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"فیلتر میان گذر مایکروویو قابل سوئیچ با باند توقف وسیع با استفاده تشدیدکننده های امپدانس پله ای موازی بارگذاری شده"

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Electronically Switchable Microwave Bandpass Filter With Wide Stopband Using Parallel Loaded Stepped-Impedance Resonators

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Abstract—**In this paper, a new switchable bandpass filter based on loaded stepped-impedance resonators (SIRs) is introduced. A PIN diode is used to switch the resonant frequency of the SIRs between ON and OFF state according to its bias conditions. The designed filter consists of three SIRs with same fundamental frequency and different spurious frequencies in order to have bandpass filter with wide stopband characteristics. Measured results show insertion loss of 1.14 dB at 2.3 GHz and provide wide stopband up to 4.75$f_0$in its ON state. Also, the isolation of filter is better than 20 dB at center frequency and better than 10 dB from dc up to 4.7f_0 in OFF state.**

Keywords-stepped-impedance resonators; switchable filter; wide stopband filter;

I. INTRODUCTION(HEADING 1)

Microstrip switchable filters at microwave frequencies are essential building blocks in RF and microwave systems. Microwave switches are generally designed by Field Effect Transistors (FETs) and PIN diodes. Most of these switches are based on wideband design and no sharp cutoff outside the operating band leading to poor selectivity. To increase their selectivity and to improve the out of band rejection, a series of cascaded bandpass filters are needed, which causes an increase in circuit size and overall insertion loss. Therefore, a switchable planar BPF that integrates the filter and switch save the circuit area as well as reduce insertion loss.

Planar filters are very popular due to their light weight, easy fabrication process and low cost. They can also be easily integrated with other circuit components. However, planar filters suffer from spurious response. Several methods have been proposed to resolve this drawback [1-4] in literature.

In [5] a ring resonator loaded with two PIN diodes has been presented as a switchable filter. Diodes are placed across the gaps at 90° from the feed point, so the odd modes can be electronically switched by bias conditions. In [6] a coplanar waveguide-slotline filter, using PIN diodes is proposed. A switchable microstrip bandpass filter (BPF) made by shunt connection of inductive short-stubs and FET switches is introduced in [7]. These three filters designed in [5-7] are just analyzed in vicinity of center frequency and suffer from spurious responses. Parallel-coupled BPF is realized in [8-9] based on alternate cascade of open- and short-ended coupled line sections to obtain quarter wavelength resonator filter and introduce transmission zeros to increase stopband. These filters provide wide stopband and also offer good stopband rejection in ON and OFF state but they are not compact. Stepped-impedance resonators (SIRs) are also common in designing wide stopband filters. Diode loaded stepped-impedance resonators with different length and impedance ratio were used to implement compact switchable BPFs [10] with better isolation and wide stopband. However, it requires two or three diodes which increase total loss and negative bias voltage is needed to obtain good performance. Moreover, the power consumption is not zero when the filter is switched off.

In this paper, new low profile electronically switchable filter with low insertion and wide stopband BPF is proposed using loaded and unloaded parallel coupled SIRs in which only one PIN diode is used. Simulation results show that proposed filter exhibits passband insertion loss of 0.6 dB at 2.35 GHz and also provide wide stopband up to 4.75f_0 in its ON state.

II. THEORY OF STEPPED-IMPEDANCE RESONATORS

A. *Unloaded stepped-impedance resonators*

Fig. 1 shows the structure of a stepped-impedance resonator consist of three sections with high and low impedances corresponding to narrow and wide sections respectively. Resonant condition of such resonator is occurred, while $Y_{in}=0$. Y_{in} is the input admittance seen from the open end of the resonator. Using transmission line theory, input admittance of the SIR structure is obtained by equation (1).

$$Y_{in} = jY_{02}\frac{2(k\tan\theta_1 + \tan\theta_2)(k - \tan\theta_1\tan\theta_2)}{k(1-\tan^2\theta_1)(1-\tan^2\theta_2) - 2(1+k^2)\tan\theta_1\tan\theta_2} \quad (1)$$

in which k is the impedance or admittance ratio defined as $k = Z_{o2}/Z_{o1}$ and $k = Y_{o1}/Y_{o2}$. The fundamental resonant frequency is obtained by equation (2).

$$k = \tan\theta_1 \tan\theta_2 \quad (2)$$

It is clear from (1) and (2) that by properly adjusting the impedance ratio, one can have resonators with higher order frequencies far from fundamental frequency. Also by adjusting another parameter designated by $u = \theta_2/(\theta_1+\theta_2)$ and choosing different sets of k and u, SIRs can be designed with same center frequency but different spurious frequencies leading to filter design with wide stop band characteristics [1].

