Far-End Crosstalk Reduction in PCB Interconnects Using Stepped Impedance Elements and Open-Circuited Stubs

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ABSTRACT: In this work, new trace configurations using stepped impedance elements and open-circuited stubs to reduce far-end crosstalk in printed circuit board (PCB) interconnects are introduced. The goal of this study is to reduce crosstalk without using additional PCB components in the design. Specifically, we use stepped impedance elements and open-circuited stubs of uniform length and width on the victim traces to suppress high-frequency electromagnetic interference and to equalize propagation delays or capacitive and inductive couplings between PCB traces. The overall design is very similar to the usual low-pass filter configurations, which are difficult to implement in the prototype testing. The proposed approach shows remarkably better results when compared with conventional intervening guard trace schemes. Int J RF and Microwave CAE 21:596–601, 2011.

Keywords: far-end crosstalk; open-circuited stub; printed circuit board; stepped impedance elements

I. INTRODUCTION

Crosstalk in printed circuit board (PCB) traces is a well-known electromagnetic compatibility (EMC) and signal integrity problem. A typical scenario involves coupling of a high-frequency signal (e.g., a digital clock) onto a low-frequency trace (e.g., a power or a ground trace). As low-frequency traces are typically long traces routed on multiple layers on a PCB, high-frequency interference may easily radiate from multiple and/or unsuspected locations on the PCB. Therefore, it is usually very difficult to determine the actual location of the radiating area on the board.

Normally, the first line of defence is to mitigate the radiation source by reducing the current strength, slewing the rise/fall time of the digital signal (e.g., by adding series resistors or ferrites [1]) or shortening/straightening the high-frequency trace. Though such countermeasures may provide a limited improvement, they may not even be an option for a given design (e.g., for signal integrity constraints).

Another way to reduce crosstalk is to exploit the inherent parasitic effects (i.e., mutual capacitance and inductance) among PCB traces [2–5]. To this end, different configurations of guard traces have been used in between adjacent interconnects [2, 6–8]. However, routing additional traces may not be possible in a crowded layout. Furthermore, crosstalk reduction provided by guard traces is limited and is usually insufficient [2, 9–11]. Therefore, it is highly desirable to explore new trace configurations that may provide better crosstalk reduction and can be routed in a crowded layout. One way is to use a low-pass filter (LPF) configuration on the victim traces. A typical LPF uses either stepped impedance elements or open-circuited stubs on the victim trace. This method achieves much better performance than designs using guard traces alone. However, as stepped impedance elements and open-circuited stubs have nonuniform lengths and widths, it is very difficult to implement different LPF configurations on PCB traces in a prototype testing.

To this end, this article introduces new victim trace configurations to reduce far-end crosstalk coupling between two adjacent PCB traces. The far-end crosstalk is of particular interest due to the significantly stronger coupling when compared with that at the near end [12]. The proposed configurations have LPF characteristics [13] as they use stepped impedance elements and open-circuited stubs. However, these elements have uniform lengths and,

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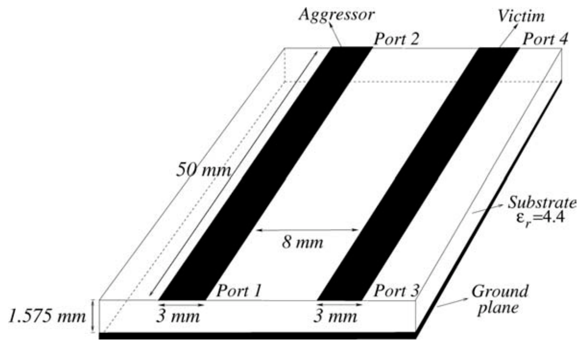

Figure 1 PCB structure with two uniform adjacent traces.

therefore, are easier to implement in the prototype testing in EMC pre-compliance/compliance chambers.

The organization of this article is as follows. Section II discusses both conventional and proposed crosstalk reduction configurations. Section III compares these PCB configurations in terms of crosstalk reduction in adjacent PCB traces, while conclusions are given in Section IV.

