Vertically Integrated Comblines Filters in Multilayer PCB

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Abstract—Vertical stacking of planar line resonators in multilayer media is an effective footprint reduction technique for high order filters, but strong broadside line coupling often negates the possibility of narrowband filters. It is shown that vertically stacking combline resonators with rotated centerlines leads to moderate bandwidth filters. Four variations of a 5th order filter are demonstrated, achieving 1.92 – 3.3 dB IL over 10% FBW around 10 GHz while occupying between 6.62 – 22.47 mm² surface area on a 7 layer PCB.

Keywords—Comblines filter, microwave filter, multilayer technology, printed circuits.

I. INTRODUCTION

Compact, low-loss filters of moderate and narrow fractional bandwidth (FBW) are required for a variety of applications. Vertical stacking resonators [1], often taking the form of interdigital filters [2]–[5], reduces the planar layout size. Thin dielectric layers, however, lead to strong broadside coupling and wide FBW in these filters, even if spread across the planar surface [6]. The problem is further constrained by prescribed or predetermined layer thicknesses, necessitating coupling control using solely lateral geometry definition.

This work explores the use of planar combline resonators [7] in a multilayer PCB stack to realize filters of narrow to moderate (~10% FBW) bandwidth. The principles are demonstrated by means of full-wave simulation (CST Microwave Studio 2021).

II. PRACTICAL COUPLING RANGES

Using classical coupled resonator synthesis methods [8], a 5th order all-pole filter of 1 GHz bandwidth centred at 10 GHz (10% FBW), with -15 dB pass-band return loss, is found to require inter-resonator couplings of $k_{12} = k_{45} = 0.0773$ and $k_{23} = k_{34} = 0.0598$ along with $Q_{EI,2} = 12.32$. These values are used to explore the range of practically achievable coupling values in the stack shown in Fig. 1. Five copper signal layers (and two ground layers either side) are created using 3 sheets of 8 mil thickness Mercurywave 9350 ($\epsilon_r = 3.5$, $\tan\delta = 0.0038$) [9] with 0.5 oz (17 μm) copper cladding, interspaced by layers of 1080 ($\epsilon_r = 3.57$, $\tan\delta = 0.0038$) and 2116 ($\epsilon_r = 3.57$, $\tan\delta = 0.0039$) prepregs.

A. Interdigital coupling range

The achievable k_{23} range around 10 GHz (coupling lines on M2 and M3) is first evaluated using an interdigital geometry (Fig. 2(a)) [2] with $L = 3.3$ mm, varying the dimensions in Fig. 2 as $w \in [0.2, 0.5]$, $w_g \in [0.2, 0.5]$ and horizontal displacement $w_o \in [0, 2]$ mm. The even and odd-mode resonances [8] are found using an Eigenmode solver. The resulting distribution of coupling values in Fig. 3 would indicate a minimum practical coupling of ~ 0.15, placing a lower FBW limit of ~ 25 % on a filter of this prototype function.

Fig. 1. 5 metal (+ 2 ground) multi-layer PCB stack.

Fig. 2. Broadside coupling mechanisms. (a) Interdigital, (b) Comblines with centerline offset, (c) Comblines with centerline rotated.

B. Comblines with centreline displaced coupling elements

Fig. 2(b) shows the coupling of two combline resonators of width w and length L 3.5 mm displaced both vertically by the thickness of the 9350 core material, and horizontally by w_o . Both lines are surrounded by a coplanar ground plane separated by a gap w_g . Capacitive end-loading may be implemented as shown in e.g. [7], it is omitted here to reduce the board stack complexity and cost. The coupling is varied by adjusting $w \in [0.2, 0.5]$, $w_g \in [0.2, 0.5]$ and $w_o \in [0, 1]$, with coupling values calculated and plotted in Fig. 5. This topology would lend itself up to FBW ~ 5 %, though the low

achievable unloaded Q-factor of ~ 115 would lead to a filter of ~ 5.5 dB IL at this FBW. While this is a promising avenue to explore for narrowband filters in low-loss media such as LTCC, or where compact layouts may be augmented with Q-enhancement [10], it is not suitable for the current 10 % FBW.

Fig. 3. Coupling range of interdigital elements.

Fig. 4. Coupling range of centreline displaced coupling elements.

