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Design of Generalised Chebyshev Lowpass Filters Using Coupled Line/Stub Sections

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Abstract — **A new method for the design of distributed lowpass filters enables exact realisation of the series short circuited transmission lines which are normally approximated via unit elements in other filter realisations. The filters are based upon basic sections using a pair of coupled lines which are terminated at one end in open-circuited stubs. The approach enables realisation of transmission zeros at the quarter –wave frequency hence giving improved stopband performance. A complete design is presented and demonstrates excellent performance in good agreement with theory.**

Index Terms — **Distributed lowpass filters, Generalised Chebyshev, Meander Line, Selectivity, TEM.**

I. INTRODUCTION

Lowpass filters are often needed in microwave systems to 'clean up' spurious responses in the stopband of coaxial and dielectric resonator filters.

There exist many realisations for lowpass filters. One popular type is the stepped impedance lowpass filters consisting of interconnections of commensurate lengths of transmission lines of alternating low and high impedance [1]. This type of filter has low selectivity for a given network order because the transmission zeros are on the real axis in the complex plane.

In order to increase selectivity, transmission zeros may be placed at finite frequencies using generalised Chebyshev prototypes [2]. The problem is that there is no direct realisation of the series short circuited stubs associated with this prototype. In the existing physical realisation [3] the series short circuited stubs are approximated by short lengths of high impedance transmission line while the shunt series foster is realised exactly as an open circuited stub of double unit length. The approximation involved results in relatively poor stopband rejection. In this paper, solutions have been found in which the series short circuited stubs are exactly realised within the equivalent circuit of the filter. With slight adjustment in the circuit layout, another solution has been found which allows for more flexible physical realisation.

In section II the design theory is described with two possible physical realisations given. A prototype filter was built with measurement results analysed.

II. DESIGN THEORY

A. Physical Realisation I

In Fig. 1 below, the physical layout is given for the proposed method. The structure consists of the cascade of n basic sections composed of a pair of coupled lines terminated at one end in an open-circuit stub as in Fig. 1. All the transmission lines are of commensurate length.
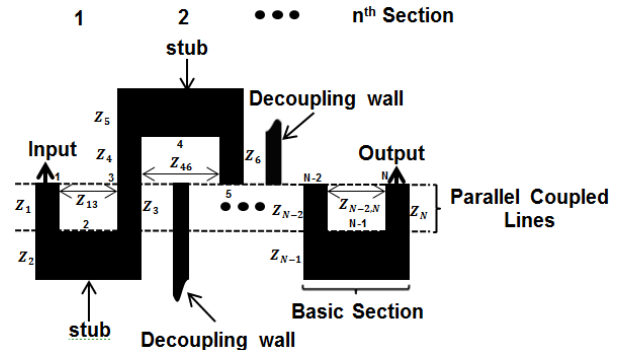

Fig. 1 Proposed physical layout for generalised Chebyshev distributed lowpass prototype filter consisting of coupled striplines and stubs

The equivalent circuit of Fig. 1 may easily be derived and is shown in Fig. 2. It may be shown, by using a series of circuit transformations as in [4], without approximating the series short-circuited stubs in Fig. 3, that equivalent circuit may be transformed into the distributed generalised Chebyshev lowpass filter shown in Fig. 3.
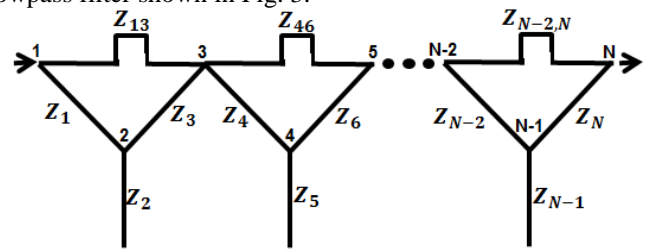

