Cancellation of Delays in the High-Rate Interconnects with UWB NGD Active Cells

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Abstract

This paper is devoted to the extension of the interconnect effect equalization concept with NGD circuits for UWB applications. First, RC interconnect effects are considered. It was found that by cascading with the NGD structure, the propagation delay of the considered rate 4 Gbps signal was compensated for about 98-%. Then, the feasibility of the technique by taking into account the interconnection inductive effect with RLC-model is also investigated. It was demonstrated that the technique proposed brings opportunities to compensate for simultaneously the propagation delay and distortions. Then, the application of the proposed technique for the optical interconnect correction is discussed.

Keywords: Equalization technique, Negative group delay (NGD), Interconnects, Signal integrity (SI), Ultra-wideband (UWB) applications

1. Introduction

The constant increasing of operating frequencies and the scale of integration of complex functions in microelectronic applications, allows the researchers and the industry to support the design of innovative solutions (ITRS 2010 Edition). Nowadays, this fascinating evolution has led to the nanometer scale integration and the multi gigahertz operation in many applications such as telecommunications, high definition multimedia, multi core microprocessors or biochips and so on. Hence, propagation delays, matching, reflections, near-end or far-end crosstalks are straightforwardly related to the topology of interconnects (Rabay, 1996). So, various interconnect models have been proposed and so far, the most popular among those currently used in the industry is the one proposed in (Elmore, 1948). Emphatically, it takes into account only the RC-model. Nevertheless, by neglecting the inductance effect, this model may create relative errors up to 30-% of the exact circuit propagation delay (Ismail & Friedman, 2000. This illustrates clearly that these issues of Signal Integrity (SI) and Electromagnetic Compatibility (EMC) in modern high-speed microelectronics are high desirable fields of research and innovation (Buckwalter, 2009)(Kim & Li, 2010) (Jun et al., 2010)(Eudes et al., 2011a and 2011b).

The optical solutions that have been proposed for on-die interconnects, presenting potential usages in interconnect architectures, are currently very hopeful (ITRS 2010 Edition). Indeed, the optical distribution allows further considerable advantages regarding the broadcasting, the simplification of design and layout constraints arising from undesirable crosstalk, as well as minor contributions in terms of skew and jitter. Doubtless, optical interconnects suffer some disadvantages in terms of consuming power, effective cost and complexity (ITRS 2010 Edition). Despite those inconveniences, optical interconnects are sources of challenges at present time notably with optical polymer waveguides for the industries of PCBs and backplanes (Granberg, 2004) (Dangel et al., 2007) and CMOS optical components (Lockwood & Pavesi, 2011). To the extent that the propagation delay is the most important degradation regarding high-rate digital applications (Rabay, 1996, and

Deutsch, et al., 1997), the Negative Group Delay (NGD) equalization technique has been introduced recently (Ravelo et al., 2007c May, 2009 May, and 2010) in order to improve the repeater architectures (Adler & Friedman, 1998). This statement motivates us to improve the mastering of interconnect technologies until the ultimate performances by combination of the NGD and the optical technology.

