MICROSTRIP STRUCTURE RESONANCE NGD-EQUALIZATION

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Nanjing University of Information Science & Technology

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LEMA

Outline

A/ State of the Art (SoA) on negative group delay (NGD) circuits

B/ NGD ideal specifications and design method

C/ Principle of NGD equalization

D/ Discussion on Proof-of-concept (PoC) result showing resonance reduction

E/ Conclusion

H. Du, F. Wan, M. Guerin, F. Haddad, W. Rahajandraibe, G. Fontagalland & B. Ravelo, "Microstrip structure resonance NGD-equalization," Proc. of 21ème Colloque International & Exposition sur la CEM (CEM 2023), 13-15 June 2023, Toulouse, France, pp. 1-5

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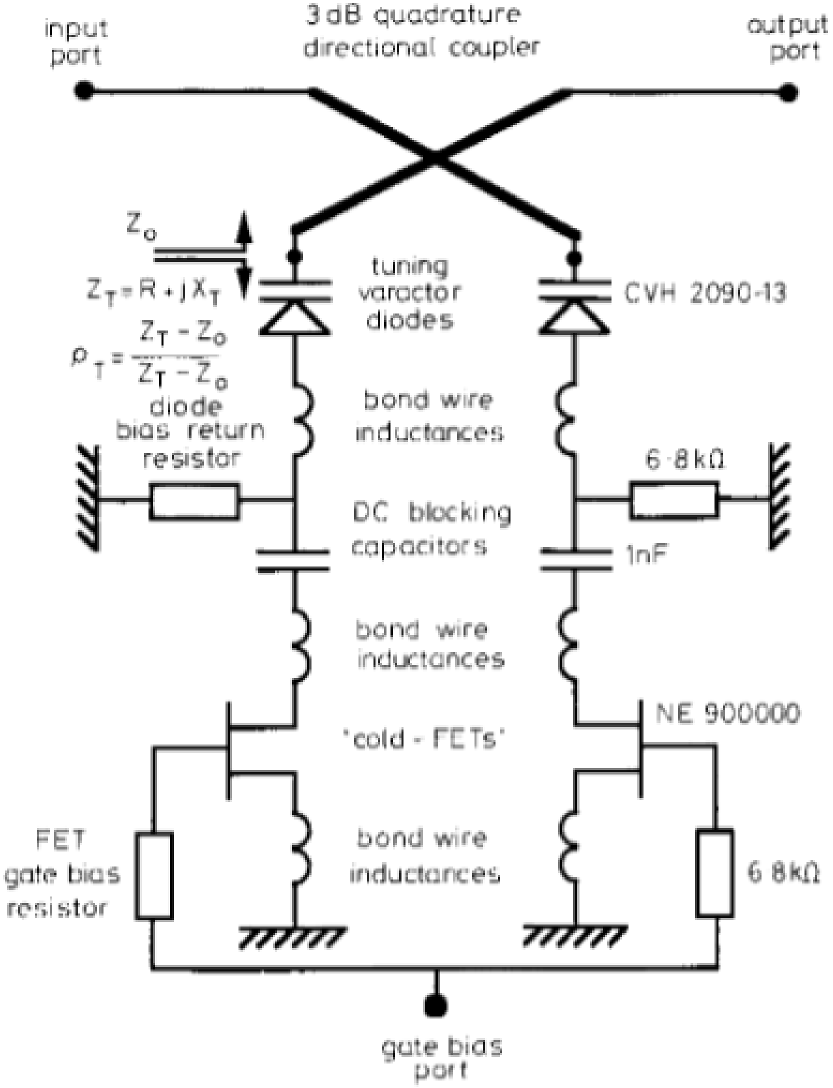
A/ SoA on NGD circuits

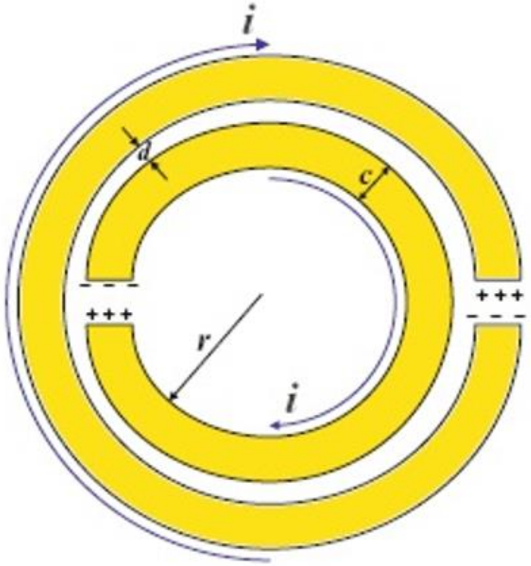
- In the early 1990s, the NGD effect was demonstrated in electronics engineering …
- Theoretical and experimental investigations in the field of RF and microwave engineering confirmed that certain passive and active circuit topologies are susceptible to generate the NGD phenomenon[1,2]
- Based on the GD analytical definition, this counterintuitive physical phenomenon occurs when the linear circuit or media structure differential phase presents a positive slope in function of the frequency[1,2]

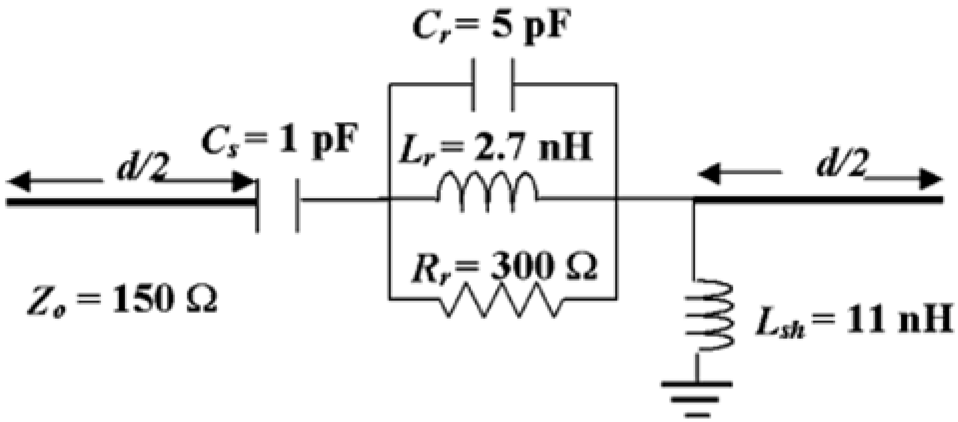


[1] S. Lucyszyn, I. D. Robertson and A. H. Aghvami, "Negative Group Delay Synthesiser," Electron. Lett., Vol. 29, 1993, pp. 798-800

[2] S. Lucyszyn and I. D. Robertson, "Analog Reflection Topology Building Blocks for Adaptive Microwave Signal Processing Applications," IEEE Trans. MTT, Vol. MTT-43, No. 3, Mar. 1995, pp. 601-611

