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TRANSIENT ANALYSIS OF A MICROSTRIP DIFFERENTIAL PAIR FOR HIGH-SPEED PRINTED CIRCUIT BOARDS

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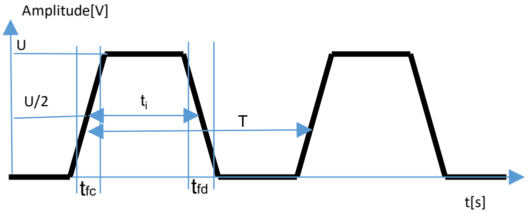
This paper analyzes the behavior of a microstrip differential pair manufactured on Rogers 4003 C substrate for high-speed printed circuit boards (PCBs). The electromagnetic parameters of the structure are computed using the full-wave electromagnetic method, then the primary parameters are extracted, and a circuit is built to analyze the transient regime. The influence of the propagation delay and the asymmetry of the input signals are simulated by choosing specific parameters of the input pulses.

1. INTRODUCTION

Differential signaling is a method employed in digital systems to improve signal-to-noise ratio and increase electromagnetic susceptibility. It supposes to use two transmission lines instead of one for sending data or command /control signals. The two lines are driven with signals out of phase. Nevertheless, there are some drawbacks too, which include the increased number of traces as well as the need for a tight synchronization. One of the most used schemes is the low voltage differentiating scheme (LVDS) [1] where one bit of information is obtained with two signals. Microstrip differential pair consists of two microstrip traces which are fed with differential signals. This type of differential pair has specific behavior because the two traces are in the vicinity of the ground/reference plane. In the ideal case, when the differential pair consists of two conductors, the direct current goes through a conductor and the return current through the other one. In a microstrip differential pair, the direct current flows through a trace and the return current goes through the reference plane. On the second trace, the current will travel in the opposite direction as the first trace, and it will close through the reference plane. As a result, there will be two currents flowing through the reference plane in opposite directions which will be partially overleaped, depending on the distance between the two microstrip lines. The paper analysis the transient regime of a microstrip differential pair, made on Rogers 4003 C substrate, based on parameters computed by full-wave simulations. Unless the results reported in [2], where the study is made in the frequency domain and Megatron 6 dielectric was used, the transient regime is analyzed in the time domain using pulse sources defined in Ansoft Nexxim.

2. COMPUTING THE SPECTRAL COMPONENTS OF A TRAPEZOIDAL PULSE

The signals which send data in the digital systems as well as synchronization and command/control signals are in the ideal case rectangular pulses. The transitions from 0L to 1L and the other way around are not instantaneous, but they need some time, so the pulses are trapezoidal with the following parameters: pulse width-t_i, rise/fall time-t_{fc}/ t_{fd}, repetition time -T. The parameters of a trapezoidal pulse are displayed in Fig. 1. Usually, the ratio between the pulse width and the repetition period is ½, and the rise/fall time represents the interval between 10% and 90% from the total rise/fall edge of the pulse. The rise and fall time have a very important impact on electromagnetic interferences generated by these signals as they pass vias and microstrip traces on high-speed PCBs. A very simple way to analyze the interferences generated by a periodic trapezoidal pulse is to apply the Fourier series and look for the amplitude of the different spectral components of the signal in the frequency domain.



The parameters of a trapezoidal pulse.

In most applications, the trapezoidal pulses are symmetrical, which means that the rising and falling edges of the pulse are identical (t_f). In this hypothesis, by applying the Fourier series to the periodic trapezoidal pulse, the complex expression of the signal is given by:

$$\dot{u}(t) = U\frac{t_i}{T} + 2U\frac{t_i}{T}\sum_{n=1}^{\infty}\left[\frac{\sin\left(n\pi f_0 t_i\right)}{n\pi f_0 t_i}\right]\left[\frac{\sin\left(n\pi f_0 t_f\right)}{n\pi f_0 t_f}\right] e^{-j\pi n f_0 (t_i + t_f)} e^{j2\pi n f_0 t}. \quad (1)$$

According to formula (1) the periodic trapezoidal pulse, with the same rise and fall time, has a DC component Ut_i/T and an infinite number of harmonics with the amplitude expressed by the formula:

$$2U\frac{t_i}{T}\sum_{n=1}^{\infty}\left[\frac{\sin\left(n\pi f_0 t_i\right)}{n\pi f_0 t_i}\right]\left[\frac{\sin\left(n\pi f_0 t_f\right)}{n\pi f_0 t_f}\right]. \quad (2)$$

As in eq. (2) there are two functions sin(x)/x, which means that the graphic has two inflection points, where the slope varies with –20 dB per decade. The two points are defined by the pulse width and the rise/fall time of the pulse. In the more general case, when the rise and fall times are different, there will be 3 inflection points.

