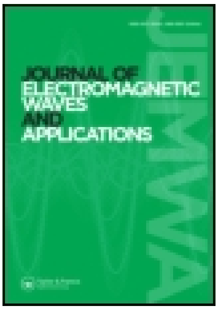

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Non-uniform PCB traces with prescribed frequency bands for improved crosstalk immunity

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Non-uniform PCB traces with prescribed frequency bands for improved crosstalk immunity

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In this work, a new design approach for realizing printed circuit board (PCB) trace configuration with continuous impedance perturbation to reduce crosstalk in PCB interconnects is investigated. The purpose is to reduce far-end crosstalk without incorporating additional PCB components in order to modify the reactive couplings between the adjacent traces, however at the expense of the available frequency band. This is achieved by replacing a uniform victim trace on a PCB with a continuously varying-impedance trace that exhibits a lowpass filter frequency characteristic. A simplified design approach of the proposed trace impedance profile which is governed by a truncated fourier series is presented. The proposed trace shows better crosstalk reduction results compared to conventional intervening guard trace schemes. Several configurations were designed, implemented, and tested to demonstrate the advantages of the underlying principle.

Keywords: electromagnetic compatibility (EMC); crosstalk; fourier-based trace; guard trace; printed circuit board (PCB)

1. Introduction

The increasing interest to evaluate electronic systems for possible susceptibility to electromagnetic interference and to ensure their electromagnetic compatibility (EMC) with nearby circuits has attracted researchers to conduct several studies on reducing crosstalk between circuit traces.[1] A typical EMC problem involves coupling of a high-frequency signal (e.g. a digital clock) onto a low-frequency trace (e.g. a power/ground trace). Low-frequency traces are typically long traces routed on a printed circuit board (PCB), thus, high-frequency interference may radiate from multiple unsuspected locations. It is usually very difficult to capture the actual location of the radiating area on the board. Normally, far-end crosstalk can be alleviated by shortening the length of the high-frequency trace, increasing the spacing between the traces, reducing the current strength, or slewing the rise/fall time of the digital signal. However, such techniques may provide a limited enhancement, and may not even be an option for a given design constraints.

Far-end crosstalk is particularly investigated due to the stronger coupling as compared to that at the nearend. To date, several attempts to reduce the far-end crosstalk were reported. This was achieved by adding a guard trace between the victim

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and aggressor traces of the circuit or by adding a guard trace grounded with equally spaced vias.[2–4] Since a large number of grounded vias degrade the SI and reduce the flexibility of the circuit routing, it is always desired to explore new trace configurations that may provide better crosstalk reduction and can be routed in a crowded layout. For this reason, one may employ a lowpass filter (LPF) configuration on the victim traces either with stepped impedance elements or with open-circuited stubs.[5] This method achieves better performance than designs using guard traces alone; however, a drawback on stepped impedance designs is their low capability in handling high current densities due to the narrow trace width of the high impedance sections. Moreover, the open-circuited stubs design suffers from high radiated emissions.[5] In our proposed trace depicted in Figure 1, such limitations do not exist as a non-uniform trace of a continuously varying impedance $Z(z)$ with tolerable corresponding width $W(z)$, and propagation constant $\beta(z)$ is employed.

The organization of this paper is as follows: Section 2 discusses the design of the proposed non-uniform trace configuration and the conventional guard trace techniques used to reduce crosstalk; one by using guard trace, and another by incorporating guard trace grounded by a number of uniformly separated vias. Section 3 compares the performance of the above-mentioned PCB configurations with the proposed non-uniform trace in terms of crosstalk reduction, while conclusions are given in Section 4.

2. Trace configurations

In our experiment, we assume that one trace is acting as an aggressor and carrying high-frequency signals which may couple into the adjacent trace (i.e. the victim trace) carrying relatively low-frequency or DC currents. To reduce this coupling, referred to as crosstalk, various configurations are investigated including both conventional and proposed non-uniform trace configuration as shown in Figure 2. The PCB structures are built on a 40 mm × 50 mm board and supported by a 1.524 mm thick RO4835 substrate [6] with a dielectric constant of 3.66 and a loss tangent of 0.0037. Both the aggressor and the victim traces in Figure 2 are spaced 8 mm apart with a uniform trace width of 3.5 mm (i.e. equivalent to a transmission line with 50 Ω characteristic impedance) and a length of 50 mm.