A/ SoA on NGD circuits



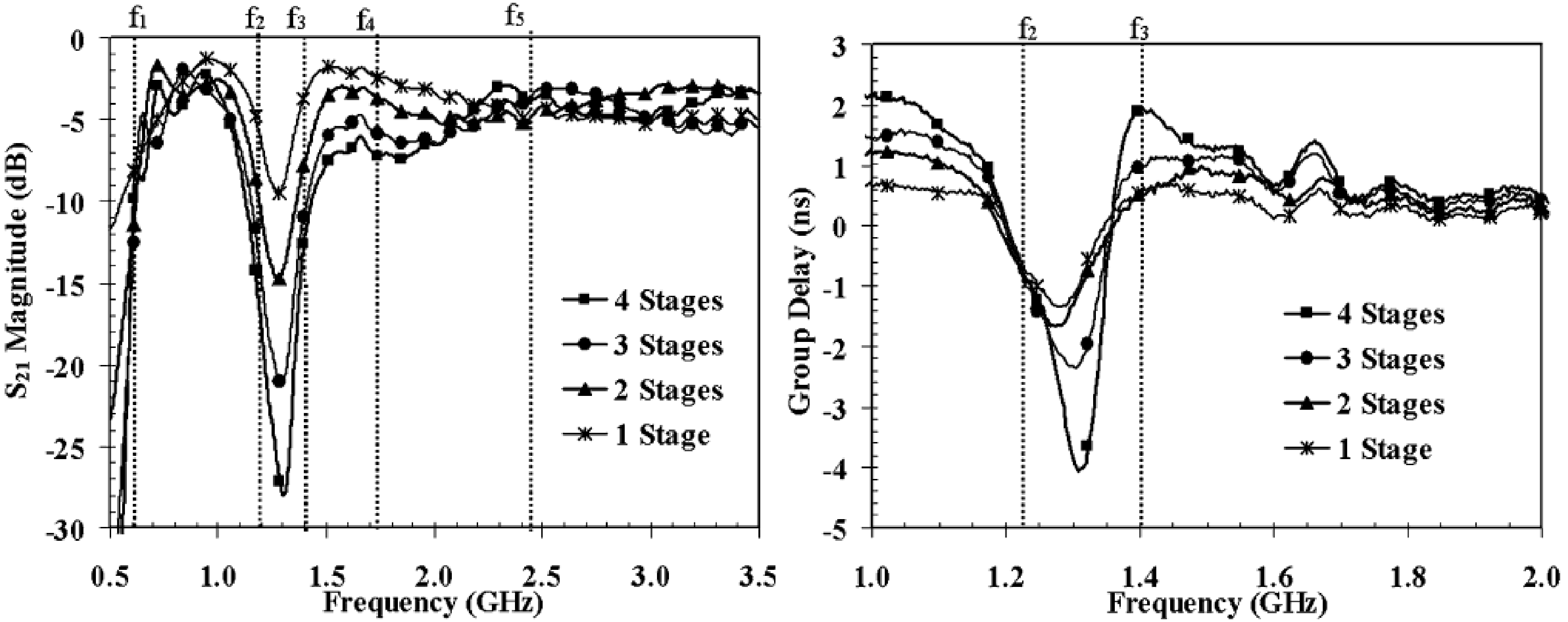


- In 2000s, more interests on NGD study was developed by using the TL and passive/active RF/microwave circuit theories
- The NGD electrical equivalent circuit[15,16,17] was established in function of the split ring resonator (SRR) physical and geometrical parameters by considering the transmittance
- The NGD distributed equivalent circuit[15,16,17] was established from physical dimension reduction 3-D-to-2-D and 2-D-to-1-D
- The equivalent NGD circuit constituted by classical R, L and C component elements was obtained from 1-D-to-0-D transpositions[15,16,17]

[15] O. F. Siddiqui, et al, IEEE T-AP, Vol. 51, No. 10, pp. 2619-2625, Oct. 2003
[16] G. V. Eleftheriades, et al, IEEE MWCL, Vol. 13, No. 2, Feb. 2003
[17] O. F. Siddiqui, et al, IEEE T-MTT, Vol. 52, No. 5, May, 2004

A/ SoA on NGD circuits

- Theoretical and experimental studies confirm the NGD effect at RF and microwave frequencies
- But, the periodical SRR-based structures operate with more than 20 dB attenuation in order to generate significant NGD values
- Therefore, research works were made on the development of low attenuation loss NGD circuits



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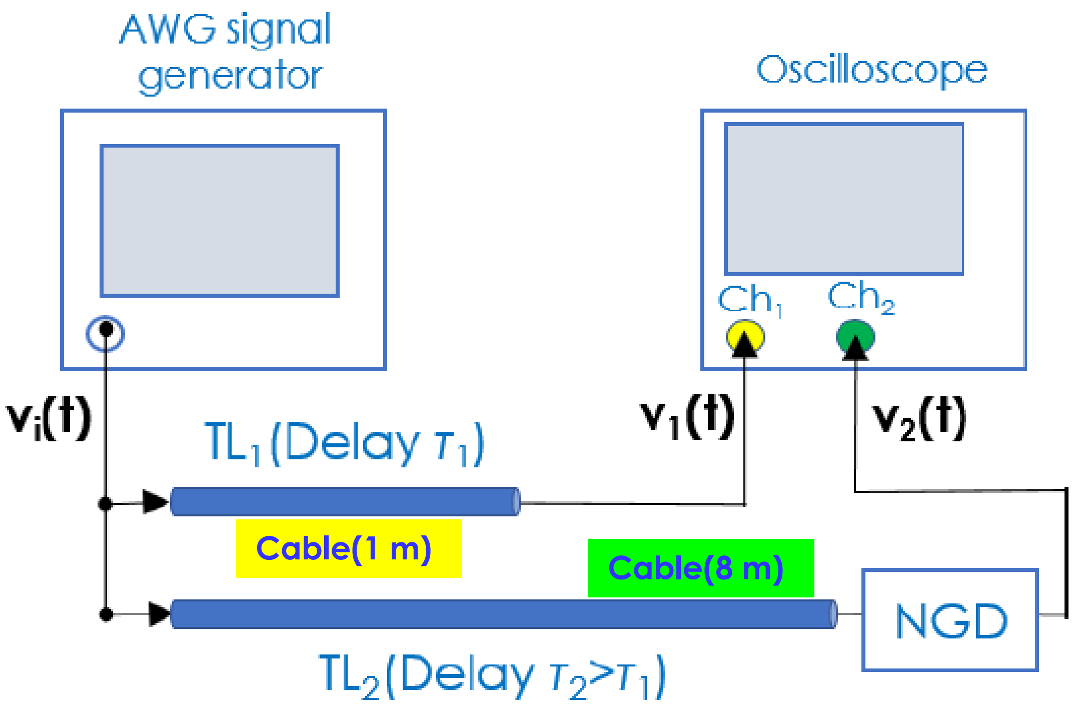
A/ SoA on NGD circuits

- The meaning and interpretation of NGD effect remain an open question to SI/EMC design and test engineers
- To highlight the meaning of negative time (t<0), some experimentations[1,2,3] were experimented at NUIST in early 2020s
- … Some demos of t<0 for reducing or cancelling out the **propagation delay** **(cable(8 m)+NGD) < *Delay*(cable(1 m))**



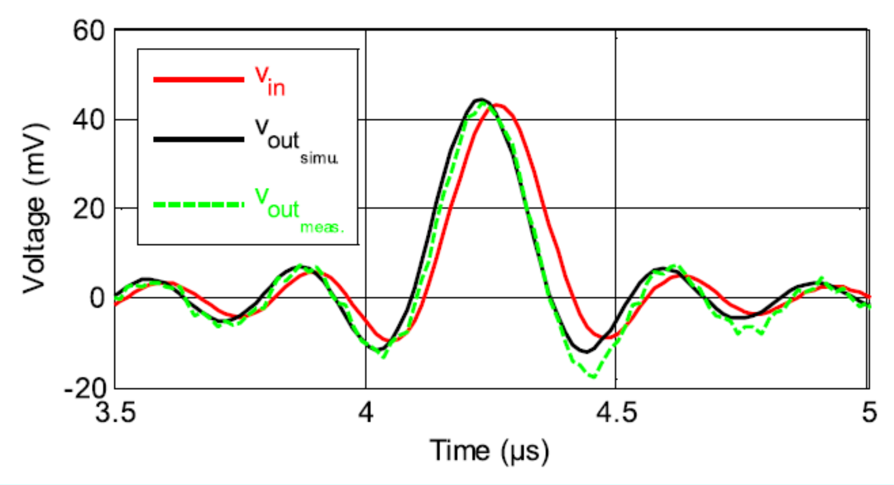
[1] F. Wan, T. Gu, B. Ravelo, B. Li, J. Cheng, Q. Yuan and J. Ge, "NGD Theory of a Four-Port RC-Network Feedback Operational Amplifier," IEEE Access, Vol. 7, No. 1, Dec. 2019

