Design Techniques for Passive Planar Reconfigurable RF Circuits: Reconfigurable RF Circuits

Design Techniques for Passive Planar Reconfigurable Radio Frequency Circuits

Aijaz M. Zaidi, Binod K. Kanaujia, Jugul Kishor, Sumer Singh Singhwal, Vikrant Kaim, Amit Kumar, Karumudi Rambabu, Sembiam R. Rengarajan

I. INTRODUCTION

Reconfigurable systems play an important role in the design of reconfigurable wireless communication systems. In the traditional approach, a separate transmit and receive pathways are required for every supported communication standard/frequency band for a radio frequency (RF) front-end architecture. However, this approach increases the complexity and size of the system. This problem can be solved by employing subsystems or blocks that can function across multiple frequency bands and standards, or that can reconfigure themselves based on the spectrum. This flexibility can free up finite spectrum resources to enable a miniaturized system. Therefore, microwave subsystems should ideally reconfigurable and frequency agile in order to handle the vast frequency allocation of the regulated communication bands and the multitude of standards to which these radios must function. Such subsystems would allow for the implementation of new architectures with fewer functional components. Therefore, Reconfigurable circuits can be useful for several wireless applications, such as telecommunication and military applications, where new frequency bands are coming or are expected to come. A flow graph for designing reconfigurable circuits is shown in Fig.1.

Despite these advantages, reconfigurable circuits cannot be used everywhere because the inclusion of new bands for the same application is not a required everywhere. Reconfigurable circuits are designed by employing tuning components such as varactor diodes or varactor, PIN diodes, and micro-electromechanical system (MEMS) switches. The tuning components have their drawbacks and limitations, (e.g., varactors show poor linearity, and PIN diodes have high power consumption). Furthermore, bias circuitry is also required to provide bias to PIN diodes and varactors, thereby making the circuit complex. Therefore, it is not advantageous to use reconfigurable circuits. So, whenever the reconfigurable operation is not necessary, it is better to choose single-band circuits. RF circuits are required for any wireless communication system. RF passive circuits play a key role in active circuits as well as subsystems of the wireless communication system. For example, couplers, crossovers, power dividers, filters, and multiplexers play key roles in the design of power amplifiers (PAs), Butler matrices, signal selection, beamforming networks, radar systems, and antennas [1] - [6]. There are many types of RF passive circuits, and each circuit can support multiple reconfigurable design techniques.

This paper aims to present a comprehensive review of the reconfigurable design techniques for passive circuits. A few review papers dedicated to a reconfigurable circuit and its applications, such as couplers [7], Wilkinson power dividers [8], filters [9] - [10], and multiplexers [11], are available in the literature. However, these review papers provide information about a single reconfigurable circuit. For example, [7] is soley dedicated to reconfigurable couplers. Thus, the available review papers have limited scope. The article fills that gap by discussing classical design techniques used for reconfigurable RF passive circuits presented in the last two decades that employ varactor, PIN diodes, MEMS switches, resonators, varactor loaded coupled lines, substrate integrated waveguides (SIWs), and π-shaped network using diode, along with emerging technologies for reconfigurable circuits such as phase change material (PCM) and digitally tunable capacitors (DTC). In addition, the article provides a detailed comparative analysis of reconfigurable components such as varactor, MEMS, and PIN diodes used to design reconfigurable RF circuits. This comparison will help researchers choose the most suitable reconfigurable components based on their requirements. The authors hope that this article will be helpful to new researchers working in this field and will also motivate them for new findings.

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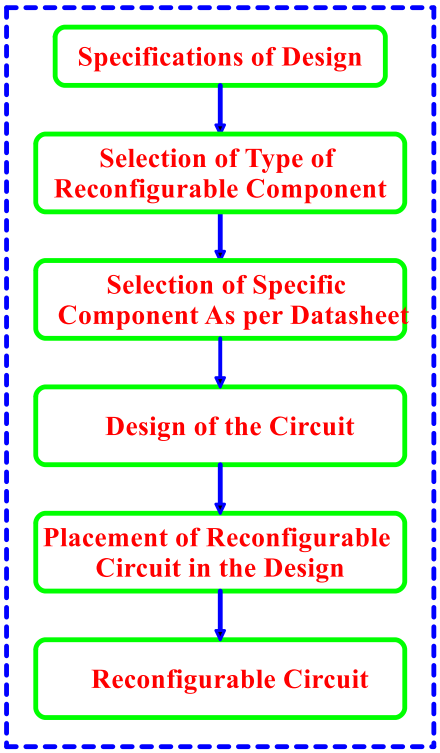


Fig.1 Design flow graph for reconfigurable circuits.

II. Varactor

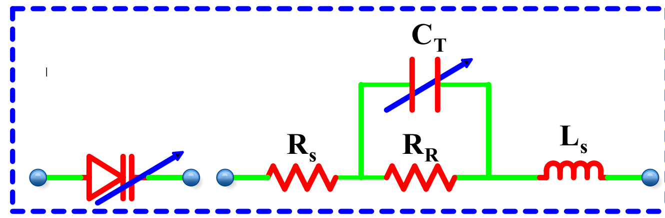
The varactor is the most important element in the design of reconfigurable RF passive circuits. Fig. 2 depicts the symbol, equivalent circuit, and characteristics graph of a varactor [12]. The transition capacitance C_T of the p-n junction diode is established by the isolated uncovered charges as given in (1).

$$C_T = \varepsilon \frac{A}{W_d} \tag{1}$$

where ε is the permittivity of the semiconductor material, A is the p-n junction area, and Wd is the width of the depletion region. The width (Wd) of the depletion area expands as the reverse bias potential (V_R) increases, which in turn reduces the transition capacitance (C_T). As shown in Fig.2, C_T initially declines sharply as reverse bias increases. A formula for calculating transition capacitance can be given in (2).

$$C_T = \frac{K}{(V_T + V_R)^n} \tag{2}$$

where K is a constant defined by the semiconductor material and fabrication method, V_T is the knee potential, n = 1/2 for alloy connections, and n = 1/3 for diffused junctions. By changing the bias potential, the junction capacitance of the diode can be changed. Therefore, if the circuit is designed by employing varactor, the characteristics of the circuit can be altered by changing the reverse bias voltage of the diode. In this way one can create reconfigurable RF circuits using this characteristic of the diode. Varactors have been used in the construction of several reconfigurable circuits, such as couplers [13] - [14], power dividers [15] - [16], filters [17], and filtering power dividers [18] – [19]. Varactors can be connected in a variety of ways to get the desired properties and reconfigure the circuits. For example, to make the branch line coupler (BLC) reconfigurable and to acquire the appropriate properties, varactor can be connected to the branch line [14], of the BLC. By adjusting the capacitance of the attached varactor, the electrical length of the stub can be adjusted [13]. Alternatively, the coupling coefficient of the BLC can be altered by connecting the diodes in the branch line [14]. A varactor can also assist in



