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Research paper

Reconfigurable Hairpin Bandpass Filter for Wireless Applications

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Abstract

This paper introduces a reconfigurable Hairpin Bandpass Filter incorporated with PIN diode switching mechanism with good return loss and band pass characteristics for wireless communications. The proposed filter consists of hairpin bandpass filter incorporated with switching mechanism placed over Arlon substrate with an effective dielectric constant of 2.2 and is designed to operate at two different resonant frequencies, i.e., at 1.75 GHz and 3.5 GHz independently by controlling the switching conditions of the PIN diodes. The filter is designed to offer a fractional bandwidth of 11% at 3.5GHz and 13% at 1.75GHz. A proto type is fabricated and tested accordingly and the corresponding results are presented. The design is validated using the commercially available simulating software CST Microwave Suite and the results are compared with the measured values and a good agreement between them is obtained. The structure is better suitable for reconfigurability applications when attached to an antenna with the appropriate biasing network and finds many applications in wireless communication systems.

Keywords: *Hairpin Bandpass Filter, PIN diodes, Reconfigurability, Wireless communications, CST Microwave Suite*.

1. Introduction

Microstrip bandpass filters gain much attention in microwave communication systems due to their good pass band response, low insertion loss, reduced size, ease of fabrication and its ability to integrate with other devices. The Hairpin bandpass filters are most widely used compact narrow band microwave structures with a suitable ground plane. It is basically a parallel coupled half wavelength resonator formed by folding back the end of the resonators in "U" shape [1]. In these filters, the space is saved by folding the resonator which is half the wavelength long and the design is similar to that of a parallel coupled filter. However, it is essential to consider the reduction of coupled line lengths, which reduces the coupling between the resonators by folding the resonators. Also, the spacing between the resonators should be small so as to increase the coupling effect [2]. The Hairpin filters consist of a transmission line resonators having the electrical length of $\lambda/4$ and these elements are open at one edge for the possible conversion into the short circuits and vice versa. The small distance between the elements is to influence the electromagnetic field which results in coupling between the elements. The different elements of the filter are designed to have the impedance matching by looking into their characteristic impedance Z_0. This kind of structures offers high-quality factor Q. However, they are restricted by the usage of the dielectric substrate, the limited conductivity of the patch and radiation losses [3]. In general, the basic Hairpin Band Pass filter consists of folded arms of the coupled resonators and the design of a three arm filter is discussed below. The basic Hairpin band pass filter and its equivalent resonator circuit are shown in the Fig. 1. Fig.2 represents an element of a hair pin band pass filter structure and its equivalent circuit.

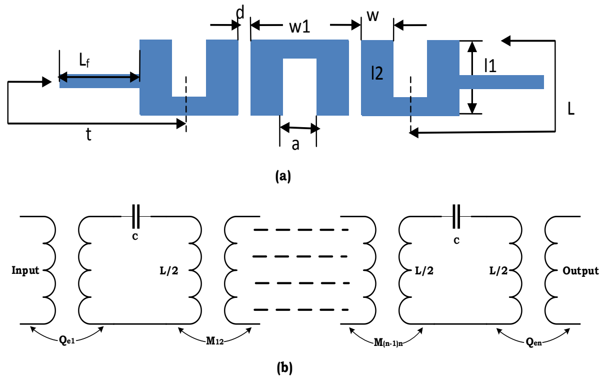


Fig. 1: (a) Hairpin Bandpass Filter (b) Equivalent RLC resonant circuit

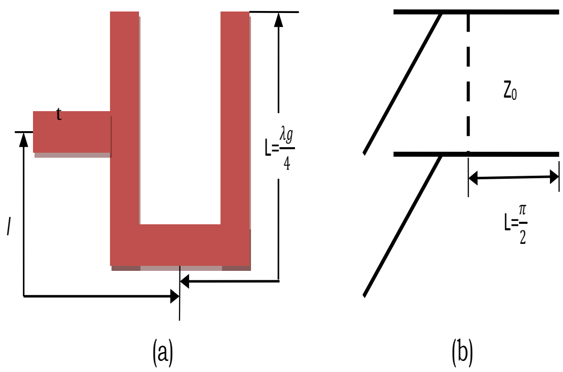


Fig. 2: (a) Arm of Hairpin Bandpass Filter (b) Equivalent circuit

The design is based on Chebyshev response because it is more selective than that of Butterworth filter response. The combination of the inductance and capacitance is used for the design of the resonators and $M_{i,j+1}$ is the mutual coupling coefficient between the resonators. Upon the selection of the resonant frequency and the fractional bandwidth and pass band ripple of the filter, the low pass prototype parameters are used to calculate the band pass parameters by using the quality factors Q_{e1} and Q_{en}. These relations are used to determine the overall size and the gap between the resonators and can be derived from the following relations [3] and are given by

