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# BP-NGD Signal Integrity Application for RLC-Cable Parasitic Dispersion Reduction

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**Abstract**—A cable RLC-parasitic dispersion reduction by using bandpass (BP) negative group delay (NGD) circuit for signal integrity (SI) and EMC application is stressed. The theoretical formulas of uncommon BP-NGD circuit dedicated to SI enhancement versus parasitic parameters are established. The BP-NGD SI application is confirmed by AC results with circuit design under 250-MHz resonance frequency confirming dispersion reduction of magnitudes and group delays from (18-dB, 10-ns) to better than (2-dB, 2-ns). The SI improvement is validated by transient results showing input and output signal delay reduction and envelope cross correlation enhancement from 76% to 98%.

**Keywords**—Negative group delay (NGD), Bandpass (BP) NGD circuit, RLC-network, electric cable, dispersion effect, BP-NGD EMC application, SI improvement

## I. INTRODUCTION

Cables and connectors constitute key elements for the interconnections of electric system [1-2]. Relevant EMC models of these interconnect elements are necessary to predict the electric system performance [3-5]. Accurate high frequency cable models based on transmission line (TL) theory were proposed [6-7]. The interconnect EMC parasitic affecting signal integrity (SI) degradation from cable is usually modelled by lumped and distributed RLC-networks [8-9]. To reduce the undesirable dispersion effect, one can proceed with BP-NGD equalization method [10-11]. For the case of base-band signals, low-pass type NGD equalizer must be used [12-13]. The basic specifications of NGD behavior different types were initiated by analogy with filter theory [14].

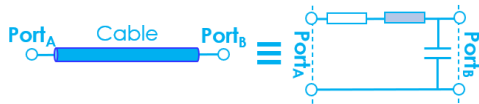


Fig. 1. Interconnect cable RLC network model configuration. The present research work elaborates AC and transient study on RLC-dispersion reduction with BP-NGD equalizer showing RF and microwave SI improvement feasibility.

## II. BP-NGD THEORY ON RLC-DISPERSION REDUCTION

This section introduces the RLC-dispersion reduction BP-NGD theory established from transfer function (TF) denoted  $TF_d(jf)$  and group delay (GD)  $GD_d(f)$  versus frequency  $f$ .

### A. Dispersion Problem Formulation

The dispersion effect is modeled by RLC equivalent circuit constituted by  $R_d$ ,  $L_d$  and  $C_d$  components depicted by Fig. 2(a). The dispersion is represented by the  $TF_d$  magnitude and GD shown by Figs. 2(b) and 2(c), respectively. Under condition  $L_d > R_d^2 C_d / 2$ , the resonance frequency is [10]:

$$f_d = (2L_d - R_d^2 C_d)^{1/2} / (2\sqrt{2}\pi L_d C_d^{1/2}). \quad (1)$$

The dispersion magnitude and GD peaks are respectively:

$$T_d = 4L_d^2 / [R_d^2 C_d (4L_d - R_d^2 C_d)]. \quad (2)$$

$$t_0 = 2L_d / R_d. \quad (3)$$

We denote  $T_1 = T_d(f_i) = T_d(f_h)$  and  $t_1 = GD_d(f_h)$ , and frequency band  $\Delta f = f_h - f_i$ . The dispersion effect is characterized by the magnitude flatness  $\Delta T_d = T_1 / T_0$  and GD flatness  $\Delta t_d = t_0 - t_1$ .

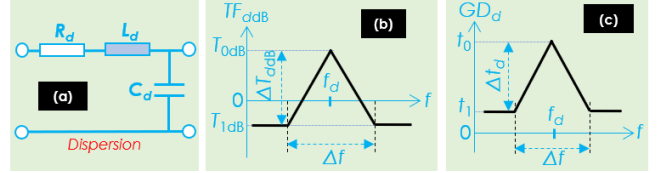


Fig. 2. Dispersion (a) equivalent circuit, (b)  $TF_d$  and (c)  $GD_d$  specifications. Knowing  $R_d$ , the dispersion model parameters are given by:

$$L_d = R_d \sqrt{\sqrt{T_d^2 - 1} (T_d + \sqrt{T_d^2 - 1})} / (2\sqrt{2}\pi f_d) \quad (4)$$

$$C_d = 1 / \left[ \sqrt{2}\pi f_d R_d \sqrt{\sqrt{T_d^2 - 1} (T_d + \sqrt{T_d^2 - 1})} \right]. \quad (5)$$

### B. BP-NGD Circuit Topological Description

To reduce the dispersion effect, the BP-NGD cell composed of RLC-parallel network combined to resistance,  $R_0$  shown in Fig. 3(a) is used. The expected BP-NGD TF magnitude  $TF_n$  and GD  $GD_n$  are ideally plotted in Figs. 3(b) and 3(c), respectively. The NGD circuit is specified by its NGD center frequency,  $f_n$ , where  $T_n = |TF_n(jf)|$  and  $t_n = GD_n(f) < 0$ , and bandwidth,  $\Delta f$ . The NGD cut-off frequencies must be chosen close to  $f_i$  and  $f_h$ , with  $GD_n(f_i) \approx 0$  and  $GD_n(f_h) \approx 0$ .