Formerly the NGD was initiated in optical domain, Brillouin and Sommerfeld have pointed out, in 1960, that the refractive index can be less than one and even negative (Brillouin, 1960). Separately, in 1968, Veselago has established the concept of negative permeability and permittivity (Veselago, 1968). Garrett and McCumber have consolidated the theoretical concept, in 1970, showing that a Gaussian pulse of light through this anomalous medium remains a Gaussian with superluminal propagation (Garrett & McCumber, 1970). Chu and Wong have verified experimentally the predictions of Garrett and McCumber in 1982, with the first observation of the superluminality of a laser beam through an anomalous dispersion medium (Chu & Wong, 1982). This was closely followed by the Ségard and Macke works, where the NGD in optical domain with amplification has been observed (Ségard & Macke, 1985). It is only 13 years after that, where the NGD has been applied to the electronic circuits with low frequency amplifiers and band-pass filters (Mitchell & Chiao, 1998). From this situation many works has been made especially regarding causality and electronic circuit approaches (Broomfield & Everard, 2000) (Wang et al., 2000) (Dogariu et al., 2001). Thereby, in 2003, the group of Kitano has demonstrated once for all that the NGD really exists with an experimental setup that operates with LEDs. They have shown that the output signal can be in advance with the input signal respecting the causality (Kitano et al., 2003). At the same time, the first works with RF circuits have been led by the University of Toronto using passive structures and metamaterials (Eleftheriades et al., 2003) (Siddiqui et al., 2004). Despite this fascinating breakthrough, yet too many losses have been engendered by these RF/microwave passive structures. To cope with this issue, a technique was recently introduced in order to aim the equalization of interconnect effects by using NGD microwave active circuits. The principle and properties of this intriguing circuit were widely developed for the first time in (Ravelo, 2011a, 2011b and 2011c). This innovative circuit proved to open potentially the way to applications such as described in (Ravelo et al. 2007a and 2007c).

For the better understanding this paper is structures in three main sections. Section II establishes the theory on the cancellation method proposed in (Ravelo et al., 2007c May, 2009 May, and 2010) by using the NGD for the baseband application developed in (Ravelo, 2011a). First, the synthesis of two-stage NGD circuit with identical NGD active cells is presented in order to compensate for RC effects. Afterwards, inductive interconnect effects are introduced. In section III, simulations and results expose that these active UWB cells are able to compensate for 98-% of the propagation delay and to reduce distortions for a 4 Gbps signal. Lastly, the potential integration of this principle with optical interconnects are discussed in section IV (Granberg, 2004) (Lockwood & Pavesi, 2011) (Doany et al., 2007) (Moll et al, 2006) (Zimmermann, 2010).

2. Theory on the synthesis of NGD cells for RC- and RLC-interconnect effects cancellation

This section presents the theoretical analysis enabling to determine the parameters of the NGD circuit prior to the cancelation of the interconnect effects which can be assumed as RC- or RLC-models.

2.1 RC effects equalization with two baseband cascades NGD functions

This NGD circuit consists of a Field Effect Transistor (FET) in feed back with a resistor and an inductor in series as depicted in Fig. 1. Because of the FET Drain-Source current direction, the output voltage naturally generated by this circuit and the input one are opposed, thus it is better to use two or an even number of cells (Ravelo et al. 2007a Oct. and 2007c May). Consequently, this paper will deal with the synthesis method of a two-stage circuit with identical NGD active cells in order to compensate for the RC-interconnect model line effects as shown in Fig. 1. To reduce the effects of the RC-line (with resistance, R_L, and capacitance, C_L, per unit length) of length, d, we searched for a transfer function of the whole circuit of Fig. 2 close to unity ($H(j\omega)=1$) and that the group delay should be null (1):

$$\tau(\omega) = -\frac{\partial \angle H(j\omega)}{\partial \omega} = 0. \tag{1}$$

Therefore, by taking $R_c = R_s + R_L \times d$ and $C = C_L \times d$ and searching for $|H(0)| \approx 1$ and $\tau(0) \approx 0$ at very low frequency, we have the following resistance and inductance expressions of the NGD cells:

$$R = \frac{R_c + 3R_{ds} + \sqrt{R_c^2 + 2(4g_m R_{ds} - 1)R_{ds}R_c + 9R_{ds}^2}}{2(g_m R_{ds} - 1)}, \tag{2}$$

$$L = \frac{R_c C(g_m R_{ds} - 1)[R^2 + R_{ds}R(3 + g_m R_{ds}) + R_{ds}^2]}{(g_m R_{ds} + 1)\left[(g_m R_{ds} + 2) + g_m R_c\right]R + (4g_m^2 R_{ds}^2 + 5g_m R_{ds} + 1)R_c + 3R_{ds}(1 + g_m R_{ds})}. \tag{3}$$

Note that the FET is modeled by the conductance g_m in cascade with the Drain-Source resistor R_{ds}.

