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## LITERATURE REVIEW ON RF AND MICROWAVE DESIGN OF PASSIVE MICROSTRIP CIRCUIT WITH BANDPASS TYPE NGD BEHAVIOR

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### ABSTRACT

Due to its counterintuitive aspects, the negative group delay (NGD) circuits remain an unfamiliar electronic function to majority of radio frequency (RF) and microwave design engineers. The present book chapter provides a literature review for non-initiated graduate students and non-specialist engineers to afford an overview about the recent research progress about the NGD microwave circuit design and the main roadmap on NGD future applications. A simple and fundamental NGD theory inspired from filter analogy was initiated. The types of low-pass (LP), high-pass (HP), bandpass (BP) and stop-band (SB) NGD specifications were defined. The NGD microwave passive circuit applications are still not widely developed because of their attenuation and reflection loss critical performances. Progressive research work was made the three-last decades to improve the RF and microwave NGD performances. One of the main challenges is the low attenuation loss NGD microstrip design susceptible to operate in the GHz range as L- and S-bands. This chapter reviews different designs of BP-NGD microstrip passive circuits. The BP-NGD specifications as NGD value, center frequency, bandwidth, attenuation and reflection losses are defined. The BP-NGD microstrip passive circuit design method in function of expected specifications is described. The BP-NGD performances of diverse topologies are compared.

**Key words:** Negative group delay (NGD), microstrip circuit, bandpass (BP) NGD specifications, BP-NGD design method, literature review.

# 1. INTRODUCTION

Some decades ago, particular engineering and scientific work efforts were paid on the development of the negative group delay (NGD) electronic circuit design with remarkable research results [1-79]. Indeed, it was outstandingly theoretically and experimentally demonstrated that the NGD circuits present a strange property of generating outputs in advance of its input [1-17]. Some of curious interpretations want to state that the NGD effect is like an impossible phenomenon or also classified as anomalous physical phenomenon. So, it is somehow hard for many engineers and researchers to believe the existence of such counterintuitive property. This finding is susceptible to limit also the development of NGD RF and microwave electronic and communication applications for many non-specialist engineering. So, many curious questions are still open about the understanding of assumed as mysterious NGD circuit engineering.

## 1.1. FUNDAMENTAL DEFINITIONS AND TYPES OF NGD CIRCUITS

Remarkable and outstanding research works need to be done about the understanding and interpretation of NGD circuit responses. Because of infinite diversity of NGD electronic circuit topologies, the simplest and fundament NGD circuit theory from similitude with the filter one was initiated [1-4]. In difference with the filter theory which is based on the magnitude frequency response, the NGD theory depends on the group delay (GD) diagram [1-4]. The types of low-pass (LP) [5-17], high-pass (HP) [18-23], bandpass (BP) [24-27], stop-band (SB) [28-29] and all-pass (AP) [30] NGD circuit topologies were introduced with R, L and C lumped components. Somehow, one may confuse NGD and filter behaviors. Table 1 indicates the main differences between these two electronic functions.

Table 1 – Technical notable differences between filter and NGD circuit behaviors [1-2]

Characteristics	Filter	NGD
<b>Cut-off frequencies</b>	Root(s) of transmission coefficient magnitude equation	Root(s) of GD equation
<b>Operation frequency bands</b>	Transmission coefficient magnitude higher than -3 dB	GD is negative
<b>Center frequency</b>	Harmonic average of filter operation frequency band	Harmonic average of NGD frequency band

## **1.2. STATE OF THE ART ON LP-NGD ELECTRONIC CIRCUITS**

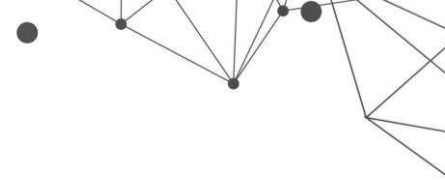
Like all electronic basic topologies, it is capital for the circuit design researchers to identify the simplest topologies satisfying the required specifications. To design LP-NGD circuit, the main specifications are the NGD value, NGD cut-off frequency and transmittance magnitude at very low frequencies [5-17]. All electronic circuit engineering design leads to the identification of elementary NGD circuit based on first order RC or RL network-based topologies [5-6]. Feedback network-based topologies operating with LP-NGD effect were also identified [7-8]. Miniature LP-NGD integrated circuits in CMOS technology was recently designed [9-10]. By playing on the circuit equivalent theory, some innovative LP-NGD circuit as via-hole based lumped circuit was designed [11]. It is noteworthy that the LP-NGD circuits are expected to operate with baseband signals [12-17].

## **1.3. STATE OF THE ART ON BP-NGD LUMPED CIRCUITS**

The basic understanding of BP-NGD behavior can be theoretically, numerically and experimentally investigated with lumped circuits [1-4, 24-27]. The initial validation of NGD behavior was performed with RLC-network based topologies as reported in [1-4, 24]. But thanks to the knowledge of LP- [5-17] and HP- [18-23] NGD behaviors, it was inspired from filter responses that BP-NGD circuit can be designed without use of inductance component [25]. Some unexpected innovative topologies of RC-network based bridged-T network were recently proposed [26-27]. However, because of attenuation loss and lumped component, research works have been made by RF and microwave engineers to develop microstrip topologies as introduced in the following paragraph.

## **1.4. STATE OF THE ART ON BP-NGD MICROSTRIP CIRCUITS**

The main challenge of BP-NGD RF and microwave circuit design [31-70] was the feasibility of topologies susceptible to operate with low-attenuation loss and also miniaturized sizes. The less expensive, theoretically, numerically and experimentally affordable solutions lead to the deployment of microstrip topologies [31-70]. Outstanding diversity of microstrip circuit topologies as based-on structures as stub terminated [31-32] and parallel interconnect line [33-39] was found. But the most significant NGD research work on microstrip circuit design is based on coupled interconnected line [40-54]. In order to optimize certain BP-NGD



performances as bandwidth, some mixed topologies as proposed in [55-56] were also designed. To compensate losses, BP-NGD active circuits using transistors or low-noise amplifier were introduced [59-64]. It was also investigated that there are possibilities to design multi-band BP-NGD circuits [64-66].

### **1.5. STATE OF THE ART ON BP-NGD TIME-DOMAIN MEASUREMENTS**

The NGD behavior interpretation is hardly understandable in the frequency domain. Therefore, time-domain investigation seems needed to answer to some curious questions. One of the most challenging tasks about the BP-NGD investigation are the time-domain measurements [67-70]. Modulated signals with BP-NGD center frequency as carrier is necessary to perform such experimentations. The final results should be the comparison of signal envelopes [67-70]. The main limit of current research results on the BP-NGD time-domain experimentation is on the consideration of high-speed signals used in 5G- and 6G-technologies.

### **1.6. STATE OF THE ART ON MULTI-PORT NGD CIRCUITS**

At the beginning, all the research work on LP-, HP- and BP-NGD circuit design was focused on two-port topologies [1-70]. In the past two year, more general topologies of NGD circuit with multi-port accesses were performed [71-78]. The design feasibility was verified with three-port topologies as Y- or T-shape circuits [71-74]. The BP-NGD function was also verified with  $\Delta$ -shape lumped circuit [75]. More complex topologies as H-shape circuits were proposed [76-77]. Compared to filter, power combiner and power divider, the multi-port NGD design remains a non-explored field. A lot of research work are expected in the future to the design and experimentation techniques of NGD multi-port circuits. But before this challenging study, the present chapter is devoted on the illustrative literature review of BP-NGD circuit design.