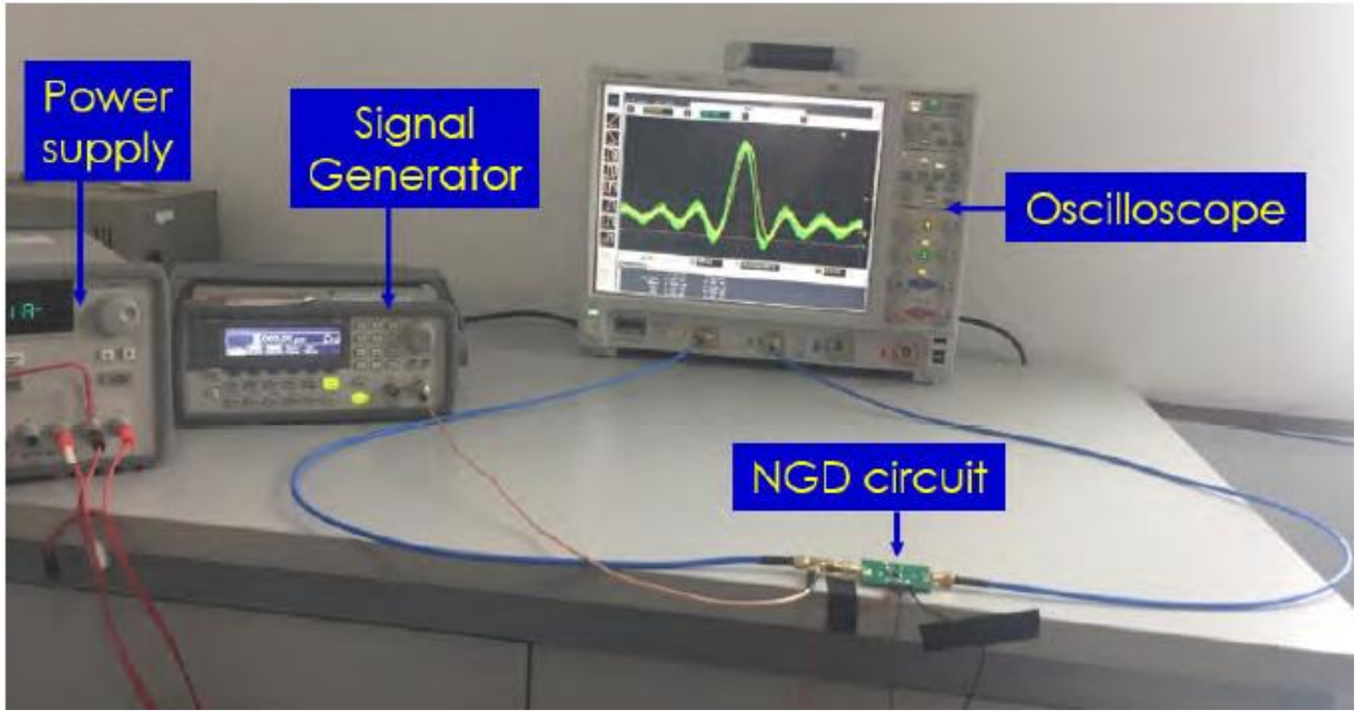
[2] F. Wan, X. Miao, B. Ravelo, Q. Yuan, J. Cheng, Q. Ji, and J. Ge, "Design of Multi-Scale NGD Circuit for Sensors Signal Time-Delay Cancellation," IEEE Sensors Journal, Vol. 19, No. 19, Oct. 2019

[3] F. Wan, J. Wang, B. Ravelo, J. Ge, and B. Li, "Time-Domain Experimentation of NGD Active RC-Network Cell", IEEE Trans. CAS II: Express Briefs, Vol. 66, No. 4, Apr. 2019

A/ SoA on NGD circuits

- Recent wonderful NGD experimentations[1,2,3]
  - Observation of *t*<0
  - ***Delay*(cable(8 m)+NGD) < *Delay*(cable(1 m))**





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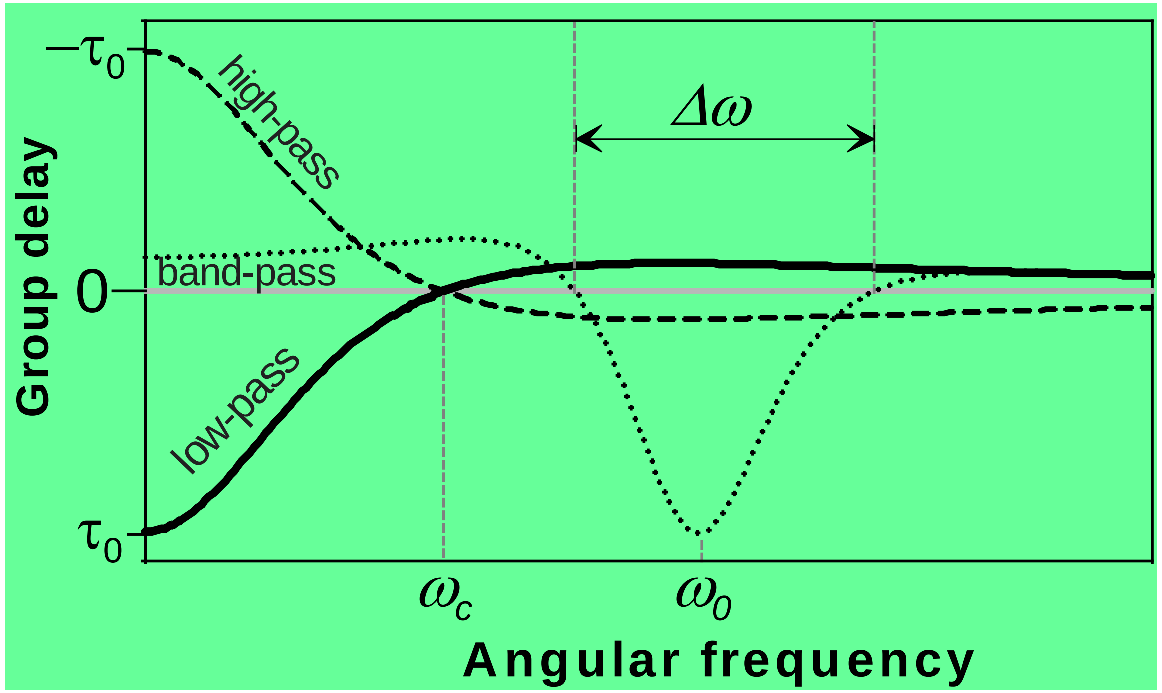
B/ NGD ideal specifications & design method

- An NGD design is necessary to democratize further the topic to all electronic design, fabrication, test and commerical engineers
- Elementary topologies of NGD cells were identified in function of the GD diagram and the NGD frequency band positionning
- By the analogy with the filter theory, the classes of NGD functions were initiated:
  - Low-pass (LP) NGD function
  - High-pass (HP) NGD function
  - **Bandpass (BP) NGD function**
  - Stop-band (SB) NGD function
  - All-pass (AP) NGD function



[1] B. Ravelo, "Methodology of elementary negative group delay active topologies identification," IET Circuits Devices Syst., May 2013

[2] B. Ravelo, "Similitude between the NGD function and filter gain behaviours," Int. J. Circ. Theor. Appl., Oct. 2014

B/ NGD ideal specifications & design method

B. Ravelo, "On the low-pass, high-pass, bandpass and stop-band NGD RF passive circuits," URSI Radio Science Bulletin, Vol. 2017, No. 363, Dec. 2017, pp. 10-27

