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A 10Gb/s serial communication transceiver in 0.13μm CMOS for a 2m micro twisted-pair cable

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ABSTRACT: The next generation of pixel chips will generate a large amount of data. In the envisaged application, the data has to be transported off chip via a micro twisted-pair cable. Because of the low bandwidth of the cable, equalization is needed. Pulse-Width Modulation turns out to be the best equalization method at the transmitter side. However, at 10Gb/s the eye-opening at the receiver side is very sensitive to the exact value of the pulse-width. This sensitivity can be significantly reduced by using an on-chip parallel RC combination in series with the transmitter. A demonstrator chip in 0.13μm CMOS has been designed to prove the concept.

KEYWORDS: Analogue electronic circuits; Electronic detector readout concepts (solid-state)

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1 Introduction

Pixel chips for future applications produce a virtually infinite amount of data. For instance, high energy physics experiments will run at a higher luminosity, meaning more hits per second. All this data has to be transported off the pixel chip.

For the upgrade of the vertex detector of the LHCb experiment at CERN [1], the expected link speed is about 10Gb/s. Because of the extreme radiation dose, optical transceivers can not be placed directly onto the pixel modules, but will be placed on optical modules that are placed 1 to 2m away from the pixel modules. The electrical data transmission between pixel and optical modules will be done over micro twisted-pair cables. To minimize the material budget, these twisted-pair cables are very thin, limiting the bandwidth severely. The transfer function for a characteristically terminated cable of 2m has already a loss of 42dB at 5GHz. This makes communication at a data rate of 10Gb/s challenging.

2 Analysis

2.1 Micro twisted-pair cable

Our micro twisted-pair test cable has an inner diameter (d) of about 100μm for each wire and a distance between the centers of both wires (D) of 150μm (25μm of insulation). In order to model the cable, its s-parameters were measured with a network analyzer. The measured s-parameters for a 2.5m long cable are in figure 1. In order to measure the cable, SMA connectors were soldered onto the twisted pair. As the analyzer was not able to incorporate these connectors in the calibration, the resulting s-parameters include the SMA connectors. This could explain the difference in s11 and s22 at higher frequencies.

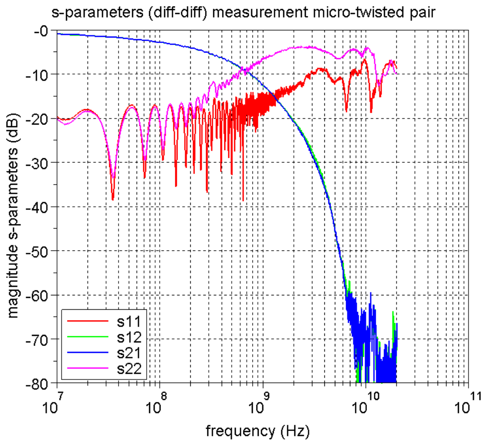

Figure 1. Measured s-parameters of 2.5m micro twisted-pair cable.

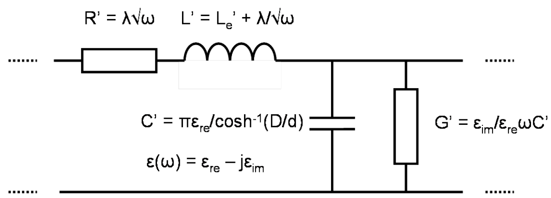

Figure 2. Transmission line model.

Table 1. Model parameter values.

parameter	value	parameter	value
d	106 μm	ε_∞	1.89
D	149 μm	$\Delta\varepsilon$	0.6
λ	0.45 m$\Omega/\sqrt{(\text{rad/s})}$	ω_1	1 krad/s
L_e	0.5 μH	ω_2	100 Trad/s

The measured s-parameters were fitted to the transmission line model of figure 2 [2]. The model uses an infinite number of RLGC sections. In this figure, the frequency-dependent dielectric permittivity is given by the following equation.

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{\log 10(\omega_2/\omega_1)} \cdot \log 10\left(\frac{\omega_2 + j\omega}{\omega_1 + j\omega}\right)$$

A good fit between measurements and model was found with the values as given in table 1.