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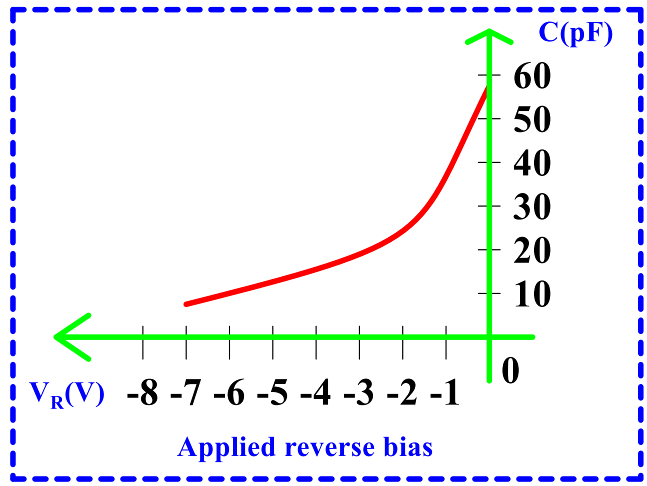

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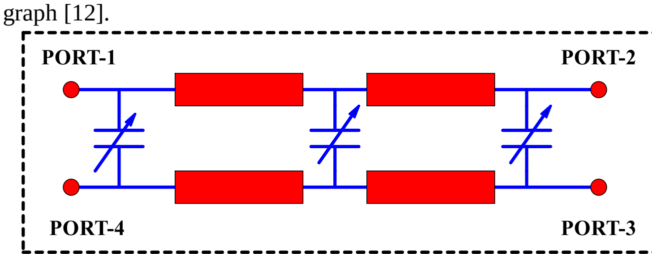
Fig.2 Varactor a) symbol and equivalent circuit; b) characteristics graph [12].



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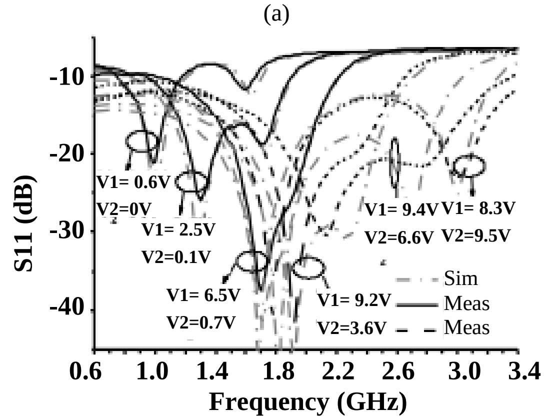

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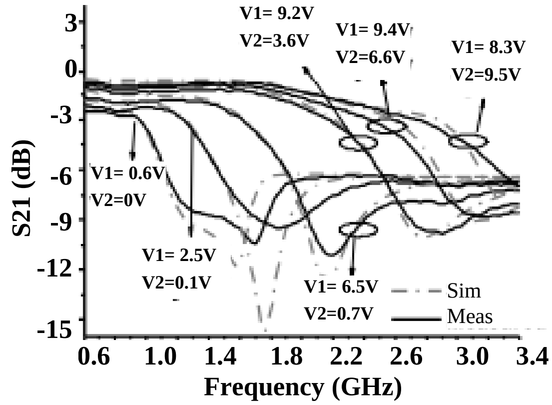


(c)

Fig.3 a) Configuration of the reconfigurable coupler; simulated and measured results of the designed coupler for tuning frequencies b) S11; c) S21; [14].

achieving reconfigurability with versatility [15] and variable power division [16]. Varactors can also be utilized to create reconfigurable filters; however, in that instance, common mode suppression is removed using the defective ground structure [17]. Using varactors with a resonator, filtering power dividers can also be created. The operational center frequency of the filtering power divider, which influences the circuit's bandwidth, can be changed by tuning the varactor [18] - [19]. A reconfigurable BLC has been created by including a varactor in the branch lines of a BLC in [14]. Fig.3 displays its schematic and scattering parameters. It achieved tuning of the coupling coefficient from 0.86 to 9.5 dB at the center frequency and tuning of the operating frequency in the range of 1 to 3 GHz.

The advantage of this technique is that varactors are cheap, compact in size, and easily connected to the constituted element of the circuit to reconfigure and acquire the desired characteristics of the circuit at the operating band. However, the disadvantage of the varactor technique is that it can only provide the change in capacitance of the connected element by varying the bias voltage applied to it. It is not always advantageous to vary the capacitance of the design or element to design reconfigurable circuits. Secondly, the bias circuitry used to provide bias to the varactor makes the circuit structure complex. The maximum bias voltage ranges up to several volts, and the corresponding change in capacitance ranges up to several pF, as per the datasheet of varactors provided by such manufacturers as Skyworks, and MACOM. Table I compares the varactors used to design reconfigurable circuits, and important characteristics such as quality factor, power dissipation, size, frequency range (limitation), and capacitance tuning ratio range. The operating frequency range of the varactor dictates which varactor to use for a particular application.

Table I

Comparison of varactors used in the design of reconfigurable circuits

Varactor	Quality Factor	Size (mm)	Operating Frequency (GHz)	Power Dissipation(mW)	Capacitance ratio
MA46H120	3000	0.69*0.22	ISM band	100	5.5
SMP1340	400	2.1*3.04	0.01-10	400	1.42:1
SMV1248	1500	1.52*1.37	…………	250	10:1
SMV2019	500	3.04*2.64	…………	250	2.3:1
MA46H070	4500	4.95*1.27	ISM band	50	10:1

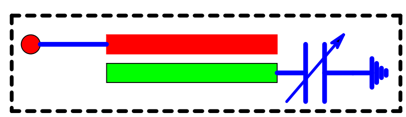
III. VARACTOR LOADED COUPLED LINE

Dual-band circuits with reconfigurability can be designed with the help of varactor-loaded coupled lines (CLs) [20]-[21]. Several dual-band circuits use π-shaped TLs [22]-[24]. These dual-band circuits can be converted into reconfigurable circuits by replacing each stub of the π-shaped TL with a varactor -loaded CL. The varactor-loaded CL structure is equivalent to the stub, and tuning the capacitance of the varactor provides reconfigurability at two frequencies. The design equations of Fig.4(a) structure are given in (3).

$$\frac{4Sin^2\theta(f_1)}{(Z_{CC}+Z_{CO})Sin2\theta(f_1)}+2\pi f_1C=\frac{Z_1+Z_2}{Z_1Z_2}\left(Cot\frac{\theta}{2}-\tan\frac{\theta}{2}\right)\quad(3)$$

varactor-loaded coupled lines were used to produce a reconfigurable dual-band BLC in [20]. Using this method, the upper operating frequency can be changed from 3.4 to 4.2 GHz while the lower operating frequency remains set at 2.4 GHz. The return loss for the lower and upper operating frequencies is better than 18 and 22 dB, respectively, for each state. The maximum amplitude imbalance is 0.17 and 1.31 dB at the lower and upper frequencies, respectively.