<table>
<tr><th>Characteristics</th><th>Normal Filter</th><th>NGD Function</th></tr>
<tr><td>Basic specifications</td><td>Transfer function gain</td><td>Transfer function group delay</td></tr>
<tr><td>Cutoff frequencies ω_c</td><td>Root of the equation $\left|S_{21}(j\omega_c)\right| = \left|S_{21}(j\omega)\right|_{\max} / \sqrt{2}$</td><td>Root of the equation $\tau(\omega_c) = 0$</td></tr>
<tr><td>Bandwidth</td><td>$\left|S_{21}(j\omega_c)\right| \geq \left|S_{21}(j\omega)\right|_{\max} / \sqrt{2}$</td><td>$\tau(\omega) \leq 0$</td></tr>
<tr><td>Low-pass with bandwidth defined by $\omega \leq \omega_c$</td><td rowspan="4">In the bandwidth, we have $\left|S_{21}(j\omega_c)\right| \geq \left|S_{21}(j\omega)\right|_{\max} / \sqrt{2}$</td><td rowspan="4">In the bandwidth, we have $\tau(\omega) \leq 0$ and $\left|S_{21}(j\omega)\right|$ should be as flat as possible.</td></tr>
<tr><td>High-pass with bandwidth defined by $\omega \geq \omega_c$</td></tr>
<tr><td>Bandpass with bandwidth defined by $\omega_{c_1} \leq \omega \leq \omega_{c_2}$</td></tr>
<tr><td>Stop-band with bandwidth defined by $\omega \leq \omega_{c_1}$ and $\omega \geq \omega_{c_2}$</td></tr>
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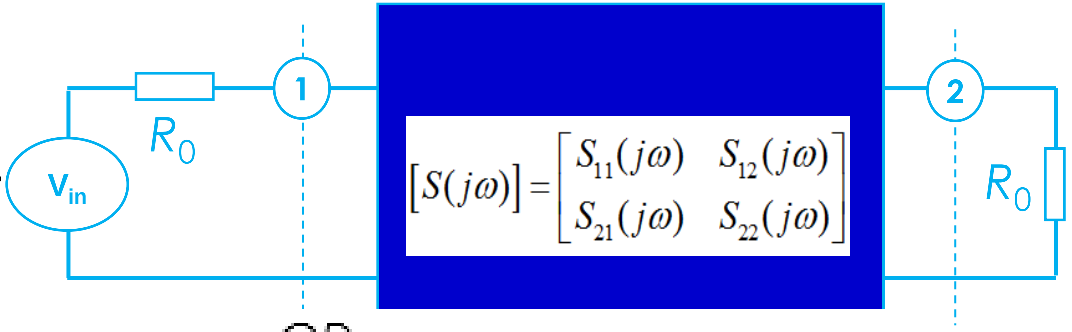
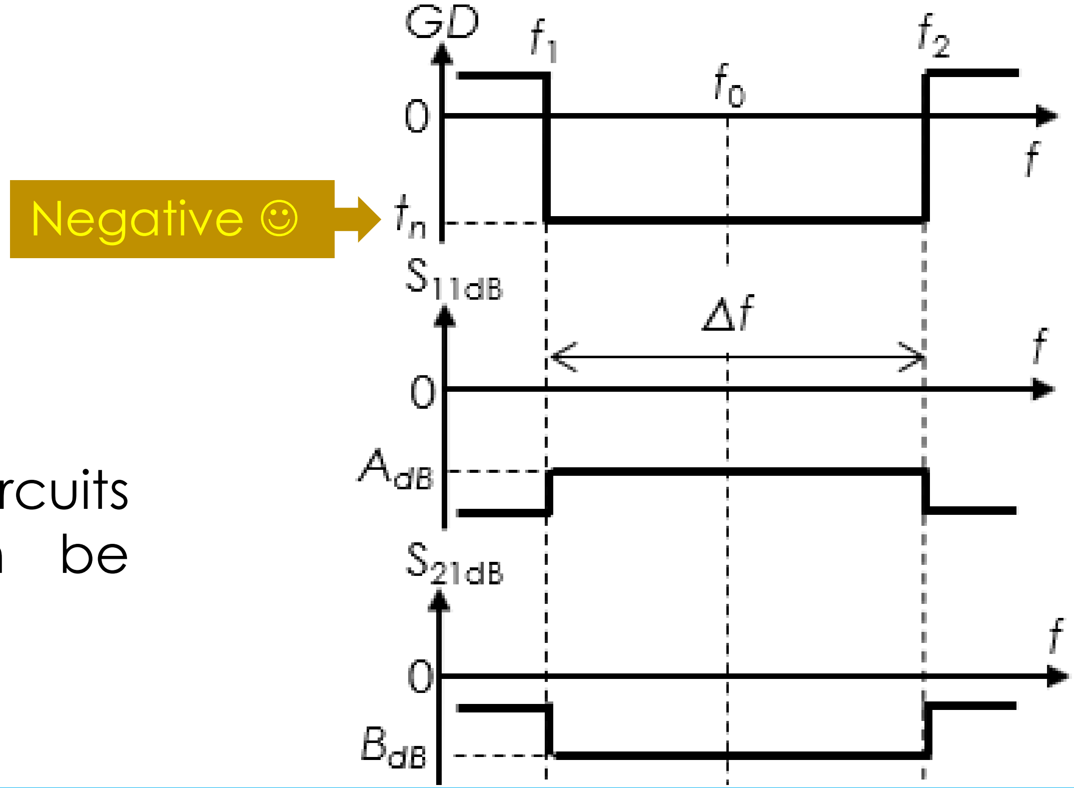
B/ NGD ideal specifications & design method



- The NGD specifications are defined from magnitude and GD diagrams
- BP-NGD circuit specifications:
  - ✓ NGD center frequency: f_0
  - ✓ NGD value: $t_n = GD(f_0) < 0$
  - ✓ Insertion loss: $|s_{21}(f_0)|$
  - ✓ Reflection losses: $|s_{11}(f_0)|$, $|s_{22}(f_0)|$
  - ✓ NGD bandwidth: $\Delta f = f_2 - f_1$
- BP-NGD NGD figure of merit (FoM) for passive circuits integrating these different parameters can be defined by: $FoM_{NGD} = t_n \cdot \Delta f \cdot \sqrt{(|s_{21}(f_0)| / |s_{11}(f_0)|)}$



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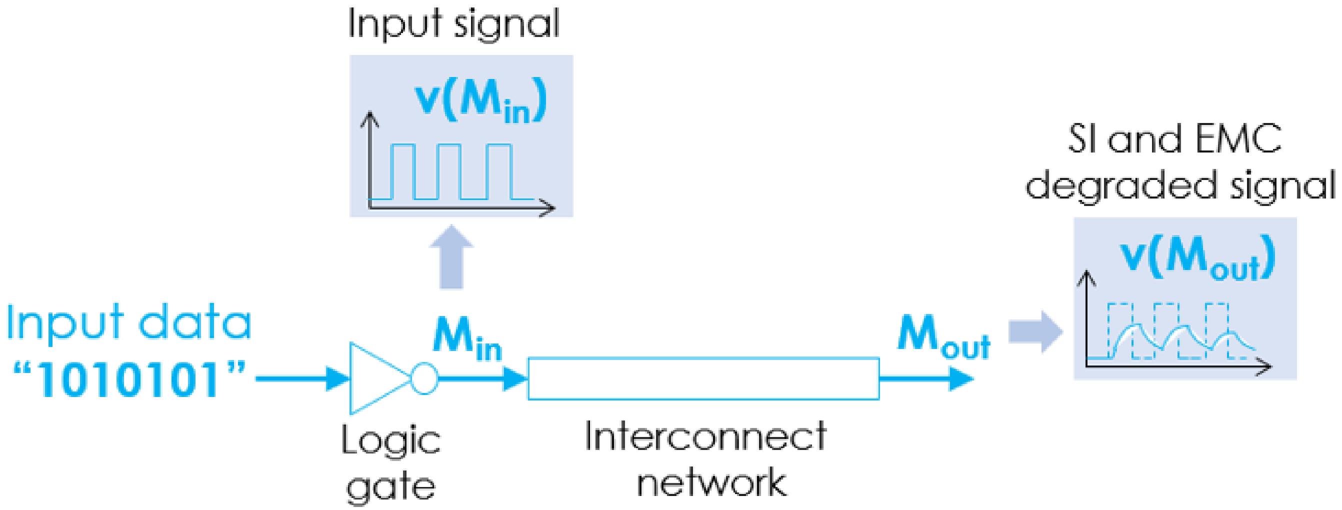
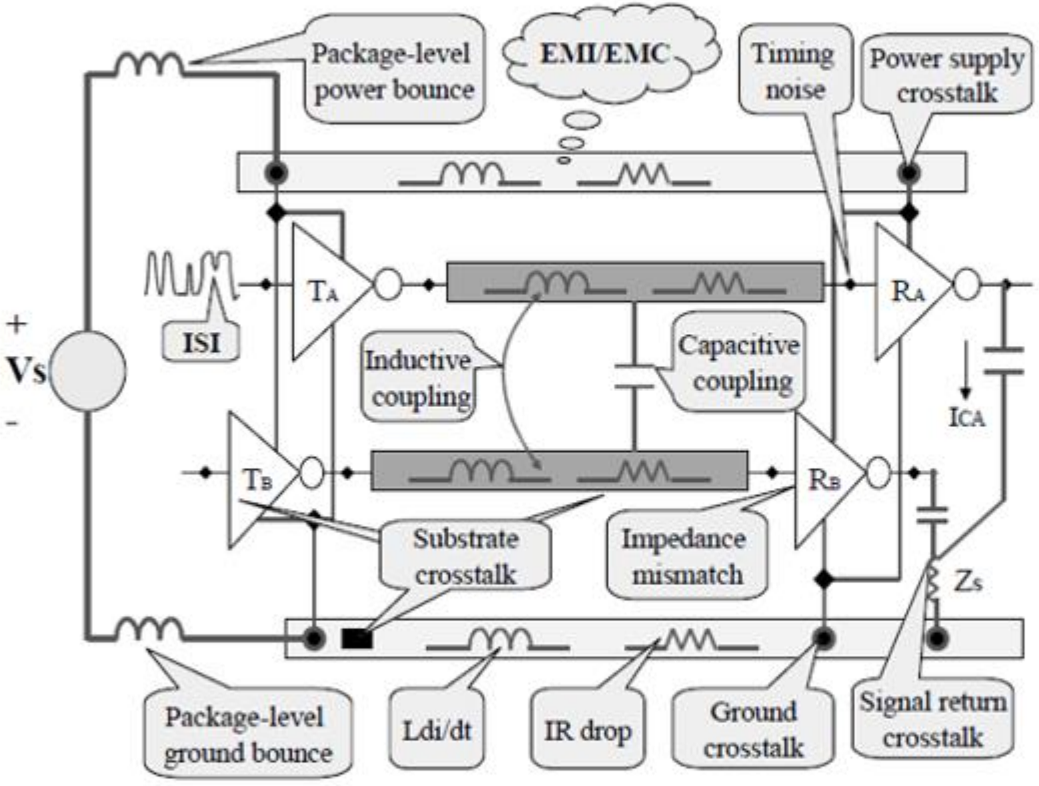
C/ Principle of NGD equalization

❑ How to minimize or cancel out the undesired EMC/EMI, SI and PI[1] effects in the high density as in the mixed circuits?