The differential characteristic impedance of the micro twisted-pair cable is 90Ω.

2.2 Analysis method

With the model of figure 2, it is possible to calculate a transfer function for the cable. For this, we assume that the transmitter can be modeled by a voltage source with source impedance Z_S and the receiver by a load impedance Z_L. The voltage source puts symbol shapes on the cable. These symbol shapes have a symbol period T_S and can for instance be a voltage of plus or minus $V_{DD}/2$ for the whole symbol period (Pulse-Amplitude Modulation (PAM) signaling). With the help of the transfer function from transmitter to receiver, the resulting symbol response (voltage across Z_L) can be calculated.

Figure 3 shows such a symbol response for a 2m long cable with Z_S = Z_L = 90Ω. The symbol shape at the transmitter is 1V for T_S = 100ps. With the help of the symbol response, the eye-

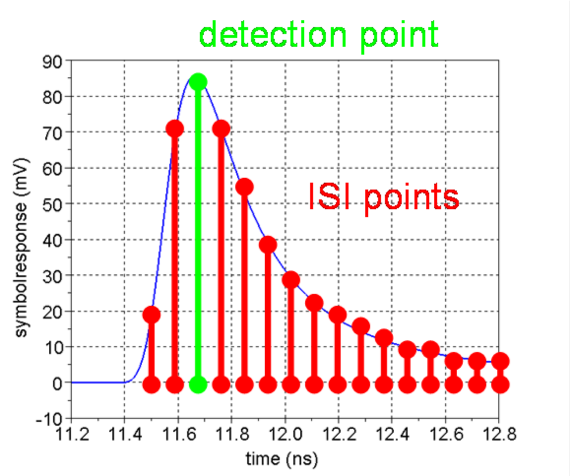

Figure 3. Symbol response with detection point and ISI points.

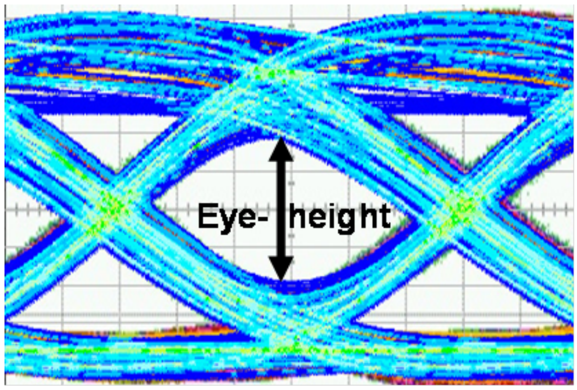

Figure 4. Eye-diagram.

opening (figure 4) at the receiver can be calculated. Suppose that the receiver makes a decision for a 'one' or a 'zero' at a certain detection point. A symbol time later, the next decision will be made. However, at this moment the symbol response of the previous symbol shape is not zero yet. This will give intersymbol-interference (ISI). By adding all absolute values at the ISI points and subtracting them from the value at the detection point, the eye-opening corresponding to this detection point is found. By shifting the detection point in time, the maximum eye-opening can be found, which we will call the eye-height (figure 4).

In this paper, we assume that 10b/8b encoding will be used for clock recovery at the receiver. With this encoding it is not possible to have a longer series of ones or zero's than five. So, not all values at the ISI points should be subtracted. For instance, in figure 3 the values at the 6^{th}, 12^{th}, etc. ISI points should be added instead of subtracted from the detection point value.

2.3 Equalization methods

The bandwidth of the micro twisted-pair cable is severely limited. This can for instance be seen in figure 1. Also, figure 3 shows a long tail in the symbol response, meaning many ISI points. In order to reach the high data rate of 10Gb/s, equalization will be needed. This section will explore different equalization methods at the transmitter side and see which of them will give the largest eye-height.

Figure 5 shows the symbol shapes for sending a 'one' of six different equalization methods. For sending a 'zero', the symbol shape has to be inverted. All symbol shapes are normalized between +1 and -1. Pulse-Width Modulation (PWM) has a symbol shape that first is +1 for a period of pwm*T_S and then -1 for the remainder of the symbol period. Finite Impulse Response (FIR) equalization uses different amplitudes. Note that for FIR equalization, voltages of +/-1 and +/-(1–2*fir) are possible for a long bit stream. The other four equalization methods are based on the first two.