II. CROSSTALK REDUCTION SCHEMES

Figure 1 illustrates a PCB structure (50×40 mm^2) with two adjacent uniform traces that are spaced 8 mm apart. Both traces are 3 mm wide and 50 mm long. As illustrated, the PCB structure is supported by a 1.575-mm thick FR4 substrate with a dielectric constant of 4.4 and a loss tangent of 0.02. We assume that one trace (acting as an aggressor) is carrying digital or high-frequency signals. These signals may couple onto the adjacent trace (hereby referred as the victim trace) which is carrying low-frequency or DC currents.

To reduce this coupling, referred to as crosstalk, various configurations can be used. Below, we discuss conventional configurations as well as our proposed configurations.

A. Conventional Configurations

As illustrated in Figure 2, a guard trace is usually introduced (as a shield) in between the aggressor and the victim trace. For additional shielding, one may also ground the guard trace with via fences (see Fig. 3). In this article, we

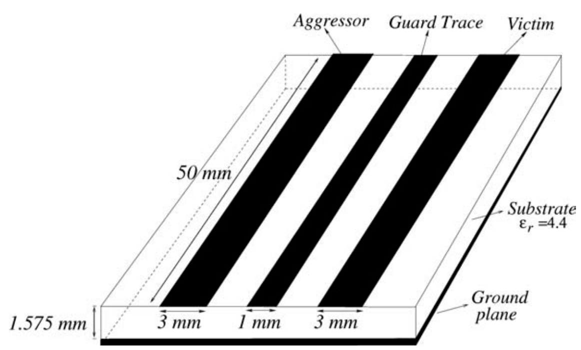

Figure 2 PCB structure with a guard trace between two uniform adjacent traces.

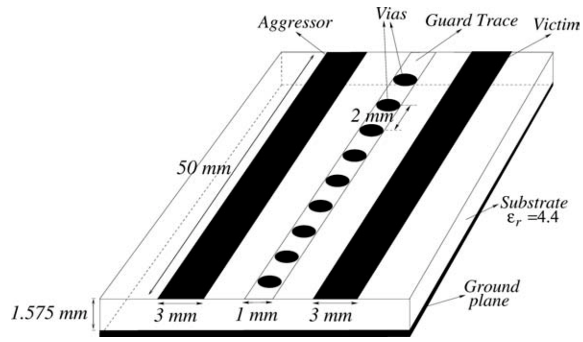

Figure 3 PCB structure with a guard trace grounded with vias between two uniform adjacent traces.

will assume that the guard trace is 1 mm wide and is terminated at both ends by the matched impedance (i.e., 87 Ω) to prevent any standing waves. We further assume that the spacing between each via on the guard trace is 2 mm.

B. Stepped Impedance LPF Configuration

1. Stepped Impedance LPF Design. In our recent conference paper [15], the stepped impedance trace for crosstalk reduction was presented. Here, if the victim trace is a low-frequency or DC trace, one may use a stepped impedance LPF configuration (i.e. using elements of alternating high and low impedance on the trace). The length l_{Hi} of the high impedance (Z_{H}) element can be calculated using the electrical length defined as [13],

$$\beta l_{\mathrm{Hi}} = \frac{LR_0}{Z_{\mathrm{H}}}, \tag{1}$$

where $\beta = 2\pi/\lambda$, λ corresponds to the cutoff frequency of the LPF, and R_0 represents the feed trace characteristic impedance. Similarly, the length l_{Li} of the low impedance element (Z_{L}) can be calculated as,

$$\beta l_{\mathrm{Li}} = \frac{CZ_{\mathrm{L}}}{R_0}, \tag{2}$$

where L and C are the normalized lumped element values [14]. The width of the elements is chosen corresponding to impedances Z_{H} and Z_{L}. Here, Z_{H} and Z_{L} are usually set to the highest and lowest characteristic impedance values that can be practically fabricated. It is worth mentioning that the difference between the two impedances should be as high as possible for excellent filter performance (i.e., sharp cut-off). However, in our case, sharp cutoff is not an essential requirement. Figure 4 illustrates an example

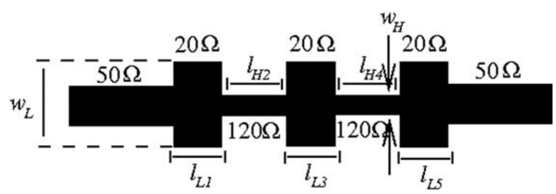

Figure 4 5-Element stepped impedance LPF design.

