Modeling of Compact, Broad-stopband Lowpass Filter using Modified Stepped Impedance Hairpin Resonators

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Abstract—A compact elliptical function lowpass filter using modified stepped impedance hairpin resonators is proposed. The filter is analyzed from the equivalent lumped-element model using transmission line theory. The model is evaluated with EM simulation with good agreement. For single lowpass filter, the return loss is better than 13 dB from DC to 1.5 GHz where the insertion loss is less than 0.5 dB with considerable pass band ripple, ± 0.3 dB. The rejection is greater than -15 dB from 2.0 GHz to 10 GHz. By cascading proposed lowpass filters with different length and width, more rejection in stopband, low insertion loss, broad stopband can be obtained to design an efficient filter for many wireless communication systems.

Index Terms—Low pass filter, micro strip, hairpin resonator, broad stopband.

I. INTRODUCTION

Microstrip hairpin resonator has been drawing much attention to microwave filters designing. From half-wave length to the stepped impedance resonator, a broad stop band and compact size has been emerging in recent research [1]-[4]. Microstrip elliptical filter has more advantage than Chebyshev and Butterworth filters, i.e, high performance, low cost and easy fabrication [5-6]. However, L. H. Hsieh et al. has modelled the microstrip stepped impedance hairpin resonators with transmission line theory [7]. It has broad stopband and compact in size. An improved design has been proposed by M. H. Yang with modified stepped impedance hairpin resonator [8]. But it has not been yet modeled in circuit elements.

In this paper, a new microstrip lowpass filter using stepped impedance hairpin resonator with a pair of couple triangular stepped impedance resonators inside is modeled. The couple stepped impedance resonators are used as a capacitor to have sharp cutoff and create transmission zero for a broad stopband. At the same time it has been optimized by EM simulation. For the simulation Agilent Advanced Design System (ADS) version:2011.01 is used.

II. EQUIVALENT CIRCUIT FOR MODIFIED STEPPED IMPEDANCE HAIRPIN

Fig-1 shows the layout of modified stepped impedance hairpin resonator. It has three parts- series line (fig-2(a)),

parallel couple line (fig-2(b)) and the modified triangular couple line (fig-2(c)). First, the series line has a length of $l_s = 2l_3 + l_2$ and width of w_2 . As the length, l_s is larger than the width, w_2 , it shows good inductance. Then the parallel couple line has large width, w_3 , length, l_4 and gap between parallel plates, g . The modified triangular couple line has a length, l_6 , width, $w_c' = l_2 - 2.w_4$ and a gap between the triangular plates, x . If Z_s is the characteristic impedance of the single transmission line l_s , Z_o and Z_e are the odd and even impedance for the parallel couple line, we took $Z_s > \sqrt{Z_o Z_e}$ to reduce the size of conventional hairpin resonator [3].

ABCD parameter of Pi-model of single transmission line which has a length of l_s is shown here below,

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \cos(\beta_s l_s) & jZ_s \sin(\beta_s l_s) \\ jY_s \sin(\beta_s l_s) & \cos(\beta_s l_s) \end{pmatrix} \quad (1)$$

where, β_s and $Y_s = \frac{1}{Z_s}$, are the phase constant and characteristics impedance. The ABCD parameter of the equivalent L-C pi-network (shown in fig-2(b)),

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 + Z_L Y_C & Z_L \\ Y_C(2 + Z_L Y_C) & 1 + Z_L Y_C \end{pmatrix} \quad (2)$$

where, $Z_L = j\omega L_s$ and $Y_C = j\omega C_s$.

Computing equation (1) and (2),

$$L_s = \frac{Z_s \sin(\beta_s l_s)}{\omega} \quad (H) \quad (3)$$

Fig. 1. Stepped impedance hairpin resonator.

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Fig. 2. Equivalent circuit of (a) single transmission line, (b) Symmetric couple lines, and (c) triangular line capacitance (d) stepped impedance hairpin resonator by combining (a), (b) and (c).

$$C_s = \frac{1 - \cos(\beta_s l_s)}{\omega Z_s \sin(\beta_s l_s)} \quad (F) \quad (4)$$

Now the symmetric triangular couple line can be shown as an equivalent circuit (fig-2(c)). The elements of this equivalent circuit can be derived from Z_o and Z_e . ABCD parameter for symmetric parallel couple line is shown as below [9]:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \frac{Z_e \cot \theta_e + Z_o \cot \theta_o}{Z_e \cot \theta_e - Z_o \cot \theta_o} & -j \frac{2Z_e Z_o \cot \theta_e \cot \theta_o}{Z_e \cot \theta_e - Z_o \cot \theta_o} \\ j \frac{2}{Z_e \cot \theta_e - Z_o \cot \theta_o} & \frac{Z_e \cot \theta_e + Z_o \cot \theta_o}{Z_e \cot \theta_e - Z_o \cot \theta_o} \end{pmatrix} \quad (5)$$

where, $\theta_o = \theta_e = \beta_c l_c$, and β_c is the phase constant of the couple lines. Also the ABCD parameter of couple line equivalent circuit,

