Coupled Microstrip Filters:
Simple Methodologies for Improved Characteristics

Kamaljeet Singh, R. Ramasubramanian, S. Pal
Communication Systems Group, ISRO Satellite Center, Bangalore, India
kamaljaz@yahoo.co.in

Abstract:

This paper presents improved characteristics of the hairpin filter topology. Standard hairpin configuration has the drawback of broader bandwidth, more insertion loss along with poor skirt rate. This paper demonstrates the approach to overcome the limitation inherent in hairpin as well as suppression of the harmonic which is prominent in the microstrip coupled filter topology. This has been achieved using the concept of the Q involved along with the compensation of the phase velocity. The modified topologies of the hairpin along with the concept of transmission zeros for better skirt rate has been explained in this paper. Furthermore, presented topologies are insensitive to parameter variations and standard design equations can be used. The band pass filter topologies were designed at the center frequency of 1.24 GHz, aimed to be part of the multiplier chain, in satellite communications.

Keywords: Hairpin filter, Q factor, coupled lines, even and odd mode

Introduction:

Filters are essential in the RF front end of microwave and wireless communication systems. Parallel coupled topology proposed by Cohn is the most commonly used filter. Several configurations like stepped impedance filter, open stub filter, semi lumped filter, parallel coupled filter, inter digital filter, capacitive gap filter are widely used in microwave and millimeter wave integrated systems. These configurations either increase the complexity of the design or having less Q. Also, all the filters designed traditionally have a major drawback of the spurious response at twice the basic pass band frequency ($2f_0$), which causes asymmetry in the upper and lower stop band and limits its application. The other major constraint comes from the weak lateral coupling between the lines in the conventional structure which causes small values of strip width and strip spacing which cannot be accurately fabricated. These constraints are due to inhomogeneous nature of micro strip lines which results in the inequality of even and odd mode phase velocities and also due to tight specifications resulting in fabrication inaccuracies. This paper concentrates on the hairpin topology which was in use for so many years, but still limitations have not been fully overcome yet. The traditional design of the hairpin topology has the advantage of compact structure compared to edge coupled filter but wider bandwidth, poor skirt rate due to unavoidable coupling, are the limitations in this approach. The second aspect is the second harmonic content prominent in coupled lines. Many works have been done to tackle this problem either providing different lengths for the even and odd modes or equalizing the modal phase velocities. Some recently reported structures like Wiggly Line Filters [IEEE-MTT, 2001, Ref4], Uni planar Coupled Photonic Band gap Filter [IEEE-MTT, 1999], Corrugated Coupled Micro strip lines Filter [IEEE-MTT, 2002, Ref 2], Meandered Parallel Coupled Line Filter [IEEE-MTT, 2005, Ref 3] have been proposed, but limitations like fabrication tolerances, large size, recalculation of design parameters, controllable phase velocities, practical realizability, and compatibility with other circuits are the major constraint of these circuits.

So, in this paper we have shown that second harmonic content can be suppressed by modifying the hairpin topology. This is cross-verified with the close agreement with the simulated and practical results. The concept of Q has been explained for the first proposed topology along with reallocating the transmission zero for better rejection characteristics has been used. The second proposed topology is based on the equalization of the phase velocity. This not only gives the second harmonic suppression but also have controllable transmission zeros which gives better attenuation rate.

1. Conceptualization for the Design

A. Concept of Transmission Zeros

The design criteria for the filter topology sometimes demand higher skirt rate. The traditional method is to increase the number of sections. Another concept is to use cross coupling between the resonator section along with over coupling gives controllable zero producing mechanism. The placement of zero is determined by the polarity of the cross coupling. The Figure 2 shows the concept of the zero producing mechanism in the case of triplet**.** Any realizable transfer function can be obtained by adjusting the coupling between the resonators. The mechanism of producing improved pass band delay or sharper filter skirt lies in the finite transmission zeros lying on the real axis. The placement of zeros is determined by the polarity of the cross coupling. Cross coupled filter design is to reduce the coupling matrix so that minimum number of resonators are coupled. The coupling between the resonators is basically electric as open ends are on the same side. Figure 1 shows the cross coupling phenomena. M12 shows the coupling between the 1^{st} and the 2^{nd} section. M23 shows the coupling between 2^{nd} and 3^{rd} section. M13 shows the coupling between 1^{st} and 3^{rd} section. This overall coupling affects the circuit Q in the coupled resonators which can be varied. Microstrip model can predict this behavior more accurately.