2.1. Conventional trace configurations

A guard trace (Figure 2(b)) is usually introduced as a shield in between the aggressor and the victim trace and for additional shielding one may also ground the guard trace with stitching vias (Figure 2(c)). In this work, we will assume that the guard trace is 1 mm wide and is terminated at both ends by its matched impedance (i.e. 92 Ω) to avoid the occurrence of standing waves. The spacing between each via on the guard trace is

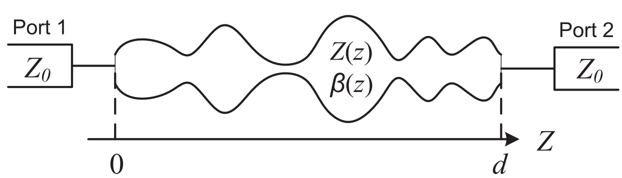

Figure 1. Topology of the proposed PCB traces incorporating variable characteristic impedance and propagation constant.

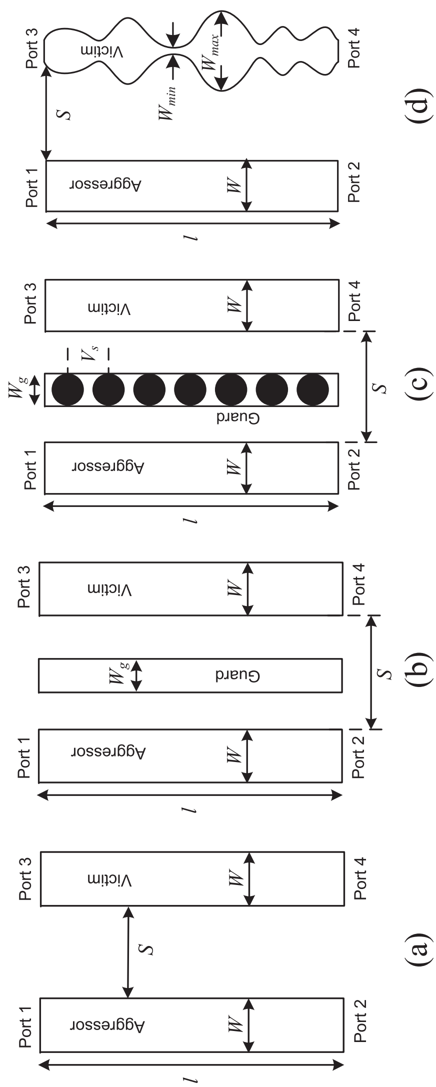

Figure 2. Schematic layouts of two parallel PCB traces: (a) uniform traces with no guard trace; (b) uniform traces with a guard trace; (c) uniform traces with a guard trace grounded by vias; and (d) victim trace with fourier-based profile and no guard trace.

Table 1. The optimized fourier coefficients of the designed LPF.

C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
0.0102	−0.008	−0.0432	−0.2007	0.9185	−0.0509	−0.0823	−0.1429	−0.152	−0.1213	−0.1274

set to 2 mm, which is the optimal distance required to achieve an improved crosstalk performance.[7]

2.2. Proposed non-uniform trace configuration

If victim trace is a low-frequency or a DC trace, one may employ a LPF configuration. It is worth mentioning that the sharper the cutoff of the LPF, the better the far-end crosstalk at the cutoff frequency.[5] This allows controlling the location of the steepest reduction in the crosstalk response.

The synthesis of a non-uniform trace [8,9] starts by subdividing the line length (d) into K electrically commensurate short sections with a length of Δz as given below:

$$\Delta z = \frac{d}{K} \ll \lambda = \frac{c}{f} \tag{1}$$

Then, the total transmission *ABCD* matrix of the full non-uniform trace is obtained by multiplying the 2 × 2 *ABCD* parameters of each section as follows [10]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \cdots \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \cdots \begin{bmatrix} A_K & B_K \\ C_K & D_K \end{bmatrix} \tag{2}$$

The electrical length ($\Delta\theta$) of each segment can be written as:

$$\Delta\theta = \frac{2\pi}{\lambda}\Delta z = \frac{2\pi}{c} f \sqrt{\varepsilon_{eff}}\Delta z \tag{3}$$

where c is the speed of light, λ is the wavelength, f is the frequency of interest, ε_{eff} is the effective dielectric constant, and K is the number of the non-uniform sections along the proposed PCB trace. Now the width or the characteristic impedance of each section can be calculated through the following truncated Fourier series expansion for the normalized characteristic impedance $\bar{Z}(z) = \frac{Z(z)}{Z_0}$ is considered:

$$\ln(\bar{Z}(z)) = \sum_{n=0}^{N} C_n \cos\left(\frac{2\pi n z}{d}\right) \tag{4}$$