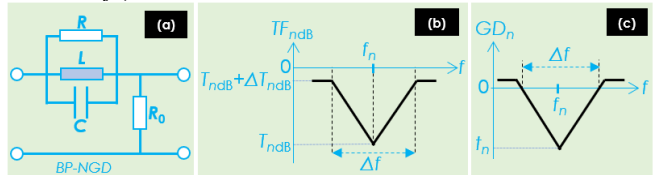


Fig. 3. BP-NGD (a) equivalent circuit, (b)  $TF_n$  and (c)  $GD_n$  specifications.

### C. NGD Function Parameters Analytical Determination

The cable dispersion reduction under investigation consists originally in cascading the culprit cable and BP-NGD circuit as illustrated in Fig. 4(a). The BP-NGD equalization is aimed to operate with total TF magnitude  $TF = |TF(jf)| \ll T_0$  and GD  $GD(f) \ll t_0$  as presented in Fig. 4(b) and Fig. 4(c). Meanwhile, the equalized cable magnitude and GD flatness's must be improved conditions  $\Delta T \ll \Delta T_d$  and  $\Delta t \ll \Delta t_d$  in  $[f_i, f_h]$ .

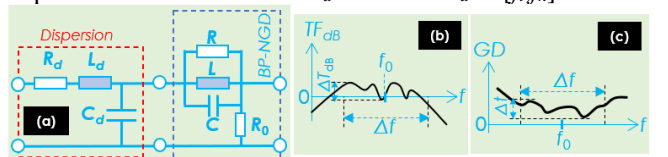


Fig. 4. TF (a) magnitude and (b) GD specifications of (c) cascaded dispersion-NGD circuit.

To achieve this dispersion reduction, the NGD parameters are calculated knowing  $T_0$ ,  $f_0$  and  $R_0$  by synthesis formulas:

$$R = (T_d - 1)R_0 \quad (6)$$

$$L = R_0(T_d - 1)^2 / \left[ \sqrt{2\pi f_d} \sqrt{T_d \sqrt{T_d^2 - 1} + T_d - 1} \right] \quad (7)$$

$$C = T_d \sqrt{T_d \sqrt{T_d^2 - 1} + T_d - 1} / \left[ 2\sqrt{2\pi f_d} R_0 (T_d - 1)^2 \right]. \quad (8)$$

#### D. SI Assessment Transient Parameters

The SI performance transient parameters are referred to the comparison of input  $v_{in}$  and output  $v_{out}$  characteristics. Doing this, we can consider amplitude ratio  $r = \max(v_{out}) / \max(v_{in})$ . By taking the half-maximum  $x = \{\text{rise, fall}\}$  instant times of input  $v_{in}(t_{in}^x) = \max(v_{in}) / 2$  and output  $v_{out}(t_{out}^x) = \max(v_{out}) / 2$ , the signal delays are defined as  $\Delta t_x = t_{out}^x - t_{in}^x$ . The input and output relative correlation is equated by MATLAB® instruction  $xc = \text{corrcoef}(v_{in}, v_{out})$ .

### III. CABLE DISPERSION REDUCTION VALIDATION

#### A. POC Design

The dispersion reduction POCs are designed in the schematic environment of the ADS® commercial tool from Keysight Technologies® as displayed by Figs. 5 with corresponding parameters addressed in Table I. The RLC resonant circuit inductance,  $L_d$  and capacitance,  $C_d$ , were calculated from equations (4) and (5) by fixing the value of resistor,  $R_d = 10.25 \Omega$ . The BP-NGD parameters were synthesized by mean of formulas (6), (7) and (8) by assuming  $R_0 = 50 \Omega$ .

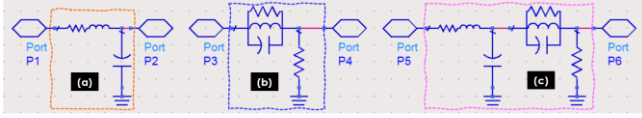


Fig. 5. (a) Dispersion, (b) BP-NGD and (c) equalized circuit ADS® POCs.