### **1.7. OUTLINE OF THE CHAPTER**

The present chapter is focused on the literature review of BP-NGD microstrip circuit design. For the basic understanding of counterintuitive circuits, we propose three different sections:

- Section 2 describes the S-parameter modelling approach and design methodology of BP-NGD microstrip circuit. The proposed approach permits to guide the beginners to identify the NGD RF and microwave circuit topologies.

The fundamental knowledge for RF and microwave engineering graduate students, engineers and researchers is dedicated.

- Once the NGD circuit topologies are correctly identified, the verification of NGD effect is always a critical task for the NGD circuit design researchers. Section 3 introduces different RF and microwave validation results of different microstrip circuit topologies. Various microstrip circuit proofs of concept (POC) are described. The validations are based on comparison between simulated and measured GDs. For the better comprehension, the chapter section is only focused on the passive microstrip circuit.
- Against the signal time-delay issues in printed circuit boards (PCBs) [78-79], Section 4 presents some tentative potential applications of NGD circuits [80-113] especially in electronic and communication engineering.
- Last section 5 is the conclusion of the chapter.

## 2. DESIGN METHODOLOGY OF BP-NGD MICROSTRIP CIRCUIT

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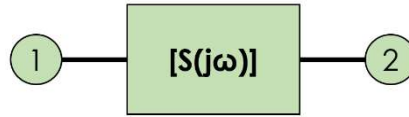
The design method of BP-NGD microstrip circuit must be performed with good knowledge of S-parameter analysis. Somehow, the analytical modelling is quite complex. However, there are still possibilities to perform simulations especially with 2-D or 3-D structures. The measurements must be performed with vector network analyzer (VNA).

### 2.1. S-PARAMETERS AND GD MODELLING

The S-parameter analyses are traditionally performed in the frequency domain. High level mathematic skills associated to circuit and system (CAS) fundamental knowledge, are needed to develop RF and microwave NGD circuit theory and analytical modelling. Doing this, let us denote  $\omega$  the angular frequency variable. For the two-port RF and microwave circuits as represented by the black box of Fig. 1, the S-parameter model can be represented by 2-D matrix:

$$[S(j\omega)] = \begin{bmatrix} S_{11}(j\omega) & S_{12}(j\omega) \\ S_{21}(j\omega) & S_{22}(j\omega) \end{bmatrix} \quad (1)$$

Figure 1 – Two-port S-parameter black block [31-58]



For the case of symmetrical circuit, we have reflection and transmission coefficients as complex number:

$$S_{11}(j\omega) = S_{22}(j\omega) = \text{Re}[S_{11}(j\omega)] + j \cdot \text{Im}[S_{11}(j\omega)] \quad (2)$$

$$S_{12}(j\omega) = S_{21}(j\omega) = \text{Re}[S_{21}(j\omega)] + j \cdot \text{Im}[S_{21}(j\omega)] \quad (3)$$

To characterize the NGD RF and microwave circuit, we need:

- the traditional reflection and transmission coefficient magnitudes:

$$|S_{11}(j\omega)| = \sqrt{\text{Re}[S_{11}(j\omega)]^2 + \text{Im}[S_{11}(j\omega)]^2} \quad (4)$$

$$|S_{21}(j\omega)| = \sqrt{\text{Re}[S_{21}(j\omega)]^2 + \text{Im}[S_{21}(j\omega)]^2} \quad (5)$$

- The transmission phase associated to expression (3) is defined as:

$$\varphi(\omega) = \arg[S_{21}(j\omega)] \quad (6)$$

- But the capital analysis should be performed with the less familiar expression of GD defined by:

$$GD(\omega) = -\partial\varphi(\omega) / \partial\omega \quad (7)$$

These basic definitions enable to explore the microstrip circuit NGD specifications as described in the following paragraph.

## 2.2. NGD SPECIFICATION DIAGRAM

In addition to the Bode diagrams, we should consider the GD frequency domain diagram to practice NGD RF and microwave electronic engineering. Figs. 2 depict all the essential parameters constituting the unfamiliar BP-NGD specifications.

Figure 2 – BP-NGD (a) GD, (b) reflection and (c) transmission parameter specifications [2-58]

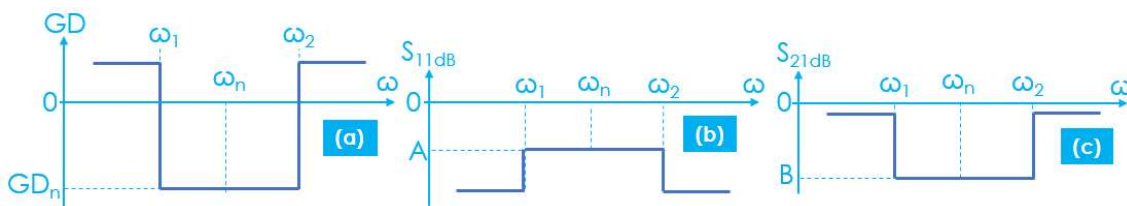


Fig. 2(a) shows the ideal GD diagram of BP-NGD ideal RF and microwave circuit. The diagram of Fig. 2(c) indicates the main NGD specifications as GD center frequency  $f_n = \omega_n / (2\pi)$ , NGD value  $GD_n$  and NGD frequency bandwidth  $[\omega_1, \omega_2]$  which are analytically given by:

- where we have the GD value:

$$GD_n = GD(\omega_n) < 0 \quad (8)$$

- The NGD cut-off frequencies  $\omega_1$  and  $\omega_2$  are the root of equation:

$$GD(\omega) = 0 \quad (9)$$

- The NGD cut-off frequencies  $\omega_1$  and  $\omega_2$  are the root of equation:

$$GD(\omega) = 0 \quad (10)$$

In the given NGD frequency band  $[\omega_1, \omega_2]$ , the BP-NGD circuit should operate with respect to all classical RF and microwave device requirements. For example, the reflection and transmission coefficients can be ideally represented as shown in Fig. 2(b) and in Fig. 2(c), respectively. Given the specifications denoted  $A$  for the matching condition (which is generally equal to -10 dB), we should verify:

$$|S_{11}(j\omega)| < A \quad (11)$$

Given the maximal attenuation loss, we should verify:

$$|S_{21}(j\omega)| > B \quad (12)$$

### 2.3. NGD DESIGN ROUTINE METHODOLOGY

Like all classical electronic circuits, the BP-NGD circuits can be designed with a relevant method. The design methodology of BP-NGD microstrip circuit can be started from the required specifications. In the present chapter, we are focusing only to the case of two-port microwave circuits. It means that the simulations and measurements should generate the S-matrix introduced in equation (1). To start, it is particularly important for the NGD design engineers to have a good knowledge of microstrip technology of the microstrip transmission line (TL) structure displayed in Fig. 3. Then, the NGD circuit (NGDC) design engineer must choose the topology corresponding to the application requirements. The different stages of analysis from ideal to realistic situations must be investigated. Mathematical analyses are one of the most critical tasks in this stage. However, S-parameter simulations of the microstrip structures can also be performed with commercial software tools as ADS® from Keysight Technologies or HFSS® from ANSYS® or CST MWS from



DASSAULT SYSTEM®. The specifications indicated in Figs. 2 must be extracted after simulations. The main task behind is to determine the good geometrical parameters and physical shape of the structure allowing to get the optimal results in the expected operating frequency band.