❑ In term of SI, we can underline that propagation delay and distortion may induce undesirable ISI and they limit the HDI circuit performance as the speed of operation data (***f_{max}<1/delay***)





[1] *L.-R. Zheng and H. Tenhunen, "Wires as interconnects", chap. 2, interconnect centric book, 2003*

C/ Principle of NGD equalization

Characterization of EMC and EMI perturbation VTF which causes the signal distortion

- The parasitic or perturbation is modelled by the VTF $T_p(s)$
- The input $v_{in}(t)$ is changed into output $v_p(t)$
- The corresponding VTF can be determined by $T_p(s)=V_p(s)/V_{in}(s)$

B. Ravelo, et al., "New Technique of Inter-Chip Interconnect Effects Equalization with NGD Active Circuits," VLSI, Chap. 20, Intech Book, Feb. 2010, pp. 409-434

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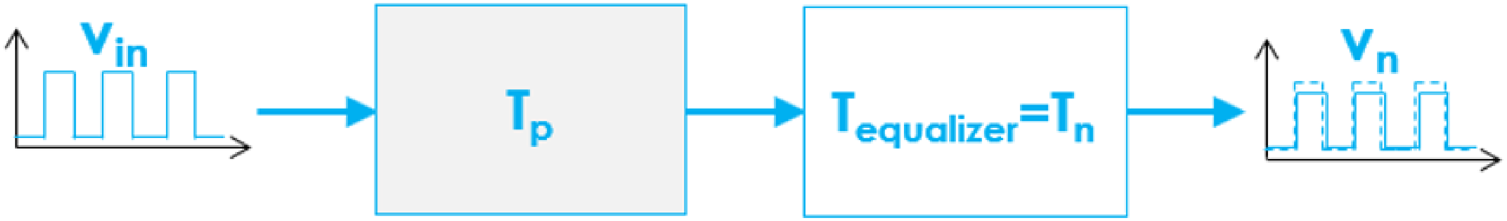
B. Ravelo, "Recovery of Microwave-Digital Signal Integrity with NGD Circuits," Photonics and Optoelectronics (P&O), Vol. 2, No. 1, Jan. 2013, pp. 8-16

C/ Principle of NGD equalization

- To obtain the equalization, we need to generate an output like the input
- It means that we can assume: $v_{out}(t) \approx v_{in}(t)$ ➔ $V_{out}(s) \approx V_{in}(s)$ ➔ $V_{out}(s)/V_{in}(s) \approx 1$
- As analytical solution, you need a function T(s) which verify: $T_p(s) \times T(s) = 1$
- The unique solution is a LP-NGD function



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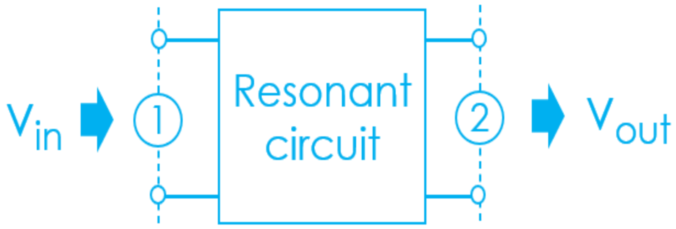

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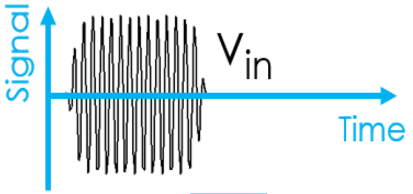

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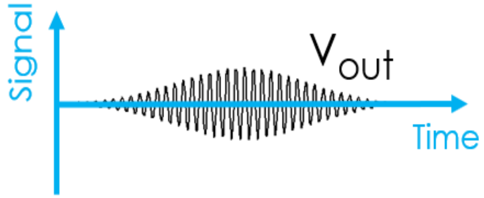

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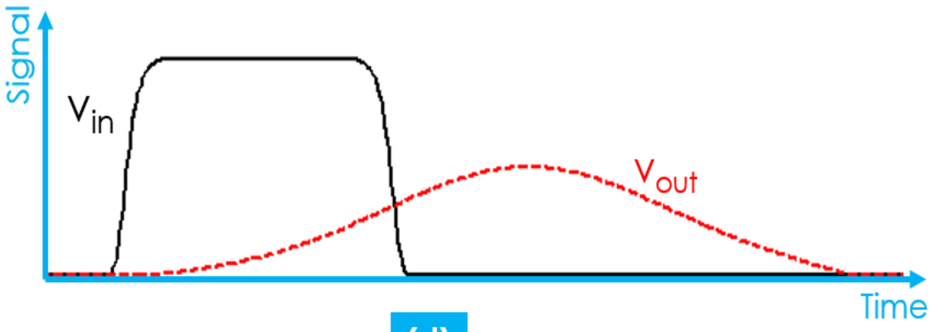


(d)

C/ Principle of NGD equalization

- ❑ S-parameter (SP) Laplace symbolic model with reference impedance R_0=50 Ω:

$$[S_r(s)]=[S_{11}(s)\ S_{12}(s);\ S_{21}(s)\ S_{22}(s)]$$

- ❑ For the time-domain analysis, we can assume the TF model which can be updated if we want to consider S_{11}:

$$TF(s)=S_{21}(s)=V_{out}(s)/V_{in}(s)$$

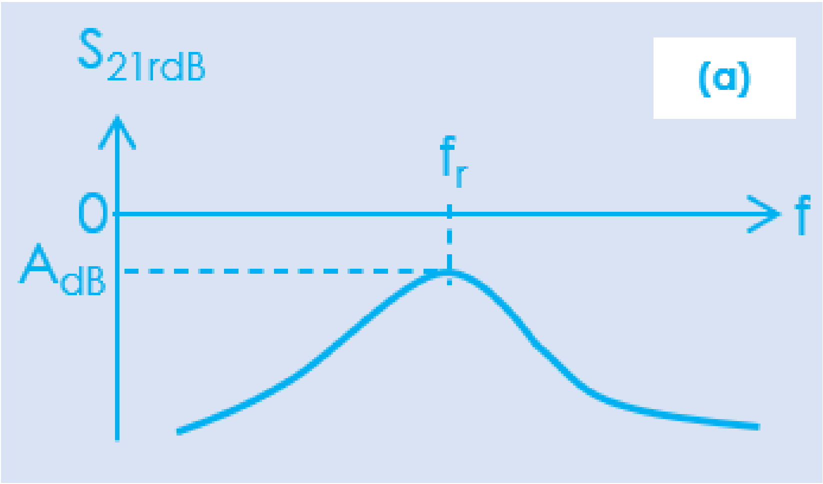
- ❑ And the GD model:

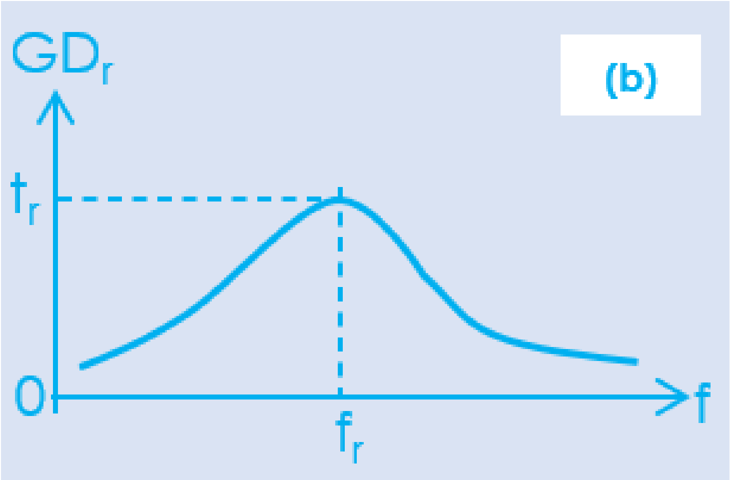
$$GD(f)=-\partial arg[TF(jf)]/(2\pi\partial f)$$

