ASYMMETRIC, MULTI-CONDUCTOR LOW-COUPLING STRUCTURES FOR HIGH-SPEED, HIGH-DENSITY DIGITAL INTERCONNECTS

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ABSTRACT

Small inter-line spacings and ultra-fast switching speeds emphasize the problems of crosstalk and coupling distortion in high-speed, high-density digital interconnects. However, the use of substrate compensation allows the design of structures where crosstalk and coupling can be essentially eliminated, even for inter-line spacings of less than one center conductor width. Some of the characteristics of this novel method are presented for asymmetric multi-conductor transmission lines. The study shows that it is possible to choose a substrate combination which significantly reduces coupling and crosstalk for wide range of conductor configurations.

INTRODUCTION

Higher switching speeds and decreasing inter-line spacing increase the effects of coupling and crosstalk in high-speed, high-density digital circuits. Although lumped element approximations of high-speed VLSI interconnects [1] are presently adequate for the design process, the next generation of high-speed interconnects will require an accurate, field theory analysis which includes the effects of coupling, dispersion, and losses.

Pulse distortion and coupling in microstrip structures has been studied using the Spectral Domain Approach (SDA) in the frequency domain and an inverse-Fourier transform to obtain time-domain results [2],[3]. Crosstalk reduction in high-speed, digital interconnects using a grounded isolation line has been studied in both the spectral [4] and spatial domains [5]. Although this method can provide some reduction in forward crosstalk, the return voltage at the generator end of the driven line is significantly increased, which can couple to the non-driven line and increase the overall amount of crosstalk [4]. In addition, the extra grounded line increases the fabrication costs, makes the inter-line spacing greater than two center conductor widths and requires via holes to short the ends of the additional line, increasing the stray inductance in the circuit.

An alternative approach, discovered by the authors, can essentially eliminate coupling and crosstalk while retaining small inter-line spacing, through the choice of the electrical parameters of the substrates in a multi-layer structure [6]. The proper choice of substrate heights and dielectric constants makes the phase velocities of the even and odd modes approximately equal over a very wide bandwidth, essentially eliminating coupling and crosstalk. This method is effective for very small line spacings, even those less than one center conductor width. Although this new low-coupling structure shows great promise, there is still very little information available in the open literature concerning the design methodology and performance of these types of structures.

This paper addresses the problem of high-speed signal propagation on tightly coupled transmission lines and the reduction of crosstalk and coupling distortion through substrate compensation. The use of substrate compensation for general asymmetric structures is studied, showing how it can be used for asymmetric coupled lines and symmetric multi-conductor lines. The characteristics of substratrate-compensated symmetric coupled lines are also presented as a function of substrate dielectric constant and inter-line spacing.

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THEORY

The use of the Spectral Domain Approach has been well documented in the open literature [7], and so the technical details are omitted here. The geometry for asymmetric multi-layer, multi-conductor interconnects is shown in Fig. 1. Two substrates are shown in the figure, although any finite number of substrates can be easily considered using the recurrence formulation from [6]. In this investigation, the substrates are assumed to be lossless and isotropic, and the conductors have zero thickness and are perfectly conducting.

The expansion functions for the current densities used in this analysis are given by

$$J_{zn}(x) = \frac{T_n(2x/w)}{\sqrt{1-(2x/w)^2}} \quad (1)$$

$$J_{xn}(x) = U_n(2x/w)\sqrt{1-(2x/w)^2} \quad (2)$$

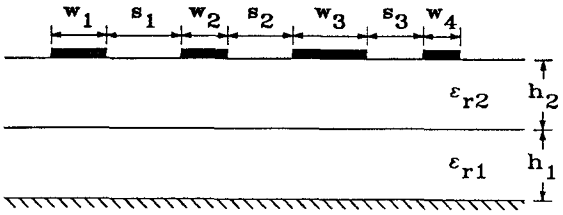

Figure 1: Geometry of an asymmetric multi-layer, multi-conductor interconnect.

for $n = 0, 1, 2, \ldots$ and $|x| \leq w/2$. $T_n(x)$ and $U_n(x)$ are the Chebyshev polynomials of the first and second kind, respectively. The Fourier transforms of these expansion functions are given in closed form by

$$\tilde{J}_{zn} = (-j)^n \frac{\pi w}{2} J_n\left(\frac{\beta_x w}{2}\right) \tag{3}$$

$$\tilde{J}_{xn} = (-j)^n \frac{\pi(n+1)}{\beta_x} J_{n+1}\left(\frac{\beta_x w}{2}\right) \tag{4}$$

where $J_n(x)$ is the Bessel function of the first kind of order n.