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 + Z_g Y_p & Z_g \\ Y_p (2 + Z_g Y_p) & 1 + Z_g Y_p \end{pmatrix} \quad (6)$$

Now comparing the two matrices in (5) and (6), the equivalent capacitance can be derived as below:

Fig. 3. Stepped impedance resonator (a) and its equivalent circuit (b) with dimension parameter.

$$C_g = \frac{Z_o - Z_e}{2\omega Z_o Z_e \cot(\beta_c l_c)} \quad (F) \quad (7)$$

$$C_p = \frac{1}{\omega Z_e \cot(\beta_c l_c)} \quad (F) \quad (8)$$

Now, combining these two equivalent circuit shows the final equivalent circuit where, $C_{ps} = C_p + C_s$. Here, we have neglected the junction discontinuity for simplicity.

The modified symmetric parallel couple line can be shown as an equivalent circuit (fig-2(d)) [10],

$$C'_p = \frac{C_{even}}{2} \quad (F) \quad (9)$$

$$C'_g = \frac{C_{odd}}{2} - \frac{C_{even}}{4} \quad (F) \quad (10)$$

where, C_{odd} and C_{even} are the even and odd capacitance for the modified triangular coupled line.

Now, combining these three sections of equivalent circuit, the total equivalent circuit can be calculated from the equation (3), (4), (7), (8), (9) and (10).

III. COMPACT MODIFIED ELLIPTICAL FUNCTION LOW-PASS FILTERS

Fig-3 shows the geometry and equivalent circuit of the elliptical function low-pass filter using one modified stepped impedance hairpin resonator with feed lines, l_f . Also L_s is the equivalent inductance of the single transmission line of the filter. C_g is the equivalent capacitance of the couple lines and C_{ps} is the sum of the capacitances of the transmission line l_1 and the couple lines. The low pass filter has been designed for a 3dB cut-off frequency of 1.5GHz and fabricated on a 0.254mm thick RT/Duroid 5880 substrate with a relative dielectric constant $\epsilon_r=2.2$. The dimensions considered in this modeling are as below: $l_1=18\text{mm}$, $l_2=5\text{mm}$, $l_3=5.3\text{mm}$, $l_4=6.2\text{mm}$, $l_5=1\text{mm}$, $w_1=0.79\text{mm}$ for a 50Ω line, $w_2=0.2\text{mm}$, and gap size $g=0.2\text{mm}$, $w_4=w_6=0.2\text{mm}$, $w_5=0.4\text{mm}$.

The modeled filter has a -3dB passband from DC to 1.5GHz and has a better attenuation -15dB from 2.0GHz to 10GHz. Its insertion loss at passband is less than 0.5dB as seen in Fig-5. It has two spurious modes at 5.3GHz and 7GHz. Our attention is to suppress these two spurious modes with changing its width and length as design parameter by both circuit modeling and EM simulation. The EM simulation has been carried out by Momentum (MoM simulator) of Agilent ADS. The proposed filter has a dimension of 5.4 mm x 13.49 mm or $0.037 \lambda_g \times 0.093 \lambda_g$, where λ_g is the guided wavelength at 1.5GHz.

Fig. 4. (a) Layout of modified stepped impedance resonator with variation of width, (b) equivalent circuit approximation of symmetrical couple line resonator, (c) configuration of the broadband stopband lowpass filter.

IV. CASCADED MODIFIED ELLIPTICAL FUNCTION LOW-PASS FILTERS FOR BROAD STOP-BAND

The low pass filters using four multiples cascaded modified stepped impedance hairpin resonators is shown in Fig-4. Two resonators can be cascaded by inserting a local variable width for different resonant frequency.

Though it becomes asymmetrical resonator, it can be assumed as symmetrical for simplicity. Fig-4(a) shows the layout diagram of cascaded modified stepped impedance resonators and fig-4(b) shows the circuit diagram. If the local variable width can be thought of a shunt capacitor, C_{sp} is given by,

$$C_{sp} = \epsilon_0 \epsilon_r w / h \quad (F/m)$$

where, w is the width of the adjacent transmission line and h is the substrate height.

From fig-6 and fig-7, the cutoff frequency from the EM simulator is 1.270GHz and from circuit simulation it is 1.263GHz with a difference of 7MHz. This is because of negligence of small inductance created at the junction of series line and couple line.

