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A Novel High-Performance Length Matching Element for High-Speed Interconnect Differential Channels

Rosa J. Sánchez-Mesa[1, 2], Diego M. Cortés-Hernández[1], Benjamín Gálvez-Sahagún[1], José E. Rayas-Sánchez[2], and Zabdiel Brito-Brito[2]

[1] Intel Corp., Zapopan, Jalisco, 45019 Mexico
[2] Department of Electronics, Systems, and Informatics, ITESO – The Jesuit University of Guadalajara Tlaquepaque, Jalisco, 45604 Mexico

***Abstract* — Length matching elements (LME) are used for intra-pair length matching and inter-pair skew reduction to get high data rates in high-speed differential channels. Although these structures are widely used in printed circuit boards (PCB), the effectiveness of the structure depends on its geometry and dimensions, allowing different design alternatives. In this work, a novel LME for PCB designs is proposed. It is formed by three sub-structures, such that the insertion and impedance profile can be parametrically controlled by the geometry of the proposed LME without affecting the length matching. Mixed-mode parameters, extracted from simulation data, shows that the proposed LME presents lower insertion loss and less electromagnetic interference (EMI), than trapezoidal LME. In addition, time domain reflected analysis (TDR) shows better impedance profile for the proposed LME than for the trapezoidal shape. Both frequency- and time-domain results indicate that the proposed LME can be a good alternative for length matching compensation in high-speed channels.**

***Index Terms* — ADS, differential interconnects, full-wave EM simulation, high-speed, HFSS, length matching element, mode conversion, PCB, S-parameters, TDR.**

I. Introduction

As the requirements for high data rate increases, high-performance channels for data transfer are needed. For high-speed applications, edge-coupled interconnects have been widely used in printed circuit boards (PCB). They allow high data transfer, high common mode noise rejection, and exhibit an overall reduction of EMI [1]-[3]. The main advantages of these differential interconnects depend on the capacity to keep a symmetrical topology [4]. However, it is difficult to achieve homogeneous channels due to the limited available routing area in the PCB, as well as the need to use vertical and horizontal transitions, such as vias and bends, to fulfill customer requirements without significantly compromising signal integrity by undesired effects, such as skew or crosstalk [5]. Increasing the spacing between interconnects allows reducing undesired EM coupling between signal traces (crosstalk), at the expense of larger areas. On the other hand, for signal skew it is necessary to modify the shape of the interconnects by using length matching elements (LME) in order to get intra-pair length matching.

Different LME for skew length compensation has been proposed. For instance, a trapezoidal shape is used in [6] as LME (see Fig. 1), however, it requires small segments to avoid EMI effects. Other LME with more complex geometries have been reported, such as serpentine and trombone shapes [7], however, the available area required for implementation is critical in most PCB real implementation, making these proposals difficult to implement.

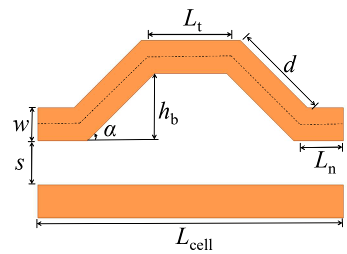

Fig. 1. Top view of trapezoidal length compensation element commonly used for intra-pair length matching.

In this work, a new structure for LME in edge-coupled interconnects is proposed. The structure is formed by three basic subsections: rectangular, semicircular, and parallel traces. This allows controlling losses and impedance profile simultaneously. The LME is simulated in HFSS[1] and incorporated into a high-speed PCB. The results are compared with those using the trapezoidal LME. Our comparative study shows that the proposed new LME has better frequency and time domain performance than the trapezoidal LME.

II. Proposed Length Compensation Element

The LME proposed in this work is formed by three planar shapes: the first one is a semicircular shape, the second one is formed by the parallel traces forming the edge-coupled interconnect, and the third one is a rectangular shape connecting the semicircular trace and the parallel traces.

The geometry of the proposed LME is shown in Fig. 2. w is the width of the interconnects, L_{cell} is the length of the LME, s is the spacing between the parallel traces, θ is the angle formed between the edge and the center of the parallel trace, r is the radius of the semicircular shape, $L_n = L_{cell}/2 - x$ is the length of the parallel strips, with $x^2 = r^2 - (w/2)^2$, and a and b are the height and the width of the rectangular shapes, respectively. Notice that when a signal is traveling along the proposed structure, it encounters two discontinuities: the rectangular and

[1] ANSYS Electromagnetics Desktop 2017, Release 18, ANSYS Electromagnetics Suite, 2016.

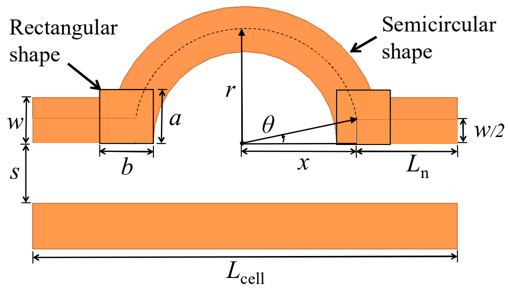

Fig. 2. LME proposed in this work. Notice the rectangular and semicircular shapes, and the parallel traces forming the LME.