The time-domain response of coupled transmission lines is found by computing the inverse Fourier transform of each of the independent modes. For symmetric coupled transmission lines, the even/odd mode approach is used [6]. However, if the structure is asymmetric or has three or more lines, then the time-domain responses is obtained by forming a linear combination of the time-domain response of the independent modes which reproduces the signal at the input.

RESULTS

As an example of substrate compensation for asymmetric structures, the ϵ_{reff} of asymmetric coupled microstrips on a two-layer substrate is shown in Fig. 2. The effective dielectric constant of the c (in phase) and π (out of phase) modes are shown as a function of the height ratio, h_1/h_{tot}, for the structure shown in Fig. 2. Also included is the ϵ_{reff} of a single isolated strip of width w_1 and one of width w_2, which are the limiting cases for the c and π modes as the spacing is increased. As the inter-line spacing approaches to zero, the limiting case for the c mode is a strip of width $w_1 + w_2$ with an even symmetric current distribution and for the π mode it is a strip of width $w_1 + w_2$ with an odd symmetric current distribution. In Fig. 2, the ϵ_{reff} for the odd-symmetric isolated strip, $w = w_1 + w_2$, is essentially the same as the ϵ_{reff} of the π mode, as would be expected for a structure with very small inter-line spacing. Likewise, the ϵ_{reff} for the even-symmetric isolated strip, $w = w_1 + w_2$, is very close to that of the c mode.

For single substrate structures, ϵ_{reff} increases as the width of the microstrip is increased. However, as shown in Fig. 2, there are values of the height ratio for which the thinner strip, $w = w_1$, has larger ϵ_{reff} than the wider strip, $w = w_2$. Also note, that while the c mode has a higher ϵ_{reff} than the π mode for single substrate structures, for some values of the height ratio, this is reversed and at two points the ϵ_{reff}'s of the two modes are equal. Thus it is possible to design low-coupling structures using asymmetric-coupled lines as well as by using symmetric-coupled lines.

An example of a multi-conductor, symmetric interconnect is shown in Fig. 3 where the ϵ_{reff} of the four independent modes is shown as a function of the height ratio. The relative signs of the currents on the four conductors is shown for each of the four modes in the graph titles in Fig. 3. As with the symmetric and asymmetric two-conductor cases, the ϵ_{reff} of each mode in the four-conductor case changes at a different rate as the height ratio is varied. Thus while mode 3 has the highest ϵ_{reff} on single layer structures, for height ratios between 0.3 and 0.85 it has the lowest ϵ_{reff}. However, unlike two-conductor cases, it may not possible to find a height ratio where all four modes have exactly the same ϵ_{reff}. On the other hand, it is possible to choose a height ratio where the differences between the ϵ_{reff}'s of the four modes is minimized.

One important characteristic of a low-coupling structure is the value of ϵ_{r1} which equalizes the even and odd mode phase velocities. In Fig. 4 the value of h_1/h_{tot} which either minimizes the difference between the modal phase velocities or makes them exactly equal is plotted as a function of ϵ_{r1} with $\epsilon_{r2} = 9.7$ for the structure shown. For $9.7 \geq \epsilon_{r1} \geq 4.0$, there is one value of the height ratio that minimizes the difference between the modal ϵ_{reff}, but for which they are not equal. However, at $\epsilon_{r1} \approx 4.0$ the graph splits because there are now 2 values of the height ratio for which the modal phase velocities are exactly equal. The value of ϵ_{r1} at which this split occurs is the maximum allowed value of ϵ_{r1} for which the phase velocities can be exactly equalized.

In Fig. 5 the maximum value of ϵ_{r1} which allows the equalization of the modal phase velocities is plotted as a function of ϵ_{r2}. Two different strip widths, each with three different spacings, are considered. All values of ϵ_{r1} below a given curve can be used with that conductor configuration to create a zero-coupling structure, i.e. one where the modal phase velocities are exactly equal. For example, if $\epsilon_{r2} = 5.5$, then values of $\epsilon_{r1} \leq 2.1$ allow the design of structures with zero coupling. However, note that the coupling can still be greatly reduced, but not eliminated, by using an ϵ_{r1} which is somewhat greater than the maximum allowable value. The height ratio is then chosen to be that which minimizes the difference in the modal phase velocities, per Fig. 4. Note that as the spacing between the center conductors is increased the maximum allowable value of ϵ_{r1} decreases. However, as the spacing increases, the overall coupling between the two lines decreases and so the restriction on ϵ_{r1} becomes less critical.