TABLE I 5-Element Stepped Impedance LPF Design

Element Values	Impedance (Ω)	Electrical Length	Length (mm)	Width (mm)
$C_1 = 0.618$	$Z_L = 20$	14.163^0	$l_{L1} = 1.492$	$w_L = 11$
$L_2 = 1.618$	$Z_H = 120$	38.626^0	$l_{H2} = 4.657$	$w_H = 0.4$
$C_3 = 2.000$	$Z_L = 20$	45.836^0	$l_{L3} = 4.828$	$w_L = 11$
$L_4 = 1.618$	$Z_H = 120$	38.626^0	$l_{H4} = 4.657$	$w_H = 0.4$
$C_5 = 0.618$	$Z_L = 20$	14.163^0	$l_{L5} = 1.492$	$w_L = 11$

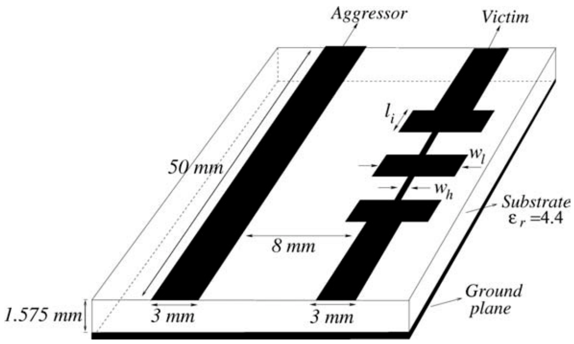

Figure 5 PCB structure of the proposed stepped impedance configuration with five elements.

of a 5-element LPF design. Here, we chose $Z_H = 120\ \Omega$, $Z_L = 20\ \Omega$, and $R_0 = 50\ \Omega$. We also selected a cutoff frequency of 4 GHz and a 7 dB insertion loss at 4.4 GHz. The calculated values using (1) and (2) are given in Table I.

2. Previously Proposed Stepped Impedance Configuration. The stepped impedance configuration (Fig. 5) is based on the LPF design. However, unlike the LPF, the proposed structure uses uniform lengths (l_i) for all elements. This length may be selected to lie within the minimum and the maximum values calculated for the LPF design. For example, for the 5-element design given in Table I, the length for an element in the proposed configuration should be selected to be between 1.492 and 4.828 mm. Choosing a particular uniform length for all elements will affect the cutoff frequency and the return loss of the filter. However, as we are assuming low-frequency or DC signals on the victim trace, cutoff frequency and return loss are not the primary concerns. Fixing the element lengths simplifies the LPF design procedure and makes it easier to implement the design in EMC prototype testing (e.g., using copper tape). Furthermore, selecting a particular number of elements is arbitrary and affects the performance of the proposed configuration in terms of

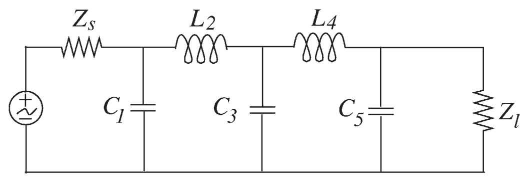

Figure 6 Circuit prototype of 5-element open-circuited stub LPF.

crosstalk. In our investigation, we have selected 3-element and 5-element configurations for comparison with the uniform trace configuration (Fig. 1).

