Optimally-Placed Twists in Global On-Chip Differential Interconnects

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Abstract:

A bus-transceiver test chip in 0.13 µm CMOS achieves 3 Gb/s/ch over 10 mm long uninterrupted differential interconnect of only 0.8 µm pitch. As crosstalk would impede this high data rate, twists are used. Analysis shows that the optimal positions of the twists depend on the termination of the interconnect. Theory and measurements show that only one twist at 50% of the even interconnects, two twists at 30% and 70% of the odd interconnects and equal source and load impedances are very effective in mitigating the crosstalk.

1. Introduction

On-chip communication is a field that is getting more attention, as (global) interconnects are rapidly becoming a speed, power and reliability bottleneck for digital systems [1]. In [2] we demonstrate a bus-transceiver test chip in 0.13 µm CMOS that uses 10 mm long uninterrupted differential interconnects of only 0.8 µm pitch (82 MHz RC-limited bandwidth) and achieves 3 Gb/s/ch. However, in [2] we do not analyze the twists that we use to cancel crosstalk. These twists are necessary, because due to small spacings (0.4 µm) and the 10 mm long parallel interconnects in the bus, there is a considerable amount of crosstalk. This crosstalk limits the achievable data rate if it is not mitigated.

Twists are also used in CMOS memory cells to cancel crosstalk between bitlines [3]. Recently, the use of twists in on-chip global interconnects was proposed [4]. They use eight evenly-spaced twists, thereby overlooking via resistance. In our chip, we show that only one twist in the even interconnects and two twists in the odd interconnects are sufficient. Furthermore, it turns out that the optimal positions for these twists depend on the termination of the interconnect.

In section 2, the optimal positions for the twists, depending on the termination, are calculated. Section 3 shows measurement results from our test chip.

2. Optimal twist positions and termination

2.1 Interconnect model

Fig. 1 shows a model of the global bus (cross-section). The global bus is placed in metal 5 as we assume the top metal layer (metal 6) to be reserved for power and clock routing. Perpendicular interconnects in metal 4 and metal 6 are modeled by two metal plates.

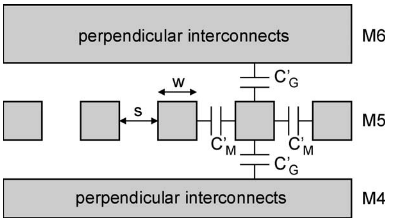

Figure 1: Interconnect model.

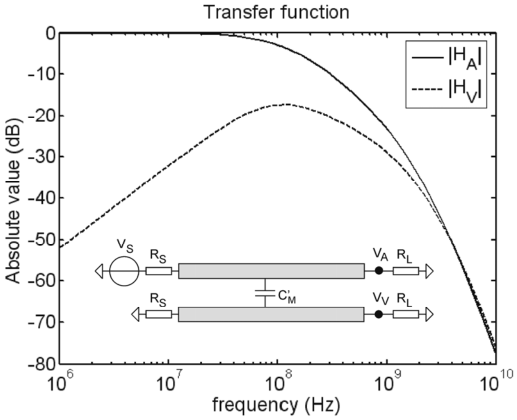

Figure 2: Transfer functions of 10 mm long interconnects.

The width (w) and spacing (s) are chosen for highest bandwidth per cross-sectional area: w = s = 0.4 µm [2].

For these narrow interconnects, the distributed resistance R' = 0.15 kΩ/mm and the total distributed capacitance C' = $2C_G' + 2C_M'$ = 0.23 pF/mm are simulated with a 3D EM-field simulator. The distributed inductance L' = 0.25 nH/mm only starts to dominate over the distributed resistance at a frequency of R'/L'/(2π) = 95 GHz. For 10 mm long interconnects, the attenuation at this frequency is very large (> 150 dB), so inductance does not play an important role.

The distributed capacitance between two interconnects, C_M' = 0.05 pF/mm, results in crosstalk (see Fig. 2): a signal from source V_S will not only appear at the output of the aggressor line (V_A), but also at the output of the victim line (V_V). The transfer functions $H_A = V_A/V_S$ and $H_V = V_V/V_S$ for 10 mm long interconnects are shown in Fig. 2 (low-ohmic R_S and high-ohmic R_L, modeling an open or a small capacitive load).