Fig. 5. EM and circuit simulated results for the lowpass filters designed for 1.5 GHz 3dB cut off frequency.

Fig. 6. Simulated results of the broad stopband lowpass filter with approximated dimensions while different width is considered.

Fig. 7. Comparison of circuit model and EM simulation with approximation of dimension. Here, difference between these two cut-off frequencies is 7 MHz, return loss is lower than -13dB and passband ripple is less than ± 0.42 dB

After 3dB cutoff frequency, rejection region goes below -80dB in EM simulation and a -140dB in circuit simulation. Here, circuit simulation only approximates the cutoff frequency and rejection degree in stopband. The ripple at passband is ± 0.4 dB.

Fig. 8. Layout of modified stepped impedance resonator by cascading with variation of its length.

TABLE I: CIRCUIT ELEMENTS OF CASCADED MODIFIED STEPPED IMPEDANCE RESONATOR

Elements Circuit No.	Cascaded with width variation				Cascaded with length variation					
	(1) $W_{extna} = 0.8$ mm	(2) $2 \times$ $W_{extna} = 1.6$ mm	(3) $3 \times$ $W_{extna} = 2.4$ mm	(4) $4 \times$ $W_{extna} = 3.2$ mm	(1) $X=3$	(2) $X=2$	(3) $X=1.4$	(4) $X=1$	(5) $X=0.8$	(6) $X=0.5$
L_s	6.943 nH	6.943 nH	6.943 nH	6.943 nH	10.25 nH	10.925 nH	9.024 nH	6.943 nH	5.706 nH	3.6717 nH
C_g	0.057 pF	0.057 pF	0.057 pF	0.057 pF	0.2215 pF	0.1253 pF	0.083 pF	0.057 pF	0.0456 pF	0.0283 pF
C_{sp}	2.353 pF	2.353 pF	2.353 pF	2.353 pF	9.268 pF	5.1495 pF	3.386 pF	2.353 pF	1.864 pF	1.1523 pF
C'_g	0.315 pF	0.315 pF	0.315 pF	0.315 pF	1.187 pF	0.7509 pF	0.489 pF	0.315 pF	0.228 pF	0.0969 pF
C'_p	0.837 pF	0.837 pF	0.837 pF	0.837 pF	3.1557 pF	1.9965 pF	1.301 pF	0.837 pF	0.605 pF	0.258 pF
C_1	0.3328 pF	--	--	--	0.985 pF	--	--	--	--	--
C_2	--	0.6656 pF	--	--	--	0.6656 pF	--	--	--	--
C_3	--	--	0.998 pF	--	--	--	0.466 pF	--	--	--
C_4	--	--	--	1.3312 pF	--	--	--	0.333 pF	--	--
C_5	--	--	--	--	--	--	--	--	0.2663 pF	--

X is the length multiplier compared to single modified stepped impedance resonator (shown in Fig-3).

In Fig-8 the length of the cascaded modified stepped impedance resonator is varied along the x-axis. For different length, cut-off frequency varies from minimum (leftmost lowpass filter) to higher (rightmost). As the area of lowpass

filter decreases cut-off frequency increases. Again, observing the frequency response (fig-5) of the low-pass filter (fig-3), the stopband bandwidth is limited by harmonics, especially for the second harmonic. In order to extend the stop band bandwidth, additional attenuation poles at the second harmonic can be added. The additional attenuation poles can be implemented by cascading small size lowpass modified stepped impedance filter. Thus we have a better broad stop band, -60dB from 502 MHz to 10 GHz.

Fig. 9. Simulated results of the broad stopband lowpass filter with approximated dimensions while different length is considered.

Fig. 10. Comparison of circuit model and EM simulation with approximation of dimension. Here, difference between these two cutoff frequencies is 63 MHz, return loss is lower than -10dB and passband ripple is less than ± 0.4 dB

In Fig-9 and Fig-10, we have two results, one from EM simulation and other, from circuit model. Cutoff frequencies of these models differ from 63 MHz which is because of negligence of inductance of series line and couple line. Insertion loss inside passband is less than 0.8 dB, return loss is greater than -12 dB for EM simulation and -5 dB return loss for circuit simulation. The ripple inside the passband is

± 0.42 dB.

V. CONCLUSION

The proposed filter shows very good response as a stop band filter. The equivalent circuit proposed using transmission line theory and lumped elements shows very close result to EM simulation for the cut-off frequency, rejection and passband ripple. By varying the width and the length of the hairpin, the cutoff frequency of the filter can be modified. To obtain broad stop band and sharp rejection, the proposed structure can be cascaded. In both case, insertion loss is within the limit of operation. This broad stopband, compact, sharp rejection elliptical filter will be useful in many wireless communication systems.

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