C. Open-Circuited Stub LPF Configuration

4. Open-Circuited Stub LPF Design. One drawback of using the stepped impedance design is the narrow width of the high-impedance sections. This could be an issue for the flow of high current densities. Therefore, a new trace configuration is introduced. Here, one may use an open-circuited stub LPF on the victim trace. In this configuration, the element lengths are essentially equal to $\lambda/8$ at the cutoff frequency. The widths for both stubs and transmission line sections correspond to their characteristic impedance values. Figure 6 depicts a 5-element LPF circuit prototype. Here, by using Richard's transformation [13] to convert lumped elements to distributed elements, the reactance of an inductor can be calculated as

$$jX_L = jL\tan(\beta l) \quad (3)$$

and the susceptance of a capacitor can be calculated as

$$jB_C = jC\tan(\beta l), \quad (4)$$

where L and C are the normalized lumped element values, $\beta = 2\pi/\lambda$, λ corresponds to the cutoff frequency of the LPF, and X_L and B_C are the reactance and the susceptance of the lumped element components.

These equations indicate that an inductor can be replaced with a short-circuited stub of length βl and characteristic impedance L, while a capacitor can be replaced with an open-circuited stub of length βl and characteristic impedance $1/C$. Moreover, Kuroda's identities [13] are used to separate filter elements using transmission line sections and also to transform short-circuited stubs into open-circuited stubs. In PCB technology, open-circuited stubs are easier to fabricate than short-circuited stubs, because a via hole through the substrate is not needed. Figure 7 illustrates a distributed model of a 5-element open-circuited stub LPF with a cutoff frequency of 4 GHz

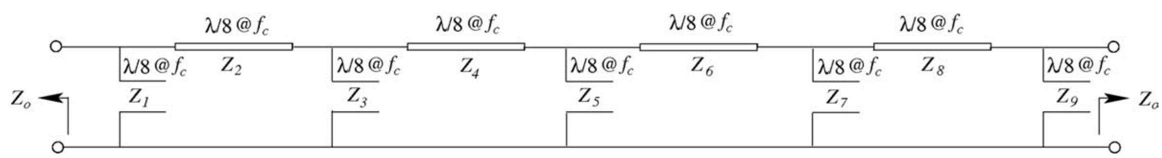

Figure 7 A distributed circuit model of a 5-element open-circuited stub LPF design.

TABLE II 5-Element Open-Circuited Stubs LPF Design at 4 GHz Cutoff Frequency

Element Values	Impedances (Ω)	Electrical Length	Length (mm)	Width (mm)
$C_1 = 1.7058$	$Z_0 = 50$	45°	4.47	3.0
$L_2 = 1.2296$	$Z_1 = 129.3$			0.28
$C_3 = 2.5408$	$Z_2 = 81.52$			1.14
$L_4 = 1.2296$	$Z_3 = 24.04$			8.74
$C_5 = 1.7058$	$Z_4 = 79.96$			1.19
	$Z_5 = 19.68$			11.27
	$Z_6 = 79.96$			1.19
	$Z_7 = 24.04$			8.74
	$Z_8 = 81.52$			1.14
	$Z_9 = 129.3$			0.28

and 0.5-dB equal-ripple characteristics. The corresponding stub and transmission line section lengths as well as the widths after impedance and frequency scaling are given in Table II.

5. *Proposed Open-Circuited Stub Configuration.* The proposed open-circuited stub configuration (Fig. 8) is easier to realize, more compact in size, and has fewer concerns for high current densities when compared with the stepped impedance configuration. The proposed structure uses a uniform stub width (w) and a uniform transmission line section width (w_t). These widths may be selected to lie within the minimum and the maximum values calculated for the LPF design.

For example, for the 5-element design given in Table II, the width for a stub can be selected between 0.28 and 11.27 mm, while the width for a transmission line section can be selected to be around 1 mm. As is the case in stepped impedance design, choosing particular widths uniformly for all stubs and for all transmission line sections will affect the cutoff frequency and the return loss of the filter. However, in our case, cutoff frequency and return loss are not the primary concerns.

III. RESULTS AND DISCUSSIONS

Both conventional and proposed PCB configurations were simulated using *Ansoft HFSS* to calculate the far-end crosstalk (S_{41}) over a sweep of frequency from 0 to 6 GHz. Below we present a comparison of the calculated results. First, the crosstalk between uniform adjacent PCB traces (Fig. 1) using a conventional guard trace (Fig. 2) and a guard trace with vias (Fig. 3) was calculated. The results, plotted in Figure 9, show that the guard trace alone does not provide any significant improvement in the crosstalk reduction. Similarly, using the guard trace with via fences shows a slight but insignificant improvement in crosstalk reduction.