Figure 6 shows the eye-heights for the different equalization methods. Note that 10Gb/s signaling will give an effective data rate of 8Gb/s due to the 10b/8b encoding. For every data rate, the

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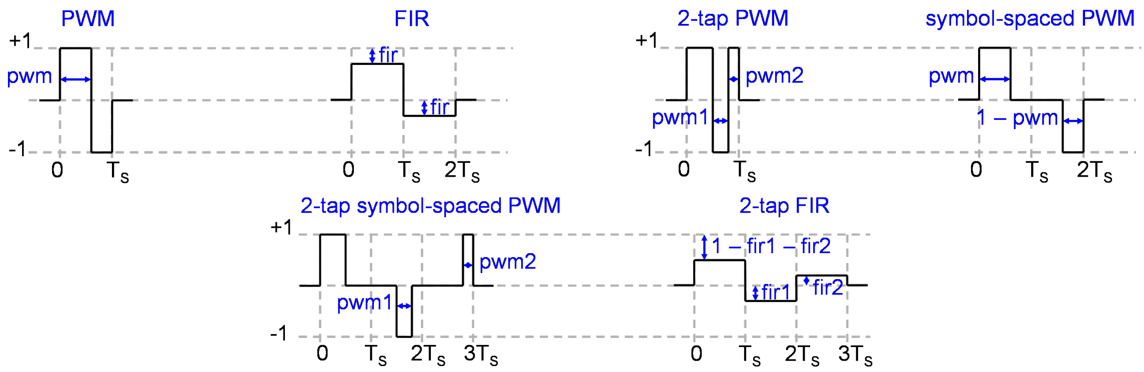

Figure 5. Equalization methods.

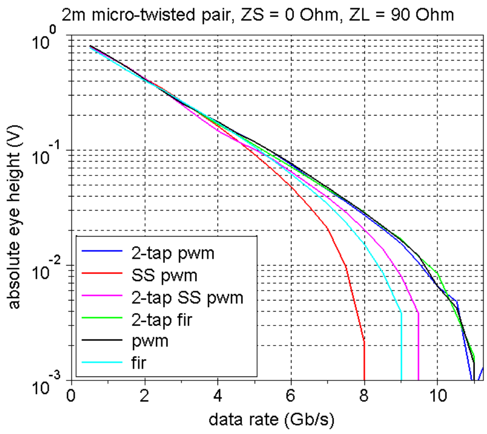

Figure 6. Eye-height vs. data rate for the different equalization methods of figure 5.

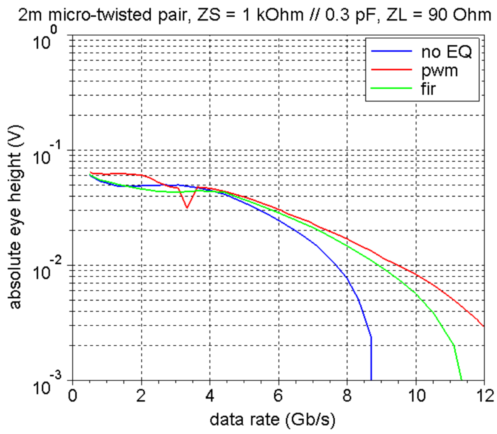

Figure 7. Eye-height vs. data rate with a parallel RC combination as source impedance.

optimal parameters of the equalization are chosen. Figure 6 shows that PWM equalization outperforms FIR equalization. The two symbol-spaced equalization methods perform worse than PWM equalization, while the 2-tap PWM and FIR equalization perform almost equal compared to PWM equalization. Because the 2-tap equalization methods add complexity, PWM equalization seems to be the best choice.