$$Q_{e1} = \frac{g_0 g_1}{FBW}; Q_{en} = \frac{g_n g_{n+1}}{FBW} \quad (1)$$

$$M_{i,j+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \text{ for } i = 1 \text{ to } n-1 \quad (2)$$

where Q_{e1} and Q_{en} are the external quality factors of the resonator at the input and out circuit and $M_{i,j+1}$ are the coupling coefficients between the adjacent resonators. The normalized low pass parameters of the desired band pass filter approximation are denoted by g_0, g_1, g_2 …g_{n+1} and FBW is the fractional bandwidth.

These coupling coefficients are determined by the spacing between the resonators and the corresponding coupling coefficient can be determined by the formula given in [4]

$$M = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \quad (3)$$

where, f_1 and f_2 are two peak resonant frequencies obtained from the adjacent resonators. If the self-coupling is neglected in the filter, then the tapped position can be computed from the equation given by [5]

$$t = \frac{2L}{\pi} sin^{-1}\left(\sqrt{\frac{\pi}{2}\frac{Z_0}{Q_e Z_r}}\right) \quad (4)$$

where, Z_0 is the terminating line Impedance, Z_r is the characteristic impedances, Q_e is the external quality factor and L is the section size of the Hairpin filter. The arm Length L can be calculated by formula given by

$$L = \frac{\lambda_g}{4} \quad (5)$$

Where

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{re}}} \quad (6)$$

Moreover, λ_0 is the wavelength, λ_g is the guide wavelength of the Hairpin bandpass filter with resonant frequency f_0 in free space. Also when the ratio between the microstrip width w and substrate height h is less than the value of 2, then the effective dielectric constant ε_{re} is given by

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + (12h/w)}} \quad (7)$$

Where, ε_r is the dielectric constant, h is the height, w is the width of the substrate. It is necessary to shorten the resonators at the input and output to compensate the coupling effect in between the tapped line and the adjacent resonator in the realization of the Hairpin band pass filter. However, the tapping position and the spacing between the adjacent resonators can be adjusted to have multi band operation. Also, it is required to match the microstrip length and width of the tapped position to 50 Ω to avoid the spurious responses out of the filter and to attain the stable pass band characteristics. However, these equations are helpful in the design of a parallel coupled line filter and obtained values can be used for the electromagnetic simulations.

It is found in the literature that there are wide varieties of the designs to change the performance characteristics of the realized Hairpin bandpass filters. Yang et al. [6] have demonstrated a dual band microstrip bandpass filter for K_u band applications. The design offered the dual band operation by adopting different spacing values between the adjacent resonators and the insertion loss is reported when the filter is operated at higher frequencies due to the losses in the substrate.

Kershaw et al. [7] have demonstrated a Hairpin bandpass filter with square shaped defected ground plane structure. The proposed design was used for radar and satellite communications at S-Band because of good pass band characteristics and the structure has resulted to a sharp mid-frequency with improved return loss but needs improvement in the insertion loss.

A wideband Hairpin bandpass filter demonstrated by Gunjal et al. [8] functional at ISM band, is achieved by the usage of a high dielectric constant material. The structure consists of five microstrip U shaped resonators and the positions of the two resonators are shifted in their positions with respect to centre and the structure is tapped in this type of construction. However, the usage of higher dielectric constant substrate results in losses at higher frequencies.

Vidhya et al. [9] have demonstrated a filter structure with a defected ground plane under the feed line attached with dumbbell shaped open stubs. The defected ground structure is useful in improving the stop band rejection without affecting the centre resonant frequency and insertion loss. However, the improvement in the pass band ripples can be observed with this design, but the open stubs have resulted in the out of band suppression.