The variations of the amplitude of the Fourier harmonics, in dB, for a trapezoidal pulse are displayed in Fig. 2. One can see that for $0 < t_i \le T/\pi$ the first harmonic has the amplitude $2U\frac{t_i}{T}$, and for $T/\pi < t_i < T$ it is on the line with –20 dB slope.

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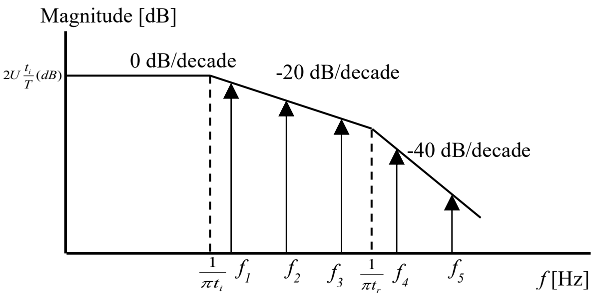
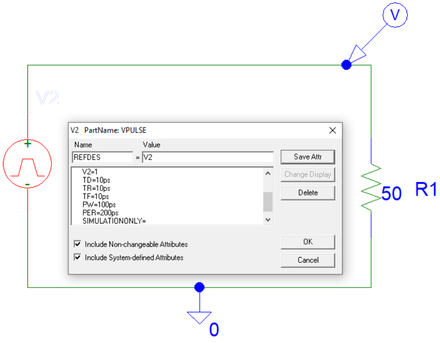


Fig. 1 – Magnitude of the spectral components of a periodic trapezoidal pulse, in dB [3].

The second point of inflection, in the hypothesis that the trapezoidal pulse is symmetrical, depends on the rise/fall time. Some authors consider that the bandwidth of a trapezoidal pulse is given by this point [3]. There are other authors who say that from an electromagnetic compatibility perspective the bandwidth should be $1/t_f$ [4].

3. FAST FOURIER TRANSFORM OF TRAPEZOIDAL PULSES

To determine the maximum frequency of the interference signal which should be considered some simulations had been done in PSpice [5,6]. The periodic rectangular and trapezoidal pulses were generated using a pulse source that is connected to a 50 Ω load, as in Fig. 3. The simulations with a rectangular pulse are made to have a reference for trapezoidal pulses. The spectral content is obtained by applying the fast Fourier transform (FFT).



REFDES = V2

V2=1
TD=10ps
TR=10ps
TF=10ps
PW=100ps
PER=200ps
SIMULATIONONLY=

☑ Include Non-changeable Attributes
☑ Include System-defined Attributes

Fig. 2 – The layout used for simulations.

The parameters of the generated pulses were chosen to take into consideration the operating frequencies of different electronic applications. The simulations were carried out for both rectangular and trapezoidal pulses. The parameters are presented in Table 1 for a clock frequency of 5 GHz.

Table 1

The parameters of the pulses with a frequency repetition rate of 5 GHz

Pulse-type Parameter	Rectangular pulse	Trapezoidal pulse
Voltage	1 V	1 V
Delay	10 ps	10 ps
Pulse width	100 ps	100 ps
Pulse repetition period	200 ps	200 ps
Pulse repetition frequency	5 GHz	5 GHz
The rising edge	0 ps	10 ps
The falling edge	0ps	10 ps

The spectral components of rectangular pulses are presented in Fig. 4. Because the duty cycle is ½ only the odd components are different from 0. The highest frequency harmonics in Fig. 3 has 45 GHz with an amplitude of 70 mV, which means 7 %.