where C_n,s ($n = 1, 2 \ldots, N$) are the Fourier coefficients, N is the number of coefficients, and Z_0 is the characteristic impedance of the trace. Upon determining the *ABCD* matrix of the non-uniform trace, the following objective function is considered for minimization to obtain a LPF characteristic with a cutoff frequency of f_c, and a maximum frequency of f_m:

$$E = \sqrt{\frac{1}{N_f}\left(\left(|S_{11}|^2 + ||S_{21}| - |S_{21}|_{\text{desired}}|^2\right)_{0 \le f \le f_c} + \left(||S_{21}| - |S_{21}|_{\text{desired}}|^2_{f_c \le f \le f_m}\right)\right)} \tag{5}$$

In the above error function (E), $|S_{21}|_{\text{desired}}$ corresponds to −0.1 dB in the [0, f_c] band and −30 dB in the [f_c, f_m] band. N_f corresponds to the number of frequency points in the [0, f_m] frequency range. S_{11} and S_{21} are the S-parameters corresponding to the *ABCD* equivalency parameter of the non-uniform LPF trace.[10] Moreover, the error function has to be accompanied with constraints which lead to reasonable fabrication and physical matching, as given below:

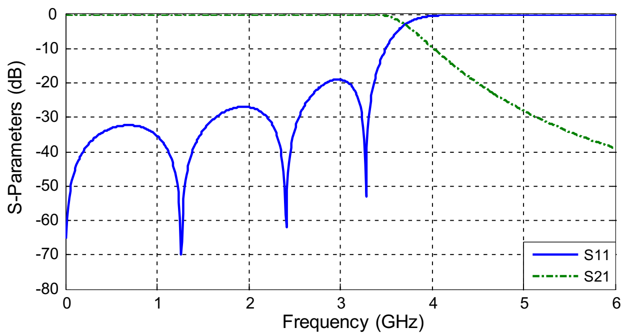

Figure 3. |*S*-parameters| for the optimized non-uniform LPF.

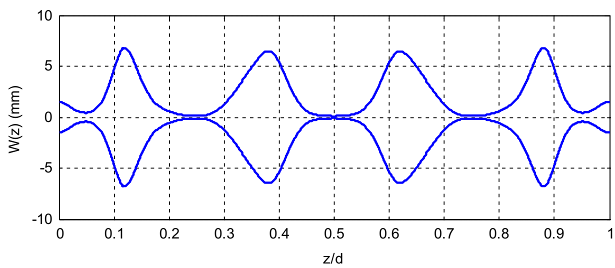

Figure 4. The resulting impedance profile of the non-uniform LPF.

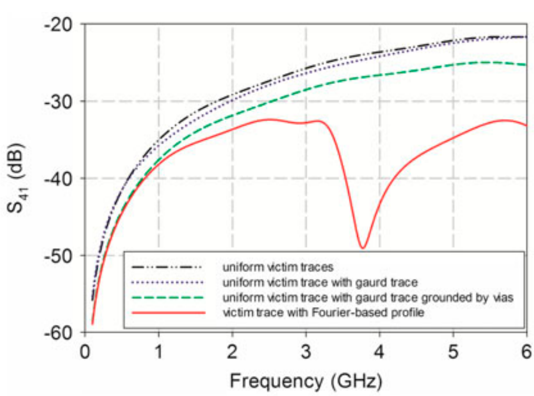

Figure 5. Simulated far-end crosstalks using conventional guard trace schemes and the proposed non-uniform LPF victim trace configuration.

$$\bar{Z}_{\min} \leq \bar{Z}(z) \leq \bar{Z}_{\max} \tag{6}$$

$$\bar{Z}(0) = \bar{Z}(d) = 1 \tag{7}$$

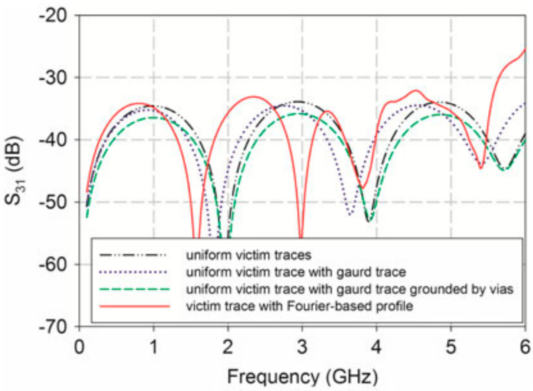

Figure 6. Simulated near-end crosstalks using conventional guard trace schemes and the proposed non-uniform LPF victim trace configuration.