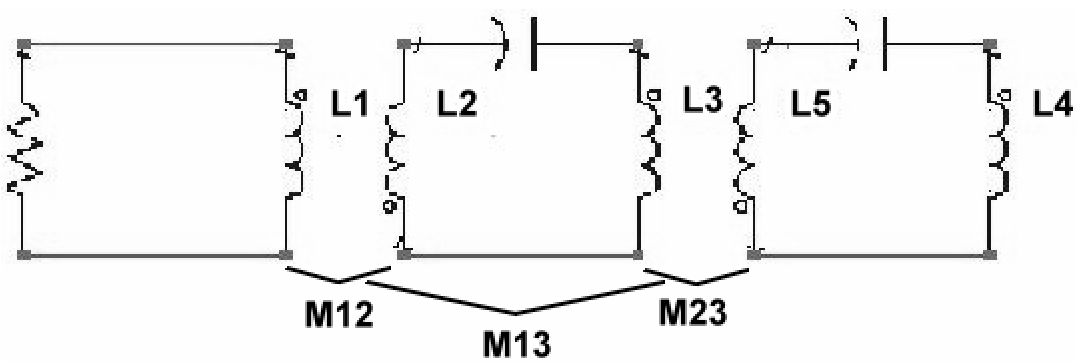

Figure 1 Cross Coupling Between Three Resonator Sections

B. Equalization of modal phase velocities

Due to inhomogeneous nature of the micro strip lines, the odd mode phase velocity is faster than the even mode phase velocity. Mathematically it can be represented as βo< βe. This can further be written as for the odd mode as

$$\beta_o = \frac{\omega}{V_0}; \quad \beta_o \ell = \frac{\omega \ell}{V_o}; \quad \theta_o = \frac{\omega \ell}{V_o}; \quad \theta = 2\pi f \sqrt{\varepsilon_{eff}}\, \frac{\ell}{c}$$

$$\beta_e = \frac{\omega}{V_e}; \quad \beta_e \ell = \frac{\omega \ell}{V_e}; \quad \theta_e \ell = \frac{\omega \ell}{V_e}$$

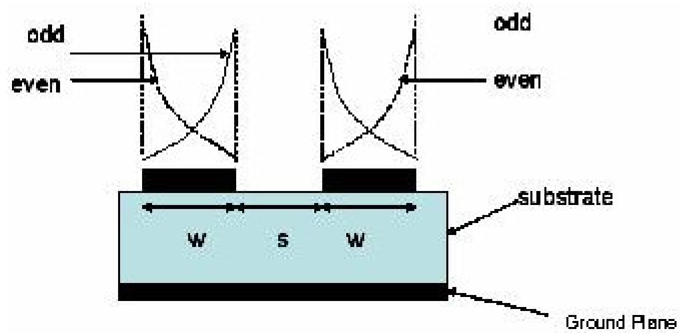

Figure 2 Concept of Even/Odd Mode Current Distribution in the Coupled Line

So in the microstrip structure, because the even mode phase velocity of a microstrip coupled line is always slower than that of the odd mode θ_e is always larger than θo for all frequencies. Therefore, the spurious pass band of a conventional microstrip parallel coupled filter at $2f_0$ occurs. This implies that odd mode length has to be lengthened to equalize the phase velocity. To equalize the phase velocity, the traveling path for the odd mode has to be extended. For a symmetric coupled microstrip lines, typical current distribution of the odd and even mode is shown in Figure 2. It shows that electromagnetic energy for the odd mode gathers around the center gap, while for the even mode, it gathers around the outer metallic edges. So for equalization, one way is to extend the path of the odd mode and another way is to shorten the path for the even mode. Other reported topologies are with the use of shield, which makes the redistribution of the fields, second one involves lumped capacitors and third one the dielectric overlay. In the proposed design, reduction in even mode is achieved by trimming the coupled line section in the middle. This is due to the fact that odd mode transmission phase θ_0 is not affected by meandering but even mode path got reduced. This makes the energy propagation of odd mode nearer to the even mode resulting in $\theta_e = \theta_0$. This methodology gives the harmonic suppression.

