DESIGN METHODOLOGY FOR MULTILAYER COUPLED LINE FILTERS

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Abstract

This paper presents a methodology for designing asymmetric coupled line band-pass filter circuits in multilayer substrates. Filter specifications are used for deriving normal mode parameters for various asymmetric coupled sections. Method for arriving at filter dimensions is described for the embedded (homogeneous dielectric) configurations. The method developed is verified by comparison with results obtained from a full-wave electromagnetic simulation.

I. INTRODUCTION

Although multilayer circuit configurations have been widely used for digital and low frequency systems, RF and microwave circuits are usually fabricated in single-layer configurations. The use of multilayer circuit configurations makes microwave circuits more compact and the design more flexible. A few directional couplers and baluns implemented in multilayer circuits have been developed in recent years [1, 2], however, the design of filters in multilayer configurations has been limited to broadside coupled symmetrical strip configuration only [3]. The design procedure of single-layer filter using symmetric coupled microstrip lines is well documented in literature [4, 5], however, very tightly coupled lines are difficult to be fabricated in this configuration. Multilayer configurations overcome this kind of restriction. The band-pass filters composed of asymmetric coupled microstrip lines in multilayer configurations provide more design feasibility compared with broadside coupled filters. This paper presents, for the first time, a methodology for the design of multilayer asymmetric coupled line filter circuits.

II. METHODOLOGY

A general configuration for a coupled line band-pass filter made up of four coupled line sections ($\lambda/4$ each at the center frequency) is shown in Fig. 1. For multilayer band-pass filter design, various conductors (1,2,3,etc.) may be located at different layers as shown in Fig. 2 or Fig. 3. The overall procedure developed for the design of such a multilayer filter is summarized in Fig. 4. This design procedure can be broken up into three steps:

1. Evaluation of normal mode parameters [6] for various coupled line sections,
2. Determination of physical dimensions (width, spacing, etc.) to obtain the required normal mode parameters as computed in Step (1), and
3. Simulation of physical structure obtained in Step (2) to verify the design.

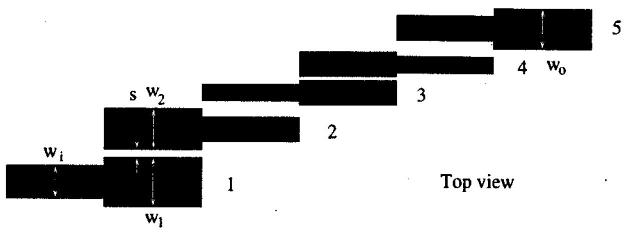

Figure 1: The layout of a coupled line filter using 4 coupled line sections

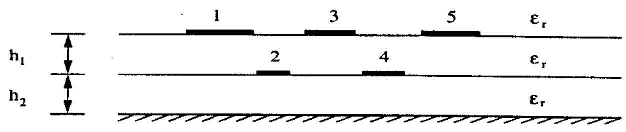

Figure 2: Cross sectional view of 2 layer filter configuration

For Step (1), we start with filter specifications (bandwidth, number of coupled sections, ripple level, etc.) and then find 'g' parameters, prototype low pass filter elements, from classical filter design tables given in [4] . From filter specifications, 'g' parameters and selected terminating impedances (Z_{01}, Z_{02}), we derive

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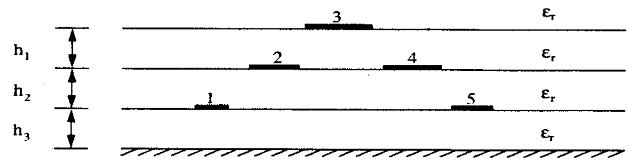

Figure 3: Cross sectional view of 3 layer filter configuration

admittance inverter model [4, 5] for each asymmetric coupled section as:

$$J_1 = \frac{Z_{0i}}{Z_{01(1)}^2}\sqrt{\frac{\pi\,\Delta\, Z_{0i}(Z_{02(1)} + Z_{01(2)})}{4Z_{02(1)}Z_{01(2)}g_1}}$$

$$J_n = \frac{\pi\,\Delta}{4}\sqrt{\frac{(Z_{02(n-1)} + Z_{01(n)})\,(Z_{02(n)} + Z_{01(n+1)})}{Z_{02(n-1)}Z_{01(n)}Z_{02(n)}Z_{01(n+1)}g_{n-1}g_n}}$$

$$J_{n+1} = \frac{1}{Z_{02(n-1)}}\sqrt{\frac{\pi\,\Delta\, Z_{0o}(Z_{02(n)} + Z_{01(n+1)})}{4Z_{02(n)}Z_{01(n+1)}g_n g_{n+1}}}$$

where Δ is bandwidth, Z_{0i} is the impedance of the input line, Z_{0o} is the impedance of the output line, and J is the admittance of admittance inverter.