Figure 3 – 3-D design of microstrip transmission line with physical length  $d$  and width  $w$  having substrate thickness  $h$  under metallization thickness  $t$  [31-58]

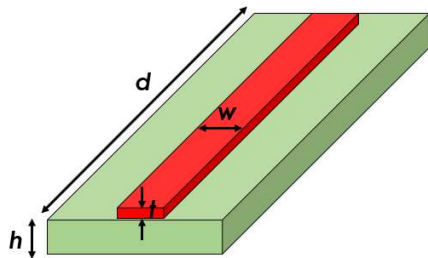
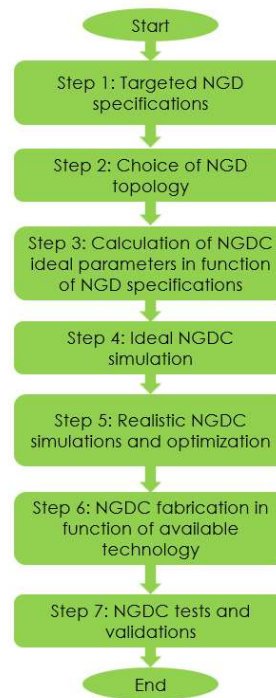


Figure 4 – Design flow of BP-NGD microstrip circuit [31-58]



To summarize the different tasks of the BP-NGD design, we proposed the design flow shown in Fig. 4. For further understanding on the application results of this design flow, simulation and experimental results of different BP-NGD microstrip circuits from literature are described in the following section.

### 3. SIMULATION AND EXPERIMENTATION OF BP-NGD MICROSTRIP CIRCUITS

The present section describes examples of BP-NGD validation results from literature review. Different microstrip structures designed following the routing methodology of Fig. 4 are considered.

#### 3.1. RLC-NETWORK PASSIVE CIRCUIT-BASED BP-NGD DESIGN

The BP-NGD behaviors were investigated with resonant RLC-networks composed of R, L and C lumped components [1-4]. For the fundamental understanding and to develop solid skills, it is worth to recommend NGD design

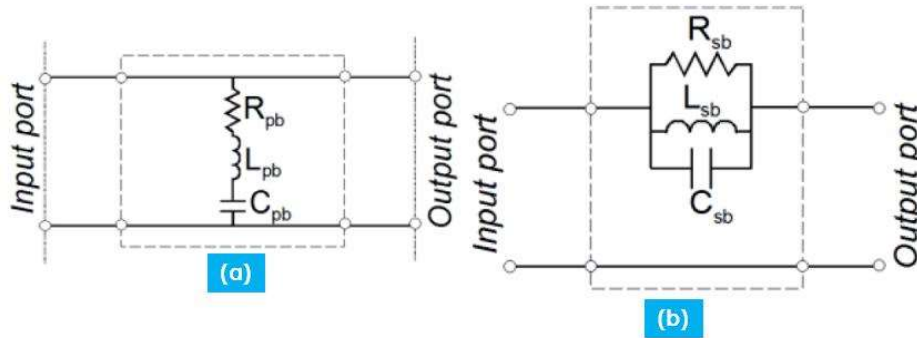
engineer beginners to start to elaborate the NGD model of these RLC-network topologies.

### 3.1.1. NGD THEORETICAL APPROACH

The simplest topologies of that circuits with RLC-series and RLC-parallel networks are displayed in Fig. 5(a) and Fig. 5(b), respectively. For both topologies, we can assume that the NGD center frequency as:

$$\omega_n = 1 / \sqrt{LC} \quad (13)$$

Figure 5 – BP-NGD RLC (a) series and (b) parallel network topologies [2]



At this frequency, it was theoretically demonstrated that [2]:

- For the BP-NGD RLC topology shown in Fig. 5(a), the reflection, transmission coefficients and GD become:

$$|S_{11}(j\omega_n)| = R_0 / (R_0 + 2R_{pb}) \quad (14)$$

$$|S_{21}(j\omega_n)| = 2R_{pb} / (R_0 + 2R_{pb}) \quad (15)$$

$$GD(\omega_n) = -2R_0L_{pb} / [R_{pb}(R_0 + 2R_{pb})] \quad (16)$$

- For the BP-NGD RLC topology shown in Fig. 5(b), the reflection, transmission coefficients and GD become:

$$|S_{11}(j\omega_n)| = R_{sb} / (2R_0 + R_{sb}) \quad (17)$$

$$|S_{21}(j\omega_n)| = 2R_0 / (2R_0 + R_{sb}) \quad (18)$$

$$GD(\omega_n) = -4R_{sb}C_{sb} / (2R_0 + R_{sb}) \quad (19)$$

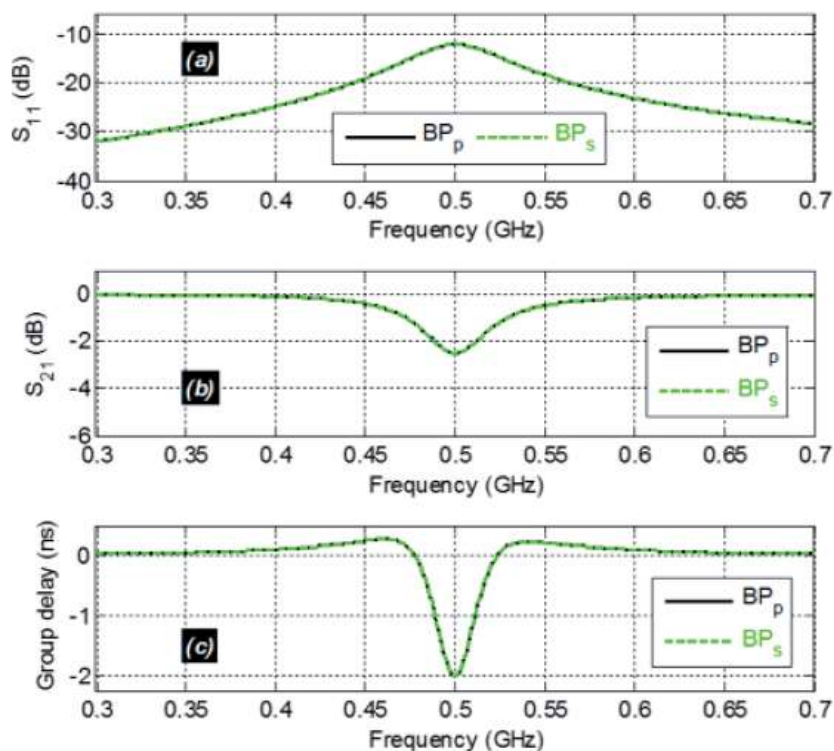
We can underline that the GDs are always negative for both RLC-resonant topologies. This finding simplifies the design feasibility during the circuit study.