Another important parameter of a low-coupling structure is the inter-line spacing. For a given spacing and width on a low-coupling structure, there are two values of the height ratio which eliminate coupling and crosstalk at a given frequency. As the spacing changes, the values of this height ratio change as well. Thus, it is interesting to consider the following question: if a structure were designed to have zero-coupling for a certain center conductor width and spacing, what would the effect be on the coupling and crosstalk for lines with different spacings on the same substrate combination? To answer this question, a symmetric coupled microstrip with two-substrates is considered with a total substrate height of 0.635mm, $\epsilon_{r1} = 2.2$, $\epsilon_{r2} = 9.7$, a center conductor width of 0.5mm, and spacing of 0.5mm. The height of the lower substrate, h_1, is chosen to be 0.6036mm, which equalizes the even and odd mode phase velocities in the quasi-static frequency range. Pulse distortion on this structure is then considered for line spacings of 0.5, 1.0, and 1.5mm. These results are compared to the undistorted pulse, an isolated line of the same width, and symmetric coupled lines of the same widths, with a spacing of 0.5mm. All three of the latter cases are computed for a single substrate of $\epsilon_r = 2.2$ and height 0.635mm.

The time domain responses for all six cases are shown in Fig. 6 for the signal or intended line and in Fig. 7 for the sense or adjacent line. A Gaussian pulse with a half-width, half-maximum of 10 picoseconds is used and the transient response for both lines is taken at a distance of 50mm. The amplitude of the signal line response for the uncompensated line has been significantly reduced from the amplitude of the undistorted pulse and it has almost doubled in width. On the other hand, the pulse on the compensated substrate with a spacing of 0.5mm has almost no degradation of amplitude nor has it widened noticeably. The signal line responses of the pulses on compensated substrates with spacings of 1.0 and 1.5mm show only a little loss of amplitude due to coupling distortion.

The sense line response for the uncompensated and compensated stuctures is shown in Fig. 7. The amplitude of the sense line response for the uncompensated structure is almost 50 percent of the amplitude of the undistorted pulse, showing a significant amount of crosstalk. The amplitude of the sense line response for the compensated substrate with a spacing of 0.5mm is only 15 percent of the amplitude of the original pulse, much less than that of the uncompensated line. For the other two spacings, the amplitude of the sense line response is about 22 percent of the amplitude of the undistorted pulse, which is still less than one-half of that of the uncompensated line.

Note that as the spacing increases beyond 1.5mm, the coupling and crosstalk will decrease, since the coupling varies inversely with the spacing. Thus, it is possible to choose two dielectrics and a height ratio for which the coupling and crosstalk are significantly reduced for a wide range of center conductor spacings. This allows a great deal of flexiblility in the design of the low-coupling structures for high-speed interconnects. Many different conductor geometries can be used on a particular substrate configuration with the crosstalk being significantly reduced for all of the geometries. Also, only open structures have been considered here, but the techniques and results can be extended to structures with a cover sheet and/or side walls.

CONCLUSION

Due to the increasing speeds of digital circuits and the small inter-line spacings, a full-wave anlysis of multi-layer, multi-conductor structures is required to accurately predict the coupling and crosstalk on these structures. Using the Spectral Domain Approach, it is shown that substrate compensation can be used for asymmetric coupled lines and symmetric multi-conductor lines. Some of the characteristics of substrate compensated low-coupling structures were also investigated, showing that one substrate configuration can be used to reduce coupling and crosstalk with a variety of conductor configurations. By designing high-speed interconnects with substrate-compensation it will be possible to achieve an extremely high density of signal conductors, using inter-line spacings of less than one center conductor width, while keeping crosstalk and coupling distortion to a minimum.

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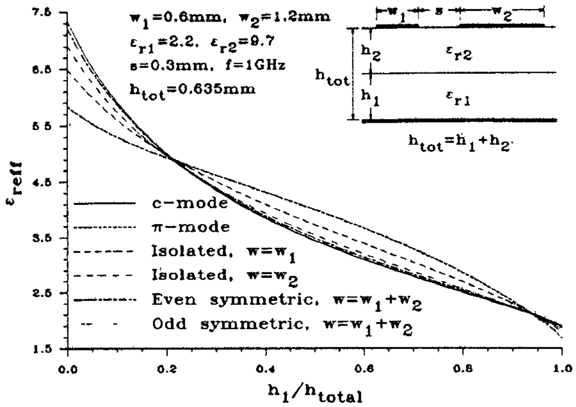

Figure 2: The ϵ_{reff} of asymmetric coupled microstrips and single isolated microstrips on a two-layer substrate vs. the height ratio, h_1/h_{tot}.