Fig. 5. Coupling range of centreline rotated coupling elements.

C. Combine with centreline rotated coupling elements

Maintaining the same line geometry (L , w and w_g) from Fig. 2(b), the geometry in Fig. 2(c) varies the coupling between the two combine elements by rotating them by an angle θ around an axis at the common grounded xy point. By again varying $w \in [0.2, 0.5]$ and $w_g \in [0.2, 0.5]$, with $\theta \in [0, 45^\circ]$, the coupling values in Fig. 5 are achieved with even and odd resonances as shown in Fig. 6. For the given prototype function, this topology would lend itself to implementation of filters of FBW up to 30%, and is implemented here.

III. FILTER IMPLEMENTATIONS

Selecting $\theta_{ij} > 0$ in all cases leads to a filter shaped like a spiral staircase, while selecting θ_{34} and $\theta_{45} < 0$ (creating counter-clockwise rotation, with the middle element the furthest rotated) creates a more compact layout reminiscent of an antique plough blade. Fig. 5 would further indicate that the same value of k_{ij} may be achieved by using one of two θ_{ij} values either side of the local maximum, leading to either narrow-rotation or wide-rotation filter implementations. As a result, four variations of the 5th order filter are demonstrated here (Fig. 8), designated “WS” for wide staircase, “NS” for “Narrow Staircase”, “WR” for “Wide Plough” and “NR” for “Narrow Plough”, each using $w = 0.6$ mm and $w_g = 0.2$ mm. The other dimensions in Table I indicate the lengths of the five resonators $L_{1..n}$ and the offset angles θ_{ij} . The first and last resonators are use a direct tapped feed, offset by a distance d_f from the ground base as shown in Fig. 7, with $w_f = 0.18$ mm ensuring a 50 Ω transmission line feed.

Fig. 6. Even and odd mode resonances for centreline rotated elements.

The results in Fig. 9 would indicate that all four approaches yield feasible filters. The best performing filter is the NS topology with mid-band IL of 1.92 dB, followed by NP (2.64 dB), WP (2.8 dB) and WS (3.3 dB). As expected, NP and NS yield the most compact layouts.

Fig. 9 further indicates that the WS, NS and NP filters all feature asymmetric transmission zeros unaccounted for in the simple all-pole coupling model. This may be due to unintended cross-coupling between elements, or by the presence of non-resonating modes [11].

TABLE I. FILTER DIMENSIONS

	WS	NS	WP	NP
L_1 (mm)	3.08	3.38	3.34	3.44
L_2 (mm)	3.02	3.34	3.27	3.37
L_3 (mm)	3.11	3.36	3.06	3.37
L_4 (mm)	3.02	3.34	3.25	3.34
L_5 (mm)	3.19	3.39	3.45	3.43
θ_{12} (deg)	27	6.45	37.5	6.40
θ_{23} (deg)	36	4.60	50.5	4.60
θ_{34} (deg)	37	4.50	49.5	4.40
θ_{45} (deg)	28	7.25	32	6.20
d_f (mm)	0.25	0.47	0.43	0.51
A (mm ²)	6.14×3.66 = 22.47	3.98×2.54 = 10.11	3.78×4.21 = 15.91	3.87×1.71 = 6.62

Fig. 7. Coupling range of centreline displaced coupling elements.

Fig. 8. Four filter layouts. (a) NP, upper ground planes removed for clarity, (b) WP, exploded view, (c) NS, (d) WS.

IV. CONCLUSION

Three broadside coupled geometries for vertical integration of planar filters in multi-layer PCB is investigated, with rotationally offset combline elements found to provide suitable coupling values for moderate 10% FBW filters using typical line geometry. Based on this, four X-band 5th order all-pole filters are demonstrated by simulation, of which the most compact only requires 6.62 mm² surface area (IL of 2.64 dB), while the best performing filter features a minimum in-band IL of only 1.92 dB, at the expense of a larger 10.11 mm² area.

Future work will improve the synthesis to incorporate the visible asymmetric transmission zeros into the synthesis procedure. Further work may develop a synthesis based on total static capacitance between lines that accounts for the non-uniform per-unit length capacitance of the rotated combline elements. Finally, the results will be validated by prototyping and measurement.

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Fig. 9. Comparison of filter transmission responses.

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