### 3.1.2. NGD VALIDATION

Following the synthesis formulas of each constituting components by taking  $f_n=0.5$  GHz,  $GD_n=-2$  ns and  $S_{21}(f_n)=-3$  dB, we can design a proof-of-concept. Figs. 6(a) show the GD responses from 0.3 GHz to 0.7 GHz.

As expected, we can emphasize here that we have  $GD(f)<0$  around  $f_n$ . This means that the considered circuit behaves as a BP-NGD function. Moreover, we can see also that the transmission coefficient presents an attenuation exactly equal to the expected requirement. Then, the reflection coefficients in the NGD frequency are lower than -10 dB. It is interesting to get the BP-NGD designability with such topologies but they are not always working for certain cases above GHz frequency range because of the reactive component manufacturing. As solution against such technological limitations, we can use distributed circuits as based on microstrip technologies.

Figure 6 – BP-NGD responses from topologies shown in Fig. 5 [2]

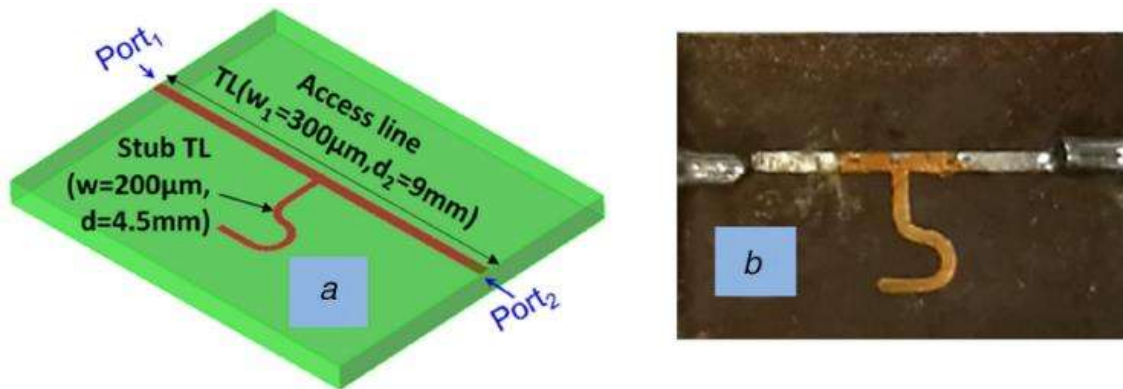


### 3.1.3. BP-NGD OPEN STUB CIRCUIT-BASED DESIGN [31]

Based on the TL theory, we have an equivalent between RLC-series network and open-ended stub. This is one main idea allowing to design microstrip circuits

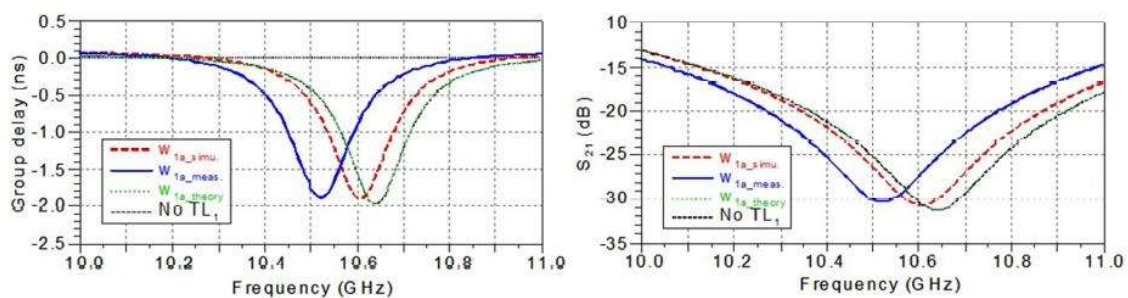
equivalent to the RLC topology introduced in Fig. 5(a). The 3-D design solution and the prototype photograph are presented in Fig. 7(a) and Fig. 7(b), respectively.

Figure 7 – Open-stub BP-NGD microstrip circuit: (a) 3-D design and (b) prototype photo [31]



This microstrip circuit was implemented on Kapton substrate with copper metallization. The validation study of the open-ended stub circuit was performed from 10 GHz to 11 GHz. In left of Fig. 8, we have the GD diagram of the compared simulation and measurement. In right of Fig. 8, we have the transmission coefficient magnitude. We emphasize that the open-ended circuit is significantly lossy up to more than 30 dB attenuation around the NGD center frequency. To limit the attenuation loss, different other microstrip topologies were explored with results presented in the following subsections.

Figure 8 – Compared simulated and measured (in left) GD and  $S_{21}$  (in right) of open-stub circuit shown in Fig. 7 [32]

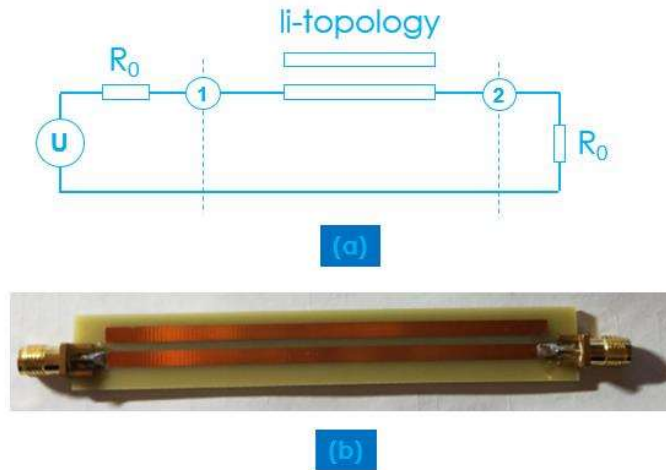


### 3.1.4. BP-NGD “LI” MICROSTRIP CIRCUIT DESIGN [40]

The li-topology is a distributed circuit constituted by coupled line (CL) as displayed by Fig. 9(a). To study the design feasibility and the BP-NGD behavior, a POC is needed. Accordingly, a prototype of the fabricated li-microstrip circuit is presented by the photograph of Fig. 9(b). It acts as two pieces of straight microstrip lines placed in proximity. Before early 2020, this simple TL based distributed

topology was quite familiar and well-known by RF and microwave design engineers. But we should emphasize that by curiosity, few of them were aware of its BP-NGD responses.

Figure 9 – (a) li-topology and (b) photograph of microstrip circuit prototype [40]



This prototype was designed and implemented on FR4 substrate under copper strip metallization. Because of the EM coupling between them we have again the BP-NGD effect.