The transfer functions of Fig.2 show two properties of the interconnect: First, the interconnect has a limited bandwidth of only 100 MHz (82 MHz for a differential interconnect) that limits the achievable data rate. In order to have a data rate of 3 Gb/s, we make use of a low-ohmic R_L and pulse-width (PW) equalization [2]. Second, the neighboring interconnect creates severe crosstalk. Especially for frequencies above 1 GHz, the transfer functions H_A and H_V are almost equal. Therefore, in order to achieve the data rate of 3 Gb/s, it is necessary to mitigate the crosstalk.

2.2 Twist analysis

The neighbor-to-neighbor crosstalk in the bus is reduced by using differential interconnects with twists. Fig. 3 shows how the twists are organized (interconnects in metal 5 and part of the twists in metal 4). Every differential interconnect has only one or two twists (alternately). The positions of the twists are at $x_1 * l_T$, $x_2 * l_T$ and $x_3 * l_T$, with l_T the total length of the interconnect.

In this section, we show how to calculate the transfer functions H_A and H_V for differential interconnects with twists. First, we calculate the transfer functions $H_{A+} = \text{out+}/V_{S1}$ and $H_{A-} = \text{out–}/V_{S1}$ with $V_{S2} = 0$ (see Fig. 3). Then, $H_A = H_{A+} - H_{A-}$. After that, the transfer functions $H_{V+} = \text{out+}/V_{S2}$ and $H_{V-} = \text{out–}/V_{S2}$ with $V_{S1} = 0$ are calculated. For differential mode (DM) crosstalk $H_V = H_{V+} - H_{V-}$ and for common mode (CM) crosstalk $H_V = ½*(H_{V+} + H_{V-})$.

H_{A+}, H_{V+}, H_{A-} and H_{V-} can be found by using an even and odd analysis: $H_{A+/-} = ½*(H_{\text{even}+/-} + H_{\text{odd}+/-})$ and $H_{V+/-} = ½*(H_{\text{even}+/-} - H_{\text{odd}+/-})$ where $H_{\text{even}+/-} = (\text{out}+/\_)/V_{S1}$ with $V_{S2} = V_{S1}$ and $H_{\text{odd}+/-} = (\text{out}+/\_)/V_{S1}$ with $V_{S2} = -V_{S1}$. In the remainder of this section we show how to calculate $H_{\text{even}+/-}$ and $H_{\text{odd}+/-}$.

The characteristic impedance and propagation constant of a distributed RC-line are [5]:

$$Z_C = \sqrt{\frac{R'}{j\omega(2C_G' + MC_M')}} \text{ and}$$

$$\gamma = \sqrt{j\omega R'(2C_G' + MC_M')}\,.$$

M is dependent on the signal that is on the neighboring interconnects (Miller multiplication of capacitance C_M'). The twists divide the interconnect into four sections. For every section k, M can have a different value. These values of M are shown in the table below. Also, the length of every section is given.

k	**M**				**l_k**
	$H_{\text{even}+}$	**$H_{\text{odd}+}$**	**$H_{\text{even}-}$**	**$H_{\text{odd}-}$**	
1	3	3	4	2	$x_1 * l_T$
2	3	3	2	4	$(x_2 - x_1) * l_T$
3	4	2	3	3	$(x_3 - x_2) * l_T$
4	2	4	3	3	$(1 - x_3) * l_T$

Table 1: Values for M and l_k for every section k.

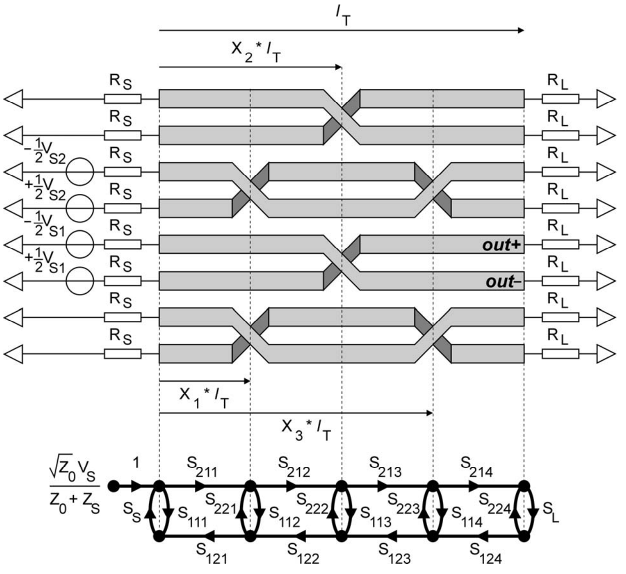

Figure 3: General model for twisted interconnects.