The benefit of the varactor -loaded coupled line technique is that it provides a wider bandwidth and can reconfigure the designs at two bands, which makes it a good option for cognitive radio applications. Since this technique is dependent on CL, it has more manufacturing constraints, such as the coupling coefficient of the CL must be less than -6dB to be implemented. Furthermore, this technique also uses varactor as a tuning component which makes the circuit more complex, as already explained.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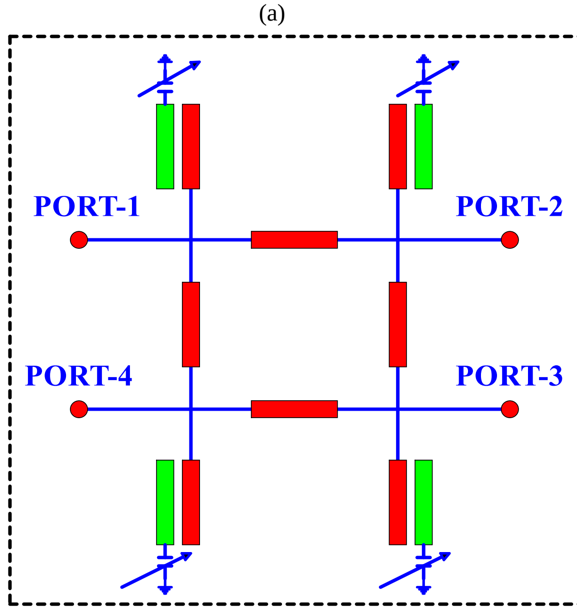

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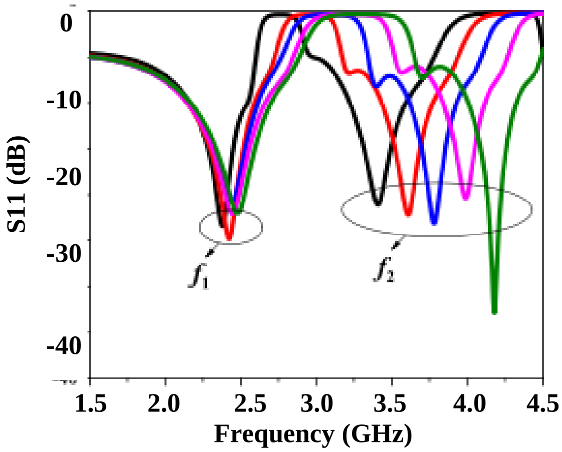

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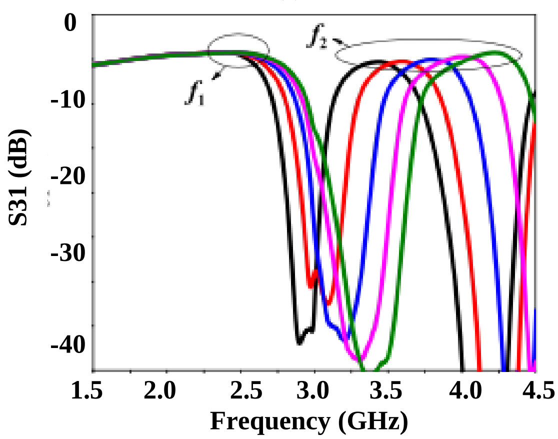


(d)

Fig.4 (a) Varactor loaded coupled line; (b) Reconfigurable dual-band coupler; Simulated S-parameters of the implemented dual-band coupler with the tunable upper operating frequency. (c) S11; (d) S31; [20].

IV. PIN DIODE

A PIN diode is an important component in the design of reconfigurable RF circuits. A PIN diode is a current-controlled device that operates as a variable resistor at RF frequencies. Its cross-section with an equivalent circuit is shown in Fig.5. By controlling the bias, its resistance can be zero (on) or infinite (off). Therefore, it can be used as a switch by controlling the bias current, hence its resistance. This characteristic of the PIN diode is used to achieve reconfigurability in passive RF circuits. Several reconfigurable circuits have been designed with PIN diodes, for example, phase shifters [26], couplers [27], and power dividers [28]. An angular phase shift can be achieved at the desired frequency using the switching properties of PIN diodes [26]. A re-configurable N-way power divider can also be designed with coplanar waveguides and PIN diodes because this provides multiway reconfigurability with constant impedance [28].

A 6-way reconfigurable power divider has been designed using PIN diodes in the frequency range of 0.58 to 0.76 GHz in [28].

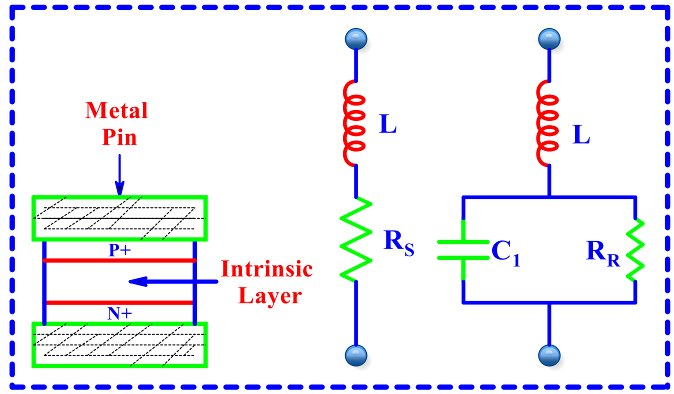
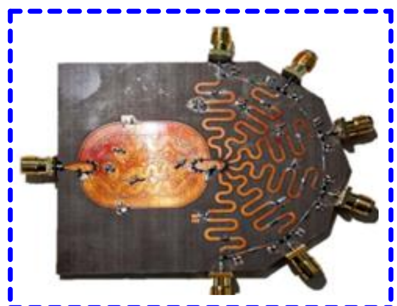


Fig.5 Cross-section of basic PIN diode, forward bias equivalent circuit, reverse bias equivalent circuit [25].