Figure 10 – Mapping's of (a) GD, (b)  $S_{21}$  and (c)  $S_{11}$  of the li-circuit shown in Fig. 9 [40]

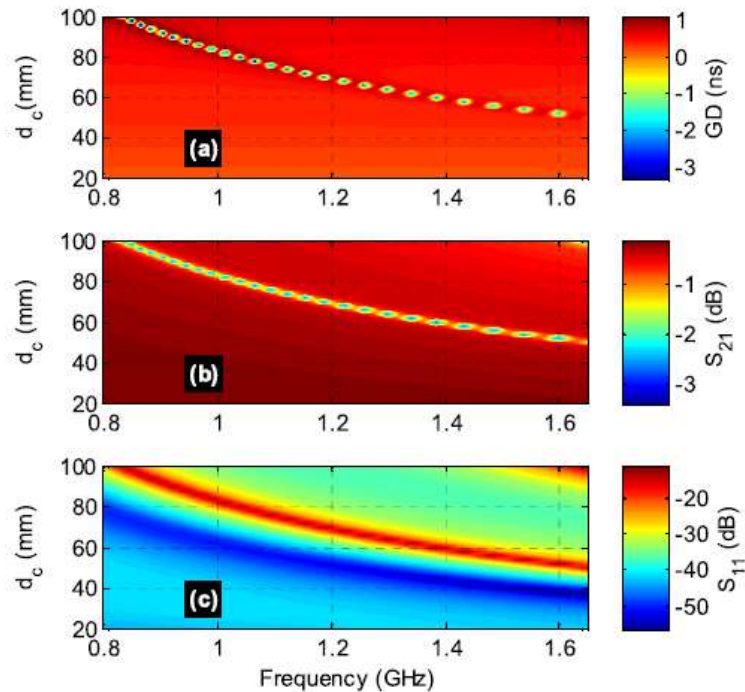
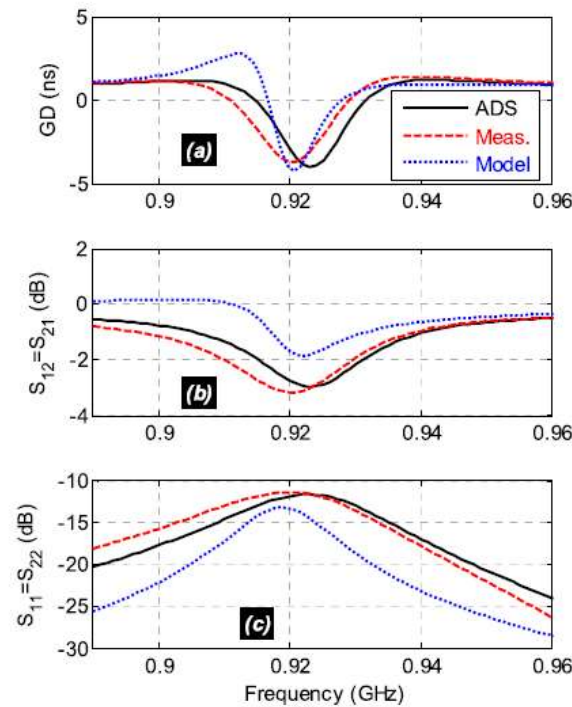


Figure 11 – Calculated, simulated and measured (a) GD, (b)  $S_{21}$  and (c)  $S_{11}$  of the li-circuit shown in Fig. 9 [40]



To understand the effect of the length ( $d_c$ ) on the NGD responses, parametric S-parameter analyses were performed. Fig. 10 presents the obtained results in the operating frequency chosen from 0.8 GHz to 1.62 GHz. It can be seen that the NGD center frequency is inversely proportional to  $d_c$ . The comparison of simulated and experimented results shown in Figs. 11 confirms that we have again the BP-NGD behavior with center frequency around 0.92 GHz.

### 3.1.5. BP-NGD “10” MICROSTRIP CIRCUIT DESIGN

Substituting the “i”-shape element of previously described “li” structure by “0”-shape element, we have a “10” microstrip topology presented in Fig. 12(a). The two-cell design of such topology is displayed in Fig. 12(b). We can see in Fig. 12(c) the photograph of the experimental setup using a VNA. Fig. 13(a) depicts that the 10 circuit behaves also as a BP-NGD function. The NGD absolute value is increasing with the number of cells. In this case of study, the attenuation loss around the NGD center frequency is around 4 dB.

Figure 12 – (a) Single and (b) double cell “10”-microstrip circuits, and (c) Experimental setup [44]

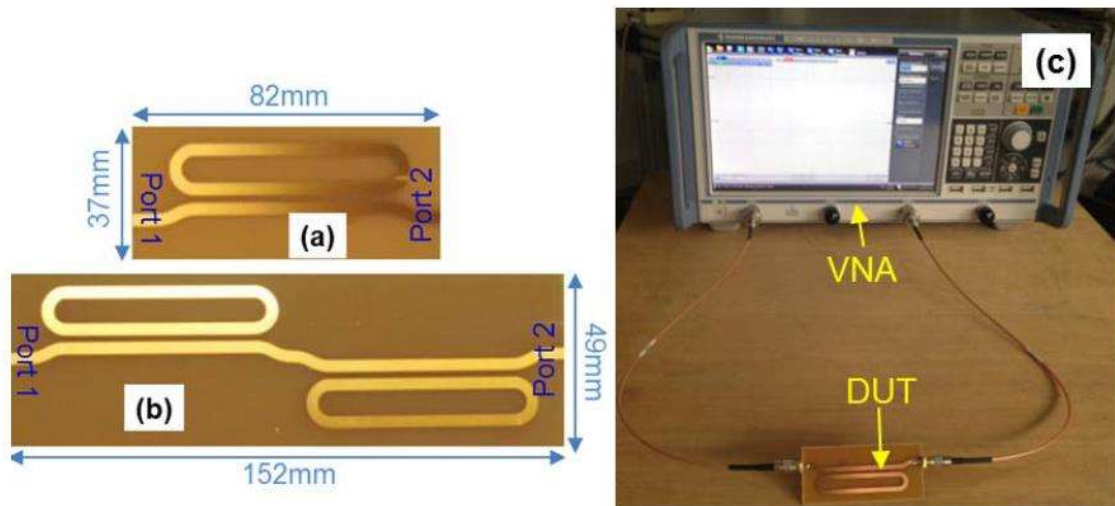
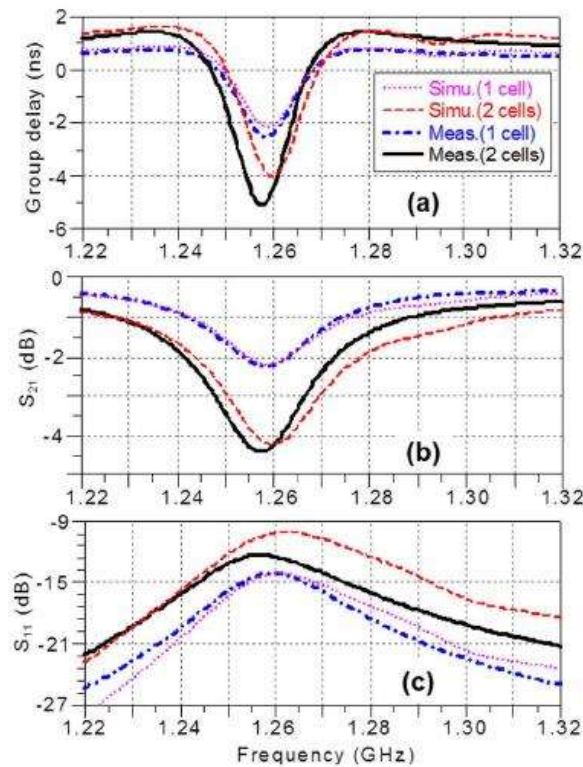


Figure 13 – Simulated and measured (a) GD, (b)  $S_{21}$  and (c)  $S_{11}$  of the “10”-circuit shown in Fig. 12 [44]