Fig. 2 Graphical representation of the equivalent circuit for physical structure of Fig. 1 consisting of interconnection of a basic section containing a pair of coupled line and a stub
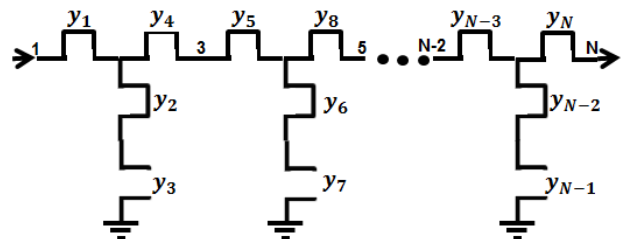

Fig. 3 Generalised Chebyshev distributed lowpass prototype equivalent circuit of Fig. 2

By using the synthesis technique given in [1], the network of Fig. 3 may be synthesised from an Nth (N odd) degree Chebyshev transfer function with $(N-1)/2$ pairs of symmetrically located transmission zeros in the p domain, where p is the complex frequency variable. Richard's transformation [5] may be applied to yield the characteristic polynomials in the θ domain from which network synthesis to obtain the elements of Fig. 3 may be carried out. Using a series of circuit transformations by repeated application of an equivalent circuit transformation based on Table I of [4], Fig. 3 may be transformed to Fig. 2.

Design Example:

A 7th degree lowpass filter was designed using the techniques described above with cutoff frequency at 1GHz , 20 dB return loss with a triple pairs of finite transmission zeros at $\pm 3, \pm 2$ and ± 3 rad/s (2.18, 1.72 and 2.18 GHz) and $\theta_c = 25^o$.

TABLE I
7TH DEGREE LOWPASS FILTER SYNTHESISED ADMITTANCE VALUES (℧)

Section 1	Section II	Section III
$y_1 = 0.4983$	$y_5 = 0.5830$	$y_9 = 0.4983$
$y_2 = 5.5807$	$y_6 = 2.5671$	$y_{10} = 5.5807$
$y_3 = 2.8517$	$y_7 = 2.9514$	$y_{11} = 2.8517$
$y_4 = 0.4983$	$y_8 = 0.5830$	$y_{12} = 0.4983$

TABLE II
7TH DEGREE LOWPASS FILTER IMPEDANCE VALUES (Ω) AFTER TRANSFORMATION II (A)-(C) IN 50 Ω SYSTEM

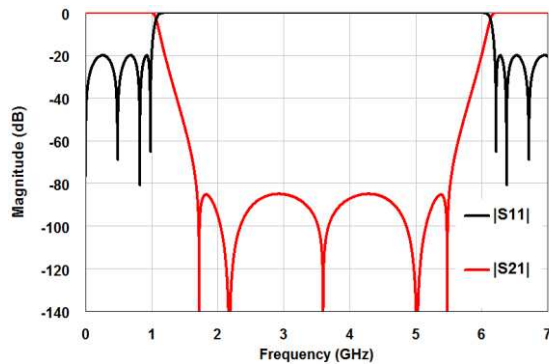|		
Section 1&3	$Z_1 = 153.3$	$Z_{13} = 580.7$
	$Z_2 = 22.73$	
	$Z_3 = 153.3$	
Section 2	$Z_4 = 158.6$	$Z_{46} = 373.5$
	$Z_5 = 21.54$	
	$Z_6 = 158.6$	

Fig. 4 Circuit simulation response for example I

The element values are shown in Table I corresponding to the circuit of Fig. 3 where symmetry is assumed for the

element values. Using the circuit transformation in [4], the circuit was transformed to Fig. 2 with the element values shown in Table II. Fig. 4 shows the circuit simulation of the design example.

B. Modified Physical Realisation II – *'Meander-like' Lowpass Filter*

A more general realisation is achieved by using the layout of Fig. 5 forming a 'meander-like' structure. The circuit consists of a parallel coupled line middle section with open circuited stubs placed at alternate ends. Grounded decoupling walls must be utilised to eliminate coupling between the open-circuited stubs. Higher order filters may be formed from the basic section by adding a parallel line to the parallel coupled lines section and an open circuited stub at one end to form an interconnect each time to increase the network degree by 2.
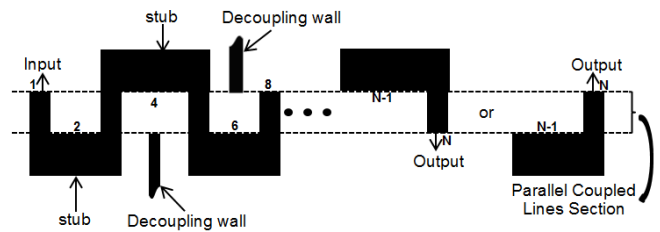

Fig. 5 Physical layout of the striplines for the general 'meander-like' lowpass filter with allowed coupling between parallel lines of the adjacent basic sections.