- ❑ Due to EMC/EMI resonance ➔ The signal integrity (SI) highlighted by transient response v_{out} can be degraded compared to vin
- ❑ We are looking for an analytic and design solution to deal on it

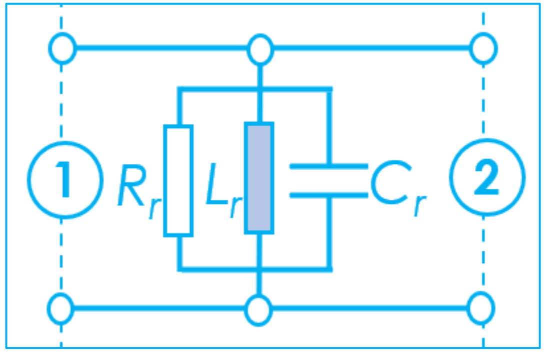
C/ Principle of NGD equalization

- In the frequency domain, the magnitude behavior can be characterized by $A_{dB} = S_{21rdB}(f_r)$
- … Similarity with the GD behavior characterized by $t_r = GD_r(f_r)$
- Such a behavior can be modelled by $R_rL_rC_r$ tank network characterized by:
  - ✓ Optimal frequency: $f_r = 1/[2\pi\sqrt{(L_rC_r)}]$
  - ✓ Peak: $A = 2R_r/(R_0+2R_r)$
  - ✓ GD: $t_r = 2R_0R_rC_r/(R_0+2R_r) > 0$





- The following synthesis equations can be demonstrated
  - ✓ $R_r = R_0A/[2(1-A)]$
  - ✓ $C_r = (0.5/R_0 + 1/R_r)t_r$
  - ✓ $L_r = 1/(4\pi^2 f_r^2 C_r)$



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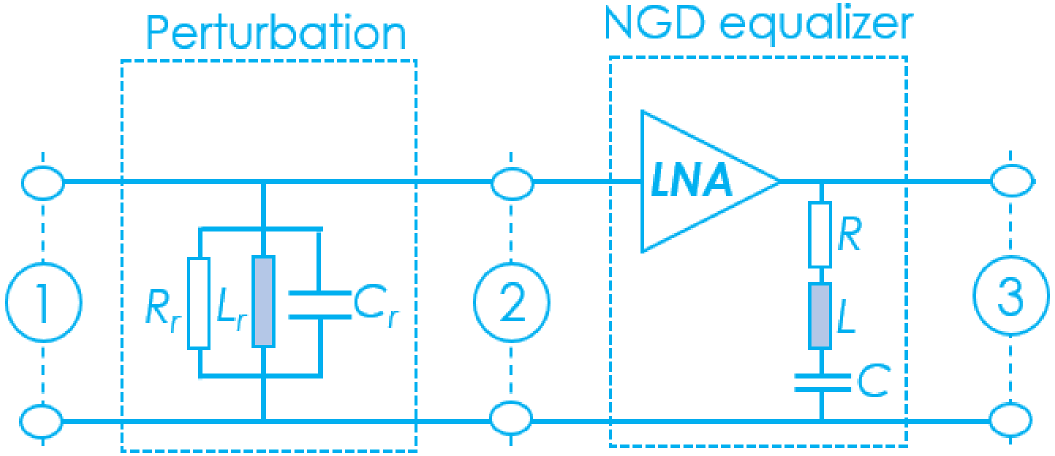
- ❑ The basic concept of NGD equalization is to find an suitable circuit able to reduce the degradation

- ❑ Analytical solution:
  - ✓ $S_{21r}(s) \times S_{21n}(s) \approx 1$ ➔ $S_{21n}(s) \approx 1/S_{21r}(s)$

- ❑ As we have $|S_{21r}(jf_r)|<1$ and $GD_r(f_r)>0$, the systemic solution should be:
  - ✓ Magnitude: $|S_{21n}(jf_r)| \approx 1/|S_{21r}(jf_r)|>1$
  - ✓ GD: $GD_n(f_r) \approx -GD_r(f_r)<0$
  - ✓ ➔ NGD active circuit (LNA+RLC series network) ☺



B. Ravelo, A. Perennec & M. Le Roy, "Study and Application of Microwave Active Circuits with Negative Group Delay", Microwave and Millimeter Wave Technologies Modern UWB antennas and equipment, Chap. 21, Intech Book, Mar. 2010, pp. 415- 439

B. Ravelo, "Recovery of Microwave-Digital Signal Integrity with NGD Circuits", Photonics and Optoelectronics (P&O), Vol. 2, No. 1, Jan. 2013, pp. 8-16

D/ Discussion on PoC result showing resonance reduction

- The NGD design equations are established from system:
  - ✓ NGD center frequency: $f_n=1/[2\pi\sqrt{(L_nC_n)}]$ by solving the equation $f_n=f_r$
  - ✓ Magnitude @ $f_n=f_r$: $|S_{21n}(jf_n)|\approx 1/A$
  - ✓ Or also by considering the access matching (for example r<-10 dB) @ $f_n=f_r$: $|S_{11n}(jf_n)|\approx r$
  - ✓ GD value: $GD(f_n)=-t_r$
- Therefore, we have the following design formulas:
  - ✓ $R=0.5(1/r-1)R_0$
  - ✓ $L=0.25(1-r)R_0t_r/r^2$
  - ✓ $C=r^2/[\pi^2f_r^2R_0t_r(1-r)]$
  - ✓ LNA gain $G=1/(A(1-r))$
- From the opposite GD: $GD_n(f_r)\approx -GD_r(f_r)<0$

  ➔ NGD circuit ☺

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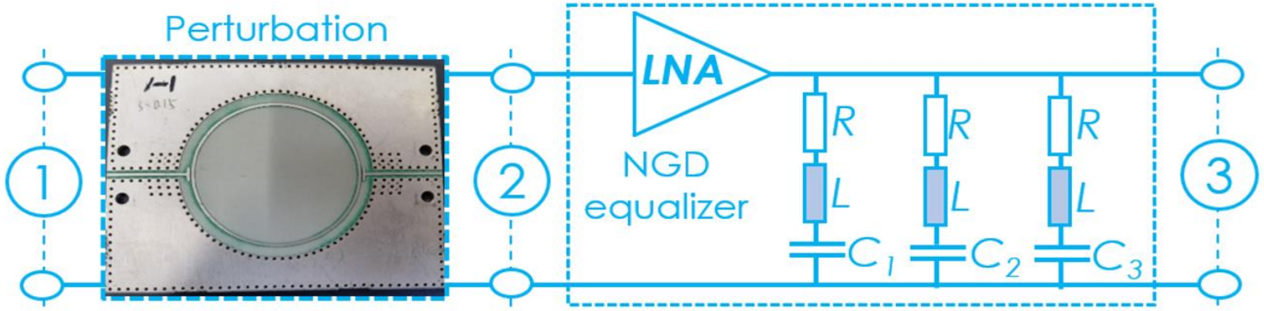
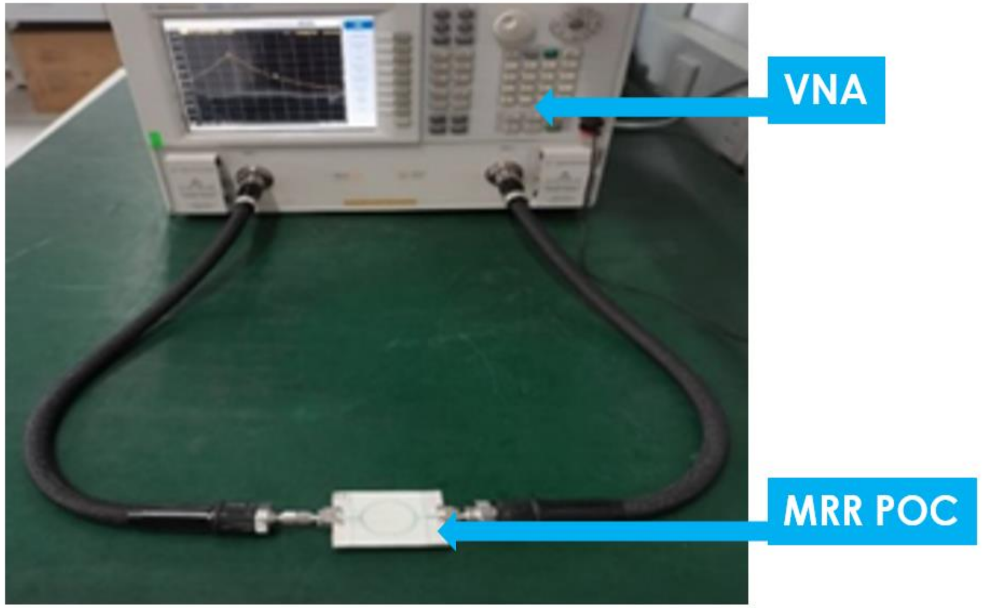
D/ Discussion on PoC result showing resonance reduction