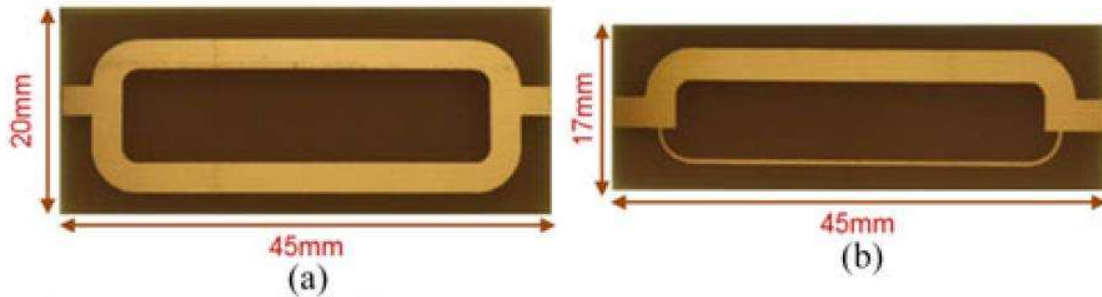


### 3.1.6. BP-NGD PARALLEL INTERCONNECT LINE (PIL) MICROSTRIP CIRCUIT DESIGN

The most fundamental distributed topology of BP-NGD circuit is the PIL structure. This topology is composed of two different interconnect lines connected in parallel. Figs. 14 show two different cases of PIL microstrip circuits. Fig. 14(a) is an example of structure with constituting TLs same characteristic impedance but

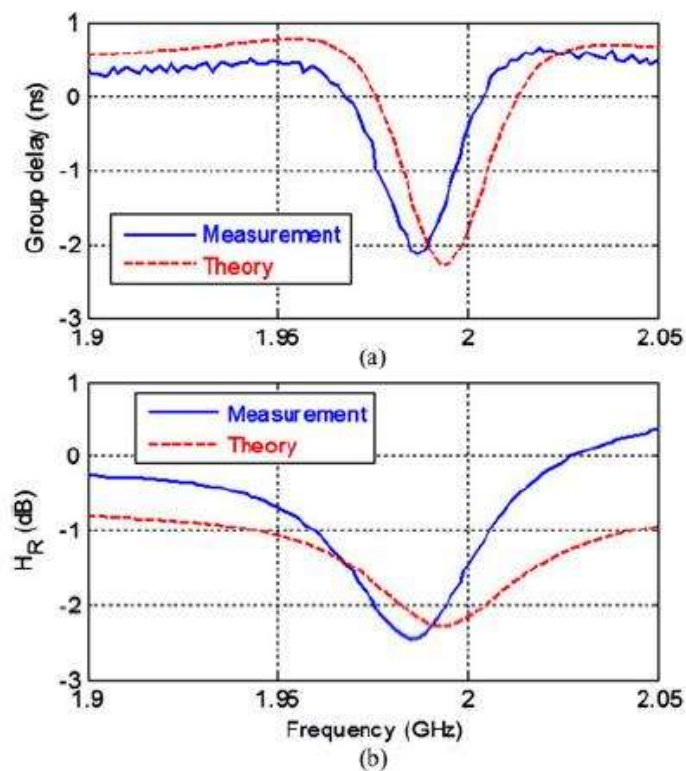
different physical lengths. However, Fig. 14(b) presents another example with different characteristic impedance but the same physical lengths.

Figure 14 – BP-NGD PIL microstrip circuit with different (a) length and (b) impedance arms [33]



Similar to the previous case, Figs. 15 show that we have BP-NGD behaviors with both circuits with NGD center frequency slightly below 2 GHz.

Figure 15 – Simulated and measured (a) GD, (b)  $S_{21}$  and (c)  $S_{11}$  of the PIL-circuit shown in Fig. 14 [33]



### 3.2. BP-NGD LADDER-SHAPE MICROSTRIP CIRCUIT DESIGN

Figs. 16 present the design and photograph of two-cell based ladder microstrip circuit. The S-parameter simulations from 3.8 GHz to 4 GHz were performed to study the BP-NGD behavior of this structure.



Figure 16 – (a) HFSS® design and (b) photo of BP-NGD ladder-shape microstrip circuit [38]

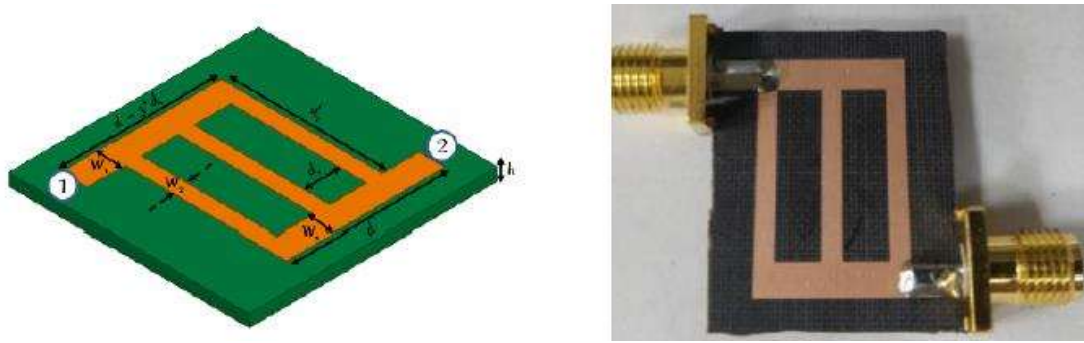


Figure 17 – Cartographies of (a) GD, (b)  $S_{21}$  and (c)  $S_{11}$  vs ( $f$ ,  $w_1$ ), and (d)  $\min(\text{GD})$ , (e)  $\min(S_{21})$ , and (f)  $\min(S_{11})$  [38].