The prototype of this 6-way power divider and its characteristics graphs are shown in Fig.6. It achieves a low insertion loss of 1.89 dB and high port isolation of greater than 30 dB. The advantages of PIN diode switches include that they can be utilized to design reconfigurable circuits up to 60GHz for power level that can handle power up to 10W. However, their drawback are that they consumes greater amount of power and occupy more space. In addition, multiple diodes cannot be connected close to each other because the bias circuitry required to connect to them takes up too much space.



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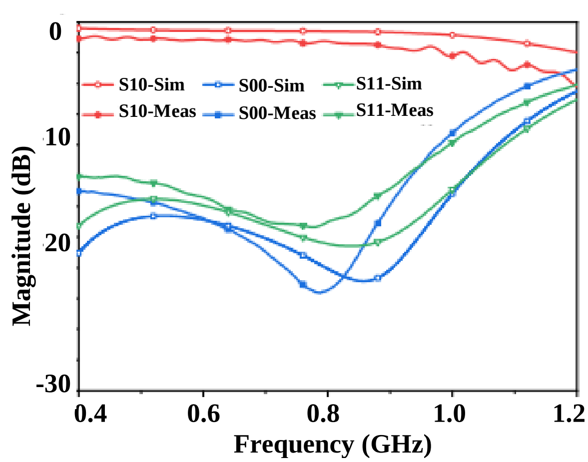

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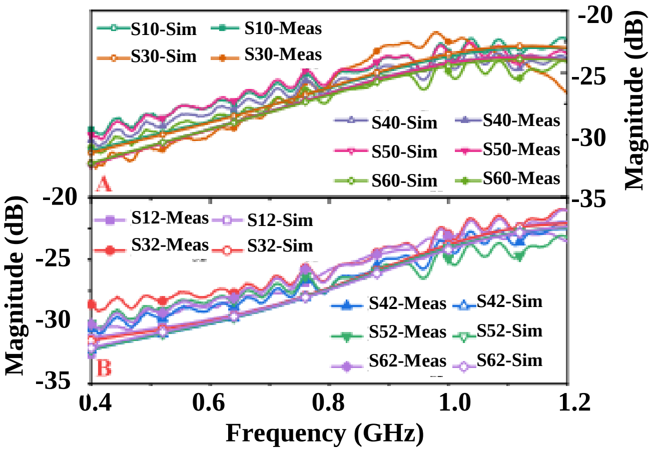

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Fig.6 a) Photograph of the fabricated six-way reconfigurable power divider in [28]; simulated and measured results in the single-path mode for port 1; b) Insertion loss and return loss; c) Isolation between input port and isolation ports, and transmission port and isolation ports [28].

V. Substrate Integrated Waveguide

Re-configurability in RF circuits can also be designed using substrate-integrated waveguide (SIW) technology. A SIW is type of transmission line that consists of a waveguide filled with dielectric, with conducting vias put into the substrate to connect the top and bottom conducting walls of the substrate electrically. SIW benefits from low radiation loss like a waveguide, compact size, and simple integration like a micro-strip line [29] - [30]. SIW with varactor and PIN diodes is useful for designing compact reconfigurable circuits. A few circuits have been designed with this technique, for example, phase shifters [31] – [32], filters [33], phase shifters [34] - [35], crossovers [36] - [37], and couplers [38]. Utilizing SIW with gap waveguide technology helps to reduce the magnetic leakage of a phase shifter [34]. By adjusting the piezoelectric actuators and varactors between the four SIW evanescent-mode cavity resonators, re-configurable crossovers can be created [37]. In [35], a reconfigurable phase shifter was designed by employing SIW technology, and impedance matching was accomplished, offering a 15.8% impedance bandwidth. The results show a maximum phase shift of 250° and maximum and mean insertion loss (IL) of 3 dB and 1.7 dB, respectively.

The benefits of the SIW technique are greater power handling capacity, compact size and simple integration. However, the leakage losses are high in SIW due to the via holes placed in the top plane.

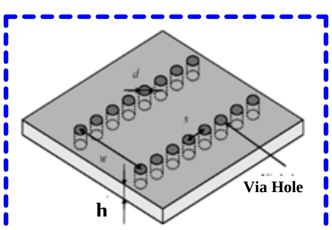


Fig.7 Configuration of an SIW structure synthesized using metallic via-hole arrays [30].

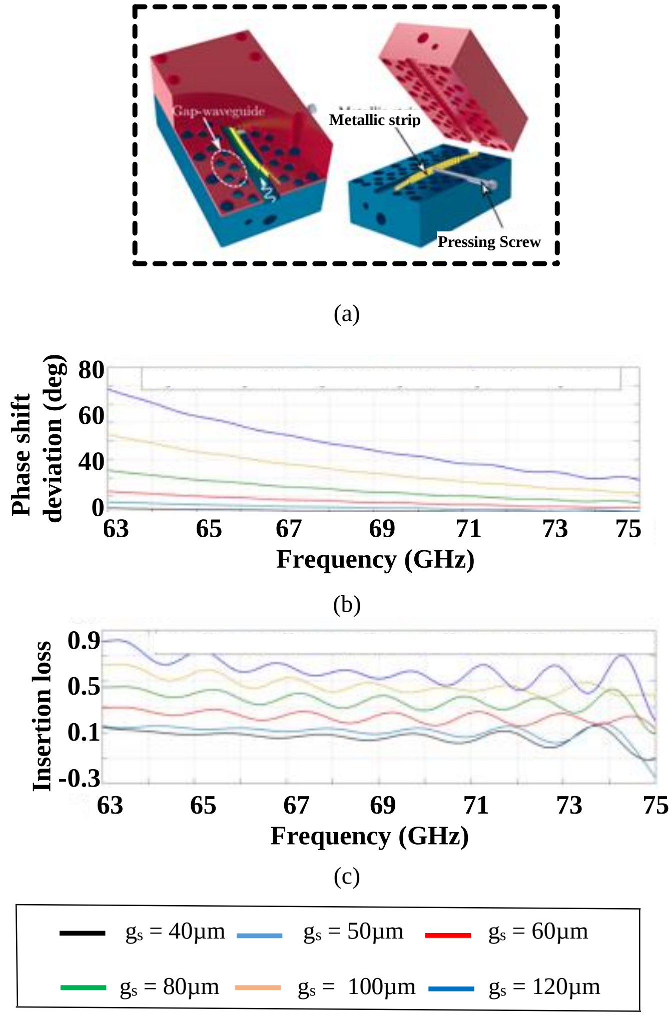


Fig.8 a) Re-configurable phase shifter design model-effect of the vertical gap g_s between the metallic strip and the upper and lower surfaces of the waveguide: b) on the phase shift, and c) on the insertion losses [35].