- Design rule and different steps to implement an BP-NGD equalizer:
  - *Step 1: Definition of the dispersion effect (center frequency, bandwidth, peak of magnitude)*
  - *Step 2: Resonance equivalent circuit modelling*
  - *Step 3: BP-NGD topology identification*
  - *Step 4: BP-NGD equalizer synthesis*
  - *Step 5: POC with simulations*
  - *Step 6: Prototyping and fabrication*
  - *Step 7: Test and characterization*
- For the present work, we propose a POC with microstrip ring resonator (MRR) to be equalized with NGD active network composed by R, L and C lumped components

D/ Discussion on PoC result showing resonance reduction

- The POC is a MRR passive circuit constituted by a ring coupled to the access TL and the $R_rL_rC_r$ equivalent model was determined from measured S-parameters
- 3 cells of NGD circuits constituted by RLC_1, RLC_2 and RLC_3 parallel network were synthesized from the established design formulas
- The validation of resonance reduction was performed by SP simulation with ADS® commercial tool from Keysight Technologies®





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D/ Discussion on PoC result showing resonance reduction

- The MRR is modelled by $R_rL_rC_r$ corresponding resonance frequency, attenuation and delay indicated by the blue table
- The NGD circuit parameters as LNA gain, R, L and $C_{k=1,2,3}$ indicated by the green table were calculated from the synthesis formulas by optimizing the equalization effect

Constituting element	Parameter	Value
MRR physical size	Length×Width	57.34×46.2 mm
Substrate relative permittivity	ε_r	3.78
Conductor	Length	5 cm
	Width	0.56 mm
Ring resonator	Radius	14 mm
	Gap with access lines	0.1 mm
Resonator measured parameter	f_r	1.95 GHz
	A	-25.36 dB
	t_r	11.9 ns

Role	Component	Name	Value
Equivalent circuit	Resistor	R_r	1.43 Ω
	Inductor	L_r	1.5 pH
	Capacitor	C_r	4.43 nF
NGD	Resistor	R	149 Ω
	Inductor	L	1.77 µH
	Capacitor	C_1	3.75 fF
		C_2	3.77 fF
		C_3	3.74 fF
LNA	Gain	G	27.9 dB

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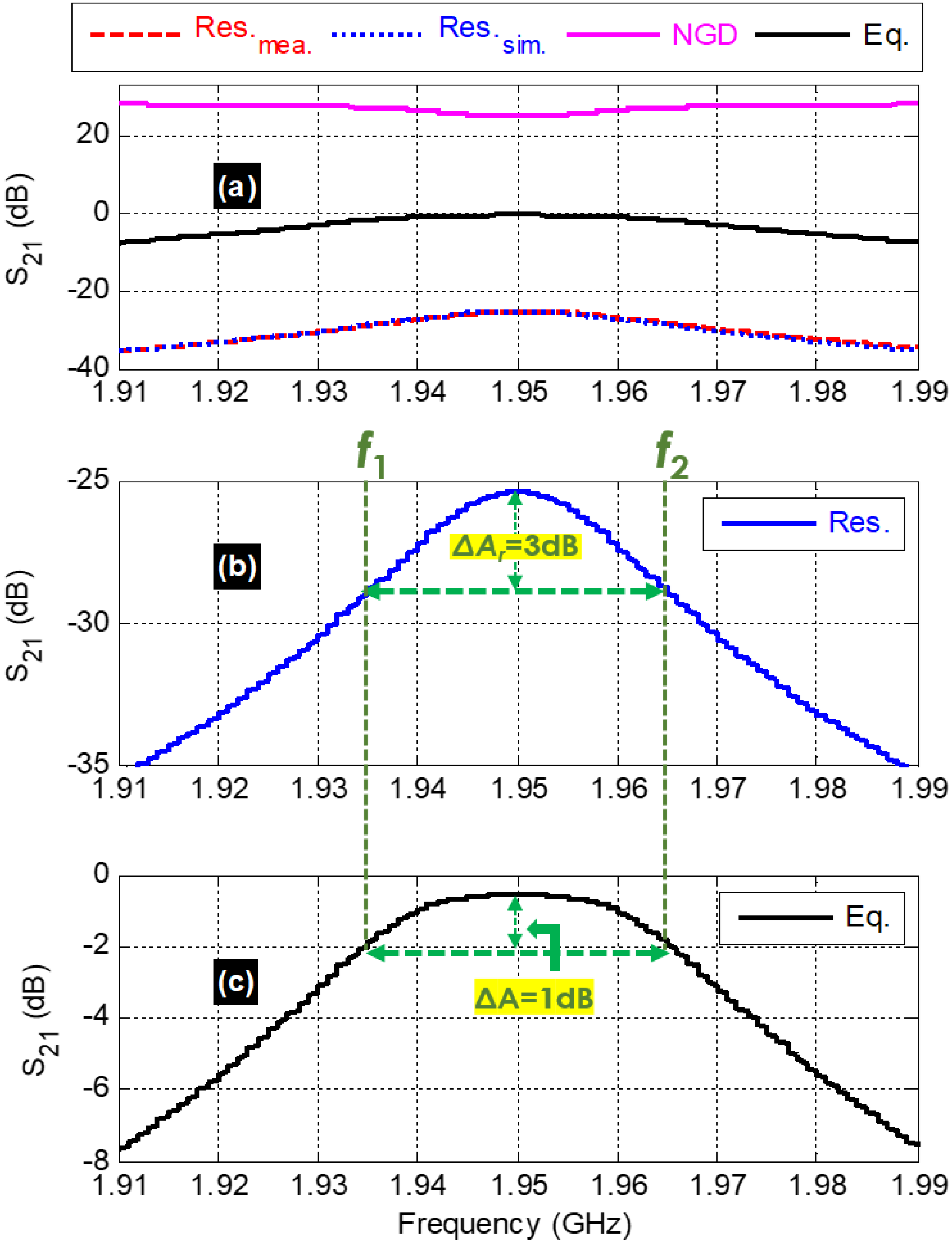

D/ Discussion on PoC result showing resonance reduction

- SP simulation from f_{min}=1.91 GHz to f_{max}=1.99 GHz was proposed
- The frequency domain validation of the NGD equalization method is illustrated by the transmission coeff. magnitudes ($S_{21Res.}$, S_{21NGD}, $S_{21Eq.}$)
- Thanks to the NGD-equalization, the transmission coefficient flatness in 3-dB bandwidth [f_1, f_2] with f_1=1.937 GHz and f_2=1.965 GHz is literally improved

POC	S_{21}	Value
MRR	$\max[S_{21r}(f_r)]$	-25.36 dB
	ΔS_{21r}	3 dB
NGD-MRR	$\max[S_{21}(f_r)]$	-0.5 dB
	ΔS_{21}	1 dB