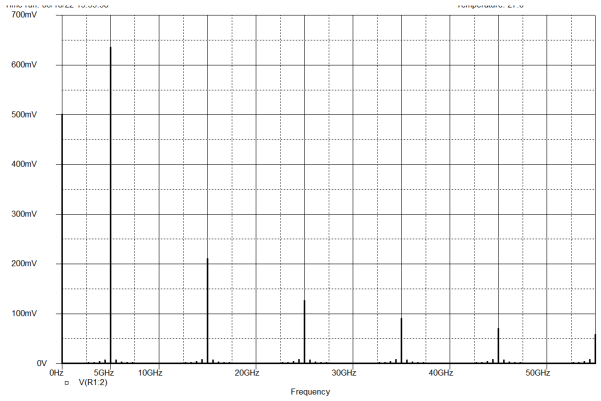


Fig. 3 – The spectral components of the rectangular pulse with parameters are presented in Table 1.

For a trapezoidal train of pulses, the spectral components are displayed in Fig. 5. One can see the presence of both odd and even harmonics and that at 50 GHz the amplitude of the spectral component is 40 mV, which means 4 %.

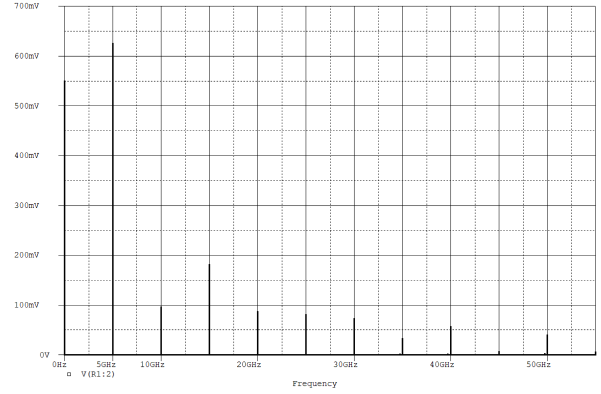


Fig. 4 – The spectral components of the trapezoidal pulse with parameters are presented in Table 1.

The maximum frequency can be computed using the formula [3]:

$$f_{\max} = \frac{0.4375}{t_f} = \frac{0.4375}{10 \cdot 10^{-12}}\,\mathrm{Hz} = 43.75 \quad \mathrm{GHz}. \qquad (3)$$

4. TRANSIENT REGIME ANALYSIS OF TRAPEZOIDAL PULSES

To analyze the transient regime of a differential pair, a geometrical model consisting of two microstrip traces was designed in a high-frequency structure simulator (HFSS) [7]. The traces are 3.1 mm in width, 60 mm long and 7.1 mm apart. As the study is designated for a high-speed digital system, the substrate used was Rogers 4003 C. It was chosen due to its low losses. The loss tangent for this substrate is 0.0027 much better than 0.02 for FR4 and the dielectric permittivity is 3.55. In addition, it has a reasonable price compared with other types of microwave substrates working till 50 GHz. At the two ends of the differential pair, two wave ports are defined and the differential pair is fed with +1V and -1V. The full-wave electromagnetic analysis is used to compute the electromagnetic parameters, then the Z parameters are extracted to use a circuit-oriented method for studying the transient regime [8,9]. As can be seen in Fig. 6, a two ports circuit is imported from HFSS in Ansoft Nexxim. To run the simulations, the two ports circuit is connected to two pulse sources and to a differential load.

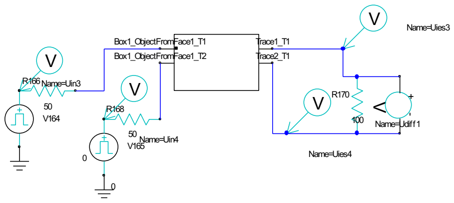


Fig. 5 – Electronic scheme used to analyze a differential microstrip pair.

The terminals in Fig. 6 are numbered as: Port1 = Box1_ObjectFromFace1_T1; Port2 = Box1_ObjectFromFace1_T2; Port3 = Trace1_T1; Port4 = Trace2_T1.

After running the simulation in HFSS the S, Z, and Y parameters can be exported for building a circuit for time-domain simulations. Considering the clock frequencies for computers on the market two frequencies were selected and the extracted Z parameters are presented in Table 2.