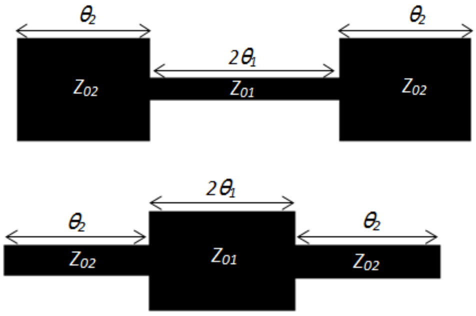


Figure 1: Two SIR Structures

B. *Loaded stepped-impedance resonators*

A loaded SIR structure is shown in Fig. 2. Impedance Z_L placed at one end of the resonator represents the equivalent circuit of a microwave switch. Using a PIN diode switch and changing its bias condition, a SIR with variable electrical length is obtained. Therefore, resonant frequency of the loaded SIR varies accordingly. Capacitive loaded SIR acts as a half-wavelength resonator whereas inductive loaded SIR behaves like a quarter-wavelength one, so the filter will be ON or OFF respectively and so, an electronically switchable bandpass filter with wide stopband is realized. Insertion loss of switchable filters is mostly due to loss of the switch, and so using fewer diode leads to lower insertion loss.

Input impedance of the loaded SIR and its resonant frequency is derived using equations (3) to (5).

$$Z_{in2} = Z_{02}\frac{Z_L + jZ_{02}\tan\theta_2}{Z_{02} + jZ_L\tan\theta_2} \quad (3)$$

$$Z_{in1} = Z_{01}\frac{Z_{in2} + jZ_{01}\tan 2\theta_1}{Z_{01} + jZ_{in2}\tan 2\theta_1} \quad (4)$$

$$Z_{in} = Z_{02}\frac{Z_{in1} + jZ_{02}\tan\theta_2}{Z_{02} + jZ_{in1}\tan\theta_2} \quad (5)$$

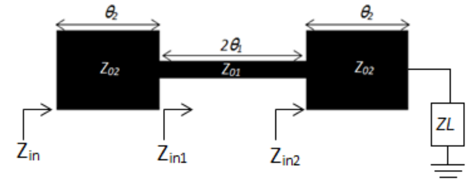


Figure2.Structure of a loaded SIR

Resonant condition of the loaded SIR can be obtained by applying $1/Z_{in}$=0. Resonant condition can be written by (6).

$$\begin{gathered}\left[Z_{02}^2 Z_{01}(1-\tan^2\theta_2) - Z_{02}\tan\theta_2\tan 2\theta_1\right] \\ + j\left[2Z_{01}Z_{02}Z_L\tan\theta_2 + Z_L\tan\theta_2\tan 2\theta_1(Z_{02} - Z_{01}^2)\right] = 0\end{gathered} \quad (6)$$

Depends on bias condition of PIN diodes, the SIR can be ON or OFF. As it is obvious from (6), resonant condition of a loaded SIR like an unloaded one can be adjusted by properly choosing characteristic impedances of high and low impedance sections, where $Z_L$is the equivalent circuit of a PIN diode in ON or OFF state. When PIN diode is in reverse bias its equivalent circuit can be approximated by a capacitor, so by replacing Z_L= $-jX_C$ in equation (6), the resonant condition of SIR is obtained by equation (7).

$$\begin{gathered}[Z_{02}^2 Z_{01}(1-\tan^2\theta_2) - Z_{02}\tan\theta_2\tan 2\theta_1] + \\ [2Z_{01}Z_{02}X_c\tan\theta_2 + X_c\tan\theta_2\tan 2\theta_1(Z_{02} - Z_{01}^2)] = 0\end{gathered} \quad (7)$$

In case of forward bias for PIN diode switch, the equivalent circuit is approximated by an inductance. As a result, Z_L= jX_L is replaced in equation (6) and resonant condition is given by equation (8).

$$\begin{gathered}[Z_{02}^2 Z_{01}(1-\tan^2\theta_2) - Z_{02}\tan\theta_2\tan 2\theta_1] - \\ [2Z_{01}Z_{02}X_L\tan\theta_2 + X_L\tan\theta_2\tan 2\theta_1(Z_{02} - Z_{01}^2)] = 0\end{gathered} \quad (8)$$

The diode used in this paper is Infineon's BAR65-02V [11] with equivalent lumped elements listed in table I.