2.2 Analysis of inductive interconnect effects on the NGD equalizer

Let us consider the interconnect RLC-line model with unit-length R_L, L_L, and C_L presented in Fig. 2. Relations (4) and (5) were specifically developed for the synthesis of the NGD active circuit in order to compensate for effects induced by the RLC-line where $R_t = R_s + R_L \times d$, $L_t = L_L \times d$ and $C = C_L \times d$:

$$R = \frac{2R_{ds} + (g_m R_{ds} + 1)R_t}{g_m R_{ds} - 1}, \tag{4}$$

$$L = \frac{(g_m R - 1)\left[(R + R_{ds})CR_t + (1 + g_m R_{ds})L_t\right]}{g_m^2 R_{ds} R_t + g_m(R_{ds} + R_t) + 1}. \tag{5}$$

3. Simulations and results

One points out that during the simulations performed in the SPICE schematic environment, we consider the FET parameters $g_m = 200$ mS and $R_{ds} = 200\ \Omega$.

3.1 RC effects equalization with two baseband cascades NGD functions

The two-stage NGD circuit was simulated with ADS Software Simulator of *Agilent*^{TM} with the parameters shown in Table 1. Frequency- and time-domain results are presented in Fig. 3 and Fig. 4. Moreover, the equalization of the magnitude and group delay, $|H(j\omega)|$ and $\tau(\omega)$, respectively, are depicted in Fig. 3, where the frequency response of the RC circuit (thin line) is compensated by that of the NGD circuit (dashed line); the response obtained by cascading both is shown in thick line. In addition, with an trapezoidal input signal with a rate of more than 4 Gbps/s, we see clearly the efficiency of the proposed technique upholding the reduction of the 50-% propagation delay from $T_{rc50\%} = 320$ ps to $T_{rcNGD50\%} = 5$ ps. A significant decrease of the 50-% propagation delay of about 98%, accompanied with a partial recovery of the distorted signal is found.

3.2 Inductive interconnect effects

During this study, as the Drain-Source current direction gives naturally an output voltage is of opposite sign compared to the input one, then, the opposite of v_{out2} was used in plots. Simulations with ADS Software were performed by considering the parameters shown in Table 2. Therefore, one gets the afterward time-domain simulation results. Fig. 5-a compares the time-domain responses produced by the RLC-interconnect line alone and by the whole circuit (RLC *plus* NGD) for a trapezoidal input pulse at a rate of about 4 Gbits/s. It shows that the signal is distorted and more and more delayed with the inductance value as shown in Fig. 6-a. Then, insertion of the NGD active circuit synthesized from relations (3) and (4) at the output of the RLC line led to Figs. 5-b and 6-b. These results highlight the efficiency of the proposed method. However, one should note that, depending on the inductance value, some overshoot may appear in the compensated response; a way to overcome this problem would be to further optimize the NGD circuit elements or to cascade two or more NGD cells.

4. Discussion and conclusion

To sum up, a synthesis method of NGD active circuit aimed at decreasing or annihilating the effects of the interconnections is presented. This method brings opportunities to compensate for simultaneously the time delay and distortions. In the continuation of this work, the development of a CMOS UWB transistor is under study and expected for the first “NGD buffer” realization.

Since integrated optical systems benefit of a tremendous breakthrough, as explained in (Granberg, 2004) (Moll et al., 2006) (Dangel et al., 2007) (Doany et al., 2007) (Lockwood & Pavesi, 2011), the short-haul optical interconnects become a reality, especially for multi-chip modules (MCMs). Furthermore, recent works on the hybrid integration approach have been implemented with MCMs for digital, analog, microwave and optoelectronic applications (Zimmermann, 2010). In conclusion, the recent mastering of optical waveguides, optical switches, optical sensors, optical transceivers or optical pick-up devices lead to imagine complete optical systems at the PCB scale. For this reason the NGD structures, either active or based on metamaterials, can be implemented directly at the optical transceiver or waveguide level.