Normal mode parameters (c- and π-mode voltage ratios and impedances) are obtained from this admittance inverter model. For a homogeneous dielectric medium, explicit expressions for even and odd mode impedances are known for symmetrical coupled lines used in single layer filter configurations (for example, see [5] p.512). For multilayer configurations, the two lines of a coupled line section are located on different layers and the geometry becomes asymmetric. For this case we have derived explicit expressions for determining normal mode parameters for the n^{th} coupled section as:

$$R_c = \sqrt{Z_{02(n)}/Z_{01(n)}} = -R_\pi$$

$$Z_{c1} = Z_{01(n)}\,(1 + J_n\sqrt{Z_{01(n)}Z_{02(n)}} + J_n^2 Z_{01(n)}Z_{02(n)})$$

$$Z_{\pi 1} = Z_{01(n)}\,(1 - J_n\sqrt{Z_{01(n)}Z_{02(n)}} + J_n^2 Z_{01(n)}Z_{02(n)})$$

$$Z_{c2} = -R_c R_\pi Z_{c1}$$

$$Z_{\pi 2} = -R_c R_\pi Z_{\pi 1}$$

where R_c, R_π represent voltage ratios and Z_{c1}, Z_{c2}, $Z_{\pi 1}$, $Z_{\pi 2}$ represent mode impedances for the n^{th} coupled section.

For Step (2), normal mode parameters obtained from Step (1) are utilized to come up with physical dimensions which are later plugged into an electromagnetic simulator to verify the design. In order to obtain physical dimensions for each coupled section we use the optimization process which compares these normal mode parameters with those calculated from capacitance and inductance matrices which can be determined using *SBEM* (Segmentation and Boundary Element Method) analysis [7] of the physical structure. Approximate values of physical dimensions based on capacitance values are used for an initial guess for the iterative evaluation of physical dimensions.

For Step(3) of the design procedure, S–parameters are determined for each coupled section starting from the physical dimensions finally arrived at, and then these S–parameters are plugged into a network simulation package (*Microwave Design System* from HP). The complete circuit combining all coupled sections is simulated for calculating the insertion loss and the return loss. At the same time, an electromagnetic simulation is carried out using the physical dimensions on *Momentum*™(HP-EEsof product), a simulation package using the method of moments. Eventually the filter performance obtained from physical dimensions is compared with the desired filter specifications.

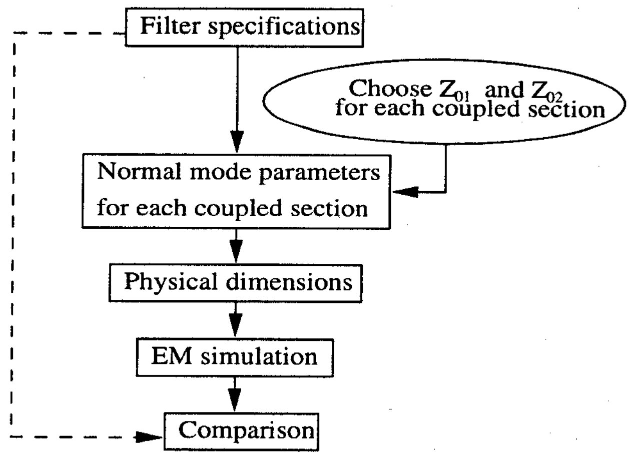

Figure 4: Procedure for the design of multilayer coupled line filter

III. DESIGN EXAMPLE

We illustrate this procedure by taking two examples for multilayer filters embedded in a homogeneous dielectric as shown in Fig. 2 and Fig. 3. The filter specifications are selected as:

Center frequency	10 GHz
Bandwidth	20 %
Ripple	0.5 dB
Number of filter elements	3
Number of coupled sections	4
ε_r	2.2
h_1=h_2(=h_3)	1/32 inch
$Z_{0i} = Z_{01(1)} = Z_{02(4)} = Z_{0o}$	50 Ω
$Z_{02(1)} = Z_{01(2)}$	60 Ω
$Z_{02(2)} = Z_{01(3)}$	70 Ω
$Z_{02(3)} = Z_{01(4)}$	60 Ω

Section #	1	2	3	4
W_1	3.0156	1.3434	2.0050	1.9403
W_2	1.9403	2.0050	1.3434	3.0156
S	-0.6274	0.4867	0.4867	-0.6274
W_i, W_o	4.2460			

Table 1: Physical dimensions for 2 layer configuration (units in mm)

Section #	1	2	3	4
W_1	1.4600	2.7389	3.1001	2.1288
W_2	2.1288	3.1001	2.7389	1.4600
S	-0.4499	1.0670	1.0670	-0.4499
W_i, W_o	2.1588			

Table 2: Physical dimensions for 3 layer configuration (units in mm)

where $Z_{01(n)}$ and $Z_{02(n)}$ are terminating impedances at two ports of the n^{th} coupled line section. These impedances are selected so as to avoid too narrow or too wide line widths and spacings.

Optimization process for evaluating physical dimensions is carried out using the '*Simplex*' algorithm [8] which finds the minimum value for a specific function. Making iterations with *SBEM* leads to the physical dimensions appropriate for two filter examples as shown in Table 1 and Table 2. W_1, W_2, W_i, W_o and S are layout dimensions as shown in Fig. 1. The length of each line of all coupled sections is made shorter than the physical dimension shown in Table 1 and Table 2 to take into account open end discontinuity [9]. The physical layouts of these two filters utilized for a full-wave electromagnetic simulation are shown in Fig. 5 and Fig. 6.