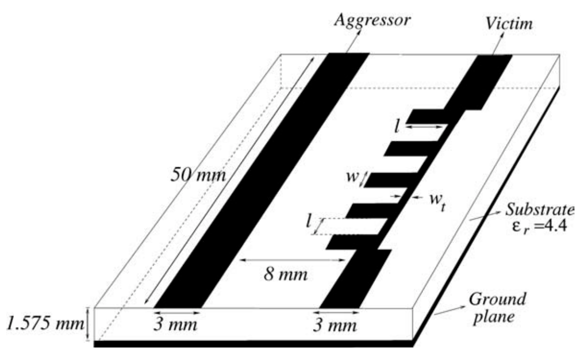

Figure 8 PCB structure of an open-circuited stub configuration with five elements.

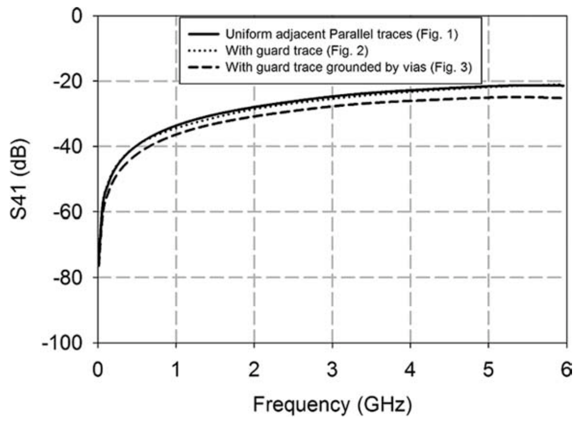

Figure 9 Comparison of far-end crosstalk in adjacent PCB traces using a guard trace and a guard trace grounded with vias.

Next, the performance of the stepped impedance configuration (Fig. 5) using 3-mm long elements and the performance of the proposed open-circuited stub configuration (Fig. 8) with $w = 4.4$-mm stub width, $w_t = 0.6$-mm transmission-line sections width, and $l = 5.8$ mm element (i.e., stubs and transmission line sections) lengths were investigated.

As can be seen in Figure 10, the proposed design with open-circuited stubs provides significant reduction in crosstalk when compared with the performance of the guard trace configurations in Figure 9 as well as compared to the stepped impedance configuration. It is observed that

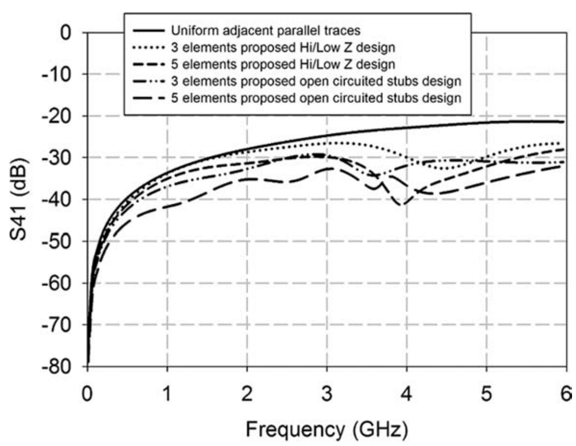

Figure 10 Far-end crosstalk in PCB traces using the proposed configurations.

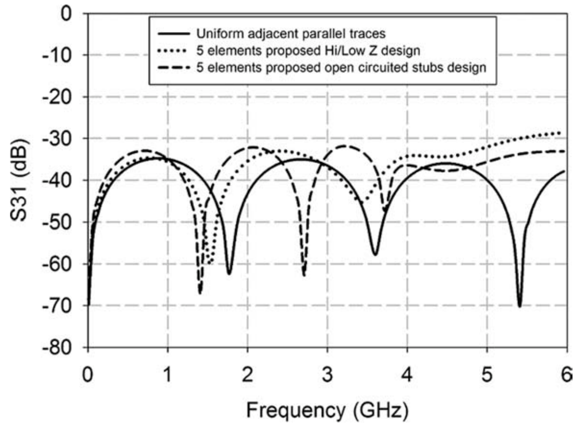

Figure 11 Comparison between the proposed configurations and the uniform trace configuration for the near-end crosstalk.