TABLE I  
POC DISPERSION AND PARAMETERS

Dispersion	Parameter	$f_d=0.25\text{GHz}$	$T_d=18\text{dB}$	$t_d=10\text{ns}$
	RLC-model	$R_d=10.25\Omega$	$L_d=51.2\text{nH}$	$C_d=8.24\text{pF}$
BP-NGD parameter		$R=362\Omega$	$L=21.6\text{nH}$	$C=19.5\text{pF}$

#### B. Dispersion Reduction AC Validation Results

The POC AC analysis was carried in the frequency band delimited from  $f_{min}=0.15$  GHz to  $f_{max}=0.35$  GHz. The significant flatness of magnitudes and GDs of TF, respectively displayed in Figs. 6(a) and 6(b), reveals the effectiveness of the dispersion reduction. The calculated (“ $TF_{Dc}$ ,” “ $TF_{Nc}$ ” and “ $TF_{DNc}$ ”) and simulated (“ $TF_{Ds}$ ,” “ $TF_{Ns}$ ” and “ $TF_{DNs}$ ”) responses, plotted in solid and dotted curves, respectively are in excellent agreement. The dispersion, NGD and total TF responses, denoted  $TF_D$ ,  $TF_N$  and  $TF_{DN}$ , respectively are plotted in solid black, red dashed and blue dotted curves, respectively. Table II summarizes the magnitude and GD at  $f_d=f_h$ . Thanks to the BP-NGD function with cut-off frequencies,  $f_l$  and  $f_h$  under about 80 MHz NGD bandwidth, obvious reduction of resonance magnitude,  $TF_D$ , is observed compared to  $TF$ , and also the GD,  $GD_D$ , compared to  $GD$  in the NGD frequency band.

TABLE II  
NGD AND DISPERSION SPECIFICATIONS

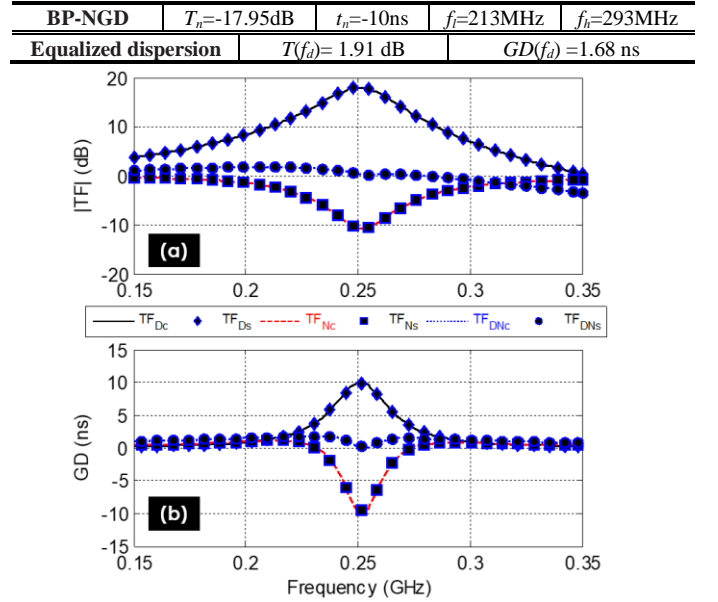


Fig. 6. Comparisons of calculated and simulated (a) magnitudes and (b) GDs. As expected,  $TF$ , of the equalized dispersion presents a better flatness.

#### C. BP-NGD Transient Signature

To highlight the BP-NGD meaning, input pulse signal  $v_{in}$  of circuit proposed in Fig. 5(b) modulated by 1 V amplitude modulating since carrier frequency  $f_d$  was considered. The test input signal spectrum belongs also to the NGD bandwidth with 60 ns period under transient analysis within 100 ns duration the time window. Fig. 7(a) and Fig. 7(b) show the plots of the input and BP-NGD output transient signals  $v_{in}$  and  $v_{NGD}$ . As explained by normalized envelopes  $\text{Env}[v_{in}]$  (plotted in black solid line) and  $\text{Env}[v_{NGD}]$  (plotted in blue solid line) compared in Fig. 7(c), despite the slight ripple distortion, the BP-NGD signature is confirmed by time-advance effect.