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Table 1. Simulation parameters

R_s	R_L	C_L	d	R	L
10 Ω	30 Ω/cm	2.6 pF/cm	2 cm	28 Ω	890 pH

Table 2. Simulation parameters for the RLC equalizer

R_s	R_L	C_L	L_L	d	R	L
20Ω	35Ω/cm	5.16pF/cm	3.47nH/cm	1.5cm	65.5Ω	8.2nH

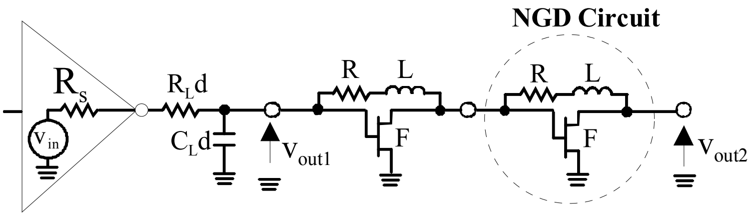


Figure 1. Whole compensated circuit including the NGD active circuit

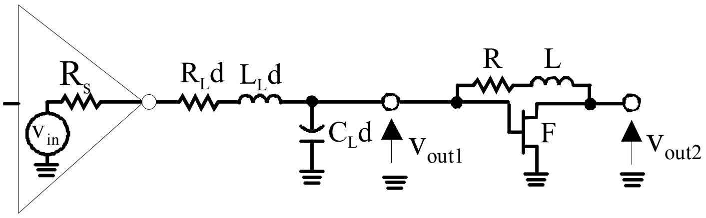


Figure 2. RLC-line model driven by a gate and including the NGD active circuit

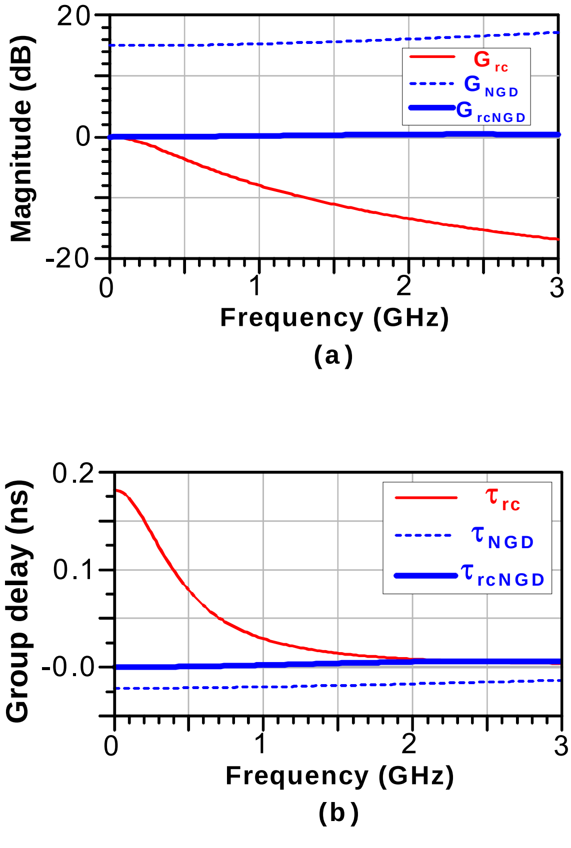


Figure 3. (a) Magnitude and (b) group delay frequency responses