2. Hairpin Topologies

A. Design Equations for Coupled Line Filter

To design coupled band pass filter a low pass filter prototype is selected .For the required roll off five sections are selected. Designed topology is converted into band pass using standard transformation equations. Further lumped sections are converted into distributed elements using Richard's transformation. The required coupling coefficient is found by equation 1[1].

$$K = \frac{f_l - f_h}{f_0} \qquad \text{-------------------------------------} \qquad (1)$$

and the inverter constants were found using (2),(3),(4)

$$Z_o J_1 = \sqrt{\frac{\pi \cdot K}{2g_1}} \qquad \text{-------------------------------------} \qquad (2)$$

$$Z_o Jn = \sqrt{\frac{\pi \cdot K}{2(g_{n-1} \cdot g_n)}} \qquad \text{---------------------------} \qquad (3)$$

$$Z_o J_{n+1} = \sqrt{\frac{\pi \cdot K}{2(g_n \cdot g_{n+1})}} \qquad \text{---------------------------} \qquad (4)$$

The $g_1,g_2,g_3.....g_n$ are found from the filter tables. From the obtained results the even and odd impedances are found by (5) and (6).

$$Z_{0e} = Z_o\left[1 + (JZ_o) - (JZ_o)^2\right] \quad \text{---------------------------} \quad (5)$$

$$Z_{0o} = Z_o\left[1 + (JZ_o) + (JZ_o)^2\right] \quad \text{---------------------------} \quad (6)$$

with the Z_{0e} and Z_{0o} of each section the width, spacing and length of each section is found out.

B. Design Aspect

The coupling between the resonator sections in the hairpin topology is mainly inductive. Five sections resonator has been chosen with the given specifications. The tapping position is calculated from the singly loaded Q of the first and the last section. It is related to the tapping position as defined by equation (7):

$$Q = \frac{Z_0\pi}{R \cdot 2\sin^2\left(\frac{\pi\ell}{2L}\right)} \quad \text{-----------------------------------} \quad (7)$$

where ℓ is the tapping position and L is the length of the filter.

The detailed procedure can be looked into in Ref[10]. Bandwidth of the filter is set up by the loaded Q of the resonator. The loaded Q_L, of a resonator depends on its losses and the external circuit connected to it. The relation $Q_L^{-1}=Q_U^{-1}+Q_C^{-1}$is well known, and when Q_E<<Qu, the bandwidth is almost independent of the Qu but $Q_E \approx$ Qu, and then the circuit becomes lossy. These effects in three major parameters: broaden the bandwidth, introduces extra insertion loss and reduces rejection in the stop band [10]. To demonstrate the effect of Q, two hairpin topologies has been simulated and realized. The first topology has been based on the standard design where the spacing between coupled sections is equal and line widths are kept to be 1.13 mm corresponding to 50 ohms [Figure 3]. However, this approach results in poor Q resulting from the Qu approaching towards QE, resulting in high insertion loss and poor stop band characteristic. This cannot be overcome with the standard design.

The five section hairpin filter has been further modified by having different coupling coefficients and widths to have better skirt and harmonic suppression [Figure 5]. This has been found out that in MIC design the Q of middle resonator section has a greater role in determining the overall Q rather than outer resonator section [11]. The high impedance line along with greater spacing makes inequality between Q_E with that of Qu, thus the performance of the overall circuit can be improved as shown in the Figure 6. This approach is compounded by the transmission zero theory which shows the improved attenuation rates keeping the same size which has been done by optimization using EM software tool. The bandwidth got reduced to 10% from the standard topology bandwidth of 20%. The corresponding spacing termed as A equals to 1.18 mm and the middle section width comes out to be 0.84 mm whereas the 50 ohms width corresponds to 1.13 mm. The spacing between the resonator termed as B equals to 3.2 mm. Still alignment and tuning is difficult as all couplings are responsible in a collective way to produce poles and zeros. So, a second harmonic peak is difficult to avoid in these configurations.