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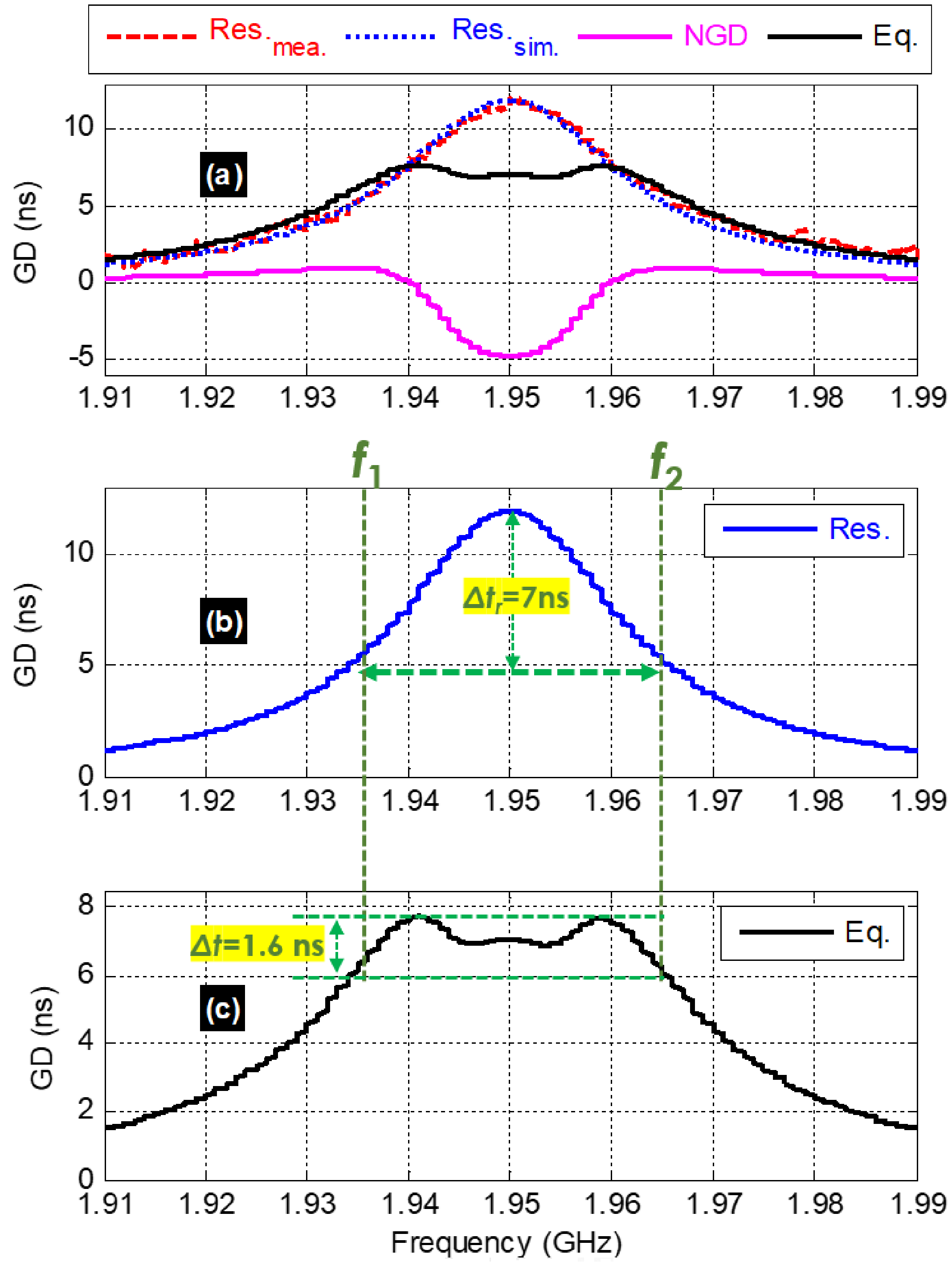

- ❑ The resonance effect NGD-equalization feasibility is confirmed by GD response from SP-simulation
- ❑ The measured and modelled MRR GDs are in very good correlation
- ❑ The GD comparison from resonator, NGD and combined both circuits underlines the flatness improvement notably within the resonator 3-dB bandwidth [f_1, f_2]

POC	GD flatness	Value
MRR	Δt_r	7 ns
NGD-MRR	Δt	1.6 ns

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D/ Discussion on PoC result showing resonance reduction

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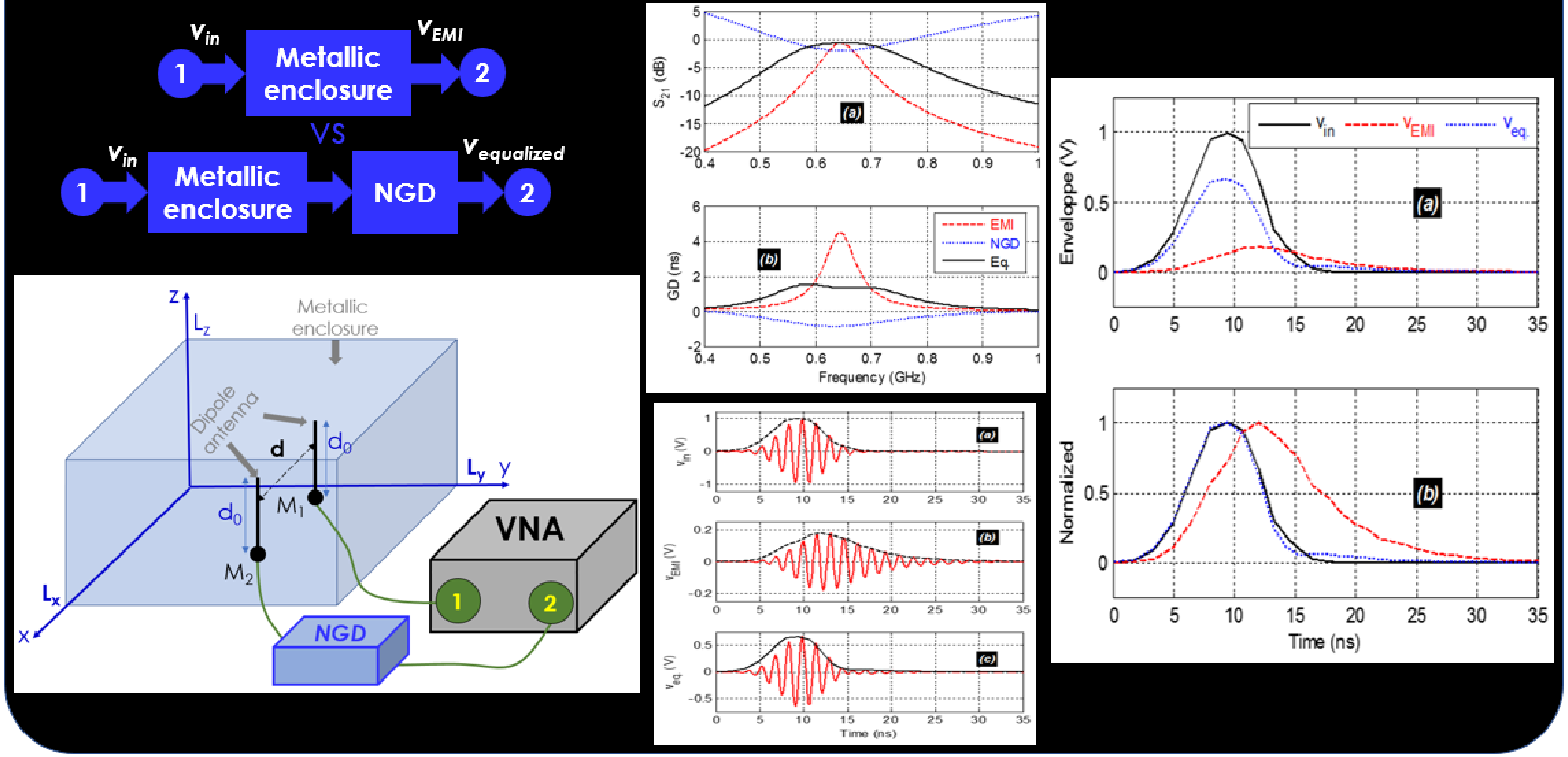
Metallic enclosure EMI resonance equalization with BP NGD function (IEEE TEMC 2021)



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E/ Conclusion

- 🕮 The SoA on design and experimentation of unfamiliar NGD circuits is overviewed. The BP-NGD theory and design method are presented. The NGD application in EMC/SI engineering for resonant circuit dispersion reduction principle is described.
- 🕮 An innovative feasibility study of microstrip structure resonance equalization with BP-NGD circuit is developed. The BP-NGD parameter formulation in function of resonance frequency, transmission coefficient peak and GD is introduced. The validity of the NGD-equalization method is verified with a POC of MRR passive circuit. The equalization result is confirmed with frequency responses of S_{21} and GD flatness.
- 🕮 As future work about the NGD-equalization, we are working on the development of IC NGD equalizer to be integrated in the PCBs victim of resonance effect. Our research group is currently developing 180-nm CMOS BP-NGD circuit to fabricate an IC-NGD prototype fulfilling the expected performance of resonance reduction.

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Thank you for your kind attention ☺☺☺☺☺

Questions / comments please

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