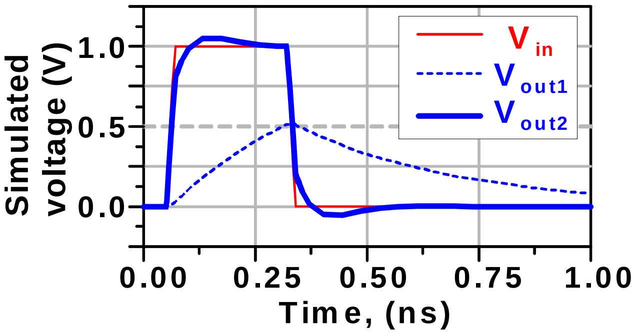
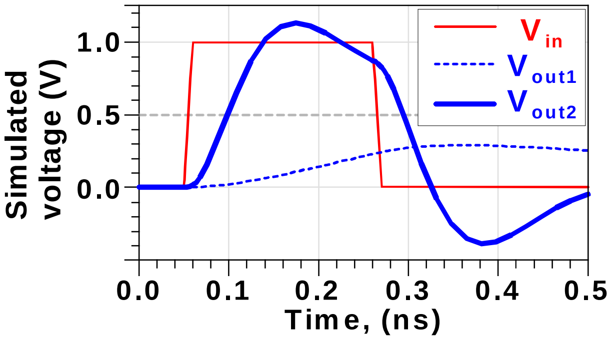
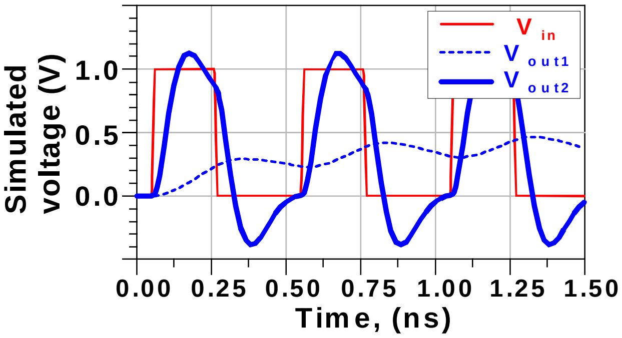


Figure 4. Time-domain results for 4Gbps square wave input

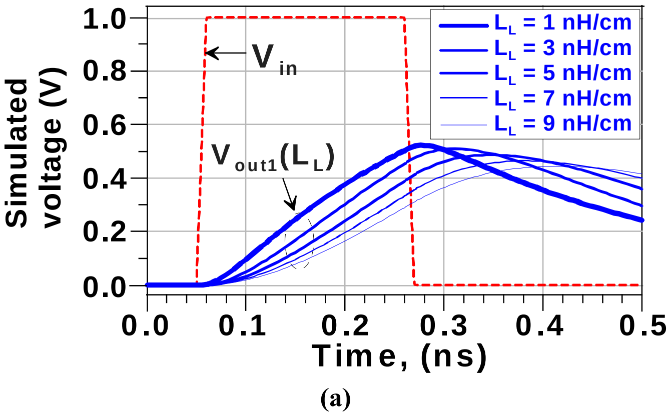


(a)

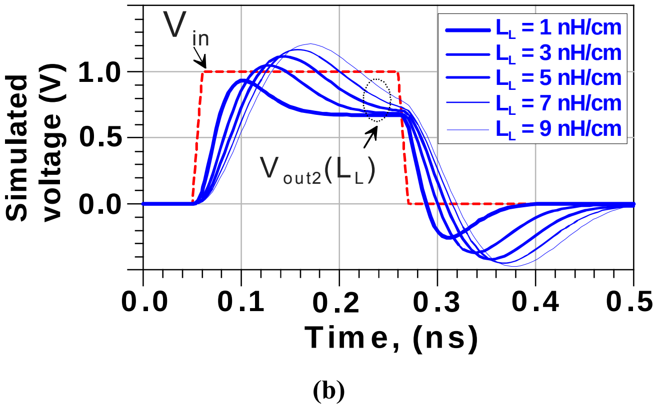


(b)

Figure 5. Time domain responses for the RLC-line model and for the whole circuit compensated driven by a gate (see Fig. 2) for a trapezoidal input signal (a): one period and (b): three periods



(a)



(b)

Figure 6. Time-domain responses for a trapezoidal input signal; a: RLC-line b: the whole circuit compensated