With these values for M and l_k, the s-parameters [5] of every section k are (see bottom of Fig. 3):

$$S_{ijk} = \frac{1}{2Z_0 Z_{Ck}\cosh(\gamma_k l_k) + (Z_0^2 + Z_{Ck}^2)\sinh(\gamma_k l_k)} \times \begin{bmatrix} (Z_{Ck}^2 - Z_0^2)\sinh(\gamma_k l_k) & 2Z_0 Z_{Ck} \\ 2Z_0 Z_{Ck} & (Z_{Ck}^2 - Z_0^2)\sinh(\gamma_k l_k) \end{bmatrix}$$

Z_0 is a reference impedance and can be chosen freely. The source and load impedance are reflected in S_S and S_L:

$$S_S = \frac{Z_S - Z_0}{Z_S + Z_0}\,,\ S_L = \frac{Z_L - Z_0}{Z_L + Z_0}\,.$$

Now, with the help of Mason's Rule [5], the transfer functions $H_{\text{even}+/-}$ and $H_{\text{odd}+/-}$ can be found and thus H_A and H_V can be calculated. As the formulas are very complex, they are not shown here.

2.3 Signal-to-Crosstalk-Ratio

With the help of these transfer functions, the optimal positions for x_1, x_2 and x_3 can be found. We define the signal-to-crosstalk-ratio (SCR) as follows:

$$SCR = \frac{signal\ \ power}{crosstalk\ \ power} = \frac{\int_0^\infty X(f)H_A(f)df}{\int_0^\infty X(f)H_V(f)df}$$

where X(f) is the power spectral density of the input signal.

Fig. 4 shows the DM SCR (differential mode crosstalk) as a function of x_2. In this case, $x_1 = 0$, $x_3 = 1$, $l_T = 10$ mm and $R_S = 50\ \Omega$. The SCR is highest if x_2 is 0.5 and $R_L = R_S$. However, if R_L is larger then R_S, the optimum

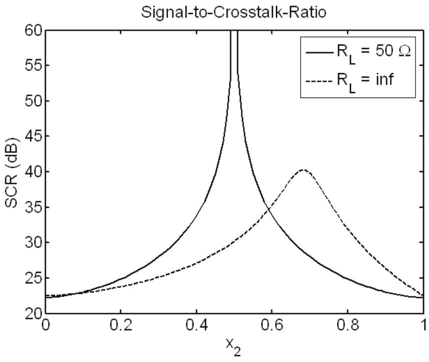

Figure 4: Calculated DM SCR as a function of x_2 and R_L ($x_1 = 0$, $x_3 = 1$, $l_T = 10$ mm and $R_S = 50\ \Omega$).

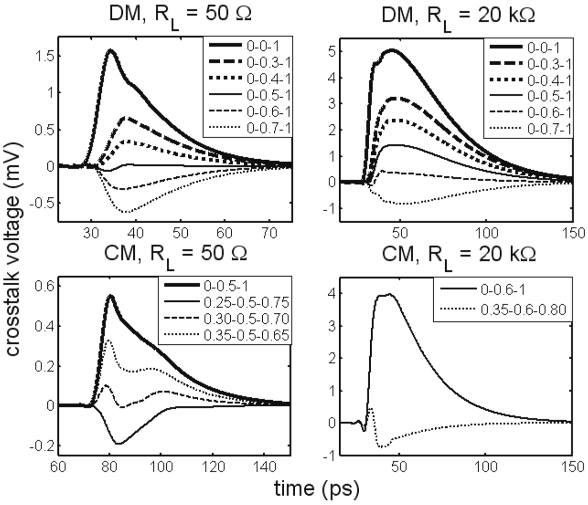

Figure 6: 3D EM-field simulation step responses for different positions of the twist (x_1-x_2-x_3) and for two different load resistances. Both differential mode (DM) and common-mode (CM) step responses are shown. The length of the interconnects $l_T = 1$ mm.

value for x_2 is shifted towards 0.7 and the peak value of the SCR decreases. Note that the optimal case, one twist at $x_2 = 0.5$ and choosing $R_L = R_S$, nicely coincides with the fact that for highest bandwidth, both R_S and R_L should be chosen low-ohmic [2].