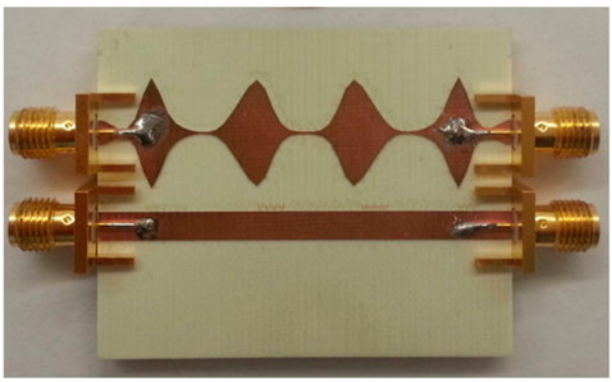

Figure 7. A photograph of the fabricated non-uniform trace configuration.

where $\bar{Z}_{\min}$ and $\bar{Z}_{\max}$ are the minimum and maximum normalized impedances corresponding to the maximum and minimum trace widths, respectively. Considering the substrate material mentioned above, an example of non-uniform LPF with a maximum frequency ($f_{\max}$) of 6 GHz, a frequency step size of 0.2 GHz, and a length (d) of 50 mm is designed and optimized using Matlab. The LPF non-uniform trace has a width varying between 0.45 and 14 mm and a cutoff frequency (f_c) of 3.6 GHz. Here, width variations are corresponding to the optimized Fourier coefficients, while the desired input and output port impedances are maintained unaltered as stated in (7).

It is worth pointing out that in our design, both minimum and maximum widths are subject to optimization, and the same frequency characteristics of a conventional stepped-impedance filter can be easily achieved utilizing a non-uniform transmission line/trace without being forced to choose very narrow widths. This is unlike conventional stepped impedance LPFs, where high impedance sections are usually required to improve the filter's selectivity and thus better crosstalk reduction can be achieved.

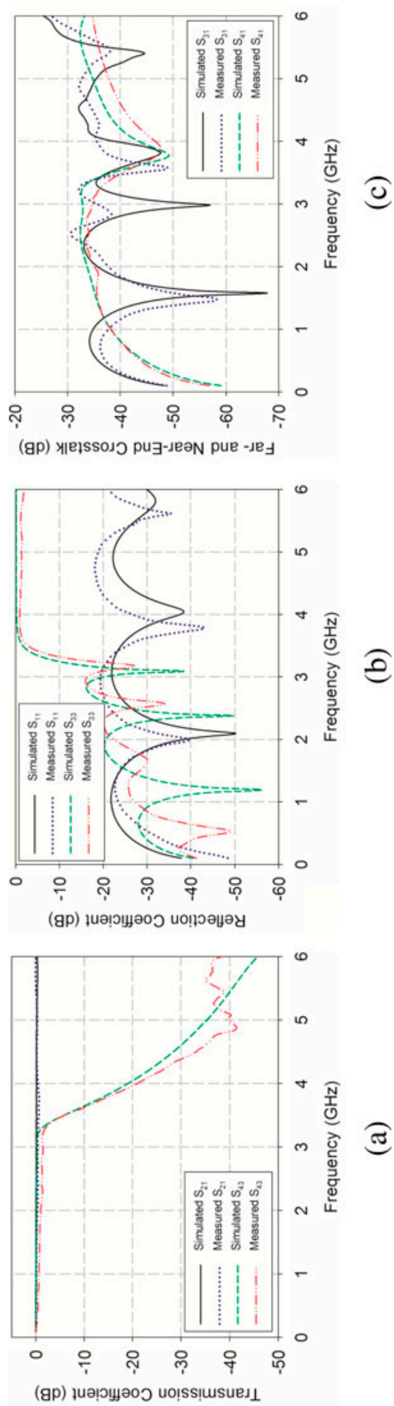

Figure 8. Measured and simulated frequency characteristics of the non-uniform PCB trace configuration.

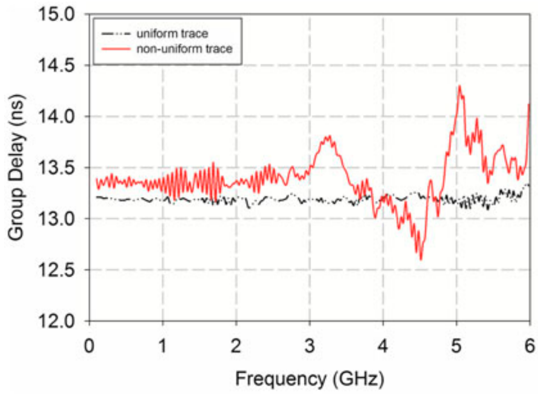

Figure 9. Measured group delay of both uniform and non-uniform trace of Figure 2(d).