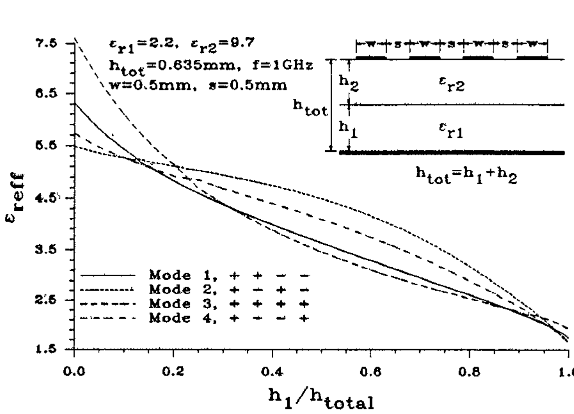

Figure 3: The ϵ_{reff} for the four modes of a symmetric coupled four-line structure on a two-layer substrate vs. the height ratio h_1/h_{tot}.

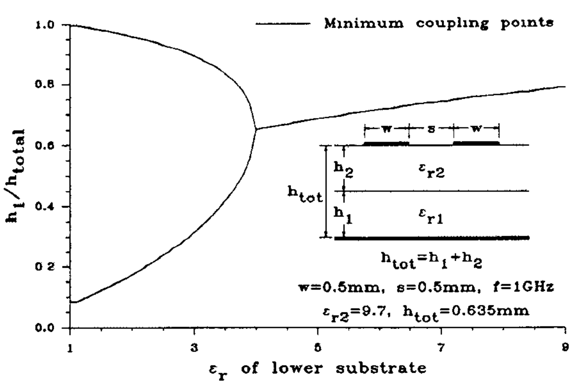

Figure 4: Minimum coupling points vs. ϵ_{r1} for a substrate-compensated low-coupling structure.

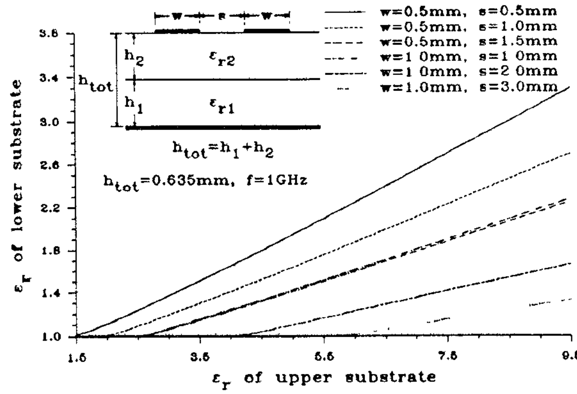

Figure 5: Maximum ϵ_{r1} which can be used to design a zero-coupling structure vs. ϵ_{r2} for various conductor geometries.

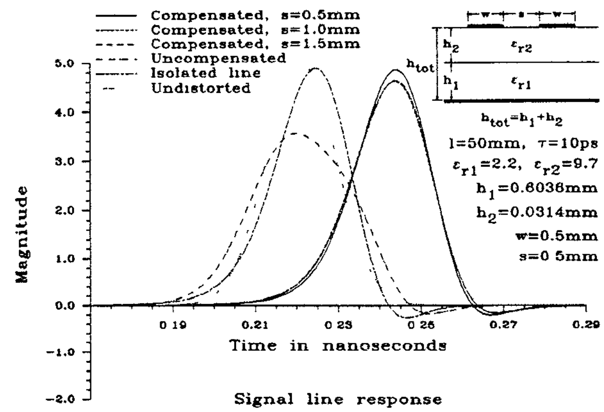

Figure 6: Pulse distortion on symmetric coupled microstrips, signal line response.

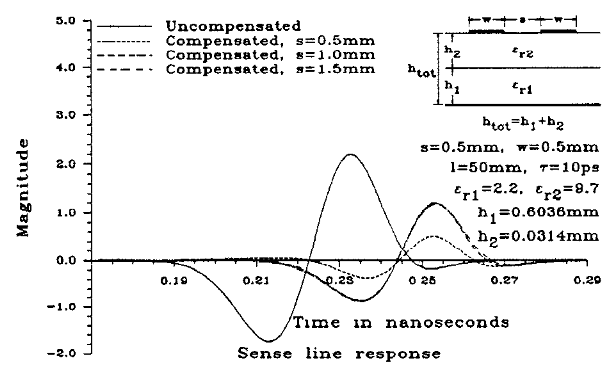

Figure 7: Pulse distortion on symmetric coupled microstrips, sense line response.