TABLE I
SIMULATED TEST CASES

Case	Name / Description	Geometry
1	Homogeneous edge-coupled transmission line	No bends, l = 2600 mil
2	Trapezoidal	L_t = 15 mil. L_n = 8 mil, h_b = 12.25 mil, d = 17.75 mil, and α = 45°
3	Proposed LME 1	a = 6 mil, b = 6 mil, r = 19 mil
4	Proposed LME 2	a = 8 mil, b = 15 mil, r = 19 mil
5	Proposed LME 3	a = 9 mil, b = 14 mil, r = 19 mil

the semicircular shapes. When the signal is crossing the rectangular shape, the current tends to distribute along its total area, increasing the capacitance on the line. Once the current flows through the semicircular shape, the area between both traces increases, increasing the inductance of the LME. Therefore, both the rectangular and the semicircular shapes allow controlling the impedance, as well the return and insertion loss of the LME. In this regard, the LME not only helps to compensate the total length but also has an impact on the impedance, return and insertion losses of the channel.

Based on the LME geometry (Fig. 2), it is possible to calculate the resultant length compensation Δl. We can define the radius of the semicircular shape from the required length compensation, Δl, as follows.

Δl can be calculated by

$$\Delta l = (\pi - 2\theta)r \tag{1}$$

where θ is given by

$$\theta = \sin^{-1}(w/2r) \tag{2}$$

Substituting (2) in (1), Δl can be calculated by

$$\Delta l = \pi r - 2\, r \sin^{-1}(w/2r) \tag{3}$$

Expressing (3) as an implicit equation,

$$\Delta l - \pi r + 2\, r \sin^{-1}(w/2r) = 0 \tag{4}$$

Hence, the radius of the semicircular shape can be obtained from the required additional length by solving (4) for r.

III. Simulated Test Cases

To test the proposed LME, a routing scheme is defined in this work. The routing scheme consists of a 1,300 mils homogeneous edge-coupled microstrip transmission line followed by a right angle bend. This bend introduces a 200 mils mismatch compensated with cells of the proposed LME. Each cell is designed using (4). Assuming a Δl = 10 mils, 20 LME cells in cascade compensate the mismatch. The cell's size is 55 mils and the total length section is 1,100 mils. So, the total length of the routing scheme is 2,600 mils, corresponding to the sum of the homogeneous edge-coupled microstrip transmission line, the right angle bend, and the 20 LME cells in cascade.

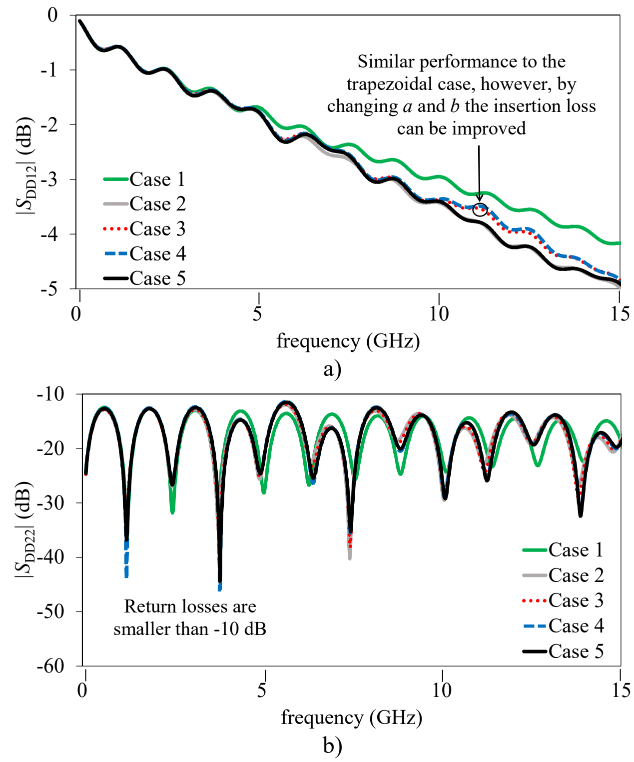

Fig. 3. S-parameters describing the a) insertion loss and b) return loss of the LME analyzed in this work.

The impedance of the edge-coupled microstrip transmission line is Z = 80 Ω. The trace's width is w = 6.6 mils, the dielectric thickness is h = 3 mils, the spacing is s = 8 mils, the length of the ground plane is l = 2,600 mils and the width of the ground plane is w_g = 10h. The PCB substrate has a dielectric permittivity of ε = 4.2 and a loss tangent of tanδ = 0.02; the metal layer is copper with a conductivity $\sigma = 5.7\times10^7$ S/m and a conductor thickness t = 1.5 mils.