DM crosstalk can be cancelled with the twist at x_2, but there will still be CM (common mode) crosstalk. This can be removed by the twists at x_1 and x_3. Fig. 5 shows the SCR for both DM crosstalk and for CM crosstalk as a function of x_1 and x_3 ($x_2 = 0.5$ and $R_L = R_S$). The figure shows that the DM crosstalk is canceled if $x_3 = 1 - x_1$. On this line, the CM crosstalk is minimal at $x_1 \approx 0.3$ and $x_3 \approx 0.7$.

So, the optimal twist positions are at $x_1 = 0.3$, $x_2 = 0.5$, $x_3 = 0.7$ and $R_L = R_S$. However, the SCR remains adequate (>35 dB) for large variations in x_i and R_L (Figs. 4 and 5).

2.4 3D EM-field simulations

In order to check the optimal positions, two differential interconnects have been drawn in a 3D EM-Field simulator. The length l_T is only 1 mm to limit the simulation time. Note that for $l_T = 1$ mm, the crosstalk voltage is much lower than for $l_T = 10$ mm.

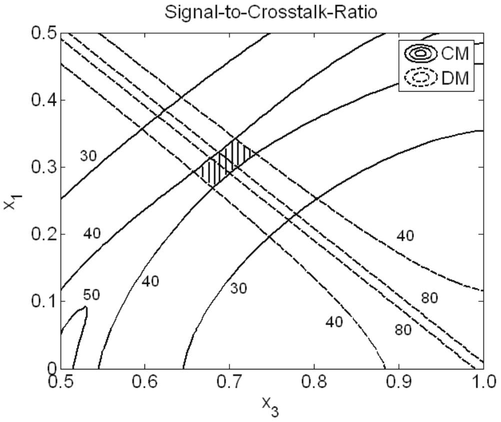

Figure 5: Calculated contour plot of SCR as a function of x_1 and x_3 ($x_2 = 0.5$, $l_T = 10$ mm and $R_S = R_L = 50\ \Omega$).

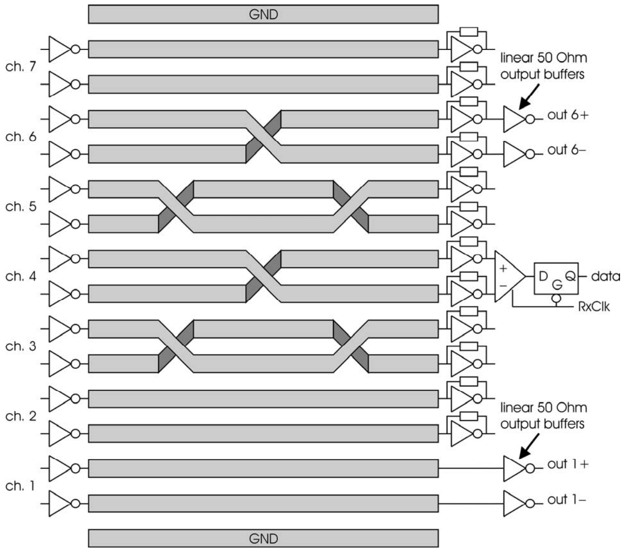

Figure 7: Bus configuration of test chip.

One of the differential interconnects has one twist and the other has two twists. Fig. 6 shows the simulated crosstalk voltage (step response) for different positions of the twists ($R_S = 50\ \Omega$). For DM crosstalk, the optimal position of the twist (x_2) is at 0.5 for an R_L of 50 Ω and between 0.6 and 0.7 for an R_L of 20 kΩ. This coincides with the theory, as the model of the previous section predicts 0.5 and 0.64 respectively.

For CM crosstalk, the optimal positions of the twists (x_1 and x_3) are at 0.3 and 0.7 for an R_L of 50 Ω and at 0.35 and 0.8 for an R_L of 20 kΩ. Again, this coincides with the theory that predicts $x_1 = 0.27$ and $x_3 = 0.73$ for an R_L of 50 Ω and $x_1 = 0.37$ and $x_3 = 0.82$ for an R_L of 20 kΩ.

3. Measurements

On a test chip [2], a bus of seven 10 mm long differential interconnects is measured. The seven channels (see Fig. 7) are driven by inverters with an R_S of 65 Ω. The R_L of about 150 Ω is made with inverters with a feedback resistor. So both R_S and R_L are low-ohmic.