Sharma et al. [10] have proposed a compact Hairpin multi fold filter structure for GSM, GPS and wireless LAN applications operating at ISM band. The filter is designed by using fifth order Chebyshev polynomial and reported to have good pass band characteristics. However, the design demonstrated the spurious modes due to inhomogeneities of the structure.

Therefore, it is found that the Hairpin bandpass filter offers narrowband characteristics and they can be easily integrated with the antenna structures so as to filter out a specific frequency of interest from their operation. In this context, the design of a Reconfigurable Hairpin bandpass filters suitable for the proposed work is discussed in the next section.

2. Design of Reconfigurable Hairpin Bandpass Filter

In this section, the design of the reconfigurable filter using a hairpin band pass filter incorporated with PIN diode switching mechanism is discussed. Therefore, this structure can work at different resonant frequencies independently by operating the switches in various states. These filters can be used for reconfigurability applications when attached to the antenna with the appropriate biasing network.

In the proposed structure, a hairpin band pass filter is preferred to operate at two different resonant frequencies, i.e., at 1.75 GHz and 3.5 GHz independently by controlling the switching conditions of the PIN diodes. The reconfigurable filter can be constructed using three independent U shaped hair pin sections and the length of each microstrip arm is extended to a suitable gap arrangement so as to place the PIN diode switches. The filter is designed to offer a fractional bandwidth of 11% or FBW =0.11 at a mid-frequency of f_0 = 3.5 GHz and the corresponding upper cut of the frequency of 3.7 GHz and the lower cut off frequency is 3.3 GHz when all the PIN diodes are in OFF state. Similarly, when all the PIN diodes are in ON state, the filter can have a fractional bandwidth of 13 %, FBW=0.13 with a mid-frequency of f_0 =1.75 GHz and the corresponding upper cut off frequency is 1.82GHz and the lower cut off frequency is 1.58 GHz. The frequencies that are considered in this design are to be cascaded with an antenna structure working at 1.75 GHz and 3.58 GHz.

The substrate used in this design is Arlon with a dielectric constant of 2.2 with a thickness of 1.6 mm and loss tangent tan δ =0.0009 having zero surface roughness. The length and width of the substrate are given by 100 mm and 36 mm respectively. The selected order for this structure is n=3 and the corresponding low pass prototype parameters for the Chebyshev response with a pass band ripple of 0.1 dB are given by g_0 = 1.000, g_1 =1.0315, g_2 =1.474, g_3 =1.0315 and g_4 =1.000 normalized with respect to a 50 Ω impedance. The dimensions of the distributed elements can be calculated using these values through which the corresponding coupling factor and the impedance are estimated. The design dimensions of the Hairpin sections are estimated by the Eq. (1) to (7) as discussed in Section I. The design values obtained for the proposed reconfigurable hairpin filter are as follows; the width of the strip is given by W=0.316 mm, the length of the feed line is L_f = 0.5 cm. The length of each U arm at the edges is given by L= 2.162 cm ($l1 = 1.774\ cm, W1 = 0.776\ cm, l2 = 1.774\ cm$) while the Length of the middle U arm is given by 2.212cm ($l1 = 1.774\ cm, W1 = 0.876cm, l2 = 1.774\ cm$) and the successive difference in between two arms is a = 0.144 cm. The separation between the different Hairpin sections is given by d= 0.138 cm. Similarly, in this construction, the length of each microstrip line is extended by a value of 0.13 cm and width by 0.316 cm with a gap of 0.3 cm to integrate the PIN diode switches. These switches can be used to realize the reconfigurability mechanism and the PIN diodes used in this design is of Skyworks make, SKY13351-378LF, GaAs SPDT switches [11] with an operating frequency range of 20MHz to 6GHz. The operating voltages of these diodes are up to 1.8 V and they offer a very low insertion loss of 0.35 dB and an isolation of 24 dB. Three blocking capacitors of 100 pF and two bypass capacitors of 33 pF are placed in the biasing network so as to prevent the back current flow into the circuitry. A total of six number of PIN diodes are placed in gaps provided between each microstrip line of hairpin section and the extension of the arms. The schematic of the reconfigurable Hairpin bandpass filter is shown in the Fig. 3. The corresponding AutoCAD layout for the reconfigurable Hairpin Band Pass filter is shown in Fig.4.