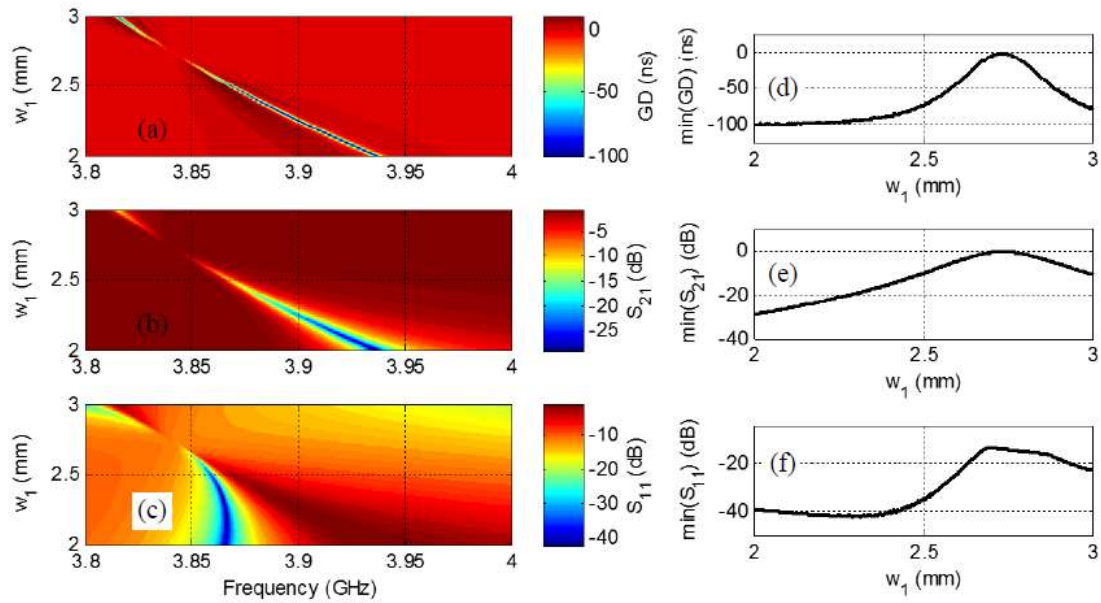
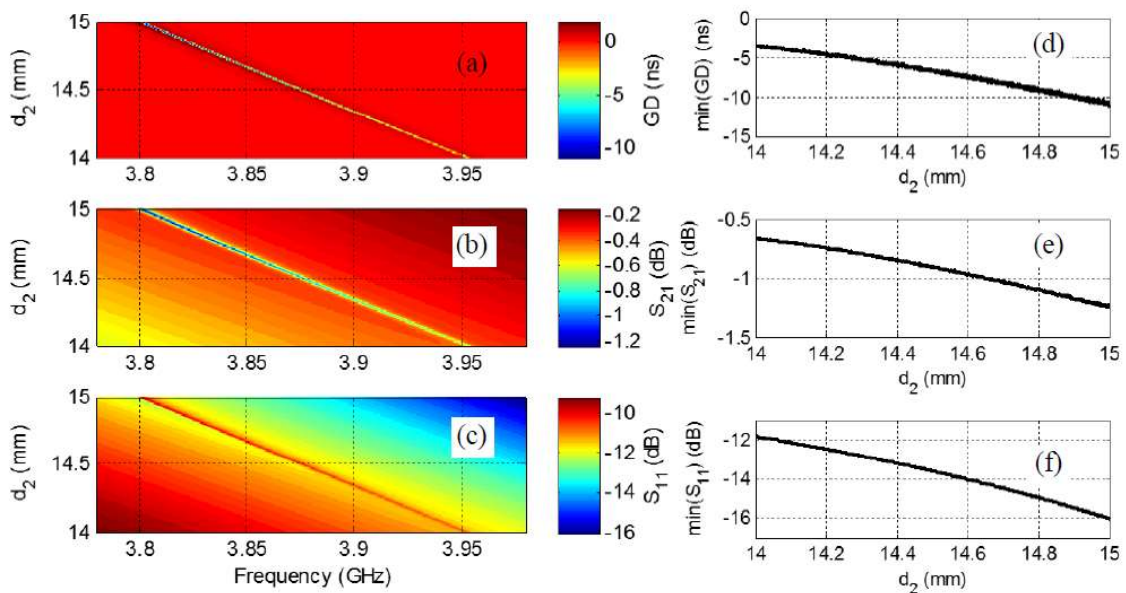
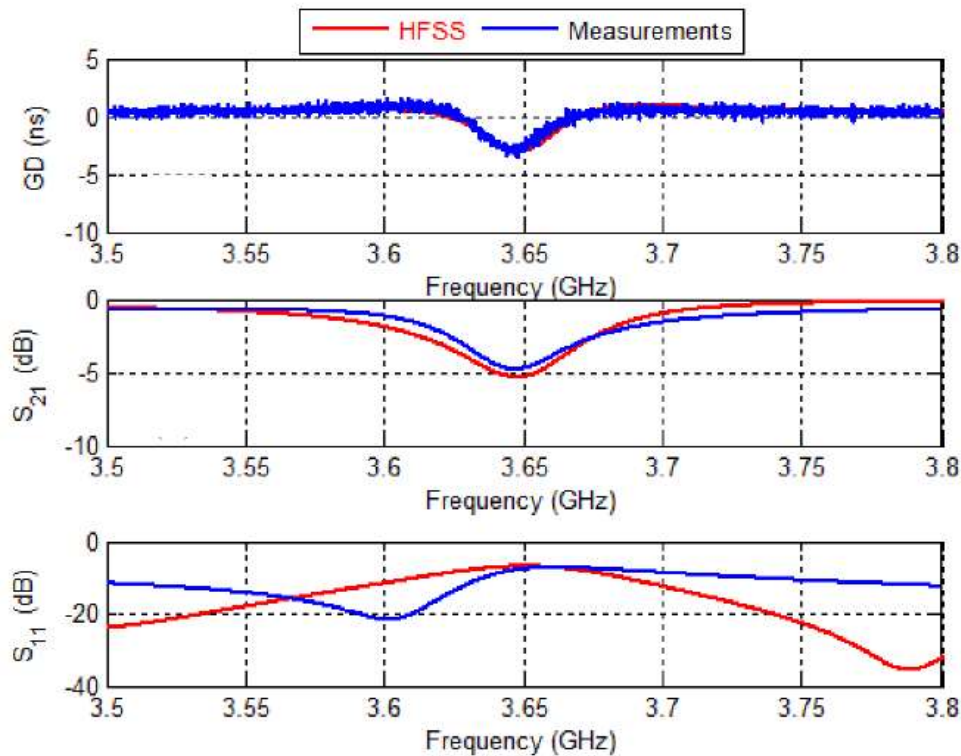


Figure 18 – Cartographies of (a) GD, (b)  $S_{21}$  and (c)  $S_{11}$  vs ( $f$ ,  $d_2$ ), and (d)  $\min(\text{GD})$ , (e)  $\min(S_{21})$ , and (f)  $\min(S_{11})$  [37].



The sweep of the geometrical width  $w_1$  and length  $d_2$  enables to understand how they can influence the BP-NGD performances as seen in Figs. 17 and in Figs. 18. The BP-NGD behavior validity is verified with the results of Figs. 19. We have NGD center frequency around 3.65 GHz.

Figure 19 – Simulated and measured (a) GD, (b)  $S_{21}$  and (c)  $S_{11}$  of the ladder-circuit shown in Fig. 16 [37]



Owing to the hopeful research progress about the BP-NGD microstrip circuit design, all engineers and scientists are today wondering about the NGD RF and microwave electronic engineering application.

#### 4. BRIEF DISCUSSION ON RF AND MICROWAVE ELECTRONIC ENGINEERING APPLICATIONS OF NGD CIRCUIT

The present chapter section is dedicated to brief discussion about the NGD circuit original and innovative applications. The NGD solutions introduced herein may revolutionize the future RF and microwave communication engineering. These applications are nowadays the NGD RF and microwave electronic circuit design future research work with industrial companies.

#### **4.1. NGD CIRCUIT DESIGN APPLICATION CONTEXT**

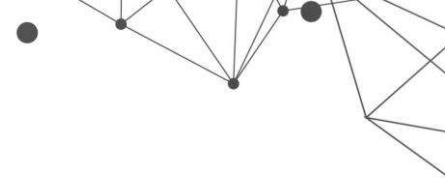
So far despite the progress of RF and microwave electronic engineering, the communication circuits and systems suffer from signal time delay as the electric interconnection effects in PCBs [78-79]. The NGD RF and microwave electronic engineering is the most promising solution against the time-delay problem in the communication systems and all electronic circuits. Since the late of 2000s, some potential tentative applications [80-113] were proposed in the literature. The present section describes basically some of them. But in few near future years, industrial funding's from small, medium and large RF and microwave communication engineering companies are expected to develop those potential applications.