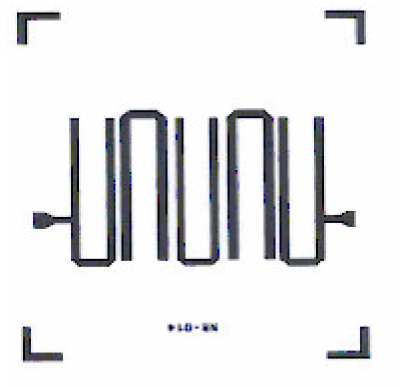

Figure 3 Hairpin Standard Topology

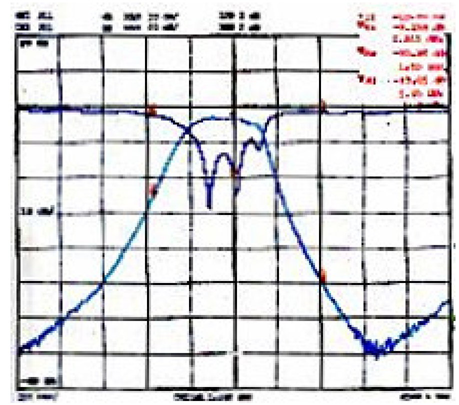

Figure 4 Measured Results

The other way round in this approach is to make strip width as wide as possible to maximize the Qu. But as the strip width becomes wider, the first section gap becomes smaller and put hindrance on the practical limitation of the realizability [12].

$$\text{InsertionLoss(dB)} = \frac{4.343 \cdot f_0}{BW \cdot Q_U} \cdot \sum g_i \qquad \text{----------} \qquad (8)$$

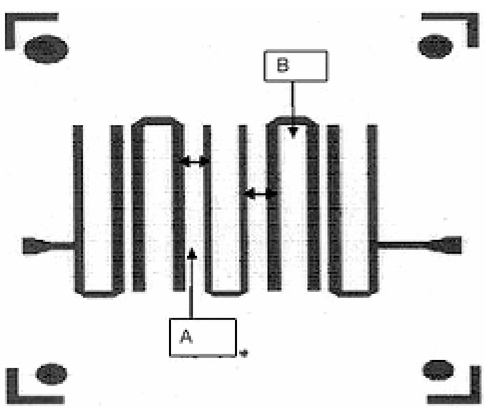

Figure 5 Hairpin Modified Topology

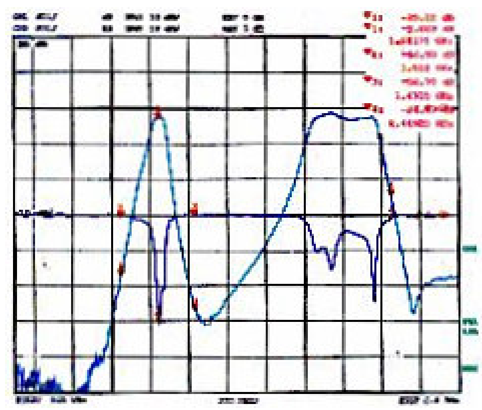

Figure 6 Measured Results

The measured results shows improved characteristics along with better insertion loss, which validates the theory adopted.

C. Harmonic Suppression Topology

The proposed structure giving harmonic suppression along with steep attenuation rate is shown in Figure 7. The concept of edge coupled has been clubbed with the hairpin giving a compact size and better performance. The standard design equations as described in section 2A are used to find out the number of sections and coupling coefficients. The number of sections chosen is six for symmetry. The elimination of second harmonics has been achieved due to phase velocity equalization which is explained in section 1B. Also the coupling coefficient and coupled lengths have been optimized for controlling transmission zeros. Further more the input and output planes are aligned without much bending.