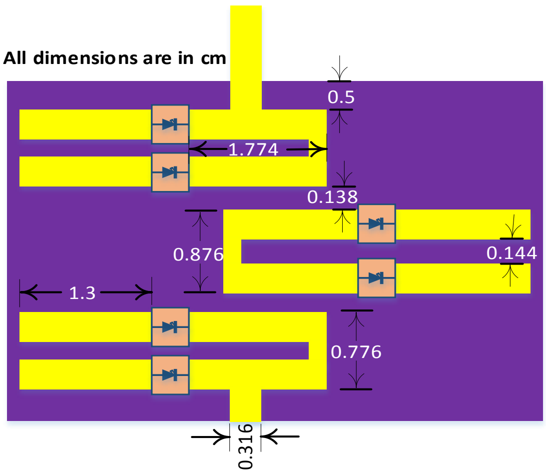


Fig. 3: Schematic of the Reconfigurable Hairpin Bandpass Filter

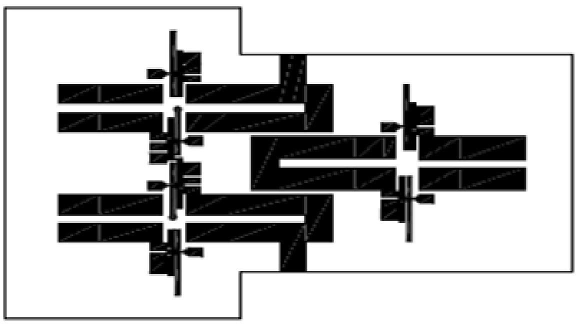


Fig. 4: AutoCAD Layout of the Reconfigurable Hairpin Bandpass Filter

The design dimensions and the corresponding specifications of the reconfigurable hairpin band pass filter are tabulated in Table 1.

Table 1: Design Specifications of the Hairpin reconfigurable filter

S.No	Name of the Item	Parameter	Value
1	Substrate: Arlon	Dielectric constant (ε_r) Loss Tangent (tan δ) Substrate thickness (t)	2.2 0.0009 0.16 cm
		Length (Ls) Width (Ws)	10 cm 3.6 cm
2	3.5GHz Filter Pass band 3.3- 3.7 GHz f_0 =3.5GHz	Length of the U arm Width of the U arm Spacing with in U arm Separation of two arms Feed Length	7.524 cm 0.316 cm 0.144 cm 0.138 cm 0.5 cm
	1.75GHz Filter Pass Band 1.58-1.82GHz f_0 =1.75GHz		
3	PIN diode switches (06 no's)	Skyworks make, SKY13351-378LF, GaAs SPDT	20MHz-6GHz

The reconfigurable Hairpin bandpass filter using PIN diode switching mechanism is designed based on the specifications given in Table 2.4. The design is validated using the CST Microwave Suite and the schematic drawn in the simulator along with the fabricated prototype is shown in the Fig. 5.