The low-ohmic termination in combination with pulse-

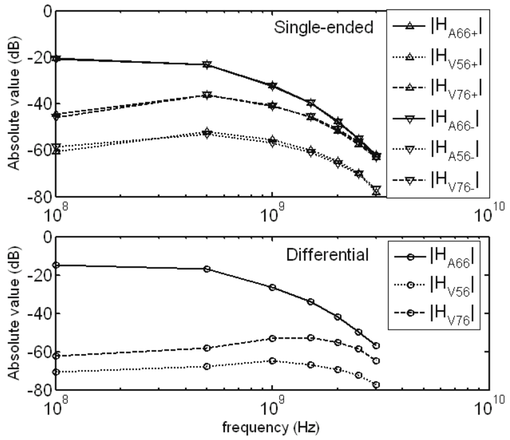

Figure 8: Measured transfer functions on output of channel 6.

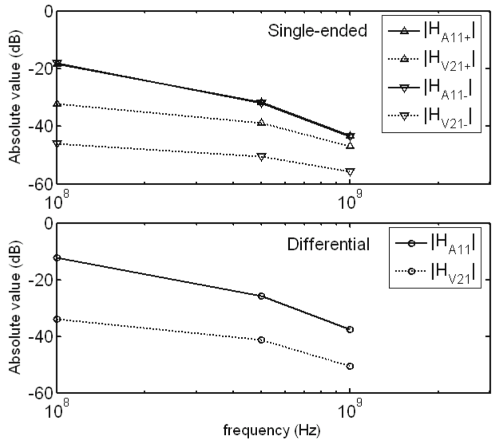

Figure 9: Measured transfer function on output of channel 1.

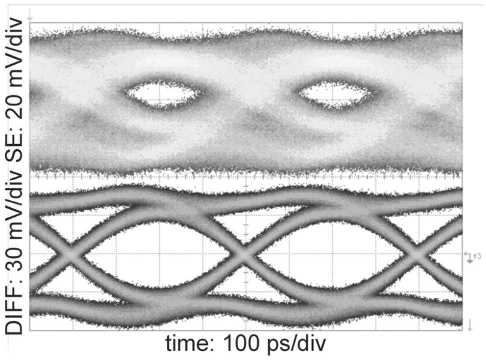

Figure 10: Single-ended (SE) and differential (DIFF) eye-diagram measurements.

width equalization is used to achieve a data rate of 3 Gb/s. This data rate is measured on channel 4, as described in [2]. In this paper, we show the results of measurements on channels 1 and 6. These measurements show the effectiveness of the twists.

Fig. 8 shows the measured transfer function from ch. 6 and the crosstalk transfer functions from ch. 5 and 7 to ch. 6. As expected, the crosstalk from ch. 5 is less than the crosstalk from ch. 7 (double twist in ch. 5 reduces CM crosstalk, see top Fig. 8) and both the crosstalk from ch. 5 and ch. 7 is reduced for the differential output (single twist in ch. 6 reduces DM crosstalk, see bottom Fig. 8).

The transfer functions of Fig. 9 have a smaller bandwidth due to the high-ohmic termination of ch. 1. There is more crosstalk from ch. 2 on out1+ then on out1−, because out1− has no signal carrying neighbor. The bottom graph shows that the crosstalk is not reduced for the differential output (no twist in ch. 1).

In Fig. 10 the measured single ended (SE) output and the differential (DIFF) output of ch. 6 are plotted in eye-diagrams for a data rate of 2.5 Gb/s. For reliable communication, the eye should be open. The eye-diagram for the SE output is almost closed (crosstalk from ch. 7). Looking at the DIFF output, the influence of the twist is seen. The eye is almost completely open.

4. Conclusions

By using pulse-width equalization and low-ohmic termination, we achieve a data rate of 3 Gb/s over 10 mm long differential interconnects with a bandwidth of only 82 MHz [2]. However, because of the small spacing, long interconnects and high data rate, the crosstalk is considerable. Therefore, in order to achieve 3 Gb/s the crosstalk has to be mitigated also. The twists that we use for this are analyzed in this paper. Our analysis shows that the optimal positions of the twists depend on the termination of the interconnect. Differential mode crosstalk can be canceled with only one twist at 50% by choosing equal load and source resistances. Two twists in the neighboring interconnects at 30% and 70% reduce common mode crosstalk. Measurements show the effectiveness of the twists.

5. Acknowledgements

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