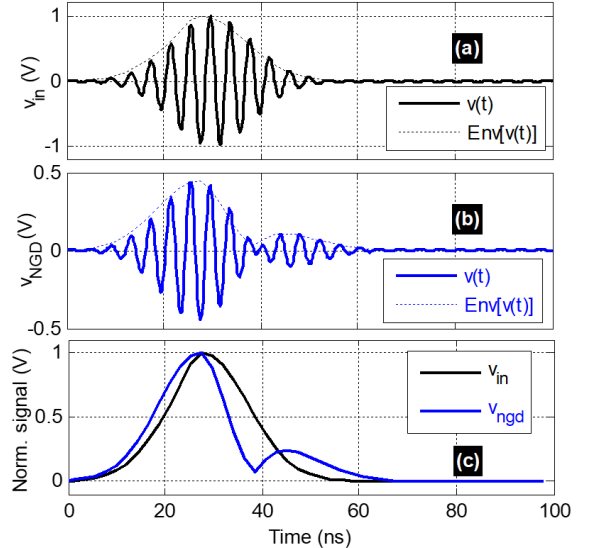


Fig. 7. Transient plot results illustrating BP-NGD signature.

#### D. Transient Results Showing Dispersion Reduction Implying SI Improvement

In addition to the previous AC analysis, the previously considered input signal  $v_{in}$  was injected to the dispersion and equalized circuits described in Fig. 5(a) and Fig. 5(b). Fig. 8(b) and Fig. 8(c) show the plots of the dispersion and equalized signals  $v_d$  and  $v_{eq}$ . The associated signal envelopes

$\text{Env}[v_d]$  (plotted in red dashed line) and  $\text{Env}[v_{eq}]$  (plotted in pink solid line) compared to  $\text{Env}[v_{in}]$  are plotted in Fig. 9(a).

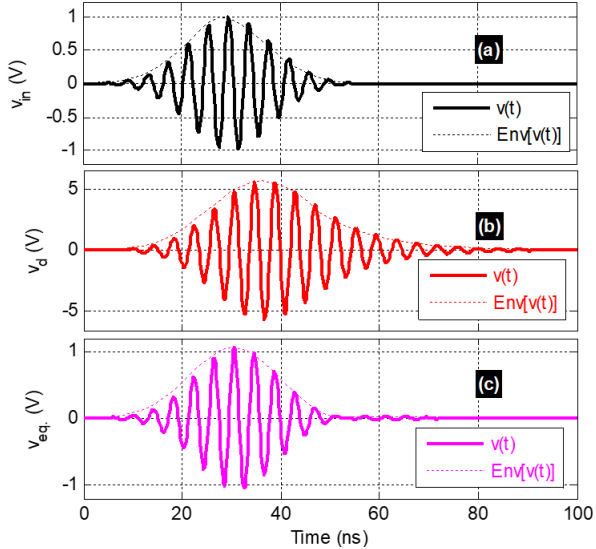


Fig. 8. (a) Input, (b) dispersion and (c) equalized transient signal results. It can be seen that  $v_d$  is literally distorted by showing wider time width pulse. This distortion effect is significantly reduced by referring to  $v_{eq}$  shown in Fig. 9(b). We remark that the original and BP-NGD equalized signals present a highly improved correlation coefficient and signal delay reduction as summarized in Table III.

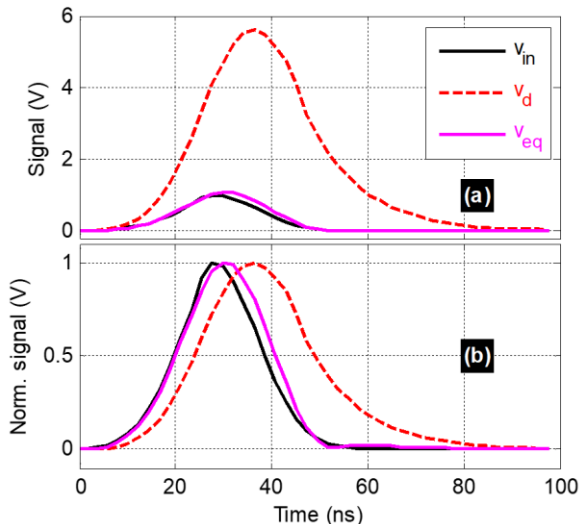


Fig. 9. Comparison of input, dispersion and equalized (a) natural and (b) normal envelopes.

TABLE III  
COMPARISON OF DISPERSION AND EQUALIZED SI PARAMETERS

Output/input SI parameters	$\alpha c$	$\Delta t_{rise}$	$\Delta t_{fall}$	$r$
Dispersion	76%	5 ns	10 ns	15 dB
BP-NGD equalization	98%	0.5 ns	2 ns	1.1 dB

#### IV. CONCLUSION

A SI application of uncommon BP-NGD circuit for

reducing interconnect cable RLC-dispersion is studied. The BP-NGD circuit design equalization method is formulated. Relevant AC and transient results confirm the BP-NGD dispersion reduction method effectiveness for EMC and SI engineering.

#### ACKNOWLEDGMENT

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