VI. Resonators

Resonators are useful components in the design of reconfigurable passive RF circuits. An open/short stub loaded stepped impedance can function as a basic resonator [39], Fig.9. For open stub loaded stepped impedance, the resonant condition occurs when $Y_{op} = Y_1$, and in this case the resonant condition can be expressed as in (4) – (5).

$$\tan\theta_1 - \cot 2\theta_1 + \tan\theta_q = 0 \tag{4}$$

$$\theta_1 = \left(\frac{1}{2} + n\right)\pi \quad where\ (n = 0,1,2......) \tag{5}$$

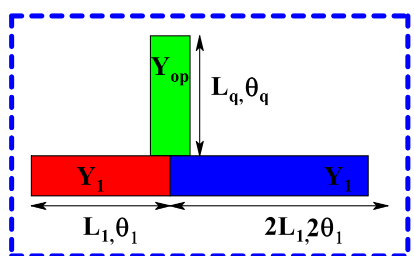
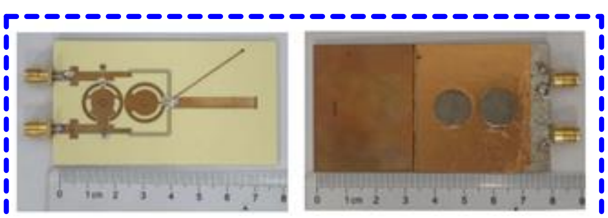


Fig.9 Structure of an open-circuited stub loaded resonator [39].

Further modifications can be made to the resonator structure to design reconfigurable circuits, for example, cross-shaped resonators [41], T-shaped resonators [42], quarter wave TL [43], and hairpin resonators [44]. Several circuits have been designed employing resonators such as couplers [40], and filters [39], [41] - [48]. A micro-strip terminated cross-shaped resonator with a pair of symmetrical parallel coupled lines and open-ended stubs called a multimode resonator is loaded with the variable capacitor at the lower stub to design a reconfigurable filter in [41]. With the variation of the capacitor value, the frequency of the transmission poles and zeros are altered to enhance the bandwidth of the first passband of the design [41]. According to [42], it is also possible to create independently changeable filters using a pair of parallel-coupled lines connected by a short-ended stub loaded with a varactor. A pair of quarter-wavelength resonators that are loaded with varactors and by short-ended parallel coupled-line stages are employed to produce the filter's reflection-free performance [43]. Dual behavior in terms of flatness and reconfigurable bandwidth of a filter can be achieved by employing a resonator cascaded with a hairpin resonator in which open ends are loaded with varactor for coupling and frequency tunability [44]. The resonator configurations presented in [41] – [44] are only useful to design reconfigurable filters that have either tunable bandwidth or tunable center frequency.

For a fully reconfigurable filter, the ability to simultaneously tune its bandwidth, center frequency, out-of-band attenuation, intrinsic switching capabilities, and multi-level transfer function with low insertion loss can be developed using a symmetrical parallel coupled line connected with two varactors loaded short stubs [45] - [46]. In [45], these capabilities are accomplished for only the second order passband. A fully controllable filter with the potential to realize multi-level transfer function can be demonstrated as in [46]. But, a multi-layer design makes the design structure complex [45] - [46]. In [47], a triple-mode micro-strip resonator coupled with a two notch resonator forms a pair of resonators that can be used to design a band-pass filter with a tunable notch by incorporating transmission zeros. To compensate for insertion losses in a filter, an active capacitance network is used in [48].

A fifth-order band-pass filter has been designed in [47] by employing two coupled notch resonators. The wideband BPF features a repositionable in-band notch that can be tuned for frequencies between 1.494 and 2.004 GHz. It is 0.9 λg x 0.45 λg in size (where λg is the guided wavelength at 1.87 GHz). For any tuning condition, the achieved passband return loss is better than 10 dB.



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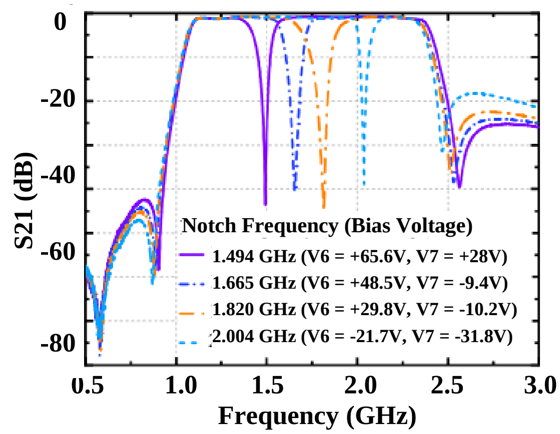

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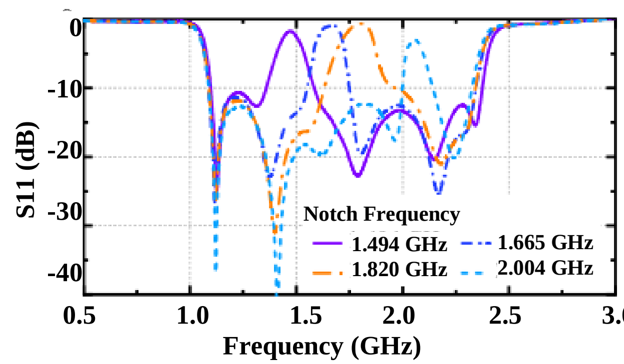

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Fig.10 a) Top and bottom views of the fabricated wideband BPF with reconfigurable notch prototype. b) Measured S21 and c) measured S11 of the filter when the frequency of the in-band notch is tuning and the notch attenuation level is fixed at 40 dB [47].

The advantage of microstrip resonators is that they provide high-frequency stability, which is more suited to microwave and mm-wave applications. However, reconfigurability in the design is achieved by employing varactor and PIN diodes. As a result, these circuits become complex.

