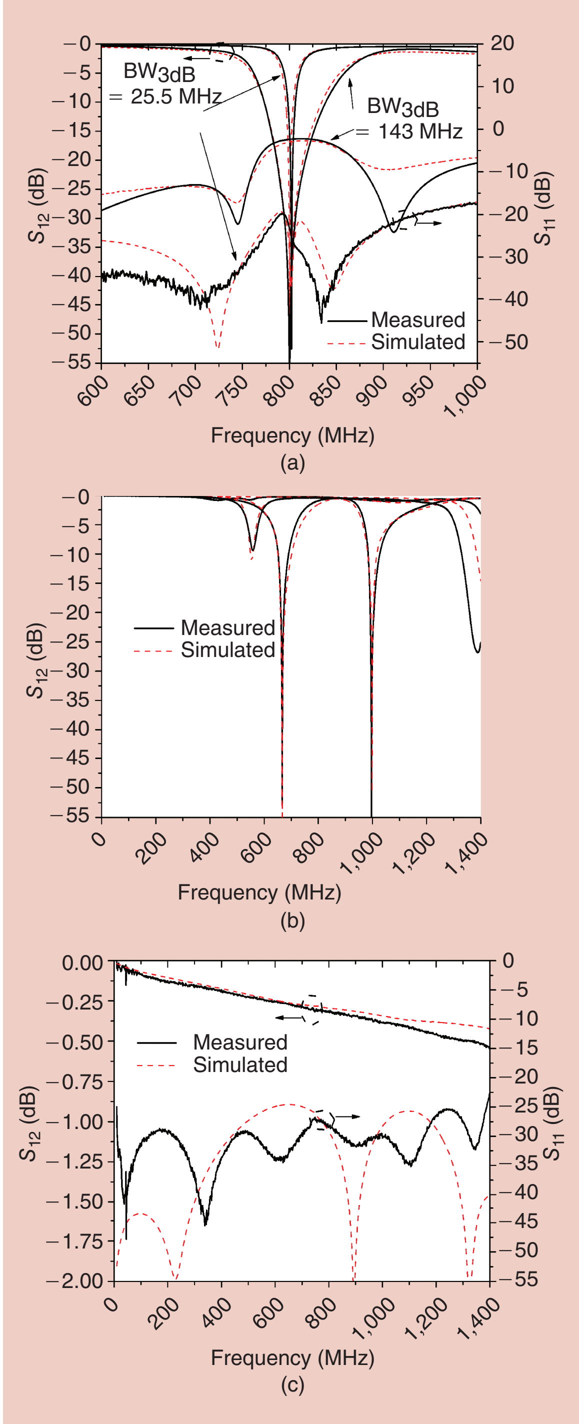

Figure 10. *An intrinsically switched tunable notch filter prototype simulated (AWR Microwave Office and SONNET) and measured results: (a) bandwidth tuning, (b) center frequency tuning, and (c) intrinsic off state.*

through line at which coupling occurs, as illustrated in Figure 7(b). This effect can then be used to realize coupling cancellation with a novel coupling topology. Shown in Figure 8 is a bandstop section consisting of a resonator coupled across a length of transmission line. The bandwidth of the section depends not only on the strength of the couplings K_1, but also on the length of the through line θ_0. The normalized bandwidth of this section can be shown to be [6]

$$\omega_{3\text{dB}} = K_1^2(1 + \cos\theta_0). \tag{2}$$

The coupling can be tuned down to zero by tuning θ_0. By combining this bandwidth-tuning property with the coupling-plane shifting property shown in Figure 7(b), it is possible to design a bandstop section that can switch off using only tuning elements attached to the resonator, without the need for control components in the through line. The ratio of electric to magnetic coupling between the resonator and the through line can be controlled with the use of offset-tuned resonators, as done for the intrinsically switched bandpass filters. Figure 9(a) shows a layout of a microstrip intrinsically switched bandstop prototype utilizing this concept. The prototype consists of two intrinsically switched bandstop sections in cascade. The resonators are coupled to the through line twice, in effect realizing the two-path bandstop topology of Figure 8. As the capacitors C_1 and C_2 are offset tuned, the ratio of electric to magnetic coupling between the resonator and the through line is changed, which in turn changes the coupling reference plane, which in turn controls θ_0 of Figure 8. When θ_0 is 180°, the bandwidth of the filter goes to zero and the filter turns off. It should be noted that in the intrinsic off state, the circuit effectively becomes a through line without the group delay ripple present in other approaches [Figure 9(b)] [9]. There is a small amount of coupling introduced between the two resonators; this has the effect of creating a small amount of destructive interference, which significantly increases stopband attenuation [10]. The notch bandwidth is tunable from 143 down to 25.5 MHz while maintaining more than 50 dB of isolation [Figure 10(a)]. As shown in Figure 10(b), the center frequency is tunable from 665 to 1,000 MHz. Figure 10(c) shows the intrinsic off state in which the resonators are tuned to 725 MHz but the bandstop response is completely suppressed.