The derived equivalent circuit is shown below in Fig. 6 with the element impedance values named sequentially from input to output. This realisation is optimal since an Nth degree filter requires N commensurate length transmission lines. At the quarter wavelength frequency, all the series short circuited stubs becomes open circuited while all the open circuited stubs becomes short circuited so that the alternate ends of the parallel coupled lines are shorted to ground. Thus the lowpass filter of Fig. 6 has at least one transmission zero at the quarter wavelength frequency. The other transmission zero pairs may exist at real and imaginary axis (real frequency) in the complex p variable due to multipaths in the structure.
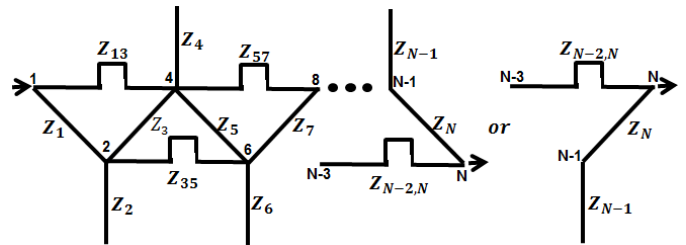

Fig. 6 Graphical representation of the equivalent circuit of Fig. 4 for a 'meander-like' lowpass filter

However, analytical methods to find the elements values are yet to be found. Fortunately, since the equivalent circuit is known, the element values may be obtained by optimisation.

Design example:

An experimental 9th degree 'meander-like' lowpass filter was designed with cutoff frequency at 1GHz, 20 dB minimum return loss and $\theta_c = 45^o$ using optimisation in AWR Microwave Office. The stopband insertion loss was defined to be above $70\ dB$ between $1.3\ GHz$ and $2.7\ GHz$. The circuit simulation of the optimised values in Table III (assuming symmetry) is shown in Fig. 9.

TABLE III
9TH DEGREE 'MEANDER-LIKE' LOWPASS FILTER IMPEDANCE VALUES (Ω)

$Z1 = 97.95$	$Z12 = 336.3$
$Z2 = 64.55$	$Z23 = 1569$
$Z3 = 200.0$	
$Z4 = 34.88$	
$Z5 = 149.1$	

TABLE IV
9TH DEGREE LOWPASS FILTER OPTIMISED DIMENSIONS (MM)

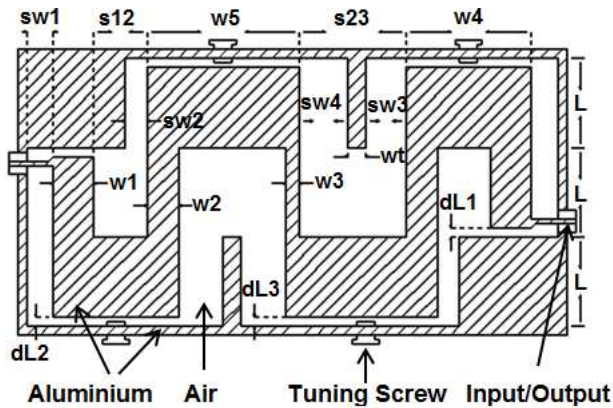|			
$w1 = 9.04$	$sw1 = 12.5$	$s12 = 6.75$	$dL1 = 2.5$
$w2 = 1.85$	$sw2 = 3.00$	$s23 = 23.25$	$dL2 = 8.5$
$w3 = 2.33$	$sw3 = 7.25$	$b = 25$	$dL3 = 6.5$
$w4 = 17.64$	$sw4 = 3.00$	$t = 5$	$wt = 13.0$
$w5 = 27.44$		$L = 37.5$	