VII. MEMS SWITCH

Micro-electromechanical systems (MEMS) switches, for designing reconfigurable circuits [49]. MEMS switches developed with analog devices (RF-MEMS) have exceptional precision, RF performance, and strong reliability and can be used for 0 Hz (DC) to mm-wave frequencies [50]. In the most recent generation, capacitive technology is used in the majority of RF MEMS switches. Due to their use of capacitive coupling, capacitor switches are perfect for high-frequency RF applications [49]. MEMS switches are utilized to design a reconfigurable BLC in [51] and matching circuits in [52]-[55]. A MEMS single-pole, double-throw (SPDT) switch can be used to reconfigure matching circuits of a low noise amplifier (LNA) and a PA [52] - [53]. With reconfigurable matching circuits, real-time adaptation of gain or bandwidth [52] and efficiency [53] of power amplifier were achieved. However, to achieve reconfigurability at two bands, SPDT and single-pole-single-throw (SPST) MEMS switches are used to construct matching circuits for the PA and to make the PA capable of operating at the desired band with the help of switches [54] - [55]. Using MEMS technology, reconfigurable matching circuits were developed and utilized to design an active circuit that is a dual-band PA for 900 MHz and 1800 MHz operating bands in [58]. The PA achieves power-added efficiency of at least 57.9%, a power gain of 10.5 dB, and delivers 38.5 dBm power for both bands.

RF MEMS have several benefits, including low insertion loss, high Q factor, low power consumption, high linearity, and the capacity to operate at higher frequencies up to 120GHz. Low insertion and high Q are essential characteristics for reducing the phase noise and power consumption of oscillators and amplifiers. But, RF MEMS switches suffer from low power handling capability.

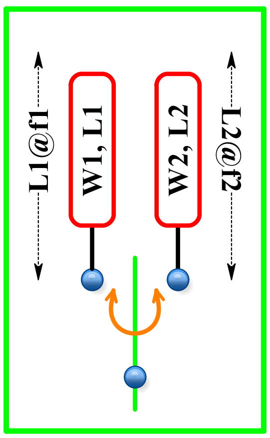
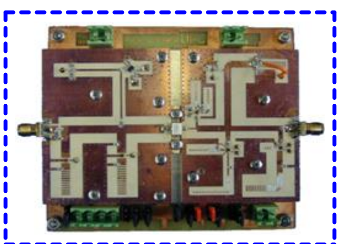


Fig.11 Reconfiguration using SPDT switches [54].



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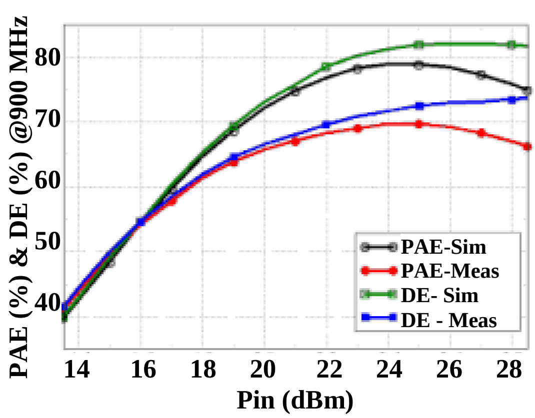

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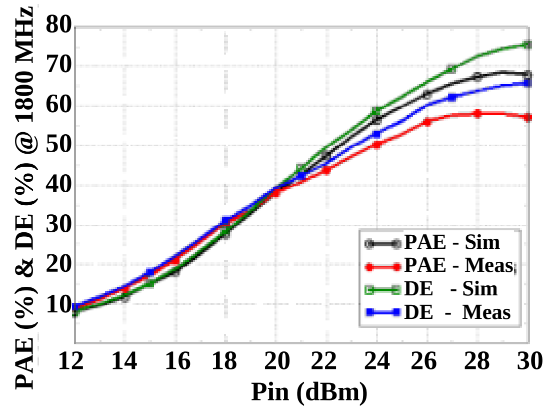


(c)

Fig.12 a) Fabricated circuit; b) Measured and simulated PAE, DE @ 900MHz; c) Measured and simulated PAE, DE @ 1800MHz; [54].

VIII. Π-SHAPED NETWORK OF DIODES

A Diode-loaded π-shaped TL can be used to design reconfigurable circuits. Several reconfigurable dual-band circuits have been developed using this technique, such as in-phase, out-of-phase power dividers [56] and matching circuits [57] - [58]. Fig.12 depicts a π-shaped network of diodes. The structure consists of two shunt varactors C_A and a lumped inductor L in series connection with a varactor C_B. This structure serves as a reconfigurable TL. The concept behind this structure is that it can work as a TL, and by adjusting the values of C_A and C_B, the TL's properties can be obtained for a different frequency range. Consequently, reconfigurable circuits can exploit this topology. Let us assume that this structure is equivalent to the TL of the characteristics impedance Z and electrical length θ. The values of C_A and C_B can, therefore, be stated as in (6).

$$C_A = \frac{Cos\theta - 1}{\frac{1}{C_B} - \omega^2 L} \quad , \quad C_B = \frac{1}{\omega\left(\omega L - ZSin\theta\right)} \tag{6}$$

The TL can be modified to meet requirements by adjusting C_A and C_B. Using a π-shaped structure of diodes, a reconfigurable matching network has been developed for the operating bands of 800 MHz and 1800 MHz [57]. Its prototypes with characteristics graphs is shown in Fig.14. At design bands, it achieves less than 20 dB return loss and 0.21 dB transmission. The advantage of this technique is that it provides reconfigurability at two bands. However, it uses three diodes for a TL structure, thus making the design structure complex because of the need to bias the diodes.

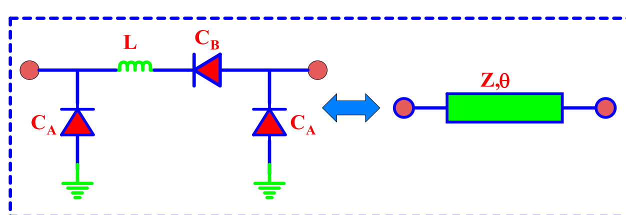


Fig.13 π-shaped network of diodes [56].