Intrinsically Switched Bandpass Filter Banks

Intrinsically switched bandpass filters allow for the realization of switched bandpass filter banks without the need for signal routing using RF switches. The intrinsically switched filters can either be fixed-tuned, in that there is only a single on state, or the filters can be tunable, in that the center frequency and/or bandwidth of the on-state response can be tuned. In the fixed-tuned case, RF switches can be used as control elements, and since they are used to control the ratio of electric to magnetic interresonator coupling instead of for the purpose of signal routing as in conventional switched banks, their effect on performance can be

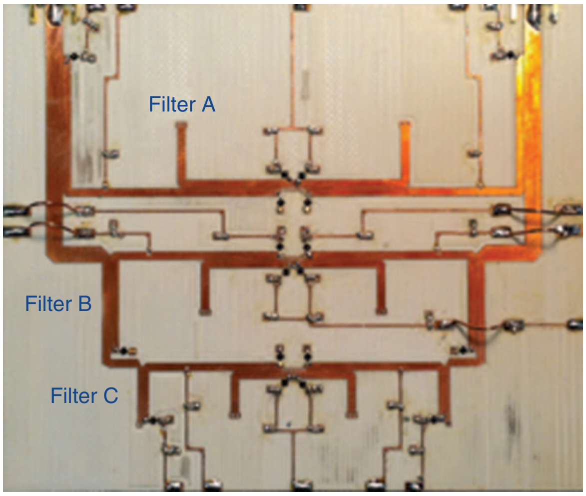

Figure 11. *A fabricated intrinsically switched tunable bandpass filter bank prototype of overall dimension 11.9 cm × 10.1 cm. The substrate is 60-mil Roger Duroid 4003. Inputs are SMA connectors at the top, Filter A is the low-band channel filter, Filter B is mid band, and Filter C is high band [6].*