Fig. 7 Diagram showing the layout of the fabricated 9th degree lowpass filter using equivalent circuit of Fig. 6. Dimension shown are as given in Table IV
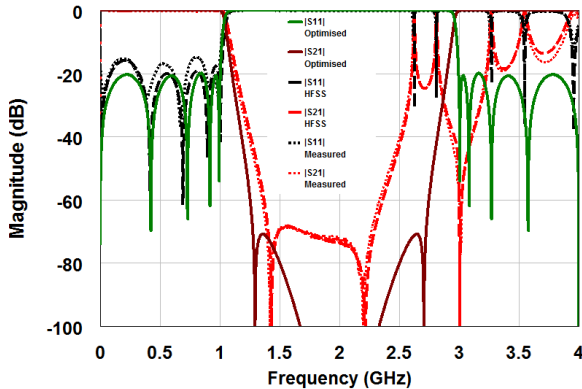

Fig. 8 Comparison of simulated response of the optimized equivalent circuit, HFSS and measurement of meander-like lowpass filter
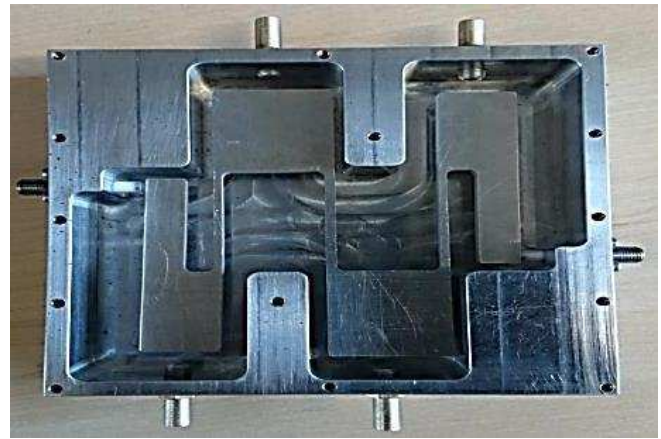

Fig. 9 Physical hardware of the fabricated 9th degree 'meander-like' lowpass Filter (top cover removed)

The lowpass filter is then realised using rectangular bars or striplines. The technique by Getsinger [6, 7] was used to determine the initial physical dimensions. The final optimised dimensions are given in Table IV. The nomenclature used in Table IV corresponds to Fig. 7 and Fig. 9 after fabrication. Fig. 8 shows good correspondence between the measured and theoretical simulation using HFSS.

The overall length of the lowpass filter realisation is three times the electrical length at the cutoff frequency. High order modes do exist in the structure that potentially could worsen the stopband response especially with relatively larger ground plane spacing. The effect is to shorten the effective stopband frequency window as the design example shows in Fig. 8. The choice of the ground plane spacing affects the spurious resonances within the filter structure which in this case appeared above $2.6\ GHz$.
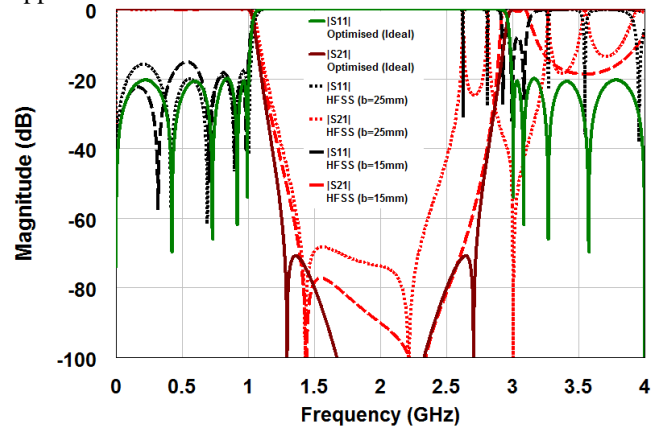

Fig. 10 Comparison of optimised equivalent circuit simulation and HFSS simulations of meander-like lowpass filter with different ground plane spacing.