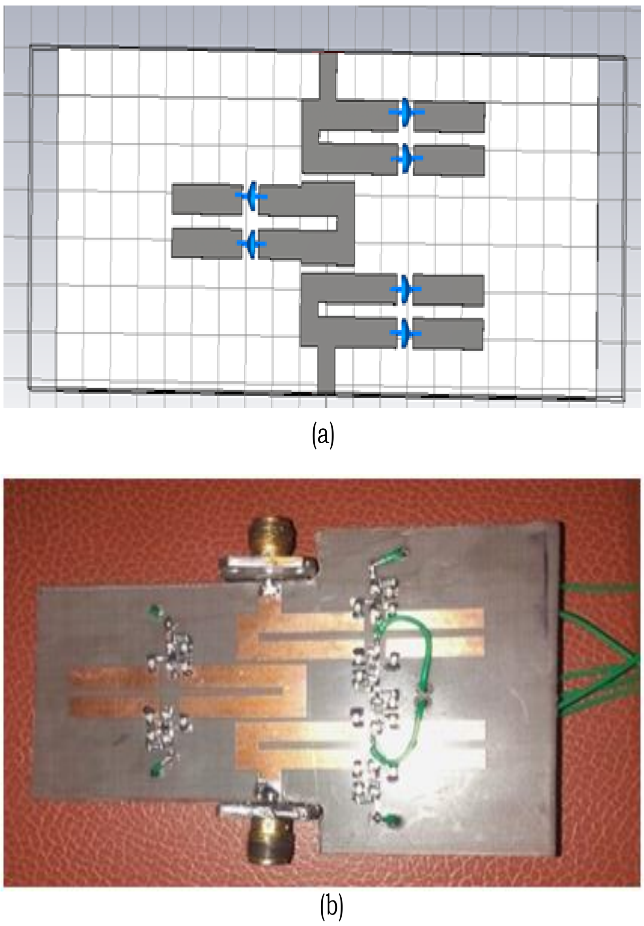
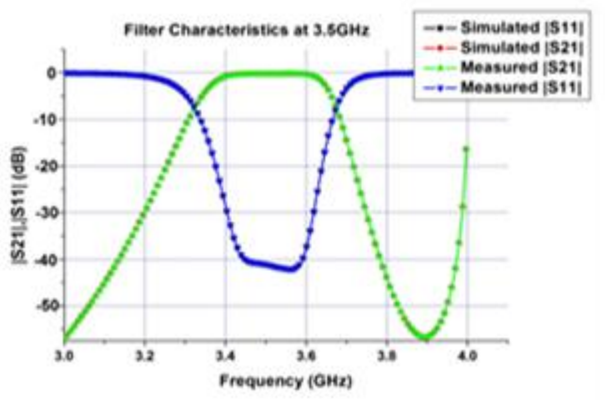


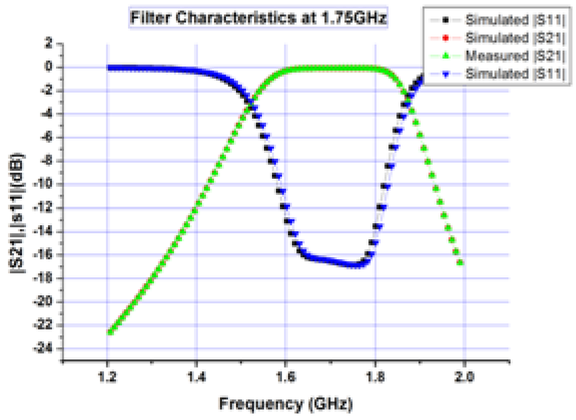
Fig.5: Reconfigurable hairpin Band Pass Filter (a) Schematic drawn in CST Simulator (b) Fabricated prototype

3. Results and Discussion

These filters are tested using a standard Vector Network Analyzer and the corresponding simulated and measured results are shown in the Fig. 6.



(a)



(b)

Fig. 6: Filter responses at (a) 1.75GHz (b) 3.5GHz

The response plot from Fig. 6 shows that the reconfigurable filter offers good pass band characteristics in both the modes. The filter is resonating at 3.5 GHz when all the PIN diode switches are in OFF condition with good pass band characteristics from 3.3 GHz to 3.7 GHz with a return loss value -41 dB. Similarly, the Reconfigurable Hairpin band pass filter offers a resonant frequency of 1.75 GHz with good pass band characteristics from 1.6GHz to 1.8GHz range with a return loss -17.23 dB. It can be observed from the above results that the filter is offering a fractional bandwidth of FBW = 0.11 or 11% at 3.5 GHz and offering a pass band from 3.3 GHz to 3.7 GHz. Similarly, the structure offer the pass band characteristics from 1.58 GHz to 1.82 GHz for a centre frequency of 1.75 GHz with a FBW = 0.13 or 13%. This makes the structure further compact by directly switching the PIN diodes ON and OFF to achieve the reconfigurability.

4. Conclusions

Therefore, the reconfigurable filter is found to be very compact and can offer the reconfigurability with in single structure which is suitable for wide variety of applications in the wireless communication systems. These filters are helpful in achieving the frequency reconfigurability when operated along with the antenna structures. They provide constant gain over the band of frequencies over which the antenna is resonating as they are external to the antenna system and do not alter the current distributions of the structure. Further, the additional isolation is provided by the usage of PIN diodes will help out in reducing the interference at the receiver. Furthermore, the combination of the antenna structure along with filtering mechanism reduces the size and cost of the structure with increased ease of fabrication and can find many applications in the reconfigurable systems.

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