Table 2

The extracted Z parameters for 1.78 GHz and 5 GHz

Parameter [ohms]	1.78 GHz		5 GHz	
	Magnitude	Phase	Magnitude	Phase
Z_{11}	29.19115	-86.60126	27.11172	-84.50459
Z_{12}	1.81511	93.51163	4.89001	98.73546
Z_{13}	57.81529	90.61118	57.28868	90.87420
Z_{14}	0.20420	-28.21066	1.29371	-63.99581
Z_{22}	29.17388	-86.59999	27.06315	-84.49596
Z_{23}	0.20417	-27.87705	1.28828	-63.84797
Z_{24}	57.81205	90.61100	57.30501	90.87195
Z_{33}	29.17635	-86.60075	26.98612	-84.48374
Z_{34}	1.81438	93.51089	4.88786	98.72861
Z_{44}	29.18701	-86.60166	27.04272	-84.49447

For each frequency, the parameters of the two pulse sources are set. In table 3 the pulse sources parameters for a clock frequency of 1.78 GHz are given.

Table 3

The parameters of the pulses with a frequency repetition rate of 1.78 GHz

Parameter	Source 1 (V164)	Source 2 (V165)
Voltage	1 V	-1 V
Delay	10 ps	10 ps
Pulse width	280 ps	280 ps
The rising edge	20 ps	20 ps
The falling edge	20 ps	20 ps

The variation of the input voltages applied at port 1 of the differential pair from the two sources, the output voltages, and the differential voltage is displayed in Fig. 7. The two microstrip lines are perfectly symmetrical, so, there are no delays between the output voltages of the lines.

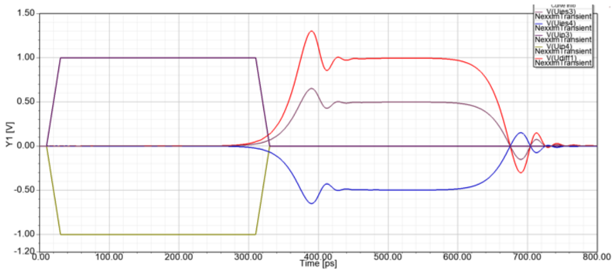


Fig. 6 – The input and the output signals (Y1) when the microstrip differential pair is fed with trapezoidal pulses having 280 ps width and 20 ps rising and falling edge.

If the clock frequency is increased to 5 GHz, then the pulse repetition interval will be 200 ps and the front time 10 ps, as in Table 4.

Table 4

The parameters of the pulses with a frequency repetition rate of 5 GHz

Parameter	Source 1 (V164)	Source 2 (V165)
Voltage	1 V	-1 V
Delay	10 ps	10 ps
Pulse width	100 ps	100 ps
The rising edge	10 ps	10 ps
The falling edge	10 ps	10 ps

The output signals at the differential microstrip pair, when the pulses with parameters from Table 1 are applied to the input, are presented in Fig. 8. One can see that for the duration of the pulse of 100 ps, the propagation through the differential pair strongly affects the shape of the pulse. The maximum variation of the amplitude is around 40 %. At the same time, if the input pulses have 10 ps front time, in the end, the rising time increases to almost 80 ps.

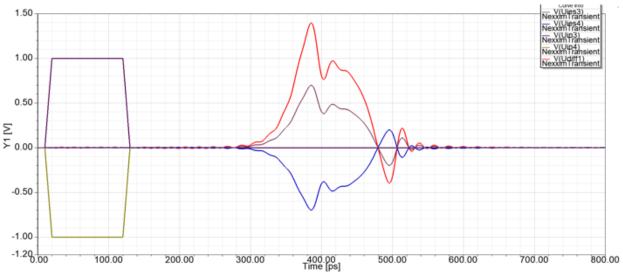


Fig. 7 – The input and the output signals (Y1) when the microstrip differential pair is fed with trapezoidal pulses having 100 ps width and 10ps rising and falling edge.

As one can see in Fig.7 the transmission of the two trapezoidal pulses through the differential pair will produce a delay proportionally with the microstrip line length and will change the shape of the pulse. The variation of the differential voltage is around 30%, while the rising edge of the pulse is almost 4 times higher (around 80 ps).

Other issues which can produce interferences in the case of differential lines are given by the different speeds of propagation for odd and even modes in the case of microstrip lines and by the fact that the pulses applied at the input are not fully symmetrical. The speeds of odd and even modes for microstrip lines are different because of the different field distributions produced by the unsymmetrical geometry. The traces have a ground plane beneath the substrate and are open above. The second issue can be produced by the different delays within the device for positive and negative pulses applied at the input of the differential pair. To analyze these situations some simulations have been done with pulses having different durations, different rising/falling edges, and different delays. For instance, in Table 5 positive and negative pulses with different parameters with respect to pulse width and front time are presented.