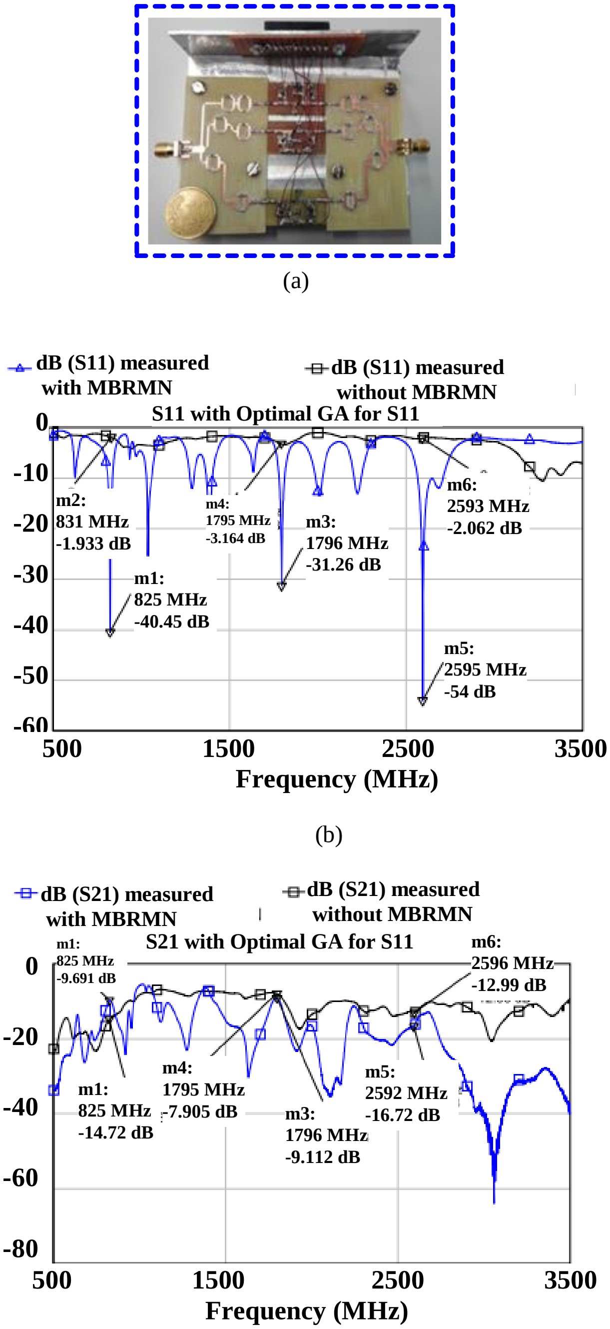


Fig.14 a) Prototypes of a reconfigurable matching network; comparative results with and without MBRMN b) S11; c) S21 [57].

IX. PHASE-CHANGE MATERIAL

A phase-change material (PCM) can change its state from crystalline to amorphous and amorphous to crystalline repeatedly when thermal, electrical, optical, mechanical, and chemical excitations to it [59]-[61], Fig.15. Germanium-antimony-tellurium (GST) and Germanium telluride (GeTe) are examples of PCMs used for RF and photonics applications [62]. Several reconfigurable circuits have been designed using PCM, such as switches [63], and matching circuits [64]. GeTe is one of the stoichiometric compositions of GST, and it has primarily been investigated for RF switching applications due to its better thermal stability in the amorphous state, fast reversible phase transition, and high contrast in resistivity ratio.

In [64], a chalcogenide GeTe material is characterized for PCM-based RF switches. Fig.16 shows the performance of the RF-PCM switch in terms of insertion loss (dB) and isolation (dB). When all the capacitors are unloaded (Cmin), the impedance tuner shows an insertion loss of 3.8 dB and a return loss of better than 22 dB. However, the impedance tuner exhibits a minimum insertion loss of 5 dB and a return loss of greater than 10 dB at maximum capacitor loading (Cmax).

The PCM has some special features, such as low insertion loss, high cut-off frequency, fast switching speed, and better broadband characteristics compared to RF MEMS switches of the same size. However, PCM encounters challenges of high power consumption and low power handling capability.

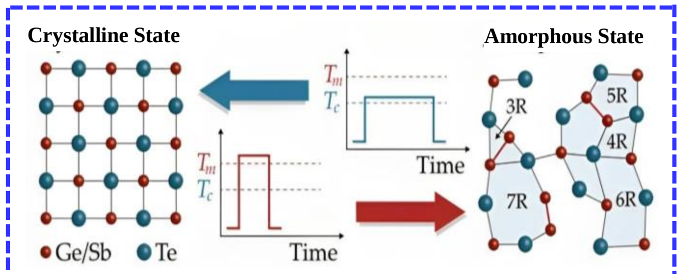


Fig.15 Reversible switching of a PCM using an electrical pulse signal [61].

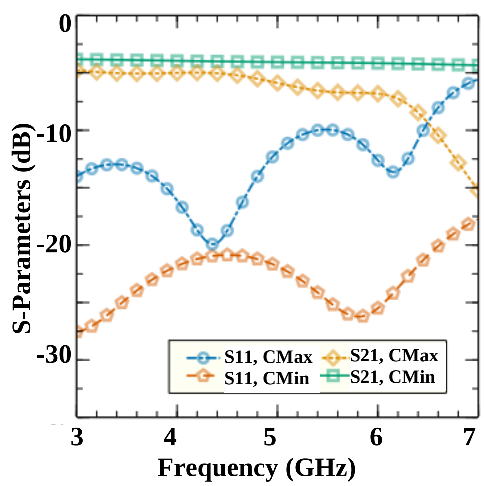
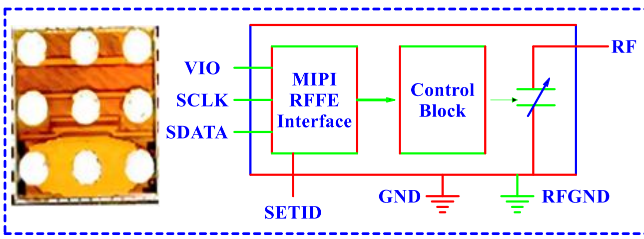


Fig.16 Reconfigurable matching netwotk response for C_{Max} and C_{Min} [64].

X. DIGITALLY TUNABLE CAPACITORS

Digitally tunable capacitors (DTCs) are microwave devices that deliver a variable capacitance while maintaining an approximately constant Q factor. The tuning ratio of the capacitances depends on the maximum and minimum values of the DTC's capacitance. The ratio of Cmax and Cmin of the DTC is related to the quality factor of the DTCs. Radiofrequency micromachined electromechanical systems (RF MEMS), varactor, CMOS, and pHEMT are important technologies used to design DTCs [65]. The important performance characteristics of a DTC are the quality factor, capacitive tuning ratio, linearity, power handling, size, and temperature stability. The technology employed depends on the applications and requirements of the design, and it affects the characteristics of the DTC. For example, the MEMS technology DTC switches from Qorvo offer Q = 700 at Cmax = 1 pF at 700 MHz with a tuning ratio of 2.5 and a size of 1.5mm x 1.5mm. However, highly doped GaAs varactor diodes might operate well for continuous mild tuning ranges $\eta < 3$. A MEMS-based DTC is shown in Fig.17.