TABLE I. EQUIVALENT LUMPED ELEMENTS OF PIN DIODE BAR65-02V

L_s(nH)	R_p(kΩ)	L_p(nH)	C_j(pF)	R_f(Ω)
0.1	10	0.8	0.33	1

III. ELECTRONICALLY SWITCHABLE FILTER DESIGNE

Fig. 4 shows the schematic view of the proposed BPF filter and fig. 5 depicts photograph of proposed switchable filter. It consists of three parallel SIR, while two SIRs are unloaded and the middle one is loaded by a PIN diode at one end. Three SIRs are designed to have same center frequency but provide different spurious frequencies when diode is ON. When the diode is forward-biased the filter is in its OFF state. In this condition, according to equation (6), the loaded SIR no longer resonates at 2.35 GHz, results in suppressing the two other SIRs and makes the filter OFF. Based on the equivalent circuit of PIN diode, in ON state resonator 2 has capacitive load whereas in OFF state its load is inductive.

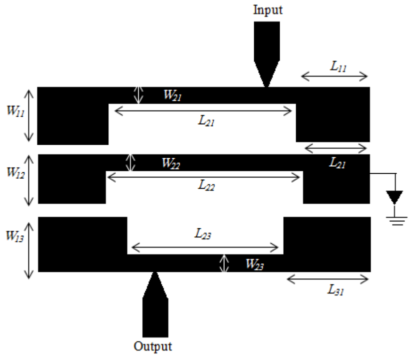


Figure 3.Schematic view of the proposed switchable filter

Figure 4.Photograph of the proposed switchable filter

The third-order Butterworth filter is used for the design procedure of the filter at center frequency of 2.35 GHz with at least 12% fractional bandwidth. The coupling coefficients and external quality factor of this filter are calculated using equations (9) [12].

$$\begin{cases} M_{12} = \dfrac{FBW}{\sqrt{g_1 g_2}} = 0.08 & M_{23} = \dfrac{FBW}{\sqrt{g_2 g_3}} = 0.08 \\ Q_{ei} = \dfrac{g_0 g_1}{FBW} = 8 & Q_{eo} = \dfrac{g_3 g_4}{FBW} = 8 \end{cases}$$

in which g_i's are lowpass element values of Butterworth prototype filter and are listed in Table II.

TABLE II. LOWPASS ELEMENT VALUES OF CHEBYSHEV PROTYPE FILTER

g_0	g_1	g_2	g_3	g_4
1	1	2	2	1

The coupling coefficients are used to determine the distance between adjacent SIRs. The coupling coefficient is evaluated from two dominant resonance frequencies $f_1$and $f_2$given by equation (10), in which M_{ij} represents the coupling coefficient between resonator *I* and *j* [12].

$$M_{ij} = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \tag{10}$$

To obtain the exact values of the physical parameters of the three SIRs and distances between adjacent ones, full-wave simulator SONNET has been used to adjust filter characteristics for the best result. The proposed filter is simulated using TLY031 substrate with ε_r=2.17, loss tangent of 0.0009 with thickness of 0.7874 mm. The total size of the filter is 25×35 mm$^{2.}$