Table 5

The parameters of the pulses with different parameters applied at the input of the microstrip differential pair

Parameter	Source 1 (V164)	Source 2 (V165)
Voltage	1 V	-1 V
Delay	10 ps	10 ps
Pulse width	1000 ps	780 ps
The rising edge	70 ps	54 ps
The falling edge	70 ps	54 ps

The pulses with different widths and front durations will produce, at the two outputs of the differential lines, one pulse with the duration given by the difference between the widths of the two pulses applied at the input of the differential pair, as can be seen in Fig. 9. As a result, the pulse at the differential output has the same duration as the longest pulse, but with a step in the amplitude on the time interval given by the difference between the two-pulse duration.

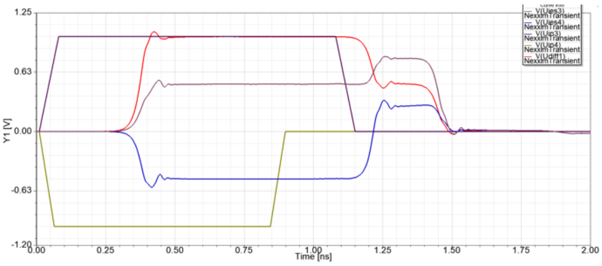


Fig. 8 – The input and the output signals (Y1) when the microstrip differential pair is fed with trapezoidal pulses having different durations (1000 ps and 780 ps) and different rising and falling edge (70 ps and 54 ps).

Another case is presented in Table 5, where the delays of the input pulses are different.

Table 5

The parameters of the pulses with different delays applied at the input of the microstrip differential pair

Parameter	Source 1 (V164)	Source 2 (V164)
Voltage	1 V	-1 V
Delay	10 ps	20 ps
Pulse width	280 ps	280 ps
The rising edge	20 ps	20 ps
The falling edge	20 ps	20 ps

Figure 10 shows the variation of two input signals out of phase and delayed each other with 10 ps, the output signals on each line, and the differential voltage. The delay between the input signals has the same effects on the output as in the case when the lines are not identical.

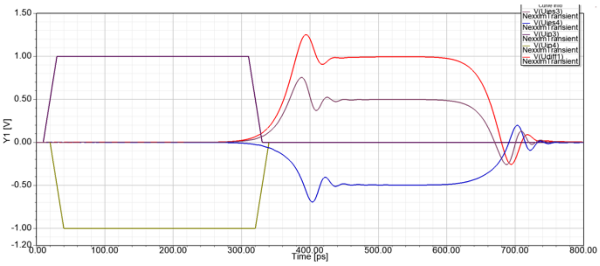


Fig. 11 – The inputs and the outputs signals (Y1) when the microstrip differential pair is fed with trapezoidal pulses having 280 ps width and 20 ps rising and falling edge, and the delays of 10 ps and 20 ps.

By comparing the signals displayed in Fig.10 with the ones shown in Fig. 7, one can see that the differential signal on the falling edge reaches zero 5 ps later and the pulse overshoot decreases from 30 % to 25 %.

5. CONCLUSIONS

The analysis of the behavior of the interconnections between different parts of a digital system can be made using a circuit-oriented method or electromagnetic computational method. The first one needs fewer resources, but it can be used only in the case when the length of the interconnections is less than 1/10 of the wavelength corresponding to the maximum frequency given by the rise/fall edge of the trapezoidal pulse. If the above condition is not met, then the full-wave electromagnetic method must be used. In this paper, the full-wave electromagnetic method is employed to analyze the behavior of a microstrip differential pair, in the frequency range 1-50 GHz. Based on this analysis the impedance parameters of the differential pair are extracted and an equivalent part was created. This part was imported in Ansoft Nexxim and fed with a differential signal. Unless the results are presented in [10], the paper covers a higher bandwidth. Likewise, it underlines the importance of precise computation using full-wave simulations at high frequency against more fast methods such as transmission line and finite-difference time-domain method. The simulations show the influence of the input parameters of the microstrip differential inputs, especially the rise/fall time against the output, the influences of the microstrip Rogers substrate, as well as geometrical dimensions against the shape of the pulse at the single-ended as well as of the differential output of the microstrip differential pair. The overshooting, undershooting of the pulse as well as the variation of the rising and falling edges are displayed and analyzed.

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