3. Results and discussion

Upon achieving an error value of 0.408 from minimizing (5), the generated Fourier coefficients, given in Table 1, are collected and reincorporated in (4) to obtain the different electrical and physical properties of the non-uniform LPF.

Figure 3 shows the input port matching and transmission parameters S_{11} and S_{21}, respectively, for the designed filter.

To realize such a varying-impedance profile, $W(z)$ is plotted vs. the normalized line's length, and a fixed periodic segmentation ($\Delta z/d$) is performed and matched to its corresponding Δw. Figure 4 shows the resulting non-uniform LPF impedance.

With the aid of Ansys-HFSS [11], full-wave electromagnetic simulations were carried out to evaluate the performance of the configurations in Figure 2. Figure 5 shows the simulated far-end crosstalk (S_{41}) of the proposed non-uniform LPF trace configuration (Figure 2(d)), conventional guard trace schemes (Figure 2(b,c)), and the uniform parallel PCB traces with no guard as a reference (Figure 2(a)). As can be seen, the proposed trace provides significant reduction in crosstalk when compared with the

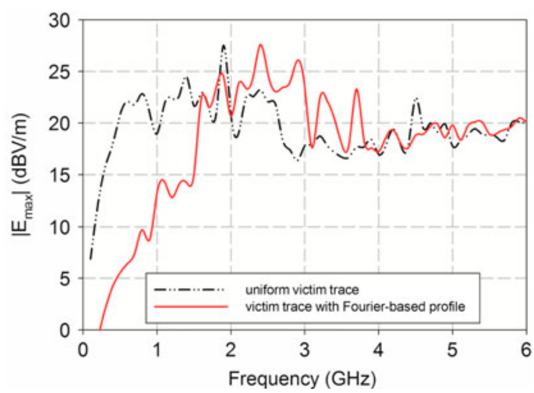

Figure 10. Maximum magnitude of the radiated electric field from both reference and proposed trace configurations (Figure 2(a) and (d)) vs. source frequency.

performance of the guard trace configurations over the same frequency span. Furthermore, the highest crosstalk reduction (i.e. −48 dB at 3.8 GHz) occurs according to the location of the cutoff frequency of the victim trace. This is advantageous in controlling the location of the steepest crosstalk reduction.

The near-end coupling is evaluated for all topologies in Figure 2 and its frequency performance is plotted in Figure 6. It is observed that both conventional and proposed configurations do not provide significant improvement on the near-end crosstalk.

The implemented non-uniform trace configuration is photographed in Figure 7 and its simulated and measured performance is shown in Figure 8. Both simulation and measurement data are in good agreement. The non-uniform trace clearly exhibits a LPF frequency characteristic. Moreover, the return loss (S_{11} and S_{33}) levels of the proposed configuration are acceptable (i.e. less than −15 dB).

Figure 9 shows the measured group delay performance of the proposed configuration. The frequency performance demonstrates a relatively constant group delay for both the uniform and non-uniform traces over the band of operation (i.e. below the cutoff frequency, 3.6 GHz).

Figure 10 illustrates the maximum radiated emissions (E_{max}) from the proposed PCB trace and the reference trace configurations. The magnitude of the radiated electric field from the PCB structures without the dielectric material was calculated on a hemispherical surface with a 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. at port 1) which connects between the uniform trace and an infinite ground plane. [12] The proposed non-uniform trace configuration has a comparable radiated emission impact when compared with the uniform parallel traces over 0.1–6 GHz frequency sweep.

4. Conclusions

A PCB trace with modulated impedance profile for improved far-end crosstalk immunity in adjacent PCB interconnects was proposed. The continuous impedance perturbation of the trace configuration follows a truncated fourier series whose width variations correspond to the optimized fourier coefficients. It is observed that a trace with a LPF frequency characteristic leads to an enhanced far-end crosstalk reduction when compared to the conventional guard trace configurations, especially at and above the cutoff frequency. This is at the cost of the available operating frequency band. The resulting trace configuration does not involve additional fabrication processes unlike those with guard traces grounded by vias, stitching capacitors, or defected ground structures. Finally, the proposed trace exhibits better handling of high current densities and relatively similar radiated emissions compared to the uniform trace configuration.

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