In order to evaluate the proposed LME, a comparative study is realized using five different structures. In Table I, a description of the structures is presented. The structures are implemented in HFSS and whole the channel is implemented in ADS[2].

IV. Results and Comparison

The S-parameters obtained of the full channel simulation described in Section III from ADS. The performance of the channel is evaluated in the frequency and time domain. Fig. 3a

[2] Advanced Design System 2016.01, 5301 Stevens Creek Boulevard, Santa Clara CA.

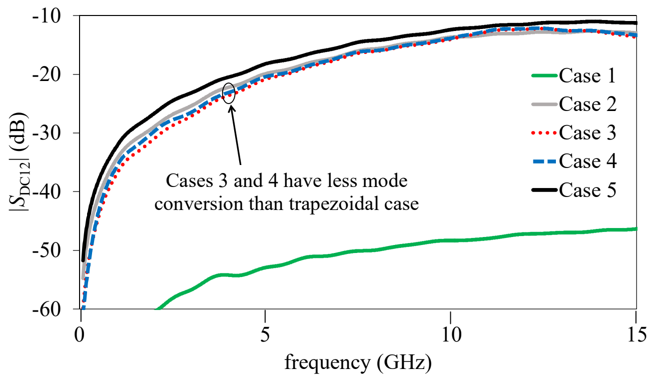

Fig. 4. Mode conversion plot for all the study cases.

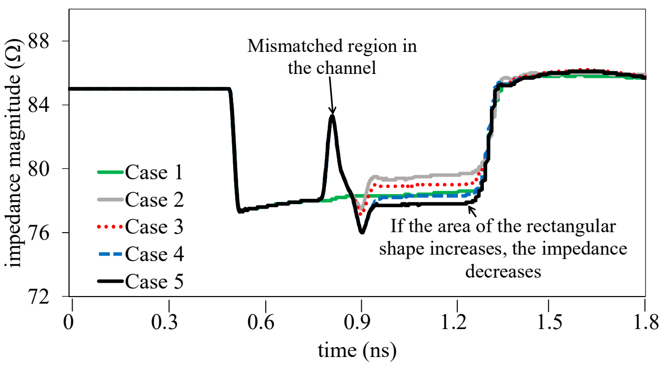

Fig. 5. TDR of the structures analyzed in this work.

shows the insertion loss of all LME's implemented, notice that the homogeneous transmission line exhibit the best performance. Additionally, two of the proposed LME's: Case 3 and Case 4 have low insertion losses in frequencies higher than 10 GHz and these losses are smaller than the trapezoidal and Case 5.

Fig. 3b shows the return losses, notice that all curves are within -10 dB and most of them overlap until 4 GHz, between 5-10 GHz the difference starts to be noticed and for frequencies higher than 10 GHz the signals look distorted as expected because many transitions are introduced in the channel. No highest differences are observed in the simulated cases. On the other hand, the mode conversion presented in Fig. 4 shows differences between all the LME cases. Notice that two of the proposed structures, Case 3 and Case 4 have the lowest values of mode conversion, showing improvements over the trapezoidal and Case 5.

In order to evaluate the performance of the structures in the time domain, a TDR simulation is performed. The TDR simulation is implemented with a rise time of 25 ps, Fig. 5 shows the impedance profile of each case. Notice that the interval between 0.6 ns to 1.3 ns shows the homogeneous transmission line response, during this time interval the impedance keeps almost constant around 78 Ω in the homogeneous case. At 0.8 ns the effect of the mismatching introduced by the bend is observed, and a sudden increase in the impedance is presented in the Cases 2-5. After 0.9 ns the impedance magnitude show a capacitive and inductive effect depending on the case. In the case of the trapezoidal structure, it is observed the inductive effect, and the impedance increases until 79 Ω. Otherwise, the proposed structures present different impedance magnitude around of 78 Ω and the same length matching.

Notice that an increases of the area of the rectangular shape ($Area = a \times b$), increases the capacitive effect of the LME, decreasing the LME's impedance. Thus the Case 5 ($Area$ = 126 mil^2) presents lower impedance than Case 3 ($Area$ = 36 mil^2) and Case 4 ($Area$ = 120 mil^2); on the other hand Case 4 and Case 1 present similar impedance profiles, as is observed in Fig. 5. Finally, based on the results of the frequency and the time domain, there is a rectangular shape that allows the best performance in a length matching application, so changing only the area of the rectangular shape the impedance profile and the insertion loss tend to improve.

V. Conclusion

This work presented a novel structure for length matching elements (LME). The proposed LME modifies the electrical characteristics of a high-speed channel by parametrically changing its geometry (the rectangular shape connecting the semicircular section and the parallel traces), resulting in an easy way to improve the performance of edge-coupled interconnects without using too much area in the PCB. The analysis in time and frequency domain, considering full-wave EM simulations, showed an improvement over the traditional trapezoidal LME, with a reduction of mode conversion and insertion losses, making the proposed LME attractive for high-speed channels.

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