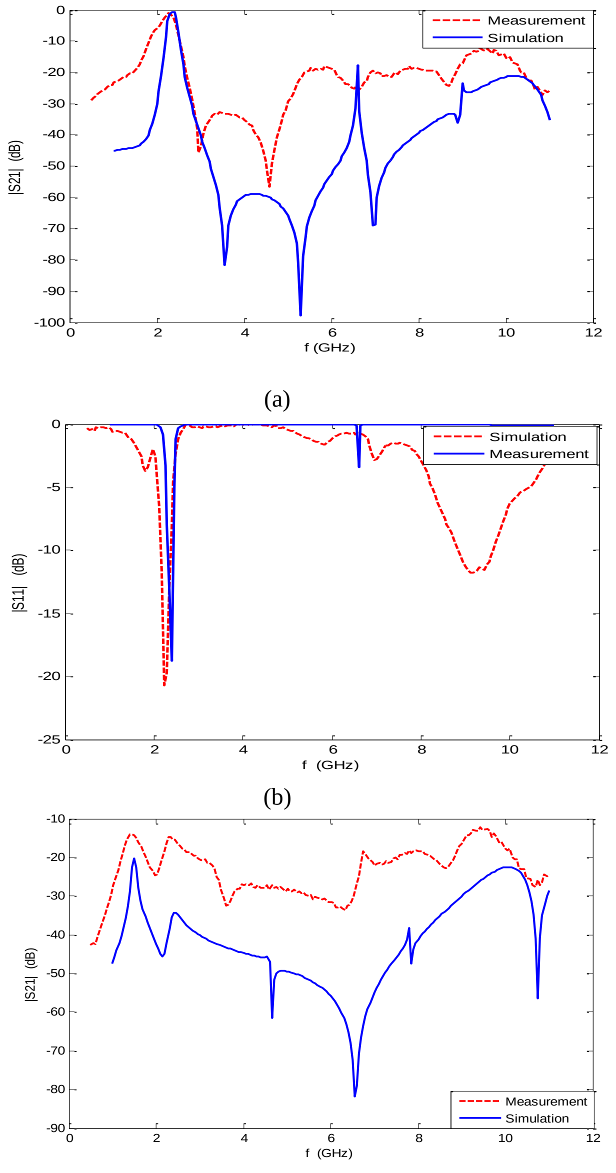
TABLE III. PHYSICAL DIMENSIONS AND RESONANT FREQUENCIES OF RESONATORS IN ON STATE

	physical dimensions (mm)	resonant frequencies in ON state		
		f_0	f_1	f_2
SIR 1	W_{11}=2.8, L_{11} =7.6 W_{21}=0.4, L_{21}=15.6	2.35	7.2	12.1
SIR 2	W_{12}=2, L_{12}=7.4 W_{22}=0.39, L_{22}=16	2.35	6.55	9
SIR 3	W_{13}=2.9, L_{13}=9.05, W_{23}=0.4, L_{23}=12.7	2.35	7.9	11.6

IV. RESULTS

The physical dimensions and resonant frequencies of the proposed filter are listed in Table III. Also, filter characteristics including measured and simulation results for reflection and transmission coefficients are presented in Fig 5a to Fig 5c. It can be seen that measured results are in a good agreement with those obtained by simulation. The filter specifications are available in table IV for comparison between these results According to Simulation results, at the center frequency of 2.35 GHz insertion loss is 0.6 dB in passband and stopband attenuation is at least 20 dB up to 4.75 f_0 in ON state. Moreover, in OFF state, stopband attenuation is better than 20 dB from dc up to 4.7f_0.

The obtained insertion loss of the proposed filter in passband is very low and its stopband bandwidth is also wide. These are the advantages of the filter. Wide bandwidth is due to tight coupling between different resonators and low insertion loss is being attributed to the use of only one PIN diode switch. The difference between simulation and measured results especially attenuation in stopband, Figure 5(b), is due to diode and substrate loss and systematic errors in measurement. Moreover, the 3-dB bandwidth of the fabricated filter is 12 %, which is narrowband due to the resonate characteristics of the SIR structures. However, using series of SIR structures with near resonate frequency a wider bandwidth filter could be designed and implemented.



(a)

(b)

(c)

Figure 5. Simulated and measured results of filter in ON and OFF state: a) $|S_{21}|$ in ON state, b) $|S_{11}|$ in ON state, c)$|S_{21}|$ in OFF state

V. CONCLUSIONS

A switchable bandpass filter using three parallel stepped-impedance resonators and one PIN diode have been designed and simulated. Stepped-impedance resonator loaded with Z_L at one end is also studied and its resonant condition is obtained using transmission line theory. Then by replacing Z_L by the equivalent circuit of PIN diode and combining loaded and unloaded SIRs, a compact bandpass switchable filter with wide stopband is designed. The proposed switchable filter provides a very low insertion loss in passband in ON state and good attenuation at center frequency in OFF state. Moreover, they offer wide stopband bandwidth with at least 30 dB attenuation.

TABLE IV. SIMULATION AND MEASUREMENT RESULTS COMPARISON

	Simulation	Measurement
f_0(GHz)	2.35	2.3
insertion loss (dB)	0.6	1.14
attenuation at f_0 in OFF state (dB)	32	20

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