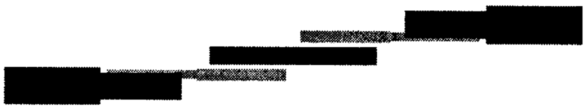

Figure 5: Layout for 2 layer filter configuration

Figure 6: Layout for 3 layer filter configuration

IV. COMPARISON WITH EM SIMULATION

Using the physical dimensions optimized for two examples, filter circuits are simulated on a microwave

	Center Frequency (GHz)	3 dB Bandwidth (%)	Ripple Level (dB)
Spec.*	10	23.34	0.5
MDS			
Example1	10	22.72	0.458
Example2	10	22.72	0.458
Momentum			
Example1	9.719	19.93	1.057
Example2	9.938	18.12	0.311

Table 3: Center frequency, bandwidth and ripple (* for Chebyshev filter design)

circuit simulator (*MDS*) and a full–wave EM simulator (*Momentum*). Center frequency, bandwidth and ripple level for these two filters as obtained from network simulation and EM simulation are shown in Table 3. Here we have compared these simulated results with ideal Chebyshev filter response. A good agreement with the desired values verifies the design procedure proposed here.

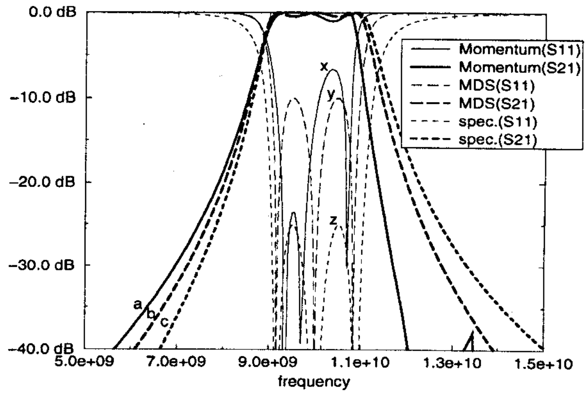

Figure 7: Performance of the filter embedded in a homogeneous dielectric corresponding to Example 1. Curve '*c*' denotes ideal Chebyshev response, '*b*' is network simulator (*MDS*) response and '*a*' is electromagnetic simulation (*Momentum*) response. '*x*', '*y*' and '*z*' are corresponding plots for reflection coefficient.

Specification and performance for two different asymmetric multilayer filters in a homogeneous dielectric, as obtained by EM simulation and network simulation (*MDS*), are shown in Fig. 7 and Fig. 8. We note that results from network simulation and EM simulation are in close agreement. However, S_{21} at frequency above the pass-band as obtained from the EM simulation decays more rapidly than that obtained by *MDS* simulation. This may be caused by discontinuity reactances which were not taken into account in

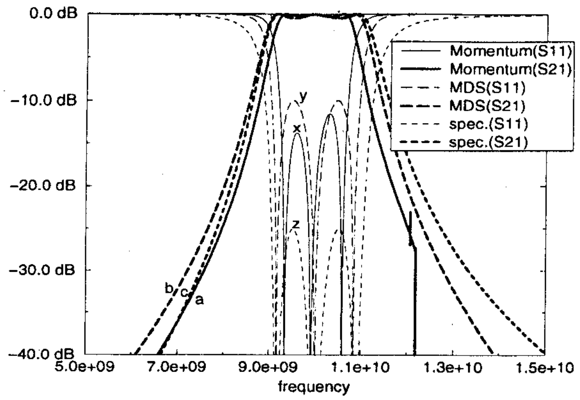

Figure 8: Performance of the filter embedded in a homogeneous dielectric corresponding to Example 2. Curve '*c*' denotes ideal Chebyshev response, '*b*' is network simulator (*MDS*) response and '*a*' is electromagnetic simulation (*Momentum*) response. '*x*', '*y*' and '*z*' are corresponding plots for reflection coefficient.

design process. Although the open end compensation was carried out in an approximate manner, the center frequency shift is also likely caused by other discontinuity reactances. Another reason for this discrepancy is perhaps the result from narrow band approximation used for determining admittance inverter parameters from lumped element '*g*' parameters. Also, the optimization process used in determining physical dimension from [L] and [C] matrices is not perfect.

V. CONCLUDING REMARKS

A systematic design procedure for multilayered asymmetric coupled microstrip filter circuits has been presented. An optimization procedure combined with *SBEM* analysis is used to arrive at the physical dimensions of the filter starting from filter specifications.

S–parameters for each coupled section are calculated separately and then combined using MDS simulator. The simulation on MDS is less accurate than that using a full–wave electromagnetic simulation, but, it provides an approximate but fast way to verify the design.

The determination of terminating impedances affects the width of each coupled section. Further research will include the systematic guidelines for selection of terminating impedances (at both ends of each of the coupled line sections) and its effect on the filter design.

The general methodology presented here is applicable to the development of design procedures for other kinds of multilayer microwave circuits also.

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