#### **4.2. DELAY COMPENSATION, CANCELLATION AND REDUCTION WITH NGD CIRCUITS [80-83]**

With the increase of design complexity, the delay influences of electrical interconnection structures as PCB traces [78-79] and also transmission cables on the performance of electronic circuits and communication systems cannot be neglected. The natural applications of the NGD circuits are the possibility to compensate, cancel out and reduce the positive delay. The feasibility of this idea was theoretically and experimentally proved in different frequency bands as reported in [80-83]. These innovative applications are currently under exploitation for the design of new generation RF and microwave electronic PCBs in terms of signal integrity, electromagnetic compatibility (EMC) and electromagnetic interference (EMI) engineering.

#### **4.3. ELECTRIC INTERCONNECT EQUALIZATION AND SIGNAL INTEGRITY (SI) IMPROVEMENT [84-93]**

Because of the possibility to investigate the NGD circuits with S-parameter approach including the transmission and reflection coefficients, the NGD solution for the signal integrity improvement is expected to be the biggest application. By means of RC-, RLC- and RLCG- interconnect equivalent circuit models, different preliminary studies [84-93] are performed to verify the feasibility of this innovative idea. So far, the NGD circuit equalizer was experimented only with large size PCBs.



The industrial solutions in real-system as communication transceiver can be expected with integrated circuits in CMOS and MMIC technologies.

#### **4.4. PULSE COMPRESSION WITH BP-NGD RF AND MICROWAVE CIRCUIT [94-95]**

The RF and microwave pulse signals are used in many areas as radar, satellite, aeronautics and space engineering. One of issues limiting the performances of radar and space communication system is the pulse signal spreading. The compression technique with BP-NGD circuits are expected to be a potential candidate against this technical limitation. The feasibility of the pulse compression NGD technique was proposed in [94-95].

#### **4.5. NGD TECHNIQUE OF RLC RESONANCE EFFECT REDUCTION FOR RF AND MICROWAVE EMC APPLICATION [96-98]**

The resonance effects are very expensive for EMC and EMI engineers. By means of NGD equalization technique, it was analytically demonstrated with RLC-network based POC circuits that the BP-NGD circuits are capable to reduce cheaply the RLC resonance effect [96-98]. The possibility to solve this EMC and EMI issues was also verified by 3-D electromagnetic full wave simulations for example with different commercial tools as HFSS®, CST MWS® and FeKo®.

#### **4.6. NGD SYNCHRONIZATION OF MULTI-BAND WIRELESS COMMUNICATION WITH 5G POTENTIAL APPLICATIONS [99-100]**

The challenge of anywhere and anytime applications of 5G technology requires a challenge in term of delay synchronization of RF and microwave signal transmission. A preliminary study with multi-band BP-NGD circuit is promising for the feasibility of propagation delay effect reduction [99-100]. The GD spectral analyses allow to state the possibility to solve the problem related to the multi-band desynchronization.

#### **4.7. RF AND MICROWAVE PHASE SHIFTER (PS) WITH NEGLECTED DELAY [101-106]**

Most of classical RF and microwave PS suffers from delay effect which may induce some phase noise in the communication system. The NGD circuits constitutes a potential candidate as solution against such issues. Under a very good matching condition, by cascading a positive GD and NGD circuits, we can obtain a PS with delay theoretically equal to zero. This NGD PS RF and microwave design represents many promising solutions for the future 5G and 6G transceiver systems.

#### **4.8. IMPROVEMENT OF RF AND MICROWAVE DEVICES PERFORMANCES WITH BP-NGD CIRCUITS FOR TRANSCEIVER COMMUNICATION SYSTEM APPLICATIONS [107-108]**

Several concepts and applications of BP-NGD circuits for transceiver communication system and their constituting devices are suggested in [107]. The concept was extended to microwave broadband Balun in [108]. The development of power divider and combiner with operating under independent frequency is currently in progress. The NGD design solution is expected to improve the performances of wireless communication receiver as introduced in [109-110].

#### **4.9. SOME LP-NGD CIRCUIT DESIGN POTENTIAL APPLICATIONS FOR LOW-FREQUENCY SENSORS AND ACTUATORS [111-113]**

In addition to RF and microwave communication system, innovative ideas of LP-NGD application were also initiated. For example, it was experimentally demonstrated that the LP-NGD circuit permits:

- To reconstruct with very high correlation distorted arbitrary signals [111],
- To anticipate signals provided by industrial actuators [112],
- To pre-detect sensed signals with possibility to increase time-advance with multi-stage LP-NGD circuits [113].

### **5. CONCLUSIONS**

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The NGD is one of the most fascinating and counterintuitive electronic functions ever being investigated. A lot of questions about the methodology to design, implemented and test the BP-NGD circuits have been wondered by students, scientists, physicists, and even non-specialist RF and microwave design, fabrication, test and commercial engineers. As answer, a literature review on the BP-NGD microstrip circuit design is presented in this chapter. A non-exhaustive state of art on the generality about the NGD circuit, theory, design and engineering is introduced. Moreover, different types of NGD topologies inspired from filter theory are defined. The main focus on the design method and the analysis of different microstrip circuits is presented.

The future research works on the NGD engineering in the next two decades will be massively on the development of applications notably for the RF and microwave devices to improve front- and back-end communication system architecture. Nevertheless, many questions about the BP-NGD circuit integrability

and testability are still open. Following the roadmap about the NGD electronic circuit utility, brief discussion on the NGD circuit potential applications are opened at the end of chapter.

## ACKNOWLEDGEMENTS

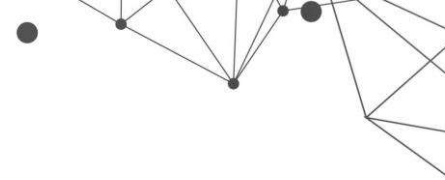
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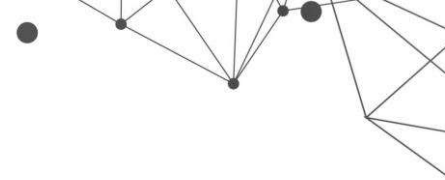
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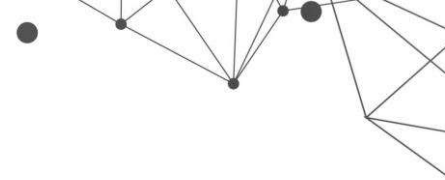
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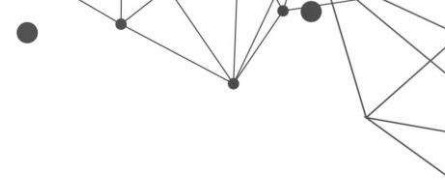
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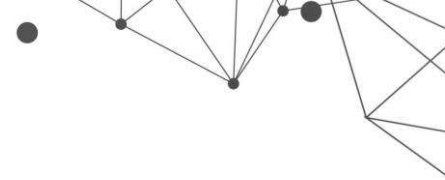


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