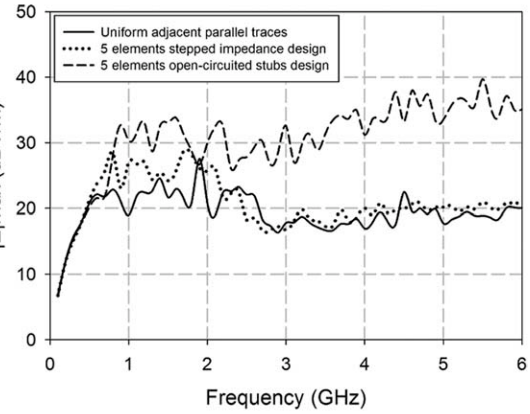

Figure 13 Magnitude of radiated electric field from the proposed PCB configurations.

the steepest crosstalk reduction (i.e., around 4 GHz) occur according to the location of the cutoff frequency of the victim trace. Moreover, it can be observed that the crosstalk can be further reduced by increasing the number of elements in both the stepped impedance and the open-circuited stub configurations. A comparison of the near-end coupling, as plotted in Figure 11, shows that the proposed configurations provide no improvement when compared with our reference configuration (i.e., uniform adjacent parallel traces). Figure 12 shows that the performance of the proposed configurations has a LPF frequency characteristic, and the performance is relatively similar for both designs in terms of the return loss (S_{33}) and the transmission coefficient (S_{43}). Moreover, the return loss levels are acceptable for the proposed configurations.

Figure 13 illustrates the radiated emissions from the proposed PCB configurations (Figs. 5 and 8) as well as our reference configuration (Fig. 1). With the aid of HFSS, the magnitude of the electric field $|E|_{max}$ radiated by the PCB structures without the dielectric material was calculated on a hemispherical surface with radius equal to 1 m. The PCB structure is located at the center of the hemisphere and a 1-V voltage source is used to excite the aggressor trace (i.e.,

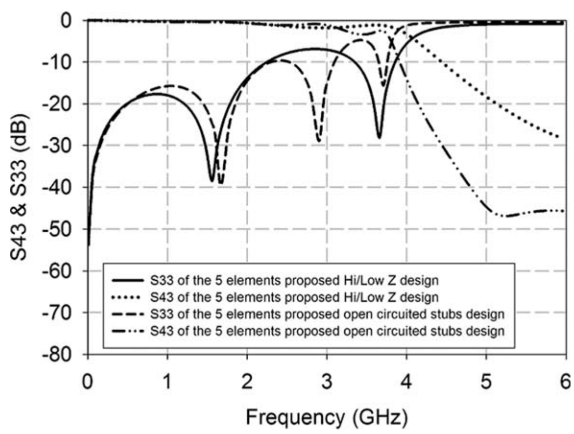

Figure 12 LPF frequency characteristics for both proposed configurations.

at port 1) which connects between the uniform trace and an infinite ground plane [16]. Figure 13 shows that, by varying the source frequency from 0.1 to 6 GHz, the 5-element-stepped impedance design has relatively similar radiated emission impact when compared with the uniform parallel trace design, whereas the 5-element open-circuited stubs design has relatively high-radiation emissions.

IV. CONCLUSIONS

In this article, stepped impedance and open-circuited stub configurations using uniform elements were investigated for reduced far-end crosstalk in adjacent PCB traces. The performance of the proposed designs was found to be similar to the LPF design. However, the proposed approaches are easier to implement in the EMC prototype testing. Both configurations provide an improved far-end crosstalk reduction; however, the open-circuited stub design exhibits better performance, more compactness, and better handling of high current densities when compared with the stepped impedance design.

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