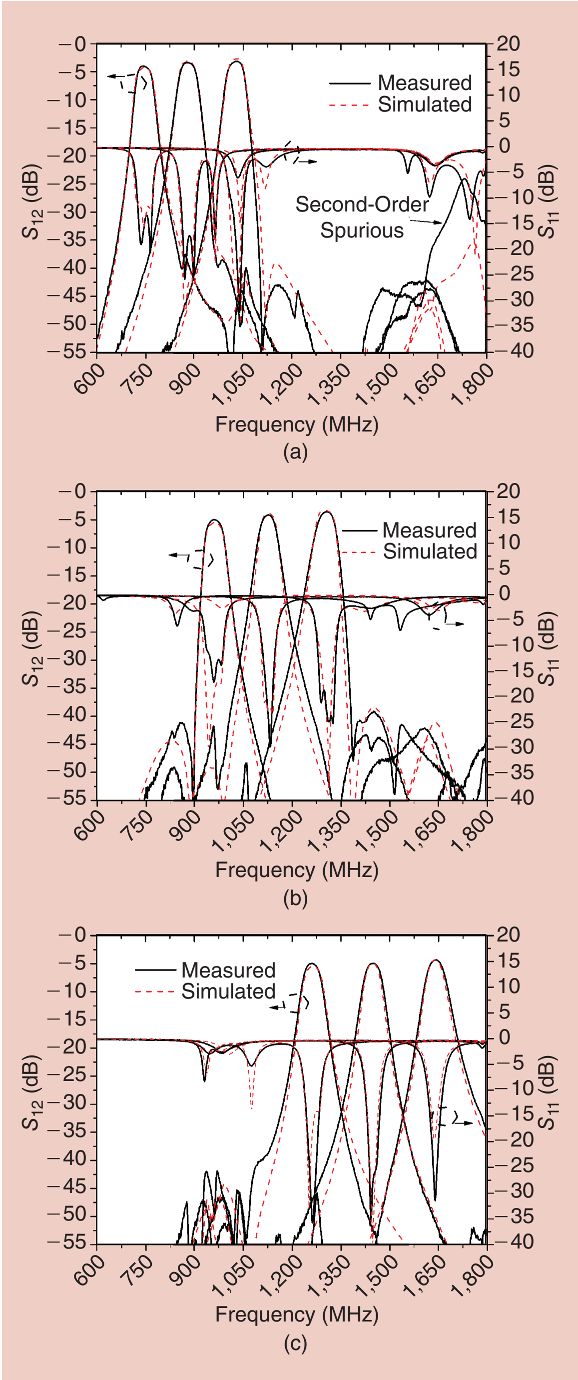

Figure 12. *An intrinsically switched tunable bandpass filter bank prototype simulated (AWR Microwave Office and SONNET) and measured results: (a) Filter A on, (b) Filter B on, and (c) Filter C on.*