Improvement in the stopband response was achieved by reducing the ground plane spacing from $b = 25$ mm to $b = 15$ mm. Fig. 10 shows HFSS simulations for different ground plane spacing versus the ideal circuit response. Clearly

the stopband performance matches very well with the prediction for $b = 15$ mm. Table V shows the corresponding optimized physical dimensions. Notice that much smaller ground plane spacing is limited by realisability of the physical dimensions as the dimensions of the lowpass filter are proportional to the ground plane spacing.

TABLE V
IMPROVED 9TH DEGREE LOWPASS FILTER OPTIMISED DIMENSIONS (MM)

$w1 = 5.42$	$sw1 = 7.5$	$s12 = 4.80$	$dL1 = 3$
$w2 = 1.11$	$sw2 = 1.8$	$s23 = 13.95$	$dL2 = 5.1$
$w3 = 1.40$	$sw3 = 7.5$	$b = 15$	$dL3 = 3.9$
$w4 = 11.33$	$sw4 = 1.8$	$t = 3$	$wt = 4.65$
$w5 = 16.46$		$L = 37.5$	

C. Comparison

A 9th degree meander-like lowpass filter was compared to other lowpass filter realisations. To achieve the same selectivity, a 9th degree generalised Chebyshev lowpass filter would be required while a 15th degree stepped impedance lowpass filter would be required as depicted in Fig. 11 below with $\pi/4$ electrical length at the cutoff frequency of 1 GHz. Thus for the same selectivity, the proposed structure requires much fewer number of filter elements than the stepped impedance lowpass filter. Although the generalised Chebyshev may be designed with the same degree as the meander-like lowpass filter, its stopband performance is much poorer in its physical realisation as shown in Fig. 11 because the series short circuited stubs are approximated by high impedance transmission lines [1]. Furthermore, both the generalised Chebyshev and stepped impedance lowpass filters' effective stopband response is much worse in practice because it is difficult to realise ideal commensurate transmission line elements and often discontinuities, high order modes and mode conversion occurs within the filter structure [8]. These reduce the effective stopband width of practical lowpass filters to as much as half of the predicted width! Even though effective stopband width may be widened by using a lower electrical length at cutoff frequency, it is often limited by element realisation as the variations in element values tend to be extreme. By utilizing relatively smaller ground plane spacing as described in section B, the proposed lowpass structure offers superior stopband performance.
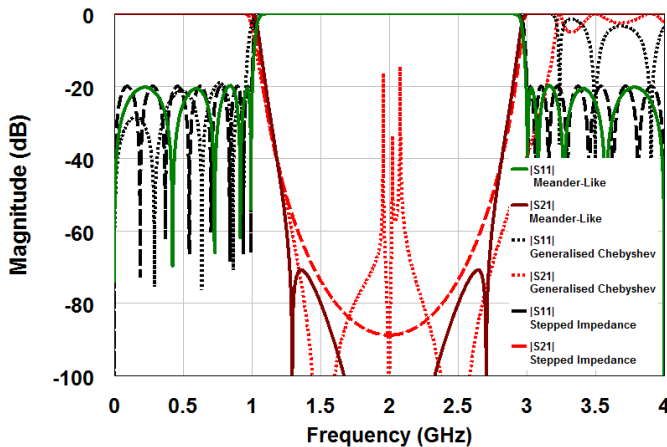

Fig. 11 Circuit simulation comparison of 9th degree meander-like lowpass filter with a 9th degree generalised Chebyshev lowpass filter and 15th degree stepped impedance lowpass filter.

III. CONCLUSION

An exact design technique for realising generalised Chebyshev lowpass filters using coupled line/stub without approximating the series short circuited stubs has been demonstrated. The physical realisation has a simple equivalent circuit where synthesis of the element values is possible. However, it requires isolation walls to eliminate coupling between basic sections. A more general physical realisation of the lowpass filter using a 'meander-like' structure with optimal number of elements and simple physical layout of transmission lines has also been presented. Its physical realisation does not require decoupling walls and hence is easier to construct. However, synthesis is not possible because simple equivalent circuit is not known. A lowpass filter design example utilising the later physical realisation was fabricated and measurement results showed good agreement with theory. Comparison with other lowpass filter realisations reviewed that the proposed lowpass filter has much wider and deeper effective stopband.

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