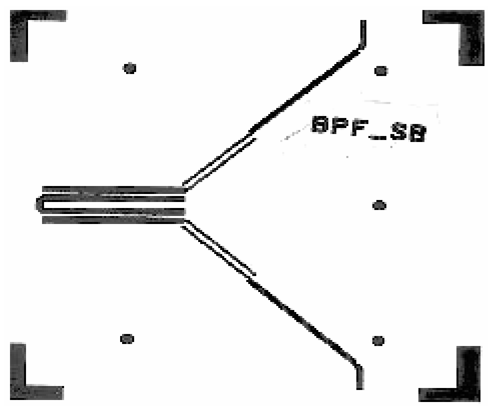

Figure 7 Harmonic Suppression Topology

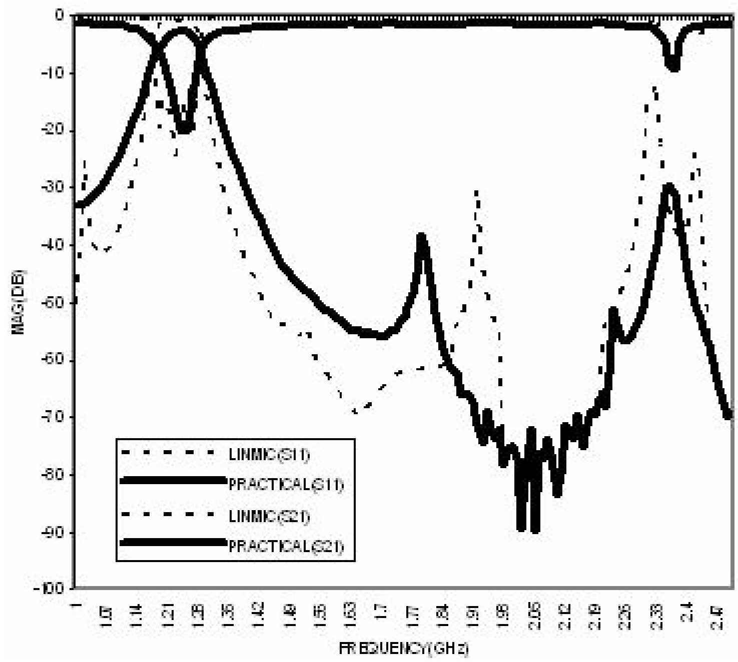

Figure 8 Simulated and Measured Results

3. Experimental Results and Discussions:

All the filter structures are simulated using EDA tools. The electro magnetic tool SFPMIC of LINMIC[9] has been used to optimize the coupling coefficient as well as minimizing cross coupling . All the filters are implemented on RT Duroid dielectric substrate having permittivity of 10.5 and thickness of 50 mils. The modified filters are designed at 1.24 GHz with bandwidth of 10%. The measured results of modified hairpin topologies are shown in Figure 6 and Figure 8. The insertion loss is better than 2.2 dB. Tapering is done for better alignment with subsequent circuit giving 0.5 dB extra loss. The return loss is better than 18 dB in both the cases. The size of the hairpin cards shown in Figure 5 is 50 mm by 32 mm. Figure 8 shows the TZ at the upper pass band due to coupling having same sign w.r.t main coupling. The harmonics are suppressed better than 20 dB in the proposed filters. The extra insertion loss compared to simulate one is due to conductor and radiation loss. The dimensions are 93 mm x 60 mm, which can be reduced further by 20 mm. These topologies validates that the novel concept can replace existing designs, with better performance.

Conclusion:

This paper reports hairpin filters with improved characteristics over conventional structures using standard design equations. The line widths and spacing can be easily etched using standard fabrication techniques. Narrower bandwidths have been achieved without additional components. The structures are validated having close match between the simulated and practical results. This approach can be extended to much higher frequency range without compromising the filter performance.

References:

[1] G.L Matthaei, L.Young & E.M.T Jones' *Microwave Filters ,Impedance-Matching Networks & Coupling structures'*, Artech House, Dedham, MA ,1980

[2] Kuo,Hsu & Huang,"_Parallel Coupled micro strip filters with suppression of harmonic response", IEEE Microwave and Wireless letters, Oct 2002

[3] Wang,Chang et al," Miniaturized Spurious Pass band Suppression micro strip filter using Meandered Parallel Coupled lines", IEE Trans. MTT, Feb 2005,pp 747-753

[4] Lopetegi et al," New microstrip Wiggly-Line Filters with spurious Pass band suppression", IEEE Trans. MTT, Sept.2001,pp 1593-1597

[5] LINMIC +/N 6.3 user guide, AC Microwave.

[6] Joseph S.Wong , "Microstrip Tapped-Line Filter Design", IEEE Trans.MTT-27 , 1 , 1979 , 44-50.

[7] Jia-Shen ,G.Hong,M.J.Lancaster, "Micro strip filters for RF/Microwave Applications" IEE Press.

[8] David M.Pozar, "Microwave Engineering", second edition, Wiley Inter-science

[9] LINMIC +/N 6.3 user guide.

[10] Inder Bahl & Prakash Bhartia," Microwave Solid State Circuit Design,", Second Edition,Wiley Inter-science

[11] C.M Tsai & H.M Lee," The Effects of component Q distribution on Microwave filters," IEEE MTT-S,Vol.54,No. 4,April 2006,pp 1545-1553

[12] Daniel G Swansen & W J R Hoefer" *Microwave Circuit Modeling Using Electro-magnetic field simulation*," Artech House, 2003