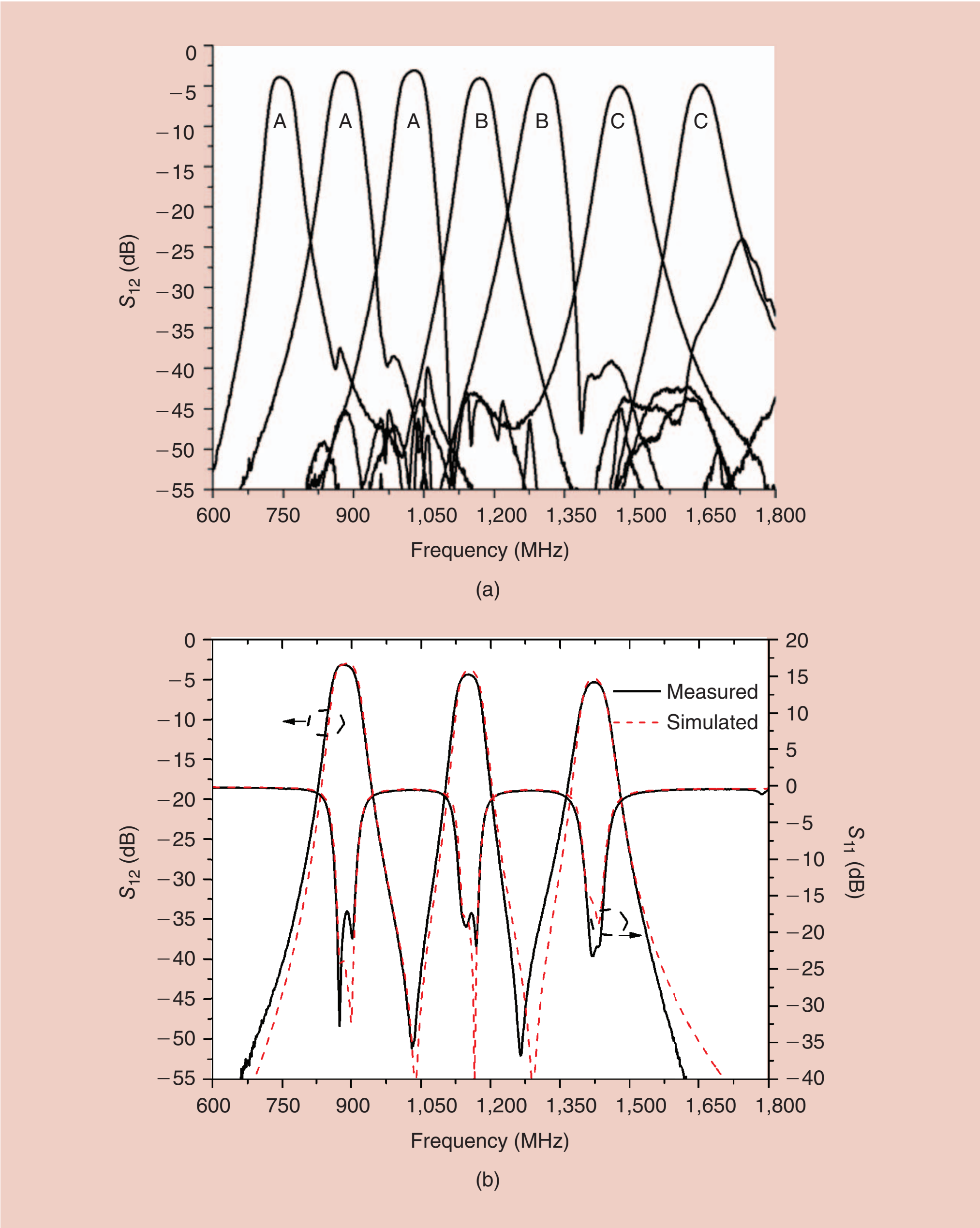

Figure 13. *An intrinsically switched tunable bandpass filter bank prototype results: (a) measured full tuning range and (b) all filters on simultaneously.*

decreased dramatically. In the intrinsically switched tunable filter banks shown in this article, varactors are used.

An intrinsically switched tunable bandpass filter bank comprising three third-order varactor-tuned intrinsically switched filters is shown in Figure 11 [6]. The topology of these filters is very similar to that used in the stand-alone prototype (see Figure 5). The filters are coupled in short-terminated transmission-line manifolds at the input and output. Only five unique control voltages are needed for standard operation (only one filter on at a time). The measured results for the three-filter intrinsically switched tunable bandpass filter bank prototype for a single channel switched on are shown in Figure 12. The composite tuning response is shown in Figure 13(a). It has a constant 50-MHz bandwidth response continuously tunable from 740 to 1,644 MHz (122%) with less than 5 dB of passband insertion loss and more than 40 dB of isolation between bands. A response with the three filters switched on simultaneously is shown in Figure 13(b). There is a limit to how close the three filter responses can come before degradation occurs, as the filters were not designed to work together in this way. An intrinsically switched bandpass filter bank that possesses this capability, called