The results of figure 6 were obtained with a source impedance $Z_S = 0\Omega$ and a load impedance $Z_L = 90\Omega$. In figure 7, the results are shown for a Z_S of 1kΩ in parallel with 0.3pF. Even without equalization, a data rate of 5Gb/s gives an open eye now. At 10Gb/s and with PWM equalization, the results are slightly better than the results of figure 6. Moreover, the RC combination for Z_S has another advantage, as we will see in the next section.

2.4 Sensitivity

The results of figures 6 and 7 were obtained with optimal values for the pwm or fir-parameters. But what happens if there is some spread in these parameters? Figure 8 shows the eye-height as a function of the pwm-parameter for Pulse-Width Modulation at 10Gb/s. This is done for three

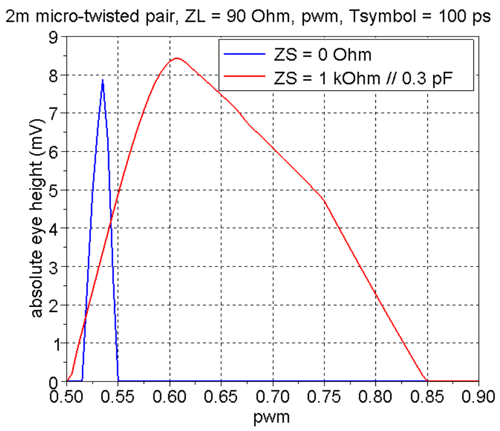

Figure 8. Eye-height vs. pulse-width.

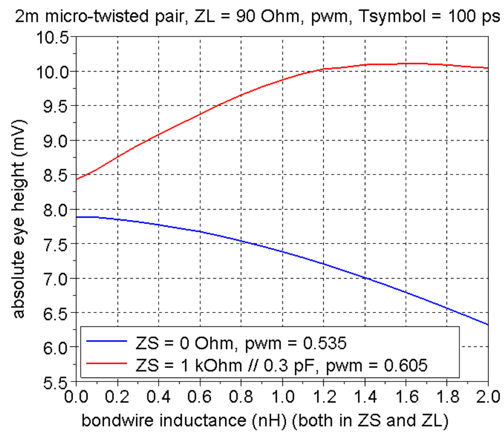

Figure 9. Eye-height vs. bondwire inductance.

different source impedances. The figure shows that with $Z_S = 0\Omega$, the eye-height is very sensitive to the exact value of pwm. Small deviations (4%) from the nominal value already close the eye completely. To make the design more robust, an on-chip parallel RC combination is placed in series with the transmitter. The RC constant is matched to the cable characteristics. The result of this RC filter is that the eye at the receiver side stays open for a much wider range of the pwm-parameter. Spread of the R and C values has little impact.

Another advantage of using the parallel RC combination is the resulting robustness against bondwire inductance. As the transmitter and receiver are on-chip, the connection to the cable will probably be done with bondwires.[1] Figure 9 shows the eye-height as a function of bondwire inductance. The eye-height of the 1kΩ // 0.3pF combination is even increased by the inductance.

3 Test chip

To prove the concept, a transceiver chip was designed in a 0.13μm 1.2V process. Current-Mode Logic (CML) cells were used throughout the design to meet the speed requirements. The transmitter uses PWM equalization and has either a low-ohmic output impedance or an adjustable parallel RC combination. In the receiver, high gain at 10Gb/s is achieved by a cascade of CML buffers. A DC feedback loop is used to compensate for offset.

Chip measurements are currently in progress. Due to a fabrication error in the printed circuit boards, affecting the characteristic impedance of the traces, full speed has not been achieved yet. However, 5Gb/s over 2.5m of micro twisted-pair cable has been achieved already.

4 Summary

Future pixel detector applications require multi-Gigabit readout links. To achieve a data rate of 10Gb/s over 2m of micro twisted-pair cable, equalization is needed. Pulse-Width Modulation turns

[1] The bondwire inductance depends on the diameter and its loop height. An inductance of 1nH/mm is often used as a rule of thumb.

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out to be the best equalization method. However, the eye-height at the receiver is very sensitive to the exact value of the pulse-width. A more robust system is created with a parallel RC combination as source impedance of the transmitter, making the transceiver also robust against bondwire inductance. A demonstrator chip has been designed to prove the concepts.

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