The benefits of DTCs are small form factor, wide tuning range, good linearity, high switching speed, high reliability, low mismatch losses, and monolithically tunable integrated impedance [65]. Several circuits have been designed using this DTC, such as a matching circuit [66], switch [67], and power amplifier [68]. Designers of reconfigurable circuits have not yet extensively utilized MEMS-based DTCs because it is still a relatively new technology. These devices reduce the complexity of radio in wireless communications and have a wide range of applications.



(a) (b)

Fig.17 a) Footprint of the digitally tunable capacitor (DTC). (b) Block diagram of the DTC [66].

XI. Selection of Components and Comparison

PIN diode, varactor , and RF MEMS are the key reconfigurable components in the design of any reconfigurable circuit. Each re-configurable component has distinct properties, and the design requirements should dictate the selection of the component . For example, it is advantageous to use components of high Q value to design a low-loss filters, matching networks, power amplifiers, and oscillators because high Q value components substantially reduce the losses/power consumption in the circuits. Furthermore, it is better to choose a component of a higher third intercept point (IP3) while designing a nonlinear circuit, such as in power amplifiers and low noise amplifiers, because a higher IP3 means the component/device will provide good linearity.

A comparative analysis of reconfigurable components in terms of their characteristics has been provided in Table. II. RF MEMS consume low power, have low insertion loss, and provide good linearity (due to a high third-order intercept point). Low insertion loss and high linearity make RF MEMS a suitable component for designing power amplifiers and LNAs. But RF MEMS can handle only low power and therefore can be used for low-power applications. Varactor and PIN diodes can handle high power but have a higher insertion loss and lower IP3 than MEMS. Therefore, varactors and PIN diodes are suitable when a component with high power handling capability is required. The operating principles of the diodes are different. The varactor should be used to design circuits where reconfigurability can be achieved by changing the capacitance. On the other hand, it is advantageous to use a PIN diode where reconfigurability can be achieved by changing the resistance of the constituted elements of the design. Both varactor and PIN diodes make the circuit design complex because of the bias circuitry. In addition, it is difficult to attach two or more diode close together.

All three components can be used individually, or in combination, or with other structures/technology to design reconfigurable circuits. But when reconfigurable components are combined with other technology/any specific structure that has inherent special qualities, the developed circuit consists of features of both, (i.e., the technology/structure and the used reconfigurable component). For example, SIW technology is used to develop compact designs with high power handling capability, and π-shaped TL is used to develop dual-band circuits. When SIW and the dual-band structures combine with reconfigurable components, the developed circuits achieve reconfigurability with other features such as compact size and dual-band operation. Furthermore, CL provides dual-band operation, and varactor provides reconfigurability when CL-loaded varactor is used to design any circuit; in that case, the developed circuit performs dual-band operation with reconfigurability.

A comparative analysis of reconfigurable design techniques is presented in Table III. The comparison is made in terms of reconfigurable range, bandwidth, size, return loss, insertion loss, and number of passbands. A better reconfigurable range can be achieved by employing the varactor technique. Furthermore, varactor -loaded coupled line is suitable for achieving reconfigurability at two bands, and the RF MEMS technique provides better return loss. A π-shaped network of of diodes can function as a reconfigurable TL, but it makes design complex because it consists of four discrete elements.

Table. II
Comparisons of reconfigurable components/switches

Characteristics	RF MEMS	Varactor	PIN diode
Power consumption (mW)	0.05 – 0.1**	20 – 250	5 – 100**
Power handling (W)	25	< 2*	< 10
Third-order intercept point (dBm)	+95	+10 – 20*	+27 – 45**
Insertion loss	0.2 – 0.8	0.1 – 0.4*	0.2 – 0.4**
Q factor (max)	4000	3200*	1000*
Series resistance (Ω)	0.01	0.20 – 2.5*	2 – 4*
Examples	ADGM1004JCPZ-RL7, ADGM1001BCCZ, MM9200, MM3100 , MM5620	SMA46H070-1056, MA46H120, SMP1340, SMV1248, BB857	SMP1320-040L, SMP1324-087LF
Manufacturers	Analog Devices Inc. Menlo Micro, Qorvo	Skyworks, MACOM, Infineon	Skyworks, MACOM

**→[69]
*→Based on several datasheets of the components.
Note → The data given in the table can vary because manufacturers design the components for specific applications. Therefore, designer engineers should consult datasheets before using the components.

Table III
Comparative analysis of design technique for reconfigurable BLC

Reference No	[8]	[10]	[18]	[20]	[27]	[40]	[42]	[54]
Technique	Varactor	Varactor	Varactor loaded CL	Varactor loaded CL	PIN diode	SIW	Resonators	MEMS switch
Reconfigurable range (GHz)	1.7–2.1	1-3	3.4-4.2	2.9 - 3.2	10.8-12.2	2.08-3.00	1.2-1.61	1.5–2.2
Bandwidth (%)	21	100	21	10	1.4	40	28.6	50
Size (λg *λg)	…….	0.41*0.18	1.38*0.73	1.36 × 1.36	…….	0.31*0.32	0.1*0.7	……..
Return loss (dB)	>15	>20	>13.6	>14	>20	>10.22	>20	>22
Maximum insertion loss (dB)	1.2	1.3	1.93	1.1	0.5	0.32	1.7	0.7
Number of bands	1	1	2	2	1	1	1	1

XII. Conclusion

This article has comprehensively reviewed reconfigurable passive planar circuit design techniques reported in the literature. It covers the most important design techniques, namely the varactor, MEMS switch, PIN diode, SIW, resonators, and π-shaped of varactor networks. A comparative analysis of the design techniques and reconfigurable components are also discussed.

Component selection for reconfigurable design has also been explained so that new researchers can choose the component for their design that will deliver the desired features. Furthermore, the impact of technology/structure when combined with a reconfigurable structure was also covered, so that researchers can learn the impact of other technology with reconfigurable components on the design.

We hope that this review will be helpful to researchers and engineers who work in the RF and microwave domains. Furthermore, we believe that our assessment will encourage engineers working in the industry to carry out fresh investigations in this field.

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