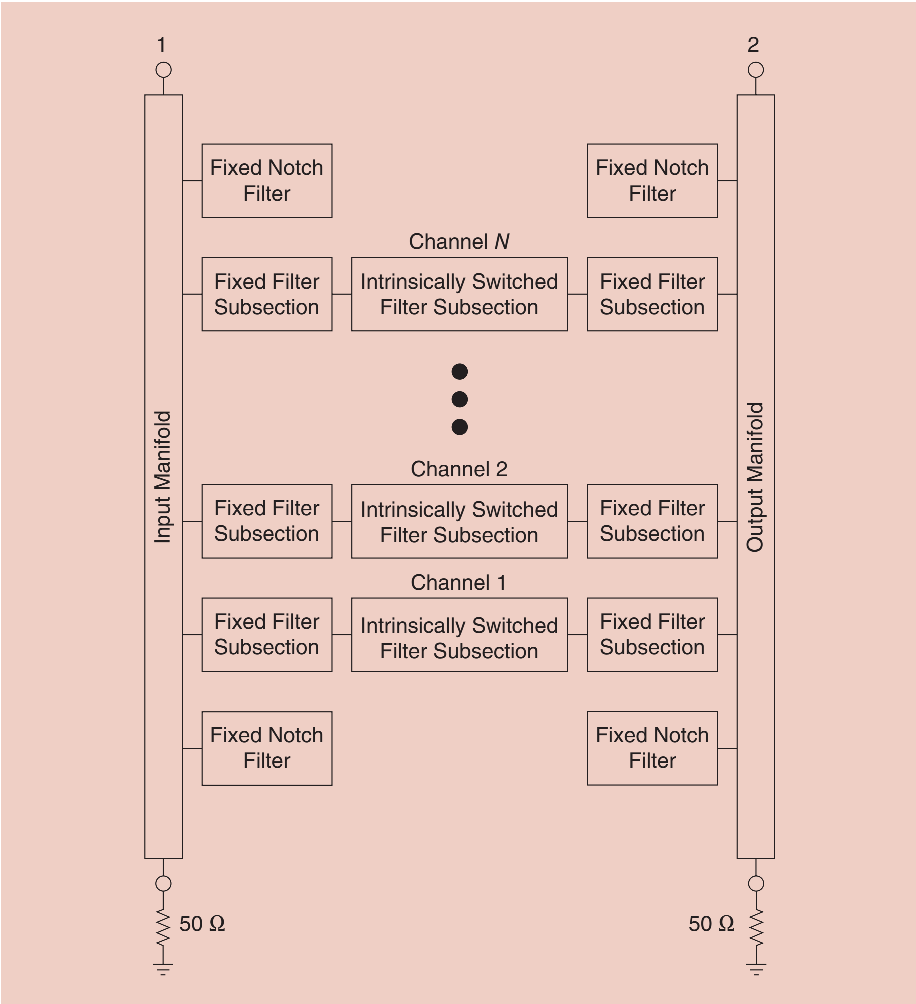

Figure 14. *An intrinsically switched multiplexer architecture. The input and output manifolds are terminated in matched loads. The highest center-frequency channel is attached closest to the input/output ports, with the rest of the channels descending in center frequency toward the matched loads. The channel filters are composed of intrinsically switched subsections and fixed subsections to maintain the impedance seen to other channels. Fixed notch filters serve as dummy channels to terminate the filter array above and below in frequency.*

an intrinsically switched multiplexer [11], has recently been demonstrated.

An intrinsically switched multiplexer is a generalized version of a switched fixed-tuned filter bank, composed of a number of independently switched contiguous bandpass filter channels that form a continuous passband or passbands when two or more adjacent channels are on, resulting in 2^N states for N channels. To avoid blind spots in the spectrum, it is a requirement that when two or more adjacent filters are switched on, they form a continuous passband with flat insertion loss and group delay through the crossover frequencies.

A scalable intrinsically switched multiplexer architecture is shown in Figure 14. The channel filters are attached to transmission-line manifolds at the input and output. The manifolds are terminated in matched loads to avoid unwanted resonances. The channel filters are arranged descending in center frequency from the input/output to the matched terminations, in a similar fashion to log-periodic and cochlear-based arrangements [12], [13]. The channel filters are intrinsically switched internally such that the out-of-band impedances looking into the input and output ports of the filters are minimally affected. Permanently switched-off channel filters in the form of fixed notch filters are used to terminate the array of filters above and below in frequency.

The channel filters of an intrinsically switched multiplexer must be designed carefully to ensure that they act cooperatively when adjacent channels are switched on. In [11] it is shown that an effective way of accomplishing this is to begin by assuming an infinite number of channels, in which case, the ideal all-channels-on transfer function is equivalent to that of a well-matched transmission line, which in turn is equivalent to a network comprising an infinite array of transversely coupled resonators (Figure 15). The resonators of this equivalent transversal coupled-resonator network can then be partitioned by frequency into filter channels of arbitrary order. Due to the initial assumption of infinite channels, partitioning channels to be of the same order will result in a set of identical filter networks scaled in frequency. The topologies of these filters can be made more practical with the use of coupling matrix similarity transforms [14]. It is shown in [11] that the topology of these filter networks can be further simplified by partitioning the transversal coupling matrix such that resonances are shared between channel filters, in effect allowing the channels to overlap slightly.

A three-channel intrinsically switched multiplexer prototype is shown in Figure 16. The measured insertion loss and group delay of the various states are shown in Figures 17 and 18, respectively. The prototype gives

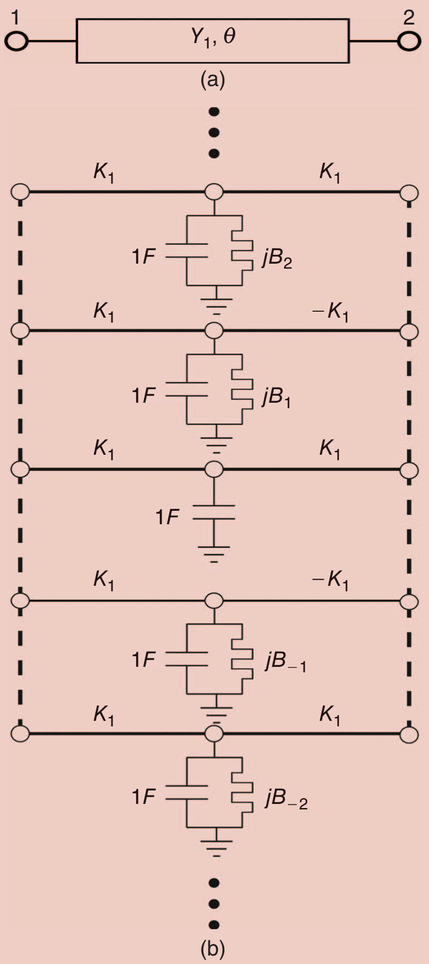

Figure 15. *(a) A transmission line with characteristic admittance Y_1 and electrical length θ and (b) equivalent infinite-order transversal resonator array comprising resonators (represented by normalized capacitances and susceptances) coupled to the input and output with admittance inverters K_1. This array can be partitioned into groups of transversal resonators to form channel filters.*

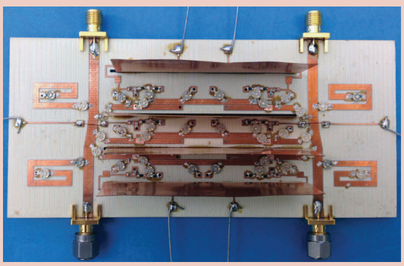

Figure 16. *A fabricated intrinsically switched multiplexer prototype. The substrate is 60-mil Roger Duroid 4003. Input ports are the SMA connectors at the top. Connectorized matched loads at the bottom provide the manifold terminations. 1-mm thick copper sheets extend up through the substrate from the ground plane to provide isolation between the channel filters. Board dimensions are 13.3 cm × 5.8 cm [11].*

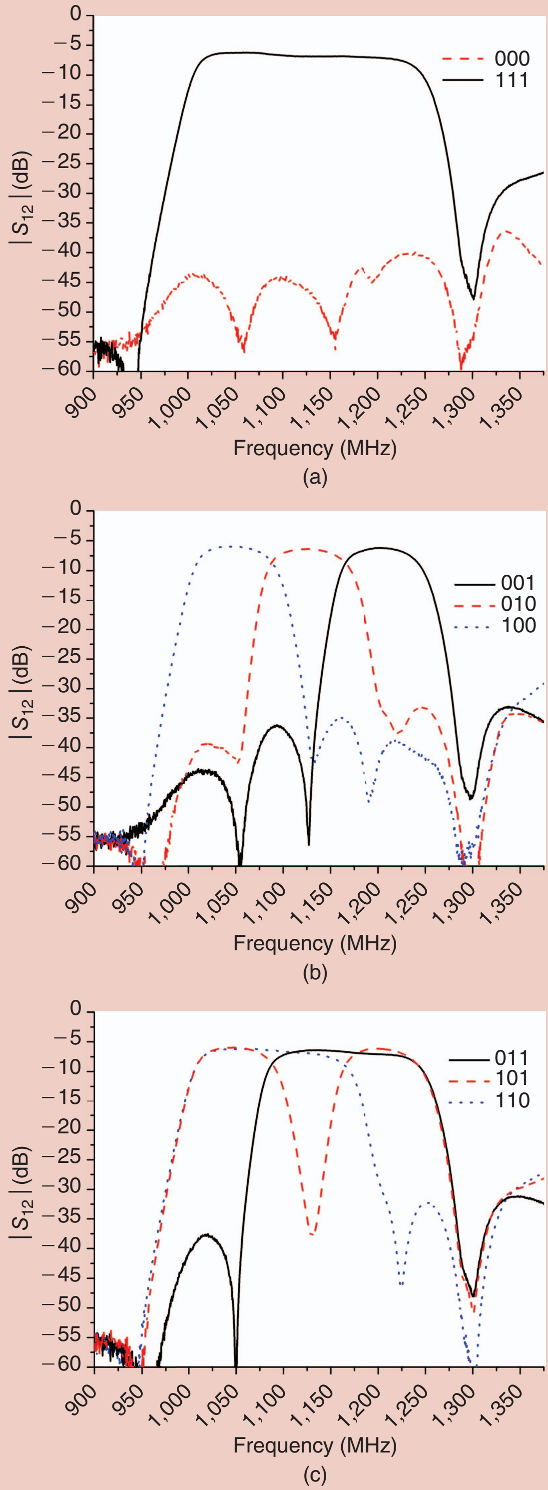

Figure 17. *Insertion loss measurements of the intrinsically switched multiplexer prototype: (a) all-off and all-on states, (b) single on-channel states, and (c) double on-channel states.*

6.7 dB of passband insertion loss and 0.15-ns p-p group delay ripple over 72% of the passband for the on state. The insertion loss for this prototype comes primarily from the large number of surface-mount components

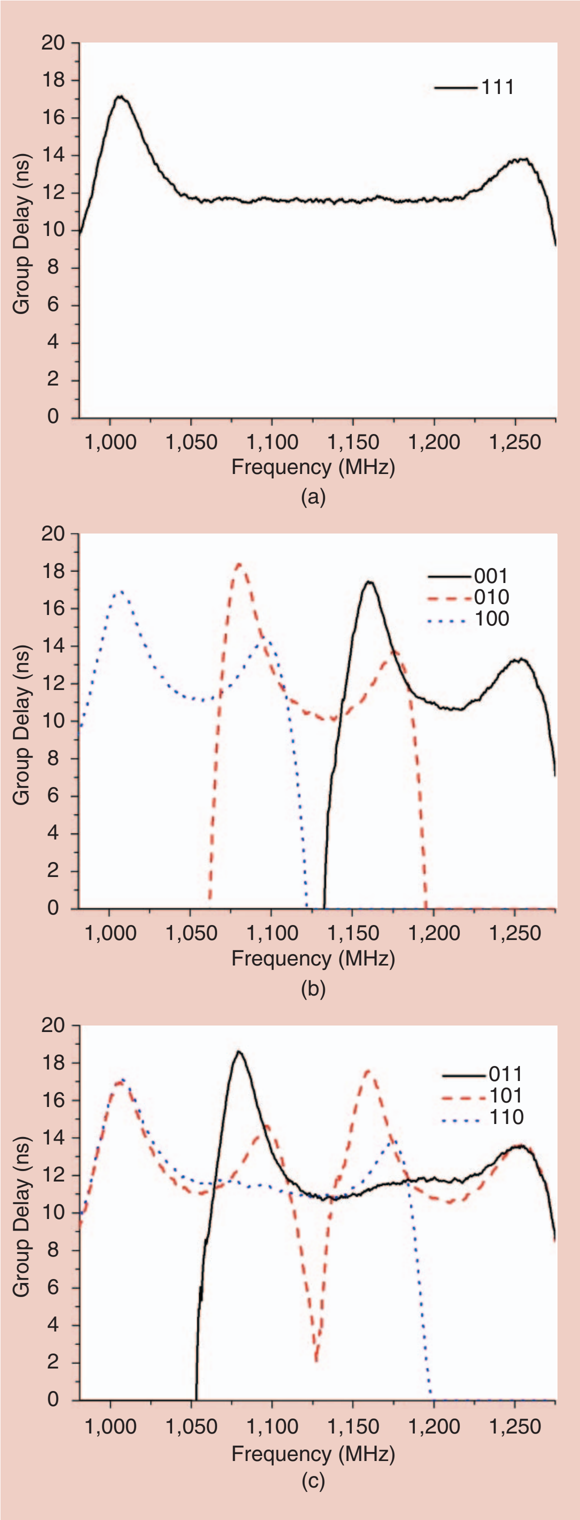

Figure 18. *Group delay measurements of the intrinsically switched multiplexer prototype: (a) all-off and all-on states, (b) single on-channel states, and (c) double on-channel states.*

attached with silver epoxy, most of which are trimmer capacitors. Most importantly, this first design proof of concept establishes the ability to have multiple filters connected at a common node, which allows for filters to cooperatively span a frequency range or create 2^N filter shapes between them.

Summary

This article has reviewed recent advances in the field of tunable and reconfigurable filters. New types of filter designs based on the intrinsic switching concept have been presented that allow for the realization of switched filter banks without requiring signal-routing RF switches. Initial prototypes have been fabricated using planar technologies; however, recent work has successfully applied these concepts to higher-performance three-dimensional resonator technologies [15].

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